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Research Article

Predicting Cost Effective Solar Thermal Technology in different climatic conditions

Gulnar Perveen[Å*] and S. K. Singh[Å]

[Å]Solar Energy Centre, Ministry of New and Renewable Energy, Delhi-110003, India

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Abstract

The objective of this paper is to evaluate the performance characterization of solar thermal technologies based on Radiation analysis correlating Global Horizontal Radiation, Global Tilted Radiation, Diffused Radiation, Ambient temperature, DNI at Leh_Ladakh, Gujarat_Gandhinagar and Chennai stations. The present work involves annual analysis of radiation/weather data and characterization of solar thermal technologies i.e. Flat Plate Collector, Evacuated Flat Plate Collector and 1.5x Non Imaging Concentrator Collector or Compound Parabolic Concentrator Collector based on technology specification. Month wise variation of Energy Gain, at different operating temperature is calculated, and a comparative simulative analysis is performed for different solar thermal collector technologies in different climatic conditions. Also, the switch over temperature from one technology to another is presented for predicting the cost effective technology. By the use of the computer program MS Excel the amount of the produced heat energy for a simple Flat Plate Collector, Evacuated Flat Plate Collector and for 1.5x Non-imaging Concentrator collector has been calculated at different operating temperature and the results are presented.

Keywords: *Evacuated Flat Plate Collector, Flat Plate Collector, 1.5x Non imaging Concentrator Collector.*

1. Introduction

In spite of being naturally diluted, solar energy may be used to obtain high temperatures for thermal, mechanical, or electric applications. Solar collectors are the key component of active solar-heating systems. At present, solar collectors having different types are being widely used and applied in the field of Solar Energy. The present research involves the comparative performance analysis of solar thermal technologies which include Flat Plate Collector, Evacuated Flat Plate Collector and 1.5x Non Imaging Concentrator Collector. The previous results obtained shows that Flat Plate Collector can easily be operated at temperature of 70^0C (M.C. Rodriguez-Hidalgo *et al* 2011) (F.F. Mammadov *et al* 2012) (Zondag *et al* 2008). However, no information about the operating temperature conditions of Evacuated Flat plate collector and 1.5x Non Imaging Concentrator Collector were available. So, this study deals with the performance characterization of FPC, Evacuated FPC and compound parabolic concentrator collector which is obtained experimentally based on the specifications of technology and the results are presented at different operating temperature. Experimental analysis of radiation data using sunshine hours have been obtained previously (Dimas Firmanda Al Riza *et al* 2011) (J. Almorox *et al* 2004) (M. Maroof Khan and M. Jamil Ahmad *et al* 2012) (Shafiqur Rehman *et al* 2000) however, based on the analysis of radiation data, operating temperature conditions of solar thermal technologies have been evaluated in different climatic condition correlating Global Tilted Radiation, DNI, Ambient Temperature and Sunshine hours. Also, Prediction of switch over temperature from one technology to another is then analysed which is concluded out to be dependent on Land cost factor, weather data and technology characterization.

2. Solar Thermal Technologies

2.1 Flat Plate Collector

Flat-plate collectors are the most common solar collector for solar water-heating systems. They operate in open loop, closed loop, and drain back solar systems, making these collectors ideal for a variety of installation designs. Flat Plate Solar Collector is designed to offer reliable hot water heating in hot, mild, or cold climates.

2.2 Evacuated Flat Plate Collector

The Evacuated Flat plate collectors are designated to be operated at a higher temperature level than the conventional ones. The use of evacuated flat plate

*Corresponding author **Gulnar Perveen** is Research Assistant and **S. K. Singh** is Director & Scientist "F"

collector has the advantage of longer lifetime compared to non- evacuated collector, because no humidity and condensation problems occur in the casing.

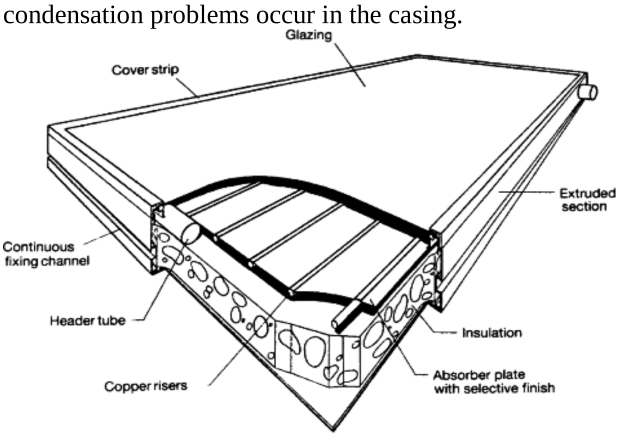

Fig. 1 Schematic of Flat Plate Collector

It consists of a glass cover, an absorber, a serpentine tube and aluminium frame. The inner gas used in evacuated flat plate collector usually is a noble gas, such as Krypton gas. The pressure is maintained below atmospheric pressure (~100 mbar). Use of noble gas inside a collector, instead of using air (as in the case of conventional flat plate collector), reduces significantly the heat loss coefficient of the collector, but the result is dependent on the pressure inside (N. Benz *et al* 1999).

Fig. 2 Experimental Demonstration of Evacuated Flat Plate Collector at SEC

2.3 1.5x Non-Imaging Concentrator Collector

Non-imaging solar concentrator collector is a very innovative design of solar collector based on the principle of non-imaging optics. Compound parabolic concentrators can accept incoming radiation over a relatively wide range of angles. By using multiple internal reflections, any radiation that is entering the aperture, within the collector acceptance angle, finds its way to the absorber surface located at the bottom of the collector (Soteris A. Kalogirou *et al* 2012). The absorber can take a variety of configurations. It can be cylindrical as shown in Figure 3 or flat. In the CPC shown in Figure 3 the lower portion of the reflector (F_B and F_A) is circular, while the upper portions (B and A) are parabolic. As the upper part of a CPC contribute little to the radiation reaching the absorber, they are usually truncated thus forming a shorter version of the CPC, which is also cheaper (O'Gallagher JJ *et al* 1982). CPCs are usually covered with glass to avoid dust and other materials from entering the collector and thus reducing the reflectivity of its walls(J. Blanco *et al* 1999)(M. Adsten *et al* 2005)(Yong Kim *et al* 2008).

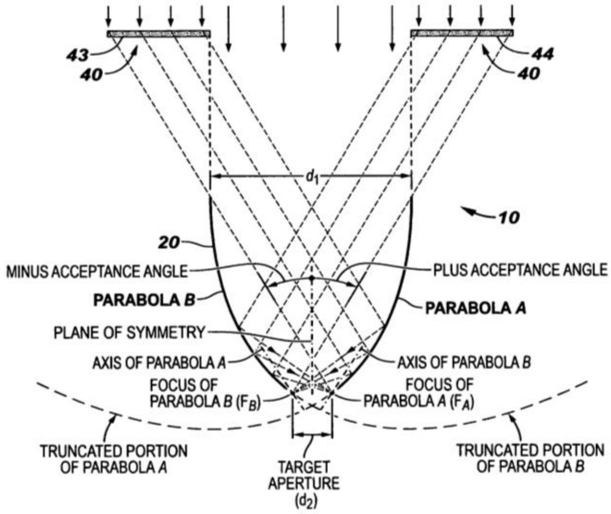

Fig. 3 Schematic of 1.5x Non Imaging Concentrator Collector (or Compound Parabolic Collector) at SEC

A non-imaging solar collector is used to maximize the amount of energy applied to a receiver, typically a solar cell or a thermal receiver. For a given concentration, non-imaging solar collector provide the widest possible acceptance angles and, therefore, are the most appropriate for use in solar concentration (Aurelian A. Radu *et al* 2000).

The simplest way to design non-imaging solar collector is called "the method of strings", based on the edge ray principle. SMS (Simultaneous Multiple Surface design method) is a more advanced way of designing non-imaging solar collector.

The main advantages of non-imaging optics for concentrating solar energy are:

- Wider acceptance angles resulting in higher tolerances
- Higher solar concentrations
- Possibility of a uniform illumination of the receiver
- Design flexibility
- For low concentrations, the very wide acceptance angles of non-imaging solar collector can avoid solar tracking altogether or limit it to a few positions a year.

The main disadvantage of non-imaging solar collector is that, for high concentrations, they typically have one more optical surface, slightly decreasing efficiency. That,

Table 1 Calculated figure from analysis of Radiation/Weather data (2012) at Leh_Ladakh

Month	Air Temp (^{0}C)	Global Horizontal Rad. Avg. (W/m^2)	Global Tilted Rad. Avg. (W/m^2)	Diffused Rad. Avg. (W/m^2)	Direct Rad. (DNI) Avg. (W/m2)	Sunshine hours (hr)	Energy Gain in KWh per meter square (Global Horizontal Rad.)	Energy Gain in KWh per meter square (Diffused Rad.)	Energy Gain in KWh per meter square (DNI)	Energy Gain in KWh per meter square (Global Tilted Rad.)
Jan	-15	417	662	178	459	108	45	19	49	71
Feb	-1.43	484	600	217	416	114	55	24	47	68
Mar	3.65	581	651	239	563	214	124	51	120	139
April	9.43	589	587	233	559	215	126	50	120	126
May	13.67	654	590	200	651	294	192	58	191	173
June	17.95	681	589	218	626	154	104	33	96	90
July	24.04	644	566	180	649	323	208	58	209	182
Aug	24.02	630	606	222	637	262	165	58	167	158
Sep	18.3	559	599	342	879	231	129	79	203	138
Oct	8.95	513	696	171	746	254	130	43	189	176
Nov	3.36	412	677	92	735	215	88	19	158	145
Dec	-1.96	369	630	135	595	168	62	22	99	105
Average	8.75	544	621	202	626					
Annual Energy Gain							1432	519	1653	1578

however, is only noticeable when the optics is aiming perfectly towards the sun, which is typically not the case because of imperfections in practical systems (Mills DR *et al* 1978).

Fig. 4 Experimental Demonstration of 1.5x Non Imaging Concentrator Collector or Compound Parabolic Concentrator Collector at SEC

3. Results and Discussions

3.1 Annual analysis of Radiation/Weather data

3.1.1 Analysis of Solar Radiation at Leh_Ladakh

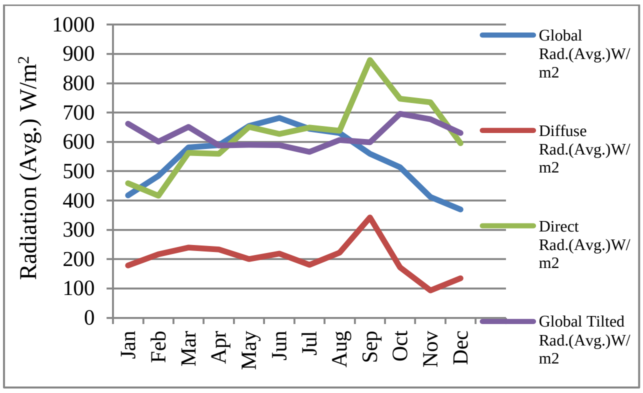

Fig. 5 The annual (2012) average analysis of Solar Radiation at Leh_Ladakh

3.1.2 Analysis of Solar Radiation at Gujarat_Gandhinagar

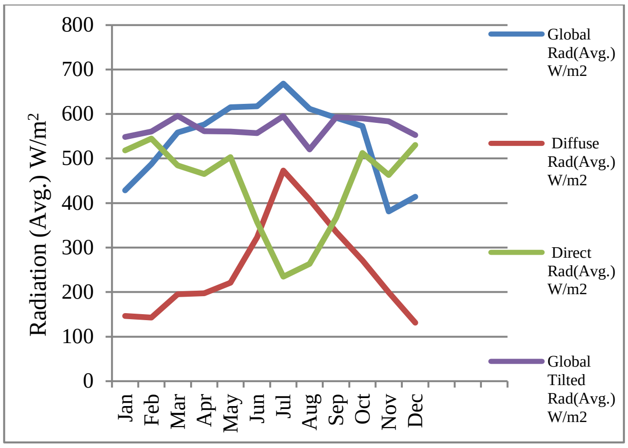

Fig. 6 The annual (2012) average analysis of Solar Radiation at Gujarat_Gandhinagar

3.1.3 Analysis of Solar radiation at Chennai

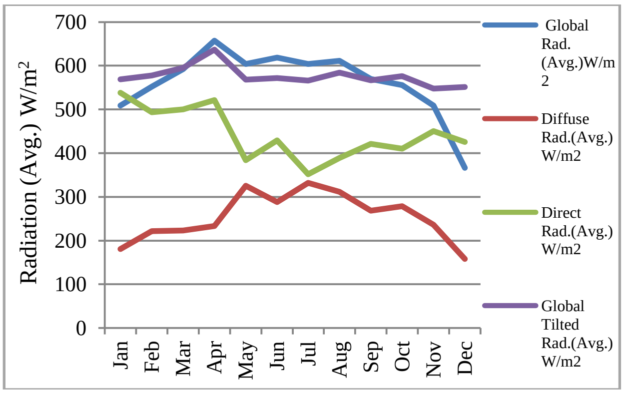

Fig. 7 The annual (2012) average analysis of Solar Radiation at Chennai

Table 2 Calculated figures from analysis of Radiation/Weather data (2012) at Gujarat_Gandhinagar

Month	Air Temp. (^{0}C)	Global Horizontal Rad. Avg. (W/m^2)	Global Tilted Rad. Avg. (W/m^2)	Diffused Rad. Avg. (W/m^2)	Direct Rad. Avg. (W/m^2)	Sunshine hour (hr)	Energy Gain in KWh per meter square (Global Horizontal Rad.)	Energy Gain in KWh per meter square (Diffused Rad.)	Energy Gain in KWh per meter square (DNI)	Energy Gain in KWh per meter square (Global Tilted Rad.)
Jan	21.97	428	548	146	518	293	125	42	151	160
Feb	24.68	487	560	142	544	294	143	41	160	164
Mar	30.05	558	595	195	484	313	174	61	151	186
April	33.97	576	561	197	465	310	178	61	144	174
May	35.03	615	560	220	502	343	211	75	172	192
June	34.64	617	557	323	357	261	161	84	93	145
July	33.29	668	595	473	234	73	48	34	17	43
Aug	34.79	611	520	407	263	62	37	25	16	32
Sep	30.17	591	593	335	366	140	82	46	51	83
Oct	22.32	572	590	271	512	187	107	50	95	110
Nov	19.17	380	583	199	463	125	47	24	57	72
Dec	18.27	414	552	130	530	202	83	26	107	111
Average	28.2	543	568	253	437					
Annual Energy Gain							1402	576	1219	1477

Table 3 Calculated figures from analysis of Radiation/Weather data (2012) at Chennai

Month	Air Temp. (^{0}C)	Global Horizontal Rad. Avg. (W/m^2)	Global Tilted Rad. Avg. (W/m^2)	Diffused Rad. Avg. (W/m^2)	Direct Rad. (DNI) Avg. (W/m^2)	Sunshine hour (hr)	Energy Gain in KWh per meter square (Global Horizontal Rad.)	Energy Gain in KWh per meter square (Diffused Rad.)	Energy Gain in KWh per meter square (DNI)	Energy Gain in KWh per meter square (Global Tilted Rad.)
Jan	27.03	508	569	180	538	278	141	50	149	141
Feb	28.26	552	577	221	493	255	140	56	125	140
Mar	30.45	592	595	222	500	295	174	65	147	174
April	31.55	657	637	233	521	232	153	54	121	153
May	34.3	604	568	325	383	242	146	78	92	146
June	34.52	618	571	287	429	205	126	59	88	126
July	32.53	603	566	331	351	159	96	52	56	96
Aug	31.63	610	584	311	388	186	113	58	72	113
Sep	31.52	569	566	268	420	174	99	46	73	99
Oct	30.18	555	576	278	410	170	94	47	70	94
Nov	28.85	509	547	236	450	226	115	53	102	115
Dec	27.62	366	551	158	425	203	74	32	86	74
Average	30.7	562	575	254	442					
Annual Energy Gain							1477	655	1186	1477

3.2 Performance Characterization of Solar Thermal Technologies

3.2.1 Specification details for Flat Plate Collector

Collector fluid temperature or Mean Desired Temperature (T_d) = 70°C
Nominal Solar Radiation (G) = 1000 W/m^2
Ambient Temperature (T_{amb}) = 30°C

Energy Performance:-
Thermal output@ 70^{0}C – 550 W/m^2 ,
(1000 W/m^2, T_{amb} – 30^{0}C)

Operating Conditions:-
Stagnation temperature- 180^{0}C, 356^{0}F
Maximum Operating Pressure – 1 bar.

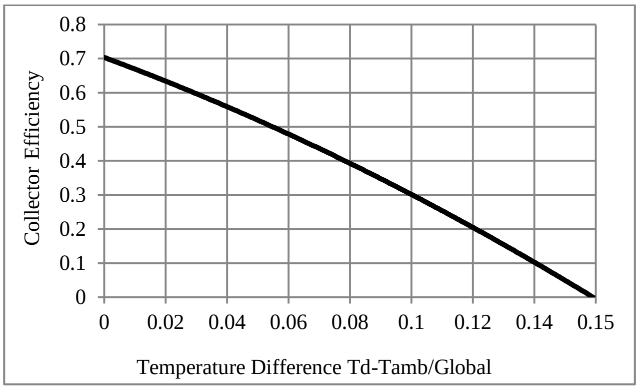

Fig. 8 Performance Characteristics Curve of Flat Plate Collector

3.2.2 Specification details for an Evacuated Flat Plate Collector

Specifications by ***TVP Solar***

Collector Mean Fluid Temperature or Mean Desired Temperature (T_d) = 180°C
Nominal Solar radiation (G) = 1000 W/m^2
Ambient Temperature (T_{amb}) = 30°C

Energy Performance:-

Thermal output@180^{0}C – 550 W/m^2 ,
1877 BTU/h (1000 W/m^2, T_{amb} – 30^{0}C).

Operating Conditions:-

Stagnation temperature- 325^{0}C, 617^{0}F
Maximum Operating Pressure -15 bar.

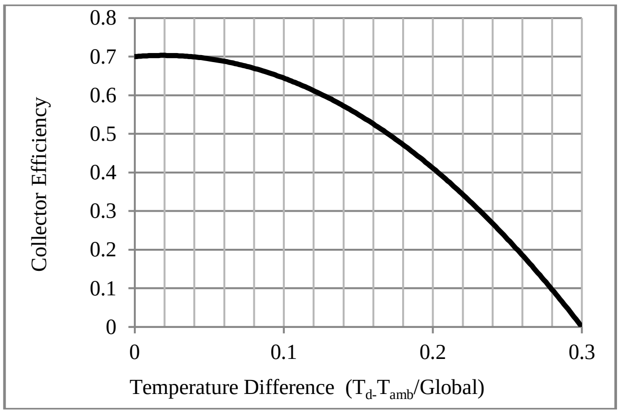

Fig. 9 Performance Characteristics Curve of an Evacuated Flat Plate Collector

3.2.3 Specification details for 1.5x Non Imaging Concentrator Collector

As per ***Stuttgart Report***

Optical Efficiency / zero loss Efficiency η_o= 64.2%
First order Heat Loss Coefficient a_1 (W/m^2K) = 0.89
Second order Heat Loss Coefficient a_2 (W/m^2K^2) = 0 .001
Collector Mean Fluid Temperature or Mean Desired Temperature (T_d) = 120°C
Nominal Solar radiation (G) = 1000 W/m^2
Ambient Air Temperature (T_{amb}) = 30°C

Energy Performance:-

Thermal output@ 120^{0}C – 553 W/m^2,
(1000 W/m^2, T_{amb} – 30^{0}C).

Operating Conditions:-

Stagnation Temperature- 500^{0}C, 932^{0}F
Maximum Operating Pressure – 2 to 4 bar.

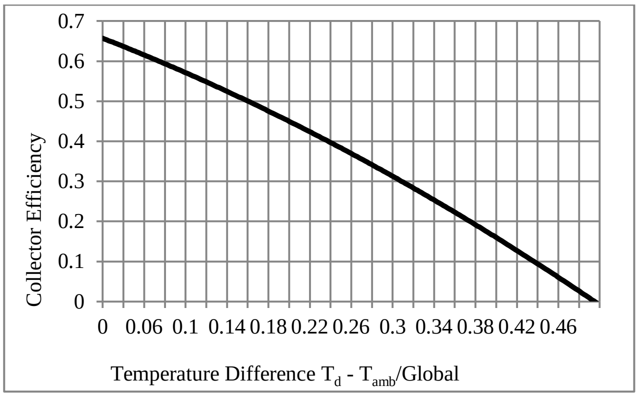

Fig. 10 Performance Characteristics Curve of 1.5x Non Imaging Concentrator Collector

3.3 Month wise variation of Energy Gain at different operating temperature for Leh_Ladakh, Chennai and Gujarat_Gandhinagar.

The annual Energy Gain received is calculated based on the analysis of radiation data and the results are simulated together with technology characterization for Flat Plate Collector, Evacuated Flat Plate Collector and Compound Parabolic Collector at different operating temperature as shown below in Figure [11-13] for Leh_Ladakh and Figure [14-16] for Chennai and Figure [15-17] for Gujarat_Gandhinagar.

3.3.1 Energy Gain received in KWh per meter square for different solar thermal technologies at different operating temperature in different climatic conditions.

3.3.1.1 Energy Gain in KWh per meter square at 90^{0}C for different collector technologies at Leh_Ladakh

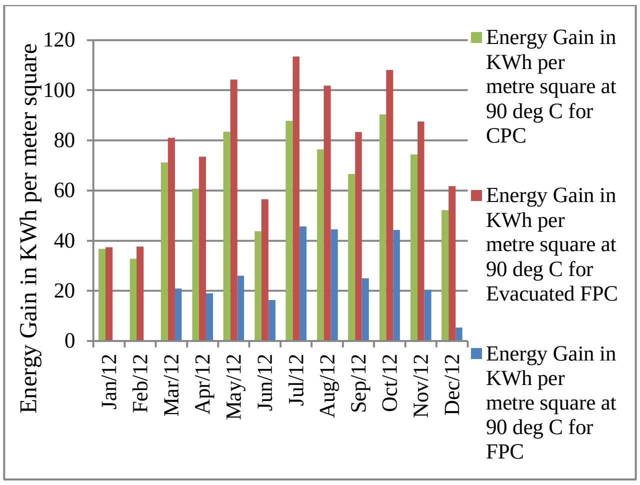

Fig. 11 Graph representing month wise variation of Energy Gain in KWh per meter square at 90°C for FPC, Evacuated FPC and CPC at Leh_Ladakh

3.3.1.2. Energy Gain in KWh per meter square at 120^{0}C for different collector technologies at Leh_Ladakh

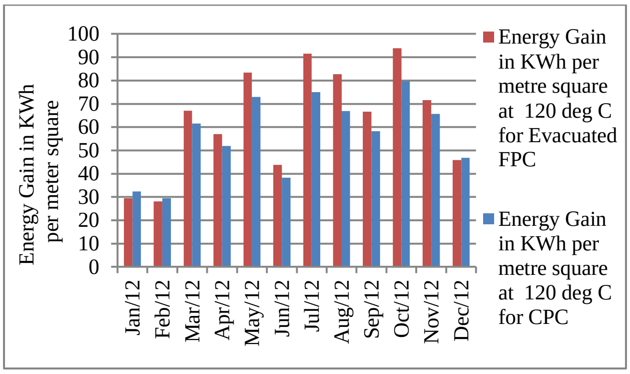

Fig. 12 Graph representing month wise variation of Energy Gain in KWh per meter square at 120°C for FPC, Evacuated FPC and CPC at Leh_Ladakh

3.3.1.3. Energy Gain in KWh per meter square at 180⁰C for different collector technologies at Leh_Ladakh

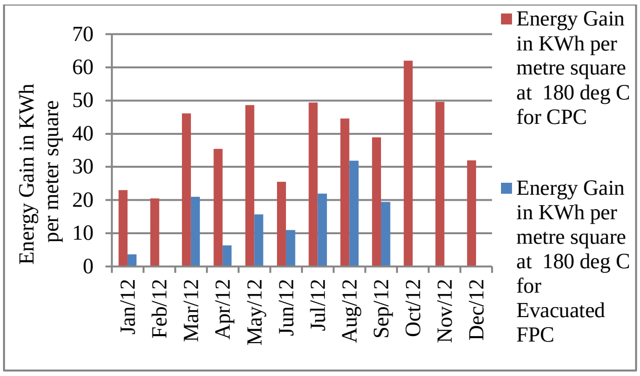

Fig. 13 Graph representing month wise variation of Energy Gain in KWh per meter square at 180°C for FPC, Evacuated FPC and CPC at Leh_Ladakh

3.3.2 Energy Gain received annually (2012) for solar thermal technologies at different operating temperature at Chennai

3.3.2.1 Energy Gain in KWh per meter square at 90⁰C for different collector technologies at Chennai

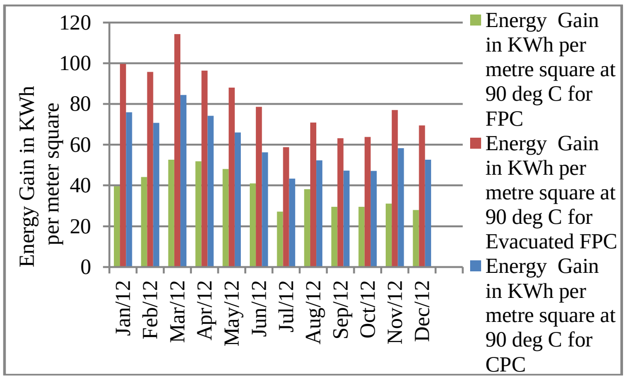

Fig. 14 Graph representing month wise variation of Energy Gain in KWh per meter square at 90°C for FPC, Evacuated FPC and CPC at Chennai

3.3.2.2 Energy Gain in KWh per meter square at 120⁰C for different collector technologies at Chennai

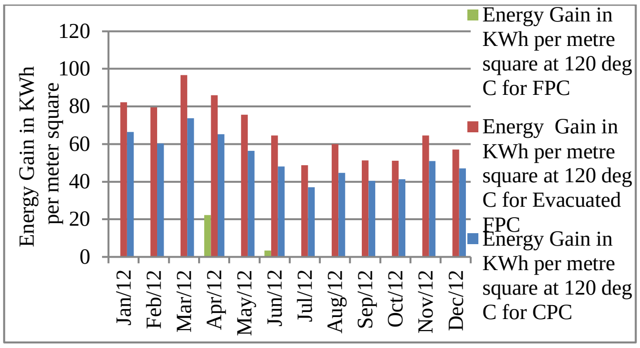

Fig. 15 Graph representing month wise variation of Energy Gain in KWh per meter square at 120°C for FPC, Evacuated FPC and CPC at Chennai

3.3.2.3 Energy Gain in KWh per meter square at 180⁰C for different collector technologies at Chennai

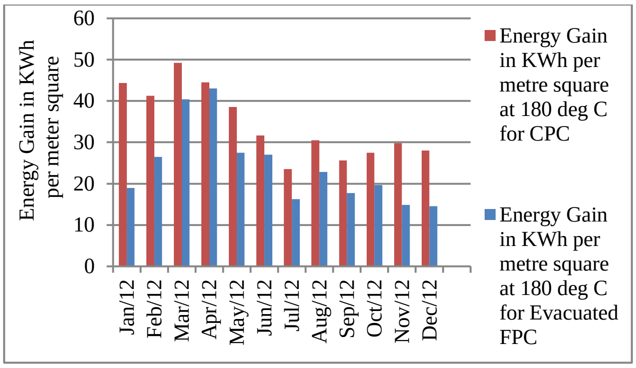

Fig. 16 Graph representing month wise variation of Energy Gain in KWh per meter square at 180°C for FPC, Evacuated FPC and CPC at Chennai

3.3.3 Energy Gain received annually (2012) for solar thermal technologies at different operating temperature at Gujarat_Gandhinagar

3.3.3.1 Energy Gain in KWh per meter square at 90⁰C for different collector technologies at Gujarat_Gandhinagar

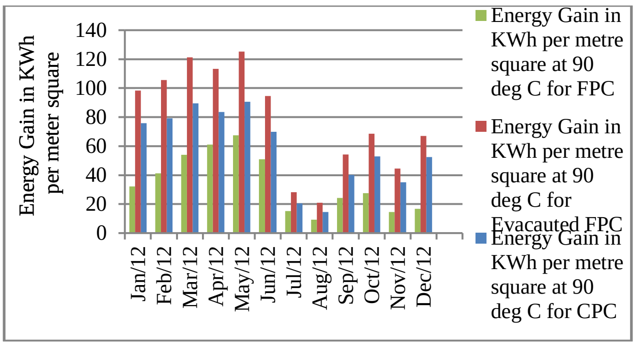

Fig. 17 Graph representing month wise variation of Energy Gain in KWh per meter square at 90°C for FPC, Evacuated FPC and CPC at Gujarat_Gandhinagar

3.3.3.2 Energy Gain in KWh per meter square at 120^{0}C for different collector technologies at Gujarat_Gandhinagar

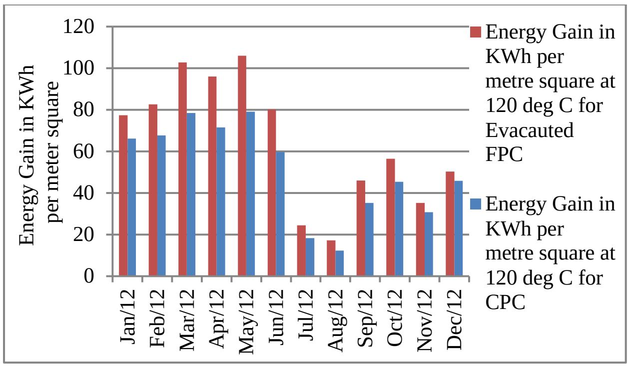

Fig. 18 Graph representing month wise variation of Energy Gain in KWh per meter square at 120^{o}C for Evacuated FPC and CPC at Gujarat_Gandhinagar

3.3.3.3 Energy Gain in KWh per meter square at 180^{0}C for different collector technologies at Gujarat_Gandhinagar

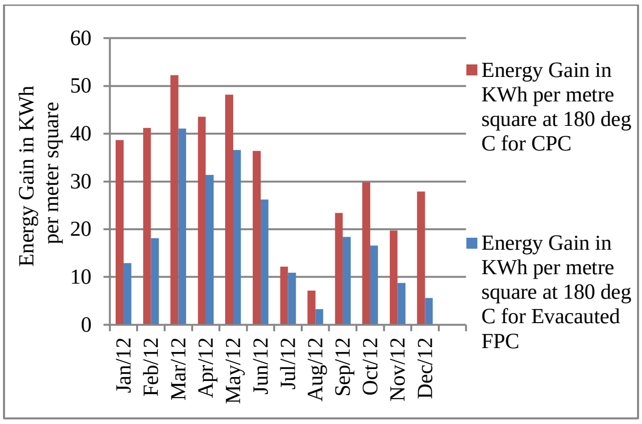

Fig. 19 Graph representing month wise variation of Energy Gain in KWh per meter square at 180^{o}C for Evacuated FPC and CPC at Gujarat_Gandhinagar

3.4 Comparative Performance analysis by evaluating operating temperature conditions for different solar thermal technologies

Table 4 Energy Gain in KWh per meter square for FPC, Evacuated FPC & CPC at different operating temperature at Leh_Ladakh

Leh_Ladakh			
Mean Desired Temp (Td(°C))	Energy Gain in KWh per meter square for Flat Plate Collector	Energy Gain in KWh per metre square for Evacuated FPC	Energy Gain in KWh per metre square for 1.5x Non Imaging Concentrator Collector
40	841	1095	925
50	738	1076	900
60	632	1054	872
70	513	1016	852
80	413	997	814
90	267	946	776
100	136	885	737
110	21	826	706
120	0	761	679
130	0	693	651
140	0	605	613
150	0	531	570
160	0	423	535
170	0	316	506
180	0	208	475
190	0	108	437
200	0	36	399

Table 5 Energy Gain in KWh per meter square for FPC, Evacuated FPC & CPC at different operating temperatures at Chennai

Chennai			
Mean Desired Temp (Td(°C))	Energy Gain in KWh per meter square for Flat Plate Collector	Energy Gain in KWh per metre square for Evacuated FPC	Energy Gain in KWh per metre square for 1.5x Non Imaging Concentrator Collector
40	974	1061	884
50	903	1054	864
60	785	1044	835
70	681	1035	796
80	578	1006	765
90	461	975	728
100	334	933	695
110	166	870	659
120	25	817	631
130	0	751	591
140	0	670	559
150	0	598	520
160	0	503	478
170	0	399	448
180	0	289	414
190	0	131	443
200	0	53	401

Table 6 Energy Gain in KWh per meter square for FPC, Evacuated FPC & CPC at different operating temperature at Gujarat_Gandhinagar

Gujarat_Gandhinagar			
Mean Desired Temp (Td(°C))	Energy Gain in KWh per meter square for Flat Plate Collector	Energy Gain in KWh per metre square for Evacuated FPC	Energy Gain in KWh per metre square for 1.5x Non Imaging Concentrator Collector
40	945	1036	858
50	843	1034	825
60	728	1007	810
70	630	1006	775
80	517	975	737
90	414	942	704
100	293	894	680
110	132	843	641
120	29	773	609
130	0	713	572
140	0	622	533
150	0	545	489

160	0	453	449
170	0	507	420
180	0	301	380
190	0	129	348
200	0	42	313

Conclusion

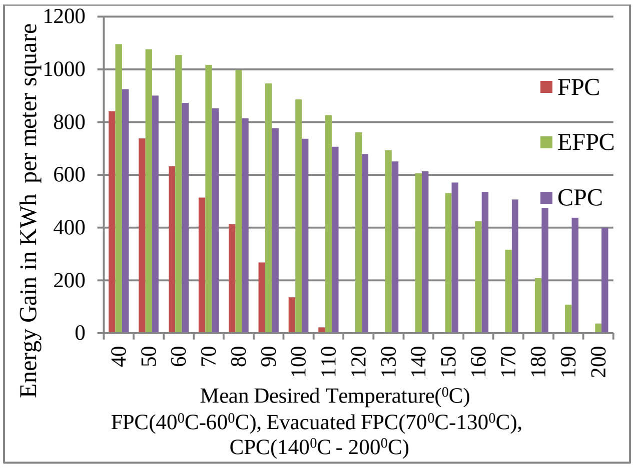

Fig. 20 Predicting cost effective Solar Thermal Technology at Leh_Ladakh

The simulative study as shown in Figure 20 reveals that FPC proves to be more cost effective below temperature of 60°C at Leh_Ladakh, however it reaches to 77°C at Chennai as shown in Figure 21 and 73°C at Gujarat_Gandhinagar offering cost of Rs.6,000 per meter square (at zero land cost) and above this temperature Evacuated FPC is more cost effective as shown in Figure 22 even though it offers higher cost of Rs.10,000 per meter square.

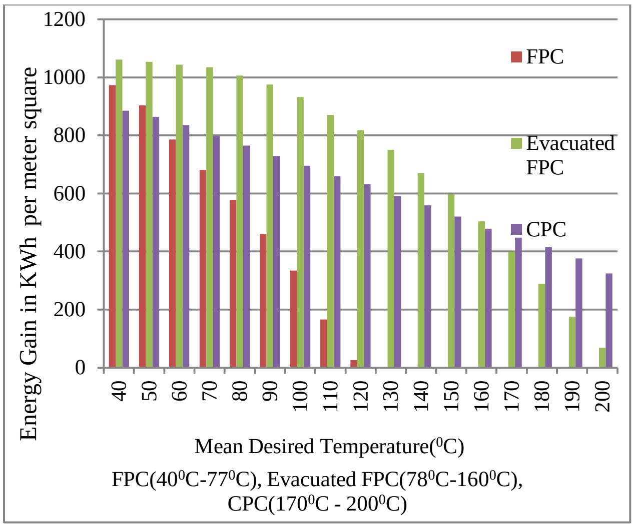

Fig. 21 Predicting cost effective Solar Thermal Technology at Chennai

However, when Land cost is Rs. 4000 per meter square, FPC is cost effective below temperature of 46°C at Leh_Ladakh as shown in Figure 23 and it reaches to 64°C at Chennai as shown in Figure 24 and it reaches to 61°C at Gujarat_Gandhinagar as shown in Figure 25 and above this temperature Evacuated FPC is more cost effective.

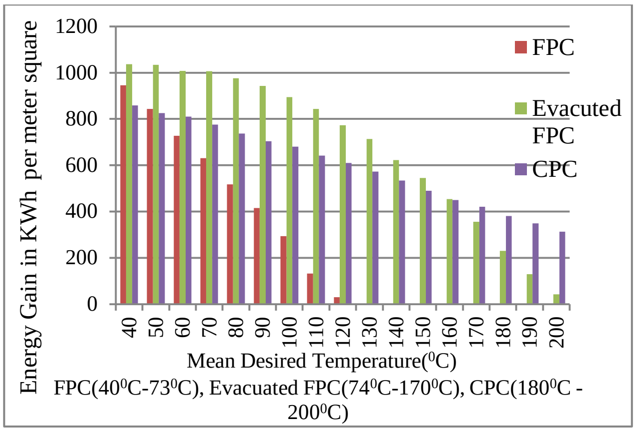

Fig. 22 Predicting cost effective Solar Thermal Technology at Gujarat_Gandhinagar

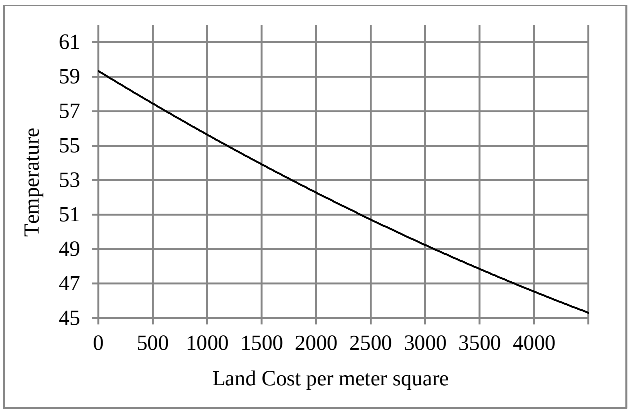

Fig. 23 Land Cost versus Temperature variation on comparing FPC and Evacuated FPC at Leh_Ladakh

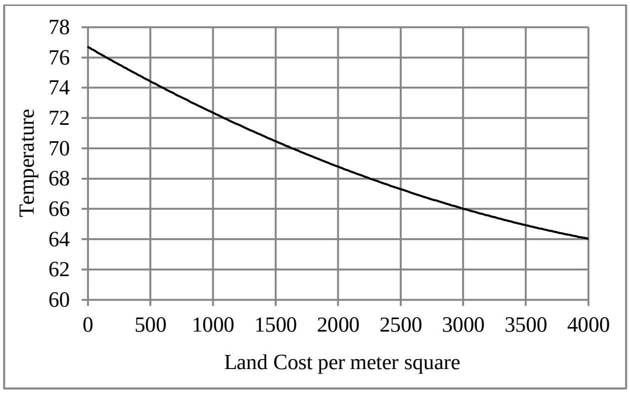

Fig. 24 Land Cost versus Temperature variation on comparing FPC and Evacuated FPC at Chennai

On comparing FPC and CPC, the switch over temperature from FPC to CPC technology is 70°C for Leh_Ladakh as shown in Figure 26 whereas for Chennai it is 93°C as shown in Figure 27 and for Gujarat_Gandhinagar it is 89^{o}C as shown in Figure 28 at zero land cost, and above this temperature CPC is more cost efficient even though it offers 1.65 times higher cost than FPC.

However, when land cost is Rs. 4,000 per meter square, FPC is cost effective below temperature of 60^{o}C at Leh_Ladakh whereas for Chennai it is below 83^{o}C as shown in Figure 27 and for Gujarat_Gandhinagar it is below 79^{o}C as shown in Figure 28 above this temperature CPC is more cost efficient.

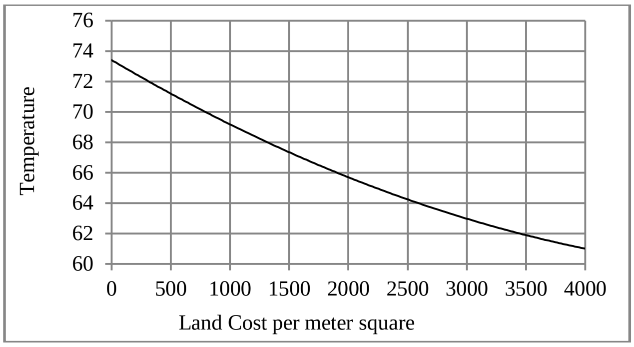

Fig. 25 Land Cost versus temperature variation on comparing FPC and Evacuated FPC at Gujarat_Gandhinagar

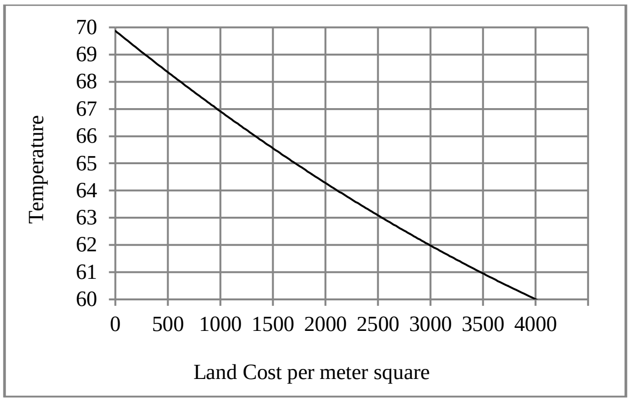

Fig. 26 Land Cost versus Temperature variation on comparing FPC and CPC at Leh_Ladakh

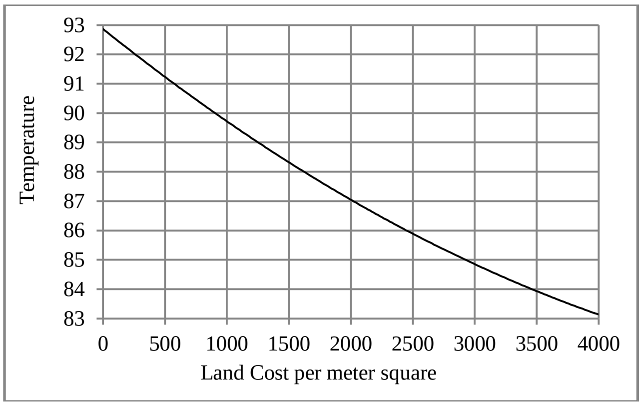

Fig. 27 Land Cost versus Temperature variation on comparing FPC and CPC at Chennai

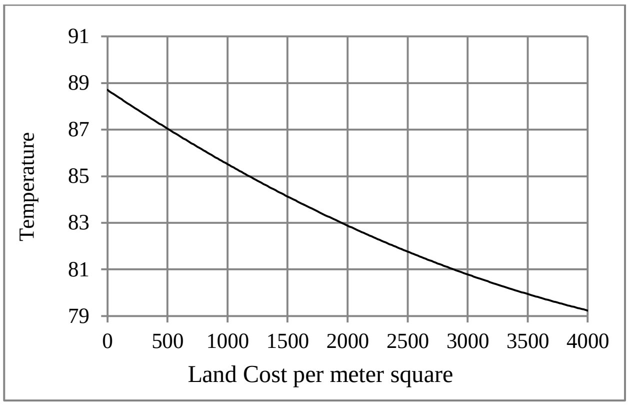

Fig. 28 Land Cost versus Temperature variation on comparing FPC and CPC at Gujarat_Gandhinagar

Between CPC and Evacuated FPC, CPC technology is cost effective above 130^{o}C at Leh_Ladakh as shown in Figure 20 and below this temperature Evacuated FPC is more cost effective, however at Chennai, the temperature reaches to 160^{o}C as shown in Figure 21, and it reaches to 170^{o}C at Gujarat_Gandhinagar as shown in Figure 22 even though both the technologies offers same cost of Rs.10,000 per meter square.

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