Calculation method for the conversion of aperture area into thermal power for tracked concentrating solar thermal systems for statistical purposes

Energy statistics usually include data on the amount of solar thermal energy installed in terms of thermal power (kW$_{th}$). While solar thermal installations often are only characterized by the installed collector area (m²). To address this inconsistency between data, a simple conversion factor is needed to convert the installed area (m²) into the approximate corresponding installed thermal power (kW$_{th}$). Such a conversion factor exists for stationary solar thermal collectors but has yet to be established for tracked concentrating collectors. This paper details a conversion factor for tracked concentrating solar thermal collectors developed in the IEA SHC Task 64 / IEA SolarPACES Task IV on Solar Process Heat and the underlying reasoning.

1. General considerations

Tracked concentrating solar thermal systems have been used for many years, but in terms of cumulated area or power are statistically not very relevant compared to other renewable technologies. However, as more suppliers enter the market, the number of installations is rising significantly, and the inclusion of tracked concentrating collectors in solar thermal statistics becomes more important. As with stationary solar thermal collectors, the statistical data for tracked concentrating collectors needs to be converted from installed collector area to installed thermal power so it can be compared to other technologies. It is important to note here that a single conversion factor never exactly represents the relation between collector area and thermal power for each plant but gives a good comparison for typical installations. Also, this conversion factor should only be used for statistical purposes, not individual project yield calculations.

For stationary solar thermal collectors, a conversion factor of 0.7 [kW$_{th}$/m²] was defined in 2004 in a recommendation by the IEA SHC. See technical note: https://www.iea-shc.org/Data/Sites/1/documents/statistics/Technical_Note-New_Solar_Thermal_Statistics_Conversion.pdf

The procedure used for stationary collectors is now adapted to tracked concentrating collectors following the same underlying concepts.

In principle, the calculation procedure for stationary collectors can be used for single-axis tracked concentrating collectors (line focusing systems) and two-axis tracking systems. Calculation of the thermal yield is based on an efficiency and incident angle modifier (IAM) function, similar to stationary collectors. Small solar tower systems for process heat are still under development; therefore, the applicability of the conversion factor for solar tower systems has not been checked and is excluded from this document.

2. Recommended conversion factor

For solar thermal statistics[1], the installed capacity (thermal power in [kW_{th}] – kilowatt thermal) shall be calculated by multiplying the net aperture area of the solar collector area [m^2] by the conversion factor 0.7 [kW_{th}/m^2].

This factor shall be used uniformly for one-axis tracking parabolic troughs, one-axis linear Fresnel collectors, and two-axis tracking systems like parabolic dishes and Fresnel lens collectors.

3. Explanatory note

The following note explains the reasoning behind the conversion factor of 0.7 kW_{th}/m^2. The suggested conversion factor is the result of performance calculations for various tracked collectors. An average value represents the entire range of tracked concentrating collectors (as previously done for stationary collectors). Below are relevant definitions for the calculation process.

Definition of collector area

For concentrating collectors, the terms "Collector net aperture area" and "Collector gross aperture area" are defined in the IEC standard IEC-62862-1-1 [3] as follows:

The solar thermal collector net aperture area (A_{net}) is the area of the perpendicular projection over the collector aperture plane of the solar thermal collector reflecting/refracting components. In a line-focus solar system, it is this surface plus the part of the perpendicular projection of the steel receiver tube onto the collector aperture plane, which does not overlap, provided that the sun-oriented side of the receiver is absorbing radiation.

The net aperture area of a Linear Fresnel collector or heliostat is defined as the sum of the net aperture areas of its mirror segment. The net aperture area of a mirror segment is the perpendicular projection of the reflective mirror area over its collector aperture plane when they are in a horizontal position.

Solar thermal collector gross aperture area (A_{gross}) is the area of the flat surface defined by the outer perimeter of the collector, including the gaps between adjacent reflectors. This definition may be used for modules, heliostats, heliostat fields, parabolic dishes, linear Fresnel reflectors, etc., as well as complete concentrating collectors.

The net aperture area is the preferred choice for calculating the conversion factor since it best represents the active collector area (as also done for the stationary collectors). For the performance calculation presented below, only the gross aperture area was available for some collector types. In these cases, the gross aperture area was used,

[1] Statistical data on solar thermal installations contains aggregated and cumulated data across a plurality of installations and usually also across different technologies. The conversion factor defined here is not meant to be used for a specific single installation. For specific installations and technologies, see ISO 9806 [1] for the thermal peak power of a collector and ISO 24194 [2] for the thermal power output of a collector field in a specific installation.

which led to a minor systematic underestimation of the conversion factor. In any case, the correct efficiency function is used with the net or gross aperture area.

Considered collector types

A variety of collector designs exist with different principles and different components, which can make a significant difference in power and annual yield:

- One-axis tracked parabolic trough collectors and Fresnel collectors
- Two-axis tracked dishes and Fresnel collectors

Since the installed thermal power is usually interpreted as the maximum power that can be delivered by the collector, the calculation of this value systematically refers to the "fully" tracked position. When fully tracked, the different tracking technologies do not have a significant impact since the aperture area is at its best orientation towards the sun. Thus, it does not make a principal difference for the following calculations if a collector is tracked in one-axis or two-axis.

Differences in the optical and thermal efficiency result from the reflectivity of mirrors (silver or aluminum reflectors) and receiver properties (anti-reflective coating, absorptivity, reflectivity and vacuum). The intercept quality varies between products mainly depending on their status of development.

Highly efficient products include vacuum receivers with anti-reflective coating and glass/silver mirrors and collectors. Examples of collectors with these features are, e.g., the HelioTrough, LF-11, Sun2Heat, SL4600 of Solarlite and the parabolic trough collector of Xuchen Energy.

Collector efficiencies

Limited data are publicly available on collector efficiencies. Other than stationary collectors, independent entities have generally not evaluated tracked concentrating collectors. The T160 collector data are from a certificate, and the data of the other collectors are from publications based on testing according to ISO 9806 [1] without certification.

Collectors with published efficiency data:

Heliotrough [4]:	η_0 = 0.816, a_1 = 0,0622 W/(m²*K), a_2 = 0.00023 W/(m²* K²)
SL4600 [5]:	η_0 = 0.77, a_1 = 0.16155 W/(m²*K), a_8 = 6.4407*10^{-9} W/(m²* K^4)
T160 [6]:	η_0 = 0.697, a_1 = 0.73 W/(m²*K), a_2 = 0 W/(m²* K²)
PTC1800 [7]:	η_0 = 0.6878, a_1 = 0.161 W/(m²*K), a_2 = 0.0022 W/(m²* K²)
LF-11 [8]:	η_{max} = 0.709, a_1 = 0.032913 W/(m²*K), a_8 = 1.4838*10^{-9} W/(m²* K^4)
	η_{max} at 5° (sun at 5° transversal zenith angle)
Sun2Heat [9]:	η_0 = 0.746, a_1 = 0.053 W/(m²*K), a_2 = 0.00024 W/(m²* K²)
Heliac 3rd Gen [10]:	η_0 = 0.602, a_1 = 0.23 W/(m²*K), a_2 = 0 W/(m²* K²)

Comments on the functions:

- The LF-11 collector has its highest efficiency when the sun is positioned at a 5° transversal zenith angle. The corresponding ηmax value was chosen because a maximum power value approach is used.
- Kd values were only reported for the T160 and the Heliac 3rd Gen collector. Their absence in the calculation led only to a slight underestimation of the conversion factor.
- Collectors with efficiency data related to net aperture area: Heliotrough, SL4600, and LF-11.
- Collectors with efficiency data related to gross aperture area: T160, PTC1800, Sun2Heat, and Heliac 3rd Gen.

Irradiance and ambient conditions
Tracked concentrating systems collect primarily direct radiation. Therefore, only direct irradiation instead of global irradiation is used for calculating the conversion factor.

A mean collector fluid temperature of 100 °C is assumed for operation at an ambient temperature of 20 °C.

The standard ISO 9806 divides the 1000 W/m² global irradiation into 850 W/m² of direct and 150 W/m² of diffuse radiation for Standard Reporting Conditions.

Normative References for "Peak Power" approach from Concentrating PV (CPV)
In the photovoltaic (PV) industry, procedures for power ratings and information related to installed power are well established. In particular, the standard "IEC 62670-1:2013 Photovoltaic concentrators (CPV) - Performance testing-Part 1: Standard conditions" [11] defines standard conditions with the objective "…to define a consistent set of conditions so that power ratings noted on data sheets and nameplates will have a standard basis". While in the non-concentrating PV, Standard Test Conditions (STC) of 1000 W/m² of global irradiance in the module plane are defined, the Concentrator Standard Test Conditions (CSTC) define an irradiance of 1000 W/m² DNI. This is the irradiance condition under which a CPV system's power is rated and usually given as installed (peak) power in Wp (peak power in Watt-peak). In the same standard, Concentrator Standard Operating Conditions (CSOC) is defined with an irradiance of 900 W/m², i.e., an irradiance lower than that defined in the CSTC.

Defining a conversion factor kW/m² for CST is straightforward. Therefore, as in other technologies, one may also try to apply a "peak power" approach. However, for thermal collectors, as mentioned above, the irradiance at peak operation conditions is defined as 1,000 W/m² irradiance in the collector plane, divided into 850 W/m² direct irradiance and 150 W/m² diffuse irradiance. As inconsistency within normative regulations in CST should be avoided, direct use of the CSTC is not recommended.

For CPV, the Concentrator Standard Test Conditions provide a (peak) power rating (and not the Concentrator Standard Operation Conditions with a lower irradiance value). For CST, only operation conditions are defined. Therefore, in the following discussion, values of thermal power under a direct irradiance of 850 W/m² and a direct irradiance of 1000 W/m² are given side by side to provide a range of thermal power values for typical concentrating collectors.

Conversion factor calculated from thermal power at perpendicular direct irradiation

Following the procedure used for stationary collectors, concentrating power is calculated for various collector types and assumes a mean collector fluid temperature. For concentrating tracked collectors, the assumed operating temperature is 100 °C, and the ambient temperature is 20 °C.

Table 1: Average conversion factors derived from various collectors

Radiation (DNI):	**850**	**1,000**	**W/m²**
Heliotrough	687	810	W/m²
SL4600	641	757	W/m²
T160	534	639	W/m²
PTC1800	558	661	W/m²
Industrial Solar LF-11	600	706	W/m²
Sun2Heat	628	740	W/m²
Heliac 3rd Gen	493	584	W/m²
Average	**0.59**	**0.70**	kW/m²

Table 1 gives the resulting thermal power for various collectors at a direct radiation of 850 W/m² and 1,000 W/m². The radiation level of 1,000 W/m² directly suggests using the conversion factor 0.7.

For a direct radiation value of 850 W/m², the resulting conversion factor is 0.59, which is significantly lower for tracked, concentrating collectors than the value of 0.7 used for flat plate and vacuum tube collectors.

By tracking the sun during the day, concentrating systems like parabolic troughs and two-axis tracking collectors compensate for the lower radiation input by using smaller incidence angle values during the day. This is visible when looking at a day profile (Figure 1).

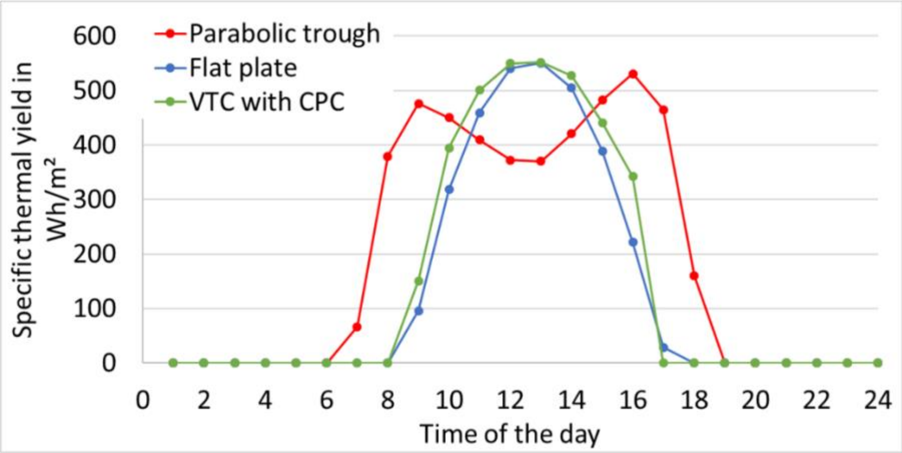

Figure 1: Profile on 14th September for the climate of Potsdam, Germany (Meteonorm 7.3), at 75 °C and a North-South axis for the parabolic trough collector.

Calculation of annual yield for reference

The effect of the incidence angle differs over the year. Therefore, the annual thermal yield for a given climate should be a better means for evaluation. Figure 2 shows the annual yield of three collector technologies with highly efficient components [12]. A typical, moderate Central European climate (Würzburg, Germany) is used for the calculation.

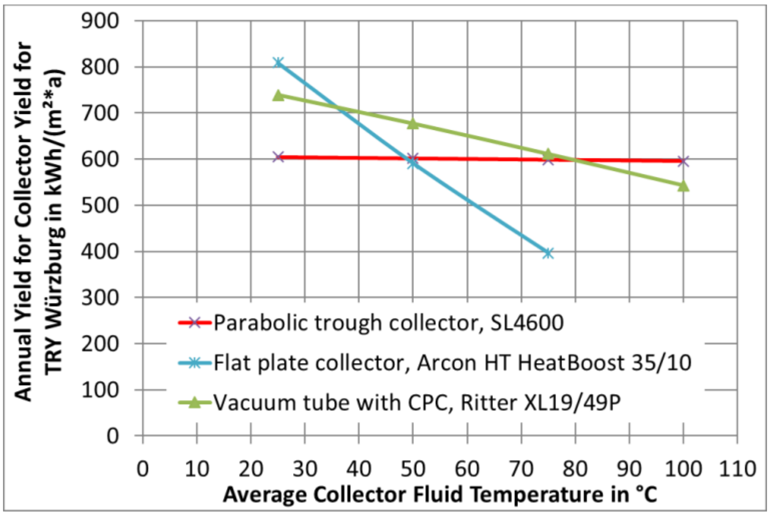

Figure 2: Calculation of annual yield with ScenoCalc

Figure 2 is a graphic representation of the annual yields calculated in ScenoCalc (ScenoCalc is the European tool for collector certification and includes annual yield calculations for selected sites). And Table 2 displays the values for the temperatures 50 °C, 75 °C, and 100 °C. For the flat plate collector Arcon HTHEATboost 35/10 and the vacuum tube VTC Ritter XL 19/49, P values were taken from certificates. The calculation of the SL4600 was performed with efficiency values from publications [12].

Table 2: Calculation of annual yield in kWh/(m² a) with ScenoCalc

	Average collector temperature		
	50 °C	**75 °C**	**100 °C**
Parabolic trough SL4600	602	599	596
Flat plate collector Arcon HTHEATboost 35/10	591	396	
Vacuum tube VTC Ritter XL 19/49 P	677	611	543

Considering operating temperatures of 50 °C for flat plate collectors, 75 °C vacuum tube collectors, and 100 °C parabolic trough collectors, the annual output is in the same range.

4. Conclusion

Similar to the procedure used for stationary collectors, thermal power is calculated for a variety of concentrating tracked collectors at a perpendicular irradiation.

Three approaches were used to define the conversion factor. The first approach uses a direct radiation value of 1,000 W/m², a peak radiation value that corresponds best to regions with high radiation (sunbelt). The result is a conversion factor of 0.7 kW_{th}/m^2 (Table 1).

The second approach is based on standards, such as ISO 9806, which define 1,000 W/m^2 global irradiation as 850 W/m^2 direct radiation and 150 W/m^2 diffuse radiation. This results in a conversion factor of 0.59.

However, when looking at the daily yield profile of tracked and stationary collectors in Figure 1, it becomes evident that tracked collectors compensate for the lower peak output by longer times of thermal yield. This leads to the third approach, which uses the annual output of the systems. Assuming operation temperatures of 50 °C for flat plat collectors, 75 °C for vacuum tube collectors, and 100 °C for parabolic trough collectors, the annual output of all three technologies is in the same range. Achieving close to the same energy output/m^2 for each collector type when operating in typical conditions for that collector means the capacity used in statistics should reasonably be the same for tracked and stationary collectors.

Therefore, a conversion value of 0.7 kW_{th}/m^2 for concentrating tracked solar thermal collectors for statistical purposes.

5. Literature

[1] ISO 9806:2017 "Solar energy — Solar thermal collectors — Test methods," https://www.iso.org/standard/67978.html

[2] ISO 24194:2022 "Solar energy — Collector fields — Check of performance," https://www.iso.org/standard/78074.html

[3] IEC 62862-1-1:2018 "Solar thermal electric plants – Part 1-1: Terminology", https://webstore.iec.ch/publication/33265

[4] N. Janotte, G. Feckler, J. Kötter, S. Decker, U. Herrmann, M. Schmitz, E. Lüpfert; "Dynamic performance evaluation of the HelioTrough® collector demonstration loop – towards a new benchmark in parabolic trough qualification," Energy Procedia 49 (2014) 109 – 117 of Solar PACES conference 2013

[5] Jan Fabian Feldhoff, Martin Eickhoff, Lothar Keller, Javier León Alonso, Mirko Meyer-Grünefeldt, Loreto Valenzuela, Johannes Pernpeintner, Tobias Hirsch; "Status and first results of the DUKE project – Component qualification of new receivers and collectors," Energy Procedia 49 (2014) 1766 – 1776 of Solar PACES conference 2013

[6] Solar Keymark Test report C1730ISO of SPF, 4.2.2019

[7] N. Janotte, S. Meiser, D. Krüger, R. Pitz-Paal, S. Fischer, H. MüllerSteinhagen, M. Walder; „Bestimmung der thermischen Leistungsfähigkeit des Parabolrinnenkollektors PTC 1800," OTTI Symposium Thermische Solarenergie 2009

[8] Datasheet LF-11 from website Industrial Solar: https://industrial-solar.de/wp-content/uploads/2022/06/LF-11_Technical-Datasheet_EN.pdf

[9] Test report of Cener ordered at: https://forms.office.com/Pages/ResponsePage.aspx?id=eruaPkhzO0SJNMu2hqJz8tKbWAP2l5tGiI-wnUu0Y9lUQUlMS1RZSFJXWjFNQUxHTUw2NU82UUVHWC4u

[10] Test report by Danish Technical University (DTU), BYG R-443, Test of Heliac 3rd Generation Solar Collector, September 2020

[11] IEC 62670-1:2013 "Photovoltaic concentrators (CPV) - Performance testing - Part 1: Standard conditions", https://webstore.iec.ch/publication/7341

[12] D. Krüger, S. Fischer, P. Nitz, J. Iñigo Labairu, Chancen für den Einsatz konzentrierender Kollektoren in Mitteleuropa, 31. Symposium Solarthermie und innovative Wärmesysteme 2021: 27. - 30. April 2021, Online, Pforzheim: Conexio, 2021, ISBN: 978-3-948176-13-6