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Dirk Krüger, Stephan Fischer, Tobias Hirsch, et al.

Concentrating Solar Systems in Moderate Climates

Dirk Krüger[1, a)], Stephan Fischer[2, b)], Tobias Hirsch [3, b)] and Javier Iñigo Labairu[1, d)]

[1]*German Aerospace Center, Institute of Solar Research, Linder Höhe, 51147 Cologne, Germany,*
[2]*University of Stuttgart, Institute of Building Energetics, Thermotechnology and Energy Storage (IGTE), Germany*
[3]*German Aerospace Center, Institute of Solar Research, Wankelstraße 5, 70563 Stuttgart, Germany*

[a)] Corresponding author: dirk.krueger@dlr.de
[b)]stephan.fischer@igte.uni-stuttgart.de
[c)]tobias.hirsch@dlr.de
[d)]javier.InigoLabairu@dlr.de

Abstract. The general perception for the application of solar concentrating collectors in moderate climates as in Central Europe and similar areas in the world, is that their energy yield is not sufficient. Clearly, the Direct Normal Irradiation (DNI) of 1000 kWh/(m² *a) is significantly lower than in sunny areas where it amounts to 2000 kWh/(m² *a) or even more. Nevertheless, if compared with stationary collectors, line focusing collectors can deliver heat at a comparable level but at higher operation temperatures. Simulations with two different tools were performed to calculate the annual energy yield from parabolic trough collectors for temperatures between 50 and 100°C, to benchmark with stationary collectors, which are commercially successful. For a variety of moderate sites worldwide parabolic trough collectors deliver the same amount of heat as stationary collectors at operation temperatures around 75°C. The amount of costs are still difficult to obtain for parabolic trough collectors. For solar plants installed and commissioned, costs for efficient collectors are reported 230 to 300 €/m² for field sizes of 10.000 m². Troughs can already be competitive at operation temperatures below 100°C. Thus if stationary collectors are successful in a market, there is the opportunity for parabolic trough collectors to succeed at least for solar field sizes from several 100 m² upwards.

INTRODUCTION

Concentrating solar collectors are typically applied in regions with a DNI of around 2000 kWh/m² or more. However, in large parts of the world the DNI is significantly lower (Fig. 1). In these yellow to green marked areas, communities cover their heat demand mostly with stationary solar thermal systems. Implementing concentrating collectors which only make minor use of diffuse radiation has also been hindered by intuitive statements saying that the Direct Normal Irradiance would be too low compared to the global irradiance in these regions and that the energy yield is not attractive.

This publication therefore discusses mainly the energy output, which can be achieved from concentrating collectors. The output is benchmarked with collector technologies which are already successfully established in the market. It is assumed, that if concentrating collectors perform as well as or better than stationary collectors, there is good reason to consider them as a similar or even better performing alternative.

The evaluation is based on calculations as sufficient measurements from operating installations by independent entities do not exist yet. Collector systems have been measured according to ISO 9806 [1] though, and the measured efficiency functions can be applied in calculations with established programs. Several sites have been investigated worldwide.

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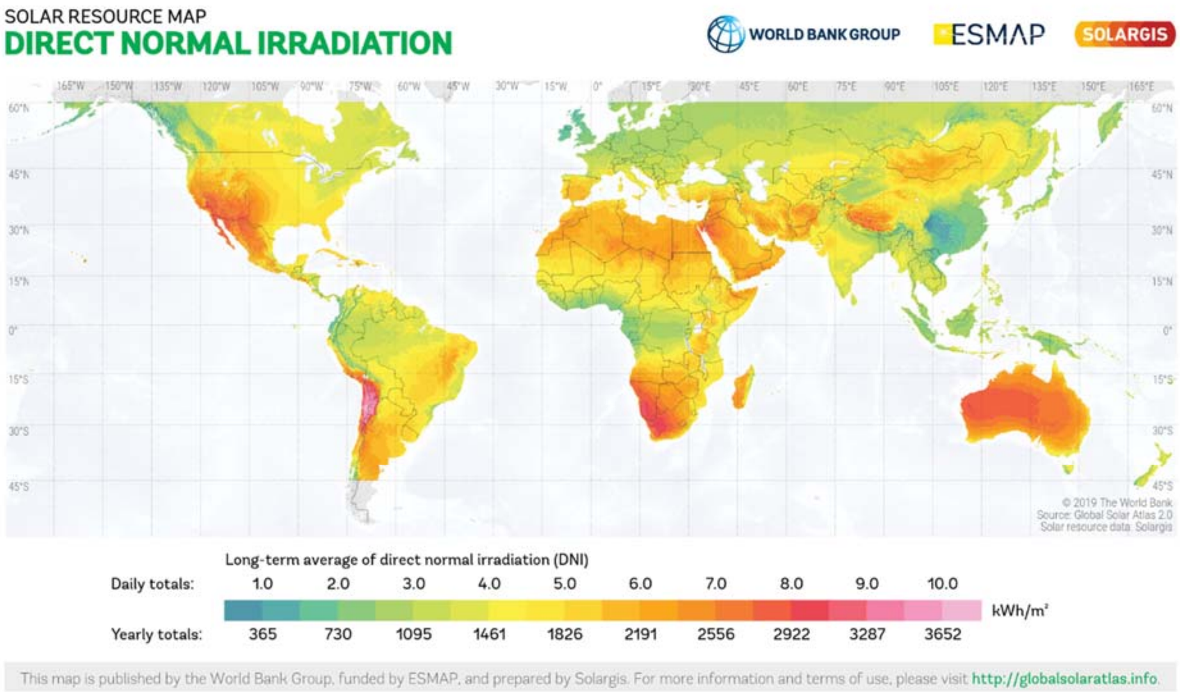

FIGURE 1. World Map of DNI [2] © 2019 The World Bank, Source: Global Solar Atlas 2.0, Solar resource data: Solargis.

YIELD IN MODERATE CLIMATES

Calculation results within a report of the Danish Technical University [3] already give an indication of the thermal annual yield for a Danish climate (Fig. 2). It compares highly efficient flat plate collectors and a parabolic trough collector of supplier Aalborg based on the radiation profile of the old reference year of Denmark. Starting at around 55°C operational temperature, the trough delivers a higher annual collector yield than the three flat plate collector systems.

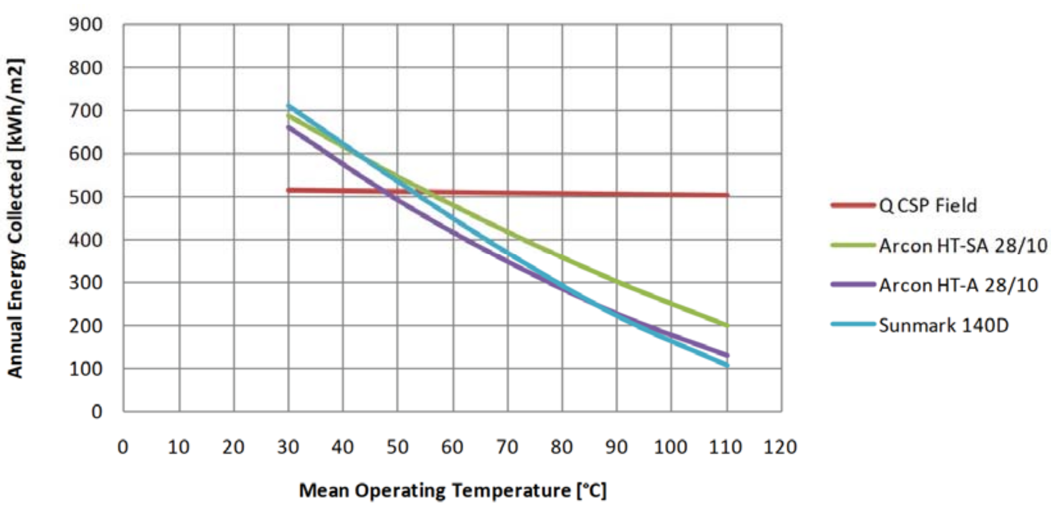

FIGURE 2. Annual yield of a parabolic trough collector compared to flat plate collectors for Denmark from DTU Civil Engineering Report R-292 (UK), 2013

Calculations within the VDI guideline "Solar Thermal Process Heat" [4] show similar results and [5] also compares a flat plate collector and a trough with improved efficiency for the Typical Meteorological Year (TMY) of Copenhagen with similar findings.

To get a better understanding, further investigations have been performed with two simulation tools for calculating annual yields from different collector types: ScenoCalc and greenius.

ScenoCalc is an EXCEL based tool for the calculation of the gross energy yield within the Solar KEYMARK certification scheme and can be downloaded free at http://www.estif.org/solarkeymarknew/component/content/article/13-public-area/163-scenocalc. ScenoCalc (Solar Collector Energy Output Calculator) was developed and validated in the European project QAiST (Quality Assurance in Solar Heating and Cooling Technology). For the calculation on an hourly basis, a constant fluid temperature is assumed and only positive yield is cumulated. In Version 6.1 the IAM function values have to be entered in the east-west function to be able to represent a north-south aligned trough. The tool is a well-established means for calculating the annual solar collector output and has been created for collector comparison, including stationary and tracking collectors for operational temperatures between 25 to 100°C.

Greenius (https://www.dlr.de/sf/desktopdefault.aspx/tabid-11688/20442_read-44865/) is a free tool for calculating energy yield and economic data for renewables with a focus on solar thermal concentrating power plants. However, models for detailed simulations of several other renewable energy technologies and other applications as process heat supply have been added, including non-concentrating solar collectors. It has been validated well in comparison studies e.g. in the IEA Task on Solar Process Heat. Greenius is especially useful in early phases of projects and for feasibility studies with hourly resolution.

ScenoCalc calculations of parabolic trough calculations have been compared with Greenius showing plausible results. Both programs calculate 848 kWh/m² for the direct radiation on a surface with north-south axis tracking.

For the evaluation, collectors with high efficiency in the relevant temperature range have been selected: The flat plate collector HT HEATboost 35/10, the vacuum tube collector CPC Ritter XL 19/49 P and the parabolic trough collector SL4600. The data for steady-state performance of the stationary collectors have been taken from Solar Keymark certificates listed at http://www.solarkeymark.nl/DBF/. For the ScenoCalc graph, the annual yield results stated in the certificates for the stationary collectors have been implemented, while the trough collector has been calculated by inserting collector function and Incidence Angle Modifier (IAM). The Greenius calculations are based on the efficiency functions and IAM.

The trough collector has always been calculated based on the correlations reported in [6] with a peakoptical efficiency of 76 %. This value can be reached if the collectors have a high intercept factor, a glass/silver mirror, an anti-reflective coating on the receiver glass and a high absorptivity. The last two are typical for vacuum receivers, which are implemented in some process heat collectors and also in the collector discussed here. The thermal losses of the vacuum receiver are very low at temperatures up to 100°C. The IAM has been taken from a HelioTrough measurement [7] as [6] did not give a function for the SL4600. Alternatively, the function with less IAM losses of the LS-2 measurement [8] could have been taken, but the authors preferred not to risk an overestimation of the function.

In all cases the gross aperture area has been used as reference area.

CALCULATIONS WITH SCENOCALC

ScenoCalc provides its own weather data files, among them data of Würzburg, Germany. Table 1 displays the radiation on this site. Whilst discussions are often based on global horizontal radiation compared to beam horizontal radiation, it is more relevant (for getting an idea of the collector output) to compare the radiation on the tilted surface of a stationary collector and the radiation on a tracked surface with the NS-axis.

TABLE 1. Annual sum of irradiation for the location Würzburg, Germany, gained from the ScenoCalc weather data file

Weather data Würzburg, Germany	kWh/(m²*a)
Diffuse horizontal irradiation	562
Direct horizontal irradiation	540
Direct normal irradiation	1014
Global irradiation on 35° south tilted surface	1244
Direct irradiation on NS-axis tracked surface	848

The gross annual yield based on this weather data in dependence of the absorber fluid temperature is displayed in Fig. 3. It must be stressed that it does not reflect the expected heat delivery to a customer, as heat losses in piping, heat capacities and other potential losses are not included. Because of the higher radiation available for the stationary collectors, their yield is higher at low temperatures. With rising operation temperatures, the low thermal losses of efficient concentrating collectors outweigh this disadvantage.

The results show that concentrating collectors can deliver an amount of energy in the same range or even higher than stationary collectors, even below operating temperatures of 100°C in a moderate climate.

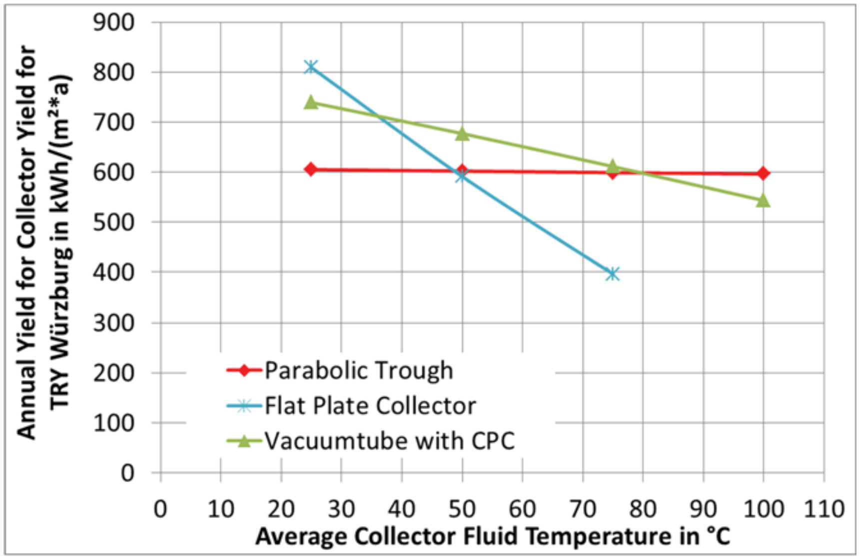

FIGURE 3. Gross annual yield for the climate of Würzburg, Germany for various collectors and average collector temperatures

CALCULATIONS WITH GREENIUS

In the software Greenius, yield calculations also include heat losses in the piping, heat capacities and soiling. By this, the results are closer to the final heat delivery to the customer since relevant losses are considered. The results therefore reflect the system's performance and the expected output of the solar field.

Several assumptions have to be made for the simulations with Greenius. The thermal inertia has always been taken into account. The solar field delivers heat to the demand circuit only if the field has reached the desired temperature. Starting from the cold state, the absorbed radiation is first used to raise the temperature of the fluid until it reaches the desired value. Likewise, during the fluid cooling process no heat is delivered even though solar radiation is still absorbed. There is no load restriction thus the plant uses as much solar heat as possible in each time step. Consequently, there is no heat dumping.

In the case of parabolic trough collectors, two collectors in a row have been simulated with an effective mirror area of 1058m². The header has a total length of 60m and a pipe inner diameter of 62.7mm. The pipes in the loop are 40m long and have a diameter of 52.5mm. The average mirror cleanliness is 98%.

In the case of flat plate collectors and vacuum tubes with CPC, a pipe length of 100m and a diameter of 50mm have been assumed. Soiling has not been considered since it has much less impact on performance than for concentrating collectors. For the flat plate, 74 collectors have been simulated with a total gross aperture area of 1004.18m². For the vacuum tube with CPC, 222 collectors have been simulated with a total gross aperture area of 1096.68m². Therefore, the aperture area of all 3 systems is similar, considering the actual size of single units. The tilt angle for the collectors has been chosen for all the analysed locations.Thermal losses outside the collector and inertia then become more significant for the output.

The balance of plant has not been taken into consideration in all cases as it differs significantly by application and does not make a difference for the benchmarking. It should be noted that the inertia there further reduces the thermal energy delivered to the consumer.

Several sites have been selected over the world for the evaluation (Table 2) from the https://globalsolaratlas.info/map. On this webpage, the annual sum of Direct Normal Irradiation, global horizontal irradiation, diffuse horizontal irradiation and global tilted irradiation at optimum angle are displayed by clicking a site on the world map. The criteria for choosing a site was the representation for a large area of a continent, where irradiation values are at the lower end. Mostly sites with a lower DNI of around 1000 kWh/m²*a were chosen as far as they could be found. In several areas, e.g. North- and South America and Africa, most sites have a higher irradiation than the sites selected (see Table 2).

The hourly weather data files for these sites were then taken from Meteonorm Version 7.3.

TABLE 2. Weather data worldwide: Annual sums from Meteonorm

Site	MONTREAL	BOGOTÁ	TEOFILO	KINSHASA	CALCUTTA	BEIJING	AUCKLAND	POTSDAM
Coordinates	45.50°N, -73.62°E	4.72°N -74.15°E	-17.86°N, -41.52°E	-4.36°N, 15.30°E	22.53°N, 88.33°E	39.93°N, 116.28°E	-37.02°N, 174.80°E	52.38°N, 13.07°E
Direct normal irradiation kWh/m²	1395	1118	1176	1157	1221	947	1491	967
Global horizontal irradiation kWh/m²	1320	1571	1595	1740	1757	1360	1549	1056
Diffuse horizontal irradiation kWh/m²	591	842	822	915	939	823	700	566
Global radiation on tilted surface kWh/m²	1598	1585	1657	1741	1882	1585	1768	1263
Direct irradiation on ns-axis tracked surface kWh/m²	1160	1061	1098	1111	1107	771	1291	808
Quotient Direct irradiation on ns-axis tracked surface / Global radiation on tilted surface	0,73	0,67	0,66	0,64	0,59	0,49	0,73	0,64

A helpful way of getting a first idea of the thermal output of different collector types, is to relate direct irradiation on a NS-axis tracked surface to global radiation on a tilted surface (Fig. 4). The values show, that the available energy for the tracked collector is always less than for the stationary collectors.

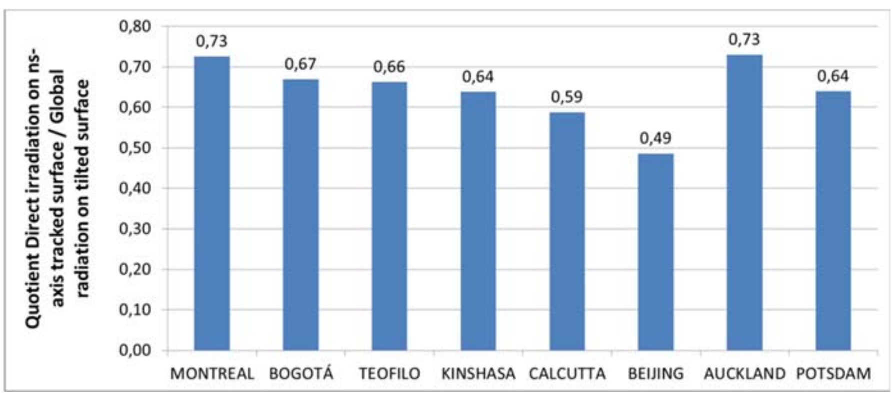

FIGURE 4. Relation of direct irradiation on a NS-axis tracked surface to global radiation on a tilted surface

For all sites, the annual output for the three collector types has been calculated as a function of the average absorber fluid temperature (Fig. 5). Because of the higher radiation available on the collector surface the stationary collectors can supply higher energy yields. At elevated temperatures this is overcompensated by the lower thermal losses of the parabolic trough collectors so that they yield more.

At the sites Montreal and Auckland with a high ratio of direct irradiation on a NS-axis tracked surface to global radiation on a tilted surface the yield of parabolic troughs surpasses that of stationary collectors at about 60°C operation temperature.

However the annual output has more influences than the relation in Fig. 4 displays. E. g. the output of the flat plate collector in Bogota is about 20% less than in Teofilo although the radiation difference is low. An important influence derives from the ambient temperature which is about 10 K less in annual average for Bogota.

In Calcutta and Beijing, the performance is better for the stationary systems at 75°C though and for vacuum tube collectors with CPC even at higher temperatures of 125°C.

In Kinshasa the yield of parabolic troughs surpasses that of stationary collectors at about 90°C.

Even though Potsdam has the furthest distance from the equator and thus the highest incidcence angles values, the yield is highest for parabolic troughs above 75°C. An explanation may be that a high amount of sunshine appears in summer when the incidence angles are lower.

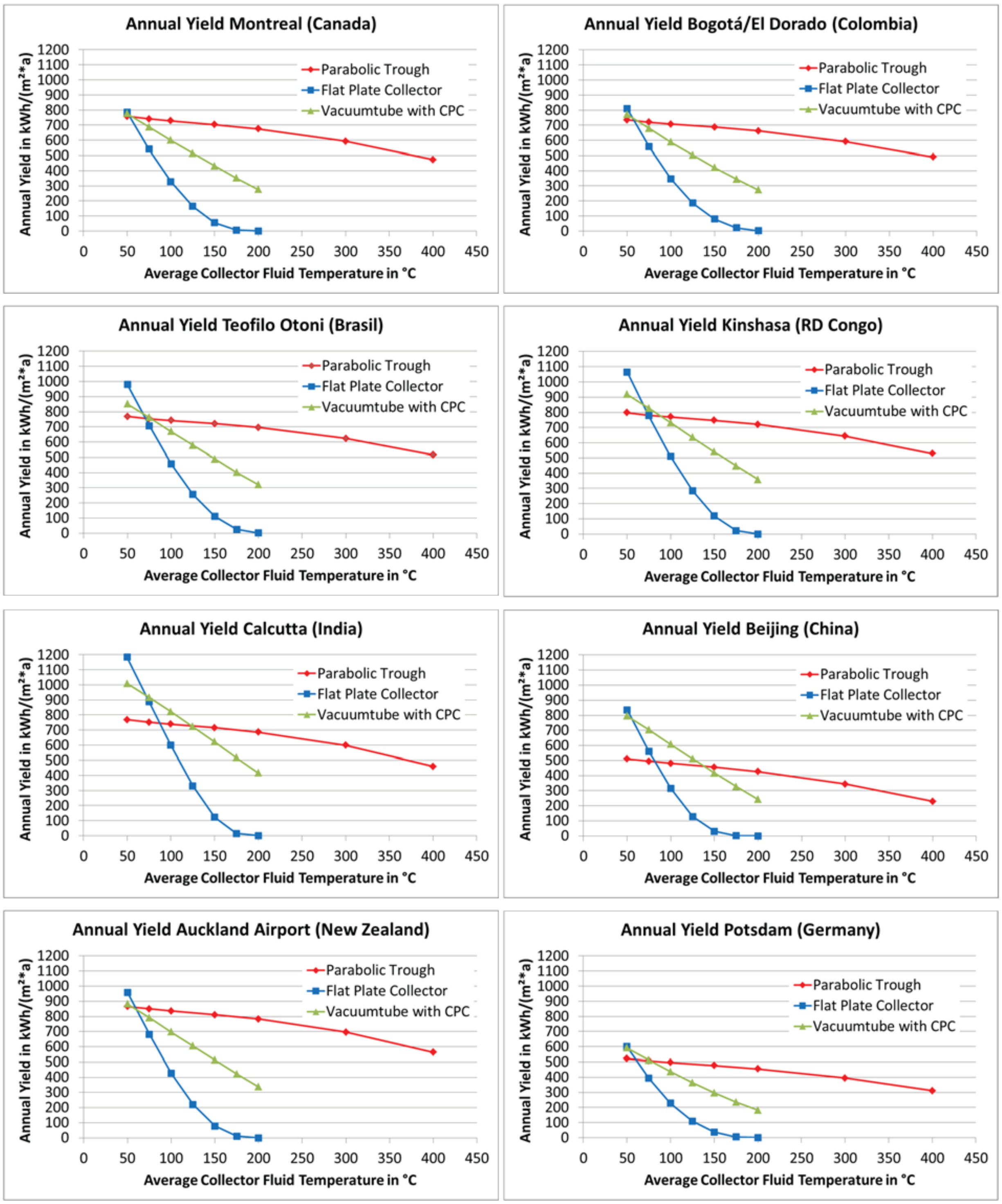

FIGURE 5. Annual yields for various sites as a function of mean operation temperature

An important result is that the energy yield from parabolic troughs for many moderate sites at 200°C operation temperature is in the same range as stationary collectors operating at 75°C.

COST OF SOLAR HEAT

Small fields of tracking collectors can induce high costs of heat because of engineering efforts, preparations on site and other fix costs. This strongly depends on the collector construction. Especially for collectors of greater size, laborious jigs may need to be placed on site. For these large collectors, the cost degression starts at higher volumes. Today, it seems to be difficult to build economically feasible solar field sizes below 1.000 m². On the contrary, the high amount of systems (about 100) with a size of only several 100 m² aperture area installed by Inventive Power in Mexico and the USA shows the opportunities for small installations of a few hundred m². The costs for these systems are reported from 200 to 500 €/m² fully installed [9].
Based on discussions with Central European parabolic trough suppliers, estimated costs for solar fields planned, ready installed and commissioned including BoP are 230 to 300 €/m² for field sizes of 10.000 m². This relates to efficient collectors with glass/silver mirrors and vacuum receivers. However, the costs highly depend on the solar field size, supplier, technology and country. With rising temperature and pressure, investments especially in the BoP will be higher.

In comparison, the costs for flat plate collectors today can come down to 200 €/m² for a similar field size of 10.000 m².

On the first glance, the comparison of heat costs would be an adequate measure to further benchmark parabolic trough collectors against flat plate collectors. However, the variety in cost estimations and the strong dependency on the field size do currently not allow a profound benchmarking. Instead, we present an example to illustrate that the costs of installation for equal thermal output are in the same range for trough and flat plate collector systems. We chose 75°C operation temperature since this can be delivered well by the flat plate system too. The following assumptions are made:

- Solar field size of 10.000 m²
- Climate of Potsdam
- The costs for a flat plate (FP) collector system are 200 €/m²
- Yield of FP collector at this climate is 393 kWh/(m² *a) (compare Fig. 5).
- Yield of trough collector at this climate is 508 kWh/(m²*a) (compare Fig. 5).

⇨ In order to reach equal output the flat plate field needs to be 29% larger than the trough field.
⇨ Equivalent costs for same thermal output would be 200 €/m² x 1.29 => 258 €/m²

The 258 €/m² are within the range of parabolic trough field costs. This example indicates that for the same thermal delivery, costs of flat plate and trough collector are rather similar.

Driven by CSP, some components like vacuum receiver pipes and glass/silver mirrors have experienced a major cost reduction in the last years. A significant reduction in costs is still expected for the future. From these trends in CSP, the process heat collectors will benefit as well and the range of costs mentioned above may fall further.

DISCUSSION

By means of the example above, we have shown that parabolic trough collectors can reach similar cost levels than flat plate collector systems, when operated at typical temperature levels of e.g. 75°C in moderate climates. In addition to this cost criterion, more criteria for the success of process heat applications are important.

In many cases, the heat of a concentrating system can easily be integrated in the infrastructure e.g. by direct connection to a steam supply line. The pressure and thereby the temperature is simply controlled by a valve at the inlet to the steam line. The advantage of concentrating systems is that they can deliver steam at typical steam line pressures of 4 or 15 bar.

There are only a few installations with concentrating collectors where the performance has been measured by independent entities. That results in uncertainty about the performance of some products, e.g. the mirror surface or the tracking may not be precise or the control system does not make use of all the radiation coming in. Performance measurements of whole years would help obtaining more confidence.

Tracking systems offer an advantage when it comes to stagnation safety, especially for systems with a high degree of coverage, when not all the heat produced in the solar field can be consumed. They can be defocused to stop the heat production and thus avoid the problems associated with overheating.

Because the absorber diameters are larger and the absorber lengths are shorter with the trough system, electricity consumption for pumping the heat transfer fluid should be less. This usually is not a topic addressed by customers, but of interest in the energy balance.

The temperature rise at the solar field can be higher for concentrating systems which reduces mass flows and related electricity consumption. Heat exchangers and pumps can be smaller and less cost consuming.

A clean reflector is essential for concentrating, whilst not so much for stationary collectors. Therefore, cleaning the concentrating systems is necessary, especially in dusty and dry areas. Cleaning in heavy rain is an option but not in dry sites. This has to be considered in the maintenance costs.

Whilst local solar companies may be familiar with stationary collectors there is nearly no experience so far with tracked systems. Repairs are therefore more expensive, especially if experts from abroad need to travel.

Troughs have a stronger peak in moderate climates during summer and therefore the distribution along the year is better with stationary collectors. During the day, the distribution is more uniform with North-South aligned troughs, as they face the sun early in the morning and late in the evening. Troughs erected in East-West axis have a better distribution over the year, but typically with less annual yield for high lattitudes.

When it comes to start-ups energy consumption and duration, the thermal capacity of the field is relevant. Due to the higher concentration, the installed steel and heat transfer fluid volume are typically less for trough collectors. Thus, especially when it comes to higher temperature operation, the trough system should be beneficial.

In order to increase the solar coverage ratio, it is necessary to store solar heat. Otherwise, only an order of magnitude of 10 to 15% coverage can be achieved for a year-round 24/7-demand in moderate climates. Efficient storage requires higher operating temperature in the collector fields (Fig. 6) since delta T from the solar field to the storage and back needs to be covered in addition to the temperature difference in the storage itself. In case of parabolic trough systems, this rise in operating temperature can easily be achieved without significant increases in heat losses.

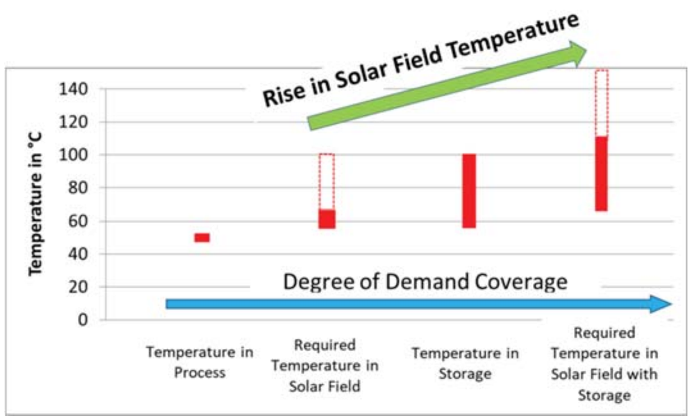

FIGURE 6. Rise in solar field temperature with higher degree of solar share

SUMMARY

Both calculation paths - along ScenoCalc and Greenius - show for a site with moderate climate that the thermal output of a parabolic trough collector equipped with glass/silver mirrors and vacuum receivers surpasses the thermal yield of stationary collectors above 75°C operation temperature.

An important result is that the energy yield from parabolic troughs for many moderate sites at 200°C operation temperature is in the same range as stationary collectors operating at 75°C.

Information on costs is difficult to obtain. The costs for about 66 installations of Inventive Power in the range of several 100 m² of aperture area range from 200 to 500 €/m² fully installed according to the ship-plants.info website [9].

Estimated costs for solar fields planned, ready installed and commissioned including BoP at 230 to 300 €/m² for field sizes of 10.000 m² are reported from some Central European parabolic trough suppliers. This relates to efficient collectors with glass/silver mirrors and vacuum receivers. But costs highly depend on solar field size, supplier, technology and country.

For a variety of moderate sites, a parabolic trough collector delivers the same amount of heat as a stationary collector at its typical operation temperatures. Thus if stationary collectors succeed in a market there is the opportunity for parabolic trough collectors to succeed at least for solar field sizes from several 100 m² upwards.

There are only a few installations with concentrating collectors where the performance has been measured by independent entities, so there is uncertainty about the performance of some products. Performance measurements according to ISO 9806 and of whole years would help obtaining more confidence.

It is worth to investigate the implementation of tower and Fresnel systems as well; unfortunately they could not be discussed in this paper.

Depending on the temperature level at which district heating is operated, the application of concentrating solar collectors can make sense. Therefore not only process heat but also district heating is potentially an application for concentrating collectors.

Up until now, very few collector fields with concentrating process heat collectors have been built. The suppliers mostly only have erected several fields. For the next years a drop in costs for concentrating collectors can be expected if they will be applied more often and the producers can turn their experiences into cost reduction.

The developments may very well improve the chances for the implementation of concentrating collectors in the next years.

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