KUNSTSTOFFKOLLEKTOR MIT EIGENSICHERER TEMPERATURBEGRENZUNG – POTENTIALE FÜR SYSTEMTECHNISCHE INTEGRATIONSMÖGLICHKEITEN

POLYMER COLLECTORS WITH TEMPERATURE CONTROL – POTENTIALS FOR SYSTEM INTEGRATION

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1. Introduction

Within the Austrian research project SolPol-4/5 it is the goal to find solutions for solar thermal systems based on cheap polymer materials but with low temperature limits in order to realize significant cost reduction potentials. Therefore one major point is to keep the temperature of the solar collector (and the complete system) below the material limits which means below 100°C for cheap polymer materials. For this, several possibilities are under investigation in many research projects. One solution is to design the collector in such a way, that the performance does not allow stagnation temperatures above 100°C (temperature limited collector – TLC). Other solutions try to keep the collector performance highest possible during operation and reduce the performance during stagnation by different technical solutions (overheat controlled – OHC) like reduction of absorption characteristic at high temperatures (Föste, 2015), reduction of transmission of the transparent cover or increasing the heat losses by activating cooling processes like internal ventilation of the collector (Harrison, 2004) or using a thermosyphon driven backcooler (Thür, 2014). This simulation study based on different parameter variations estimates how different operating conditions can influence design parameters for a solar domestic hot water system (SDHW) with different collector types.
For different possible market conditions, which can potentially be situated world-wide, the goal of these investigations is to find out dependencies of different design parameters depending on specific operating conditions for solar domestic hot water systems (SDHW). Topics of investigations based on system simulations using (Polysun, 2016) are:

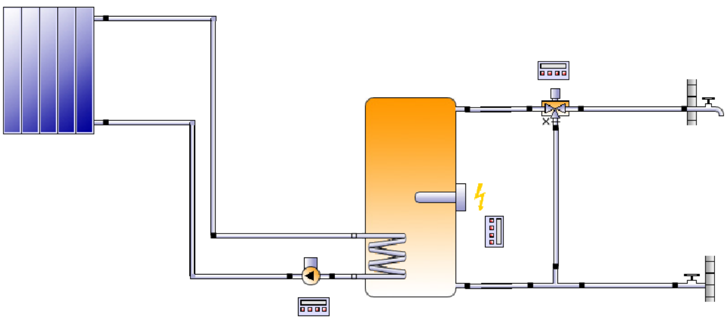
1. Collector area
2. Different collector types (3 types)
3. Domestic hot water storage volume (3 volumes)
4. Domestic hot water tap temperature and daily consumption (2 temperatures)
5. Domestic hot water consumption profile with different distribution of peaks during day (4 profiles)
6. Different Climate conditions (Irradiation, cold water temperature; 2 places)
7. Solar fraction
8. CO_2 emissions
9. Levelized energy cost for a complete system (solar heating and reference)

For comparison, as collector types 1) a high performance standard flat plate collector (FK) and two temperature limited collectors are chosen: 2) a standard flat plate collector with overheat control (FK-OHC), which uses a back-cooler during stagnation periods and 3) a temperature limited collector (TLC) which is designed to have performance parameters which guarantee not to exceed a stagnation temperature of about 100 °C. Such a TLC collector could easily be produced in mass production as a cheap polymer collector.

Two general questions are investigated from different points of view: 1) what is the difference between SDHW systems with FK and TLC collector, and 2) how big is the theoretical potential of a high performing collector with temperature control functionality (FK-OHC).
For analyzing the potential of the temperature limited collector types (compared to a standard collector) annual simulations for a solar domestic hot water system (SDHW) are performed with the following boundary conditions (see Picture 1).

As daily hot water load 2 variations are defined: 100 liters/day at 50 C tap temperature (base case) and 200 liters/day at 40°C (extreme case for very low temperature). Four types of daily load profiles were considered: Constant, Morning peak, Daily peaks and Evening peak (Table 1).

Three hot water tanks are chosen for the system: 295 liters (295L), 100 liters (100L) and 30 liters (30L). The maximum temperature allowed in the tank is 65 C. The thickness of insulation at the top in case of 295L and 100L tank is 80 mm, for the 30L tank, it is 40 mm. Thickness at the tank base is 50 mm for the 295L and 100L tank and 25 mm for the 30L tank. An electric heater was chosen as the backup heater at 50% of the tank height.



Picture 1 - Polysun simulation model

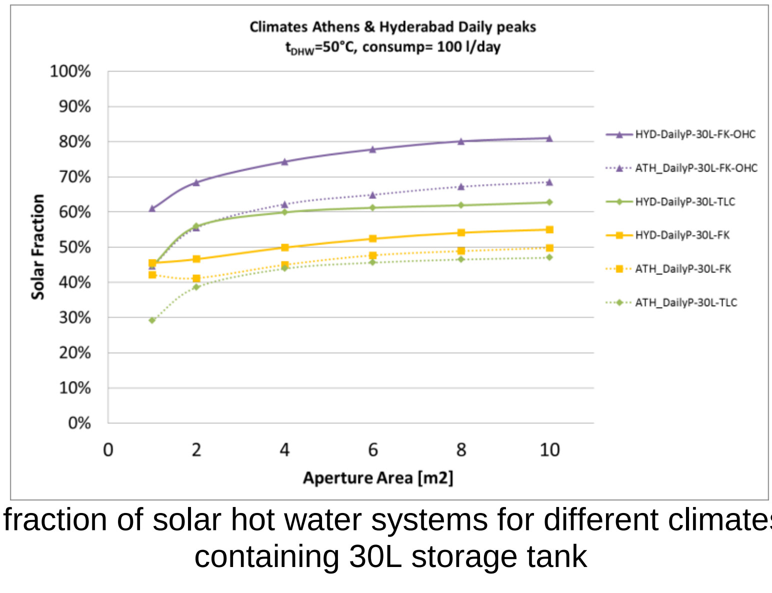
Table 1 Hot water consumption during a day

Hour	Daily Profile of Peaks [%]			
	Constant	Morning	Daily	Evening
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
4	5	2	2,3	2
5	5	2	2,3	2
6	5	2	2,3	2
7	5	2	2,3	6
8	5	12	8	6
9	5	12	8	6
10	5	12	8	6
11	5	2	2,3	2
12	5	2	2,3	2
13	5	6	8	6
14	5	6	8	6
15	5	6	8	6
16	5	2	2,3	2
17	5	2	2,3	2
18	5	6	8	12
19	5	6	8	12
20	5	6	8	12
21	5	6	2,4	2
22	5	2	2,4	2
23	5	2	2,4	2
24	0	2	2,4	2

As standard solar collector a conventional flat plate collector (FK) with the efficiency parameter of η_0 = 0.80; a_1=3.0 W/m²K; a_2 = 0.010 W/m²K² is used. For this collector, the maximum temperature is defined to be 100 C, assuming a low pressure system (like TLC collector) where steam would occur at higher temperatures. This means that the pump is allowed to run only if the collector temperature is below 100 C.
As first option, a temperature limited collector (TLC) based on polymer materials with the efficiency parameter of η_0 = 0.70; a_1 = 7.94 W/m²K; a_2 = 0.034 W/m²K² is used. The SDHW-system with this collector is also allowed to run the pump at any time when the hot water storage needs energy because the stagnation temperature is below 100°C.
As a second option, a flat plate- over heat controlled collector (FK-OHC) with the efficiency parameter of η_0 = 0.80; a_1 = 3.0 W/m²K; a_2 = 0.010 W/m²K² is used. Although the chosen efficiency parameters are the same as for the conventional flat plate collector (FK), the solar heating system with this collector is allowed to run the pump at any time when the hot water storage needs energy, thus taking into account the backcooler. This hypothetic collector shall show a theoretical potential.
Polysun simulations were carried out for a set of aperture areas of: 1, 2, 4, 6, 8 and 10 m². Incidence angle modifier (IAM50) equals 0.95 for all types of collectors.
The calculations were done for 2 different climates: City of Hyderabad (HYD) in India (Latitude: 18° N) and Athens (ATH) in Greece (Latitude: 38° N). The collector slope was chosen accordingly to the latitude with 15 and 35 ° respectively. The annual global solar irradiation on the collector aperture area result in 2,011 kWh/m^2 in Hyderabad and 1,655 kWh/m^2 in Athens. The annual mean temperature of the cold water and the storage room where the storage tank is mounted is 26.7 C in the climate of Hyderabad and 18 C in a climate of Athens. Based on the assumption of the hot water load of 100L/day at 50 °C, the estimated energy demand for one year results in 860 kWh/year in Hyderabad and 1,355 kWh/year in Athens.

2. Annual Simulations with different Tank Volumes

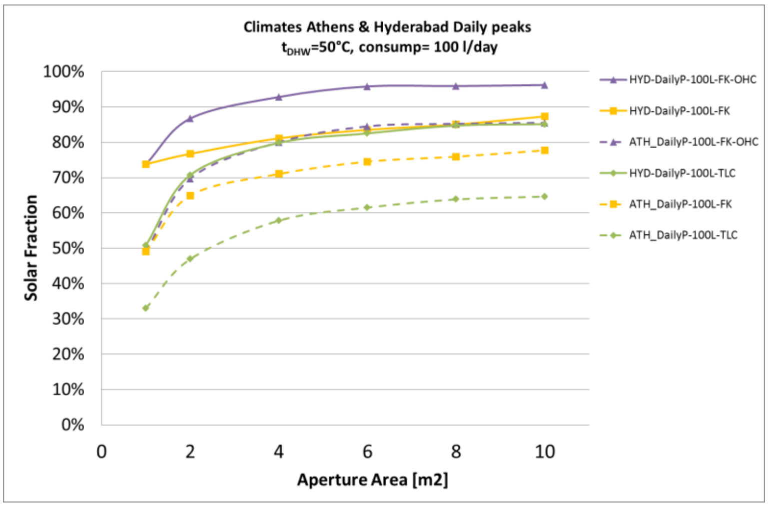
In Picture 2, the results are presented for both locations (Hyderabad: HYD; Athens: ATH) in terms of solar fraction (= $Q_{sol}/(Q_{sol}+Q_{aux})$) as a function of collector aperture area and different collector types with a very small 30L storage tank and the "daily peak" (see Table 1) profile. In general solar fractions for this small storage are comparable low, especially in Athens.
In Hyderabad (full lines) for such a very small tank the TLC collector performs equal (1 m^2) or significant better (with larger areas) than the FK collector. Reason for this result is the fact of significant stagnation periods of the FK collector during the day because of overheating. The FK-OHC collector shows the potential of a high performing overheat controlled collector with much higher solar fraction compared to FK, 1 m^2 FK-OHC has still higher solar fraction than 10 m^2 FK.



Picture 2 - Solar fraction of solar hot water systems for different climates, collector types, containing 30L storage tank

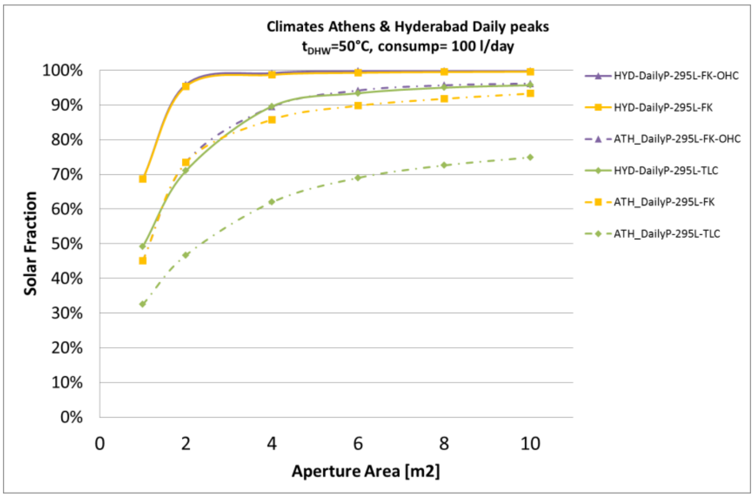
In Athens (dotted lines) the FK and the TLC collector perform almost similar, just with a very small collector area (1m^2) the FK collector does not have the stagnation problem and therefore performs significant better. Also in Athens the FK-OHC shows significant potential for increased solar fraction.

In Picture 3 the results for the SDHW-system with a 100L storage (instead of 30L) are shown. In Hyderabad (full lines) the TLC still performs equal to the FK collector with 4 m^2 or more collector area. The potential of the FK-OHC compared to FK still is significant but strongly reduced to about 10%-points (25%-points before). In Athens (dashed lines) the 100L storage significantly reduces the stagnation problem of the FK collector resulting in clear higher performance compared to the TLC. The FK-OHC still shows potential of improvement by 10%-points compared to the FK collector.



Picture 3 - Solar fraction of solar hot water systems for different climates, collector types, containing 100L storage tank

In Picture 4 the results for the SDHW-system with a 295L storage (instead of 30L or 100L) are shown. In Hyderabad (full lines) with this large tank no potential of the FK-OHC compared to the FK collector remains. The TLC collector energetically is not competitive anymore, but economically it might be of interest, if it is significant cheaper (see Picture 17).
In Athens (dashed lines) with a 295L tank only little advantage of the FK-OHC remains, but only with very large collector areas. The TLC collector with a 295L tank is energetically significant less competitive. Therefore, for this operation conditions it might be of interest to improve the TLC collector to a high performing polymer collector in combination with OHC technology.

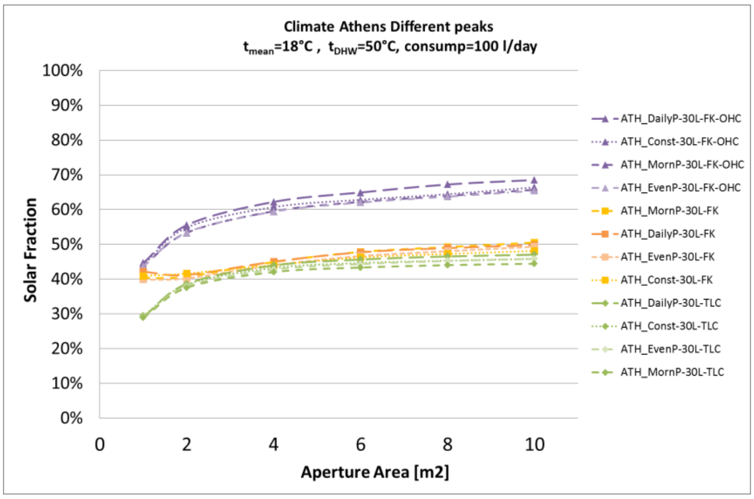


Picture 4 - Solar fraction of solar hot water systems for different climates, collector types, containing 295L storage tank

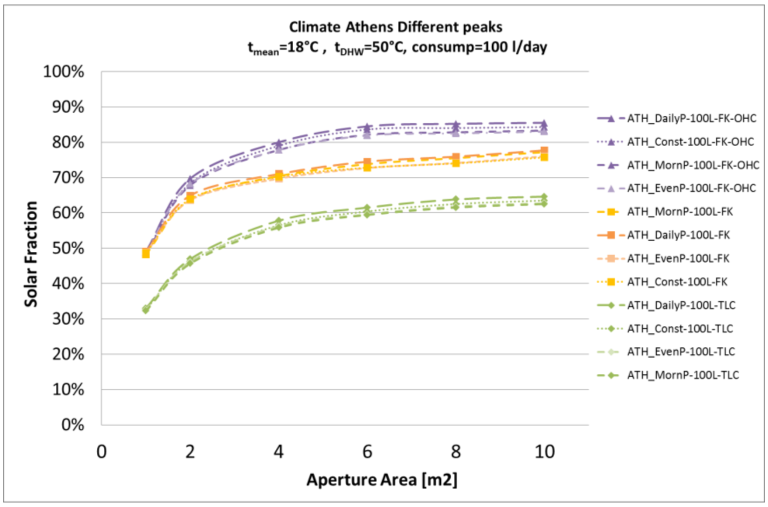
3. Annual Simulations with different Consumption Profiles in Athens

Several simulations were done to investigate the influence of the domestic hot water profile with the peaks distributed in different ways (daily, constant, morning, evening) during the day (see Table 1). The following graphs (Picture 5 to Picture 7) show the following dependencies in Athens climatic conditions:

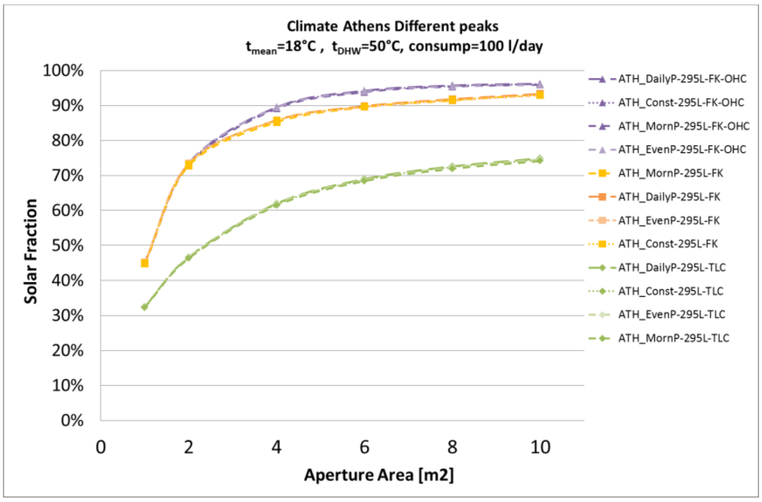
1. The band of difference in solar fraction is quite small, in the range of up to 3%-points with very small 30L tank but no remarkable range anymore with 295L tank.
2. The band of difference in solar fraction is increasing with decreasing tank volume.
3. The daily consumption results in the highest solar fractions for all collector types.
4. The morning peak consumption results in the lowest solar fractions for FK-OHC and TLC collector types, but the constant profile shows lowest solar fractions for FK collector.



Picture 5 - Solar fraction of solar hot water systems for different peak loads, collector types, containing 30L storage tank



Picture 6 - Solar fraction of solar hot water systems for different peak loads, collector types, containing 100L storage tank

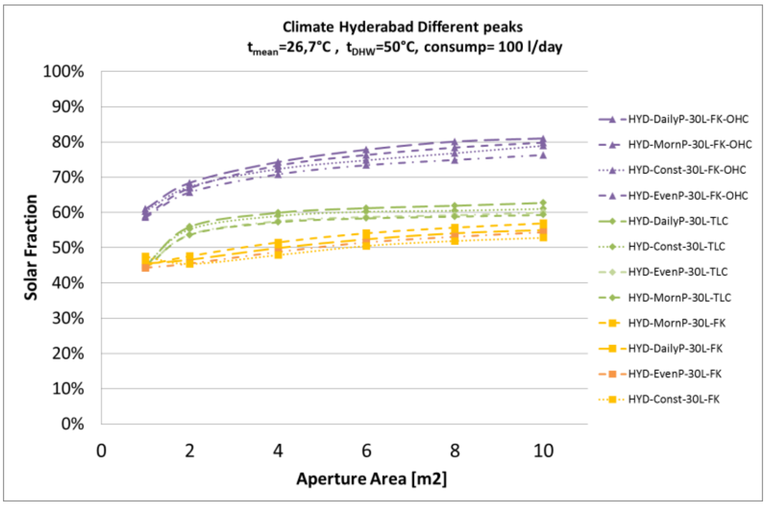


Picture 7 - Solar fraction of solar hot water systems for different peak loads, collector types, containing 295L storage tank

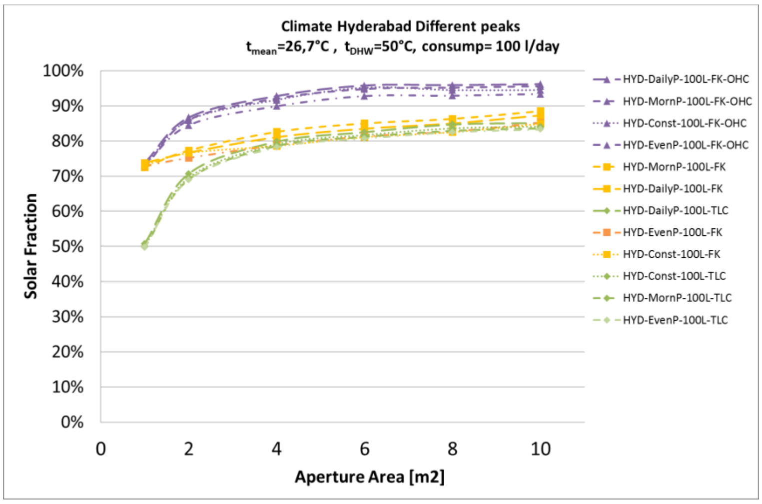
4. Annual Simulations with different Consumption Profiles in Hyderabad

The following graphs (Picture 8 to Picture 10) show the following dependencies in Hyderabad climatic conditions with hot water consumption at 50°C tap temperature and 100 L per day (860 kWh/year). The band of difference in solar fraction is larger compared to Athens, in the range of up to 5%-points with very small 30L tank but again no remarkable band anymore with 295L tank. The effects 2) to 4) mentioned before in Athens are the same as here in Hyderabad.

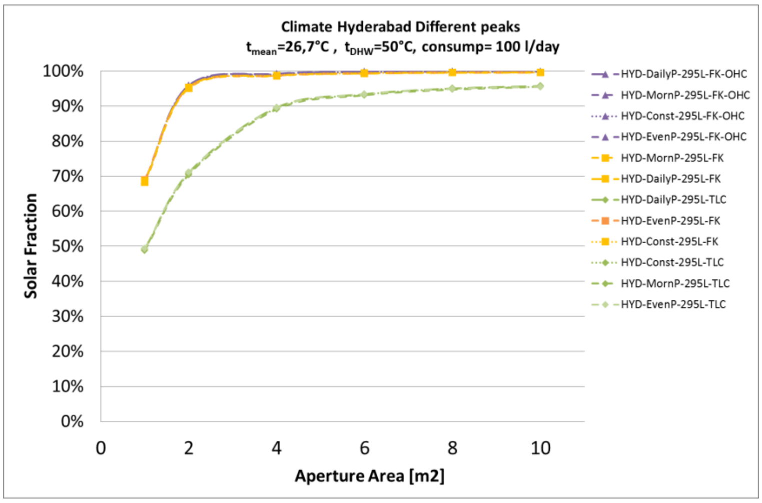
The later graphs (Picture 11 to Picture 13) show the dependencies in Hyderabad climatic conditions with hot water consumption at 40°C tap temperature and 200 L per day (860 kWh/year). The band of difference in solar fraction is again larger compared to Athens and Hyderabad with 50°C and 100L/day, now in the range of up to 8%-points with very small 30L tank but again no remarkable band anymore with 295L tank. The effects 2) to 4) mentioned before in Athens are again the same as here in Hyderabad.



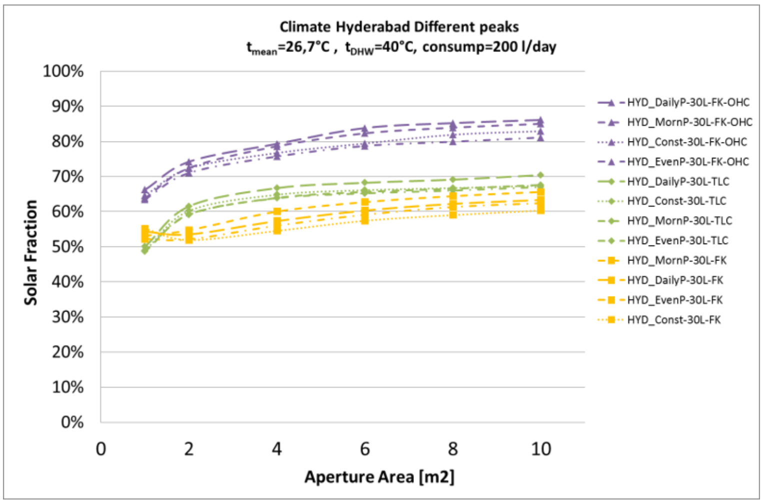
Picture 8 - Solar fraction of solar hot water systems for different peak loads, collector types, containing 30L storage tank



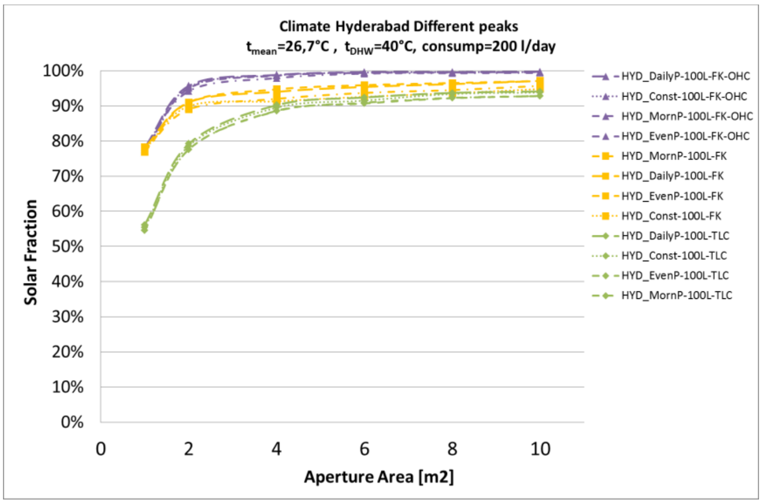
Picture 9 - Solar fraction of solar hot water systems for different peak loads, collector types, containing 100L storage tank



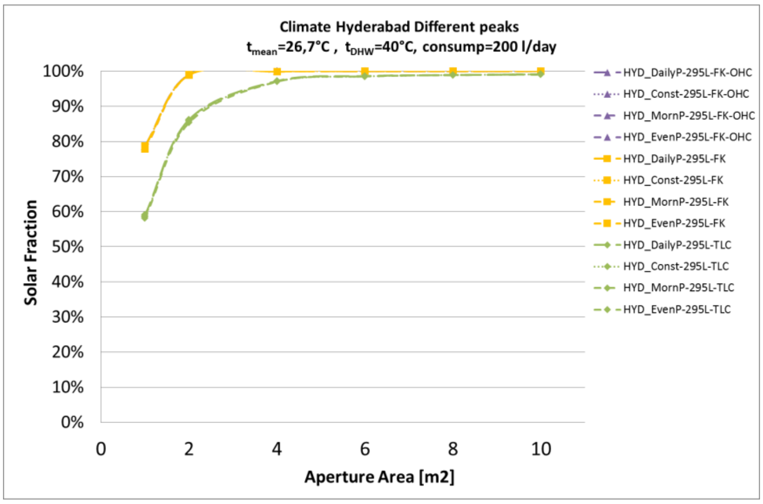
Picture 10 - Solar fraction of solar hot water systems for different peak loads, collector types, containing 295L storage tank



Picture 11 - Solar fraction of solar hot water systems for different peak loads, collector types, containing 30L storage tank



Picture 12 - Solar fraction of solar hot water systems for different peak loads, collector types, containing 100L storage tank



Picture 13 - Solar fraction of solar hot water systems for different peak loads, collector types, containing 295L storage tank

The influence of different domestic hot water profiles on the band of solar fractions therefore is increasing with: 1) decreasing tank volume, 2) decreasing tap temperature (t_{DHW}) and 3) with increasing cold water temperature depending on the climate.

5. Input data for calculation of levelized energy cost and CO_2 emissions

Based on the energetic simulations presented before, an estimation of possible heat prices with different (partly hypothetic) cost scenarios in combination with CO_2 emissions are done. Especially the assumptions for the TLC system cost scenario are done based on future scenario expectations for high possible cost reduction potentials due to industrial mass production of polymer products. However, the main goal of the investigation is to show relative changes within technology types due to parameter variations and not comparing the absolute values of the different technologies.

Inputs for the economic and ecologic calculations are based on the results of the Polysun simulations. The most important results of the simulations are Q_{aux}, Q_{use}, and Q_{sol}. Q_{aux} presents the energy transferred by the electric heater into the tank; Q_{use} presents the energy effectively consumed by the consumers as domestic hot water consumption (DHW); Q_{sol} presents energy gained by the collector to heat the hot water tank and not considering pipe losses to the tank.

Values displayed in Table 2 were used for all economic and ecologic calculations for both climates.

Table 2 Economic and ecologic values

Period under consideration	[year]	25
Credit period	[year]	10
Inflation rate	[%]	0,03
Market discount rate		0,03
Credit interest rate		0,03
Inflation rate for energy prices (electricity)		0,03
Inflation rate for energy prices (gas)		0,03

The electricity price, CO_2 factors, and cost of components differ from locations. The different price of electricity and CO_2 factors for Hyderabad and Athens are displayed in Table 3.

Table 3 CO_2 factors and electricity price (Source: [1, 2, 3])

		Hyderabad	**Athens**
CO_2 factor for electricity	[kgCO_2/kWh]	0,968	0,731
Electricity Price	[€/kWh]	0,1	0,18

The collector type is one of the main parameters influencing the overall cost of the system. Assumed prices of the collectors and components needed for the system´s running are showed in the Table 4. It is assumed that the SDHW system is a compact system with the tank direct beside the collectors. For the FK/FK-OHC system costs are assumed similar to actual costs in Europe, for the TLC system optimistic price reduction potential was assumed. No market distribution costs are taken into account.

Table 4 Prices of the collectors and all components

		TLC	**FK**	**FK-OHC**
Collector field	[€/m^2]	50	75	100
Attachment	[€/m^2]	15	25	
Pump group	[€/ construction]	30	75	
Controller	[€/ construction]	50		
Expansion vessel	[€/ construction]	25		
Piping	[€/ construction]	50		
Electric Heater	[€/ construction]	200		
Construction	[€/m^2]	5	100	

All these considered values were used to evaluate the total amount of the SDHW system excluding hot water tank. This final value obviously depends on the collector type and also aperture area. All total amounts are shown in Table 5.

Table 5 Total specific cost of the SDHW system excl. tank

Aperture area [m^2]	**TLC**	**FK**	**FK-OHC**
	[€/m^2]		
1	225	400	425
2	148	300	325
4	109	250	275
6	96	233	258
8	89	225	250
10	86	220	245

The prices of the storage tanks differ according to the volume of the tank. A reference system was used for the comparison system´s effectivity. The reference system´s storage tank volume depends on the volume of the tank used in SDHW system. Table 6 contains not only the prices corresponding to the storage tank size but also the volume of the storage tank used for the reference system. Storage prices for the FK/FK-OHC system are assumed similar to actual prices in Europe, for the TLC system optimistic price reduction potential was assumed.

Table 6 Values used in the calculations

Volume of SDHW system storage tank	**[l]**	30	100	300
Price of the storage tank for TLC SDHW system	[€]	90	140	390
Price of the storage tank for FK, FK-OHC SDHW system	[€]	200	300	700
Volume of Reference system storage tank	[l]	30	100	150
Price of Reference system storage tank	[€]	200	300	356

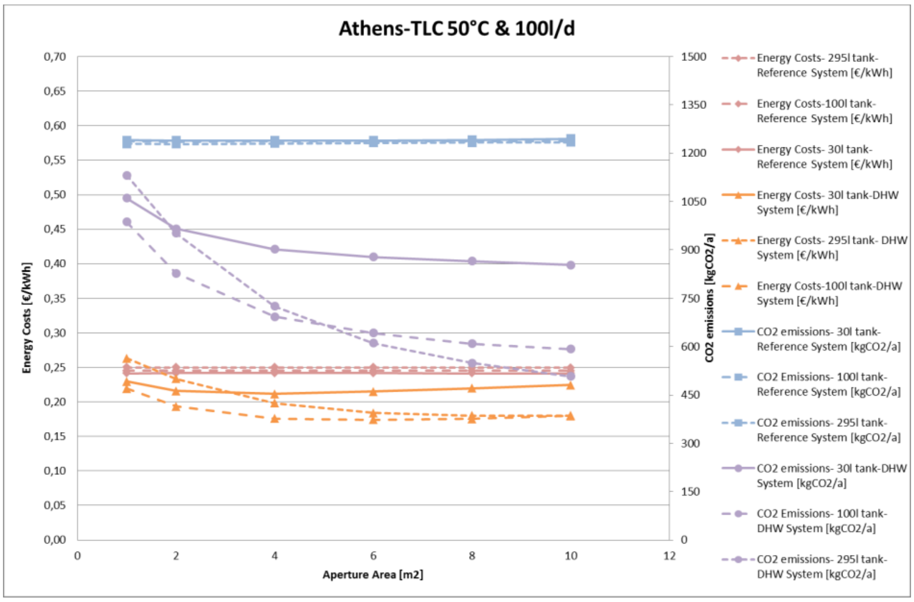
For the reference system the consumption of the electric heater (Q_{aux}) was calculated according to the IEA SHC Task26 concept: energy of DHW consumption plus reference heat loss of the storage depending on the average daily hot water consumption ($Q_{aux}=(Q_{use}+Q_{loss\_ref})/\eta_{aux}$). For DHW consumption of 200 L/day: Q_{loss_ref} = 337 kWh/a. This corresponds to a 150 liter reference tank. For the smaller reference tanks the same reference heat loss is used, assuming reduced quality/thickness of insulation. The efficiency (η_{aux}) of the electric heater is 100%.

Based on these assumptions the CO_2 emissions and the levelized energy costs for the useful domestic hot water energy consumption are calculated with an evaluation tool which is under development within IEA SHC Task53 (Nocke, 2015) and shown in the following graphs for different conditions.

6. Evaluation results for heat price and CO_2 emissions

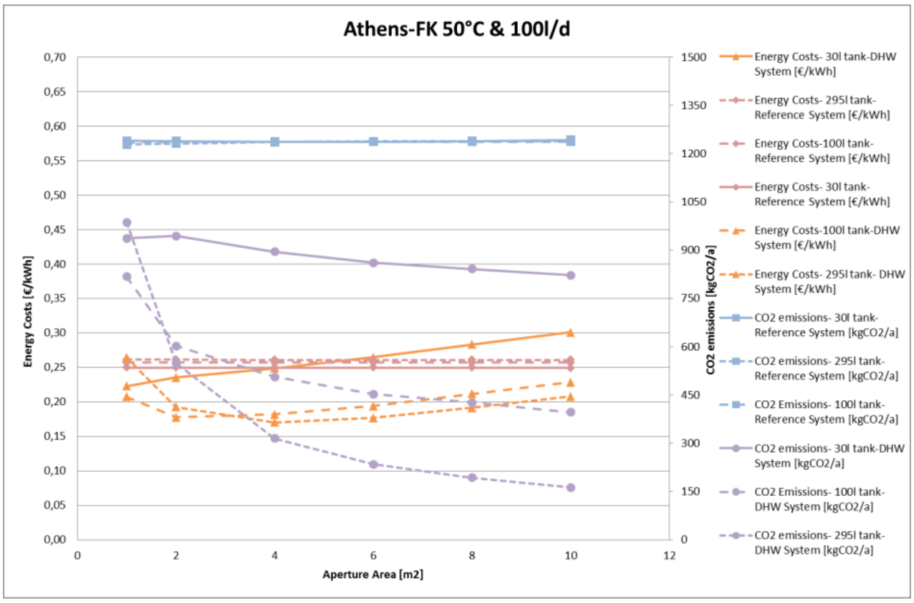
In Picture 14 to Picture 16 for Athens the results for the CO_2 emissions and the levelized energy costs for the useful domestic hot water energy are presented, divided in 3 diagrams related to the collector types: TLC, FK and FK-OHC. The reference DHW-system which is just heated with electricity (0.18 EUR/kWh) results in around 0.25 EUR/kWh annual levelized energy costs and CO_2 emissions of about 1,250 kgCO_2 per year. The small differences are due to the different costs of the three reference tank sizes and small deviations of Q_{use} in the simulation results.

For the TLC SDHW system (Picture 14) the lowest levelized energy costs of 0.174 EUR/kWh are reached with 4 m^2 collector area with a 100L tank resulting in 640 kgCO_2/year. The 30L tank in Athens operating conditions is too small resulting in higher cost and higher CO_2 emissions than other configurations, but in all cases still significant cheaper and with less CO_2 emissions than the reference system. TLC collector with the 295L tank in Athens can be used with larger collector areas of 6 to 8 m^2, achieving low energy cost and low CO2 emissions similar to the best configuration with the 100L tank. This is possible due to the fact of still significantly increasing solar fraction with large collector areas (see Picture 4).



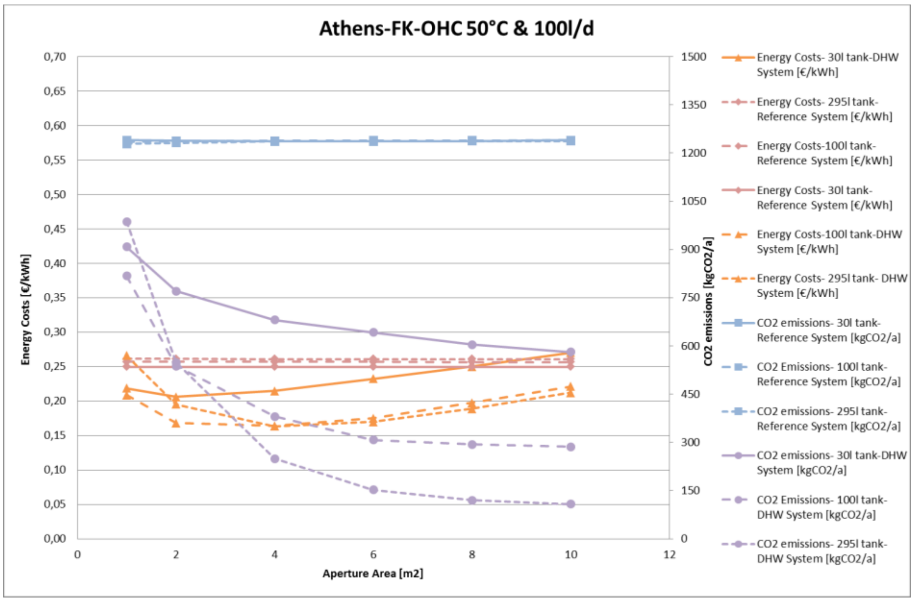
Picture 14 - Results of the economic and ecologic calculations with TLC - climate Athens

For the FK SDHW system (Picture 15) the lowest levelized energy costs of 0.170 EUR/kWh can be reached with 4m^2 collector area with a 295L tank resulting in 315 kgCO_2/year. But interesting economic alternative is the 100L tank with 2m^2 FK collector resulting in just little higher energy cost of 0.178 EUR/kWh, but with almost twice emissions of 600kgCO_2/year. The 30L tank in Athens operating conditions also with FK collector is too small, but still cheaper and with less CO_2 emissions with up to 4m^2 collector area than the reference system.



Picture 15 - Results of the economic and ecologic calculations with FK - climate Athens

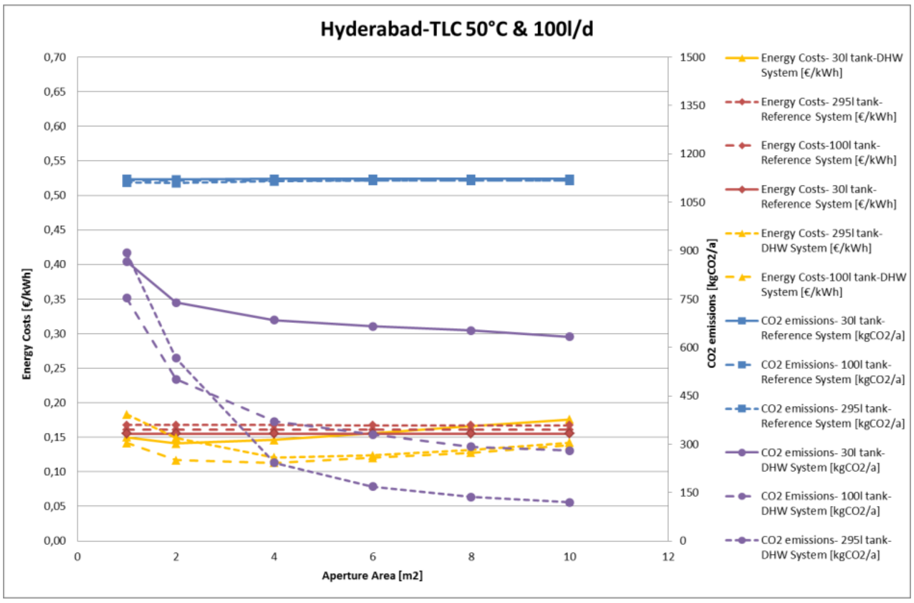
For the FK-OHC SDHW system (Picture 16) the lowest levelized energy costs of 0.164 EUR/kWh can be reached with both, a 4 m^2 collector area with a 295L tank resulting in 250 kgCO_2/year and 4 m^2 collector area with a 100L tank, but resulting in higher emissions of 380 kgCO2/year. Again the 30L tank in Athens operating conditions also with FK-OHC collector is too small (compared to other SDHW configurations), but in comparison with the FK collector an increased benefit in cost and CO_2 emission against the reference system can be obtained.



Picture 16 - Results of the economic and ecologic calculations with FK-OHC - climate Athens

In Picture 17 to Picture 19 for Hyderabad the results for the CO_2 emissions and the levelized energy costs for the useful domestic hot water energy are presented, again divided in 3 diagrams related to the collector types: TLC, FK and FK-OHC. The reference DHW-system which is just heated with electricity (0.10 EUR/kWh)) results in around 0.16 EUR/kWh annual levelized energy costs and CO_2 emissions of about 1,110 $kgCO_2$ per year. The small differences are due to the different costs of the three reference tank sizes and small deviations of Q_{use} in the simulation results.

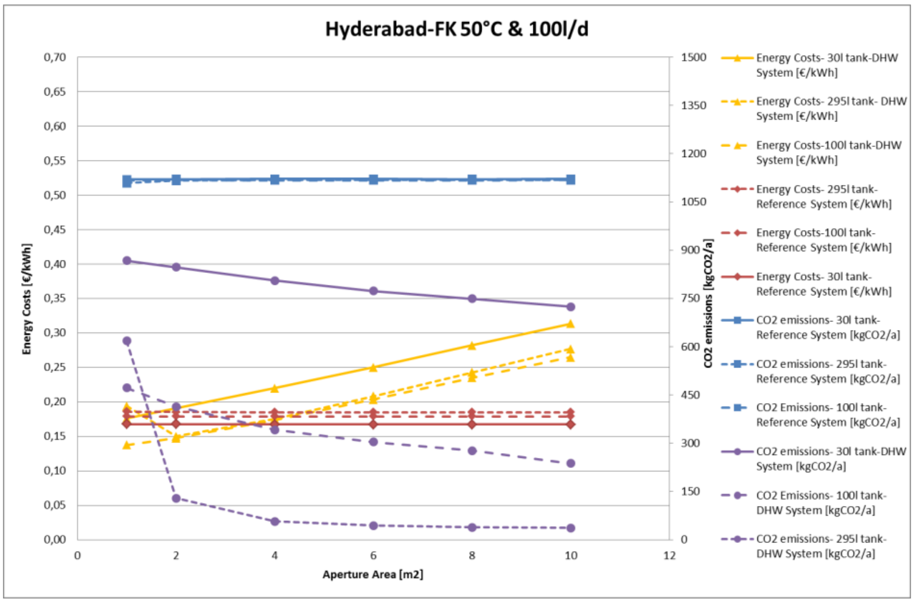
For the TLC SDHW system (Picture 17) the lowest levelized energy costs of 0.113 EUR/kWh is achieved with 4m^2 collector area with a 100L tank resulting in 370 $kgCO_2$/year. The TLC collector in Hyderabad can be used with the 295L tank and collector area of 4m^2 achieving just slightly higher energy cost of 0.121 EUR/kWh (+7%) but remarkable lower CO_2 emissions of 242 $kgCO_2$/year (-35%). The 30L tank with TLC in Hyderabad operating conditions is also too small and resulting in higher cost and higher CO_2 emissions.



Picture 17 - Results of the economic and ecologic calculations - climate Hyderabad

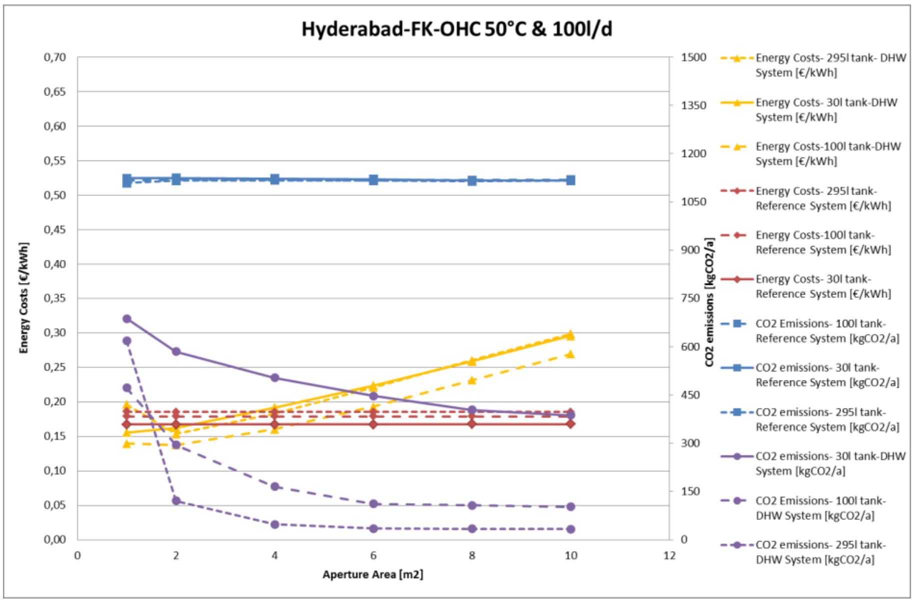
For the FK SDHW system (Picture 18) in Hyderabad the lowest levelized energy costs of 0.137 EUR/kWh is achieved with 1m^2 collector area with a 100L tank resulting in 470 $kgCO_2$/year. But the FK collector with the 295L tank can be used with collector area of

2 m^2, achieving slightly higher energy cost of 0.150 EUR/kWh (+10%) but much lower CO_2 emissions of 130 kgCO_2/year (-72%). The 30L tank with FK collector in Hyderabad operating conditions is also too small and resulting in higher cost and a higher CO_2 emission compared to the other SDHW systems and is not cheaper than the reference system but still better in terms of CO_2 emissions.



Picture 18 - Results of the economic and ecologic calculations - climate Hyderabad

For the FK-OHC SDHW system (Picture 19) in Hyderabad the lowest levelized energy costs of 0.137 EUR/kWh is achieved with 2 m^2 collector area with a 100L tank resulting in 295 kgCO_2/year. But the FK-OHC collector with the 295L tank can be used with collector area of 2 m^2, achieving slightly higher energy cost of 0.150 EUR/kWh (+10%) but much lower CO_2 emissions of 130 kgCO_2/year (-72%).
The 30L tank in Hyderabad operating conditions is also too small and resulting in higher cost and a higher CO_2 emission compared to other SDHW systems. But with small FK-OHC collector area the 30L SDHW system (compared to FK system) is again slightly cheaper than the reference system with significant reduced CO_2 emissions. This can be achieved due to significant higher solar fraction of the FK-OHC system compared to the FK system (Picture 2).



Picture 19 - Results of the economic and ecologic calculations - climate Hyderabad

7. Conclusions

The energetic system performance of TLC collector systems in all cases with 100L and 295L tanks is clear lower than for FK or FK-OHC systems. But under Hyderabad climate conditions with a very small 30L tank the TLC collector system performs better than a FK collector system due to significant differences in stagnation behavior.

The OHC concept has especially advantage with small tank volumes: In Athens with 4 m^2 FK collector and 30L tank just 44% solar fraction (with 900 $kgCO_2$/year, 0.25 EUR/kWh) would be possible, whereas a 4 m^2 FK-OHC and 30L tank system reaches a solar fraction of about 61% (with 680 $kgCO_2$/year and 0.21 EUR/kWh). With a 2 m^2 FK collector and 100L tank 65% solar fraction (with 540 $kgCO_2$/year, 0.17 EUR/kWh) would be reached or 73% solar fraction would be reached with a 2 m^2 FK collector and 295L tank (0.20 EUR/kWh, 550 $kgCO_2$/year).

This effect is even higher in the Hyderabad climate: with 4 m^2 FK collector and 30L tank just 50% solar fraction (with 800 $kgCO_2$/year, 0.22 EUR/kWh) would be possible, whereas a 4 m^2 FK-OHC and 30L tank system reaches a solar fraction of about 74% (with 500 $kgCO_2$/year and 0.19 EUR/kWh). Even a much smaller system with just 1 m^2 FK-OHC and 30L tank would reach higher solar fraction of 61% with lower cost (with 690 $kgCO_2$/year and 0.16 EUR/kWh).

Therefore the OHC concept (reducing the collector temperature during stagnation with any kind of performance reduction during stagnation) shows interesting potential to be used also for a polymer collector (TLC) which could be improved in performance during operation making this collector type more competitive.

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8. References

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