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Low Concentrating Solar Collectors for Economical Generation of Low-Medium Temperature Industrial Process Heat

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Abstract

A large fraction of the total energy consumption in the industrial sector (approximately 60%) is for direct heat/thermal applications known as Industrial Process Heat (IPH). About half of that energy is used to generate IPH, below the temperature of 300 ^{0}C. To supply this heat energy alternatively, various solar thermal technologies are being utilized. For generating heat at temp below 120 ^{0}C flat plats and evacuated tube collectors are used and for temperature above 150 ^{0}C, high concentrating technologies such as PTC, dish concentrators are used. Flat plats solar water heaters are economical and efficient in generating heat at lower temperatures. But to generate heat at temperature above 150 ^{0}C, more expensive and high concentrating solar collectors are being used. Alternative, less concentrating solar collector with zero or minimum solar tracking, can be used to generate the low-medium temperature industrial process heat. Various, more efficient low concentrating collectors are being developed and tested by researcher which can be used for such applications. These kinds of collector provide more economical solution than high concentrating collectors. In this paper we will look at some of the recently developed low concentrating solar collectors and how they can be utilized to produce low-medium temperature industrial process heat in more economical way compare to high concentrating solar collectors.

Keywords: *Industrial process heat (IPH), Solar Concentrators, Compound Parabolic Collector*

1. Introduction

Energy is the key factor contributing to economic development and quality of life worldwide. It is the basic input required to sustain economic growth. There is direct relation between the level of economic development and per capita energy consumption. Simply speaking more developed a country, higher is the per capita consumption of energy and vice-versa. But conventional energy has two major drawbacks, in the way it is produced and used. Firstly, the overall energy system has been very inefficient in the past. And secondly, major environmental and social problems are associated with the traditional energy system. According to IEA's report greenhouse gases (GHG's) emissions from the traditional energy sector will increase by 130% above 2006 levels by 2050 if new policies and practices are not implemented. (IEA, 2008) Moreover, environmental issues of conventional energy resources such as climate change and global warming are continuously forcing us for alternative sources of energy. According to the statistics released by World Health Organization (WHO), direct and indirect effects of climate change leads to the death of 160,000 people per year and the rate is estimated to be doubled by 2020. (Muneer et al., 2006) Therefore, finding clean sources of energy to satisfy the world's growing demand is one of the society's foremost challenges for the next few decades.

For last couple of decades, there is an accelerated effort, throughout the world, in R&D and implementation of various renewable energy sources i.e. solar, wind, biogas, biomass etc. Among all the renewable energy sources, solar power attracted more attentions as a greatest promising option for energy generation. Solar energy is abundance, free and clean which does not make any kind of pollution to the environment. Amount solar energy received by earth surface in a year is about 885 million terawatthours (TWh). That is 6 200 times the commercial primary energy consumed by humankind in 2008 – and 4 200 times the energy that mankind would consume in 2035 (IEA, 2011). At present consumption rate, proven fossil reserves can last for 46 years (oil), 58 years (natural gas) and almost 150 years (coal) (IEA, 2010), the energy received by the sun in one single year, if entirely captured and stored, would represent more than 6 000 years of total energy

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consumption. Capturing and distributing only one tenth of one percent of solar energy will make the energy supply problem disappear.

Presently, solar energy is being widely used for generation of electricity and heat. According to study on the world energy consumption by International Energy Agency (IEA), by 2050 around 45% of energy demand of the world will be supplied using solar energy. As electricity is the highest quality of energy it should be given priority. But energy consumption in the form of direct heat also forms a major mode of energy consumption. The importance of energy in industrial development is very crucial since major fraction of energy is used in industrial processes. It has dominated more than 50% of total energy consumption worldwide.

2. Industrial Process Heat

Industrial sector uses heat for a wide variety of applications, including washing, cooking, sterilizing, drying, preheating of boiler feed water, process heating, and much more. Three different temperature levels are used for describing the quality of the demand for heat in industries: low temperature level is defined as up to 95 °C, corresponding to the typical heat demands for space heating or industrial processes like washing, rinsing and food preparation. Temperatures between 95 ºC and 250 ºC are defined “medium”. This heat is normally supplied through steam. Temperatures over 250 ºC are “high” and needed to manufacture metals, ceramics, glass etc. To estimate the potential of solar thermal technologies for industrial process heat generation, knowledge of the required different temperature levels of process heat is essential. Following table 1, gives an overview of various industrial process and their temperature levels.

Tab 1: Temperature ranges for different industrial processes (Kalogirou, 2003a)

Industry	**Process**	**Temperature (°C)**
Dairy	Pressurization	60–80
	Sterilization	100–120
	Drying	120–180
	Boiler feed water	60–90
Tinned food	Sterilization	110–120
	Pasteurization	60–80
	Cooking	60–90
	Bleaching	60–90
Textile	Bleaching, dyeing	60–90
	Drying, degreasing	100-130
	Pressing	80–100
Paper	Cooking, drying	60–80
	Boiler feed water	60–90
	Bleaching	130–150
Chemical	Soaps	200–260
	Synthetic rubber	150–200
	Processing heat	120–180
	Pre-heating water	60–90
Meat	Washing, sterilization	60–90
	Cooking	90–100
Beverages	Washing, sterilization	60–80
	Pasteurization	60–70
Timber by-products	Thermo diffusion beams	80–100
	Drying	60–100
	Pre-heating water	60–90
	Preparation pulp	120–170

Plastics	Preparation	120–140
	Distillation	140–150
	Separation	200–220
	Extension	140–160
	Drying	180–200
	Blending	120–140

These industrial sectors/processes account for a significant share of energy consumption, and currently, energy required for these processes are supplied using fossil fuels. For industrial nation like Germany about 30% of the total energy demand is consumed by industrial sector. About 65% of this energy is used for generating industrial process heat. This energy is further divided, according to temperature level of process heat. Such as, 69 % of the industrial heat is demanded at temperatures above 250 °C (Figure 1). At temperatures below 100 °C, 21 % of the heat can be provided and further 6 % between 100 and 150 °C. And remaining 4 % of the demand occurs between 150 and 250 °C. (Lauterbach et al., 2011) This data is important to understand which solar thermal technology is suitable for specific industrial process.

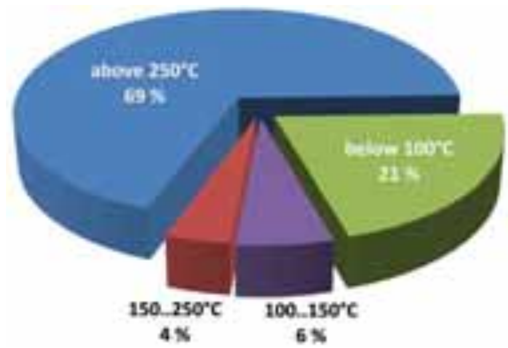


Fig 1: Industrial heat demand in Germany per temperature range. (Lauterbach et al., 2011)

Some of the sectors like steel, aluminium and ceramic have a number of processes which require high-grade heat (temperatures ranging above 800˚C), it would not be possible to provide these temperature levels with solar thermal technologies at reasonable costs. But most of the industrial processes have favourable conditions for the application solar energy. If industrial sectors actively exhibit eagerness, process heat requirement at 400 ^{0}C and below, can be successfully supplied using solar thermal technologies. Overall, an increase in solar energy in industry has the potential to contribute about 10% of all expected GHG emissions reductions in 2050. This is equivalent to the total current CO_2 emissions of France, Germany, Italy and Spain, or around one third of current emissions in the United States. (Thomas, 1995)

3. Solar thermal technologies

Among all the renewable energy sources, solar power attracted more attentions as a greatest promising option to be applied in industries. Solar energy is abundance, free and clean which does not make any kind of pollution to the environment. So far, many attempts have been made to extract solar energy by means of solar collectors, sun trackers and giant mirrors in order to utilize it for industrial purposes. To supply industrial process heat, various solar thermal technologies are being utilized. For generating heat at temp below 120 ^{0}C flat plats and evacuated tube collectors are used and for temperature above 150 ^{0}C, high concentrating technologies such as PTC, dish concentrators are used. Solar thermal technologies utilise the sun radiation to produce heat for many thermal applications. There are various solar thermal technologies available which can be utilized to supply heat at temperature between 60 ^{0}C and 250 ^{0}C. As can be seen in table 2, each technology can be characterised depending on their operating temperature, stationary or tracking etc.

Tab 2: Types of solar thermal collectors (Kalogirou, 2003b)

Motion	Collector type	Absorber type	Concentration ratio	temperature range (°C)
Stationary	Solar pond		1	30–90
	Flat plate	Flat	1	30–80

	collector (FPC)			
	Evacuated tube collector (ETC)	Flat	1	50–150
	Compound parabolic collector (CPC)	Tubular	1–5	60–240
Single-axis tracking			5–15	60–300
	Fresnel lens collector (FLC)	Tubular	10–40	60–250
	Parabolic trough collector (PTC)	Tubular	15–45	60–300
	Cylindrical trough collector (CTC)	Tubular	10–50	60–300
Two-axes tracking	Parabolic dish reflector (PDR)	Point	100–1000	100–500
	Heliostat field collector (HFC)	Point	100–1500	150–2000

These technologies can also be differentiated by the way they use solar energy. Flat plate and evacuated tube and low concentrating collectors use direct as well as diffuse solar radiation. High concentrating and tracking collector uses only direct normal solar radiation. The main component of any solar thermal technology installation is the solar collector. Solar collector collects the heat from solar radiation and transfers it to a receiver, containing stationery/circulating fluid (usually water or thermal oil). The solar energy thus collected is carried from the circulating fluid either directly to be utilized in many different thermal applications or to a thermal energy storage tank from which can be drawn for use at night and/or cloudy days.

From figure 1, it is evident that the requirement of the low-medium temperature process heat is obvious and significant. However, for the non-concentrating solar collectors, such as evacuated tube and flat plate collector, thermal efficiency of the collector decreases with increasing temperature. Especially above 80 ^{0}C, the thermal efficiency of the solar collector falls sharply, because of which they cannot be used efficiently for these applications. Therefore, to produce process heat at temperature above 80 ^{0}C, it requires solar concentrators, as opposed to non-concentrating collectors [Sardeshpande and Pillai, 2012]. On the other hand, although the high-concentration solar collectors can generate process heat at temperature above 80 ^{0}C, they need a sun tracking system, which further escalates operation and maintenance costs. Which usually make them suitable for large-scale integrated applications, such as high-temperature solar thermal power generation. At the same time, the high-concentration solar collectors, such as tower concentration solar collector and dish concentration solar collector, can get much higher temperature, which is beyond these applications temperature above, and can cause more thermal losses. What is more, high-concentration solar collectors can lead to more diffusion loss as these systems only make use of direct normal solar radiation. Therefore, high-concentration solar collectors also do not fit economically for these low-medium temperature process heat applications.Employment of low concentrating solar collectors is necessary for generating low-medium process heat more efficiently and economically. Researchers developed various efficient and economical low concentrating collector system but very few systems are commercially available.

4. Low Concentrating Solar Collector

Compound parabolic collectors (CPC), evacuated tube collector with/without CPC and flat plate collector sometime with booster reflectors, are employed as stationery and low concentrating systems. One of the main advantages of this type of system is that they can utilise direct as well as some/ all diffuse solar radiation. This make them more efficient for solar radiation collection in a region where atmospheric pollution and dust particles, minimises direct radiation and maximizes diffuse solar radiation. Compound parabolic collector hold great promise to become alternative technology to provide industrial process heat at temperature in range of 150 ^{0}C – 250 ^{0}C. Concept design of CPC was first introduced by Winston in 1974, which is a non-imaging type of concentrator. (Winston, 1974) The basic shape of the compound parabolic concentrator (CPC) is illustrated in Figure 2. A CPC is made of two halves of symmetrical parabola with closely located focal points and their axes inclined to each other, such that rays incident within the angle between the two axes (angle of the CPC) are reflected towards the region between the two focal points and get concentrated in that region, not on a point. Thus, CPCs are non-imaging concentrators and can accept incoming radiation over a relatively wide range of angles.

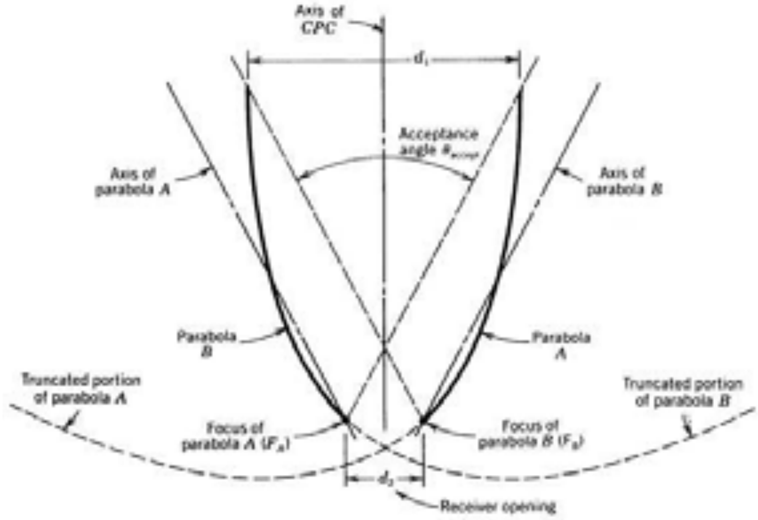


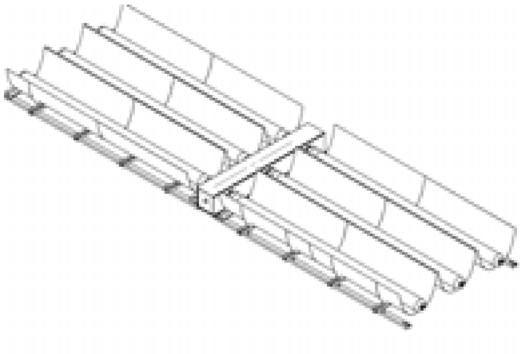
Fig 2: The geometry of conventional compound parabolic concentrator (CPC).

However, there is a trade-off, curve of a parabola has the property that its height increases very slowly as compared to its aperture, until the focal plane is reached; and it increases sharply beyond the focal plane. In the conventional design of CPC, foci of both the parabolas lie at the bottom of the CPC, and sections above the focal points of both are used. This causes rapid increase in height and a low energy concentration performance. Various designs have been proposed by several researchers to successfully overcome these limits to varying degrees.

In 2013 Jadhav et al. (Jadhav et al., 2013) proposed improved design of compound parabolic collector as compared to those reported earlier. Improved design substantially reduced the reflector height without compromising the concentration ratio. The modified design used the region below the common focus of parabolas. Based on their designed, a 100 m2 CPC system was fabricated and investigate, with aperture width 2 m, acceptance angle 3 and receiver pipe of 48 mm outer diameter had a height of around 0.5 m from base of reflector. For the same aperture width, acceptance angle and receiver dimensions, the height for conventional, untruncated CPC is around 38 m. Thus the modified CPC design needs substantially reduced support structure, and consequently, expected to be economical and easy to handle. The receiver wasn't evacuated and system generated steam at 120 ^{0}C with 43% efficiency. Cost of their 100 m^2 system was around 70 US\$/m^2 and claimed that same system with few minor refinement can generate steam at around 200 ^{0}C.

Fig. 3. A photo of the experimental 100 m^{2}CPC system.

Recently, Lun Jiang et al. (Jianga et al., 2015) published performance of eXternal Compound Parabolic Concentrator (XCPC). This prototype XCPC, as seen in figure [4] is placed East-West, with pentagon absorber as cross section. Oil is used as the heat transfer fluid in the system. The absorber tube is made of a metal glass vacuum tube due to its improved heat transfer capability compared to the all glass vacuum tubes. Their test result shows that XCPC reach working temperature of 160 ^{0}C, 200 ^{0}C and 230 ^{0}C with efficiency of about 59%, 52% and 43% respectively.



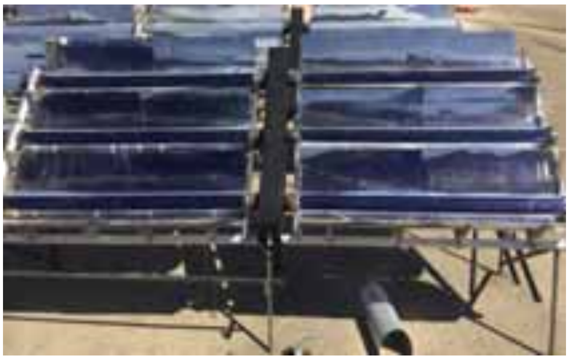
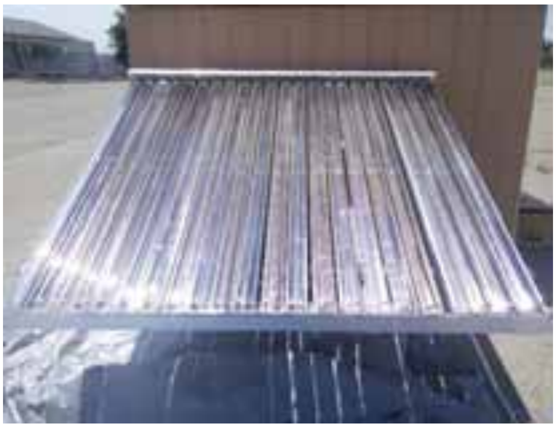


Fig 4: The XCPC collector with east west axis direction. Aperture area for each collector is 4.5 m^2

Lun Jiang et al. (Jianga et al., 2015) also published performance of full size collector of Integrated Compound Parabolic Concentrator (ICPC) (Fig.6). Each of the ICPC tube is eventually fabricated at 85mm width with a absorber of 30mm height, resulting in a concentration ratio of 1.41. The aperture area is 1900mm X 85mm for each tube. A heat pipe of 8mm diameter is inserted into the absorber fin and ultrasonic welded on to the fin to ensure the heat transfer. The reflective coating is using the Flat Plate Collector with Booster Reflectors standard silver mirroring chemical process, with a protective resin to be weather proof. The optics of the ICPC is designed for a 35 degrees acceptance angle and therefore should be positioned east-west direction. But for testing purpose and the trial of the heat pipe as a heat transfer model, we implemented them as north-south aligned, and put them on a tracker to take the measurement. The result is showing a relatively lower performance compared to the XCPC model under the same temperature. However, this is mainly due to the heat pipe not functioning as ideally as a heat transfer mechanism compared to the direct flow mechanism in the XCPC array. The ICPC collectors show 42% efficiency at 200 °C based on global irradiance.



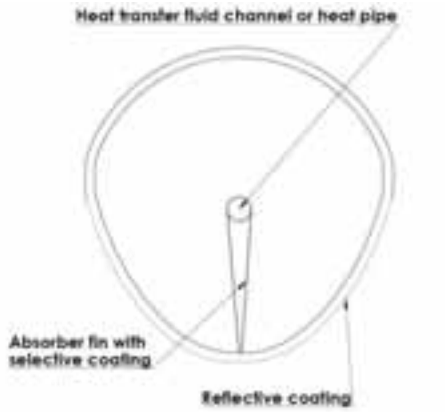


Fig 5: a) The ICPC 3.5 m^2 prototype, with full 1900mm length tube, front view. b) The cross section of the original ICPC prototype design.

Two non-tracking variation of CPC proposed by Wattana Ratismith et al. (Ratismith et al., 2014) one is more conventional double-parabolic trough, has the absorber plate perpendicular to the vertical axis of the trough cross-section. Second one is of a new flat-base shape, has the absorber plate parallel. The collectors have two novel features appropriate to non-tracking. The collectors have two novel features appropriate to non-tracking. The first is a smoothing of the power output over the day by beneficially arranging three troughs tilted at different angles. The second salient feature in the design of these solar collectors is the use of a trough which utilises the non-focussing advantages of non-parabolic shapes in achieving high acceptance angle, high intercept factor and high concentration of diffuse sunlight.

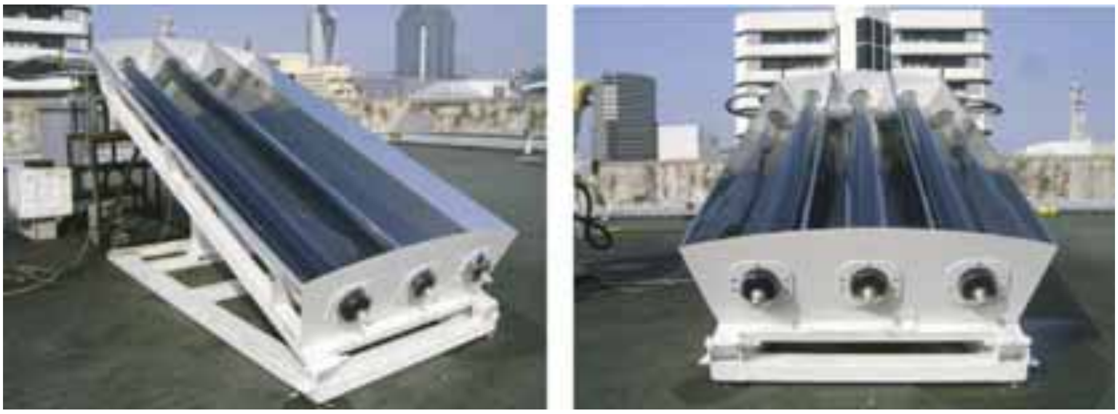


Fig 6: The non-tracking solar collector

They showed that their stationary flat base shape CPC performed better with operating temperature of 180 ^{0}C at 40% efficiency. In the experiment they used the commercially available SUNDA (SEID01) vacuum tubes of length 2.1 m with a planar absorber plate of width 9.0 cm.

Two truncated compound parabolic concentrating (CPC) solar collectors (shown in figure 7a & 7b), which combine the external CPC and the U-shape evacuated tube together, have been developed and tested by X. Li et al. (Li et al., 2013) Their CPC has concentration ratios of 3 and 6 and half-acceptance angles of 10^0 and 3^0, respectively. CPC with 3 concentration ratio will need only seasonal tracking while CPC with 10 concentration ratio will need to track sun 5 times a day. The daily thermal efficiencies of the 3X and the 6X CPC collectors can reach 40% and 46% at the collecting temperature of 200 ^{0}C, respectively. These verify that these kinds of CPC solar collectors are feasible for a wide range of intermediate industrial temperature applications.

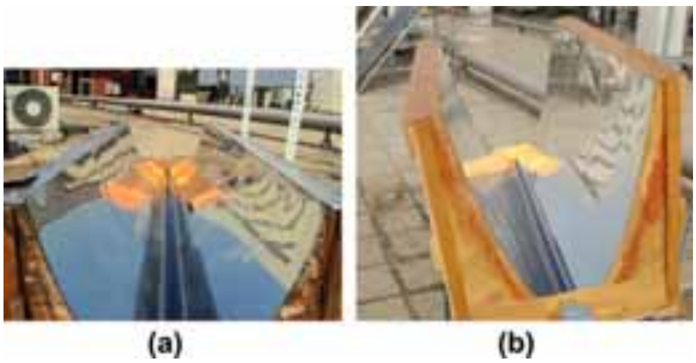


Fig 7: (a) the 3X CPC collector; and (b) the 6X CPC collector.

Last year at an international conference on solar heating and cooling, H.J. Burckhart et al. (Burckhart et al., 2013) presented results on use of novel collectors from the company SRB for heating and cooling of a building in Geneva, Switzerland. SRB Energy developed a two sided vacuum flat-plate collector, combined with CPC reflectors at the bottom side of the receiver (Figure 8a). This holds for both direct and diffuse light, which is of special importance as diffuse light amounts to about half of the total light in middle Europe. This system is stationery and according to the company, the vacuum inside the flat-plate, between 10^{-6} to 10^{-9} mbar,is expected to last for the whole service life of the collector. Figure 5b shows the collection efficiency of this system for different solar irradiations. Temperatures up to 400 °C can be reached. Figure 8b shows, that the 90 °C necessary to drive the absorption unit can easily be reached for irradiations as low as 200 W/m^2 with a reasonable efficiency. The stability and ease of operation of this solar collector has already been proven in existing installations.

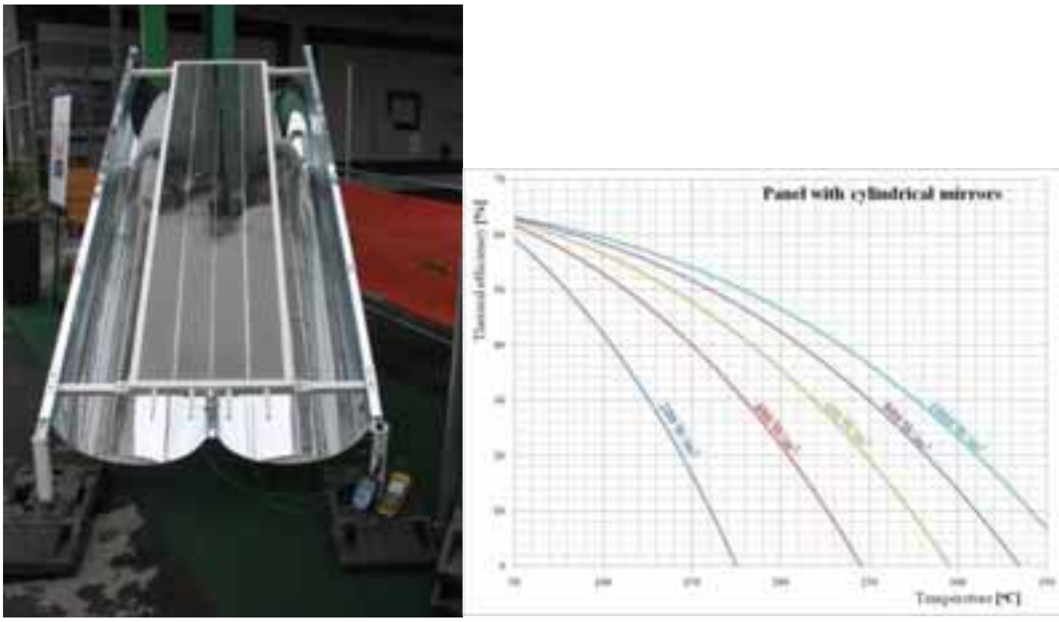


Figure 8: a) Assembly of the absorber panel and the two mirrors b) Thermal efficiency for different solar irradiation

5. Drivers for low concentrating technologies

In previous section we discussed some of stationery and low concentrating technologies, which are being developed and tested to operate at temperatures close to 250 ^{0}C. Most of these technologies, more or less are laboratory based or/and demonstration purposes only. One of the main barriers to increased deployment of solar industrial process heat systems is the high investment cost and lack of finance options. Cost plays important deciding factor for any new technology to become market ready and available to consumer. All solar process heat systems involve high initial investments in advance of a practically cost-free operating period. However, proper maintenance is required to ensure that the systems operate optimally over their full lifetime expectancy. The up-front costs particularly hamper deployment in small and medium size enterprises where financing is not available. (ESTIF, 2014)

The costs of solar thermal process heat installations in Europe range from 180 to 500 Euro / m^2 of aperture area, depending on the system concept, the size of the system, the selected components (e.g. the choice of the collector type) and on country-specific factors (e.g. salaries). Of the total costs in solar thermal technology, between 50-70% are related to the capital, while the remainder covers installation and integration. (IRENA, 2015) Table 3 provides an overview of the costs for solar concentrators: solar parabolic dish and parabolic dish are more expensive than conventional FPC and ETC but permit higher temperature ranges. Aagain these cost can vary from region to region, but for the sake of arguement Indian cost of all these technologies are taken. Comparing cost of stationery and concentrating solar collector one can easily find out that concentrating collector cost at least double than stationery solar collector. This cost difference can easily be a discouraging factor for small and medium scale industries from adopting solar process heat system.

Tab 3: Cost comparison of solar thermal collectors (IRENA, 2015)

	Stationery Solar Collectors		Tracking Concentrating Solar Collectors		
	FPC	**ETC**	**Parabolic Dish**	**PTC**	**Linear Fresnel**
Temperature Range ^{0}C	100 ^{0}C	120 ^{0}C	250 ^{0}C-700 ^{0}C	100 ^{0}C-400 ^{0}C	100 ^{0}C-350 ^{0}C
Cost (USD/m^2)	84-302	97-369	300-600	445	650-900
Cost (USD/kW)	216	203	600-1760	1580-2040	1160-1800

Stationery low concentrating collectors can play an important role of supplying low-medium temperature industrial process heat at a cost which can comfortably fit between the costs of stationery and tracking collectors. Theses collectors can be little expensive that stationery collector as they use reflector for concentration of solar radiation. At the same time low concentrating collectors will be less expensive that tracking collectors as they never/occasionally use more precision tracking mechanism and reflector curve. Developing and poor countries with high solar irradiation, small and medium size industries are an interesting market for such low concentrating solar thermal systems. As, these industries often rely on expensive fossil fuels for heat production and solar thermal systems reduce their dependence on fossil fuels and contribute to the reduction of operating costs. Also, the heat demands per plant are relatively small compared to the energy intensive industry, which makes the integration of solar heating systems easier. The sheer number of SMEs present could result in rapidly declining costs due to learning by doing and more effective operations by installers. This could create a virtuous circle in which, with declining costs and more experience, the deployment of solar heating systems is accelerated in this market segment. (IRENA, 2014)

6. Conclusion

A large fraction of energy used in industrial sector, is used for generating industrial process heat at temperature below 300 ^{0}C. To move away from polluting fossile fuel utilization, solar energy is succefully utilized for such applications. Presently, medium temeprature (150 ^{0}C - 300 ^{0}C) industrial process heat is supplied using solar concentrators similar to technologies used to produceconcentrated solar power (CSP). Instead of using the heat to produce power however,the heat is directly used in industrial processes. Such solar concentrators are parabolic dishes, parabolictrough concentrators and Linear Fresnel collectors. These collectors are made with efficient absorber, precision optics and tracking mechanism to produce temperature much greater that medium temperature range. Becuase these charecteristics of high concentrating collectors are expensive than the stationery solar collectors. For cost sensetive market in poor and developing counrties, for successful deplyment of solar industrial process, cost of these technologies needs to be brought down. An alternative for these expesive concentrator will be less concentrating technologies which are still under development stages. Less concentrating solar collector with zero or minimum solar tracking, can be used to generate the low-medium temperature industrial process heat. As discribed in this paper, researchers are developing more efficient low concentrating collectors which can be used for such applications. Cost comparsion of existing technologies shows that there a cost gap and market for low concentrating collectors which can be further explored. If developed further, commercialization of more efficient low concentrating technologies will further intensify the successful deployment of solar industrial process heat.

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