INTERNATIONAL STANDARD

ISO 24194

First edition
2022-05

# Solar energy — Collector fields — Check of performance

*Energie solaire — Champs de capteurs — Vérification de la performance*



Reference number
ISO 24194:2022(E)

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# Foreword

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This document was prepared by Technical Committee ISO/TC 180, *Solar energy*, Subcommittee SC 4, *Systems - Thermal performance, reliability and durability*, in collaboration with the European Committee for Standardization (CEN) Technical Committee CEN/TC 312, *Thermal solar systems and components,* in accordance with the Agreement on technical cooperation between ISO and CEN (Vienna Agreement).

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# Introduction

This document specifies procedures for checking the performance of solar thermal collector fields. Measured performance is compared with calculated performance - and conditions for conformity are given.

Three levels for accuracy in the checking can be chosen:

— Level I - giving possibility for giving a very accurate estimate (with low safety retention, e.g. $f_{safe}$ = 0,95) - but with requirements for use of expensive measurement equipment.

— Level II/III - allowing for a less accurate estimate (with higher safety retention, e.g. $f_{safe}$ = 0,90) - but possibility to use less expensive measurement equipment.

# Solar energy — Collector fields — Check of performance

## 1 Scope

This document specifies two procedures to check the performance of solar thermal collector fields. This document is applicable to glazed flat plate collectors, evacuated tube collectors and/or tracking, concentrating collectors used as collectors in fields.

The check can be done on the thermal power output of the collector field and also be on the daily yield of the collector field.

The document specifies for the two procedures 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 of 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 terminology databases for use in standardization at the following addresses:

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

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

**3.1**
**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 ISO 9488 | $m^2$ |
| $A_{GF}$ | Gross area of collector field | $m^2$ |
| $a_{1,\Delta Q}$ | Heat loss coefficient at $(\vartheta_m - \vartheta_a) = 0$ | $W/(m^2 \cdot K)$ |
| $T_{\Delta Q}$ | Temperature dependence of the heat loss coefficient | $W/(m^2 \cdot K^2)$ |

 

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|---|---|---|
| $v_{\Delta Q}$ | Wind speed dependence of the heat loss coefficient | J/(m³·K) |
| $T_s$ | Sky temperature dependence of the heat loss coefficient | — |
| $a_5$ | Effective thermal capacity. In some literature and data sheets denoted $C_{eff}$. Note that $C_{eff}$ unit is kJ/m²K. | J/(m²·K) |
| $v$ | Wind speed dependence of the zero-loss efficiency | s/m |
| $v_{IR}$ | Wind speed dependence of IR radiation exchange | W/(m²·K⁴) |
| $a_8$ | Radiation losses dependence | W/(m²·K⁴) |
| $b_u$ | 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/(kg·K) |
| $c_{f,i}$ | Specific heat capacity of heat transfer fluid at the collector inlet | J/(kg·K) |
| $c_{f,e}$ | Specific heat capacity of heat transfer fluid at the collector outlet | J/(kg·K) |
| $I_{DN}$ | 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/m² |
| $I_L$ | Longwave irradiance ($\lambda > 3$ µm) | W/m² |
| $f_P$ | 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. | - |
| $f_{safe}$ | Mathematical product based on the individual safety factors $f_P$, $f_U$, $f_O$ | - |
| $f_{sh}$ | Shading factor | - |
| $D$ | Gap in between adjacent collectors | m |
| $G_{hem}$ | Hemispherical solar irradiance on the plane of collector | W/m² |
| $G_b$ | Direct solar irradiance (beam irradiance) on the plane of collector | W/m² |
| $G_d$ | Diffuse solar irradiance on the plane of collector | W/m² |
| $G_{hem,tot}$ | Total daily irradiation sum on collector plane without shadow | kWh/m² |
| $h$ | Solar altitude angle. $\sin h = \cos \theta_Z$ | ° |
| $h_{min}$ | Minimum solar altitude angle | ° |
| $H_{sh}$ | Height of the shaded area | m |
| $K_{hem}(\theta_L,\theta_T)$ | 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 | — |
| $K_{hem,av}$ | Daily average incidence angle modifier for hemispherical solar radiation | — |
| $L$ | Length of a collector | m |
| $L_{pipe}$ | Overall Length of the pipe system without collectors | m |
| $L_{sh}$ | Length of the shaded area | m |
| $\dot{m}$ | Mass flow rate of heat transfer fluid | kg/s |
| $N_c$ | Number of collectors in a row | - |
| $P_X$ | Coordinate of the point C on the X-axis (C is the point that would reach the shadow formed by the top of the sun facing side of a collector row if it were unobstructed) | - |
| $P_Y$ | Coordinate of the point C on the y-axis | - |
| $\dot{Q}_{measured}$ | Measured power output | W |
| $\dot{Q}_{estimate}$ | Estimated power output | W |
| $Q_{cap,d}$ | Daily capacity heat losses of solar thermal system | J |
| $Q_{estimate\text{-}sys,d}$ | Daily yield estimation of solar thermal system | J |
| $\dot{Q}_{estimate\text{-}col,d}$ | Daily average gross power output collector field | W |
| $Q_{HM,d}$ | Daily yield measurement of the heat meter | J |
| $\dot{Q}_{pipe,d}$ | Daily average heat losses of piping | W |
| $q_{l\text{-}pipe}$ | Empirical specific heat loses per m pipe | W/m |
| $S$ | Spacing center to center in between adjacent rows | m |
| $T$ | Absolute temperature | K |
| $t$ | Time | s |
| $t_s$ | Time start of measurement | s |
| $t_e$ | Time end of measurement | 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 | $m^3/s$ |

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|---|---|---|
| $\dot{V}_i$ | Volumetric flow rate at the inlet of the solar collector | $m^3/s$ |
| $V_{pipe}$ | Volume of the pipe system without collectors | l |
| $w$ | Width of a collector | m |
| $\Delta t$ | Time interval | s |
| $\Delta T$ | Temperature difference between fluid outlet and inlet ($\vartheta_e$ - $\vartheta_i$) | K |
| $\beta$ | Slope (or tilt), the angle between the plane of the collector and the horizontal.<br>*Note: For collectors rotating around a North-South axis, $\beta$ is positive in the morning when facing eastwards - and negative in the afternoon when facing westwards* | |
| $\gamma$ | Surface azimuth angle, the deviation of the projection on horizontal plane of the normal to the surface from the local meridian, with zero due south, east negative and west positive | ° |
| $\gamma_s$ | Solar azimuth angle, the angular displacement from south of the projection of beam radiation on the horizontal plan, east negative and west positive | ° |
| $\delta$ | Declination, the angular position of the sun at solar noon with respect to the plane of the equator, north positive. | ° |
| $\phi$ | Latitude, the angular location north or south of the equator, north positive | ° |
| $\eta_b$ | Collector efficiency based on beam irradiance $G_b$ | — |
| $\eta_{hem}$ | Collector efficiency based on hemispherical irradiance $G_{hem}$ | — |
| $\eta_{0,b}$ | Peak collector efficiency ($\eta_b$ at $\vartheta_m - \vartheta_a = 0$ K) based on beam irradiance $G_b$ | — |
| $\eta_{0,hem}$ | Peak collector efficiency ($\eta_{0,hem}$ at $\vartheta_m - \vartheta_a = 0$ K) based on hemispherical irradiance $G_{hem}$ | — |
| $\eta_{hem,\dot{m}_i}$ | Collector efficiency, with reference to mass flow $\dot{m}_i$ | — |
| $\omega$ | 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 | ° |
| $\theta$ | Angle of incidence | ° |
| $\theta_L$ | Longitudinal angle of incidence: angle between the normal to the plane of the collector and incident sunbeam projected into the longitudinal plane | ° |
| $\theta_T$ | Transversal angle of incidence: angle between the normal to the plane of the collector and incident sunbeam projected into the transversal plane | ° |
| $\theta_Z$ | 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. $\cos \theta_Z = \sin h$ | ° |



 

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|---|---|---|
| $\vartheta_a$ | Ambient air temperature | °C |
| $\vartheta_{am}$ | Measured ambient air temperature | °C |
| $\vartheta_{as}$ | Ambient air temperature for the standard stagnation temperature | °C |
| $\vartheta_e$ | Collector outlet temperature | °C |
| $\vartheta_i$ | Collector inlet temperature | °C |
| $\vartheta_m$ | Mean temperature of heat transfer fluid in collector loop | °C |
| $\vartheta_{max\_op}$ | Maximum operating temperature | °C |
| $\rho_i$ | 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 | $kg/m^3$ |
| $\sigma$ | Stefan-Boltzmann constant | $W/(m^2 \cdot K^4)$ |

# 5 Procedure for checking the power performance of solar thermal collector fields

## 5.1 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 5.4.

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

— If size, 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 similar collector types can be given choosing representative collector parameters.

NOTE Similar types are e.g. flat plate collectors with single glazing and flat plate collectors with double glazing.

When giving the estimate it shall be stated if it shall be checked according to levels of accuracy I, II or level III (see Introduction and 7.2).

## 5.2 Calculating power output

### 5.2.1 General

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

a) Formula (1): Simple equation using total radiation on the collector plane, valid for:

  — Non-concentrating collector only

b) Formula (2): A more advanced equation using direct and diffuse radiation, valid for:

  — Non-concentrating collector

  — Concentrating collectors with low concentration ratio $C_R < 20$

c) Formula (3): Formula using direct radiation specifically for concentrating 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 three possible equations are given in the next three sub-sections.

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

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

b) Advanced check, using direct and diffuse radiation on collector plane when checking the power output (this document, Formula (2)).

c) Advanced check, using only direct radiation on collector plane when checking the power output (this document, Formula (3)).

Ensure that the parameters are related to gross collector area, $A_{GF}$. If necessary, the parameters shall be converted in accordance with ISO 9806.

### 5.2.2 Non-concentrating collectors — Formula (1)



A simple power performance estimate for non-concentrating collectors is given with Formula (1):



$$\dot{Q}_{estimate} = A_{GF} \cdot \left[ \eta_{0,hem} K_{hem}(\theta_L,\ \theta_T) G_{hem} - a_{1,\Delta Q}(\vartheta_m - \vartheta_a) - T_{\Delta Q}(\vartheta_m - \vartheta_a)^2 - a_5 (d\vartheta_m / dt) \right] \cdot f_{safe} \quad (1)$$



$\vartheta_m$ is mean value of collector in - and outlet temperatures.

Using Formula (1) will normally give bigger uncertainty than using Formula (2) because there is no distinction between direct and diffuse radiation.

$f_{safe}$ is chosen considering potential influences from pipe heat loss, measurement uncertainties, model uncertainties etc. and shall be specified with an accuracy of 2 digits.

$f_{safe}$ is 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 based on an evaluation of the pipe losses (e.g. by Formula (23))

$f_U$: Safety factor considering measurement uncertainty. To be estimated - with the requirements given in 7.2, a factor of 0,95 (level I) and 0,9 (level II and III) can be used – or detailed documentation for the uncertainty calculation is required according to ISO/IEC Guide 98-3.

$f_O$: 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.

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1) In older solar keymark data sheets, $a_5$ is denoted $C_{eff}$.

2) E.g. solar keymark or similar.