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Thermal Efficiency and yield of Concentrating Solar Thermal Systems at different locations in India

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Technology report:

A performance evaluation of four
Concentrating Solar Thermal (CST) technologies at different locations in India

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1 INTRODUCTION

This report has been compiled to show the thermal efficiency and yield of four different Concentrating Solar Thermal (CST) technologies at different locations in India. The five sites have been chosen to give results that are relevant to a large amount of the country.

The concentrating solar thermal technologies covered in this study are: Compound Parabolic Collector (CPC), Linear Fresnel Reflector (LFR), Paraboloid Dish Collector (PDC) and Parabolic Trough Collector (PTC). Each of these collector types has been modelled and its performance simulated at various temperatures at all the sites. The thermal output and efficiency of each collector type has been then derived from these results.

1.1 Definition of thermal efficiency as used in this report:

In order to make a comparison regarding the efficiency of the different CST technologies, the thermal energy absorbed by each type of collector and the collector's thermal losses have been calculated for each of the different locations. By subtracting the thermal losses from the thermal energy absorbed, the total thermal energy available from the collector (also called thermal yield) has been calculated. Then, by relating the actual thermal yield to the theoretical amount of thermal energy that could be collected (solar radiation x aperture area), the thermal efficiency of the specific type of collector has been determined.

In the case of the collectors that use tracking systems to follow sun during throughout the day i.e. the linear Fresnel reflector, paraboloid dish collector and parabolic trough collector, direct normal solar irradiance is used in the efficiency calculation. Whereas the efficiency of compound parabolic collector is calculated using both global and diffuse irradiance.

The performance simulations used to produce the data for the comparisons give, as an output, yield and thermal loss data on an hourly basis over a complete year. This is then used to calculate the average annual yield or average annual thermal efficiency.

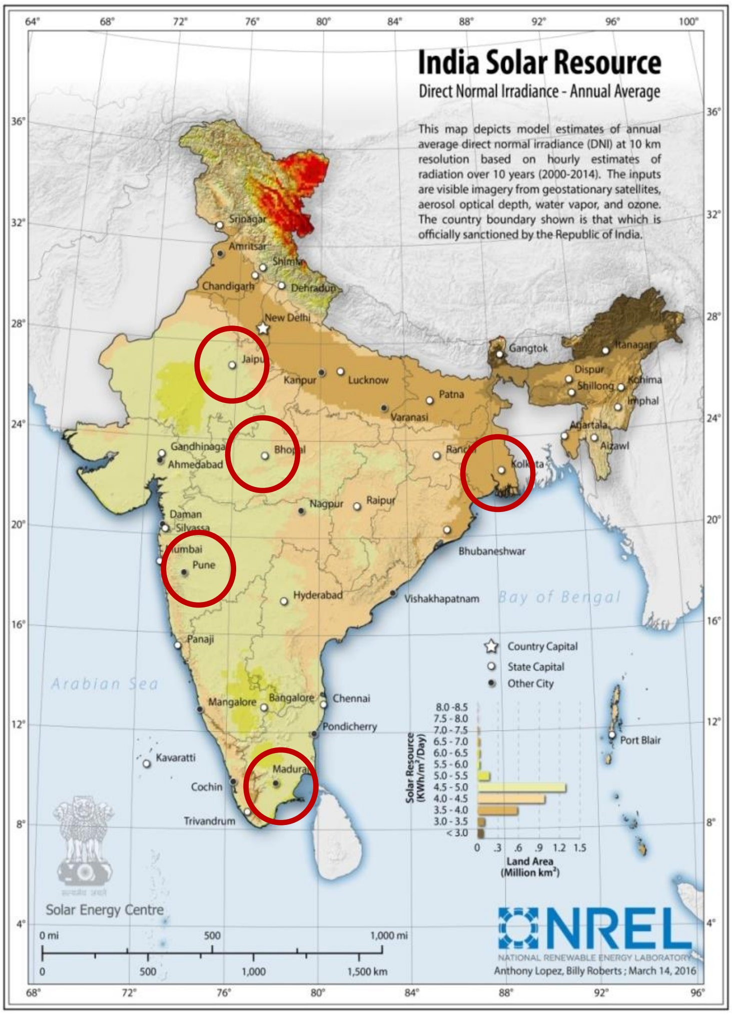
In order to ensure the best possible comparison between collector types, only the performance of each collector itself has been considered. Other factors, such as solar field losses or boiler efficiency, that are specific to an actual installation, have not been taken into account.

It should be noted that these factors will typically result in the energy actually delivered to the process being between 5 and 10% lower than that measured at the output of the collector. In the case of solar fields constructed using large numbers of paraboloid dish collectors, the losses could exceed these values.

2 SITES

To be able compare the effects of latitude and differing solar radiation, five sites throughout India have been chosen. These are shown below on the NREL solar resource map of India.

Jaipur	Lat.: 26.95°	DNI: 4.85 kWh/m^2/day = 1,772 kWh/m^2/a
		DHI: 2.26 kWh/m^2/day = 826 kWh/m^2/a
Bhopal	Lat.: 23.25°	DNI: 4.69 kWh/m^2/day = 1,712 kWh/m^2/a
		DHI: 2.25 kWh/m^2/day = 820 kWh/m^2/a
Kolkata	Lat.: 22.55°	DNI: 3.58 kWh/m^2/day = 1,308 kWh/m^2/a
		DHI: 2.42 kWh/m^2/day = 883 kWh/m^2/a
Pune	Lat.: 18.55°	DNI: 4.76 kWh/m^2/day = 1,739 kWh/m^2/a
		DHI: 2.26 kWh/m^2/day = 824 kWh/m^2/a
Madurai	Lat.: 9.95°	DNI: 5.10 kWh/m^2/day = 1,863 kWh/m^2/a
		DHI: 2.17 kWh/m^2/day = 790 kWh/m^2/a



3 CST TECHNOLOGIES

When comparing the four different technologies, there is a risk that a comparison is made between products that are at different stages of development. To try and reduce this risk, performance data from solar collectors and their components that are already on the market has been used whenever possible.

The state-of-the-art collectors selected have been used in utility-scale applications and are therefore market ready, tested, verified and available. The possible exception to this is the Parabolic Dish Collector, where a high-efficiency Tubular Cavity Receiver has been used in the model, even though, to date, the results have only been proven in scientific projects and not yet in a large scale industrial application.

The four CST technologies evaluated in this study are:

- Parabolic Dish Collector - PDC
- Linear Fresnel Reflector - LFR
- Parabolic Trough Collector - PTC
- Compound Parabolic Collector - CPC

It should be noted that the performance data given in this report assumes state-of-the-art technology, manufacturing, installation and operation. In the case that these conditions are not met, significant reductions in performance can occur.

3.1 Collector parameters

In order to model the thermal yield from each CST technology, a nominal mirror area of 5000m² has been taken for the solar field, this has then been adjusted slightly to reflect the actual collector sizes available for the relevant technology. This size of solar field not only allows a realistic simulation to be carried out, but is also representative of a typical mid-range (2.5$MW_{thermal}$ – 3$MW_{thermal}$) application.

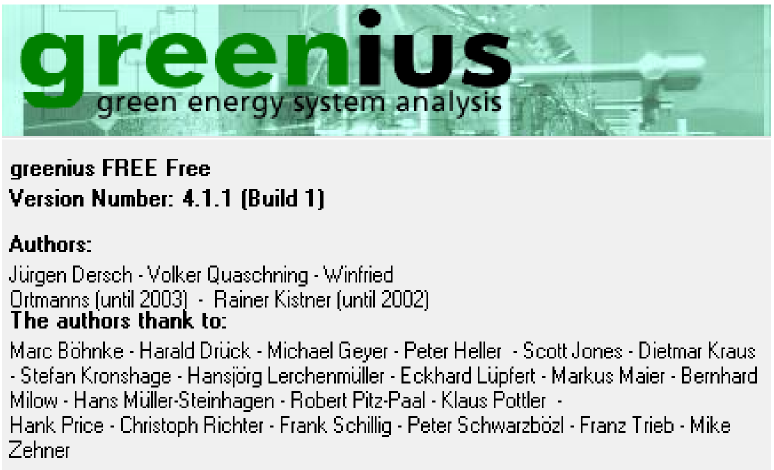
The thermal losses that have been used in the simulation are based on the average temperature of a Heat Transfer Fluid (HTF) being heated in the collector such that its temperature increases by 50°C. i.e. the temperature used the simulation is 25°C lower than the output temperature of the collector.

A soiling factor of 97% has been considered for all technologies as has an availability of 100% - i.e. uninterrupted daytime operation.

3.2 Simulation tools

The yield of the collectors has been determined using the Greenius simulation software. Developed by the German Aerospace Centre (DLR), Greenius is a powerful simulation environment for the calculation and analysis of renewable power projects such as concentrating solar thermal systems. This program offers a combination of detailed technical and economic calculations and can not only model the system thermodynamic performance but also provide the financial data needed for the project planning of renewable power projects.

Greenius was developed at the German Aerospace Centre (DLR). Dr. Rainer Kistner, Winfried Ortmanns, Dr. Volker Quaschning, Dr. Jürgen Dersch and Simon Dieckmann belonged to the development team. Development, distribution and service are made under licence of the DLR. For the calculation the Version Number 4.3.1 has been used.



In addition to the Greenius simulations, the parabolic dish and Fresnel collectors have also been modelled and run in the System Advisor Model (SAM) programme from NREL. SAM makes performance predictions based on system design parameters that are specified as inputs to the model. The software is reputable in the renewable energy sector and often used for simulation purposes.

To simulate and reflect the real metrological conditions on site, a weather reference year called the Typical Metrological Year (TMY) has been used as the basis of the calculation. To produce the TMY, key weather data from the last fifteen years, which is available as a result of a joint MNRE/NREL project, has been used.

In order to verify that the SAM and Greenius simulation results are comparable, both sets of linear Fresnel simulations have been compared. The results of this comparison are given in chapter 6.

3.3 Collector types

3.3.1 Parabolic Dish Collector

Concentrator

Single Size:	87.7m²
Amount:	57 (Array of 3*19 – 15m*15m grid)
Total mirror area:	4,999m²
Focal length:	7.45m
Reflectance:	94%
Shading:	99%
Intercept factor:	99.5%

Receiver

Aperture diameter:	0.2m
Absorptance:	90%
Receiver efficiency:	max. 95%

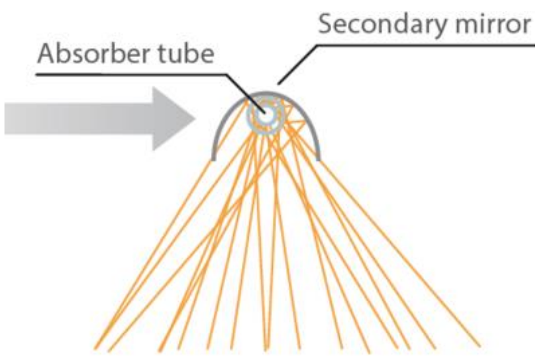
3.3.2 Linear Fresnel Reflector

Concentrator

Size module:	22m²
Length module:	4.06m
Row:	16 Modules
Loop area:	704m² (effective)
Field area:	4,928m² (7 loops)
Reflectance:	95%
Intercept factor:	100%
Optical efficiency:	max. 66.3% - (5° transversal zenith angle)
	nom. 63.5%

Receiver (evacuated)

Absorber outer diameter:	0.7m
Receiver height:	4m (above primary reflector)
Absorptance:	96%
Envelope transmittance:	97%
Bellows shading:	96.7%



3.3.3 Parabolic Trough Collector

Concentrator

Size module:	36m²
Length Module:	12m
Row:	8 Modules
Loop area:	556.3m²
Field area:	5,007m² (9 loops)
Reflectance:	94%
Intercept factor:	97.5%
Optical efficiency:	max. 79.7%

Receiver (evacuated)

Absorber outer diameter:	0.38m
Absorptance:	95%
Envelope transmittance:	95%
Bellows shading:	96.4%

3.3.4 Compound Parabolic Collector

Concentrator

Size module:	4.5m²
Length Module:	2,4m
Row:	20 Modules
Loop area:	90.0m²
Field area:	4995m² (c. 55 loops)
Reflectance:	85%
Intercept factor:	100% (Diffuse 90%)
Optical efficiency:	max. 68,8 %
Inclination angle:	Determined for each site

Receiver (evacuated)

Absorptance: 95%

Envelope transmittance: 90%

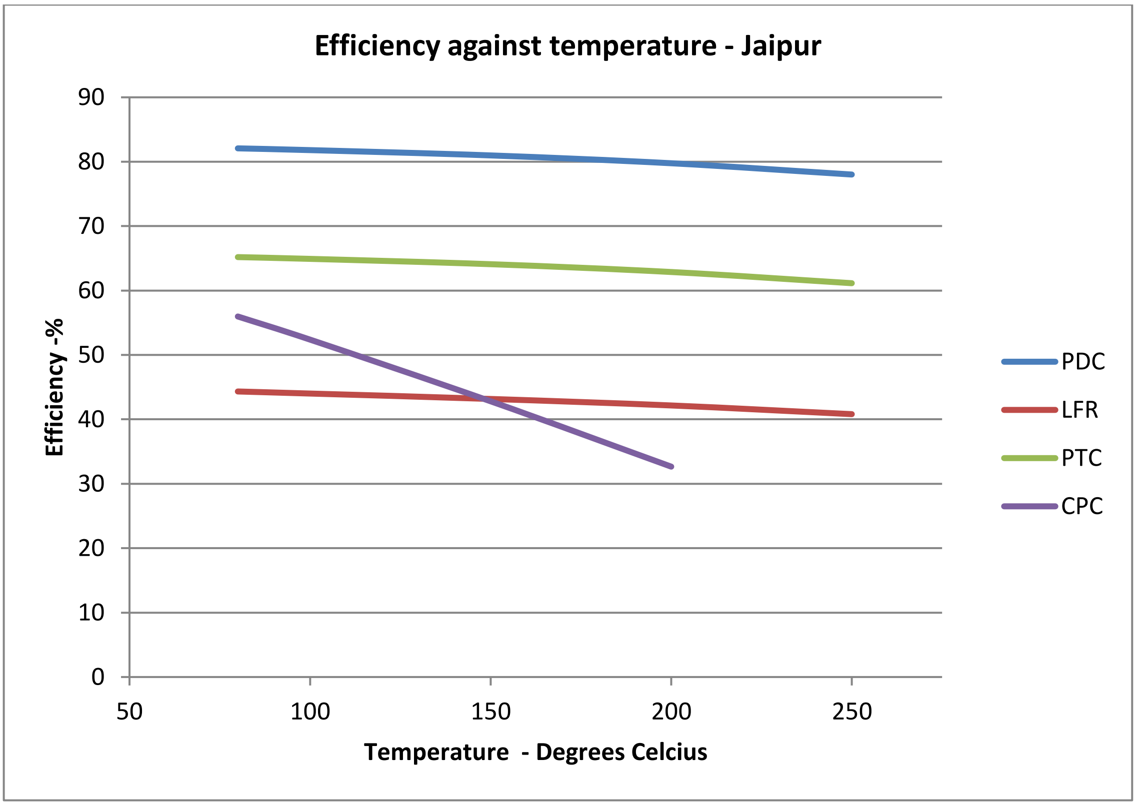
4 RESULTS

A standardised output table has been compiled for each of the locations. This table includes the main parameters for the location (latitude and solar irradiance) and then the average annual efficiency (%) and daily yield (measured in kWh/m²) for each technology, over a range of temperatures.

For this study it is assumed that the CPC collector can operate to 200°C although the very poor efficiency and design limitations would mean it is relatively unlikely that this technology would ever be used at this temperature. Similarly the yields from the PDC LFR and PTC have been calculated for an output temperature of 80°C whereas it is unlikely that these technologies would be used at such a low temperature.

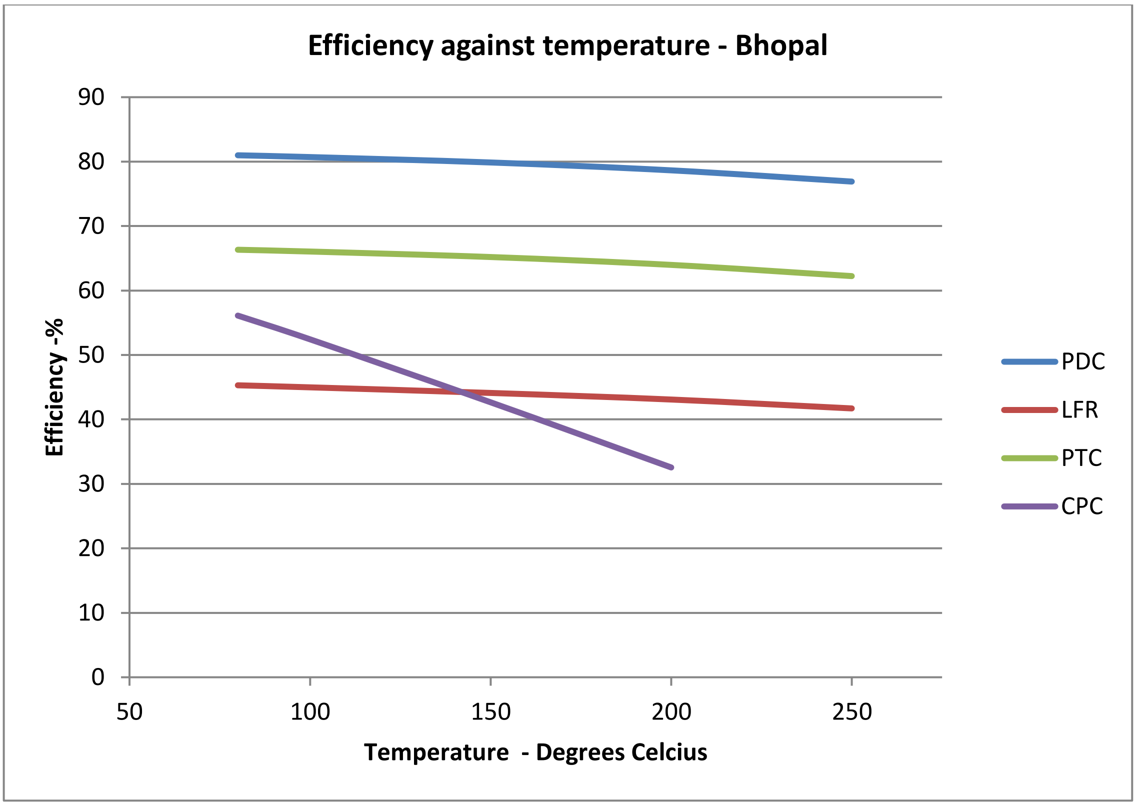
4.1.1 Results – Jaipur

Location	Jaipur		Average annual thermal efficiencies (%) and thermal output (yield) (kWh/m².day)										
Latitude	26.95		CST Tech.	80°C		100°C		150°C		200°C		250°C	
Average irradiance kWh/m².Day - Year				Eff.	Yield	Eff.	Yield	Eff.	Yield	Eff.	Yield	Eff.	Yield
			PDC	82.08	3.98	81.80	3.97	80.98	3.93	79.76	3.87	78.01	3.79
DNI	GHI	Diff.	LFR	44.33	2.15	44.01	2.14	43.17	2.10	42.16	2.05	40.81	1.98
4.85	5.54	2.26	PTC	65.19	3.16	64.92	3.15	64.09	3.11	62.88	3.05	61.14	2.97
1772	2021	826	CPC	55.97	3.39	52.38	3.17	42.81	2.59	32.66	1.98	-	-



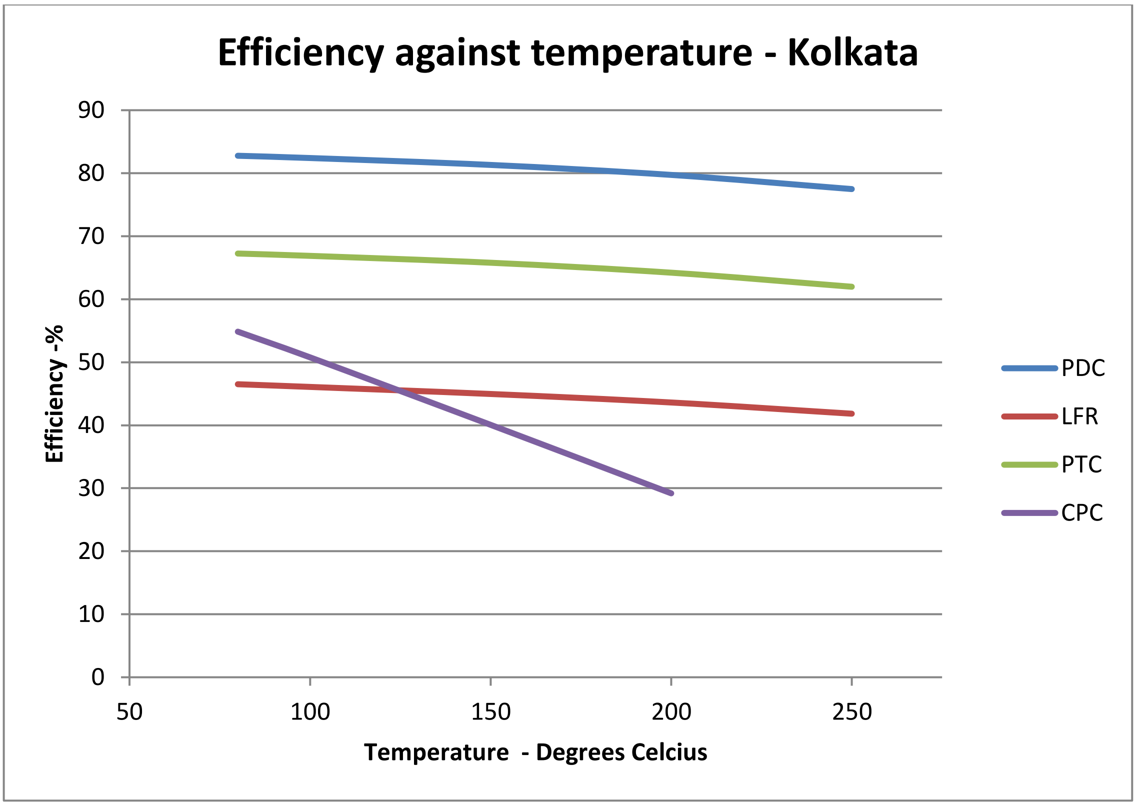
4.1.2 Results – Bhopal

Loca-tion	Bhopal		Average annual thermal efficiencies (%) and thermal output (yield) (kWh/m².day)										
Lati-tude	23.25		CST Tech.	80°C		100°C		150°C		200°C		250°C	
Average irradiance kWh/m².Day - Year				Eff.	Yield	Eff.	Yield	Eff.	Yield	Eff.	Yield	Eff.	Yield
			PDC	80.99	3.80	80.71	3.79	79.87	3.75	78.65	3.69	76.91	3.61
DNI	GHI	Diff.	LFR	45.30	2.12	44.98	2.11	44.11	2.07	43.09	2.02	41.71	1.96
4.69	5.47	2.25	PTC	66.33	3.11	66.05	3.10	65.20	3.06	63.98	3.00	62.24	2.92
1712	1997	821	CPC	56.11	3.32	52.43	3.10	42.66	2.52	32.55	1.92	-	-



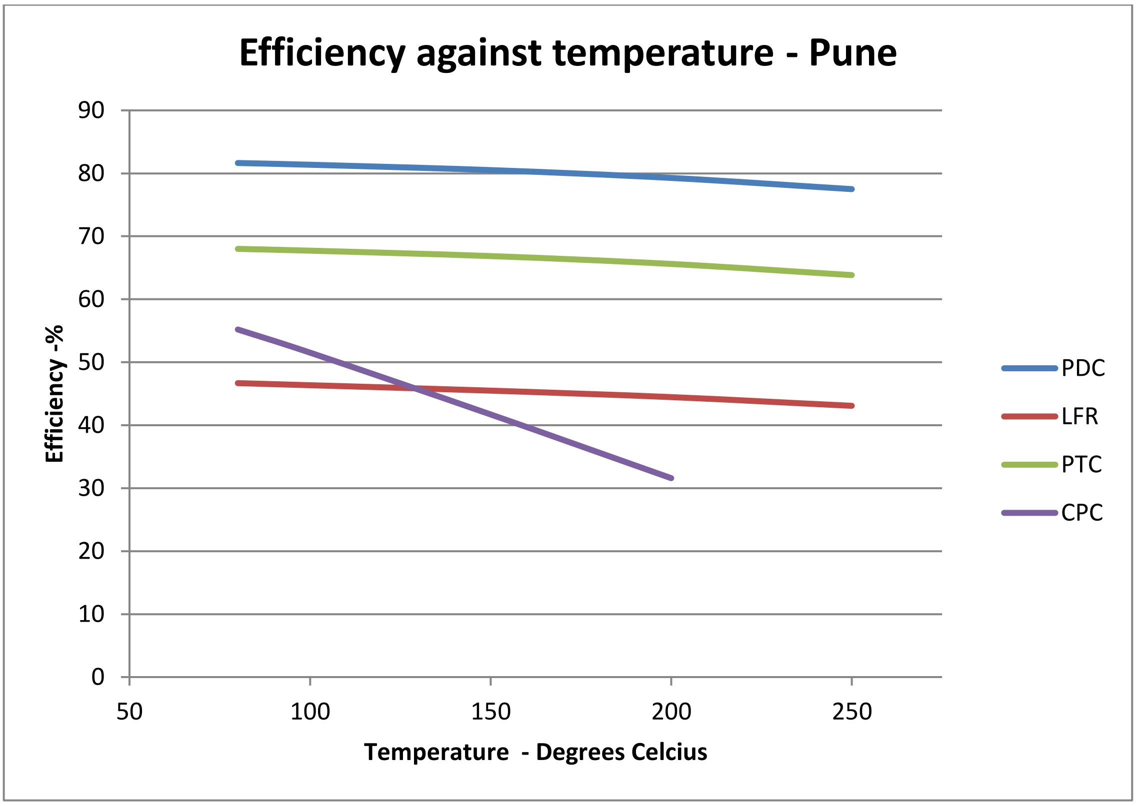
4.1.3 Results – Kolkata

Location	Kolkata		Average annual thermal efficiencies (%) and thermal output (yield) (kWh/m².day)										
Latitude	22.55		CST Tech.	80°C		100°C		150°C		200°C		250°C	
Average irradiance kWh/m².Day - Year				Eff.	Yield	Eff.	Yield	Eff.	Yield	Eff.	Yield	Eff.	Yield
			PDC	82.77	2.97	82.41	2.95	81.31	2.91	79.73	2.86	77.48	2.78
DNI	GHI	Diff.	LFR	46.51	1.67	46.08	1.65	44.96	1.61	43.61	1.56	41.83	1.50
3.58	4.96	2.42	PTC	67.25	2.41	66.88	2.40	65.79	2.36	64.21	2.30	61.98	2.22
1308	1812	883	CPC	54.85	2.91	50.77	2.69	40.06	2.12	29.19	1.55	-	-



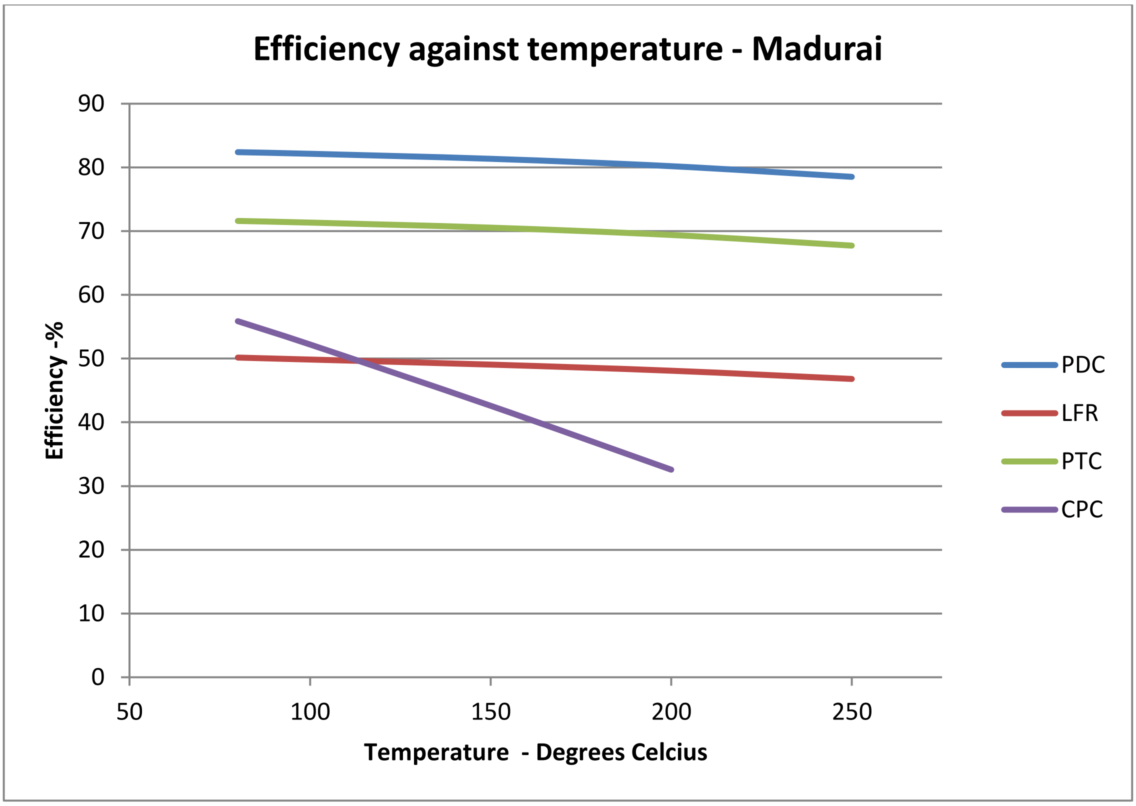
4.1.4 Results – Pune

Location	Pune		Average annual thermal efficiencies (%) and thermal output (yield) (kWh/m².day)										
Latitude	18.55		CST Tech.	80°C		100°C		150°C		200°C		250°C	
Average irradiance kWh/m².Day - Year				Eff.	Yield	Eff.	Yield	Eff.	Yield	Eff.	Yield	Eff.	Yield
			PDC	81.64	3.89	81.36	3.88	80.52	3.84	79.27	3.78	77.49	3.69
DNI	GHI	Diff.	LFR	46.68	2.22	46.35	2.21	45.49	2.17	44.46	2.12	43.08	2.05
4.76	5.61	2.26	PTC	68.00	3.24	67.72	3.23	66.86	3.19	65.61	3.13	63.84	3.04
1739	2046	824	CPC	55.20	3.28	51.52	3.06	41.71	2.47	31.59	1.87	-	-



4.1.5 Results – Madurai

Loca-tion	Madurai		Average annual thermal efficiencies (%) and thermal output (yield) (kWh/m².day)										
Lati-tude	9.95		CST Tech.	80°C		100°C		150°C		200°C		250°C	
Average irradiance kWh/m².Day - Year				Eff.	Yield	Eff.	Yield	Eff.	Yield	Eff.	Yield	Eff.	Yield
			PDC	82.40	4.21	82.14	4.19	81.35	4.15	80.19	4.09	78.52	4.01
DNI	GHI	Diff.	LFR	50.16	2.56	49.85	2.54	49.06	2.50	48.10	2.46	46.81	2.39
5.10	5.96	2.17	PTC	71.60	3.65	71.34	3.64	70.55	3.60	69.40	3.54	67.73	3.46
1863	2175	790	CPC	55.87	3.37	52.21	3.15	42.60	2.57	32.57	1.96	-	-

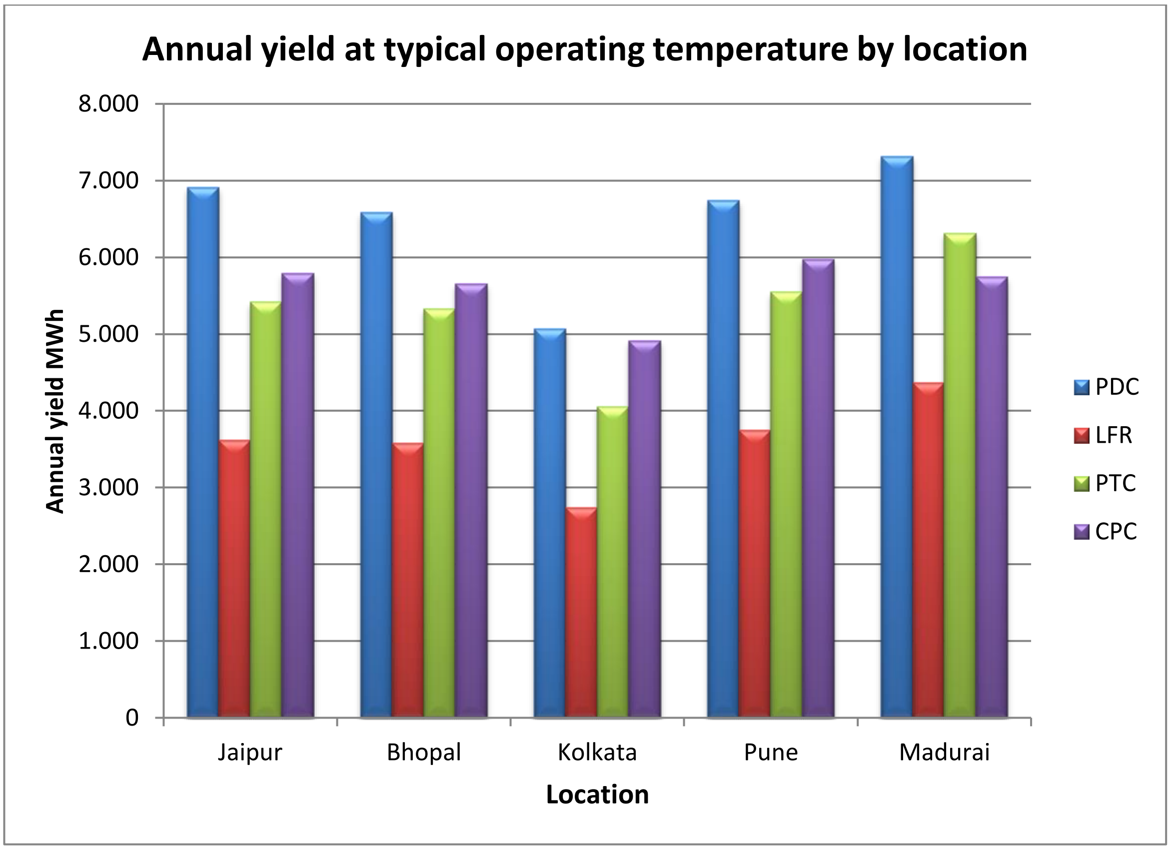


4.2 Results - Thermal yield

In order to provide a better visualisation of the annual energy yield that can be expected from a system with an aperture area of circa 5000m², tables and graphs showing the output of each type of collector at each site are given below. However, when making such a comparison, the issue of the very different typical operating temperature of the CPC when compared to the other types of collectors arises. In order to solve this two sets of data have been prepared.

The first data set gives the yield at typical operating temperatures, namely 250°C for the PDC, LFR and PBC collectors and 100°C for CPC. Whilst this gives a good idea of the type of yields that can be expected, it is not valid as a comparison between technologies due to the advantage given to the CPC system by its lower operating temperature.

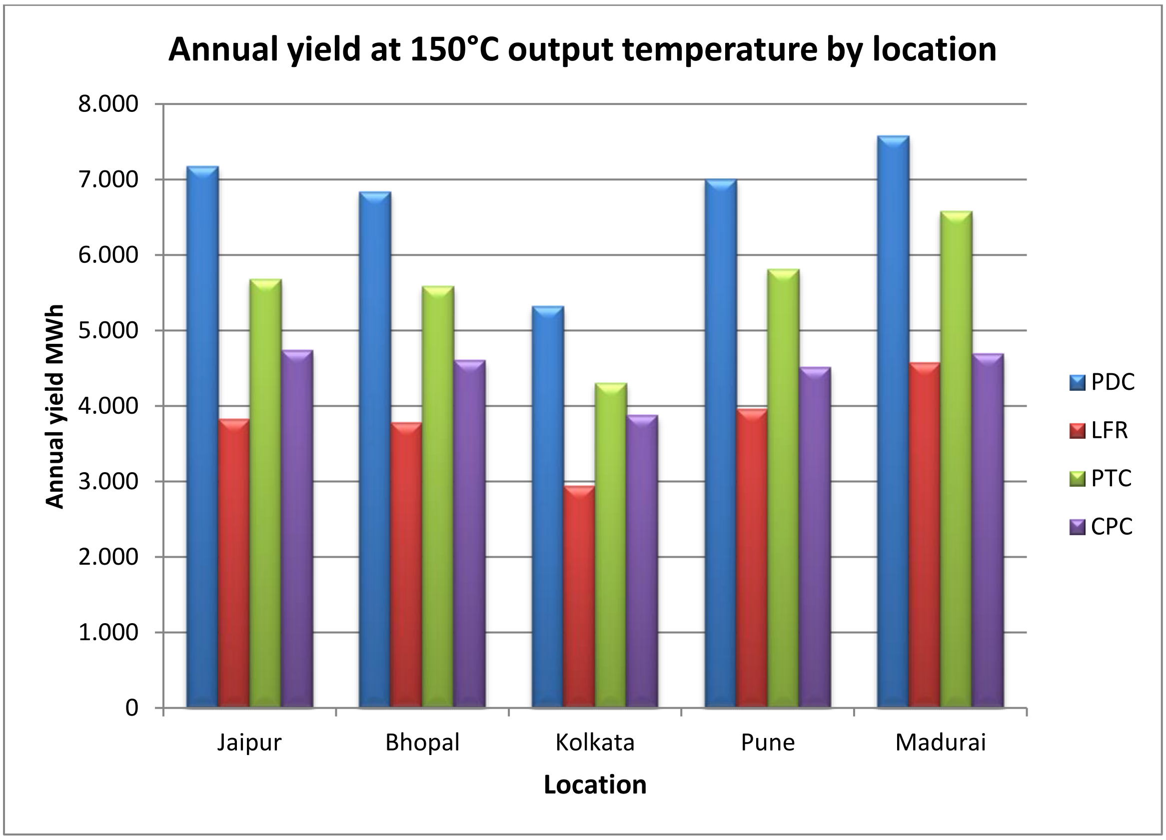
Annual yield (MWh) at typical operating temperature by location					
	Jaipur	Bhopal	Kolkata	Pune	Madurai
PDC	6,911	6,583	5,067	6,736	7,315
LFR	3,617	3,573	2,737	3,747	4,363
PTC	5,416	5,328	4,056	5,551	6,310
CPC	5,794	5,657	4,912	5,977	5,747



To make a more meaningful comparison between performance possible, a second set of data has been produced using the same temperature (150°C) for all technologies.

The temperature chosen is at the lower end of the likely usage range for the three tracked collectors and is at the upper end of the temperatures normally seen by CPC collectors, however, by using this value the performance of the systems can be compared against a single temperature datum.

Annual yield (MWh) by location - All systems operating at 150°C output temperature					
	Jaipur	Bhopal	Kolkata	Pune	Madurai
PDC	7,173	6,837	5,318	6,999	7,578
LFR	3,825	3,777	2,940	3,955	4,570
PTC	5,678	5,582	4,304	5,813	6,573
CPC	4,735	4,603	3,875	4,517	4,690



4.3 Peak thermal power

The peak thermal power of each of the Concentrating Solar Thermal technologies at a DNI of 850W/m² (no incidence angle considered, clean mirror and receiver surfaces) is as follows.

Parabolic Dish:	@250°C	ca. 3.6 MW_{th}
Fresnel:	@250°C	ca. 2.6 MW_{th}
Parabolic Trough:	@250°C	ca. 3.3 MW_{th}
CPC:	@100°C	ca. 2.5 MW_{th}

As discussed in section 4.2 the peak simulation is based on a collector of 5000m² under typical operating temperatures.

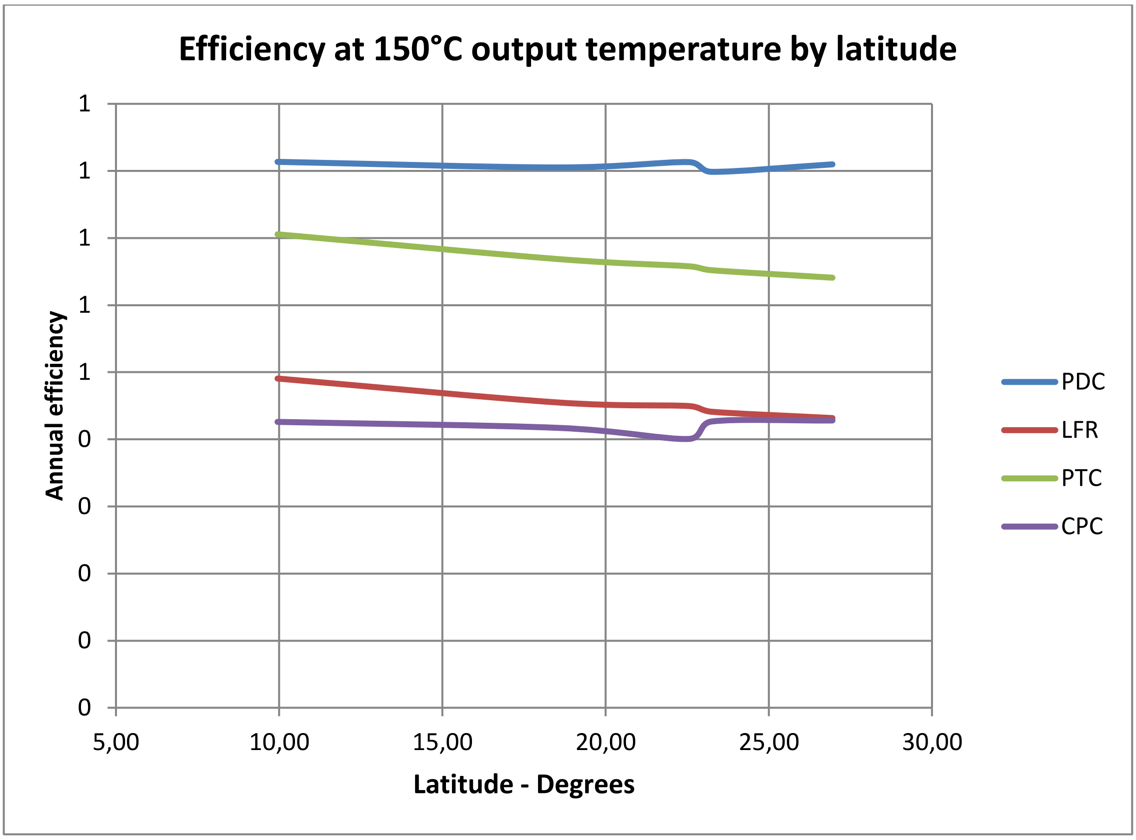
4.4 The effects of latitude

The effects of latitude on collector average annual thermal efficiencies at 150°C are shown in the following table.

Collector efficiency at 150°C output temperature by latitude					
Latitude	26.95°N	23.25°N	22.55°N	18.55°N	9.95°N
PDC	80.98%	79.87%	81.31%	80.52%	81.35%
LFR	43.17%	44.11%	44.96%	45.49%	49.06%
PTC	64.09%	65.20%	65.79%	66.86%	70.55%
CPC	42.81%	42.66%	40.06%	41.71%	42.60%

The graph below shows the variation of annual thermal efficiency with respect to latitude. It also highlights the difference in the thermal efficiency of the four CST technologies that have been modelled.

What is evident from the graph is the effect of latitude on the two linear solar collectors (LFR and PTC), which show a reduction in efficiency as the latitude increases. In addition to this, an effect can be seen due to the different meteorological conditions found in Kolkata, where the distribution of irradiance throughout the year affects the trend line for both the tracked and non-tracked collectors albeit in different ways.

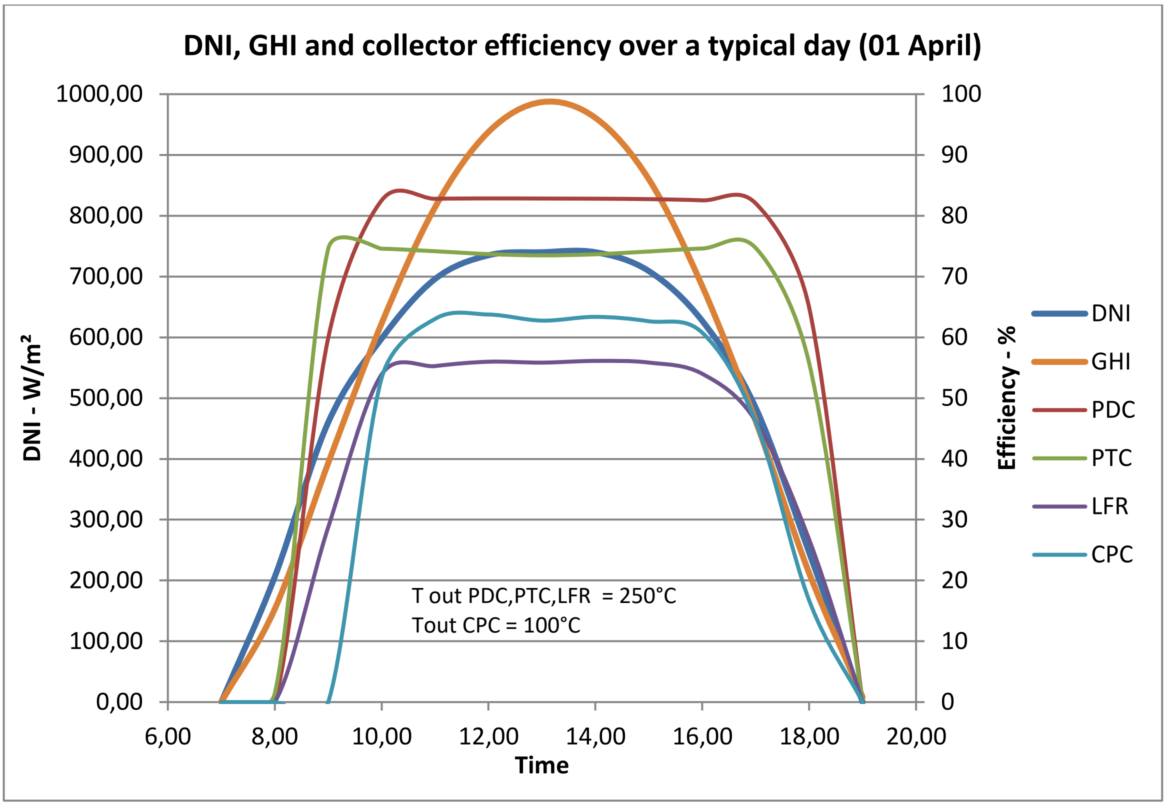


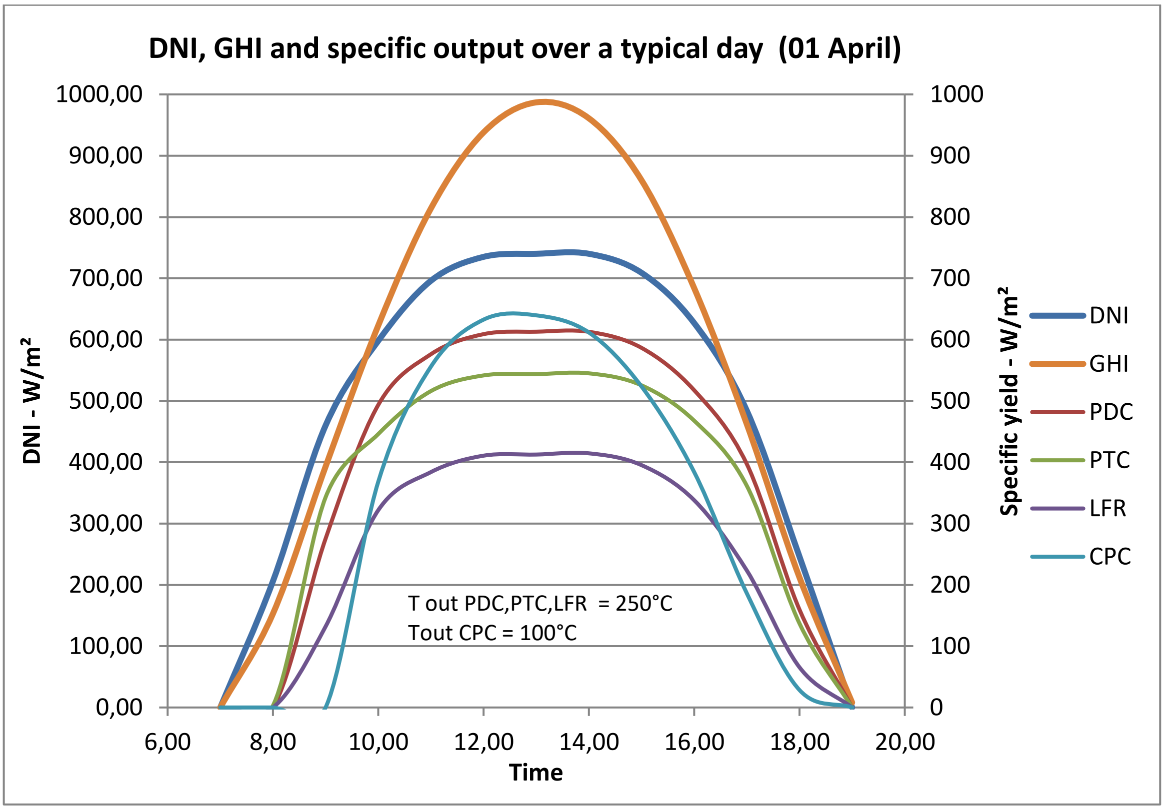
4.5 Efficiency and thermal output over the day.

The final two graphs show the daily distribution of efficiency and specific output over a typical day (1st April used) in Pune. As is typical for India in springtime, there is clear weather with no breaks in the sunshine.

The first graph shows the tracked collectors rapidly reaching a stable efficiency, with the fixed CPC taking longer to “get started” due to its fixed (non tracking) installation combined with its higher mass of working fluid in the collector.

On the specific output graph we can see the very high output of the CPC towards noon. This is due to its relatively high efficiency with the sun overhead and its ability to make use of both direct and diffuse irradiance. Its performance relative to the other collectors is further enhanced due to the 100°C operating temperature as opposed to 250°C for the other collectors.


DNI, GHI and collector efficiency over a typical day (01 April)
1000,00
900,00
800,00
700,00
600,00
500,00
400,00
300,00
200,00
100,00
0,00
DNI - W/m²
100
90
80
70
60
50
40
30
20
10
0
Efficiency - %
6,00
8,00
10,00
12,00
14,00
16,00
18,00
20,00
Time
T out PDC,PTC,LFR = 250°C
Tout CPC = 100°C
DNI
GHI
PDC
PTC
LFR
CPC


DNI, GHI and specific output over a typical day (01 April)
1000,00
900,00
800,00
700,00
600,00
500,00
400,00
300,00
200,00
100,00
0,00
DNI - W/m²
1000
900
800
700
600
500
400
300
200
100
0
Specific yield - W/m²
6,00
8,00
10,00
12,00
14,00
16,00
18,00
20,00
Time
T out PDC,PTC,LFR = 250°C
Tout CPC = 100°C
DNI
GHI
PDC
PTC
LFR
CPC

5 CONCLUSION

From the efficiency against temperature results it can be seen that regardless of which site is taken, the parabolic dish has the highest annual efficiency, followed by the parabolic trough. Whilst having lower efficiency than the parabolic trough, the compound parabolic collector has higher efficiency than the linear Fresnel linear reflector at temperatures below circa 120°C (exact crossover point dependent on latitude).

What can also be seen from the results is that as the latitude increases. the average annual performance of the linear systems (PTC and LFR) reduces. With at least a 5% decrease in performance between a system located in the southernmost parts of India and one located in the north. This reduction is due to the "cosine effect" caused by the sun being lower in the sky especially in winter (northern hemisphere) and as a result the sun's rays tending to shine "along" the axis of the linear collector rather than arriving at 90° to it.

The compound parabolic collector does not show a significant dependency on latitude, although the effects of different weather conditions, especially in Kolkata, can be seen.

The parabolic dish collector shows a different trend, with the thermal efficiency slightly increasing at higher latitudes. As the dish tracks the sun about two axes it is not subject to the "cosine effects" that affect the single axis linear collectors. However changes in the DNI distribution over the year at different sites are sufficient to give rise to changes in efficiency with location.

6 COMPARISON BETWEEN SIMULATION SOFTWARE TYPES

To demonstrate that the two types of simulation software used are able to produce comparable results, a cross check has been carried by running the Fresnel technology simulation in both SAM and Greenius.

The Greenius model for linear Fresnel is expected to be very accurate as the modelled collector is implemented into the system's distinct library and the values have been agreed with the system supplier. Therefore the collector specific properties are considered in the model. Especially the IAM is based on the specific linear Fresnel collector. In the SAM Model a general. more standard IAM is used to calculate the output as the specific IAM is not provided.

The results obtained using the Greenius simulation for Linear Fresnel and the difference to the SAM results are shown in the following tables for efficiency @ 250°C

	Madurai	Pune	Kolkata	Bhopal	Jaipur
LFR	46.8%	43.08%	41.8%	41.7%	40.8%
Δη	+0.8%	-1.1%	+0.1%	-1.2 %	-1.6%

The results show that a simulation provides an accurate value (repeatable with different simulation tools).

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