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Solar energy — Collector fields — Check of performance

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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For an explanation on the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see the following URL: www.iso.org/iso/foreword.html.

Introduction

This document defines procedures for checking the performance of large collector fields. Measured performance is compared with calculated performance – and conditions for compliance are given.

Two levels for accuracy in the checking can be chosen:

Level I – giving possibility for giving a very accurate estimate (with low safety factor) – but with requirements for use of expensive measurement equipment.

Level II – allowing for a less accurate estimate (with higher safety factor) – but possibility to use less expensive measurement equipment.

Solar energy — Collector fields — Check of performance

1 Scope

This document specifies a procedure to verify the performance of large collector fields. The collectors in the fields can be glazed flat plate collectors, evacuated tube collectors and/or tracking, focusing collectors.

The check is done on the thermal power output of the collector field – the document specifies how to compare a measured output with a calculated one.

The document applies for all sizes of collector fields.

2 Normative references

The following documents are referred to in the text in such a way that some or all their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 9060, *Solar energy — Specification and classification of instruments for measuring hemispherical solar and direct solar radiation*

ISO 9488, *Solar energy — Vocabulary*

ISO 9806, *Solar energy — Solar thermal collectors — Test methods*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 9488 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— IEC Electropedia: available at http://www.electropedia.org/

— ISO Online browsing platform: available at http://www.iso.org/obp

3.4
reflector
surface intended for reflecting radiant energy

3.5
transversal plane
plane defined by the normal to the plane of the collector and the line orthogonal to the concentrator axis, or the shortest symmetry line for flat biaxial geometries

4 Symbols

A_G	Gross area of collector as defined in the ISO 9488	m^2
a_1	Heat loss coefficient at $(\vartheta_m - \vartheta_a) = 0$	$W/(m^2 \cdot K)$
a_2	Temperature dependence of the heat loss coefficient	$W/(m^2 \cdot K^2)$
a_3	Wind speed dependence of the heat loss coefficient	$J/(m^3 \cdot K)$
a_4	Sky temperature dependence of the heat loss coefficient	—
a_5	Effective thermal capacity. In some literature and data sheets denoted C_{eff}	$J/(m^2 \cdot K)$
a_6	Wind speed dependence of the zero-loss efficiency	s/m
a_7	Wind speed dependence of IR radiation exchange	$W/(m^2 \cdot K^4)$
a_8	Radiation losses	$W/(m^2 \cdot K^4)$
b_u	Collector efficiency coefficient (wind dependence)	s/m
C	Effective thermal capacity of collector	J/K
C_R	Geometric concentration ratio	—
c_f	Specific heat capacity of heat transfer fluid	J/(kgK)
$c_{f,i}$	Specific heat capacity of heat transfer fluid at the collector inlet	J/(kgK)
$c_{f,e}$	Specific heat capacity of heat transfer fluid at the collector outlet	J/(kgK)
DNI	Solar radiation received per unit area by a surface that is always held perpendicular (or normal) to the rays that come in a straight line from the direction of the sun at its current position	W/m^2
E_L	Longwave irradiance (λ > 3 µm)	W/m^2
f_P	Safety factor taking into account heat losses from pipes etc. in the collector loop.	-
f_U	Safety factor taking into account measurement uncertainty.	-
f_O	Safety factor for other uncertainties e.g. related to non-ideal conditions such as non-ideal flow distribution and unforeseen heat losses – and uncertainties in the model/procedure itself.	-
G_{hem}	Hemispherical solar irradiance	W/m^2
G_b	Direct solar irradiance (beam irradiance)	W/m^2
G_d	Diffuse solar irradiance	W/m^2
h	Solar altitude angle. sin h = cos θ_Z	°
h_{min}	Minimum solar altitude angle	°

$K_{hem}(\theta_L,\theta_T)$	Incidence angle modifier for hemispherical solar radiation	—
$K_b(\theta_L,\theta_T)$	Incidence angle modifier for direct solar irradiance	—
$K_{\theta L}$	Incidence angle modifier in the longitudinal plane	—
$K_{\theta T}$	Incidence angle modifier in the transversal plane	—
K_d	Incidence angle modifier for diffuse solar radiation	—
$\dot{m}$	Mass flow rate of heat transfer fluid	kg/s
$\dot{Q}_{measured}$	Measured power output	W
$\dot{Q}_{estimate}$	Estimated power output	W
T	Absolute temperature	K
t	Time	s
u	Surrounding air speed (wind speed)	m/s
u'	Reduced surrounding air speed $u' = u - 3$ m/s	m/s
V_f	Fluid capacity of the collector	m^3
$\dot{V}$	Volumetric flow rate	m^3/s
$\dot{V}_e$	Volumetric flow rate at the outlet of the solar collector	m^3/s
$\dot{V}_i$	Volumetric flow rate at the inlet of the solar collector	m^3/s
Δt	Time interval	s
ΔT	Temperature difference between fluid outlet and inlet (ϑ_e - ϑ_{in})	K
β	Slope (or tilt), the angle between the plane of the collector and the horizontal	
γ	Surface azimuth angle, the deviatrion of the projection on af horizontal plane of the nornmal to the surface from the local meridian, with zero due south, east negative and west positive	
γ_s	Solar azimuth angle, the angular displacement from south of the projection of beam radiation on the horizontal plan, east negative and west positive	
δ	Declination, the angular position of the sun at solar noon with respect to the plane of the equator, north positive.	
ϕ	Latitude, the angular location north or south of the equator, north positive	
γ	Solar azimuth angle	°
η_b	Collector efficiency based on beam irradiance G_b	—
η_{hem}	Collector efficiency based on hemispherical irradiance G_{hem}	—

$\eta_{0,\mathrm{b}}$	Peak collector efficiency (η_b at $\vartheta_\mathrm{m} - \vartheta_\mathrm{a}$ = 0 K) based on beam irradiance G_b	—
$\eta_{0,\mathrm{hem}}$	Peak collector efficiency ($\eta_{0,\mathrm{hem}}$ at $\vartheta_\mathrm{m} - \vartheta_\mathrm{a}$ = 0 K) based on hemispherical irradiance G_hem	—
$\eta_{hem,\dot{m}_i}$	Collector efficiency, with reference to mass flow $\dot{m}_i$	—
ω	Hour angle, the angular displacement of the sun east or west of the local meridian due to rotation of the earth on its axis at 15 ° per hour; morning negative, afternoon positive	-
θ	Angle of incidence	°
θ_L	Longitudinal angle of incidence: angle between the normal to the plane of the collector and incident sunbeam projected into the longitudinal plane	°
θ_T	Transversal angle of incidence: angle between the normal to the plane of the collector and incident sunbeam projected into the transversal plane	°
θ_Z	Zenith angle, the angle between the vertical and the line to the sun, that is, the angle of incidence of beam radiation on a horizontal surface. cos θ_Z = sin h	
ϑ_a	Ambient air temperature	°C
ϑ_am	Measured ambient air temperature	°C
ϑ_as	Ambient air temperature for the standard stagnation temperature	°C
ϑ_e	Collector outlet temperature	°C
ϑ_i	Collector inlet temperature	°C
ϑ_m	Mean temperature of heat transfer fluid in collector loop	°C
$\vartheta_\mathrm{max\_op}$	Maximum operating temperature	°C
ρ_i	Density of heat transfer fluid at collector inlet temperature	kg/m^3
$\rho_{i,sec}$	Density of heat transfer fluid at heat exchanger inlet temperature	kg/m^3
σ	Stefan-Boltzmann constant	W/(m^{2}K^4)

5 Stating an estimate for the thermal power output of a collector field

The estimated power output of the collector array is given as an equation depending on collector parameters according to ISO 9806 and operating conditions. The measured power shall comply with the corresponding calculated power according to this equation. Measured and calculated power are only compared under some specific conditions to avoid too large uncertainties – see section 5.3.

The estimate can be given for fields of combined collector types – e.g. single glazed and double-glazed:

- If inlet and outlet temperatures are available for each field of collectors of same type, estimates can be given for each of these fields.

- An overall estimate for fields with two or more collector types can be given choosing representative collector parameters.

When giving the estimate it shall be stated if it shall be checked according to level I or level II (see 6.2).

5.1 Calculating power output

Depending on collector type and solar measurements there are three options for equations:

a) eq. 1: Simple equation using total radiation on the collector plane, valid for:
   - Non-focusing collector only

b) eq. 2: A more advanced equation using direct and diffuse radiation, valid for:
   - Non-focusing collector
   - Focussing collectors with low concentration ratio $C_R < 20$

c) eq. 3: Equation specifically for focussing collectors with high concentrating ratio, valid for:
   - Focussing collectors with concentration ratio $C_R \geq 20$

The estimate is given by stating the equation to be used for calculating the power output, including specific values for the parameters in equation.

The collector module efficiency parameters $\eta_{0,\mathrm{hem}}$, $\eta_{0,\mathrm{b}}$, $K_b(\theta_L, \theta_T)$, K_d, a_1, a_2, a_5 and a_8 should be based on certified[1] test results[2].When an estimate is given, it shall always be stated which equation shall be used for checking the performance:

[1] E.g. Solar Keymark or similar.

[2] In older Solar Keymark data sheets a_5 is denoted c_{eff}.

a) Simple check, using total radiation on the collector plane when checking the power output (ISO this standard, eq 1).

b) Advanced check, using direct and diffuse radiation on collector plane when checking the power output (ISO this standard, eq 2/3).

Note: Always be very careful if the collector area given is the gross area or the aperture area – and if collector parameters given are related to the gross area or the aperture area.

5.1.1 Equation 1

A simple power performance estimate for non-focussing collectors is given with eq. (1):

$$\dot{Q}_{\text{estimate}} = A_G \cdot [\eta_{0,\text{hem}}\, G_{\text{hem}} - a_1\,(\vartheta_m - \vartheta_a) - a_2\,(\vartheta_m - \vartheta_a)^2 - a_5\,(d\vartheta_m\,/dt)] \cdot f_{safe} \quad (1)$$

ϑ_m is mean value of collector in – and outlet temperatures.

Using eq. 1 will normally give bigger uncertainty than using eq. 2 as incidence angle modifiers for the collector are not considered.

f_{safe} is chosen considering potential influences from pipe heat loss, measurement uncertainties, model uncertainties etc..

f_{safe} could be divided into factors considering specific influences. As an example, f_{safe} could be calculated from $f_{safe} = f_P \cdot f_U \cdot f_O$, where:

f_P: Safety factor considering heat losses from pipes etc. in the collector loop. To be estimated – normally only a few %.

f_U: Safety factor considering measurement uncertainty. To be estimated – with the requirements given in 6.2, a factor of 0.95 could be recommended.

f_O: Safety factor for other uncertainties e.g. related to non-ideal conditions such as:

- non-ideal flow distribution. To be estimated – should be close to one.
- unforeseen heat losses. To be estimated – should be close to one.
- uncertainties in the model/procedure itself. To be estimated – should be close to one. *Note – it is recommended to put $f_O \leq 1$ when eq. (1) is used, as eq. (1) does not consider the influence of incidence angle modifiers. For flat plate collectors, values down to 0.95 could in some cases be recommended; for evacuated tubes the value should normally be closer to one.*

5.1.2 Equation 2

A more advanced equation for non- or low-focussing collectors ($C_R < 20$) can be used if the direct and/or diffuse radiation on the collector plane is measured or can be calculated. Equation 2 includes the incidence angle modifiers for direct and diffuse radiation:

$$\dot{Q}_{\text{estimate}} = A_G \cdot [\eta_{0,b}\, K_b(\theta_L, \theta_T) G_b + \eta_{0,b}\, K_d\, G_d - a_1\,(\vartheta_m - \vartheta_a) - a_2\,(\vartheta_m - \vartheta_a)^2 - a_5\,(d\vartheta_m\,/dt)] \cdot f_{safe} \quad (2)$$

ϑ_m is mean value of collector in – and outlet temperatures.

With respect to safety factor, f_{safe} see last part of section 5.1.1.

5.1.3 Equation 3

Equation 3 is used for focussing collectors with high concentration ratio; $C_R \geq 20$ – tracking in one or two axis, and utilizing mainly or only the direct radiation.

$$\dot{Q}_{\text{estimate}} = A_G \cdot [\eta_{0,b}\, K_b(\theta_L, \theta_T) G_b - a_1\,(\vartheta_m - \vartheta_a) - a_5\,(d\vartheta_m\,/dt) - a_8\,(\vartheta_m - \vartheta_a)^4] \cdot f_{safe} \qquad (3)$$

ϑ_m is mean value of collector in – and outlet temperatures.

With respect to f_{safe} see last part of section 5.1.1.

5.2 Stating a performance estimate

The performance estimate is given by specifying the “collector equation” (eq. 1, 2 or 3), and listing the values of the parameters to be used when calculating the power output. It shall be stated if checking shall be done according to level I or level II. In Annex B a template for stating the performance estimate is given.

5.3 Restrictions on operating conditions

To limit uncertainties, it is important to give restriction on the operation conditions for which the estimate is valid. The restrictions given here means that only measurement points taken when the collector field is close to stable full power operation are valid.

Operation condition	Limits			Comments
	Eq.1	Eq.2	Eq.3	
Shadows	No shadows			See section 5.4
Incidence angle	≤ 30°			See section 5.5
Change in collector mean temperature	≤ 5 K			To avoid big change in collector temperature during one hour
Ambient temperature	≥ 5 °C			To avoid snow, ice, condensation on solar radiation sensors
Wind velocity	≤ 10 m/s			To be measured so it is representative for the wind velocity 1 - 3 m above highest point of collectors
G_{hem}	≥ 800 W/m²	-	-	
G_b		≥ 600 W/m²	≥ 600 W/m²	

Table 1. Restrictions on operation conditions. Measured and calculated power shall only be compared for data fulfilling restrictions above.

5.4 Shadows

5.4.1 Shadows on fixed collectors in rows

To limit uncertainties, it is important to avoid shadows on the collectors. Shadows on the collectors could be from rows in front or from other objects.

Related to shadows from rows in the front, only data points for which the solar altitude angle (h) is large enough to avoid shadows shall be included – corresponding to $h > h_{min}$ in fig. 1.

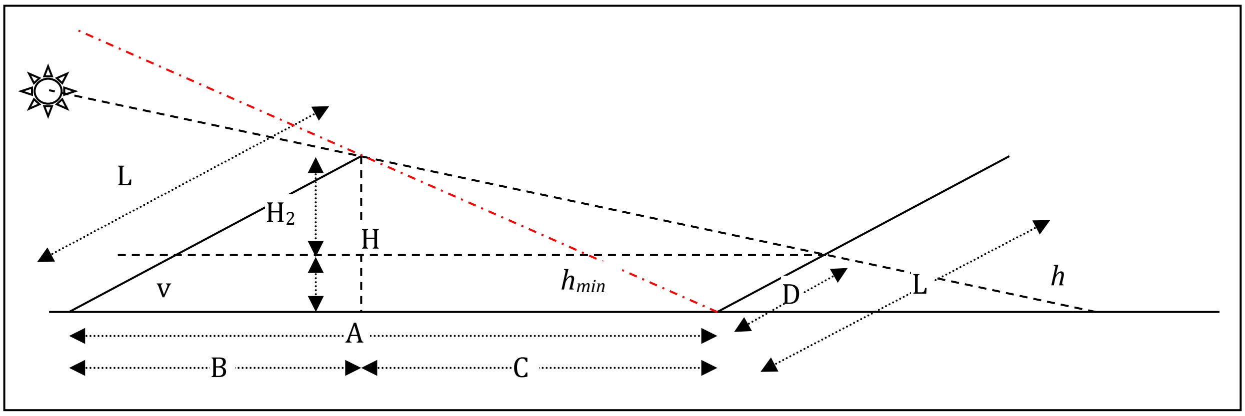

Fig. 1. Geometry for collectors placed in rows behind each other.

For fixed (non-tracking) collectors placed in rows behind each other, h_{min} can be calculated as a fixed value from the geometry of the row set-up, se fig. 1. For tracking collectors h_{min} is variable with time – 5.4.2.

The solar altitude, h can be calculated from [1] depending on location of the collector field and the time of year and day;

$$\sin h = \cos \phi \cdot \cos \delta \cdot \cos \omega + \sin \phi \cdot \sin \delta \quad (4)$$

For fixed collectors h_{min} can be calculated from:

$$\tan h_{min} = \sin v \,/\, [\, A/L - \cos v) \quad (5)$$

The declination, δ can be calculated from [1]:

$$\delta = 23.45 \cdot \sin(360 \frac{284+n}{365}) \quad (6)$$

Where n is day number.

Shadows could also origin from building, chimneys, trees, etc.. Data points at times when such shadows occur on part(s) the collector field shall be excluded.

5.5 Collector incidence angle

The collector incidence angle can be calculated from [Ref 1]:

$$\cos \theta = \cos \theta_Z \cdot \cos \beta + \sin \theta_Z \cdot \sin \beta \cdot \cos (\gamma_s - \gamma) \quad (7)$$

where the zenith angle θ_Z can be calculated from:

$$\cos \theta_Z = \cos \phi \cdot \cos \delta \cdot \cos \omega + \sin \phi \cdot \sin \delta \tag{8}$$

and:

β : slope of collector

δ : declination; $\delta = 23.45 \sin [360/365 \cdot (284 + n)]$; n being day number of the year

γ_s : solar azimuth angle

γ : collector surface azimuth angle

ϕ : latitude

ω : hour angle

For two-axis tracking collector incidence angle θ should be 0.

Note: A good reference for detailed description of calculating the collector incidence angle is *[Solar Engineering of Thermal Processes, J.A.Duffie and W.A.Beckman, 4th Edition]*.

5.6 Example of setting up an equation for calculating performance estimate

Available radiation measurements:

- Total radiation on collector plane only (G_{hem})

Collector field area:

- Type of collector: Flat-plate collector
- Module gross area: 13.2 m^2
- Number of collector modules: 1000
- A_G = 13 200 m^2

Corresponding collector efficiency parameters

- $\eta_{0,hem} = 0.80$
- $a_1 = 3.0$ W/(K·m^2)
- $a_2 = 0.01$ W/(K^2·m^2)
- $a_5 = 10.0$ kJ/(m^2K)

Other data:

- Estimated pipe heat losses: 3 % → $f_P = 0.97$
- Estimated uncertainty on measurements: 5 % → $f_U = 0.95$
- Safety factor other things: $f_O = 0.95$ (simple equation 1 is used as diffuse radiation is not measured)
- $f_{safe} = f_P \cdot f_U \cdot f_O = 0.875$

Diffuse radiation is not measured, so the equation (1) is used:

$$\dot{Q}_{\text{estimate}} = A_G \cdot [\eta_{0,\text{hem}}\, G_{\text{hem}} - a_1\,(\vartheta_m - \vartheta_a) - a_2\,(\vartheta_m - \vartheta_a)^2 - a_5\,(d\vartheta_m / dt)] \cdot f_P \cdot f_U \cdot f_O$$

$$= 13\,200 \cdot [0.80 \cdot G - 3.0 \cdot (\vartheta_m - \vartheta_a) - 0.01 \cdot (\vartheta_m - \vartheta_a)^2 - 10.0 \cdot a_5\,(d\vartheta_m/dt)\,] \cdot 0.875 \qquad [W]$$

$$= 11\,550 \cdot [0.80 \cdot G - 3.0 \cdot (\vartheta_m - \vartheta_a) - 0.01 \cdot (\vartheta_m - \vartheta_a)^2 - 10.0 \cdot a_5\,(d\vartheta_m/dt)] \qquad [W]$$

ϑ_m is mean value of collector inlet (ϑ_i) and outlet (ϑ_e) temperatures – measured close to the heat exchanger, see 6.2.3.1.

It shall be specified where the power shall be measured. In the collector primary loop – or in the secondary loop ("after" heat exchanger).

Note: The primary loop will often have some fraction of anti-freeze liquid (glycol). This may introduce some uncertainty on the physical parameters (fluid density and fluid specific heat capacity) – hence, this may be a good reason to do power measurement in the secondary loop (after the heat exchanger) which will normally be pure water with known physical parameters. The heat loss from the heat exchanger is normally insignificant compared to the power measured for the valid data points.

5.7 Determination of potential valid periods

Only periods without shading and with an incidence angle lower than 30° shall be used for checking the estimated performance. Examples of determination of potential valid periods are shown in Annex C:

- Determination the potential valid periods for **fixed collectors** mounted in rows at **latitude 50°N**
- Determination the potential valid periods for **fixed collectors** mounted in rows at **latitude 30°S**

6 Checking performance estimates

6.1 Measurements needed

To check the solar collector field performance estimate, it is necessary (at least) to measure the following data points **using eq.1** (see figure 2 below):

ϑ_e: Outlet temperature from collector field (measured in collector loop at heat exchanger inlet) [°C]

ϑ_i: Inlet temperature to collector field (measured in collector loop at heat exchanger outlet) [°C]

$\dot{Q}$: Thermal power supplied from heat exchanger [W]

G_{hem}: Hemispherical solar irradiance on collector plane [W/m²]

ϑ_a : Ambient air temperature (shadowed and ventilated) [°C]

Using eq.2 it is also necessary to know direct and diffuse radiation on collector plane (G_b and G_d); so at least one of these radiations has to be measured – the other one could then be calculated subtracting the measured one from the G_{hem}

Using eq.3 it is necessary to measure direct radiation on the (tracking) collector plane.

Other requirements:

Logging time ≤ 1minute

Recording time = 1 hour

Time and date for all recorded data are required. The values in the record shall represent the average values over the last hour (e.g. data in the record saved 2018-04-01 12:00 represent the average values in the hour from 11:00 to 12:00 on April 1st 2018). Time indication shall always be "standard time" (not "daylight saving time" nor "summer time").

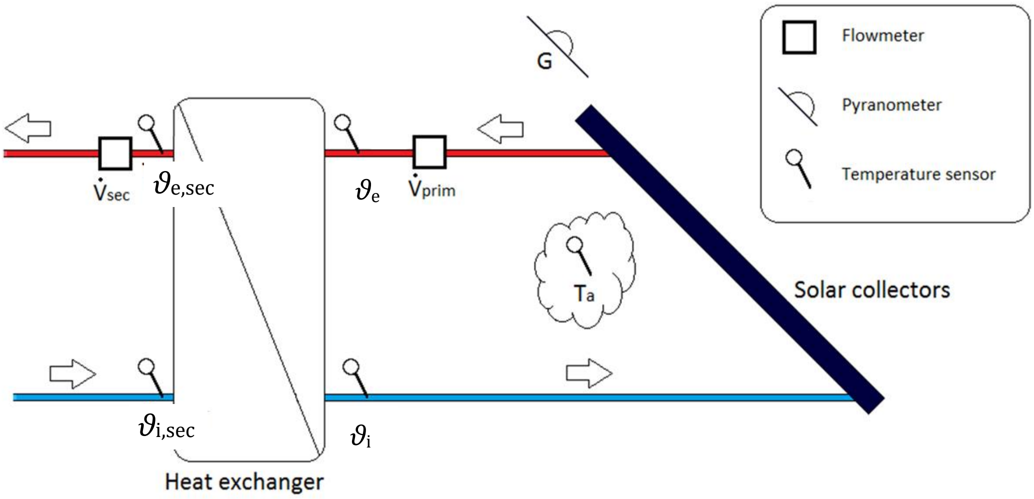

Fig. 2. Schematic drawing showing the measurement points.

(Source: PlanEnergi)

All measurement instruments/sensors should be installed as specified in section 6.2 and as recommended by the supplier.

Collector field power Q_{sec} shall be measured on the secondary side secondary side of the heat exchanger, based on plow and temperature measurements:

$$\dot{Q}_{sec} = \dot{V}_{i,sec} \cdot \rho_{i,sec} \cdot c_{f,i,sec} \cdot (\vartheta_{e,sec} - \vartheta_{i,sec}) \qquad (9)$$

where:

$\dot{V}_{i,sec}$: Volume flow at heat exchanger inlet [m³/s]

$\vartheta_{e,sec}$: Heat exchanger outlet temperature (measured in secondary loop at heat exchanger outlet) [°C]

$\vartheta_{i,sec}$: Heat exchanger inlet temperature (measured in secondary loop at heat exchanger inlet) [°C]

$\dot{Q}_{sec}$: Thermal power supplied from heat exchanger [W]

$\rho_{i,sec}$: Density of heat transfer fluid at heat exchanger inlet temperature [kg/m³]

$c_{f,I,sec}$: Specific heat capacity of heat transfer fluid at the collector inlet [J/(kg K)]

6.2 Requirements on measurements and sensors

The instrumentation and sensors should/shall be chosen to get a good accuracy.

Two levels of accuracy is given here:

- Level I: Measured solar radiation: ±3 % and power output ±2 %
- Level II: Measured solar radiation ±5 % and power output ±3 %

6.2.1 Time

Time and date for all recorded data are required. The values in the record shall represent the average values over the last hour (e.g. data in the record saved 2018-04-01 12:00 represent the average values in the hour from 11:00 to 12:00 on April 1st 2018). Time indication shall always be "standard time" (not "daylight saving time" nor "summer time").

The solar time in the middle of the standard time hour shall be calculated and used for calculation of incidence angles and checking of shadowing. The solar time is calculated from eq. 10:

$$\text{Solar time - Standard time} = 4\,(L_{st} - L_{loc}) + E, \text{ [minutes]} \qquad (10)$$

where:

L_{st} : Standard meridian for the local time zone

L_{loc} : Longitude for location

E : Equation of time; calculated from

$E = 0.017 + 0.43 \cos B - 7.35 \sin B - 3.35 \cos 2B - 9.36 \sin 2B$, [minutes], where

$B = (n-1)\, 360/365$

Other requirements:

Logging time ≤ 1minute

Recording time = 1 hour

Tolerance on time measurement:

- Level I: ≤ 0,1 %
- Level II: ≤ 0,1 %

6.2.2 Solar radiation measurement

General

The pyranometer shall be mounted such that its sensor is coplanar, within a tolerance of < 2° with the collector plane as stated by the manufacturer. Care shall also be taken to prevent energy reflected from the solar collector onto the pyranometer. – so the sensors for flat plate collector fields shall be placed on top of collectors

The body of the pyranometer and the emerging leads of the connector shall be shielded to minimize solar heating of the electrical connections.

For highly concentrating collectors ($C_R > 3$) mounted on the original manufacturer's solar tracking device, a pyrheliometer of Class 2 or better, as specified in ISO 9060, shall be used to measure the direct normal irradiance (DNI). The pyrheliometer shall be mounted on a separate solar tracking device. The pyrheliometer field of vision shall be no more than 6° of arc. The tracking errors associated to the mounting on the tracker shall not exceed ±1°.

Beam irradiance shall be calculated by $G_b = \mathrm{DNI} \cdot \cos(\theta)$.

Diffuse irradiance shall be calculated by $G_d = G_{hem} - G_b$.

The sensors shall be installed such as to receive the same levels of direct, diffuse and reflected solar radiation as are received by the complete collector field. For very large collector fields this means that several sensors might be necessary.

In fields of flat plate collectors, the first pyranometers / pyrheliometer shall be placed in the middle of the collector field.

Accuracy of solar sensors

- Level I: Pyranometers, Class 2 or better, as specified in ISO 9060, pyranometer(s) shall be used to measure the hemispherical solar radiation (Ghem) following the recommendation given in ISO/TR 9901. Class I or better pyranometer(s) equipped with a shading ring or alternatively a pyrheliometer, together with a pyranometer, shall be used to measure the diffuse short-wave radiation.
- Level II: Solar sensors with accuracy ± 5 % in the range of 600 – 1000 W/m² shall be used to measure the hemispherical solar radiation (Ghem) and the diffuse short-wave radiation.

Location of solar sensors

The required minimum number of pyranometers / pyrheliometers are determined by the size of the collector field:

- Level I: Maximum distance from any collector to nearest pyranometer / pyrheliometer ≤ 250 / 500 m
- Level II: Maximum distance from any collector to nearest pyranometer / pyrheliometer ≤ 500 / 1000 m

All radiation measurements shall be recorded. Average values for all instruments are used for the estimation of collector performance.

Cleaning of solar sensors

- Level I: The solar sensors shall be cleaned every day
- Level II: The solar sensors shall be cleaned every week

6.2.3 Temperature measurements

Five temperature sensors are required. These are the fluid temperatures and ambient air temperature:

Fluid temperatures:

Collector loop side of heat exchanger:

Collector inlet

Collector outlet

Secondary side of heat exchanger:

Heat exchanger inlet

Heat exchanger inlet

Ambient air temperature

6.2.3.1 Fluid temperatures

Certified tolerance for absolute values of collector outlet and inlet temperatures:

- Level I: <0,35 K (Class A)
- Level II: <0,35 K (Class A)

The sensor for temperature measurement of the heat transfer liquid shall be mounted at no more than 1 m from the heat exchanger, and insulation shall be placed around the pipe work both upstream and downstream of the sensor. If it is necessary to position the sensor more than 1 m away from the heat exchanger, then a test shall be made to verify that the measurement of fluid temperature is not affected. The position of temperature measurement shall be in the centre of the pipe in a pipe section without any possibility for air being trapped near the sensor.

6.2.3.2 Ambient air temperature

Certified tolerance:

- Level I: <0,35 K (Class A)
- Level II: <0,35 K (Class A)

The sensor shall be shaded from direct and reflected solar radiation by means of a white-painted, well-ventilated shelter. The shelter itself shall be shaded and placed at least 1 m above the local ground surface to ensure that it is removed from the influence of ground heating. The shelter shall be positioned not more than 100 m distance to the collector field.

6.2.4 Flow rate measurement

The flow meter on the secondary side shall be calibrated for water over the relevant range of fluid flow rates and temperatures.

- Level 1: Certified tolerance: < 1 % in relevant range
- Level 2: Certified tolerance: < 2 % in relevant range

Alternative to separate flow rate measurement on secondary side is integrated power measurement – see below.

6.2.5 Power measurement / calculation

The thermal power output on the secondary side can be measured directly by integrated instrument or calculated from separate flow and temperature sensors:

- The thermal power output can be measured[3] by an integrated power measurement device "energy meter" (calibrated for water).
    - Level 1: Certified tolerance < 2 % in relevant range
    - Level 2: Certified tolerance < 3 % in relevant range
- The thermal power output can be calculated from measured flow and temperature difference:

  $q = v * c_p * \varrho * \Delta T$, where:

  q is power, W

  v is flowrate, m^3/s

  ΔT is difference between outlet and inlet temperature, K

  c_p is temperature dependent specific heat capacity of the circulation water J/(kgK)

  ϱ is temperature dependent density of the circulating water kg/m^3

Flow rate shall be measured on inlet side (cold side) on heat exchanger secondary side (water side), and the temperature for determination of and density of the water shall be the inlet temperature. The temperature for determination specific heat capacity shall be the arithmetic mean of inlet and outlet temperatures.

6.2.6 Measurement of wind speed

Tolerance in both levels 1 m/s. Measurement of wind speed shall be done 1 - 3 m above the highest point of the collector field – not more than 100 m from the collector field.

6.3 Number of valid data records

Only data records (hourly average values) fulfilling the requirements in section 5.3 are valid.

For checking the collector performance, the measuring period shall have at least 20 data records.

All valid data records in the period shall be used unless it is obvious that errors in data or very atypical operating conditions occur (omitting valid data points shall be reported and justified). Plots like fig. 3 below can help to identify data errors.

For determination of potential valid periods (with no shadows from rows in front and with low incidence angle), see section 5.4.

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[3] Care to be taken if the liquid is not water.

6.4 Checking collector field performance

The average measured power output ($\dot{Q}_{meas}$) for all valid data point are compared with the corresponding average power calculated ($\dot{Q}_{estimate}$) according to the formula (eq.1, 2 or 3), using the measured weather data and temperatures in collector loop.

If the average measured power (for at least 20 consecutive valid data points) is equal to or greater than the average power corresponding to the calculation of the estimated power, then the estimated power is verified:

$$\text{Average}[\dot{Q}_{meas}] \geq \text{Average}[\dot{Q}_{estimate}] \Rightarrow \text{Estimate verified}$$

Plot of corresponding data points for measured and calculated thermal power should be made to check for deviations.

6.4.1 Example 3: Checking collector field performance

27 data artificial valid data points for corresponding measured and estimated power are show in fig. 3 are chosen.

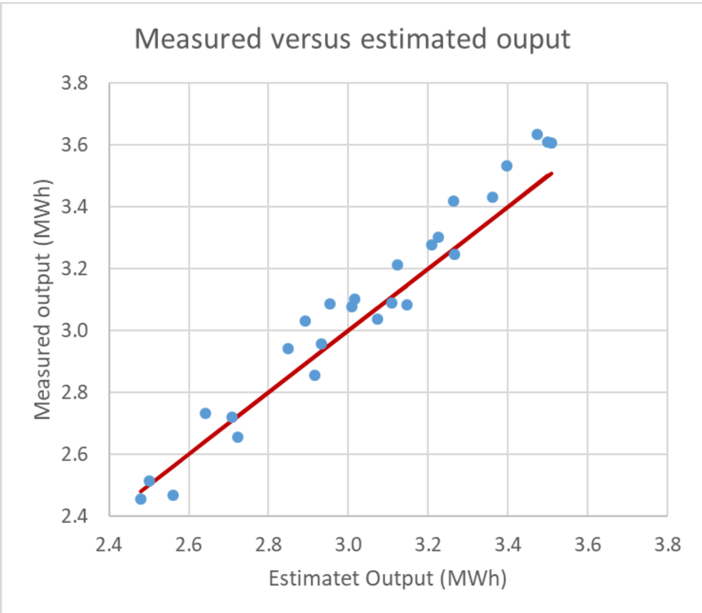


Fig.3. Example plot of measured hourly energy against corresponding guaranteed hourly points. (Artificial data).

The corresponding average hourly measured, and average estimated power output is compared in fig. 4.

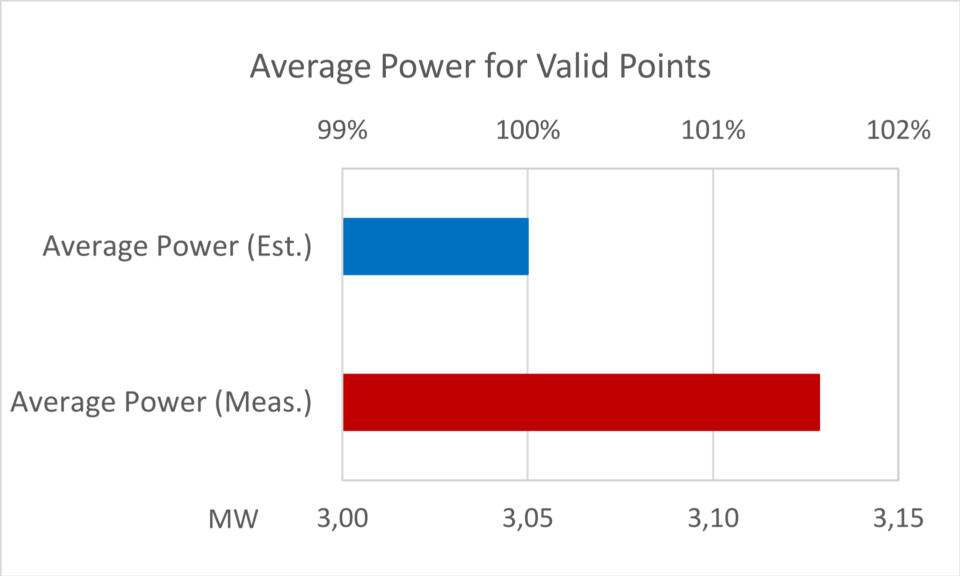


Fig.4. Plot of average measured power and corresponding estimated average power.

It is seen that:

$$\text{Average}[\dot{Q}_{\text{meas}}] \geq \text{Average}[\dot{Q}_{\text{estimate}}]$$

The estimate is then verified

Annex A. Recommended reporting format
(informative)

Collector field performance check according to ISO xxxx

Owner of plant :	Check done by :
Measuring period :	Date :
Level of check: I / II	Equation used : 1 / 2 / 3

Input data

Collector

- η_{hem} :
- η_b :
- η_d :
- a_1 :
- a_2 :
- a_3 :
- a_5 :
- a_8 :
- K_d:

Fluid data

- Fluid type: pure water / xxx
- ρ :
- c_P :

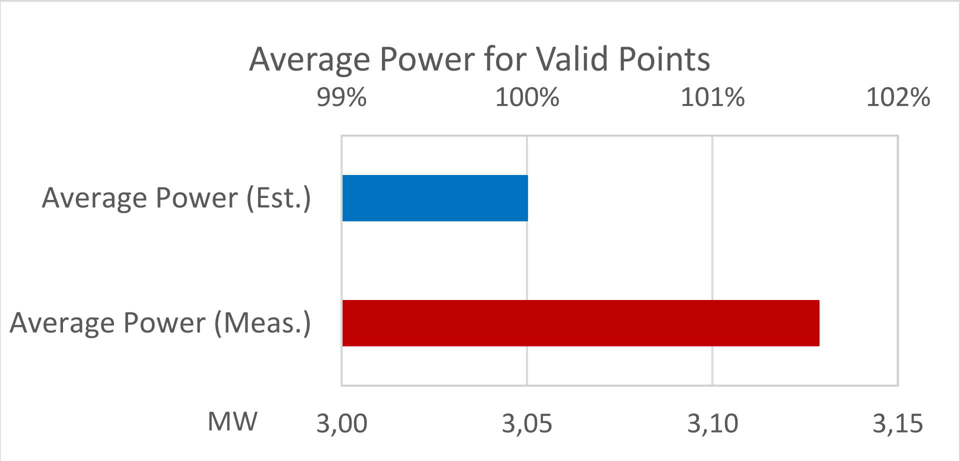
Safety factors

- f_P :
- f_U :
- f_O :
- f_{safe}:

Give either f_P, f_U, f_O – or f_{safe}

Incidence angle		10°	20°	30°	40°	50°	60°	70°	80°	90°
Transversal modifier	$K_b(\theta_T)$	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98
Longitudinal modifier	$K_b(\theta_L)$	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98

Results



Calculated estimated average power for valid points : 3.05 MW

Measured average power for valid points : 3.13 MW

Conclusion

The estimate is : verified / not verified

Collector field performance check according to ISO xxxx

Owner of plant : Measuring period : Level of check: I / II	Check done by : Date : Equation used : 1 / 2 / 3

Instrumentation

Total (hemispherical) radiation :
Direct radiation :
Diffuse radiation :
Ambient temperature :
Fluid temperatures :
Mass flow :
Volume flow :
Power :

Symbols used

a_1 :
a_2 :
a_3 :
a_5 :
a_8 :
K_d:
$K_b(\theta_L, \theta_T)$:

η_{hem} :
η_b :
η_d :

...

Data points considered							
Date/time		*Measured data*					*Calculated data*
Date	*Time*	G_{hem}	ϑ_a	ϑ_i	ϑ_e	$\dot{Q}_{meas}$	$\dot{Q}_{estimate}$
		W/m^2	*°C*	*°C*	*°C*	*MW*	*MW*
2018-01-01	*00:00*	*0000*	*00.0*	*000.0*	*000.0*	*000.000*	*000.000*
...							

Annex B. Recommended format for stating the estimated performance (informative)

Collector field performance check according to ISO xxxx

Owner of plant :

Estimated measuring period :

Level of check: I / II

Check to be done by :

Date :

Equation to be used : 1 / 2 / 3

Input data

Collector

- η_{hem} :
- η_b :
- η_d :
- a_1 :
- a_2 :
- a_3 :
- a_5 :
- a_8 :
- K_d:

Fluid data

- Fluid type: pure water / xxx
- ρ :
- c_P :

Safety factors

- f_P :
- f_U :
- f_O :
- f_{safe} : (optional)

Incidence angle		10°	20°	30°	40°	50°	60°	70°	80°	90°
Transversal modifier	$K_b(\theta_T)$	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98
Longitudinal modifier	$K_b(\theta_L)$	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98

Instrumentation	Brand	Type	Uncertainty
Total (hemispherical) radiation :			
Direct radiation :			
Diffuse radiation :			
Ambient temperature :			
Fluid temperatures* :			
Mass flow :			
Volume flow :			
Power :			
Wind velocity:			

Symbols used

a_1 :
a_2 :
a_3 :
a_5 :
a_8 :
K_d:
$K_b(\theta_L, \theta_T)$:

η_{hem} :
η_b :
η_d :

...

Annex C. Examples of determination the potential valid periods

C.1 Valid periods for fixed (non-tracking) collectors mounted in rows - examples

A few examples will be shown illustrating where potential valid measurement periods will be for collectors mounted in long rows behind each other.

It will be seen that in some cases valid recordings can only be done in some parts of the year.

It is assumed that only rows in front are coursing shadows on collectors – no other shadowing objects are involved in the following examples (other shadowing object in actual cases shall of course be taken into account).

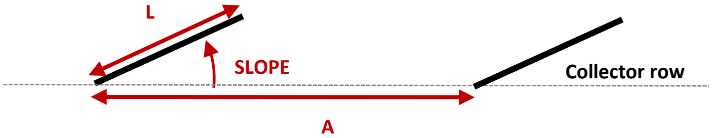
Example: Latitude 50°N

Latitude: 50° (could be e.g. Würzburg in Germany)

Collector orientation: South

Slope: 30°

Row geometry:



Collector height, L: 2.2 m

Row distance, A: 5.5 m

A/L: 2.5

In this case the number potential valid records during a year is 826.

Now merging with weather data for Würzburg[4] the actual number of points fulfilling the weather requirements (see table ?) too can be found; number of valid point are reduced to 250.

In fig.? number of points distributed on monthly basis is shown. It is seen that from April to September you can expect to get 20 valid measurement points within one month. The other months are not useable to get valid data.

The valid points will be located around noon, due to restrictions on incidence angle modifier.

[4] Generated by [METENORM]

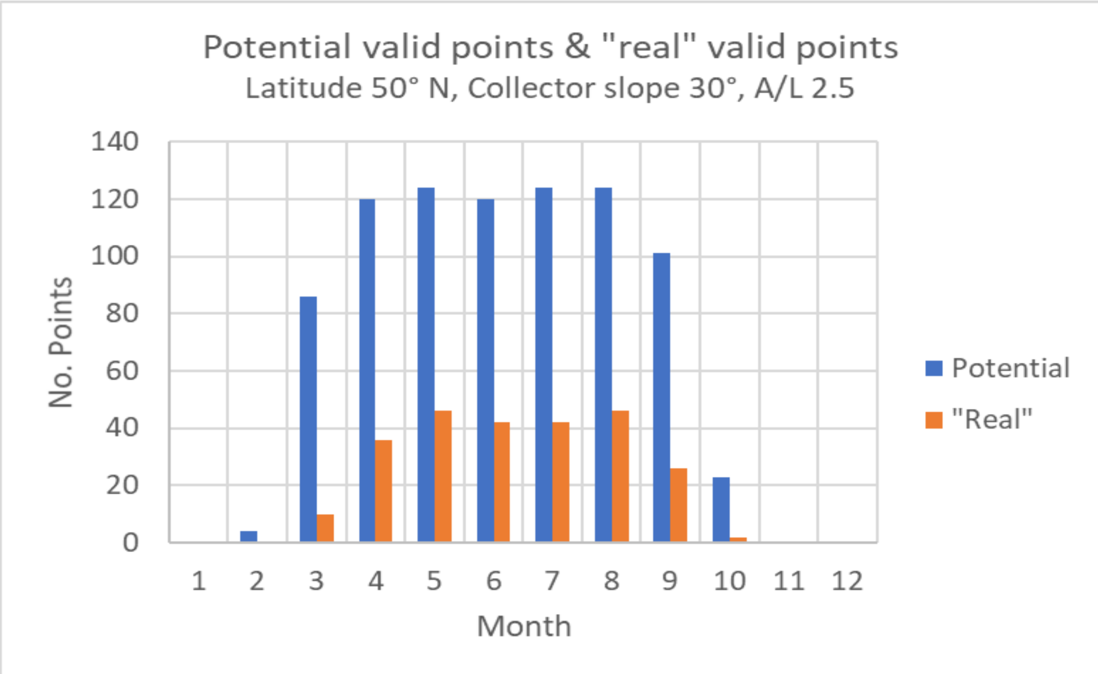


Figure ? Potential and expected number of valid measurement points distributed on months for:

Latitude: 50°N, collector slope 30°, A/L = 2.5 (Würzburg)

6.4.2 Determination the potential valid periods for fixed (non-tracking) collectors mounted in rows at latitude 30°S

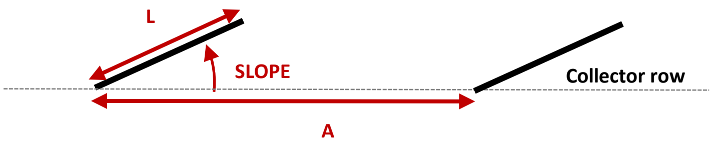
Example: Latitude 30°S

Latitude: 30°S (could be e.g. Durban in South Africa)

Collector orientation: North

Slope: 20°

Row geometry:



Collector height, L: 2.2 m

Row distance, A: 4.4 m

A/L: 2.0

In this case the number potential valid records during a year is 1053.

Now merging with weather data for Durban[5] the actual number of points fulfilling the weather requirements (see table ?) too can be found; number of valid point are reduced to 416.

In fig.? number of points distributed on monthly basis is shown. It is seen that from August to April you can expect to get 20 valid measurement points within one month. The 3 winter months are not useable to get valid data.

The valid points will be located around noon, due to restrictions on incidence angle modifier.

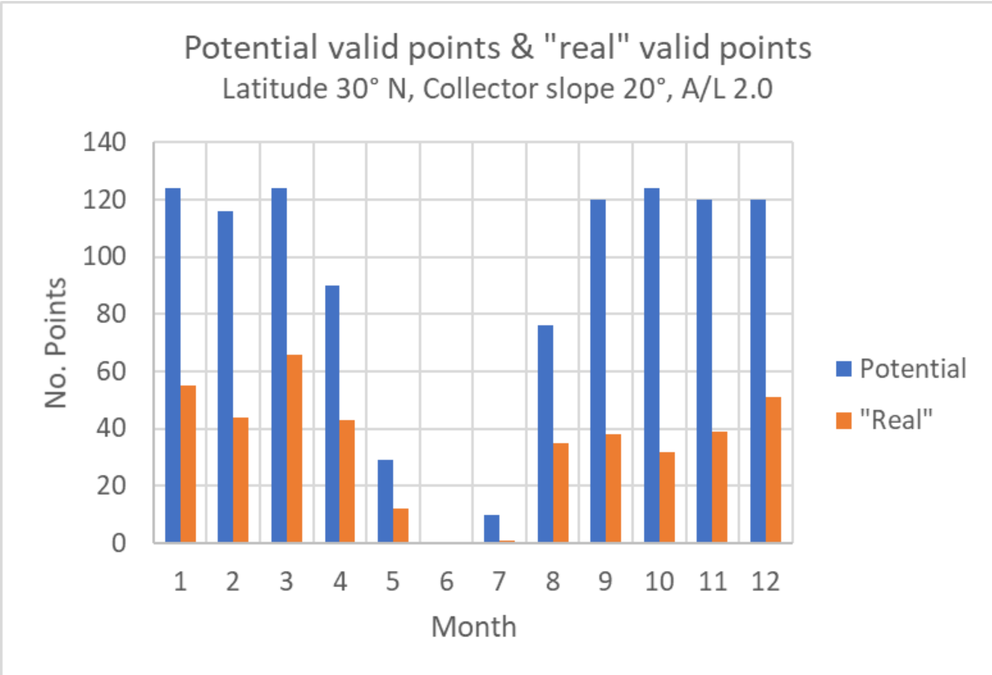


Figure ? Potential and expected number of valid measurement points distributed on months for: Latitude: 30°S, collector slope 20°, A/L = 2.0 (Durban)

C.2 Potential valid periods for tracking collectors mounted in rows

The number of valid records for tracking collectors will much higher than for collectors with fixed orientation as the incidence angle will be always much lower (and actually (close to) zero for 2-axis tracking).

[5] Generated by [METENORM]

For tracking collectors valid records will be available year round except for location with very low solar radiation or extremely cold weather.

Bibliography

[1] Duffie J.A. Beckmann W.A. *Solar Engineering of Thermal Processes, 4ed.,Wiley, 2013*