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Research Article

Comparative Performance Analysis of Solar Thermal Technologies in Delhi Region

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Abstract

This paper presents the results of an experimental investigation on the performance characterization of solar thermal collector technologies based on the analysis of radiation data at Haryana_SEC located at 28.4700^{0}N latitude. A complete collector test facility system has been tested for this purpose. Solar Collector is one of the important solar energy trapping device which uses air or water as working fluid. A comparative simulative study is performed between Flat Plate Collector, Evacuated Flat Plate Collector and 1.5x Non Imaging Concentrator Collector based on the specification of given technology and analysis of solar radiation. The performance characteristics of these solar collector concepts are presently being developed, and a comparison is done at different operating temperature. In this study, Month wise variation of Energy gain is performed at different operating temperature conditions. Flat Plate Collector can easily achieve temperature of 70^{0}C and CPC technology can be cost effective at temperature above 160^{0}C. Also, switch over temperature condition from one technology to another is calculated and results are presented.

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

1. Introduction

The technology of harnessing the solar energy has reached to the state of commercialization on mass scale. The greatest advantage of using solar energy is that it is an inexhaustible and pollution free source of energy. The Lord Sun gives approximately 1.8 x 10^{11} MW powers, which is many thousand times higher than the present consumption rate on earth. This makes it one of the most promising of the Unconventional sources of energy.

Solar collectors are the key component of active solar-heating systems. They gather the sun's energy, transform it's radiation into heat, and then transfer that heat into a fluid usually water or air (M.C. Rodriguez-Hidalgo *et al* 2011). The solar thermal energy can be used in solar water-heating systems, solar pool heaters, and solar space-heating systems.

At present, solar collectors having different types are being widely applied in solar energy field. In the present study, the different thermal collector technologies installed at Haryana_SEC are Flat Plate collector, Evacuated Flat Plate Collector & 1.5x Non Imaging Concentrator Collector, for which the comparative simulative analysis is performed at different operating temperature based on the analysis of radiation data for the year 2012.

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2. Solar Collectors

Solar collectors are well-known devices used to absorb and transfer solar energy into a collection fluid.

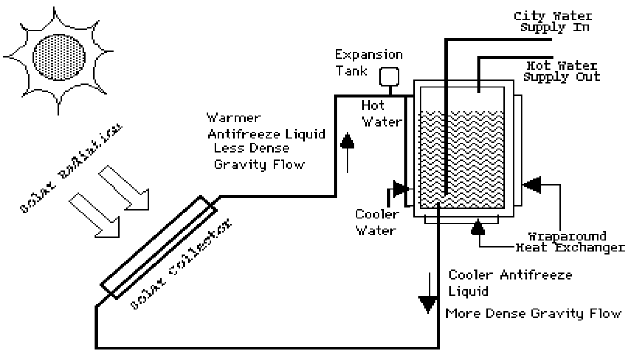

Fig. 1 Solar System employing Flat Plate Collector

Principally, solar collectors consist of a blackened absorbing plate contained in a housing which is frontally closed by a transparent window panel. Due to the diluted nature of solar light, in order to increase the operating temperature by reducing the thermal losses, solar collectors may be evacuated during use to eliminate gas convection and molecular conduction.

Figure 1 shows the schematic of a typical active solar system employing a FPC and a storage tank. With Q_i is the amount of solar radiation received by the collector. As the collector absorbs heat its temperature is getting higher than that of the surrounding and heat is lost to atmosphere by convection and radiation, this heat loss rate presented by Q_o(Smyth *et al* 2006).These designs are classified in two general types of solar collectors:-

(1) Flat-plate collectors– the absorbing surface is approximately as large as the overall collector area that intercepts the sun's rays.
(2) Concentrating Collectors– large areas of mirrors or lenses focus the sunlight onto a smaller absorber.

2. Solar Thermal Technologies

2.1 Flat Plate Collector

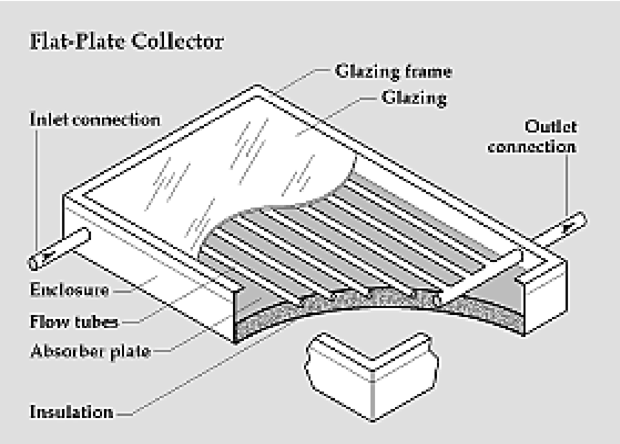

Fig. 2 Schematic of Solar Flat Plate Collector

Fig. 3 Experimental demonstration of Solar Flat plate Collector

The Flat Plate Collector is one of the most widely used devices for harnessing solar energy. In any solar collection device, the principle usually followed is to expose a dark surface to solar radiation so that the radiation is absorbed. A part of the absorbed radiation is then transferred to a fluid like air or water. When no optical concentration is done; the device in which the collection is achieved is called the flat plate collector (F. F. Mammadov *et al* 2012). The flat plate collector is the most important type of solar collector because it is simple in design, has no moving parts and requires little maintenance. It can be used for a variety of applications in which temperature ranging from 40 °C to 100 °C is required.

2.2 Evacuated Flat Plate Collector

A typical evacuated flat-plate collector consists of an absorber in an insulated box together with transparent cover sheets. The absorber is usually made of a metal sheet of high thermal conductivity, such as copper or aluminium, with integrated or attached tubes. Its surface is coated with a special selective material to maximize radiant energy absorption while minimizing radiant energy emission. The insulated box reduces heat losses from the back and sides of the collector. These collectors are used to heat a liquid or air to temperatures. The performance and operation of an evacuated flat-plate collector is governed by the fundamental laws of thermodynamics and relationships from heat transfer and fluid mechanics (Hossain *et al* 2011).

Fig. 4 Experimental Demonstration of an Evacuated Flat Plate Collector at SEC

Both collector structures are similar: a glass cover, an absorber, a serpentine tube and an aluminium frame. The difference lays in the evacuated flat plate collector inner gas and the backwards insulation. The typical inner gas in conventional flat plate collector is air at atmospheric pressure; meanwhile the inner gas used in evacuated flat plate collector usually is a noble gas.

2.3 1.5x Non-Imaging Concentrator Collector

Non imaging collector caters to heating applications up to 200°C for industrial as well as commercial applications. These collectors can be fixed on flat as well as on inclined roofs & require no tracking. This product deploys secondary reflectors to ensure maximum solar radiation capture across seasonal variations.

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. Non imaging optics solves better than imaging optics are:-

- **Solar Energy Concentration**: maximizing the amount of energy applied to a receiver, typically a solar cell or a thermal receiver (Khatib *et al,* 2012).
- **Illumination**: controlling the distribution of light, typically so it is "evenly" spread over some areas and completely blocked from other areas.

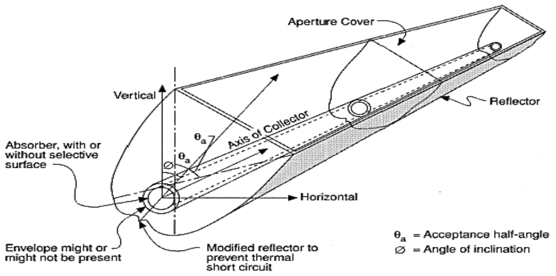

Fig. 5 Schematic of 1.5x Non Imaging Concentrator Collector

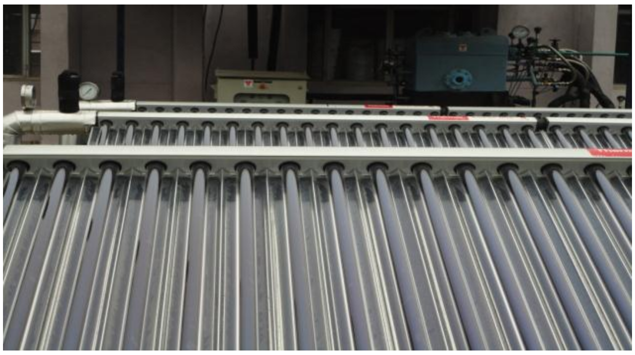

Fig. 6 Schematic of 1.5x Non Imaging Concentrator Collector

Typical variables to be optimized at the target include the total radiant flux, the angular distribution of optical radiation, and the spatial distribution of optical radiation. These variables on the target side of the optical system often must be optimized while simultaneously considering the collection efficiency of the optical system at the source (A. Eurelian *et al*, 2000).

3. Experimental analysis of Performance Characterization of Solar Collector Technologies

3.1 Performance analysis of a Flat Plate Collector

Collector fluid temperature or Mean Desired Temperature (T_d) = 70°C
Nominal Solar radiation (G) = 1000 W/m^2
Ambient Air 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.

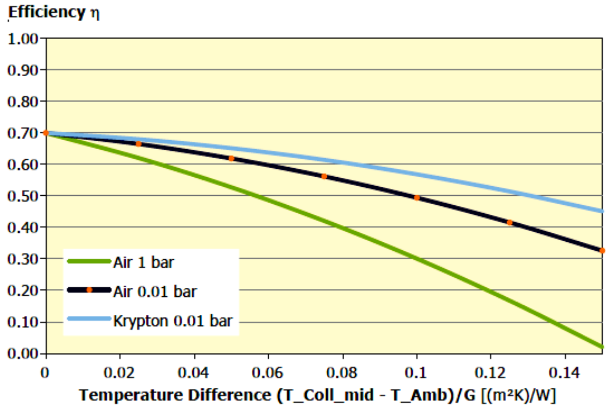

Fig. 7 Performance Characteristics Curve for different Flat Plate Collector.

3.1.1 Expressions for evaluating the Characteristics curve of Flat Plate Collector

1. Initial Point has been taken from the characteristics curve shown above, as it is 70% representing maximum efficiency for the system.

2. Efficiency Evaluation Point:-

ΔT/Global	Efficiency
0	70
0.04	58
0.10	30

3. Stagnation point:-(T_d - T_{amb})/Global = 0.15

From the graph shown the stagnation point is 0.15 means at this point the efficiency of the system is zero.

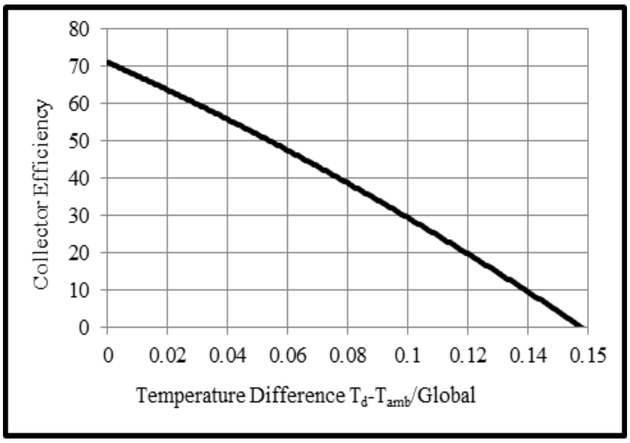

Fig. 8 Performance Characteristics curve of a Flat Plate Collector.

3.2 Performance analysis of an Evacuated Flat Plate Collector

Specification given by TVP Solar

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

Energy Performance:-
Thermal output@180^0C – 550 W/m^2,
1877 BTU/h(1000 W/m^2, T_{amb} – 30^0C).
Operating Conditions:-
Stagnation temperature- 325^0C, 617^0F
Maximum Operating Pressure -15 bar.

3.2.1 Expressions for evaluating the Characteristics curve of an Evacuated Flat Plate Collector

1. Initial Point has been taken from the characteristics curve of General Flat plate collector.
2. Efficiency evaluation point:- (T_d - T_{amb})/Global = (180-30)/1000 = 0.15

At 180^oC operating temperature, the point on x-axis is calculated to be 0.15, at which the output is 550W/m^2 which means the system is having 55% efficiency.

3. Stagnation Point:- (T_d - T_{amb})/Global = (325-30)/1000 = 0.30

At 325^oC stagnation temperature, the point on x-axis is calculated to be 0.30, at which the system is indicating stagnation point means there is no output or the efficiency of the system is zero.

The graph shown below is obtained after performing the above calculation obtained from the operating conditions of an Evacuated FPC, and based on this graph plus the yearly average analysis of solar radiation, the annual Energy gain received is realized at different operating temperature for the year 2012.

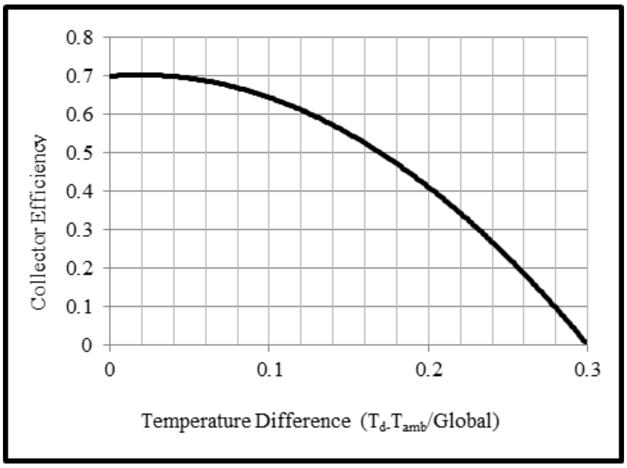

Fig. 9 Performance Characteristics curve of an Evacuated Flat Plate Collector.

3.3 Performance analysis of a Compound Parabolic Concentrator Collector

As per Stuttgart Report

Optical Efficiency or zero loss Efficiency ηo= 64.2%
First order Heat Loss Coefficient a_1 (W/m^2K) = 0.89
Second order Heat Loss Coefficient a_2 (W/m^2K) = 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@120^0C – 553 W/m^2 ,
(1000 W/m^2, T_{amb} – 30^0C).
Operating Conditions:-
Stagnation Temperature - 500^0C, 932^0F
Maximum Operating Pressure – 2 to 4 bar.

3.3.1 Expressions for evaluating the Characteristics curve of Compound Parabolic Concentrator Collector

Specific Nominal Capacity (P/A) = G*ηo - a_1*(T_d -T_{amb})-a_2*(T_d -T_{amb})^2

By substituting the values of above given data as per Stuttgart report in the above equation the following results are calculated:-

1. At Solar Global Radiation of 1000 W/m^2, and Ambient temperature T_{amb} – 30^0C, the efficient output of the system is 553W/m^2 at mean desired temperature of 120^0C.
2. Stagnation temperature obtained is 500^0C.
3. Maximum Operating Pressure 2-4 bar.

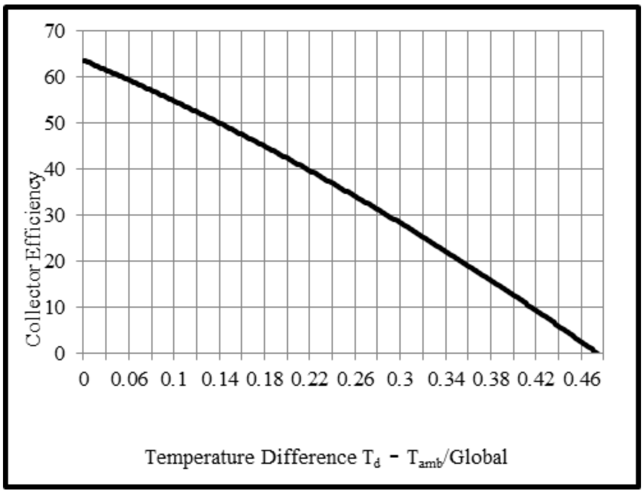

Fig. 10 Performance Characteristics Curve of Compound Parabolic Concentrator Collector.

4. Results and Discussion

4.1 Annual analysis of radiation data at Haryana_SEC for the year 2012.

Table 1 Calculated observation from analysis of radiation/weather data at Haryana_SEC for the year 2012

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 Hours (hr)	Daily Avg. hour (hr)	Day representing the month	Energy Gain in KWh per meter square (DNI)	Energy Gain in KWh per meter square (Horizontal Tilted Rad.)
Jan	15.84	386.77	494.09	195.24	362.73	187	6.05	15th Jan	67.83	92.39
Feb	19.13	479.99	554.25	208.24	448.21	240	8.3	23rd Feb	107.57	133.02
Mar	25.91	561.68	598.61	248.3	441.52	288	9.3	9th March	127.16	172.40
April	31.22	575.55	563.59	231.45	449.51	274	9.13	4th April	123.17	154.42
May	36.16	622.08	566.04	257.15	437.02	299	9.64	22nd May	130.67	169.25
June	37.53	611.89	548.1	322.38	331.23	269	8.97	25th June	89.10	147.44
July	34.41	606.12	551.85	346.86	302.91	167	5.57	24th July	50.59	92.16
Aug	31.03	601.86	572.41	370.16	290.35	258	8.32	3rd Aug	74.91	147.68
Sep	30.22	543.3	570.04	241.68	426.53	227	7.57	8th Sep	96.82	129.40
Oct	26.53	463.11	555.11	176.95	437.97	255	8.22	9th Oct	111.68	141.55
Nov	22.96	380.08	476.34	199.72	339.9	217	7.25	14th Nov	73.76	103.37
Dec	17.73	378.34	526.41	163.64	439.73	208	6.73	13th Dec	91.46	109.49
Average for the year 2012	27.38	517.56	548.07	246.81	392.3				(Annual) 1144.72	(Annual) 1592.57

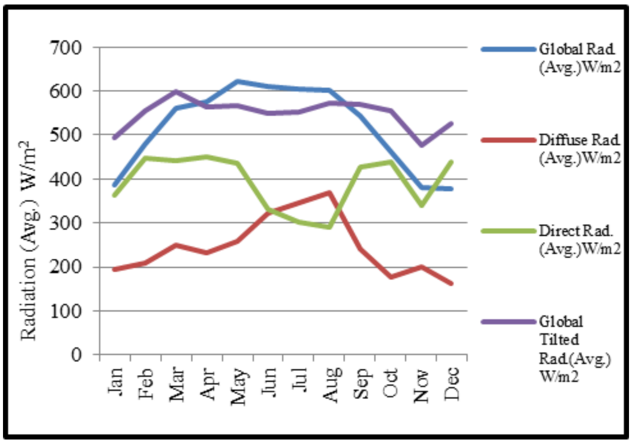

Fig. 11 The average Solar Radiation analysis at Haryana_SEC for the year 2012

4.2 Operating Temperature conditions for different technologies

Based on the analysis of solar radiation data at Haryana_SEC and performance characterization of given technologies, the Energy gain in KWh per meter square is calculated at different operating temperature.

Table 2 Energy Gain in KWh per meter square calculated for solar thermal technologies (Flat Plate Collector, Evacuated Flat Plate Collector and Compound Parabolic Concentrator Collector) at different operating temperature at Haryana_SEC for the year 2012

Mean Desired Temp Td(°C)	Energy Gain in KWh per metre square for FPC	Energy gain in KWh per meter square for Evacuated FPC	Energy Gain in KWh per meter square for CPC
40	1017.05	1116.47	924.14
50	896.82	1109.74	899.91
60	768.92	1098.82	869.13
70	651.15	1070.03	828.67
80	504.60	1042.22	783.19
90	379.45	1001.90	748.66
100	240.73	951.55	710.26
110	113.19	880.71	671.50
120	52.60	810.42	640.87
130	0	721.51	621.18
140	0	624.86	586.79
150	0	549.65	554.36
160	0	436.04	545.62
170	0	324.54	486.70
180	0	215.41	390.82
190	0	124.04	339.36
200	0	36.13	230.32

4.3 Month wise variation of Energy gain at different operating temperature at Haryana_SEC

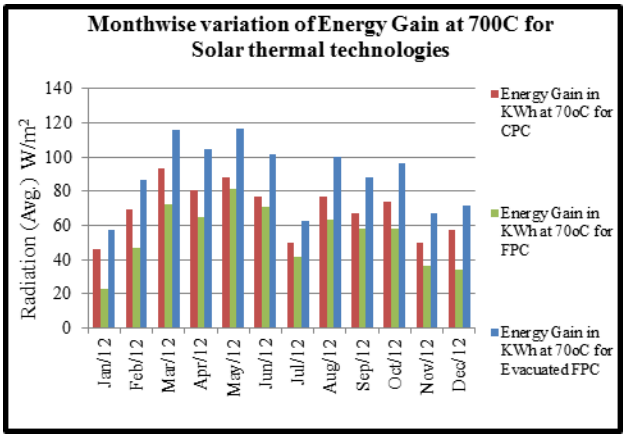

Fig. 12 Graph representing Energy Gain received per meter square at 70^{o}Cfor FPC, Evacuated FPC and CPC at Haryana_SEC for the year 2012

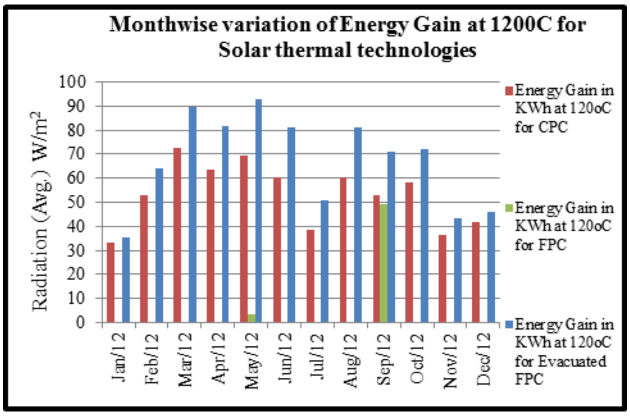

Fig. 13 Graph representing Energy Gain received per meter square at 120^{o}C for FPC, Evacuated FPC and CPC at Haryana_SEC for the year 2012

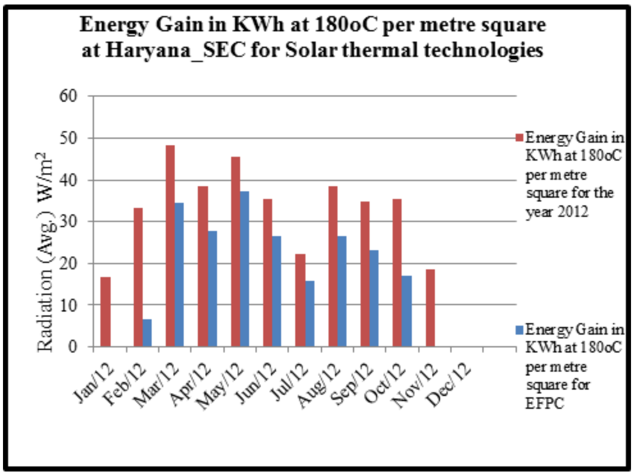

Fig. 14 Graph representing Energy Gain received per meter square at 180^{o}C for Evacuated FPC and CPC at Haryana_SEC for the year 2012

Conclusion

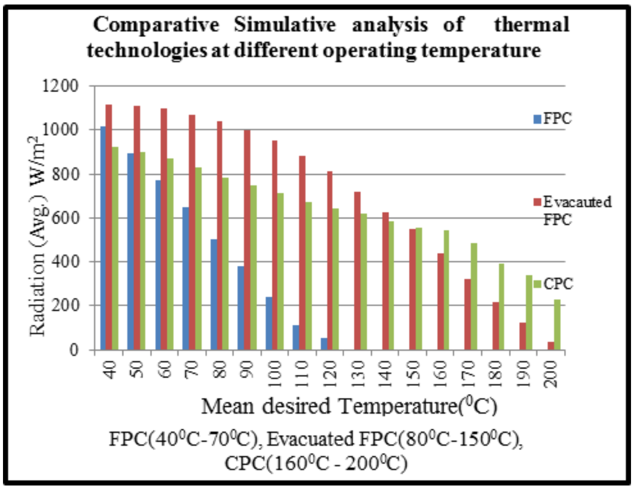

Fig. 15 Graph representing switch over temperature range for different technologies at Haryana_SEC for the year 2012

The simulative graph shown above reveals that the switch over temperature from one technology to another strongly depends on the Weather condition, Land cost and Performance Characterization of technology.

FPC & Evacuated FPC:- On comparing FPC and Evacuated FPC, FPC proves to be more cost effective below temperature of 70^{o}C as it offers cost of Rs. 6,000 per meter square (zero land cost) and above 70^{o}C Evacuated FPC is more cost effective, even though it offers higher cost of Rs.10,000 per meter square. However, when Land cost is Rs. 4000 per meter square, FPC is cost effective below temperature of 59^{o}C and above this temperature; Evacuated FPC is more cost efficient as shown in the Figure 16.

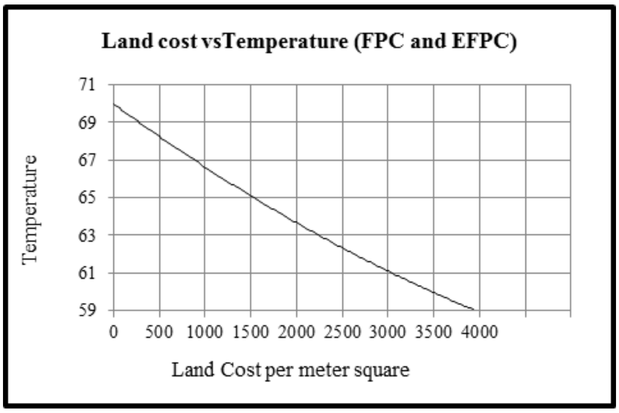

Fig. 16 Graph representing variation of Land cost and Temperature between Flat Plate Collector and Evacuated FPC at Haryana_SEC

FPC & CPC:- Similarly, on comparing FPC and CPC, FPC is more cost effective at temperature below 83^{o}C and above this temperature CPC is more cost effective even though it offers 1.65 times higher cost than FPC at zero land cost as shown in Figure 17.

However, when land cost is Rs. 4,000 per meter square, FPC is cost effective below temperature of 74^{o}C and above this temperature CPC is more cost efficient as shown in Figure 17.

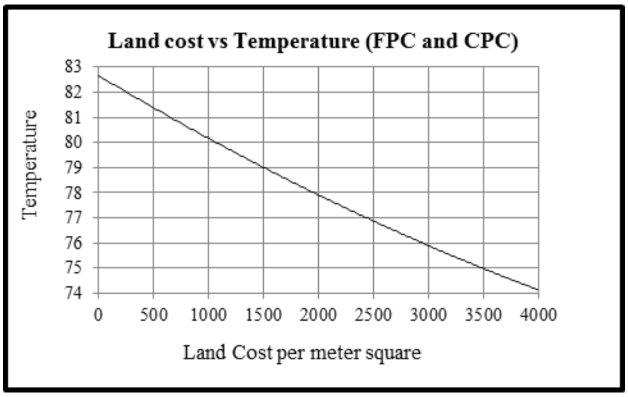

Fig. 17 Graph representing variation of Land cost and Temperature for Flat Plat Collector and Compound Parabolic Collector at Haryana_SEC

Evacuated FPC & CPC:- Between CPC and Evacuated FPC, Evacuated FPC is more cost effective at a temperature below 150^{o}C and above this temperature CPC technology is more cost effective as shown in Figure 15 even though both the technologies offers same cost of Rs.10,000 per meter square.

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