Guide to ISO 24194:2022 Power Check

Subtask B report RB2

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IEA SHC TASK 68 | Efficient Solar District Heating Systems

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Guide to ISO 24194:2022 Power Check

Procedure for checking the power performance of solar thermal collector fields

This is a report from SHC Task 68: Efficient Solar District Heating Systems

Subtask B: Data Preparation & Utilization

Editors: Daniel Tschopp (AEE INTEC / University of Innsbruck, AT), Philip Ohnewein (AEE INTEC, AT), Stefan Mehnert (Fraunhofer ISE, DE), Lukas Emberger (SOLID Solar Energy Systems GmbH, AT)

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Editors and Main Authors

Daniel Tschopp (AEE INTEC / University of Innsbruck), Philip Ohnewein (AEE INTEC), Stefan Mehnert (Fraunhofer ISE), Lukas Emberger (SOLID Solar Energy Systems GmbH)

Authors (in alphabetical order)

Stefan Abrecht (Solar Experience), Benjamin Ahlgren (WSP / Umeå University), Walter Becke (AEE INTEC), Magdalena Berberich (Solites), Dominik Bestenlehner (Ritter XL Solar), Andreas Bohren (SPF), Joakim Byström (Absolicon), Rosie Christodoulaki (CRES), Harald Dehner (FH Wels), Alexis Duret (HEIG-VD, HES-SO), Bärbel Epp (Solrico), Frej Fogelstrom (Absolicon / Umeå University), Alberto Garcia de Jalon (CENER), Geoffroy Gauthier (PlanEnergi), Federico Giovannetti (ISFH), Alexis Gonnelle (NewHeat), Wolfgang Guggenberger (SolarEngineering Guggenberger), Marnoch Hamilton-Jones (AEE INTEC / TU Graz), Adam R. Jensen (DTU), Miika Kilgast (Meriaura Energy Oy), Christian Kloibhofer (Gasokol), Gunnar Lennermo (Energianalys), Klaus Lichtenegger (BEST - Bioenergy and Sustainable Technologies GmbH), Meng Liu (China National Institute of Standardization), Eckhard Lüpfert (DLR), Claus Matzer (nahwärme St. Ruprecht GmbH), Maria Moser (SOLID Solar Energy Systems GmbH), Thomas Natiesta (AIT), Patrik Ollas (RISE), Dimitrios Papageorgiou (TVP Solar), Stefano Pauletta (HEIG-VD, HES-SO), Guillaume Pradere (NewHeat), Jiao Qingtai (Sunrain), Leo Riebenbauer (Ing. Leo Riebenbauer GmbH), Christoph Rohringer (AEE INTEC), Karin Rühling (TU Dresden), Fabienne Sallaberry (CENER), Bert Schiebler (ISFH), Michael Seiler (TU Ingolstadt), Thorsten Summ (TU Ingolstadt), Daniel Trier (PlanEnergi), Michael Zellinger (Gasokol), Andreas Zourellis (Aalborg CSP)

Layout

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Executive Summary

Purpose

The purpose of this guide is to provide both a practical overview and an in-depth understanding of the *Procedure for checking the power performance of solar thermal collector fields (Power Method)* of ISO 24194:2022. This guide refers to this method as *"Power Check"*. The presented material aims to clarify the standard, provide background information, and promote its widespread use. It complements but does not replace reading the standard. Furthermore, this guide explains how to run Power Check with the free and open-source software *SunPeek* and discusses pathways to improve Power Check.

Power Check

Power Check can be utilized for power performance verification, including power performance guarantees, and ongoing performance monitoring. These applications are crucial for the successful operation of solar thermal plants. Power Check accounts for actual solar radiation levels, system and ambient temperatures, and heat demand, unlike other evaluation methods (e.g., specific solar yield, input-output diagram). Collector efficiency parameters based on Solar Keymark or similar are factored in. The primary Power Check key performance indicator (KPI) is the measured to estimated collector field output ratio, which has proven to be a reliable quality assurance indicator for solar thermal plants.

ISO 24194:2022 is the first standard to target operational solar thermal collector field performance, unlike other standards that target individual collectors and laboratory tests. The standard currently consists of the published ISO 24194:2022 and one amendment, ISO 24194/Amd 1:2024. Because of the novelty of the standard in the solar community, the need for clarification may arise.

In a community effort, the open-source software SunPeek has been developed. It serves as a reference implementation of Power Check and is presented in this guide. SunPeek provides a transparent and consistent implementation of Power Check, making the method accessible to the solar community and stakeholders involved in solar thermal projects.

Target audience

This guide addresses the following stakeholders of solar thermal plants:

- *Plant operators* who want to use Power Check for power performance verification, e.g., performance guarantees given by suppliers during the commissioning phase, or for continuous performance monitoring. This guide summarizes experiences from practical applications.
- For *test laboratories and certification bodies*, this guide outlines areas where the standard requires clarification and highlights possible improvements for revisions.
- For *academia and industry* working on software implementations, this guide discusses modelling and automation and the implementation in the open-source software tool SunPeek.
- For *collector manufacturers, investors and other stakeholders*, this guide aims to provide a deeper understanding of the procedure.

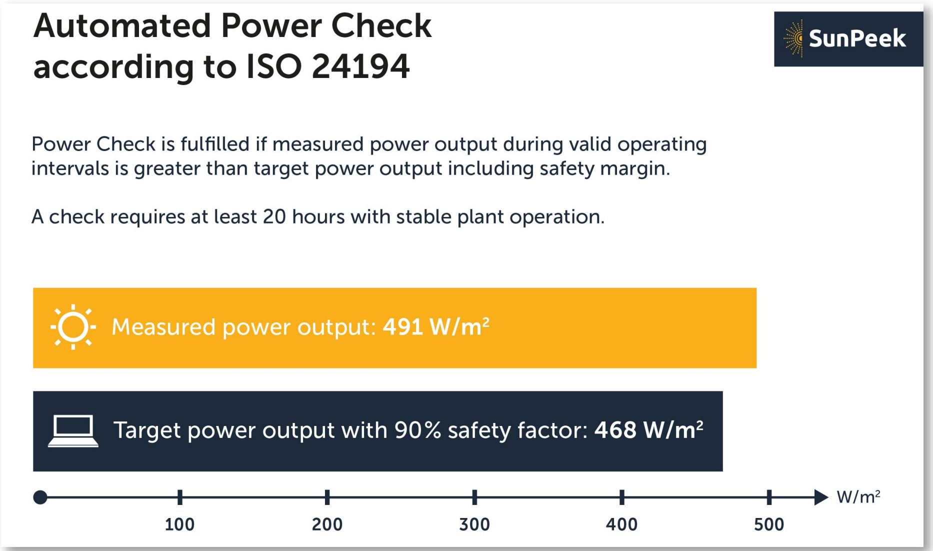
This guide draws inspiration from the *Guide to Standard ISO 9806:2017*. It considers experiences and learnings from *IEA SHC Task 68*, initiating this guide, but extends beyond the task network by including industry and research experts not participating in the task activities. Also, learnings from IEA SHC Task 45 and IEA SHC Task 55, which contributed to the development of Power Check, are incorporated.

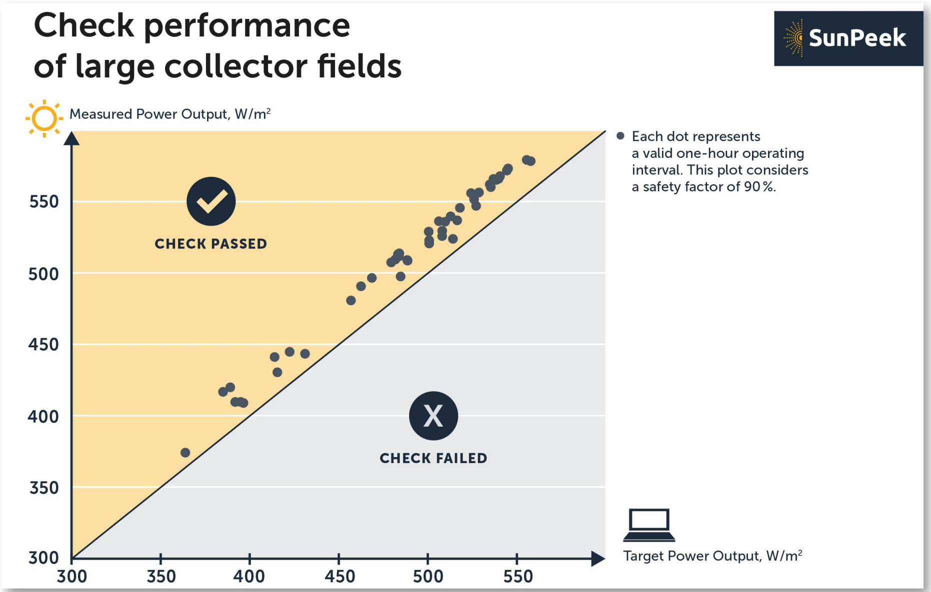
Citation of ISO standards

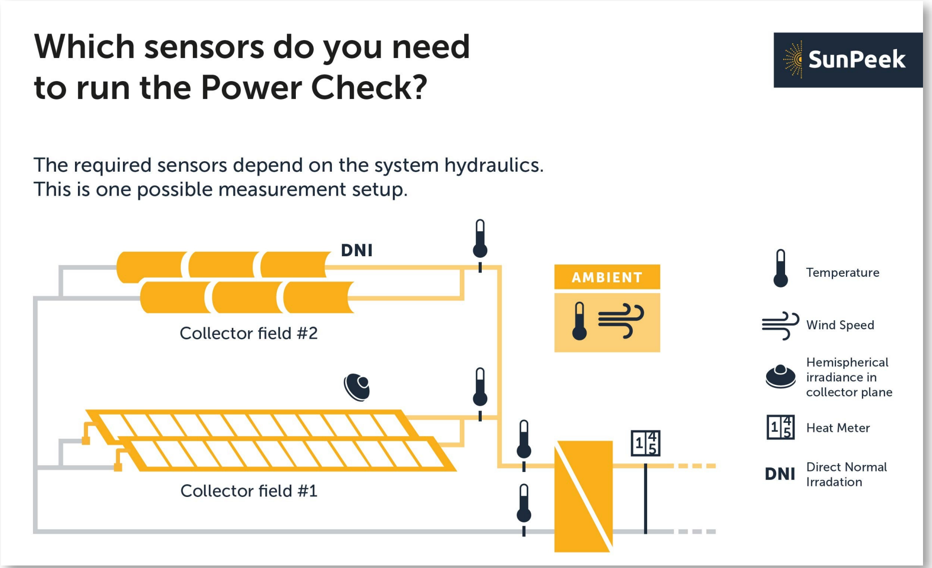
For simplicity, ISO 24194:2022 **[1]** and the related standard ISO 9806:2017 **[2]** are referred to as ISO 24194 and ISO 9806, respectively, throughout this document unless explicitly stated otherwise.

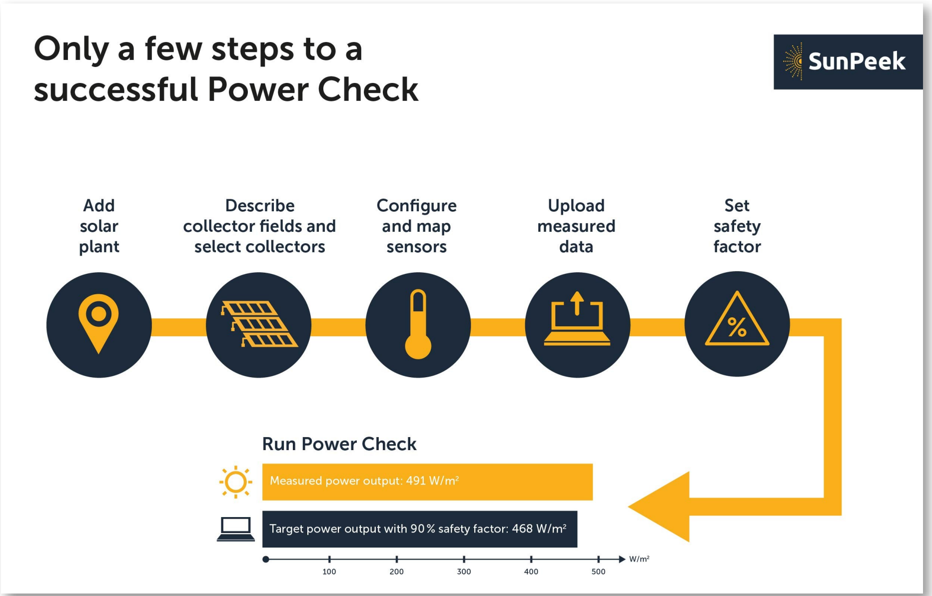
Graphical Abstract of Power Check

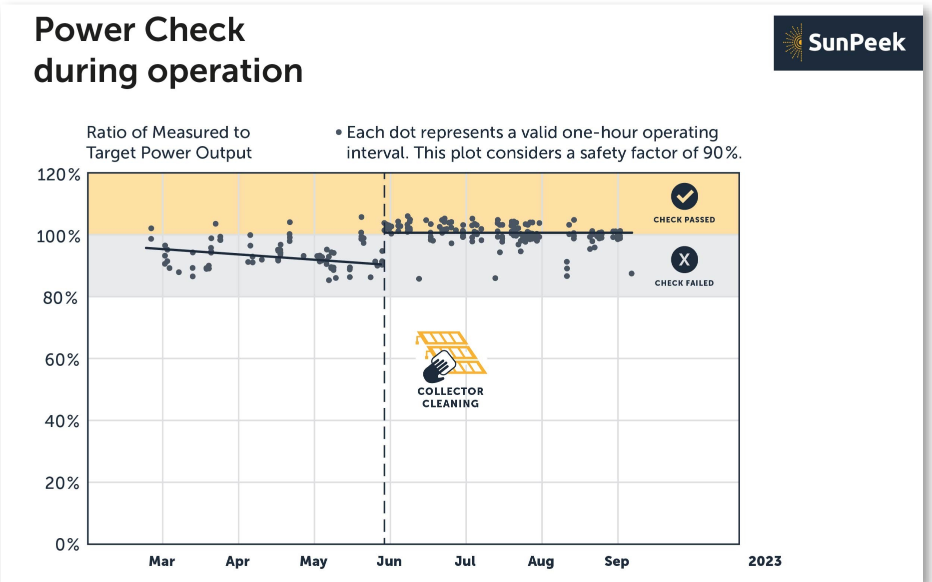
Power Check infographics






Which sensors do you need
to run the Power Check?
SunPeek
The required sensors depend on the system hydraulics.
This is one possible measurement setup.
DNI
Collector field #2
AMBIENT
Collector field #1
Temperature
Wind Speed
Hemispherical irradiance in collector plane
Heat Meter
DNI
Direct Normal Irradation


Only a few steps to a
successful Power Check
SunPeek
Add solar plant
Describe collector fields and select collectors
Configure and map sensors
Upload measured data
Set safety factor
Run Power Check
Measured power output: 491 W/m²
Target power output with 90 % safety factor: 468 W/m²
100
200
300
400
500
W/m²


Power Check
during operation
SunPeek
Ratio of Measured to Target Power Output
• Each dot represents a valid one-hour operating interval. This plot considers a safety factor of 90 %.
120 %
100 %
80 %
60 %
40 %
20 %
0 %
CHECK PASSED
CHECK FAILED
COLLECTOR CLEANING
Mar
Apr
May
Jun
Jul
Aug
Sep
2023

Main processing steps of Power Check

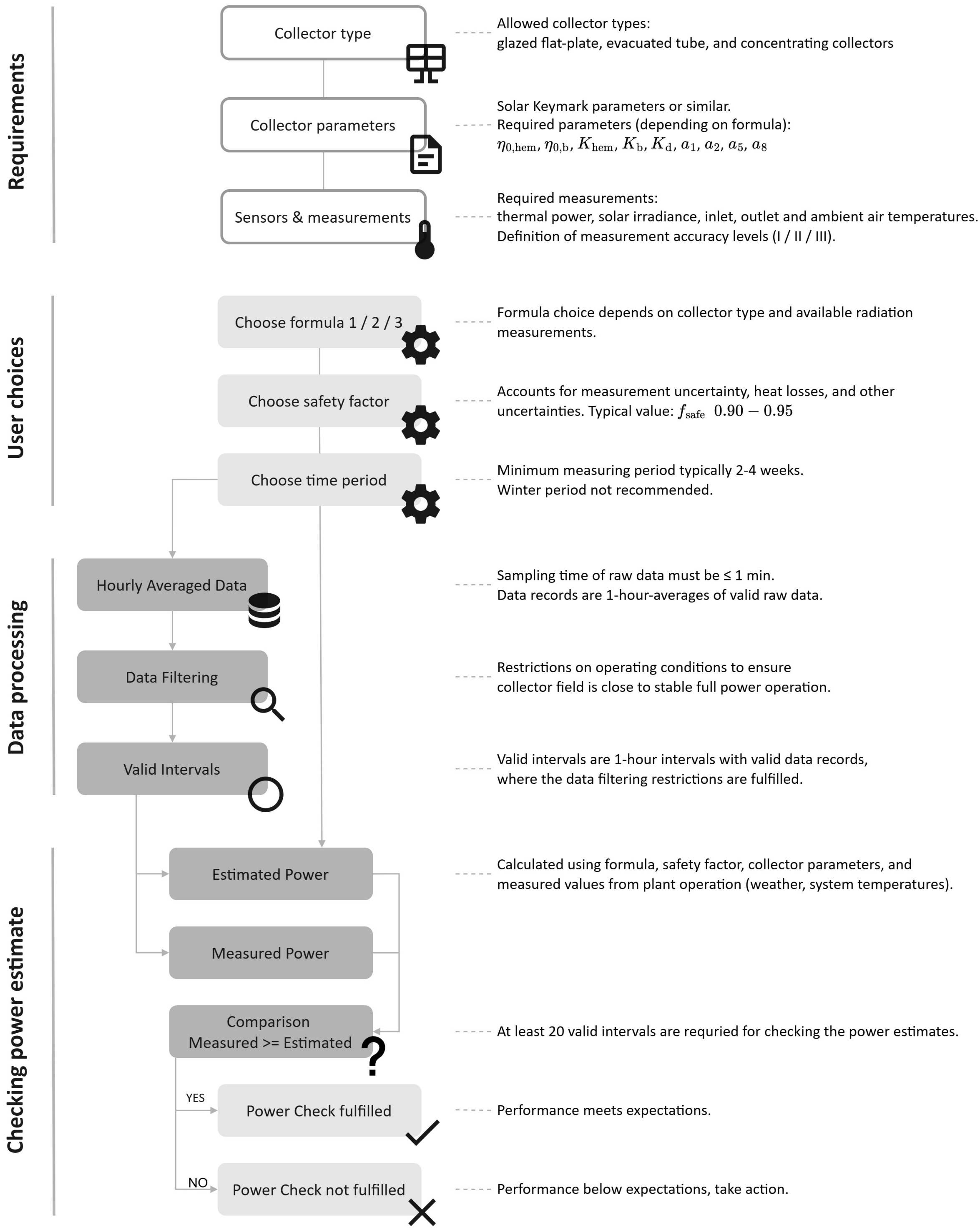


Figure 1. Step-by-step procedure of the ISO 24194 Power Check.

Table of Content

How to use this guide

Readers can consult the *"**Graphical Abstract of Power Check**"* for a quick impression of Power Check. Below is an overview of the document structure. Readers with the ISO standard at hand having questions about specific sections may want to refer to **Table 1** and navigate directly to the relevant sections of this document. The eager reader might want to directly jump to the "**Applications and usage**" chapter for graphical Power Check results from various practical applications.

Chapter **A** "**ISO 24194**" gives a comprehensive overview of the ISO 24194 Power Check. The "Summary" sections provide the content described in the standard, withholding value judgements. The "Remarks and recommendations" sections offer additional information and practical advice. They contain interpretations on how to apply Power Check, based on the authors' experience and recommendations, which may differ from the views of the ISO/TC 180/SC4 committee responsible for development of ISO 24194.

Chapter **B** *"**Enhancing the practical applicability of Power Check**"* addresses practical limitations and proposes important enhancements: an improved data averaging method, the "Extended" Power Check, in Section **B.1**; Strategies for evaluating various plant layouts and plants with multiple collector fields, in Section **B.2**; the important practical question of how to handle stagnation events in Power Check, in Section **B.3**.

Chapter **C** *"**SunPeek open-source software**"* details how to run Power Check with the SunPeek software tool, which offers a transparent, high-quality, and fully automated implementation of the ISO 24194 Power Check. SunPeek serves as the reference implementation of Power Check and is recommended by the authors of this guide. The development of SunPeek is backed by academic and industrial partners. SunPeek is available free of charge, including for commercial use.

Chapter **D** *"**Applications and usage**"* showcases real-world examples of Power Check applied to large solar thermal plants, using the SunPeek software. The chapter aims to make Power Check more accessible to the solar community, enhance methodological understanding, and demonstrate SunPeek's practical use. A detailed analysis focuses on a plant in Graz, Austria, and includes an open dataset with a full year of high-quality operational measurement data. Power Check results for each of the proposed methodological improvements of Chapter **B** are also included in this chapter.

Chapter **E** *"**Discussion**"* summarizes a list of key discussion points, suggestions, and ideas regarding Power Check, proposed by the authors. It also provides guidance for readers interested in contributing to the development of SunPeek or the ISO 24194 standard.

Chapter **F** *"**Towards a Harmonized Power Check framework**"* tries to streamline the presented insights on modeling and usage of Power Check results from the previous chapters into a new "Harmonized Power Check framework". This approach is a significant rework of Power Check, which could serve as input for future research activities, SunPeek developments, and revisions of ISO 24194.

Chapter **G** *"**Appendix**"* includes terms and definitions, and lists of symbols, figures, and tables used in this document.

Table 1. Overview of topics covered by this document and the SunPeek software, organized by chapters of ISO 24194.

ISO 24194 Chapters		*Covered in… this document*	*SunPeek*
1	Scope	**A.1**	
2	Normative Reference	**A.10**	
3	Terms and Conditions	**G.1**	
4	Symbols	**G.2**	
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	**A.2**	✓
5.2	Calculating power output	**A.3**	✓
5.2.1	General	**A.3**	✓
5.2.2	Non-concentrating collectors — Formula (1)	**A.3**	✓
5.2.3	Non- or low-focusing collectors — Formula (2)	**A.3**	✓
5.2.4	Focusing collectors with high concentration ratio — Formula (3)	**A.3**	–
5.3	Stating a performance estimate	**A.2**	✓
5.4	Restrictions on operating conditions	**A.5**	✓
5.5	Shadows	**A.6**	✓
5.5.1	Shadows on fixed collectors in rows	**A.6**	✓
5.5.2	Shadows on one-axis tracking collectors in row	–	–
5.6	Collector incidence angle	–	✓
5.7	Example of setting up an equation for calculating performance estimate	**D**	✓
5.8	Determination of potential valid periods	**A.5**, **A.6**	✓
5.9	Checking collector field power performance	**A.2**	✓
6	Procedure for checking the daily yield of solar thermal collector fields	**A.9**	–
7	Measurements needed	**A.7**	✓
7.1	General	**A.7**	✓
7.2	Requirements on measurements and sensors	**A.7**	–
7.3	Valid data records	**A.5**, **A.6**	✓
A	Annex A (informative): Recommended reporting format — Power method	**C.5**, **D.2**	✓
B	Annex B (informative): Recommended reporting format — Daily yield method	–	–

A ISO 24194 Power Check

A.1. Scope

Summary

ISO 24194, Chapter 1 contains two methods to assess the performance of solar thermal collector fields: "Power Check" (or Check of Performance – Power method) and "Daily Yield Check" (or Check of Performance – Daily yield method). Both methods allow for comparing of measured collector field output with an estimated output. Power Check applies to collector fields of glazed flat-plate collectors, evacuated tube collectors, and concentrating collectors with or without tracking. The check can be used for collector fields of all sizes. This guide covers only Power Check, which compares measured and estimated thermal power output for operating conditions close to stable full power operation.

Remarks and recommendations

Usage: For practical purposes, Power Check can be deployed for different usages, like plant power performance verification – including power performance guarantees – or ongoing performance monitoring as explained in Section **D.1**. Although ISO 24194 uses the expression "the estimated power is verified" (Section 5.9) if the measured output exceeds the estimate, it does not specify any guarantee procedure per se. The procedure itself and its usage should be clearly differentiated.

Collector types: The scope of Power Check covers the most common collector types deployed in large-scale solar thermal collector fields. Solar Keymark data sheets **[3]** indicate the collector type, distinguishing between flat-plate, evacuated tubular, concentrating and WISCs.

Solar air heating collectors: ISO 9806 and ScenoCalc **[4]** distinguish between liquid and air heat transfer fluids. ISO 24194 does not explicitly mention air collectors, but in principle, if the relevant ISO 9806 collector parameters and measurements are available, Power Check can be applied to solar air heating collectors (SHAC). However, testing and evaluating SAHC performance is complex, because it requires accounting for the enthalpy difference in the primary loop. Additionally, their thermal efficiency is highly dependent on mass flow rate, and their performance is tested at three different air mass flow rates, resulting in three separate parameter sets. For the ISO 24194 Power Check, this makes it challenging to select the appropriate parameters for estimating thermal power output, and it is discouraged to apply Power Check to these collectors, as results can be unreliable.

WISC and co-generating collectors: In contrast to ISO 9806, Power Check is *not* applicable to WISCs and co-generating / PVT collectors. For co-generating / PVT collectors, the thermal performance assessment depends on the electric part, making ISO 24194 inappropriate, as it exclusively focuses on the thermal part. A possible reason to exclude WISCs might have been that wind speed on the collector plane, accounting for convective losses as defined in ISO 9806 for laboratory tests, is difficult to determine in practical applications. Also, representative measurements of longwave irradiance are challenging for collector fields. Consequently, the models ISO 24194 defines for the power output (see Section **A.3**) do not include the wind speed and sky temperature-related coefficients a_3, a_4, a_6, a_7 of the ISO 9806 collector model.

Test certificates: ISO 24194 (Section 5.2.1) recommends that collector efficiency parameters be based on "Solar Keymark or similar". In general, collector parameters should be determined according to the latest version of ISO 9806.

A.2. Stating and checking a power estimate

Summary

ISO 24194, Section 5.1: The estimated power output of a solar collector field is given as an equation using the collector parameters according to ISO 9806, a safety factor, and measured operating conditions. The estimated power output can be given for fields with more than one similar collector type. Similar types are e.g. flat-plate collectors with single glazing and double glazing. If the requirements to calculate power output (see Section **A.3**) are available for each collector array of similar type, power output can be estimated for each field individually. An overall estimate for fields with two or more similar collector types can be given by choosing representative collector parameters.

ISO 24194, Section 5.3: The performance estimate shall include the used collector Formula, the collector parameters, the safety factor, and the accuracy level (see Section **A.8**).

ISO 24194, Section 5.9: The standard compares the average *measured* power output to the average *estimated* power output for all valid data records (valid 1-hour intervals), taking a safety factor into account (see Section **A.4**). To be included in this comparison, data records shall fulfill the restrictions on the operating conditions (see Section **A.5**). At least 20 consecutive valid data records are required. The estimate is verified if the following criterion, called "Performance Verification Criterion" (PVC) in this document, holds:

$$\text{Average}\ \left(\dot{Q}_{\text{measured}}\right) \geq\ \text{Average}\ \left(\dot{Q}_{\text{estimated}}\right) \qquad (1)$$

Remarks and recommendations

Usage of Power Check results: Although ISO 24194 does not explicitly define a procedure for performance guarantees, stakeholders often agree to take the Performance Verification Criterion (PVC) (Eq. **(1)**) when setting power performance guarantees, such as in contractual agreements. The choice of the safety factor has a decisive influence on the Performance Verification Criterion (see Sections **A.3** and **A.4**), which makes the safety factor, although designed as a technical parameter, subject to contractual negotiations, including risk assessment. To avoid this, the authors recommend to clearly distinguish between the procedure itself and its usage (see Section **D.1**) and formalize this criterion in revisions of the standard by introducing an acceptance threshold (see Section **F.9**). For guarantee applications, having at least 20 valid data records (valid 1-hour intervals) can be a good practical choice, while for ongoing performance monitoring, around five valid data records can already be meaningful in practice.

Uniform collector fields: The basic use case for applying Power Check is a collector field with one collector model and uniform orientation, called a "uniform collector field" in this document. ISO 24194 lacks detail on how to treat heterogeneous solar collector fields. The authors do *not* recommend choosing representative collector parameters but rather recommend using a methodologically more robust approach. For a conceptual treatment of this problem, see Section **B.2**, for an example, Section **D.4**.

Valid data records: According to ISO 24194, valid data records are hourly mean values. The term "valid data point" is presumably used synonymously with "valid data record" in ISO 24194. The authors recommended to deprecate this term and use "valid data record" or "valid intervals" instead. Power Check Formulas in the standard are not valid for highly dynamic plant behavior and thus require some data averaging. Intermediate quantities, e.g., thermal power calculated from volume flow, temperatures, and fluid properties (see Section **A.7**) should be calculated at the original sampling rate.

Measurement period: To obtain 20 valid data records, as required by ISO 24194, typically a measurement period of 2-4 weeks is necessary. In spring and autumn, this period might be considerably longer, and in winter it can occur that no valid data records are found at all, due to shading effects and low irradiation (see Section **A.6**).

A.3. Calculating power output

Summary

ISO 24194, Section 5.2 specifies three Formulas to calculate the collector field's estimated thermal power output. When an estimate is given, it shall always state which equation is used. If both Formula 1 and 2 can be applied for a given setup and high-quality direct irradiance data is available, the standard recommends using Formula 2, as it uses a more accurate collector output model with lower uncertainty. ISO 24194 does not apply to WISCs or co-generating / PVT collectors (see Section **A.1**).

Formula 1

$$\dot{Q}_{\text{estimated}} = f_{\text{safe}} \cdot A_{\text{GF}} \cdot \left[\eta_{0,\text{hem}} K_{\text{hem}}(\theta_L, \theta_T) G_{\text{hem}} - a_1(\vartheta_m - \vartheta_a) - a_2(\vartheta_m - \vartheta_a)^2 - a_5(d\vartheta_m / dt) \right]$$

Formula 2

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

Formula 3

$$\dot{Q}_{\text{estimated}} = f_{\text{safe}} \cdot A_{\text{GF}} \cdot \left[\eta_{0,b} K_b(\theta_L, \theta_T) G_b - a_1(\vartheta_m - \vartheta_a) - a_5(d\vartheta_m / dt) - a_8(\vartheta_m - \vartheta_a)^4 \right]$$

ISO 24194 requires an appropriate choice of Formula depending on the specific collector type and mounting used, and each Formula requires specific measurements to be available (see **Table 2**):

- Formula 1 applies to non-concentrating collectors (e.g., glazed flat-plate or evacuated tube collectors), with fixed mounting or tracked.
- Formula 2 applies to non- or low-concentrating collectors (concentration ratio $C_R < 20$), with fixed mounting or tracked.
- Formula 3 applies to focusing (high concentrating) collectors (concentration ratio $C_R \geq 20$), tracked in one or two axes.

The following table contains an overview of the collector parameters that are required to apply each of the three ISO 24194 Formulas. All collector parameters must relate to gross collector area (see ISO 24194 Section 5.2.1). For an overview of the measurements and sensors required for each Formula, see **Table 2**.

Table 2. Required collector parameters (as defined in ISO 9806) for each of the power output Formulas.

Parameter	*Formula*	*1*	*2*	*3*
a_1	First order heat loss coefficient at $\vartheta_m - \vartheta_a = 0 \ K$	✓	✓	✓
a_2	Second order heat loss coefficient (temperature dependence of the heat loss coefficient)	✓	✓	–
a_5	Effective thermal capacity	✓	✓	✓
a_8	Fourth order heat loss coefficient (radiative losses dependence)	–	–	✓
$\eta_{0,\text{b}}$	Peak collector efficiency (η_b at $\vartheta_m - \vartheta_a = 0 \ K$ based on beam irradiance G_{b}	–	✓	✓
$\eta_{0,\text{hem}}$	Peak collector efficiency ($\eta_{0,\text{hem}}$ at $\vartheta_m - \vartheta_a = 0 \ K$) based on hemispherical irradiance G_{hem}	✓	–	–
K_{b}	Incidence angle modifier for direct solar irradiance [1]	–	✓	✓
K_{d}	Incidence angle modifier for diffuse solar radiation	–	✓	–

Parameter	*Formula*	*1*	*2*	*3*
K_{hem}	Incidence angle modifier for hemispherical solar radiation	✓	–	–

[1] Various models / formulas for the beam incidence angle modifier are possible; see ISO 9806.

Remarks and recommendations

Reduced ISO 9806 model: Formulas 1–3 do not consider the dependence of collector performance on wind speed and sky temperature. The coefficients a_3, a_4, a_6, a_7 in ISO 9806 are omitted from the original ISO 9806 model. While this may be justified as WISCs are out of scope for ISO 24194, it creates an inconsistency between ISO 9806 and ISO 24194; see Section **F.2** for further discussion.

Non-zero collector parameters and choice of Formula: Although the choice of power output formula considers the collector type, it does not consider individual collector parameter values. According to ISO 9806:2017 (Section 24.1.3, 26.2.2), certain collector parameters are mandatory and shall be identified; others can be set to zero before data analysis or must be set to zero, depending on the test conditions. Checking that all collector parameters obtained through ISO 9806 which are non-zero, are incorporated in the chosen formula, is recommended. For many concentrating collectors – even with a concentration ratio $C_R \geq 20$ – data sheets show $a_8 = 0$ and $a_2 \neq 0$. Contrary to ISO 24194, Formula 2 instead of Formula 3 should be used for these collectors.

Concentration ratio: The concentration ratio C_R is not typically indicated in collector data sheets stating the ISO 9806 performance parameters. It is calculated as the ratio of (nominal) aperture area to absorber area, in the case of linear-concentrating collectors, as the ratio of mirrors aperture width to absorber tube diameter. In principle, ISO 24194 Power Check is available for all concentrating technologies, including parabolic trough (PTC), linear Fresnel, and dish-type collectors. Typical concentration ratios for these technologies are well above 20 (see **[5]**).

Reference collector area: Some collector data sheets indicate the collector parameters referring to the collector's aperture area. If this is the case, the parameters a_1, a_2, a_5 and a_8 shall be converted according to ISO 9806 Annex G, Formula (G.1).

$$p_{\text{G}} = p_{\text{Ap}} \cdot \frac{A_{\text{Ap}}}{A_{\text{G}}} \tag{2}$$

In cases where the description of the collector area is unclear, the manufacturer-reported ("nominal" or "reference") value of the area shall be used instead, if all parameters clearly refer to this same "nominal" or "reference" area.

Collector test methods and parameter conversion: Collector data sheets typically state one of the two test methods defined in ISO 9806, either QDT (quasi-dynamic) or SST (steady-state) test. Depending on the applied test method (QDT / SST) and the chosen Formula (1–3), a collector parameter conversion might be necessary; for the conversion, see **Table 3**:

- SST parameters are converted to apply Formula 2.
- QDT parameters are converted to apply Formula 1, as there are no separate beam and diffuse irradiance measurements in Formula 1.

The conversion procedure described in ISO 9806:2017 Annex B was implicitly designed to convert from SST to QDT parameters. Generally speaking, the QDT model describes the collector's behavior better than the SST model, but SST procedures were more common historically. **Table 3** follows the conversion from SST to QDT parameters from ISO 9806:2017 Annex B but uses a modified procedure to convert from QDT to SST parameters. Both directions use a "blue sky" assumption with $85\,\%$ beam / direct irradiance and $15\,\%$ diffuse irradiance. Using Formula 1 with prior conversion from QDT to SST parameters is equivalent to using Formula 2 under a “blue sky” assumption ($G_b = 0.85\ G_{hem}$, $G_d = 0.15\ G_{hem}$).

Table 3. Parameter conversion between SST (steady-state) and QDT (quasi-dynamic) tests.

Collector test	*Source*
SST (steady-state test) Given parameter: $\eta_{0,hem}$, K_{hem} Derived parameter: K_b, K_d, $\eta_{0,b}$	
$K_b(\theta_L, \theta_T) = K_{hem}(\theta_L, \theta_T)$	ISO 9806 Annex B, Formula (B.1)
$K_d = \frac{1}{W} \sum_{\theta,\ \gamma=0^o}^{90^o} K_b(\theta, \gamma) \sin(\theta) \cos(\theta)$ $W = \sum_{\theta,\ \gamma=0^o;\ steps=\ 10^o}^{90^o} \sin(\theta) \cos(\theta)$	ISO 9806 Annex B, Formula (B.3), (B.4)
$\eta_{0,b} = \frac{\eta_{0,hem}}{0.85\ +\ 0.15\ K_d}$	ISO 9806 Annex B, Formula (B.5)
QDT (Quasi-dynamic test) Given parameter: $\eta_{0,b}$, K_b, K_d Derived parameter: $\eta_{0,hem}$, K_{hem}	
$\eta_{0,hem} = \eta_{0,b}(0.85\ +\ 0.15\ K_d)$	ISO 9806 Annex B, Formula (B.5)
$K_{hem}(\theta_L, \theta_T) = \frac{\eta_{0,b}}{\eta_{0,hem}}(0.85\ K_b\ (\theta_L, \theta_T)\ +\ 0.1$	Based on ISO 9806 Annex B, Formula (B.2) and (B.5), and IAM for beam / direct irradiance; see also Guide to Standard ISO 9806:2017 [6], p. 60.

A.4. Safety Factor

Summary

ISO 24194, Section 5.2: The formulas used to calculate the estimated power output (see Section **A.3**) multiply the physical model output with a factor which lumps in all uncertainties and unmodeled effects and influences: the combined safety factor f_{safe}. When a power output estimate is given, the numeric value of the safety factor shall be stated. The safety factor f_{safe} in Formulas 1–3 is chosen considering potential influences from pipe losses, measurement uncertainty and other uncertainties and is divided into three factors:

$$f_{safe} = f_P * f_U * f_O \qquad (3)$$

where f_P is a safety factor for heat losses from pipes, f_U is a safety factor considering measurement uncertainty and f_O is a safety factor considering other uncertainties.

For Formula 1, the standard allows to set $f_U = 0.95$ for accuracy level I and $f_U = 0.90$ for accuracy level II and III if no additional information is provided. For other values, an uncertainty calculation and documentation is required according to ISO/IEC Guide 98-3 [42] (see Section A.8 for details on accuracy levels). For Formula 2 and 3, the standard does not explicitly include a safety factor recommendation, but it can be assumed that the same recommendations for Formula 1 apply. The combined safety factor f_{safe} shall be specified with an accuracy of 2 digits.

Remarks and recommendations

Interpretation of safety factor: The combined safety factor f_{safe} indicates which proportion of the collector field power output remains under ideal conditions if piping losses, measurement uncertainties and (assumed) unmodeled effects and influences are considered. In ISO 24194, it is meant to be a technical parameter, much like the collector efficiency parameters. The safety factor directly influences the Performance Verification Criterion (PVC) (Eq. (2)), which is oftentimes used when defining power performance guarantees. For such usage, its value comes under the scrutiny of contractual negotiations, including risk assessment of the contractual parties (see Section A.2). To avoid ambiguities, the authors recommended to clearly distinguish between the procedure itself and its usage and state non-technical safety margins separately, for further discussions see Sections D.1 and F.9.

Safety factor and accuracy levels: While ISO 24194 defines the concept of accuracy levels (see Section A.8), a stringent method to deduce f_{safe} from the measurement equipment and hydraulic layout of a plant is not provided in the standard. Some factors influencing measurement uncertainty can change over time, due to e.g. sensor cleaning, re-calibration, and uncertainties depending on sensor age. This would potentially require re-adjusting f_{safe} in regular intervals. For further discussions on setting the value of f_{safe}, see Section D.1.

Measurement uncertainty example: For reference, a measurement uncertainty analysis using data from the high-precision measurement setup of the large-scale solar thermal plant “Fernheizwerk” in Graz, Austria [7], showed a combined standard uncertainty (using the sensors’ data sheet values) for the measured-estimated power ratio of $3.2\% \ (\pm 2\sigma)$ [8], using Formula 1 and 2. See Section D.2 for Power Check results of this plant.

A.5. Restrictions on operating conditions

Summary

ISO 24194, Section 5.4: To limit uncertainties, restrictions on operating conditions are given. Only records (1-hour intervals) taken when the solar collector field is close to stable full power operation are valid to check the power output. The standard uses the restrictions listed in Table 4.

Table 4. Restrictions on operating conditions to select valid data records / 1-hour intervals.

Operating condition	*Limits for Formula*			*Comments*
	1	*2*	*3*	
Shading		No shadows		See Section A.6
Change in collector mean temperature	$\leq 5\ \text{K/h}$	$\leq 5\ \text{K/h}$	$\leq 5\ \text{K/h}$	To avoid large changes in collector temperature during one hour.
Ambient temperature	$\geq 5\,°\text{C}$	$\geq 5\,°\text{C}$	$\geq 5\,°\text{C}$	To avoid snow, ice, condensation on solar radiation sensors.
Wind speed	$\leq 10\,\frac{\text{m}}{\text{s}}$	$\leq 10\,\frac{\text{m}}{\text{s}}$	$\leq 10\ \text{m/s}$	Measurement shall be representative for the wind speed 1 to 3 meters above the highest point of collectors.
Hemispherical irradiance (POA)	≥ 800	-	-	in W/m^2

Operating condition	Limits for Formula			Comments
	1	2	3	
Beam irradiance	-	≥ 600	≥ 600	in $\mathrm{W/m^2}$

Remarks and recommendations

Data filtering example: **Figure 2** presents example time-series plots for two 1-hour Power Check intervals, both of which comply with the ISO 24194 restrictions outlined in **Table 4**. Note the steady operating conditions in the interval in the left plot, and the more variable operating conditions in the other interval (right plot). According to ISO 24194, restrictions on operating conditions are evaluated using hourly mean values (see Section **A.7**). This implies that individual measurements can exceed or violate the thresholds, but the hourly mean values must comply.

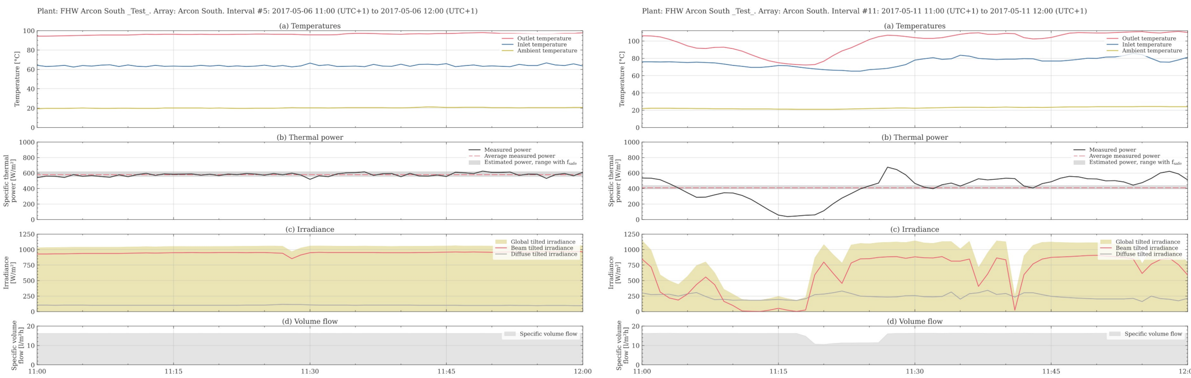


Figure 2. Example time-series plots for two 1-hour intervals. Both time-series are "valid data records", complying with the ISO 24194 restrictions in **Table 4**. Plot (a) shows steady operating conditions; plot (b) shows variable operating conditions. Plots from SunPeek PDF report, see **[28]**.

No shadows restriction: For the binary condition "No Shadows", the authors recommend excluding all hours when shading occurs at any single timestamp, as shading affects model validity. ISO 24194 only addresses internal (row-to-row) shading, but the authors advise assuming that conditions with external shading must also be excluded from Power Check analysis. See Section **A.6** for a more detailed discussion on shading.

Wind speed: Wind speed measurements are not commonly available in large-scale solar thermal plants; see Section **A.7** for a discussion on how to evaluate plants without wind speed measurement. Furthermore, one needs to be aware that ISO 9806 and ISO 24194 specify different criteria for maximum allowable wind speed: ISO 9806 sets the test condition limit at $4\ \mathrm{m/s}$ on the collector plane, while the ISO 24194 Power Check (see **Table 4**) allows wind speeds up to $10\ \mathrm{m/s}$ (presumably hourly averages, not measurements at single timestamps), at a height 1 to 3 meters above the highest collector point. Measurement of wind speed in the collector plane for a whole collector field is out of reach, compared to single collector tests in the laboratory. For Power Check, the risk of using high wind data (more than $4\ \mathrm{m/s}$) lies in potentially applying the ISO 9806 model outside its valid range. The challenge of using different reference points (collector plane vs. 1 to 3 meters above collector top) is that converting wind speed data between these references is not straight-forward and can, for example, be influenced by the collector field geometry, despite the existence of some models, usually requiring a surface roughness parameter. One option would be to further investigate methods to estimate collector plane wind speed from measurements above the collector, e.g., 1 to 3 meters above–or 10 meters above, a standard height in weather data.

Collector mean temperature change: The limitation on the collector field's mean temperature change implies that the mean temperature evaluated over one hour does not change substantially. Large temperature fluctuations, such as cold or hot plugs in the inlet or sharp temperature shifts due to irradiance changes, are not uncommon in solar plant operation. Although the ISO 9806 model in principle accounts for temperature changes (a_5 parameter), such temperature fluctuations can still affect the model validity, because the model does not account for delay effects caused by the fluid's transit time through the collector field. Generally, model validity decreases when the instantaneous collector inlet and outlet temperatures are not representative of the internal temperature state of the collector field. The overall goal of the temperature change criterion is to only accept data where the model is representative of the collector field behavior and model error is low. The intention behind the temperature change criterion can be interpreted in different ways, also illustrated in **Figure 3**:

1) Avoid significant heat up / cool down phases over an interval:

$$\left|\overline{d\vartheta_m / dt}\right| \leq 5\ \mathrm{K} \tag{4}$$

2) Avoid significant temperature peaks / dips within the interval:

$$max\left(\vartheta_m(t)\right) - min\left(\vartheta_m(t)\right) \leq 5\ \mathrm{K} \tag{5}$$

3) Avoid significant deviations compared to the mean temperature of the interval:

$$\max\left|\vartheta_m(t) - \overline{\vartheta_m}\right| \leq 5\ \mathrm{K} \tag{6}$$

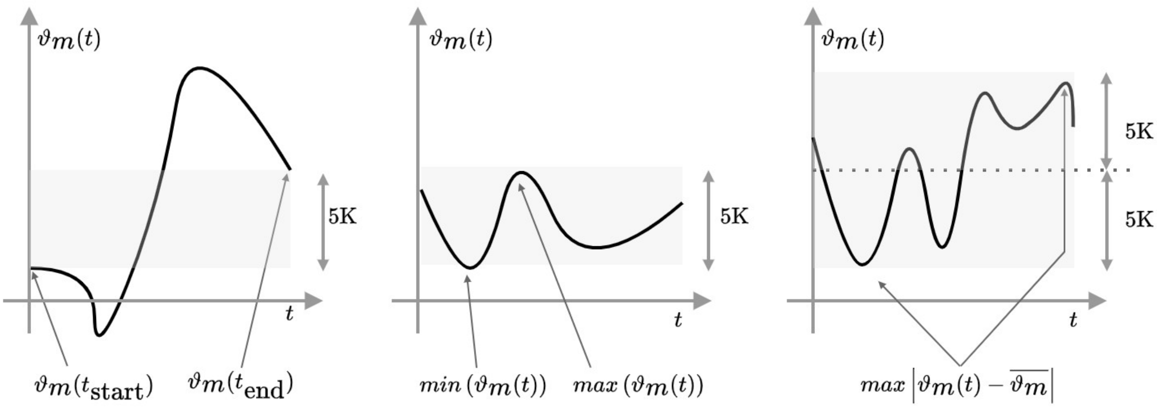


Figure 3. Data filtering criteria for mean collector temperature. Criterion (1) aims to avoid significant heat up or cool down phases, considering only the temperature at the start and end of the interval, but allowing arbitrarily large fluctuations within the interval. Criterion (2) aims to avoid significant temperature peaks or dips, considering all values within the interval. Criterion (3) targets significant temperature deviations compared to the mean temperature in the interval.

Using the same 5 K/h threshold, the second criterion is stricter than the first and third, and the third can be stricter or less strict than the first, depending on the circumstances. For practical applications, there can be a trade-off between reducing modeling errors (with a stricter criterion) and obtaining more valid data records (with a looser criterion). Currently, there seems to be insufficient practical, data-based evidence from ISO 24194 Power Check applications to provide a conclusive answer. It is therefore recommended to choose one of these criteria and document the choice made.

The current SunPeek implementation uses the first criterion. With a first-order backward difference approach to build the derivative, and assuming regularly sampled measurement data without gaps, this translates to:

$$\left|\vartheta_m\left(t_{\mathrm{end}}\right) - \vartheta_m\left(t_{\mathrm{start}}\right)\right| \leq 5\ \mathrm{K} \tag{7}$$

That is: the absolute temperature difference between the start and end of the interval must be less than 5 K. This formulation makes the criterion very sensitive to just two specific temperature measurements and their uncertainties. Therefore, the authors recommend using a numerically robust approach to obtain the derivative if the first criterion is used; see Section **C.8** for details.

"Stable full power operation": ISO 24194 mentions in Section 5.4 that **Table 4** aims to only include data records (intervals) where the collector field is "close to stable full power operation" in a Power Check. However, the standard lacks an explicit definition of "full power" and does not even require verifying that the collector field is operational (and not in stagnation or with the pump not running for some reason). Where normal operational behavior is considered, the authors recommend adding a criterion for *minimum average specific power output*:

$$\frac{\dot{Q}_{\text{measured}}}{A_{\text{GF}}} \geq \dot{Q}_{\text{sp,min}} \tag{8}$$

This criterion is to be used on averaged 1-hour data records. This can lead to including data records where the plant is in operation for only a part of the interval, e.g., in the heating up phase at the beginning of the day, but does not exclude intervals with a temporary dip in power output due to reduced irradiance, see **Figure 18** for an illustration. Further investigations are recommended to potentially find better suited criteria. A typical choice to ensure normal operational behavior is $\dot{Q}_{sp,min} = 100 \quad W/m^2$.

Stagnation: The standard does not explicitly mention stagnation and the operating condition restrictions do not contain corresponding filtering criteria. In general, it must be assumed that stagnation periods can be present in operational data. As a result, stagnation events can be included in valid data records, leading to a deterioration of Power Check results and to the occurrence of outliers (low or no measured power output, but high / some estimated power output). Therefore, a criterion to Power Check should be added in order to detect and filter stagnation from data records, see Section **B.2** for an in-depth discussion. To detect stagnation or operational interruptions within 1-hour intervals, filtering individual measurements on the original time scale is necessary.

Additional restrictions: Although the required irradiance levels may filter out most conditions with large angles of incidence (AOI), the authors nevertheless recommend explicitly adding a restriction on allowed incidence angles, e.g. AOI $\theta < 80°$ **[10]**. For concentrating collectors (tracking collectors), only operation periods in which all collectors are fully tracked shall be evaluated. The results would otherwise be affected when collectors go out of tracking to avoid overheating of the heat transfer fluid in individual collector loops.

A.6. Shading

Summary

ISO 24194, Section 5.5 contains formulas to calculate internal (row-to-row) beam shading for two cases:

- Fixed-mounted collectors (no tracking), assuming horizontal ground and no vertical offset between collector rows (ISO 24194, Section 5.5.1).
- One-axis tracking collectors, again assuming horizontal ground and no vertical offset (ISO 24194, Section 5.5.2).

Internal shading calculated in this way may be used as a restriction on operating conditions, see Section **A.5** in this document. ISO 24194 does not contain any statements on how to treat external shading, such as shadows from nearby buildings or trees, or shadows from mountains that block direct sunlight during some periods of the day.

Remarks and recommendations

Internal shading: The formulas in ISO 24194 to calculate internal beam shading assume geometrically uniformly arranged, rectangular collector fields with no ground tilt, and no vertical offset between the collector rows. The case of shading for flat ground is displayed in **Figure 4**. An extension of the row-to-row shading calculation to collector fields mounted on a tilted ground is implemented in SunPeek. For fields with different row spacings and geometry, using the most restrictive settings (narrowest row spacing, highest tilt angle) is recommended to ensure that no part of the collector field is shaded.

External shading: External beam shading is not covered by ISO 24194, although conditions with external beam shading should be excluded (see Section **A.5**). A pragmatic approach to treat external shading is to define a minimum sun elevation angle θ_{min} and exclude conditions where the sun elevation (sun altitude angle) is below that lower threshold, $\theta_{\mathrm{sun}} < \theta_{\mathrm{min}}$, see **Figure 4**. Alternatively, for improved accuracy, an external program (e.g., horizon shading features in OpenSolar **[11]** or Solargis **[12]**) could be used to derive a shading mask. One option for including horizon profiles is to use PVGIS **[13]**, which offers both an interactive and a web API interface, given latitude and longitude of the plant.

Diffuse masking: For collectors within a collector field, view obstruction of the front collector row reduces the incident diffuse radiation from the sky, an effect called diffuse masking, which alters reflection patterns. These phenomena are not addressed in ISO 24194. Diffuse masking is more pronounced for narrow row spacing and steep tilt angles and can substantially reduce the diffuse irradiance in the plane of array. For reference, measurements showed a reduction to $89\,\%$ on average, relative to the top of the collector (=$100\,\%$) **[14]**, for a collector field with $3.5\ \mathrm{m}$ row spacing, $45\,°$ tilt angle and 1.67 relative row spacing. Not taking diffuse masking into account in a Power Check overestimates the collector field's G_d and G_{hem}, resulting in a higher estimated power output, and shifting the measured-estimated power ratio unfavorably compared to the true performance. To account for diffuse masking for narrow row spacings and steep collector tilts, a radiation correction model should be used (e.g., **[14]** or the Passias model available in pvlib **[15]**), or a slightly higher safety factor.

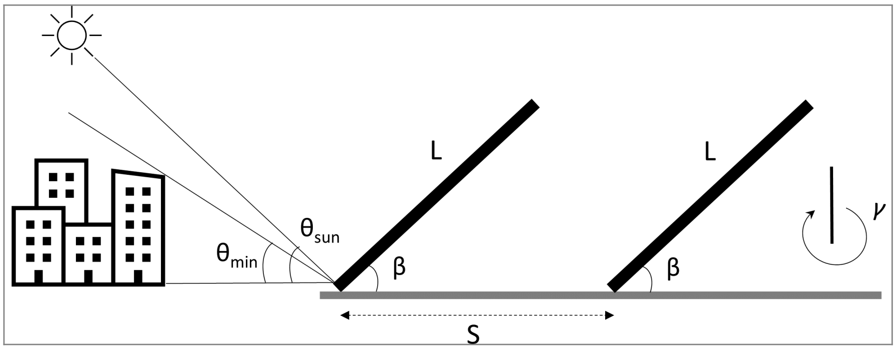
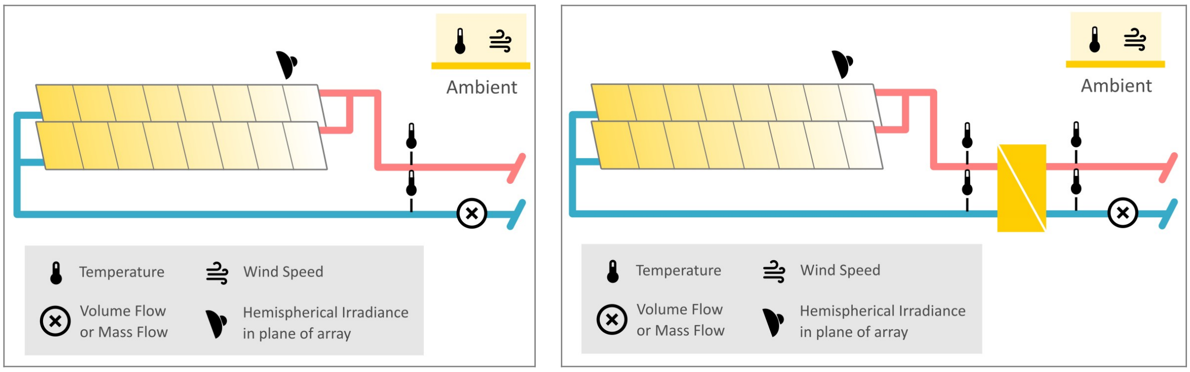


Figure 4. Collector field geometry with basic parameters and angle for external shading. In this figure the collector length (L) runs from bottom to top as stated in ISO 9488:2022 [16], in contrast to Figure 1 in ISO 24194 where the collector width runs from bottom to top.

A.7. Required measurements

Summary

ISO 24194, Section 7: The standard requires certain measurement data channels and sensors for Formula 1–3 respectively and distinguishes two system configurations, as depicted in **Figure 5**.



(a) *(b)*

Figure 5. System configurations (a) without heat exchanger and (b) with heat exchanger for systems with one collector field. Adapted from ISO 24194, Figure 5 and 6, which does not include the wind speed sensor

ISO 24194, Section 7.3: The standard defines that only data records (hourly-mean values of measurement data) that fulfill the requirements in Section 5.4 are valid to conduct Power Check.

Remarks and recommendations

Overview: In Power Check, measurements with sensors serve three purposes: first, to determine the measured power output; second, to calculate the estimated power output using Formulas 1–3, as detailed in Section **A.3**; and third, to filter measurement values based on restrictions on operating conditions, as described in Section **A.5**. **Table 5** holds an overview of all required measurement data channels, which depend on the chosen Formula (see Section **A.3** for details on Power Check Formulas).

Valid data records: Power Check uses hourly-mean values to check power estimates (see Section **A.2**). The term “valid data record” is presumably used synonymously with “valid data point” and “valid interval”. The authors of this guide recommend using either “valid data record” or “valid interval”.

The standard requires intervals to *start and end at full hours* (e.g., 11:00, 12:00, 13:00, etc.) (ISO 24194:2022, Section 7.2.2). The authors recommended that measurement data are averaged using an arithmetic mean to create data records:

$$\overline{X} = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{9}$$

Weighted averaging with the time distance to the next measurement is not recommended, as the interpretation of data gaps or irregular sampling rates is typically not straightforward.

Power measurement, fluid properties: Thermal power output is one of the principal measurements for Power Check and is the quantity used for comparison with the estimated power output, as detailed in Section **A.2**. If power output is not directly available as an input quantity, it can be calculated from primary- or secondary-side volume flow or mass flow, if the fluid properties density and heat capacity (temperature- and potentially concentration-dependent) are known:

$$\dot{Q} = \dot{V} \cdot \rho(\varepsilon, \vartheta) \cdot c_f(\varepsilon, \vartheta) \cdot (\vartheta_e - \vartheta_i) \tag{10}$$

In system configurations with a heat exchanger (see **Figure 5**), thermal power can be measured on the primary or on the secondary side. Unless there is substantial additional heat capacity in the primary circuit (e.g., tank or hydraulic shunt), it is advised to measure power output in the *secondary side*; this is also recommended by ISO 24194, Section 5.7. In the secondary side, power output is typically measured by calibrated and gauged heat meters, sometimes also used for billing purposes. Heat exchanger thermal losses can be neglected, assuming an adiabatic heat exchanger; capacitive effects from heat exchanger heat-up or cool-down are typically insignificant as well, since Power Check restricts such operating conditions, as detailed in Section **A.5**.

However, in some circumstances and generally for system configurations without a heat exchanger, it is necessary to measure thermal power in the primary loop. This is straightforward if water is used as a primary-loop heat transfer fluid (due to well-known physical properties), but more involved for other fluids with some concentration of anti-freeze liquid. In practice, the temperature- and concentration-dependent physical fluid properties (density and heat capacity) are seldom precisely known; moreover, anti-freeze concentration might change over time, for example if liquid is refilled. Consequently, true fluid properties might differ significantly from datasheet values (see [7] for an example), potentially introducing very large uncertainties in Power Check results. To obtain reliable results, fluid properties (except for water) should be determined by measurement, at least once at the start of recording measurements, even though this can be costly. It is important that the fluid properties are evaluated at the correct temperatures. Refilling with anti-freeze liquid should be documented.

Radiation measurement: The respective Power Check Formulas require different irradiance measurements, see **Table 2**. If only G_{hem} (POA hemispherical irradiance) is available, Formula 1 is used. Using Formula 1 with prior conversion from QDT to SST parameters (see **Table 3**) is equivalent to using Formula 2 under a "blue sky" assumption with constant shares of 85% beam / direct irradiance and 15% diffuse irradiance.

For systems with multiple flat-plate or evacuated tube collector fields or if only G_h is available, the collector orientation (tilt, azimuth) might differ from the radiation sensor orientation. Following an analogous case in ISO 9806 Section 19.2.2, angular deviations are acceptable if they don't affect incidence angle modifier values by more than 2%. For cases outside this limit, radiation models should be used, see Section **F.7** for further discussions. Also, if the "blue sky" assumption leads to substantial bias, radiation models could be used to calculate G_b and G_d and apply Power Check Formula 2. When giving a Power Check output, it should be stated whether radiation models have been used to compute irradiance data, include details about the modeling and evaluate the model uncertainty.

ISO 24194 also permits the use of satellite data instead of on-site measurements (see Section **A.8**). However, due to a lack of international quality standards for the satellite data and questionable fit to local conditions, the adequacy should be proven on a case-by-case basis.

Wind speed: From a practical point of view, many solar thermal plants – particularly in low-wind locations – do not have wind sensors installed. To simplify Power Check application, the authors recommended making wind speed an optional measurement, required only if the result is expected to be wind dependent. That is: If both wind-related collector parameters (a_3, a_6) are zero, Power Check is also applicable without wind speed data, and the wind criterion may be neglected in Power Check data filtering. Neglecting wind from Power Check should be documented in the results.

As an example, for the "Fernheizwerk" plant evaluated in Section **D.2**, where wind speed is measured directly at the plant, wind speed has a negligible effect on Power Check results (see **Figure 56** and **Table 20**). The plant is located in Graz, Austria, a low-wind location with an average yearly wind speed of around $1.4\ \mathrm{m/s}$, calculated based on the TMY (Typical Meteorological Year).

Alternatively, wind data from nearby weather stations could be utilized. However, since wind speeds tend to have significant local variation, on-site measurements are preferable. The representativeness of remote wind measurements for collector plane wind speeds is questionable. At best, remote data could serve to filter out very high wind conditions [7].

Table 5. Required measurements for Power Check Formulas.

Symbol	*Formula*	*1*	*2*	*3*
G_{hem}	Hemispherical solar irradiance on the plane of collector	✓	–	–

G_b	Direct solar irradiance (beam irradiance) on the plane of collector	–	✓ [1]	✓ [2]
G_d	Diffuse solar irradiance on the plane of collector	–	✓ [1]	–
ϑ_i	Collector field inlet temperature	✓	✓	✓
ϑ_e	Collector field outlet temperature	✓	✓	✓
ϑ_a	Ambient air temperature	✓	✓	✓
u	Surrounding air speed (wind speed)	✓ [3]	✓ [3]	✓ [3]
$\dot{Q}_{measured}$	Power output [4]	✓	✓	✓

[1] Measured in collector plane for low-concentrating collectors.
[2] Measured in tracking plane for concentrating collectors. For some concentrating collectors, contrary to ISO 24194, Formula 2 should be used, see Section **A.3**.
[3] Wind speed is frequently not available in solar thermal plants and should be made mandatory only if the results are expected to be wind dependent (see paragraph on "Wind speed" in this section).
[4] Alternatively, power output can be calculated if volume flow or mass flow are measured, and fluid properties are available with low uncertainty.

A.8. Measurement accuracy levels

Summary

ISO 24194 Introduction: The standard defines the concept of accuracy levels, to distinguish between more or less accurate performance comparisons. Accuracy levels are meant to reflect the reliability and accuracy of measurement equipment and acquired measurement data. Accuracy levels relate to both methods, Power Check and Daily Yield Check. The standard distinguishes three accuracy levels (I / II / III) and suggests that they should be considered when a safety factor is chosen (see Section **A.4**). The standard indicates that the accuracy level shall be stated when giving a performance estimate. However, since the standard includes only indicative safety factor values and does not include any stringent methodology to compute a safety factor based on a chosen accuracy level, the usage of accuracy levels is purely informative.

ISO 24194 Section 7.2.1: The standard requires that all instrumentation and sensors have valid calibration. Concerning the main measurements involved in a Power Check (solar radiation and power output), the standard defines limits on overall measurement uncertainty, as listed in **Table 6**.

Table 6. Measurement uncertainty tolerances for solar radiation and power output, for accuracy levels I–III.

	Accuracy level			
Measurement	*I*	*II*	*III*	*ISO 24194 Section*
Solar radiation	$\pm 3\,\%$	$\pm 5\,\%$	$\pm 5\,\%$	7.2.1
Power output	$\pm 2\,\%$	$\pm 3\,\%$	$\pm 5\,\%$	7.2.1

ISO 24194 Section 7.2.2: The standard specifies and recommends guidelines for time-related data. For *data acquisition*, raw data logging shall have a sampling rate (logging time) of 1 minute or less, and measurements without timestamps are not acceptable. Timestamps should include time zone information and avoid daylight saving time (DST). Timestamps of the 1-hour data records used in Power Check shall represent the average values over the previous hour; for instance, a data record timestamped 12:00 represents measurements from 11:00 to 12:00 on that day. Raw data must not be used twice when computing these data records. The standard sets a "time measurement tolerance" of $0.1\,\%$ but lacks a reference value for the percentage, making this criterion impractical.

ISO 24194 Section 7.2.3–7.2.7: The standard specifies in detail the accuracies for solar radiation, temperature, flow rate, power, and wind speed. Each accuracy level (I–III) includes requirements for sensor calibration, location, and installation (**Table 7**), as well as sensor specifications, measurement uncertainties and solar sensor cleaning (**Table 8**).

The standard includes ISO 9060 as a normative reference (see Section **A.10**), using mixed terminology between the withdrawn ISO 9060:1990 **[17]** and ISO 9060:2018 **[18]**. For solar radiation accuracy level I, the standard requires following the recommendations of ISO/TR 9901, while not explicitly stating a version. This document assumes the current version ISO/TR 9901:2021 **[19]**, adapted to ISO 9060:2018 **[18]**.

There is an inconsistency in the uncertainty limits for power output at accuracy level III between ISO 24194 Sections 7.2.1 and 7.2.6; see **Table 6** and **Table 8** in this document for comparison. Another inconsistency concerns the use of radiation data derived from satellites: According to Section 7.2.3.2, satellite data can be used for level II/III, but 7.2.3.3 and 7.2.3.4 only mention satellite data in connection with level III. The latter seems to align more with the standard's intention, as all other criteria regarding solar sensors are the same for accuracy levels II and III.

ISO 24194 Section 7.3: The standard states that data with obvious errors or very atypical operating conditions shall be excluded, and such omitted data shall be reported and justified. See Section **C.7** for details on how this is interpreted and implemented in the SunPeek software.

Table 7. Requirements for sensor calibration, location and installation.

Item	*Description*	*ISO 24194 Section*
Calibration	Valid calibration for instrumentation and sensors	7.2.2
Solar radiation: Sensor location	Level I: $\leq 500\ \mathrm{m}$ from any collector Level II: $\leq 1000\ \mathrm{m}$ from any collector Level III: $\leq 1000\ \mathrm{m}$ from any collector or use of satellite data	7.2.3.3
Solar radiation: Sensor placement	Placement shall avoid reflections. Fixed flat-plate collector fields: on top of collectors. Tracking collector fields: close to the tracking axis, close to southern end of row (northern hemisphere) or northern end of row (southern hemisphere)	7.2.3.1
Solar radiation: Representativity of measurements	Sensors shall receive the same levels of direct, diffuse and reflected solar radiation as the complete collector field. (i) For very large collector fields, several sensors might be necessary. (ii) For flat-plate collector fields, sensors shall be placed in the middle of the installation. (iii) In general, it is strongly recommended to have at least two solar sensors.	7.2.3.4
Solar radiation: Pyranometer coplanarity	Coplanar to collector plane within a tolerance of $< 2^{\circ}$	7.2.3.1
Solar radiation: Sensor cleaning	Level I: Twice a week in the measurement period if clean air, every day if smoke and particles in the air. Level II and III: Weekly in measurement period (for level III: not applicable for satellite data).	7.2.3.4
Installation fluid temperature sensor	Best practice rules apply, such as measuring in the center of the pipe or thermally insulating the pipe at the measurement position.	7.2.4.2
Installation of ambient air temperature sensor	Normal best practice rules apply, such as putting the sensor into a white, ventilated shelter to shade it from solar	7.2.4.3

Item	*Description*	*ISO 24194 Section*
	radiation, and measuring at least $1\ \mathrm{m}$ above the ground. Level I–III: positioned $\leq 100\ \mathrm{m}$ from collector field	
Location volume flow sensor, fluid properties	If used, flow rate shall be measured on the inlet (cold) side; fluid density at the inlet side must be used for flow or power calculation.	7.2.6
Location wind speed sensor	Level I–III: positioned $1\ \mathrm{m}$ to $3\ \mathrm{m}$ above the highest point of the collector field, $\leq 100\ \mathrm{m}$ from collector field	7.2.7

Table 8. Sensor specifications and measurement uncertainties for accuracy level I–III.

Measured quantity	*Level I*	*Level II*	*Level III*	*ISO 24194*
Global / hemispherical irradiance	Pyranometer Class C / Second Class or better. Satellite data not allowed. Recommendations following ISO/TR 9901[1]	Sensors with accuracy $\pm 5\%$ in the range $600 - 1000\ \mathrm{W/m^2}$. Satellite data not allowed [3]		7.2.3.2
Beam and diffuse irradiance	Pyranometer for G_{hem} plus either pyranometer Class B / First Class or better with shading ring for G_{d} or pyrheliometer for G_{b}	Not defined		7.2.3.2
DNI	Pyrheliometer Class C / Second Class or better [2] for highly concentrating, tracking collectors with field of vision $\leq 6°$; tracking errors $\leq \pm 1°$.			7.2.3.1
Fluid temperature	$< 0.35\ \mathrm{K}$ (Class A)			7.2.4.2
Ambient air temperature	$< 0.35\ \mathrm{K}$ (Class A)			7.2.4.3
Volume flow rate (mass flow rate)	standard uncertainty in relevant range $< 1\%$	$< 2\%$	$< 2\%$	7.2.5
Power (measured or calculated)	standard uncertainty in relevant range $< 2\%$	$< 3\%$	$< 3\%$	7.2.6
Wind speed	$< 1\ \mathrm{m/s}$			7.2.7

[1] ISO/TR 9901:2021 [19]
[2] ISO 9060:2018 [18]
[3] See the note in the text above on the inconsistency of ISO 24194 Section 7.2.3 concerning the use of satellite data.

Remarks and recommendations

Accuracy level and safety factor: The accuracy level guidelines provide practical recommendations for measuring solar collector fields. However, for Power Check, accuracy levels are purely informative, and the standard does not specify how accuracy levels translate to safety factors. Only the chosen safety factors are relevant for numerical Power Check results. If no detailed documentation for the uncertainty calculation is done, the standard recommends (without further explanation) a safety factor of $f_U = 0.95$ for accuracy level I and $f_U = 0.90$ for accuracy level II and III (see Section **A.4**). In practice, most solar plants only partly meet the requirements of levels I–III, for instance, because solar sensors are cleaned only at irregular intervals. For long-term surveillance, meeting the accuracy level guidelines is unlikely for most installations, making their practical relevance questionable, in the authors' view.

Additional documentation and inspection: To improve traceability of Power Check results, the authors recommend including documentation of the measurement setup, including the deployed sensors and their individual accuracy level as stated in **Table 8**. Additionally, the authors recommend the following:

- Maintaining a logbook of significant plant events that might affect sensor uncertainties or measurement data, such as any maintenance work, power supply interruption, or sensor calibrations.
- Following the recommendations on reliable data acquisition, validation, and storage of **[20]**.
- Regular on-site inspection of plant and measurement equipment.
- Installation of a webcam on the collector field to double-check important events and shading. For the installation of a webcam, data protection laws may apply.
- Automated plausibility checks during data analysis (see Section **C.7** for the SunPeek implementation).

Unfortunately, the standard does not cover the entire measurement chain and does not model the resulting standard uncertainties or maximum errors. It lacks guidelines for fluid properties (density, heat capacity) possibly used to compute power output and for radiation modeling possibly involved in computing estimated power output (see paragraph below, and Section **A.7**).

Fluid properties: Fluid properties are known to significantly impact measurement results. Generally, measuring thermal power in a circuit using water as a heat transfer medium is preferable. Datasheet information for non-water fluid mixtures has been found to be not always reliable (see **[7]** for an example) and should be used with caution. To obtain reliable results, fluid properties (except for water) should be determined by measurement. Refilling with anti-freeze liquid should be documented.

Weighted averaging: Is is recommended to use weighted averaing to obtain data records from raw data measurements (see Section **A.7**). ISO 24194 does not explicitly specify this.

Data quality and data processing: The standard specifies the omission of measurement data with gross errors (obvious errors or very atypical operating conditions), but does not contain instructions on practical data quality checks (e.g., min-max bounds, hanging sensor checks), how to treat data gaps (e.g., allow some missing or invalid values within a 1-hour interval), or ensuring the correctness of the time zone. For practical applications, such checks are essential and often consume a large share of the time involved in producing a Power Check result. An implementation of such data quality checks is available in the SunPeek software tool, see Section **C.7**.

Representativity of radiation measurements: The standard assumes that radiation sensors receive the same amount of direct, diffuse, and reflected solar radiation as the whole collector field and recommends placing pyranometers on top of the collectors (for flat-plate collector fields) to avoid reflections. However, the standard does not address how adjacent collector rows alter reflection patterns or obstruct diffuse radiation; this is discussed in Section **A.6** of this document. For complex collector field geometries, using multiple radiation sensors and averaging their measurements may increase accuracy.

A.9. Power Check vs. Yield Check methods

History: The development of ISO 24194 was a collaborative effort between ISO and CEN (European Committee for Standardization) under their technical cooperation agreement. The standard was prepared by ISO/TC 180, Solar energy, Subcommittee SC 4, in collaboration with CEN/TC 312, Thermal solar systems and components. Precursor versions of these methods were used in Denmark for over twenty years **[21]**, mainly for guarantee procedures between collector manufacturer and plant designer/operator. Two IEA SHC Tasks contributed substantially to its realization, namely Task 45 [22], [23] and Task 55 [24], [8], [25]. Currently, ISO/TC180/SC4/WG4 is working on a revision of the standard, ISO/AWI 24194 [26], which aims to define an “Annual Yield Check” method, based on [23] and [27]. All these methods are subsumed under the term “Performance Check”.

Power Check vs. Daily Yield Check: ISO 24194 specifies two Performance Check methods to compare measured and estimated solar output: Power Check and Daily Yield Check. Table 9 provides a comparison between the two methods. This document focuses on Power Check and does not cover Daily Yield Check. Unlike Power Check, the yield-based methods compare the solar energy yield (kWh) against an estimated yield, whereas Power Check addresses solar power output (kW). Yield-based methods may bear improved financial relevance as they directly address solar energy, the quantity sold to customers.

However, Daily Yield Check is less generally applicable, compared to Power Check: It cannot be applied to tracking and concentrating collectors and is limited to the summer half-year (for latitudes $\geq 25\,°$). Furthermore, it is a less established method with little practical experience from real-world solar thermal plants, making it difficult to provide useful recommendations at present. Some practical aspects, such as collector fields with irregular land-use ratios, require further study. The restrictions on operating conditions (Table 2 in ISO 24194, excluding low-irradiance periods and days with low daily irradiation) imply that Daily Yield Check does not fully represent plant operation, and results do not reflect the solar energy measured by a heat meter and used for billing. Annual Yield Check could address and potentially overcome some of these limitations. The fact that Power Check uses shorter chunks of data in its analysis (1-hour intervals) brings some benefits: Results can be obtained in a shorter time (a few operational hours), and if the measured output does not meet expectations, the fine-grained hourly results offer more detailed insights into possible root causes, making it easier to distinguish between partial and full load behavior or different incidence angles.

Conclusion: The authors believe that the solar thermal community could benefit from open-source implementations of yield-based methods, as highlighted in the public roadmap of SunPeek (see Section E.4). Both power-and yield-based methods have their own strengths and weaknesses. The primary advantage of yield-based methods is their direct correlation with the amount of solar energy produced, the relevant quantity for the revenue that a solar plant generates. For instance, an open-source implementation of Annual Yield Check (as discussed in the ongoing ISO 24194 revision) would allow the community to gain practical experience with yield-based methods and encourage their widespread adoption.

Table 9. Comparison of Power Check and Daily Yield Check methods.

Item	*Power Check*	*Daily Yield Check*
Focus quantity	Solar power output (kW)	Solar energy yield (kWh)
Applicable collector types	Glazed flat-plate, evacuated tube, concentrating / tracking collectors	Flat-plate; not tracking / concentrating collectors
Valid data records	1-hour intervals with minimum solar irradiance $G_{\mathrm{hem}} \geq 800 \ \mathrm{W/m^2}$ or $G_{\mathrm{b}} \geq 600 \ \mathrm{W/m^2}$ and additional criteria to ensure stable operating conditions	Data in 1-day data chunks with minimum solar irradiation $\geq 5.5 \ \mathrm{kWh/m^2}$ and additional criteria to ensure unrestricted energy delivery from the collector field
Minimum required valid data records	20	5
Seasonal limitation	No seasonal limitation but practically limited by possible shading and too low irradiance	Limited to summer half-year (for latitudes $\geq 25\,°$)
Practical experience	Well-established with real-world expe-	Less established, limited practical experi-

Item	Power Check	Daily Yield Check
	rience from several projects	ence
Performance insights	Enables insights into partial loads and root causes of underperformance	Limited insights, less detailed
Open-source implementations	SunPeek [30]	None yet

A.10. Normative References

ISO 24194 incorporates three key normative references used in the definition of Power Check and Daily Yield Check methods: ISO 9806:2017 [2], ISO 9488:2022 [16], and ISO 9060 (using a mixed terminology between ISO 9060:2018 [18] and the withdrawn ISO 9060:1990 [17]). These standards provide the framework and technical specifications that underpin the procedures outlined in ISO 24194.

- *ISO 9806* (Solar energy - Solar thermal collectors - Test methods) defines test methods for solar thermal collectors, such as QDT (quasi-dynamic test) or SST (steady-state test). Collector data sheets, available in the Solar Keymark database [3], are always tested according to ISO 9806. Collector performance parameters reported in such data sheets are used in Power Check to compute the estimated collector field power output (see Section A.3). While using collector parameters based on ISO 9806 is not mandatory (see ISO 24194 Section 5.2.1), using such collector data sheets is a typical use case for Power Check. For ISO 9806, a guide document [6] like this document exists.
- *ISO 9060* (Solar energy - Specification and classification of instruments for measuring hemispherical solar and direct solar radiation): This standard provides specifications for solar radiation sensors and guidelines for selecting and using such instruments. In Power Check, irradiance data is used to calculate the estimated power output (see Section A.3) and is the single most important influencing factor on Power Check results. ISO 9060:2018 [18] defines sensor classes used to specify the accuracy levels in ISO 24194 Section 7.2.3 (see Section A.8). Some readers might still be familiar with the ISO 9060:1990 [17] terms (like Secondary Standard, First Class and Second Class); the current ISO 9060:2018 [18] uses the terms Class A, B and C.
- *ISO 9488* (Solar energy - Vocabulary) provides the vocabulary and basic terms for solar thermal energy. In ISO 24194, the terms and definitions given in ISO 9488:2022 [16] apply. It also defines symbols such as A_G (gross collector area) which are used in ISO 24194. The latest version is ISO 9488:2022 [16]. For terms and definitions used in this document, see Section G.1.

B Enhancing the practical applicability of Power Check

This chapter outlines methodological extensions to the ISO 24194 Power Check, to address and overcome practical limitations and improve its applicability to real-world installations. The goal of this chapter is to highlight three important enhancements that deserve a detailed focus and have already been partly integrated into SunPeek [30]. In Chapter E, the authors propose further discussion points, suggestions, and ideas about Power Check. Chapter F contains an outline for a major rework of Power Check, which goes beyond the presented enhancements in this chapter.

The enhancements presented here are:

- Section B.1: Presentation of the *"Extended Power Check"* method, a method enhancement in data averaging, fully implemented in SunPeek.
- Section B.2: Extending Power Check to solar plants with *multiple / heterogeneous collector fields* – an outline of a detailed concept is given.
- Section B.3: *How to treat stagnation* in Power Check: Proposition of a concrete solution.

B.1. Extended Power Check

ISO 24194 Limitations

Power Check utilizes 1-hour averaged values of recorded measurement data to calculate both measured and estimated power output. The method outlined in the standard requires intervals to start and end at full hours (e.g., 11:00, 12:00, 13:00, etc.), a limitation that owes to practical constraints of spreadsheet-based data analysis. However, the rigid restriction of full-hour interval limits is not imperative for obtaining 1-hour averaged Power Check values and may not yield the most useful results.

Enhanced procedure

To address this limitation, an "Extended Power Check" method is proposed using a moving-window approach; this extended method has been first presented in [28]. Just like the ISO 24194 Power Check, the extended method employs 1-hour averaged values but does not confine the interval limits to full hours. For example, a 1-hour interval with the extended method could span from 10:24 to 11:24. Importantly, the extended method adheres to the same restrictions and criteria as the default method for filtering measurement data (see Section A.5). This ensures that all 1-hour intervals resulting from the extended method meet all data requirements of ISO 24194, such as the restrictions on operating conditions defined in ISO 24194 Table 1 (Section 5.4).

Figure 6 graphically depicts the data averaging methods of both the default and the extended methods. The moving-window averaging of the extended method generates a set of "candidate intervals": partly overlapping 1-hour intervals that satisfy all Power Check data filtering criteria. A technique is required to select the best among all candidate intervals. In the SunPeek implementation, a minimum-noise criterion for interval selection is used, a score calculated as minimum relative standard deviation of the thermal power. Figure 7 demonstrates the effect of the extended method's interval scoring: The highest-scoring interval (a) has one hour of nearly perfect steady state operating conditions with almost constant power output, whereas the lowest-scoring interval (b) shows considerable variability in thermal power output. Once a candidate interval is selected, overlapping intervals are discarded from the candidate set to avoid duplicate data usage, and the next best-scoring interval is chosen. While other interval selection criteria are possible (e.g. maximize the interval number), the minimum-noise criterion described above leads to the smallest output variance and thus robust Power Check results.

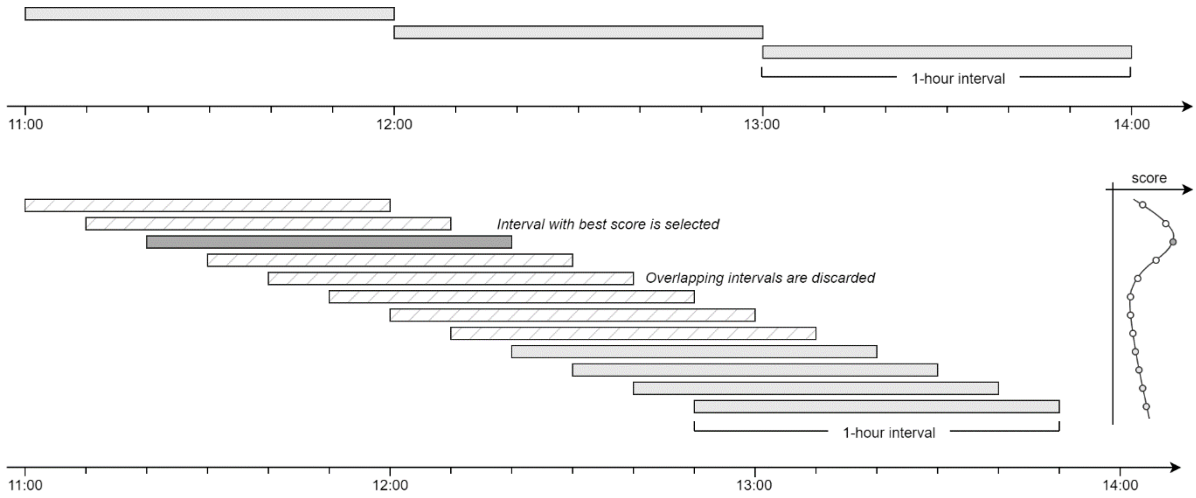
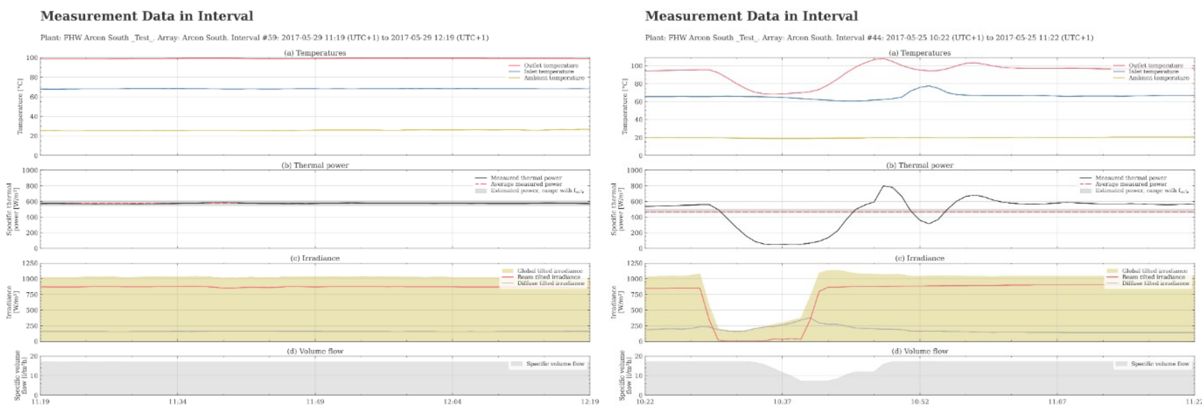


Figure 6. Comparison of Power Check averaging methods. The default method (top) is limited to intervals confined by full hours. The extended method (bottom) uses moving windows and selects intervals based on a score metric. Source: [28].



(a) Highest scoring interval *(b) Lowest scoring interval*

Figure 7. Highest scoring interval (a) and lowest scoring interval (b) selected by the Extended Power Check, showing the preference for steady thermal power output conditions. Source: [28].

Remarks

The Extended Power Check has been implemented in the SunPeek open-source software and applied to several solar thermal plants. Results from the extended method have been compared to those of the default method, with example results and comparisons presented in Section **D.2**. These analyses indicate that the extended method tends to produce more valid data records, while maintaining comparable values for the average power ratio across several intervals. Overall, the extended method results cover a wider range of operating conditions, compared to the default method described in Chapter **A**. It leverages modern data analysis techniques and enhances the practical usefulness of Power Check results.

B.2. Multiple and heterogeneous collector fields

ISO 24194 Limitations

Many solar thermal plants have complex geometric and hydraulic arrangements to optimize the layout and the solar yield. Examples include plants with multiple flat-plate collector fields with different orientations, a combination of single- and double-glazed flat-plate collectors, or flat-plate collectors combined with concentrating collectors.

ISO 24194, Section 5.1: The standard lacks a systematic treatment of complex arrangements, and only states that an overall Power Check can be conducted for collector fields with different collector types assuming "similar collector types" (see Section **A.2**).

- An overall estimate for fields with two or more "similar collector types" can be given by choosing "representative collector parameters". The standard only states that, for instance, single- and double-glazed flat-plate collectors can be regarded as "similar".
- If size, inlet, and outlet temperatures are available for each collector field of the same type, Power Check estimates can be computed for each field.

This approach has several limitations:

- The procedure to determine "representative collector parameters" is not defined and leaves room for interpretation. It is not specified, for example, how to consider different collector areas, possibly different Power Check Formulas (see Section **A.3**), or possibly different irradiance measurements, such as for differently oriented fields.
- The term "similar collector types" is not precisely defined. Details or examples of how to apply the method to combined collector types are not provided. Applications to fields with "non-similar" collector types are not specified.
- If inlet and outlet temperatures are not available, e.g., for serially connected fields, the procedure may not be applicable. For example, no procedure is defined to compute or model intermediate temperatures.
- Differences in geometric arrangements (e.g., tilt, azimuth, and row spacing) of groups of collectors are not addressed. Availability of irradiance measurements is not addressed.
- Several data filtering questions are undefined, for instance, whether the restrictions on operating conditions (see Section **A.5**) must be fulfilled for each field or for all fields combined.

Enhanced procedure

This guide attempts to clarify the situation by providing a generic and traceable procedure on how to apply Power Check to plants with complex arrangements. The basic situation is illustrated in **Figure 8** for a plant with two collector fields: Some measurements are available per field, while others are shared, for example ambient temperature, but notably also power output.

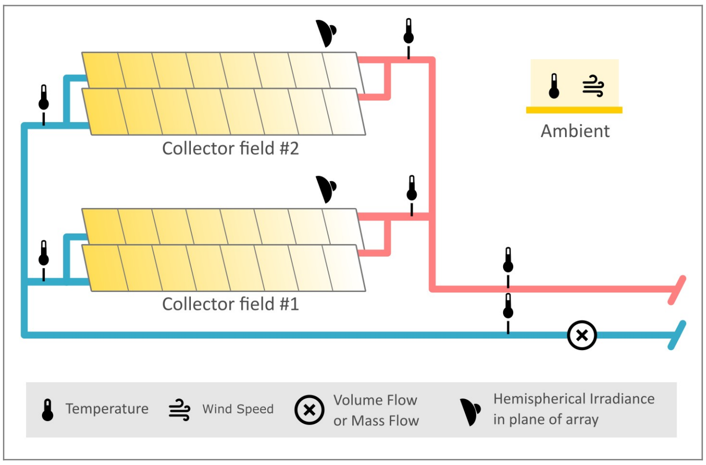


Figure 8. Example setup for a plant with two collector fields.

Before outlining the enhanced procedure, it is important to clearly define the used terms (see also Section **G.1**):

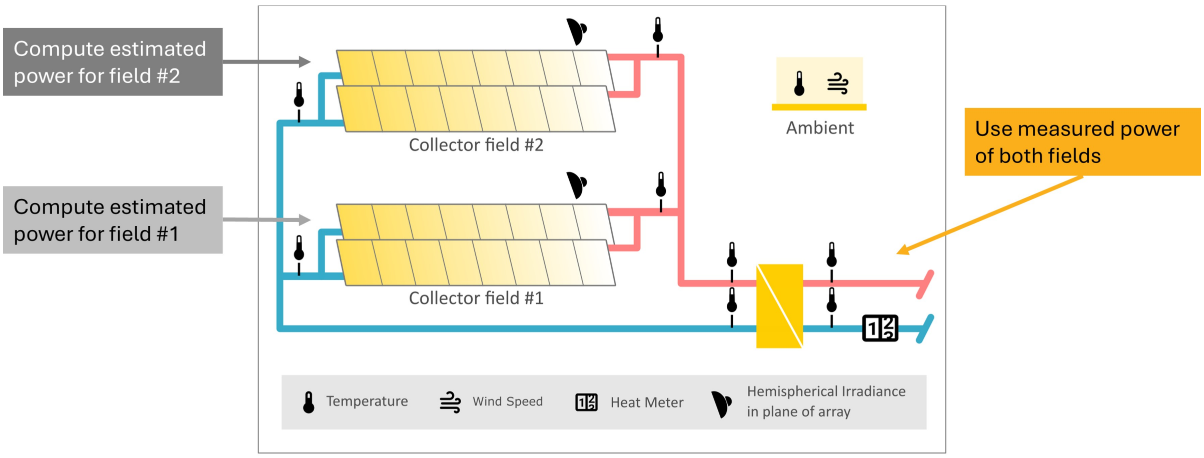
- A *plant (or system, installation)* for the delivery of thermal energy can have one or multiple collector fields, which can be uniform or heterogenous.

- A *collector field (*collector array as in ISO 9488:2022 [16]) is a group of solar collectors that are closely connected in series, in parallel or in combination of both modes, with one hydraulic input and one hydraulic output.
- A *uniform collector field*, as defined in this document, is a collector field consisting of one collector model with a geometrically uniform arrangement. A collector model has a distinct name, dimensions and one set of collector performance parameters as listed in the data sheet, whereas a collector type is a more generic (such as flat-plate, evacuated tubular collector types). A geometrically uniform arrangement means all collectors have the same mounting (tracked or fixed with constant tilt and azimuth) and row spacing with a rectangular shape on a plane (see Section A.6). This term “uniform collector field“ is used as a modeling abstraction. For example, a heterogenous collector field where the collectors have different mounting angles could be split into two uniform collector fields.
- A *heterogenous collector field*, as defined in this document, is a collector field with a more complex arrangement than a uniform collector field, e.g., due to using multiple collector types or collector models, having multiple subgroups of collectors connected in parallel or series, irregular row spacing, irregular mounting angles, etc.

Usually, there are several possibilities to conceptualize complex arrangements of solar thermal plants. The arrangement in Figure 8 could be seen as a plant with two collector fields, but also a plant with one heterogeneous collector field.

The proposed method targets hydraulic and geometric arrangements which are more complex than a plant with a single uniform collector field and treats all such cases as a plant with multiple fields. The idea is to compute the estimated power for each field individually (following ISO 24194, see Section A.3), and to compare the sum of these estimated power outputs with the corresponding sensor that measures the overall power output, for all fields.

An example is shown in Figure 9, which illustrates the idea for the case for two different collector fields (as shown in Figure 8) and combined power, ambient temperature and wind speed measurements. In this case, the estimate can be computed for each of the collector fields individually, using irradiance, inlet and outlet temperatures, incidence angle modifier, collector area and collector parameters per field in Power Check Formula (see formulas in Section A.2). The comparison of measured and estimated power can then be carried out by summing up the estimated outputs of both fields. When specific power outputs are given ($\mathrm{W/m^2}$), the area relates to the combined gross collector area of all fields.



$$A_{total} = A_{CF\#1} + A_{CF\#2}$$

$$\mathrm{Average}(\dot{Q}_{measured}) \geq \frac{A_{CF\#1}}{A_{total}} \cdot \mathrm{Average}(\dot{Q}_{estimated,\,CF\#1}) + \frac{A_{CF,\#2}}{A_{total}} \cdot \mathrm{Average}\left(\dot{Q}_{estimated,\;CF\#2}\right)$$

Figure 9. Illustration of the proposed extension of Power Check to multiple collector fields.

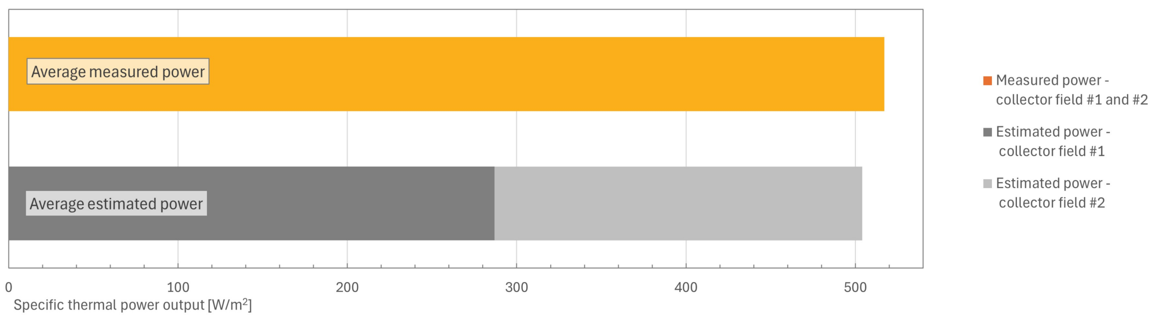


Figure 10. Proposed extension of Power Check to multiple collector fields: Comparison of average measured and estimated power output (for collector field #1 and #2) with the sum of the estimated power outputs for collector field #1 and #2.

This idea can be used to apply Power Check to plants with multiple fields in general:

- First, all *heterogeneous* collector fields of a plant will be partitioned into *uniform* collector fields which are treated individually.
- Each *uniform* collector field consists of *one collector model* and has a *geometrically uniform arrangement.* Hence, an individual estimation can be given according to ISO 24194. For simplicity, it is assumed that all measurements are available to compute the estimated power (see paragraphs later in this section for handling missing sensors).
- Uniform collector fields that have a *common power measurement* are grouped together. A *group* can consist of one or multiple collector fields.
- Data records are *valid* and thus used for Power Check, if the requirements for operating conditions (see Section **A.5**) are simultaneously fulfilled for *all* collector fields of a group. For simplicity, using one common safety factor for all fields is recommended, see the "Remarks" section for a further discussion.

Using these assumptions, comparisons between measured and estimated power can then be made for each collector field group, by summing up the estimated power of all collector fields in a group (weighted by their corresponding area) and comparing to the power measurement (similar to Eq. (**1**)):

$$\text{Average}\left(\dot{Q}_{\text{estimated}}\right)_{\text{group}} \geq \frac{\sum_{i=1}^{N}\left(A_{\text{CF},i} \cdot \text{Average}\left(\dot{Q}_{\text{estimated}}\right)_i\right)}{\sum_{i=1}^{N} A_{\text{CF},i}} \quad (11)$$

where N is the number of fields which are measured together, $A_{GF,i}$ is the gross area of the i-th field, and $Average\left(\dot{Q}_{estimate}\right)_i$ is the estimated power of the i-th field according to ISO 24194.

Following the procedure described above, the ISO 24194 Power Check can be applied to plants with multiple collector fields. A process diagram illustrating the procedure is shown in **Figure 11**. To summarize, the procedure makes the following modeling assumptions and requirements:

1) Collector fields are *not* required to have individual power measurements. Only a common power measurement for multiple fields (or for the whole plant) is required.
2) Each collector field is assumed to be geometrically *uniformly arranged*, having the same mounting (tracked or fixed with constant tilt and azimuth), collector length and row spacing.
3) Each collector field has exactly *one collector model* with its characteristic efficiency parameters. Collector types of different fields do not need to be similar (in the ISO 24194 sense). The proposed procedure perfectly works, for example, for a field of flat-plat collectors (using Formula 1) and a field with concentrating collectors (using Formula 2 or 3).

4) Given the corresponding Formula 1–3, each field has all *required data channels* (irradiance, inlet and outlet temperature, ambient temperature, etc.) to compute the estimated power and filter valid data records.
5) Ambient temperature and wind speed are assumed to be valid for all fields of a plant, although individual measurements per field can be used if available.
6) Requirements for operating conditions should be simultaneously fulfilled for all fields.

This procedure works regardless of the specific hydraulic layout (for instance, collectors connected in series, in parallel, etc.). However, each field still requires all necessary sensors for computation of the estimated power output, the same as in the single-field case described in ISO 24194. In case a sensor is missing, sensor measurements can in some cases be modeled. Below are example setups with no missing sensors, and a detailed guide how to address missing sensors, for selected plant setups.

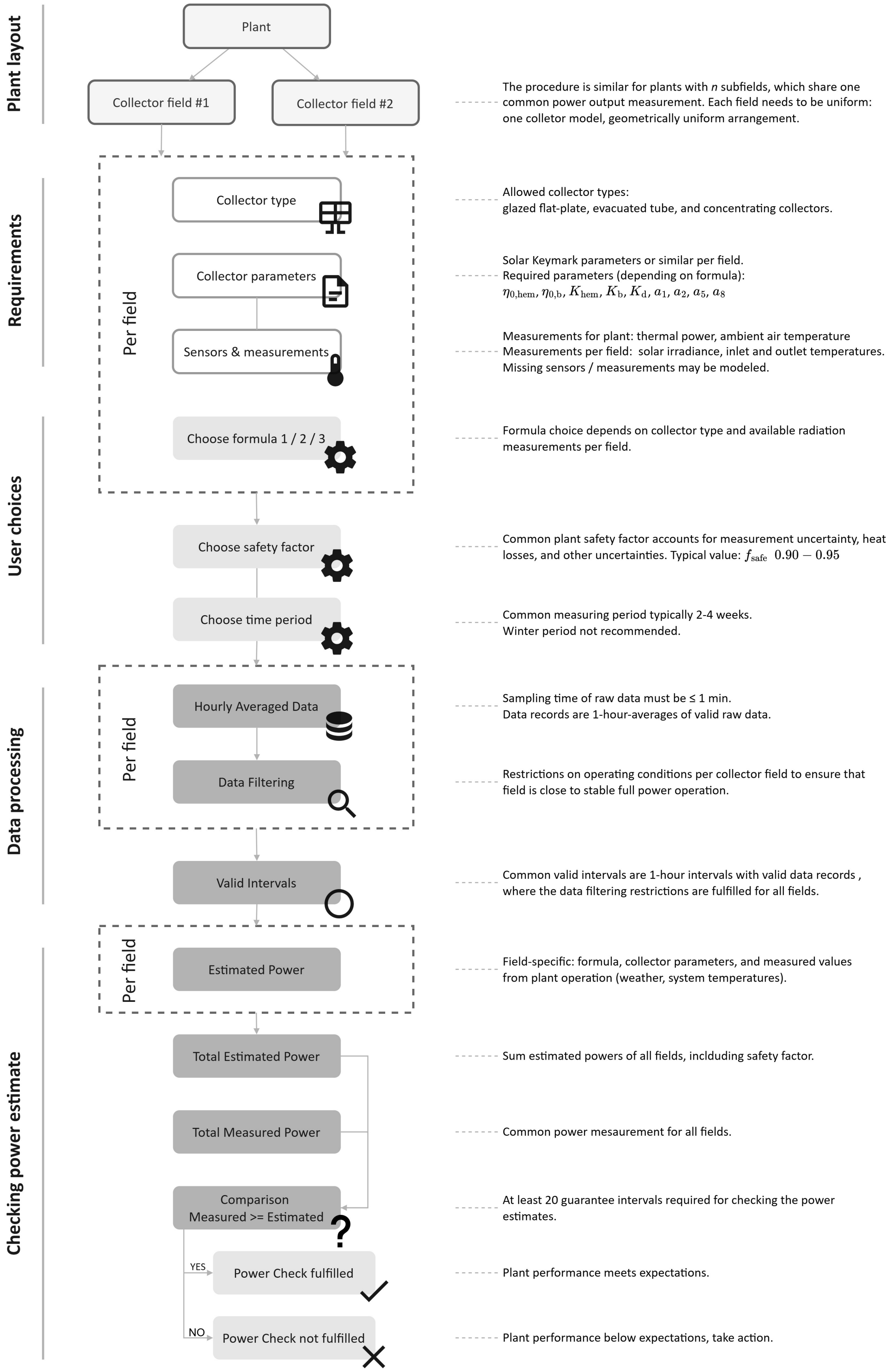
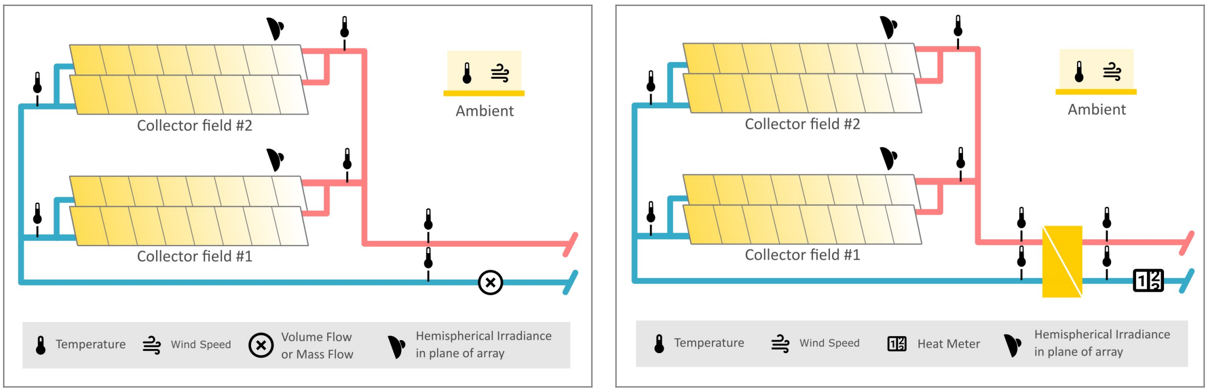


Figure 11. Process diagram for application of ISO 24194 Power Check to plants with multiple and heterogeneous collector fields. Refer to Figure 1 to compare to the single-field case.

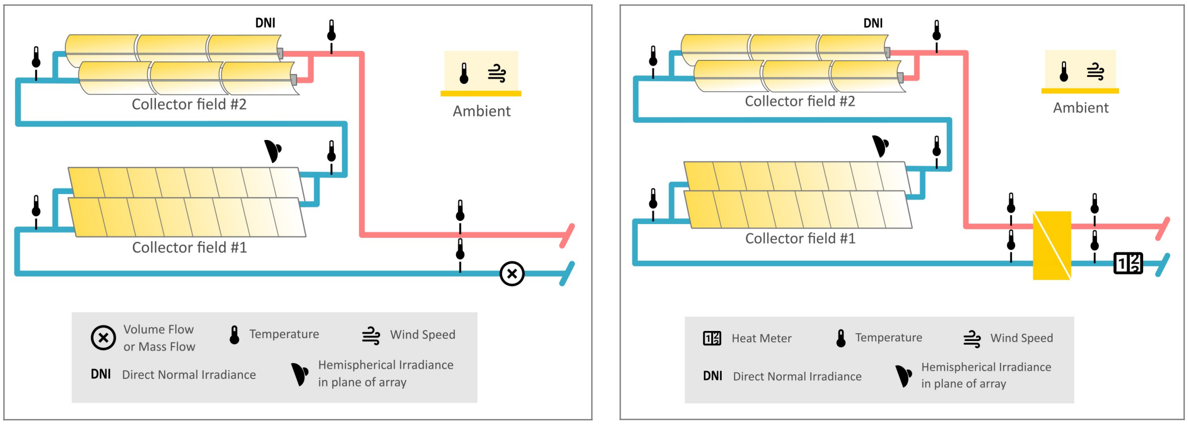
Example setups with no missing sensors

Figure 12 and Figure 13 show example setups for plants with two fields, connected in parallel and in series, where all available sensors for computing estimated power per field are given.



(a) *(b)*

Figure 12. Parallel case: Setup with two fields connected in parallel. Setup (a) without and (b) with heat exchanger. With complete sensor measurements, each collector field has inlet and outlet temperatures, and irradiance measurements.

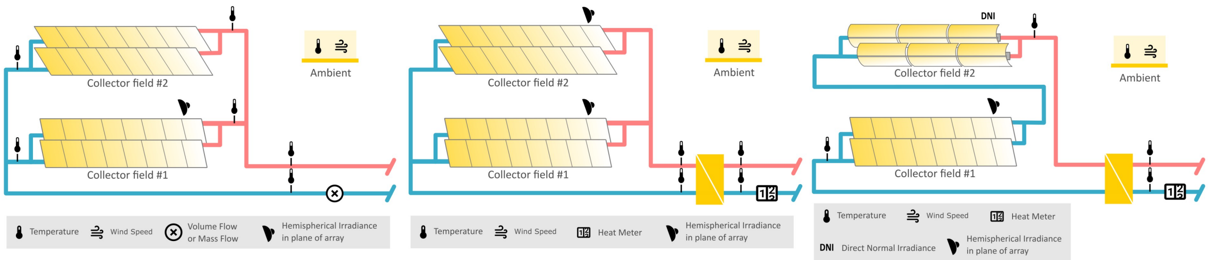


(a) *(b)*

Figure 13. Serial case: Setup with two fields connected in series. Setup (a) without and (b) with heat exchanger. Both systems combine flat-plate and concentrating collectors in series. With complete sensor measurements, each collector field has inlet and outlet temperatures, and irradiance measurements, as required for the chosen Formula.

Missing sensors

In some plants, sensor measurements required to compute estimated power output might be missing, either permanently (if no sensor was installed), or temporarily (e.g. due to a malfunction). Example cases are shown in Figure 14 (a–c).



(a) *(b)* *(c)*

Figure 14. Plant setups with multiple fields where sensors are missing. Setup (a) lacks an irradiance sensor for field #2. Setup (b) lacks inlet and outlet temperatures for individual parallel fields. Setup (c) lacks outlet temperature of field #1 and inlet temperature of field #2 (“inter-field” temperature between fields in series).

Missing sensor measurements can in some cases be deduced from models. Below is a detailed guide covering four cases which are important in practice:

1) Missing radiation measurements (**Figure 14** (a))
2) Missing return temperature for fields connected in parallel (**Figure 14** (b))
3) Missing outlet temperature for fields connected in parallel (**Figure 14** (b))
4) Missing “inter-field” temperature for fields connected in series (**Figure 14** (c))

*Case #1. Missing radiation measurements (**Figure 14** (a)):* For flat-plate collector fields, the most common impediment is that a measurement of G_{hem} in the collector plane is available for one field, but not for another field with different orientation (tilt, azimuth). Radiation modeling could be used to model G_{hem} on other fields, but ISO 24194 does not specify whether this is admissible, or how to proceed in case collector and radiation sensor orientations differ. The authors propose following the recommendations outlined in Section **F.7**.

*Case #2. Missing inlet temperature for fields connected in parallel (**Figure 14** (b))*: If inlet temperatures for fields connected in parallel are missing, each field should use the common return temperature measurement. For longer connection pipes, the safety factor may be increased, or pipe losses quantified, as outlined in Section **F.6**.

*Case #3. Missing outlet temperature for fields connected in parallel (**Figure 14** (b))*: If outlet temperatures for fields connected in parallel are missing, the common outlet temperature can be used for each field if they can be assumed to be “similar”, e.g. short connection pipes and sufficiently good hydraulic balancing. For fields with good balancing, influence on power distribution is typically negligible **[29]**.

*Case #4. Missing “inter-field” temperature for fields connected in series (**Figure 14** (c))*: In this common case, fields with different collector technologies are connected in series, usually with the intention of having each technology operate in its ideal temperature range. Computing estimated power output for each field requires knowing the temperature between the fields (i.e., the outlet temperature of field #1, and inlet temperature of field #2). In practice, the inter-field temperature measurements are sometimes missing. They can be modeled, under the assumption that the inter-field inlet and outlet temperatures (outlet field #1 and inlet field #2) are equivalent and can thus be described by the same “inter-field” temperature, ϑ_x. This unknown temperature ϑ_x is modeled as a weighted average of the field #1 inlet temperature $\vartheta_{¿,\ 1}$, and the field #2 outlet temperature $\vartheta_{out,\ 2}$ with weight $\alpha \ \epsilon \ [0,1]$.

$$\vartheta_x = \alpha \cdot \ \vartheta_{i,\ 1} + (1-\alpha) \cdot \ \vartheta_{e,\ 2} \tag{12}$$

Each choice of a weight α corresponds to setting the inter-field temperature ϑ_x and a distribution of the total power output $\dot{Q}_{\mathrm{tot}}$ between the power output of the fields, $\dot{Q}_1$ and $\dot{Q}_2$ (see **Figure 15**):

$$\begin{aligned}
\dot{Q}_{\mathrm{tot}} &= \dot{V} \cdot \rho \cdot c_f \cdot (\vartheta_{e,2} - \vartheta_{i,1}) \\
&= \dot{V} \cdot \rho \cdot c_f \cdot (\vartheta_x - \vartheta_{i,1}) + \dot{V} \cdot \rho \cdot c_f \cdot (\vartheta_{e,2} - \vartheta_x) \\
&= \dot{V} \cdot \rho \cdot c_f \cdot (1-\alpha)\ (\vartheta_{e,2} - \vartheta_{i,1}) + \dot{V} \cdot \rho \cdot c_f \cdot \ \alpha\ (\vartheta_{e,2} - \vartheta_{i,1}) \\
&= (1-\alpha)\ \dot{Q}_{\mathrm{tot}} + \alpha\ \dot{Q}_{\mathrm{tot}} \\
&= \dot{Q}_1 + \dot{Q}_2
\end{aligned} \tag{13}$$

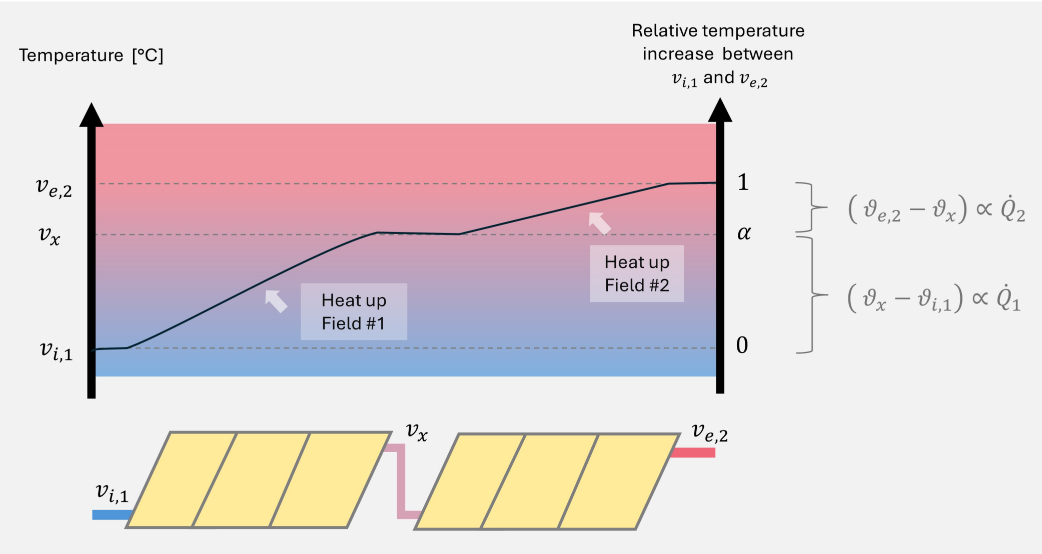


Figure 15. Illustration of inter-field temperature v_x.

The following approaches for choosing α exist, listed in increasing order of accuracy and complexity:

1) *Even split method:* Assign same thermal power output to both fields, $\dot{Q}_1 = \dot{Q}_2$. As a result, the inter-field temperature is the average of the inlet and outlet temperature.

$$\alpha = 0.5 \tag{14}$$

2) *Collector area method:* Assign thermal power output relative to the fields' gross collector areas, $A_{CF,1}$ and $A_{CF,2}$. This is equivalent to assuming both fields operate at the same efficiency. As a result, it is assumed that larger fields lead to a correspondingly higher temperature increase.

$$\alpha = \frac{A_{\mathrm{CF},\,2}}{A_{\mathrm{CF},\,1} + A_{\mathrm{CF},\,2}} \tag{15}$$

3) *Irradiance method:* Assign thermal power output relative to each field's irradiance (G_{hem}, assuming Formula 1). This is similar to method ii, but takes different irradiation conditions into account, for example when combining tracking and non-tracking collectors.

$$\alpha = \frac{A_{\mathrm{CF},\,2} \cdot G_{\mathrm{hem},2}}{A_{\mathrm{CF},\,1} \cdot G_{\mathrm{hem},1} + A_{\mathrm{CF},2} \cdot G_{\mathrm{hem},2}} \tag{16}$$

4) *Optical efficiency method:* Assign thermal power output relative to the fields' optical efficiency. The example below uses Formula 1 and 3. In contrast to method iii, this also takes different collector into account to some extent.

$$\alpha = \frac{A_{\mathrm{CF},2} \cdot \eta_{0,\mathrm{b}} K_{\mathrm{b}}(\theta_{\mathrm{L}}, \theta_{\mathrm{T}}) G_{\mathrm{b}}}{A_{\mathrm{CF},1} \cdot \eta_{0,\mathrm{hem}} \ K_{\mathrm{hem}}(\theta_{\mathrm{L}}, \theta_{\mathrm{T}}) \ G_{\mathrm{hem}} + A_{\mathrm{CF},2} \cdot \eta_{0,\mathrm{b}} K_{\mathrm{b}}(\theta_{\mathrm{L}}, \theta_{\mathrm{T}}) G_{\mathrm{b}}} \tag{17}$$

5) *Collector equation method:* Assign thermal power output according to collector efficiency equations with an iterative procedure $\alpha_0, \alpha_1, \alpha_2, \ldots$ to set α. In contrast to method 4, this takes all collector parameters into account to approximate the relative temperature increase of both fields, but requires an iterative procedure:

- Initial condition ($n=0$). Set $\alpha_0 = 0.5$.
- Step n. Calculate power with weight α_n and new weight α_{n+1} (example with Formula 1).

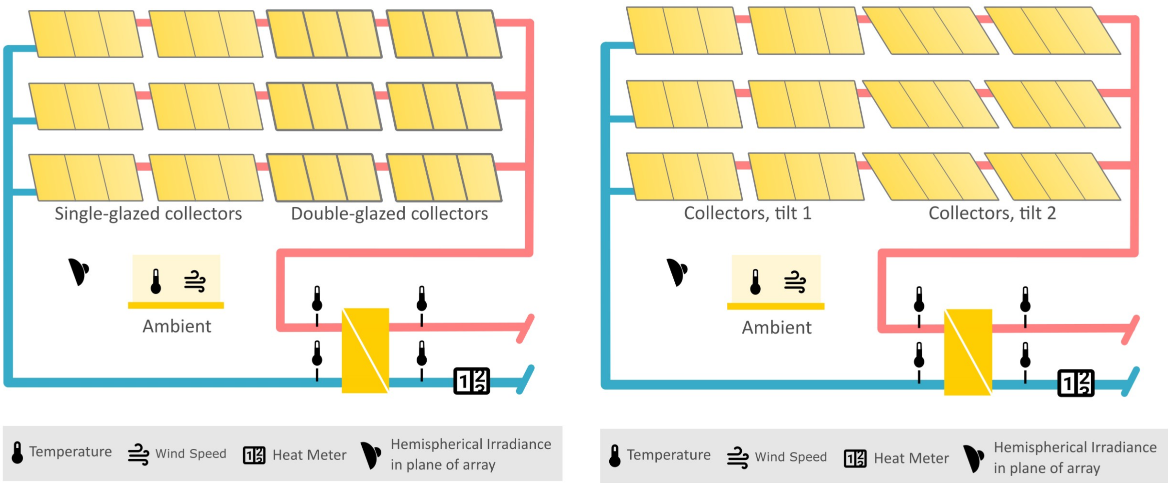
i)	$\vartheta_x(\alpha_n)=\alpha_n \cdot \vartheta_{i,1}+(1-\alpha_n)\cdot \vartheta_{e,2}$	(18)
ii)	$\vartheta_{m,1}(\alpha_n)=0.5\ (\vartheta_{i,1}+\vartheta_x(\alpha_n))$	(19)
iii)	$\vartheta_{m,2}(\alpha_n)=0.5\ (\vartheta_{e,2}+\vartheta_x(\alpha_n))$	(20)
iv)	$\dot{Q}_1(\alpha_n)=A_{\mathrm{CF},1}\cdot[\eta_{0,\mathrm{hem}}K_{\mathrm{hem}}(\theta_\mathrm{L},\theta_\mathrm{T})G_{\mathrm{hem},1}-a_1(\vartheta_{m,1}(\alpha_n)-\vartheta_a)-a_2(\vartheta_{m,1}(\alpha_n$	(21)
v)	$\dot{Q}_2(\alpha_n)=A_{\mathrm{CF},2}\cdot[\eta_{0,\mathrm{hem}}K_{\mathrm{hem}}(\theta_\mathrm{L},\theta_\mathrm{T})G_{\mathrm{hem},2}-a_1(\vartheta_{m,2}(\alpha_n)-\vartheta_a)-a_2(\vartheta_{m,2}(\alpha_n$	(22)
vi)	$\alpha_{n+1}=\dfrac{\dot{Q}_2(\alpha_n)}{\dot{Q}_1(\alpha_n)+\dot{Q}_2(\alpha_n)}$	(23)

- Iteration. Set $n=n+1$ and repeat until α_n converges.

The authors recommend using the “collector area method” (item 2), as it is reasonably precise and very simple. The “irradiance method” (3) and “optical efficiency method” (4) should be used if the fields receive substantially different irradiance levels or use hemispherical versus beam / direct irradiance. Weight α is constant for methods (1) and (2), for methods (3)–(5) it is calculated per raw data point.

Mixed collectors in rows modeled as uniform collector fields

Some collector fields deploy different collector models or collector types within each row or have other geometric characteristics that make them non-uniform, such as different mounting angles or row spacings within the field as shown in **Figure 16**. Such fields can be split into multiple uniform “collector fields” in the sense of a modeling abstraction, although they may not have one hydraulic input, and one hydraulic output as defined for the term “collector array” (collector field) in ISO 9488:2022 **[16]**. Missing sensors can be calculated according to the guidelines in the previous section.



(a) *(b)*

Figure 16. Examples of collector fields composed of different collector models within each row: (a) combination of single- and double-glazed collectors; (b) combination of collectors with different tilt angles.

Remarks

Comparison to ISO 24194: The procedure described above is equivalent to the ISO standard procedure, provided all required measurements and parameters are available, for individual field estimates. In contrast, using representative collector parameters for similar collector types when inlet or outlet temperatures are missing (plugging the parameters into one formula) effectively assumes a parallel connection of fields with identical inlet and outlet temperatures, which is not valid for fields connected in series. Generally, the more missing sensors need to be modeled, the higher the safety factor should be. Further research is required to explore methodological limits and to investigate edge cases.

Reporting: For applying Power Check to plants with multiple and heterogeneous fields, it is recommended to include a hydraulic scheme in reports and to describe the modeling assumptions.

Safety factor: The proposed procedure assigns the overall safety factors to the summed-up power estimates of all fields. Since safety factors are only relevant in connection with a power output comparison, this is a reasonable simplification. Defining individual safety factors per field is possible in principle, but this would imply that the safety factor for multiple fields would cease to be a constant. The authors see this as a major drawback and recommend using an overall safety factor per power measurement.

Edge cases: Plants with multiple fields with very divergent orientations (e.g., East and West-facing flat-plate collector fields), can only be evaluated if there are mutually including overlapping operating intervals (valid data records).

SunPeek implementation: At the time of writing, the current SunPeek version supports cases with multiple collector fields connected in parallel or series as shown in **Figure 12** and **Figure 13** if all required measurements are available and if the same formula for all fields is used. An improved implementation supporting this procedure is envisaged, as defined in the SunPeek Roadmap, see Section **E.4**.

B.3. Stagnation events

ISO 24194 Limitations

In solar thermal plant operation, several definitions of stagnation are in use. This section uses the following definition based on the current ISO 9806 standard **[2]**: stagnation is a condition where there is abundant solar irradiance, but the collector field is under no-flow or low-flow conditions, and no useful energy is taken from the solar collectors. This may be caused by a failure (e.g., power outage) or by external system conditions (e.g. maximum storage temperature reached), but it can also be a planned system state (e.g., in deliberately oversized collector fields, in an industry application with no heat demand on weekends, or due to planned downtime or maintenance).

ISO 24194 does not mention the topic of stagnation explicitly and the operating condition restrictions do not contain corresponding filtering criteria, see ISO 24194 Table 1 (**Table 4** in this document) and Section **A.5**. As a result, stagnation events can be included in valid data records as shown in **Figure 17**. The extent to which stagnation events are included depends on the interpretation of the “change in collector mean temperature” criterion, see Section **A.5** for three different interpretations of this criterion. Even with the most restrictive interpretation – the second criterion as shown in **Figure 3** – which limits temperature peaks or dips to 5 K within an hour, a stagnation event may be present although this is more of a rare edge case. The power output during stagnation events is zero (no volume flow), but Formulas 1–3 do not consider if the array is actually in operation. Therefore, data records where stagnation occurs have a lower measured-estimated power ratio, compared to normal plant behavior, potentially distorting the performance assessment.

Use cases

The key question is whether Power Check data restrictions should be extended with a restriction to exclude stagnation events, in the way that shading is already handled. There are pros and cons to this Power Check modification:

- *Pros:* Power Check is designed to estimate power output for periods of normal operation, not for stagnation. Also, the ISO 9806 model can be outside its validity range if the plant is in stagnation. Excluding stagnation events would ensure that Power Check is limited to typical operational behavior, covered by the models used.
- *Cons:* In a scenario where Power Check is constantly applied during plant operation, it would be preferable to detect stagnation events as soon as possible, preventing them from going

unnoticed – especially if stagnation is not part of plant design (as opposed to planned stagnation, due to specific operational schedules, etc.). For unplanned stagnation events, it would be useful not to exclude stagnation with additional data filters.

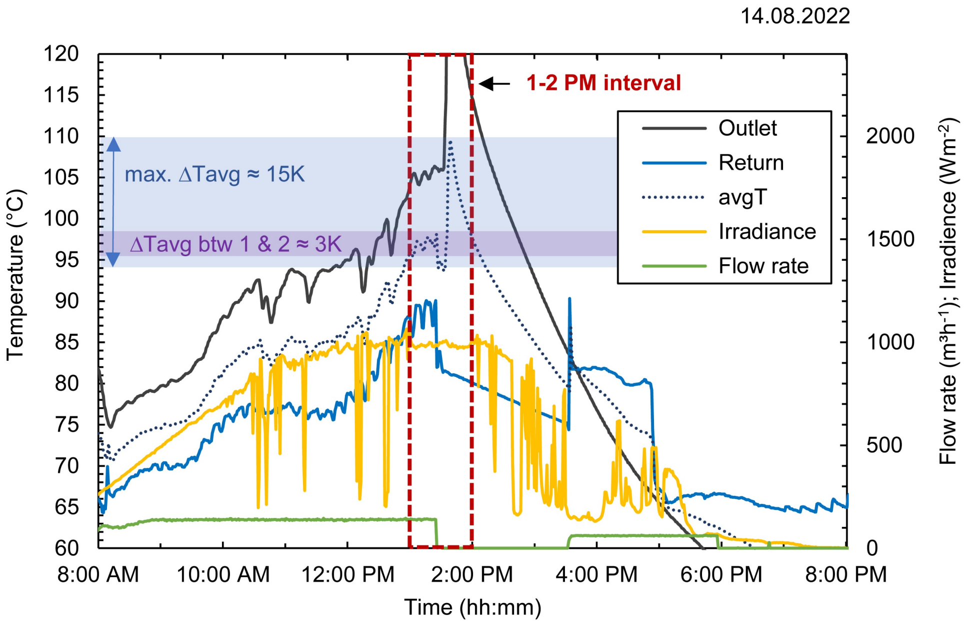


Figure 17. Impact of stagnation events on data selection of Power Check. The interval from 1–2 PM has a change in mean collector temperature of $\approx 3\ \mathrm{K}$ as the array cools down after reaching stagnation temperatures. This interval is a valid data record fulfilling all ISO 24194 criteria on operating conditions if the "change in collector mean temperature" criterion is interpreted as in **Figure 3** b, i.e. $|d\vartheta_m / dt| \leq 5\ \mathrm{K}$ within an hour.

Enhanced procedure

As filtering out stagnation seems to align better with the intention of the standard, the authors recommend adding a criterion to Power Check to detect and filter stagnation from data records. However, to ensure that stagnation does not go unnoticed, a summary of stagnation events should be documented in Power Check outputs; a recommended reporting format should be given. In an ongoing monitoring scenario, stagnation events need to be identified separately.

While it is true that, following this recommendation, Power Check may report that collector field operation is fine even if stagnation has occurred, the results are still valid and representative of collector field operation, for the included Power Check data records.

Distinguishing between stagnation and normal plant operation *within* 1-hour intervals requires filtering individual measurement data on the original sampling rate. A practical method is to use an additional criterion on minimum specific power output, in the restrictions on operating conditions:

$$\frac{\dot{Q}_{\mathrm{measured}}}{A_{\mathrm{CF}}} \geq \dot{Q}_{\mathrm{sp,min}} \tag{24}$$

The value of $\dot{Q}_{\mathrm{sp,min}}$ for distinguishing between stagnation and normal plant operation depends on technical features of the specific collector field, such as the collector technology and the normal operating temperature. For example, for conventional flat-plate collectors operating at around $\vartheta_m = 80\,°C$, a typical choice could be $\dot{Q}_{\mathrm{sp,min}} = 100\ \mathrm{W/m^2}$, essentially using the same value to ensure that the plant is in operation, although applied to individual data records and not 1-hour averages (see Section **A.5**). A drawback of this criterion is that it may exclude some 1-hour intervals where the power output temporarily dips, even though no stagnation is actually happening, see **Figure 18**.

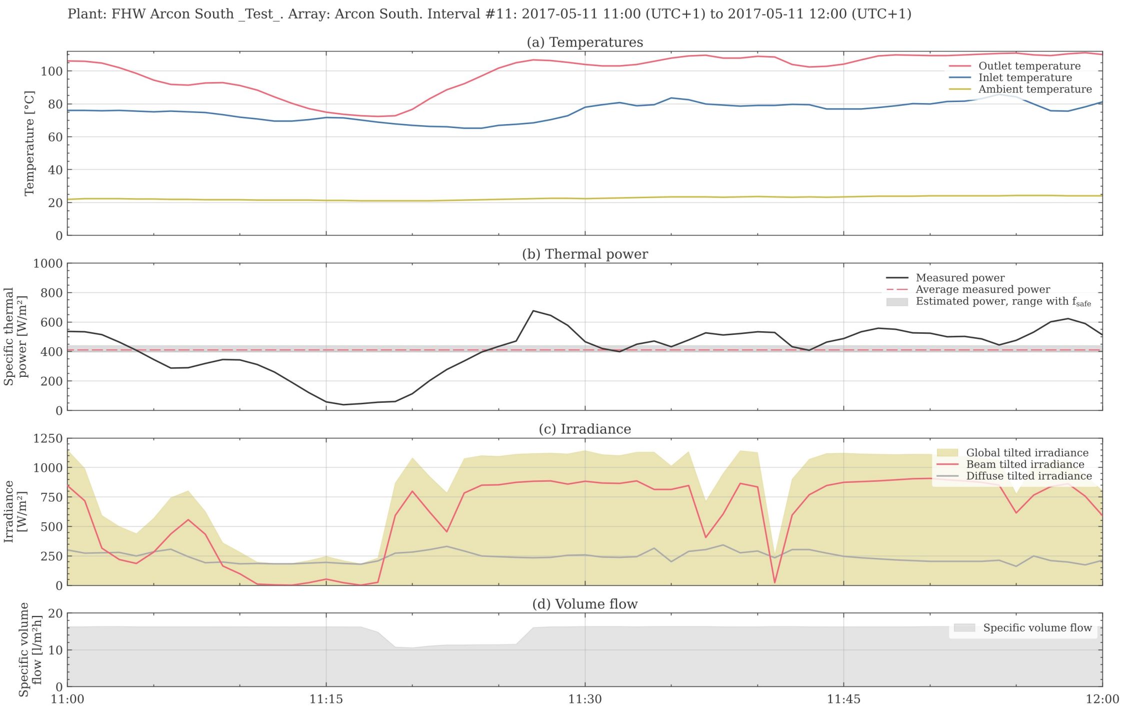


Figure 18. Data in a valid 1-hour interval showing a temporary dip in power output due to reduced irradiance. Such intervals would be ruled out by a minimum specific power output criterion used to detect stagnation.

A more targeted criterion would be to set a minimum specific volume flow:

$$\frac{\dot{V}_{\text{sp}}}{A_{CF}} \geq \dot{V}_{\text{sp,min}} \tag{25}$$

Likewise, this criterion depends on the collector technology and plant layout. Additionally, for some plants, only the thermal power output may be recorded as a data point. Collector field temperatures cannot be used as criteria to detect stagnation. This is because during stagnation, due to low / no circulation in the solar loop, the collector field temperature sensors do not reliably represent the actual collector field temperatures.

C SunPeek open-source software

This chapter presents the free and open-source software SunPeek, which includes the first open-source implementation of the ISO 24194:2022 Power Check. It briefly explains the SunPeek tool and shows how it can be used to perform Power Check.

- Section **C.1** provides a *short introduction* to the functionality of SunPeek and provides useful links for using the software.
- Section **C.2** presents a *quick guide* on how to run Power Check with SunPeek.
- Section **C.3** discusses the *plant configuration* in more detail.
- Section **C.4** outlines the *data upload and inspection* in more detail.
- Section **C.5** discusses *executing and applying* Power Check.
- Sections **C.6** to **C.9** provide *additional details* on Power Check implementation, data handling, sensor calculations, and SunPeek's envisaged link to the Solar Keymark Collector Database integration.

To analyze a plant with SunPeek, the following procedure is recommended:

1) New users can try the *public demo*[1], including the built-in *demo plant* (see Section **D.2**).
2) For installation, see the *SunPeek Installation Guidelines*[2].
3) To work with your own plant, start with the *quick guide* in Section **C.2** and go through Sections **C.3** to **C.6** for step-by-step instructions from plant configuration to Power Check evaluations.
4) Check out Chapter **D** on example applications.
5) Read Sections **C.6** to **C.9** for *background information* on SunPeek, Power Check implementation and Solar Keymark Database integration.
6) Check out the *SunPeek Documentation*[3] for additional in-depth information.

Source Code: The latest SunPeek source code is available in the *SunPeek GitLab Repository*[4].

This guide is based on SunPeek Backend version 0.4.3. Power Check implementation will be further developed with newer versions of SunPeek.

SunPeek ISO 24194 reference implementation	
SunPeek	SunPeek is designed to be the reference software implementation of ISO 24194 Power Check by ensuring an open-source, transparent, consistent, readily available and broadly validated implementation. **The authors of this guide recommend using SunPeek as the reference tool to run Power Check.**

[1] https://demo.sunpeek.org
[2] https://docs.sunpeek.org/quick_start/installation/
[3] https://docs.sunpeek.org/
[4] https://gitlab.com/sunpeek/

C.1. About SunPeek

SunPeek resources

SunPeek Public Demo

https://demo.sunpeek.org/

SunPeek Resources	
SunPeek Hub	https://sunpeek.org/
Public Demo	https://demo.sunpeek.org/
Documentation	https://docs.sunpeek.org
Software Repositories	https://gitlab.com/sunpeek/
Python Library	https://pypi.org/project/sunpeek/
DockerHub	https://hub.docker.com/u/sunpeek/
Open Dataset (Demo Plant)	https://doi.org/10.5281/zenodo.7741083
Zenodo Community	https://zenodo.org/communities/sunpeek/
LinkedIn	https://www.linkedin.com/company/sunpeek/
Contact	support@sunpeek.org

What is SunPeek?

SunPeek is an open-source software designed to automate the performance evaluation of solar thermal plants, focusing on large-scale installations. Designed as a containerized web application, SunPeek includes a web interface and a Python backend with a REST API; see [30] for details on the software design. The tool has been developed through collaboration between research institutes and industry partners and is a NumFOCUS affiliated project[5].

[5] https://numfocus.org/sponsored-projects/affiliated-projects

SunPeek software features

- Compatibility: SunPeek runs on Windows / Mac / Linux (using Docker containers)
- Automated calculation and comparison of measured and estimated power output for collector fields (Power Check according to ISO 24194)
- Real-world demo solar plant, with open dataset of measurement data from real plant operation.
- Graphical User Interface (GUI) for fast and interactive plant configuration and evaluation
- Measurement data: Support of common text-based data formats
- Connection to Solar Keymark Collector Database (work in progress) and option to add custom-defined collectors.
- PDF reports and CSV export of calculation results.
- Automatic conversion between ISO 9806 QDT (quasi-dynamic) and SST (steady-state) collector test certificates.
- Automated data pipeline for data cleaning and data calculation, compensating for missing sensors.
- Fluid properties support, with pre-defined and custom fluids, and CoolProp [33] database integration.
- Enhanced Power Check applications (e.g., filtering of stagnation events, application to multiple fields, Extended Power Check).
- Standardized interface (REST API) for integration into existing software tools and databases.
- On-premises data storage, no need to share data with third parties.

ISO 24194 reference implementation

The software incorporates the first open-source implementation of Power Check of ISO 24194:2022 and is designed to serve as the reference software implementation of ISO 24194. Specifically, SunPeek has the following goals:

- Make the ISO 24194 Power Check implementation easily accessible and free of charge, including for commercial use, without the burden of every user designing their own tool.
- Provide a fully automated implementation and transparent implementation where data handling and each calculation step is traceable.
- Start a dedicated community around an open development approach, where users can contribute, request features, or participate actively in the development process. The goal is to achieve a trusted, harmonized, consistent, high-quality and well-maintained implementation of ISO 24194 for the solar community (see Section **E.4**).
- Clarify the standard where it leaves room for interpretation when moving from a paper document to a software implementation and suggest further improvements.
- Provide a framework and development platform, aimed at performance monitoring and assessment algorithms for solar thermal plants, with a standardized software interface that allows integration of SunPeek with other software tools.

The longer-term SunPeek development goals are summarized in a Roadmap[6], as is common for open-source projects. SunPeek strives to improve the user experience and code quality, aligning with developments of the standard and integrating topics not yet covered, like Daily Yield Check (see Section **A.9**).

Licenses

The SunPeek Web-UI is available under the BSD-3-Clause license[7], the SunPeek Backend uses the GNU Lesser General Public license[8]. These licenses allow free commercial use. SunPeek is distributed without any warranty and even without the implied warranty for merchantability or fitness for a particular purpose.

[6] https://sunpeek.org/resources/roadmap
[7] https://opensource.org/license/bsd-3-clause/
[8] https://opensource.org/license/lgpl-3-0/

C.2. How to run Power Check with SunPeek

Figure 19 illustrates how SunPeek can be used to perform Power Check according to ISO 24194: After installing SunPeek, a user can configure new plants using the User Interface (or the Python Backend). In this step, the most important parameters of the plant (e.g., location, installed collectors, etc.) are defined. After providing measurement data, Power Check can be executed in the User Interface. The process is described in more detail in Sections **C.3** to **C.5**.

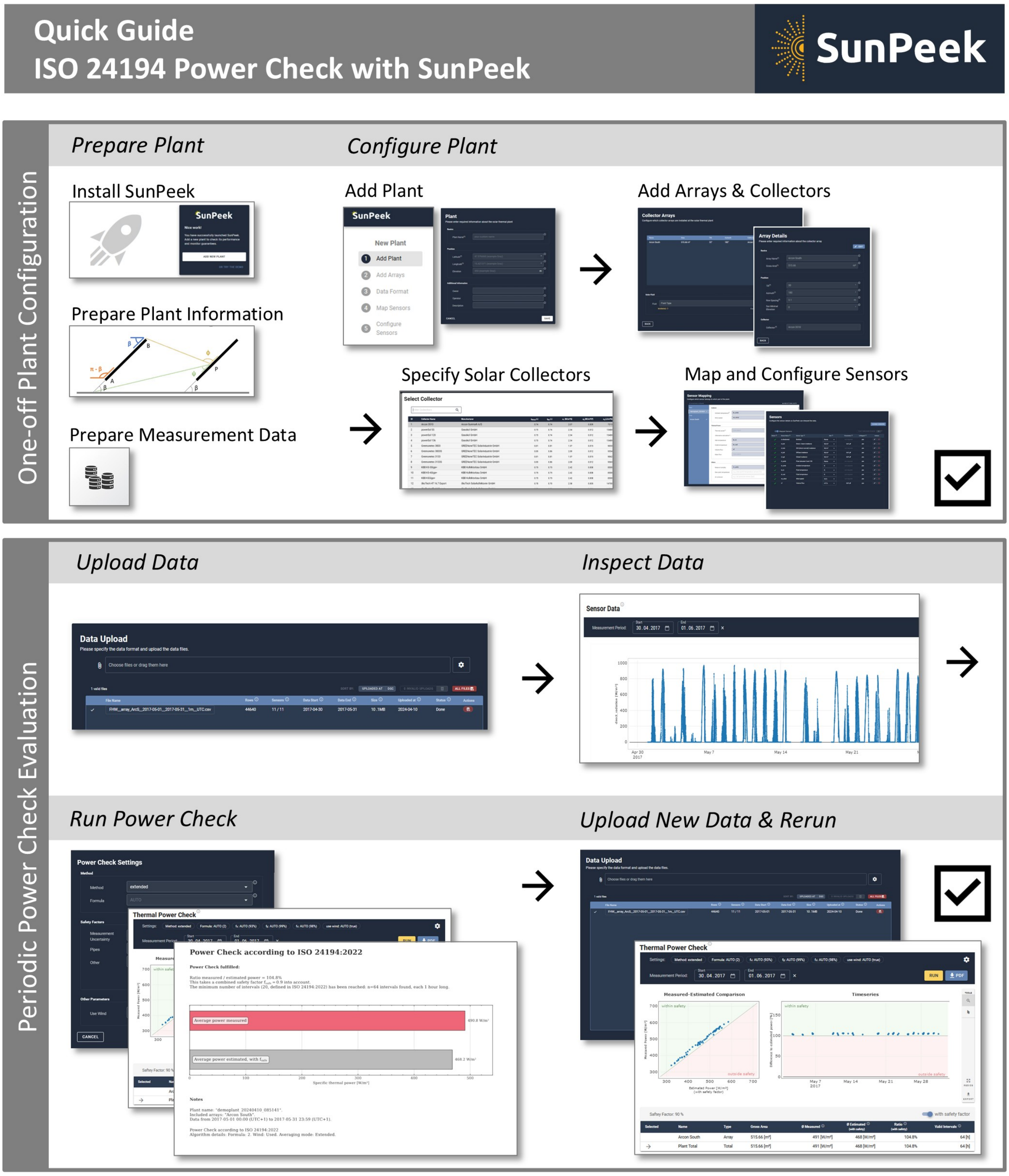


Figure 19. Quick Guide to ISO 24194 Power Check with SunPeek.

C.3. Plant configuration

This section describes how new plants can be added to SunPeek to run Power Check.

Overview

To set up a plant in SunPeek, a one-off configuration is required. The configuration collects all the information needed to run Power Check on the plant. This includes information like the plant location, collector parameters, measurement data format, and measurement setup with the respective data channels. As shown in **Table 10**, plant configuration is done in five steps, and SunPeek guides the user through each step. The following paragraphs discuss the steps in more detail.

Table 10. Plant configuration in five steps.

Step	*Configu-ration page*	*Action*
1	Plant	Enter the parameters which are *common for the whole plant*, e.g., longitude and latitude.
2	Arrays	Enter information *for all fields* and *select the collectors used*. If the power output is not directly measured (only volume or mass flow is available), select a fluid from the database, and SunPeek will calculate the power output. SunPeek requires each collector field to be uniform, i.e. consisting of one collector model with a geometrically uniform arrangement (same mounting and row spacing, rectangular shape of the field on a plane), see Section **B.2** on how to treat complex arrangements.
3	Data Format	Upload a *sample measurement data file* to provide the *data channel names,* which are later used for Power Check. Also, define the *datetime format* and *time zone* of the data. For a list of available data formats, see Section **C.7**.
4	Sensor Mapping	In Sensor Mapping, *measurement data channels are linked with input slots for computations.* In the automated SunPeek Power Check evaluation, these input slots have clearly defined meanings, accessible via *tooltip descriptions* in the Web-UI. Input slots are available for all required data channels (e.g., collector inlet temperature), but also for optional inputs (e.g., a custom shadow-horizon “Array is shadowed”). To accommodate various *measurement setups*, SunPeek offers a range of input slots and allows calculation of some data channels (e.g., thermal power output can be calculated using volume or mass flow, inlet and outlet temperature, and a heat transfer fluid). The same data channel can also be mapped *multiple times*. For example, the same temperature sensor can be used as array inlet temperature for several arrays (see Section **B.2**).
5	Sensor Properties	The sensor configuration specifies additional properties of each data channel, such as the *physical unit* in which measurements are provided. For some data channels, *additional sensor properties* are required, e.g., tilt and azimuth angles for an irradiance sensor.

Start: Add a new plant

After successfully installing SunPeek, the SunPeek Web-UI shows a welcome screen in the web browser, as shown in **Figure 20**. Using the “TRY THE DEMO” button creates a new plant with the pre-configured solar plant “Fernheizwerk” (see Section **D.2** for details). The button “ADD NEW PLANT” starts the configuration for a user-defined plant.

If plants are already added to the SunPeek instance, the welcome screen is automatically redirected to the Plant Overview screen. In this case, a new plant can be configured using the “ADD PLANT” button, another demo plant by clicking on “ADD DEMO PLANT” (see **Figure 21**).

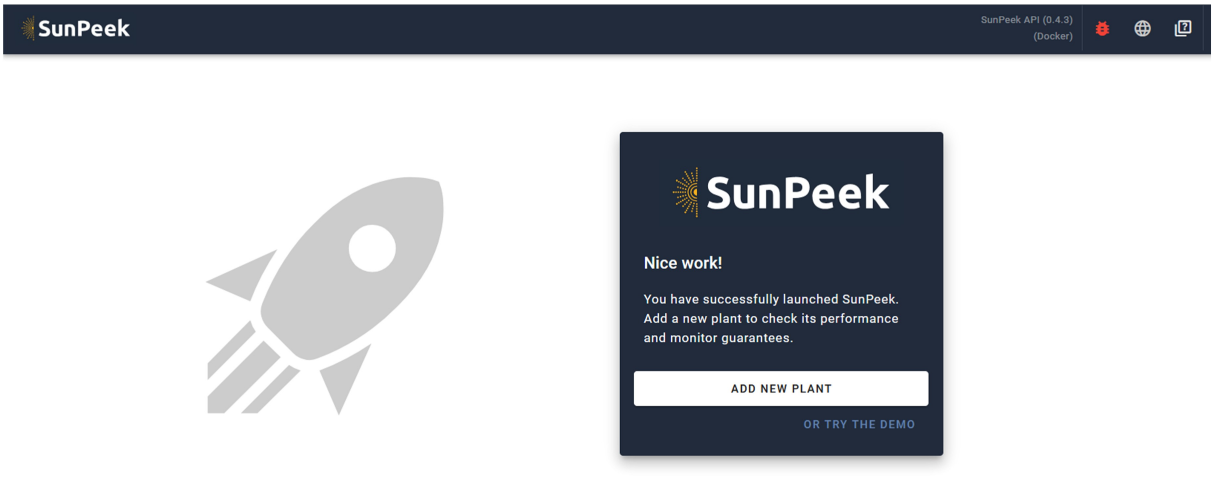


Figure 20. Welcome Screen after successfully launching SunPeek.

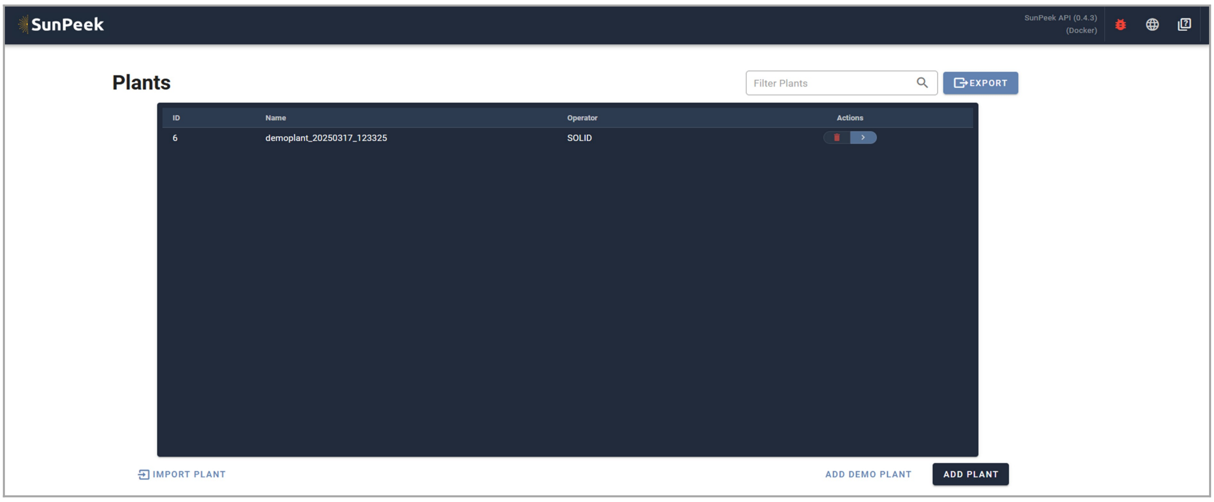


Figure 21. Plant Overview page appearing if a plant already exists.

Step 1: Plant configuration

The first step of the configuration as shown in **Figure 22** deals with parameters that are common for the whole system, e.g., longitude and latitude of the plant location. This information is used for calculations (e.g., angle of incidence) and for referencing the plant in the overview page (e.g., name of plant, operator, additional description).

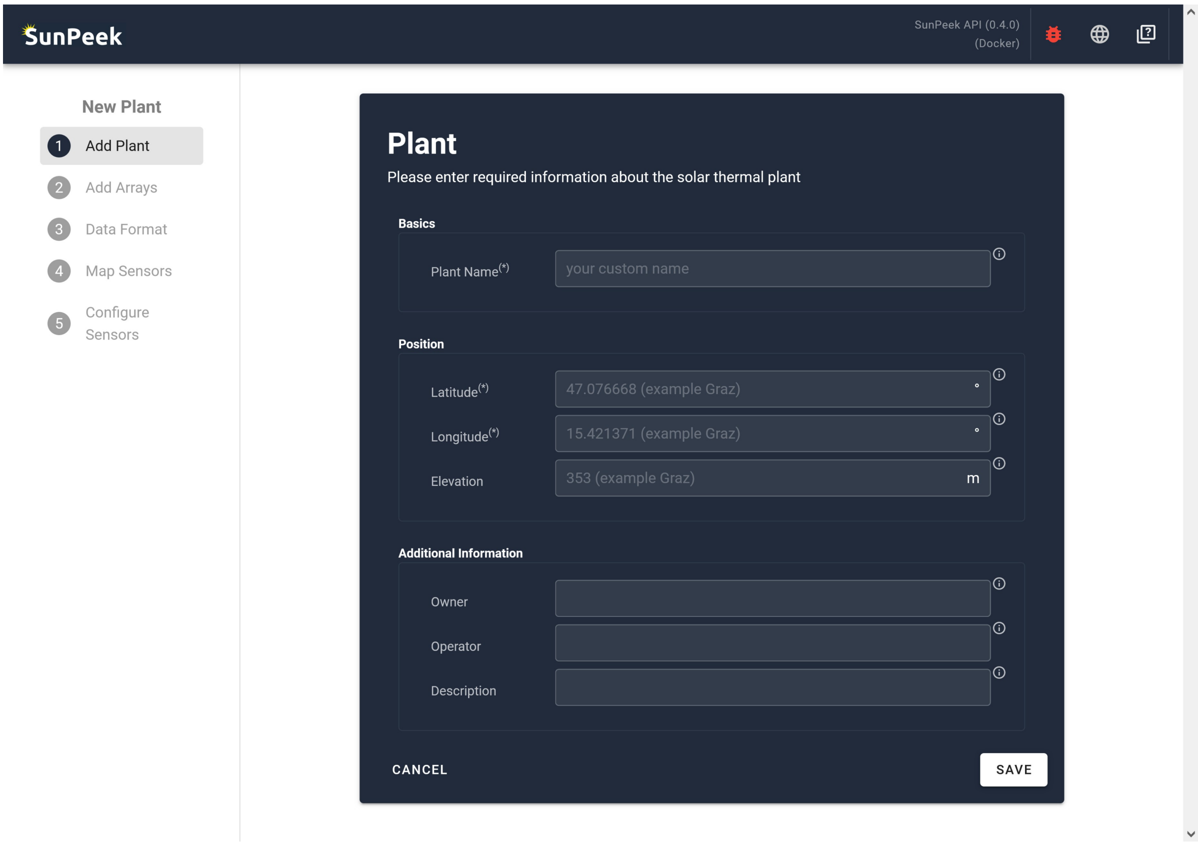


Figure 22. Screenshot of the plant configuration step.

Step 2: Array configuration

This step allows the user to define the individual collector arrays that are to be checked according to ISO 24194. SunPeek allows the user to specify multiple collector fields with different collector models and sizes (see **Figure 23**) and supports some Power Check applications with multiple collector fields connected in parallel (see Section **B.2** for details). A fluid can be selected from a dropdown menu and its concentration can be specified to allow the calculation of power based on volume flow and temperatures. If the fluid is not listed, the Python backend allows a manual configuration of fluid properties.

For each collector field the gross area, orientation, and row spacing can be specified, see **Figure 24**. In addition, a collector model (containing the Solar Keymark Parameters) can be selected from the SunPeek database or can be added manually, see **Figure 25**. Finally, a name can be added for referencing the Field inside the SunPeek application.

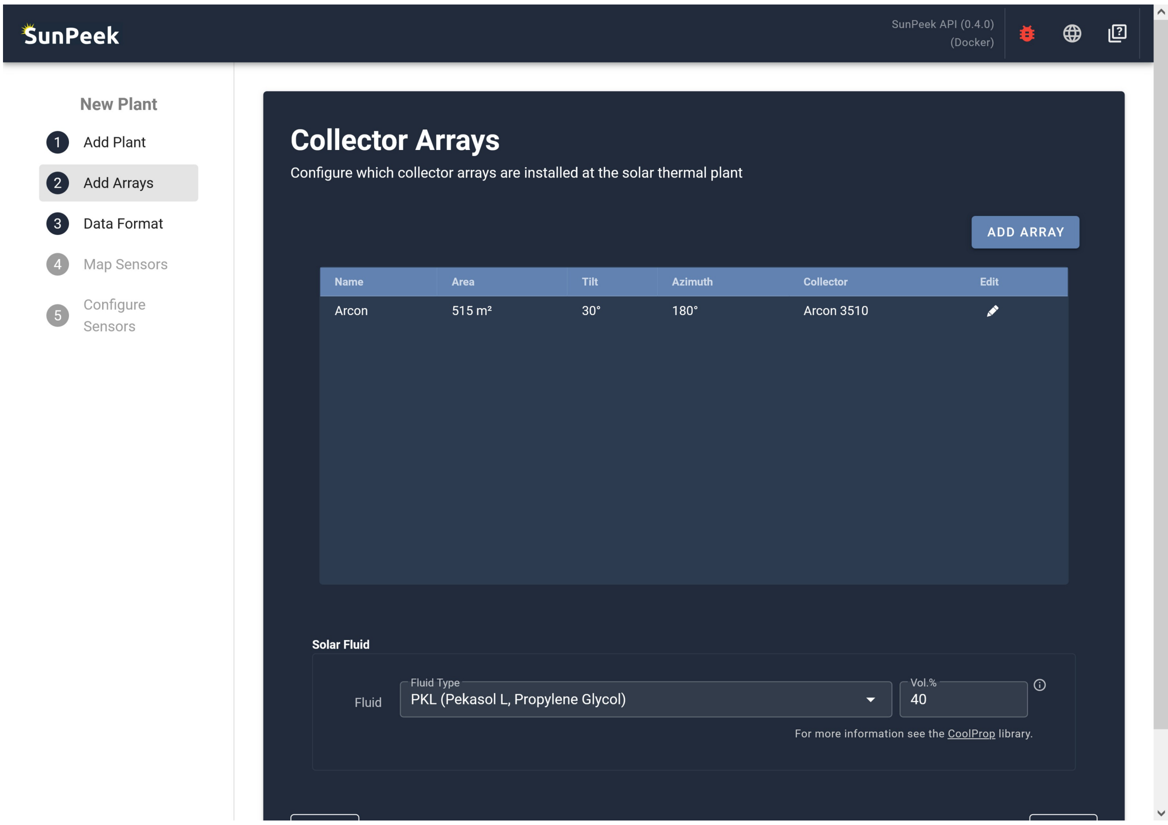


Figure 23. Screenshot of the array configuration step. Multiple collector fields can be added.

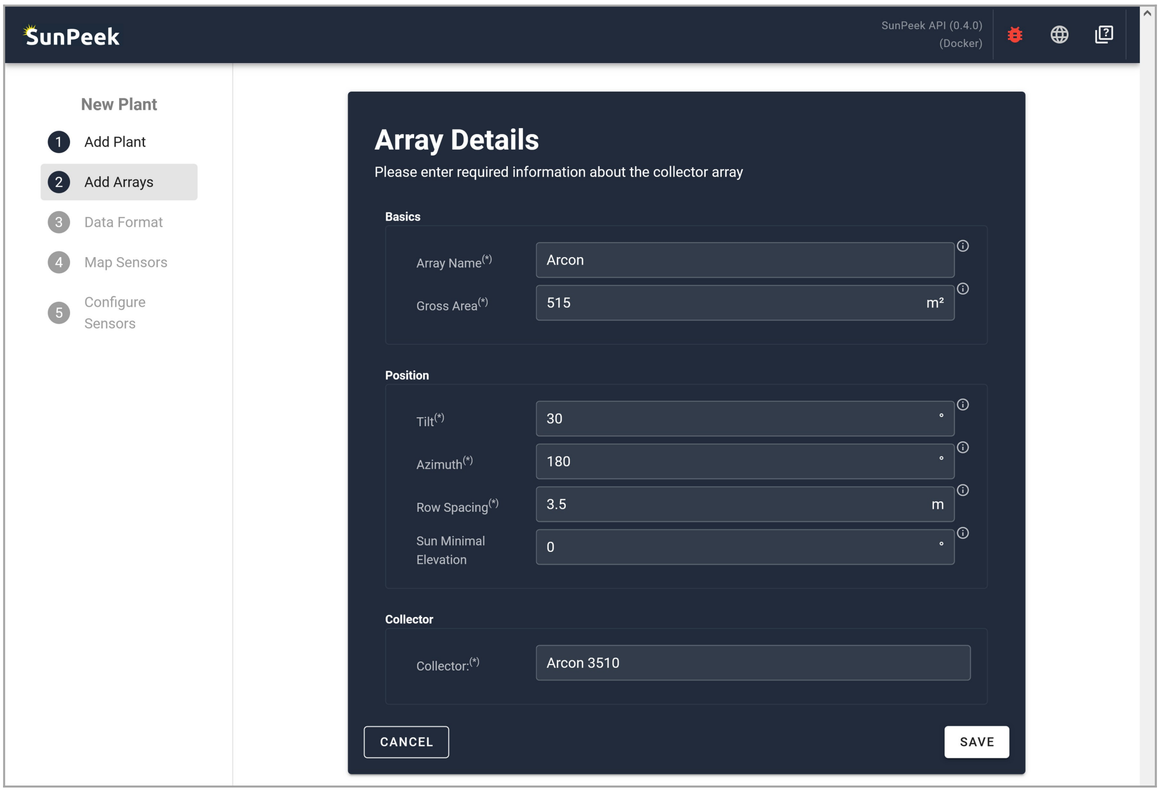


Figure 24. Screenshot of interface to add collector field details.

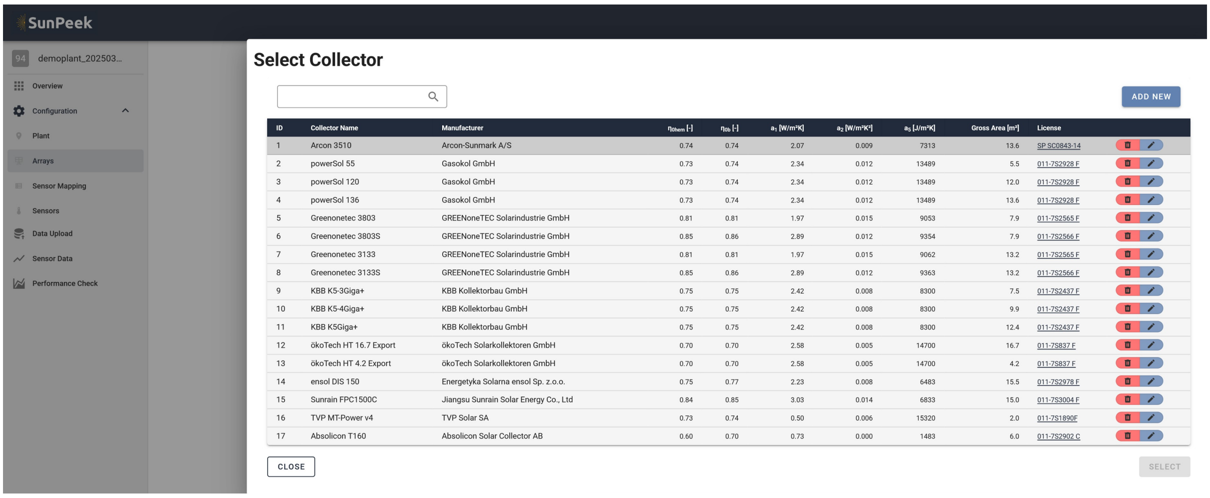


Figure 25. Screenshot of Select Collector page.

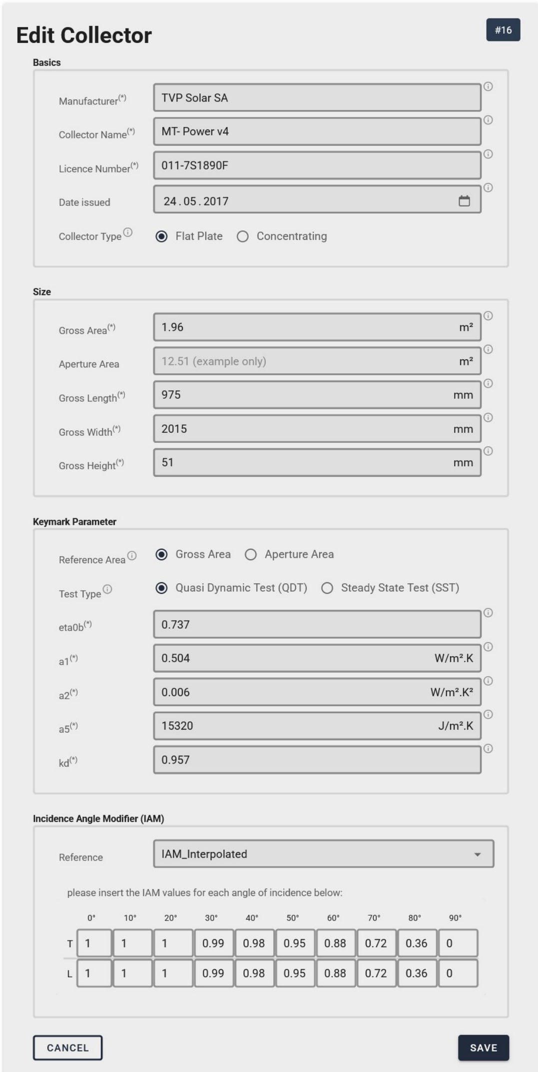


Figure 26. Screenshot of *"Edit Collector"* page, which opens when clicking on the *"Edit"* symbol in the Select Collector page.

Step 3: Data Format

SunPeek can handle tabular data in text files (e.g., TXT or CSV files, comma-separated values), accepting a variety of format details like file encoding, decimal and field separators, and time zone information. The tool must know how to interpret the measurement data that is uploaded to the application. Thus, this step allows the user to upload a sample measurement file and specify the data format and time zone parameters (see **Figure 27** and **Figure 28**). The datetime format and time zone is critical to ensure that the angle of incidence and shading calculations match with the content of the data, see Section **C.7** for background information. For convenience, the parsed data is shown to the user to check if SunPeek parses the data correctly.

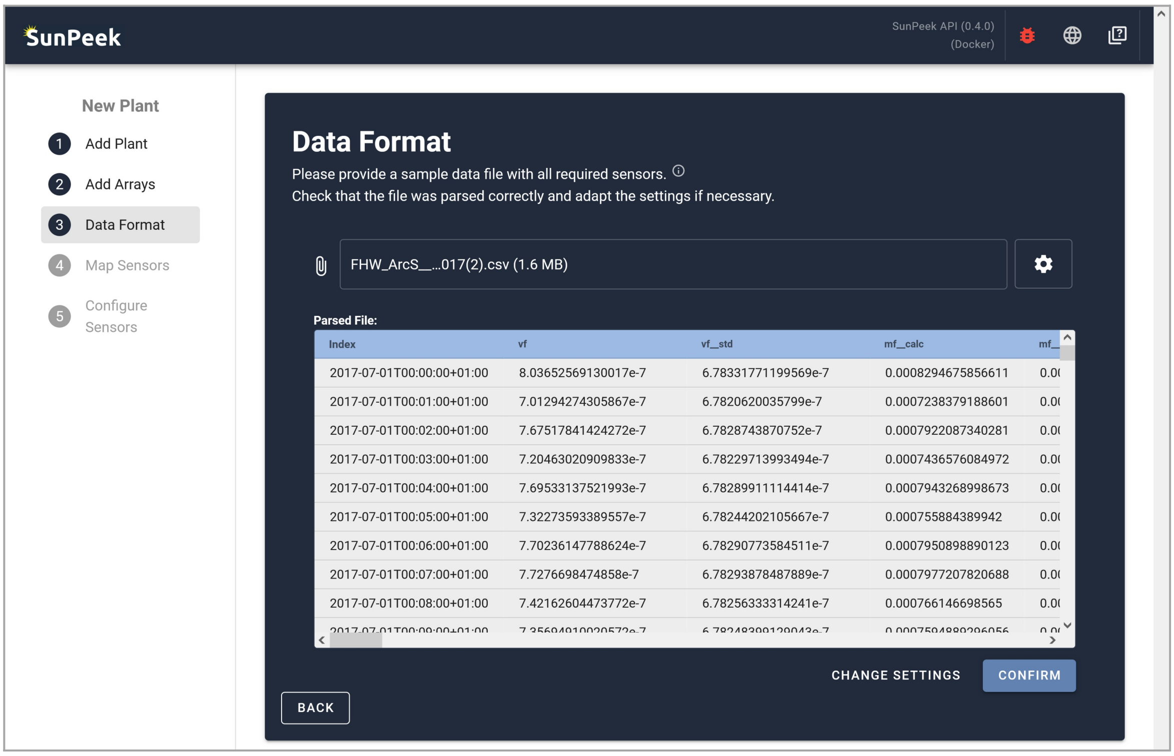


Figure 27. Screenshot of the Data Format configuration after selecting a sample CSV file in the file input. Parsed data is shown to the user to check if the parsing is correct.

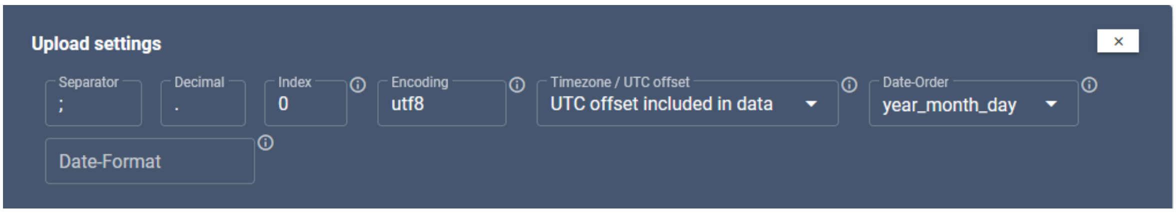


Figure 28. Screenshot of the Data Format parameters that can be specified by the user.

Step 4: Sensor Mapping

ISO 24194 describes the measurement points of two standard systems with one collector array, i.e. systems without heat exchanger and with heat exchanger respectively (ISO 24194, Figures 5 and 6), see **Figure 5** in this document. The sensor mapping for a plant without heat exchanger is shown in **Figure 29**, for the system with heat exchanger in **Figure 30**. SunPeek does not model the heat exchanger explicitly, and instead simply assigns the data channels required for the ISO 24194 Power Check to "Plant" and/or "Array". **Table 11** lists the current input slots for sensor mapping available in SunPeek, marks if they are required or optional for the standard systems with and without heat exchanger and shows some example usage for ISO 24194 calculations.

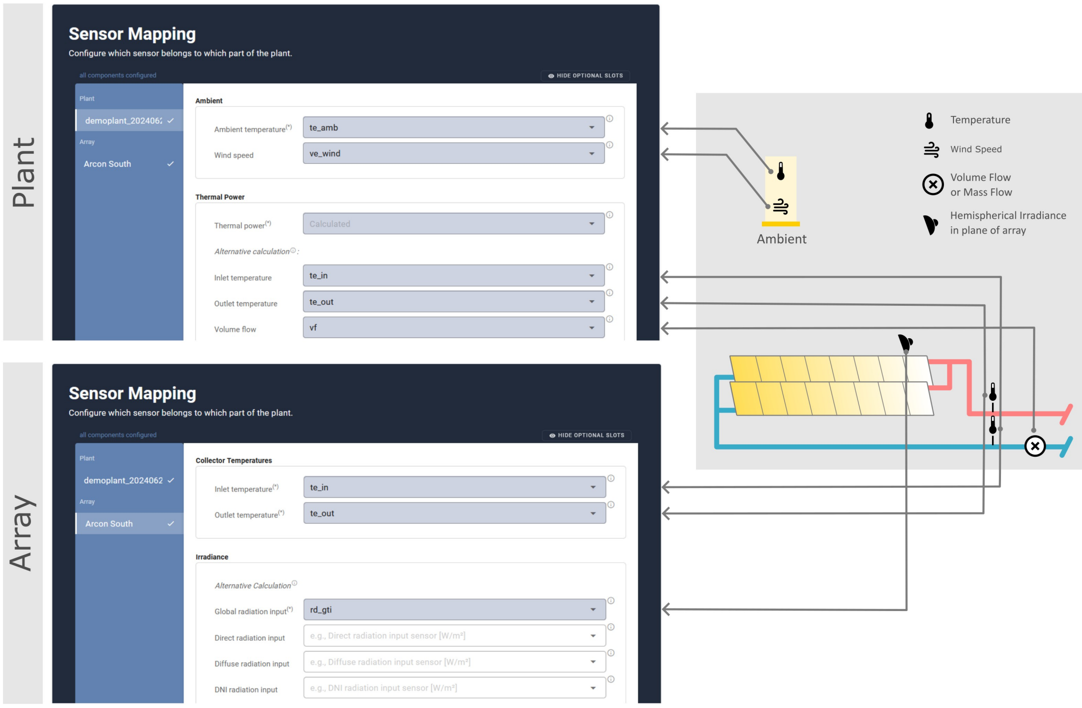


Figure 29. Screenshot of Sensor Mapping page for systems without heat exchanger and corresponding sensor position in hydraulic scheme.

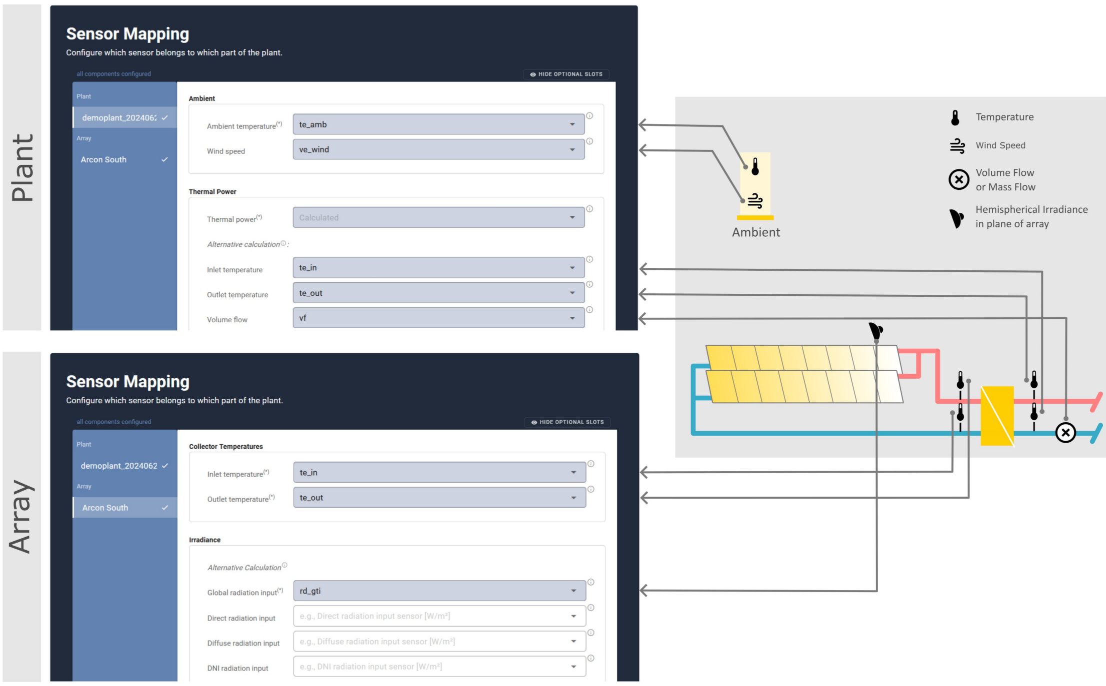


Figure 30. Screenshot of Sensor Mapping page for systems with heat exchanger and corresponding sensor position in hydraulic scheme.

Table 11. Required and optional parameters and sensors for plants with one collector field and with or without heat exchanger. Symbols refer to terms and definitions used in ISO 24194, see also Section **G.1**.

Name	*Symbol* [1]	*Requried* [2]	*Comments, Examples*
Plant level			
Ambient temperature	ϑ_a	Y	
Wind speed	u	(Y-S)	To check data filtering restrictions [3]
Thermal power (measurement)	$\dot{Q}_{\text{measured}}$	(Y-S)	Can be calculated if not directly available
Thermal power (calculation)		(Y-S)	Required if no power measurement available
Inlet temperature	ϑ_i, $\vartheta_{i,\text{sec}}$	(Y-S)	
Outlet temperature	ϑ_e, $\vartheta_{e,\text{sec}}$	(Y-S)	
Volume flow	$\dot{V}_{\text{pri}}$, $\dot{V}_{\text{sec}}$	(Y-S)	
Mass flow	$\dot{m}_{\text{pri}}$, $\dot{m}_{\text{sec}}$	(Y-S)	Alternative for volume flow
Relative humidity		N	
Dew point temperature		N	
Air pressure		N	
Array level			
Inlet temperature	ϑ_i	Y	
Outlet temperature	ϑ_e	Y	
Global (hemispherical) radiation input	G_{hem}	(Y-S)	For Formula 1 or 2
Direct radiation input	G_{b}	(Y-S)	For Formula 2 or 3 if no DNI
Diffuse radiation input	G_{d}	(Y-S)	For Formula 2 if no G_{b} or DNI
DNI radiation input	DNI	(Y-S)	For Formula 2 or 3 if no G_{b}
Thermal power	$\dot{Q}_{\text{measured}}$	N	Assumed to be same as plant, for installations without heat exchanger.
Volume flow	$\dot{V}_{\text{pri}}$	N	
Mass flow	$\dot{m}_{\text{pri}}$	N	
Array is shadowed		(Y-S)	User defined horizon mask [4]

[1] According to ISO 24194, Chapter 4. Subscript *pri* indicates measurements in collector loop (primary side), subscript *sec* after the heat exchanger (secondary side).
[2] Required for Power Check. Y = Yes (required for *all* plant / collector field configurations), (Y-S) = Yes-Setup (required for *some* plant / collector field configurations), N = No (not required).
[3] Wind speed measurement is considered optional; see remarks in Section **A.5**.
[4] Allows using more complex horizons, or shading modeled with third-party software.

Step 5: Sensor Properties

In the last step of the plant configuration, the user confirms the physical unit of each measurement data channel. This is done in the "Sensors" tab during plant configuration, see **Figure 31**. Some channels require specifying additional information, such as tilt and azimuth angles for irradiance sensors.

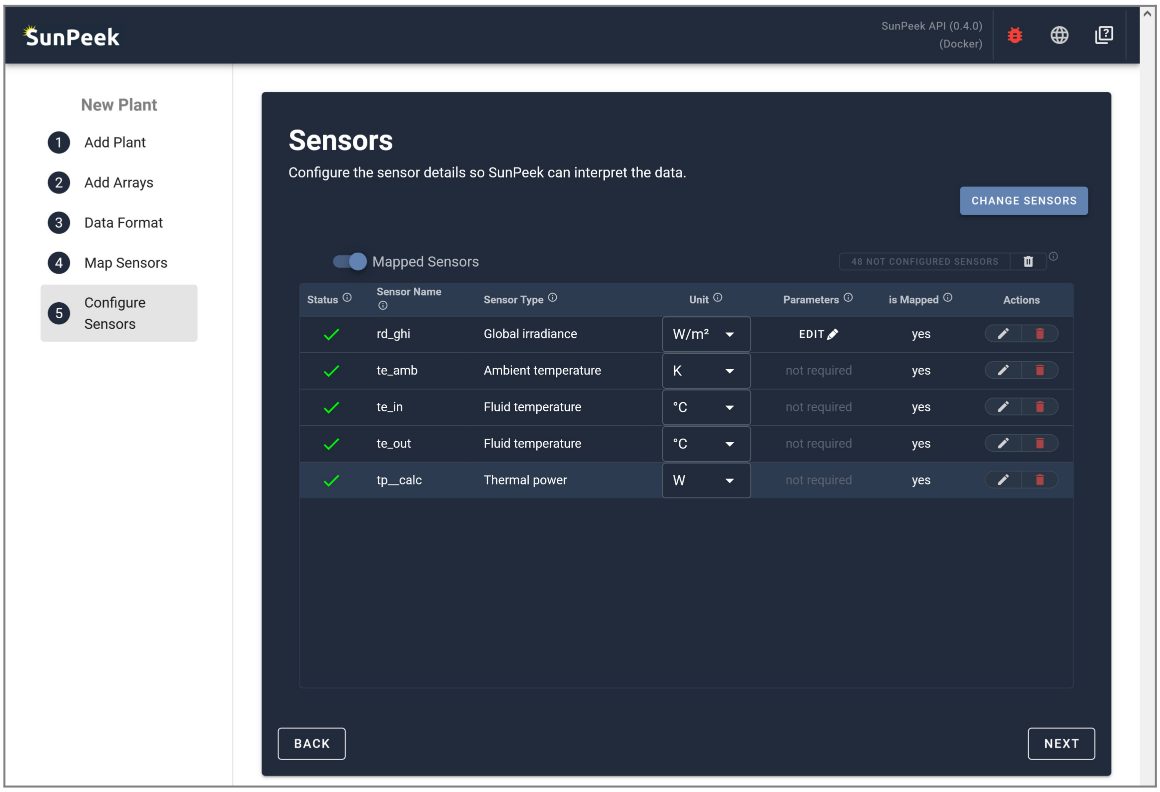


Figure 31. Screenshot of Sensor definitions like physical units and other properties for the provided sensors (data channels).

State after successful plant configuration

After the plant has been configured, a message appears to confirm the successful configuration (**Figure 32**). Users can proceed to upload measurement data (see Section **C.4**) and run Power Check (see Section **C.5**). The plant configuration only has to be done once as information is stored in the database. However, user can adapt information in the "Configuration" tab.

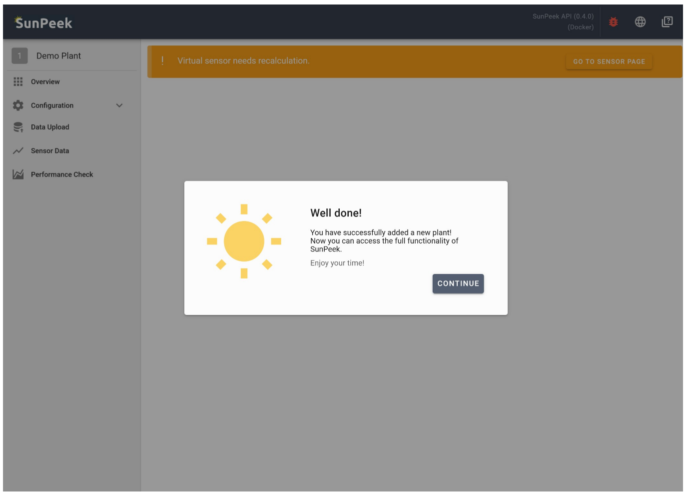


Figure 32. Screenshot of SunPeek after plant configuration was successfully completed.

C.4. Data upload and inspection

This section describes how data can be uploaded to SunPeek and how data channels can be checked.

Data upload

On the "Data Upload" page, users can upload measurement data files via drag and drop and check the data upload history (see **Figure 33**). Uploaded measurement data will be automatically processed, concatenated, and saved in the SunPeek data storage. Data can be spread across multiple files, with each file covering a specific time interval. SunPeek can receive multiple files in one go and combine them in the right time order. However, there are some notable limitations:

- If multiple data files are provided, data channel names must be the same across all files. Additionally, unused columns or data channels are unproblematic (they will not be stored however).
- For a given time interval, all data channels need to be in the same file. SunPeek cannot combine data channels from multiple files.
- For timestamps, SunPeek requires one datetime column. SunPeek does not accept timestamps split into two columns (e.g. day and time columns).

In case erroneous data has been uploaded, SunPeek allows deleting either single upload entries, or all uploaded data for the plant. If a new data upload overlaps in time with already stored data, the new data will overwrite the existing data in the overlapping period. Uploading data also triggers SunPeek to (re-)calculate all virtual sensors, such as sun position, collector field shadowing, etc., for the uploaded period. See Section **C.8** for details on virtual sensors.

The SunPeek databases are created at SunPeek installation. By default, SunPeek uses file-based Parquet storage for measurement data and SQLite for configuration data (see Section **C.7**). If SunPeek is set up on a server, an admin can grant access to multiple users or make access public, as it is for the *SunPeek Demo Server*[9]. The tool can also be installed on a single user machine for local use on that machine.

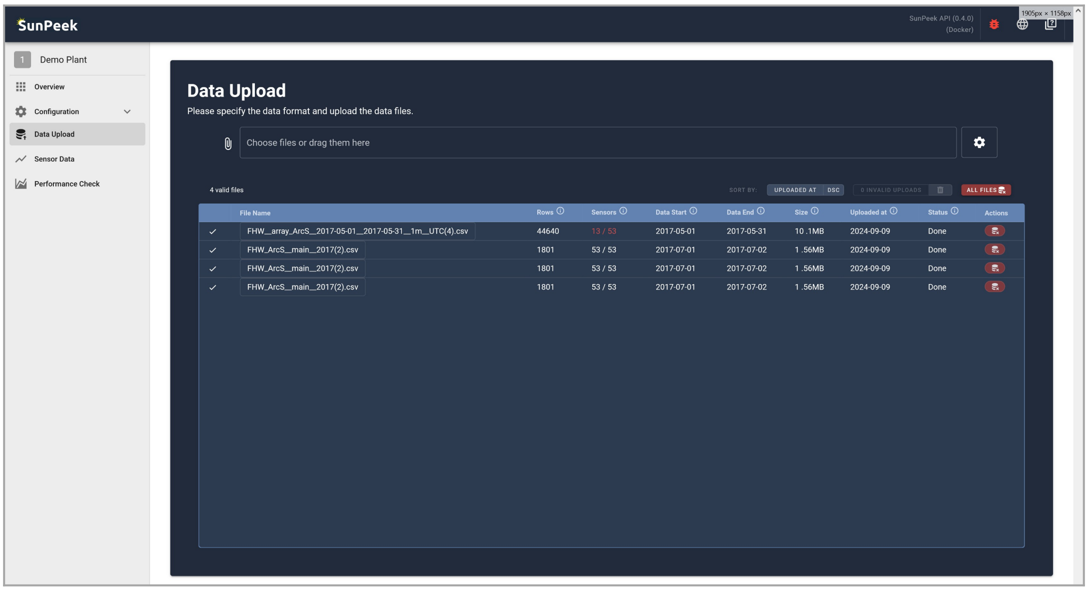


Figure 33. Screenshot of Data Upload page.

Visual data inspection

For visual data inspection, SunPeek provides a graphical time-series view of the uploaded measurement data (see **Figure 34**). This view displays the data after all internal quality checks, the same data

[9] https://gitlab.com/sunpeek/

SunPeek utilizes in its calculations and in Power Check analysis. Virtual sensors are displayed just like any of the regular data channels.

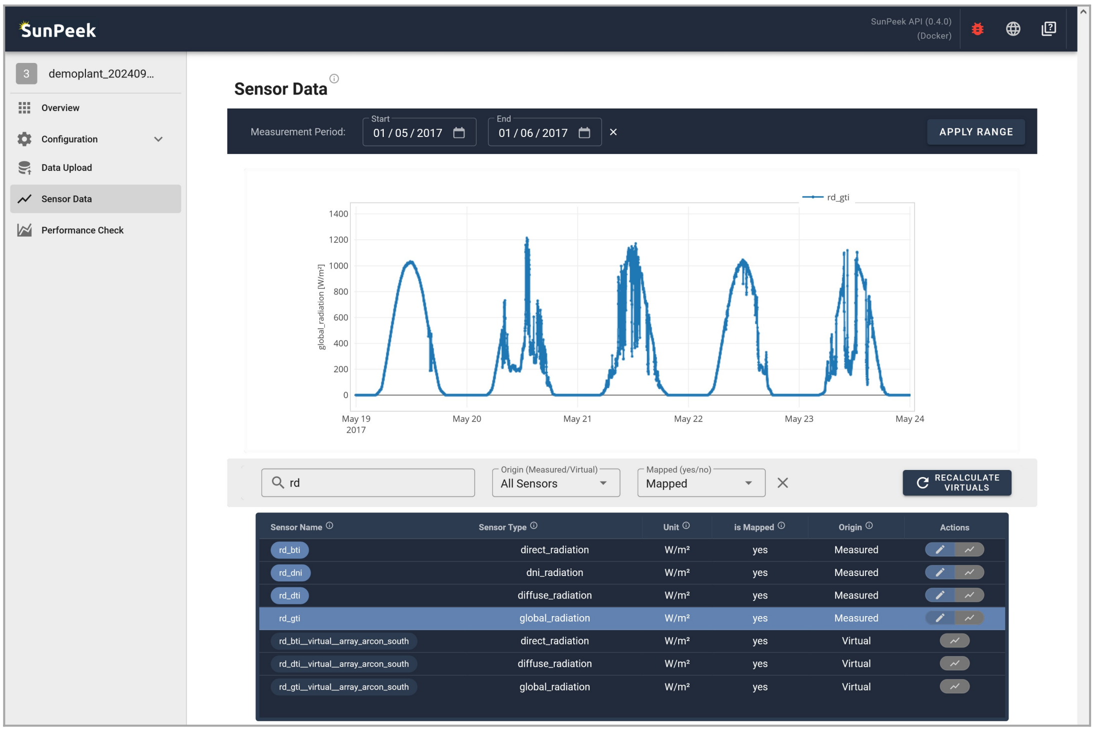


Figure 34. Screenshot of line plot for visual data inspection.

C.5. Power Check application

This section shows how to execute Power Check following the ISO 24194 recommendations and covers the export of data and figures.

Executing Power Check

After successful data upload, Power Check can be executed. The results are presented in three different segments in the SunPeek Web-UI as shown in **Figure 35**:

- *Middle left*: A measured vs. estimated comparison of power outputs for all valid data records, inspired by Figure 3 in ISO 24194.
- *Middle right*: A time-series plot of the measured-estimated power ratio of all valid data records, which is not mentioned in the standard, but is helpful to detect performance changes over time. Both these plots are also included in the PDF report.
- *Bottom*: A table containing the results of Power Check for the selected evaluation period. It shows the number of valid data records (intervals), the average measured and estimated power, and the average power ratio. Each field is represented in an individual row, while the plant total is displayed in the last row. Clicking on the individual rows allows the user to inspect the results of the fields individually, updating the plots.

A toolbar on the outer right enables zooming and allows selection of datapoints in the plot. Upon selection, the table is updated to only show results of the selected valid intervals. The Web-UI offers an interactive option to switch the chosen safety factor on or off (i.e. $f_{safe} = 1$) by using the toggle switch on the bottom-right. This updates the plots and tables immediately. The toolbar at the top allows the user to set an evaluation period / measurement period by specifying a start and end time used for calculating Power Check results.

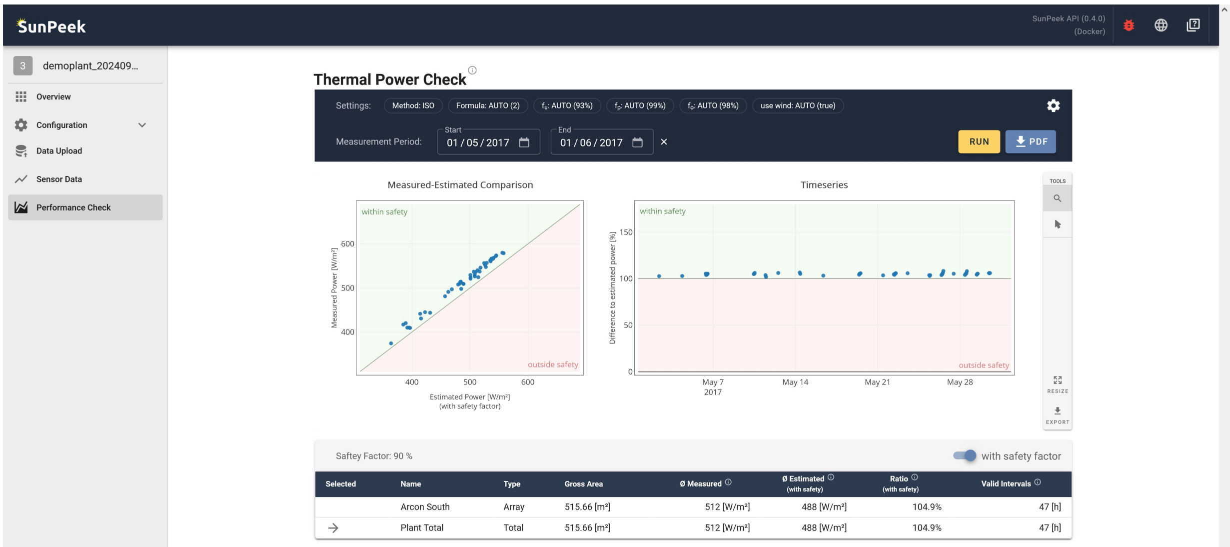


Figure 35. Screenshot of interactive graphical and tabular display of Power Check results. Each dot represents one valid data record (1-hour interval). The toggle on the bottom-right allows interactively switching the safety factor on or off.

Power Check settings

Power Check settings can be adjusted by clicking on the gear symbol at the top right of the page. The following parameters can be set on plant or array level (see **Figure 36**):

- *Method*: The user can choose between two data averaging methods. “ISO” uses intervals that start and end at full hours as described in ISO 24194 (see Section **A.7**), “Extended” uses a moving-window approach (see Section **B.1**).
- *Formula*: Choice of Formula 1–2 as defined in Section **A.3** (Formula 3 is not yet implemented). For each collector field, SunPeek checks if the formulas are consistent with the available data channels.
- *Safety factor*: Power Check uses a safety factor to compute the estimated power. The three safety factors for “Measurement Uncertainty”, “Pipes” and “Other” can be set here.
- *Use Wind*: Decide if wind speed is used as a data filtering criterion to check restrictions on operating conditions (see Section **A.5**). If the check is done with wind speed and the data channel is not available, the evaluation outputs an error.

“AUTO” settings: SunPeek simplifies plant configuration by providing sensible default values as an auto-mode, where it tries several possible settings for Power Check and chooses the most appropriate. SunPeek has an auto-mode for these settings:

- *Evaluation period / measurement period*: By default, a period that includes all uploaded data is used.
- *Method*: “ISO” is the default option for the data averaging method.
- *Formula*: For all collector types, Formula 2 is chosen if it can be applied (e.g., if beam / DNI irradiance data is available), otherwise Formula 1 is chosen.
- *Safety Factors*: By default, the safety factors are $f_P = 0.99$ for heat losses from pipes $f_U = 0.93$ for measurement uncertainty, and $f_O = 0.98$ for other uncertainties. This results in an overall safety factor $f_{\text{safe}} \approx 0.90$. Be aware that these default values do not indicate recommendations and do not consider actual accuracy levels of the installation.
- *Use Wind*: If wind speed measurement is available, use it as a data filtering criterion. If wind is not available, the wind speed requirement in ISO 24194 Table 1 is ignored.

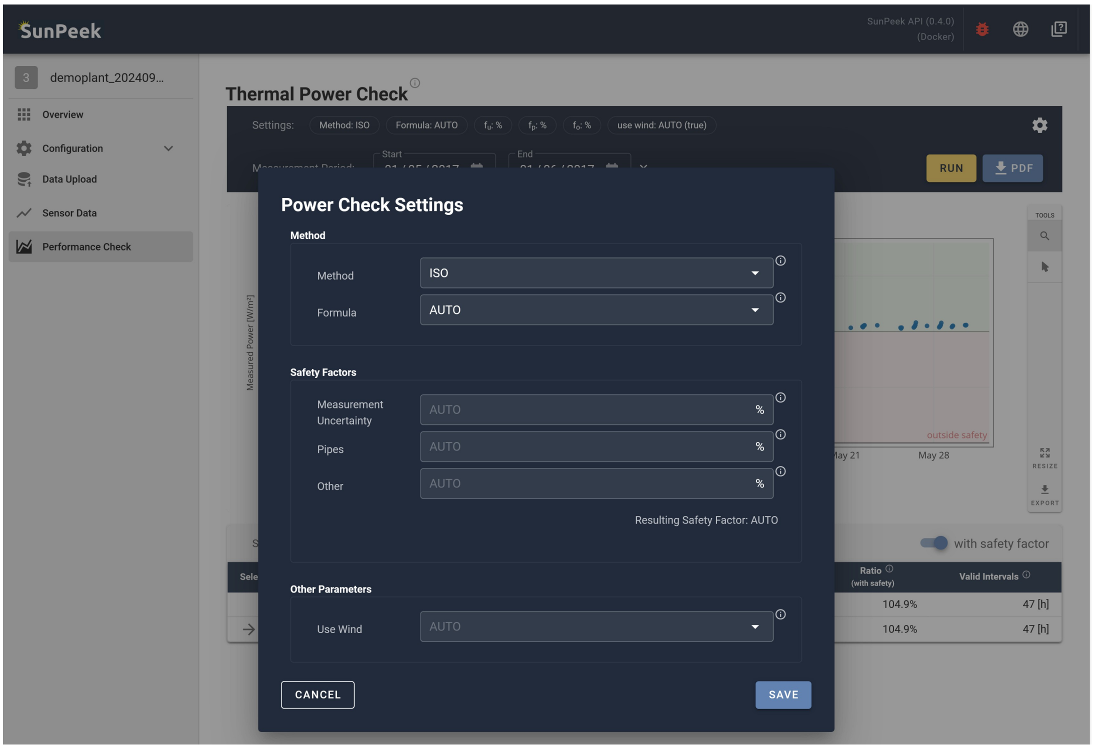


Figure 36. Screenshot of Power Check Settings, which can be adjusted when clicking on the gear icon at the top right of the toolbar.

Export

SunPeek also features an export function both via the Web-UI and Python API. The following options are available to export Power Check results:

- *CSV file:* Download the numeric calculation results as a CSV file by clicking on the "Export" button on the grey toolbar on the outer-right on the Power Check page.
- *PDF report:* Download a PDF report which comprehensively follows the content recommendations of ISO 24194 Annex A by clicking on the blue button in the top-right corner. Example pages are shown in **Figure 37** and Section **D.2**.
- *Extended PDF report*: Download an extended PDF report (API only), including a detailed time-series plot for each data record on original sampling rate, see example plots in **Figure 49**.

ISO 24194 suggests several graphical representations of Power Check results. The main plot is Figure 4 (in the standard) showing the overall Power Check result in a bar chart. SunPeek features this plot in its PDF report (see **Figure 37**), adding key numeric results such as the average power ratio.

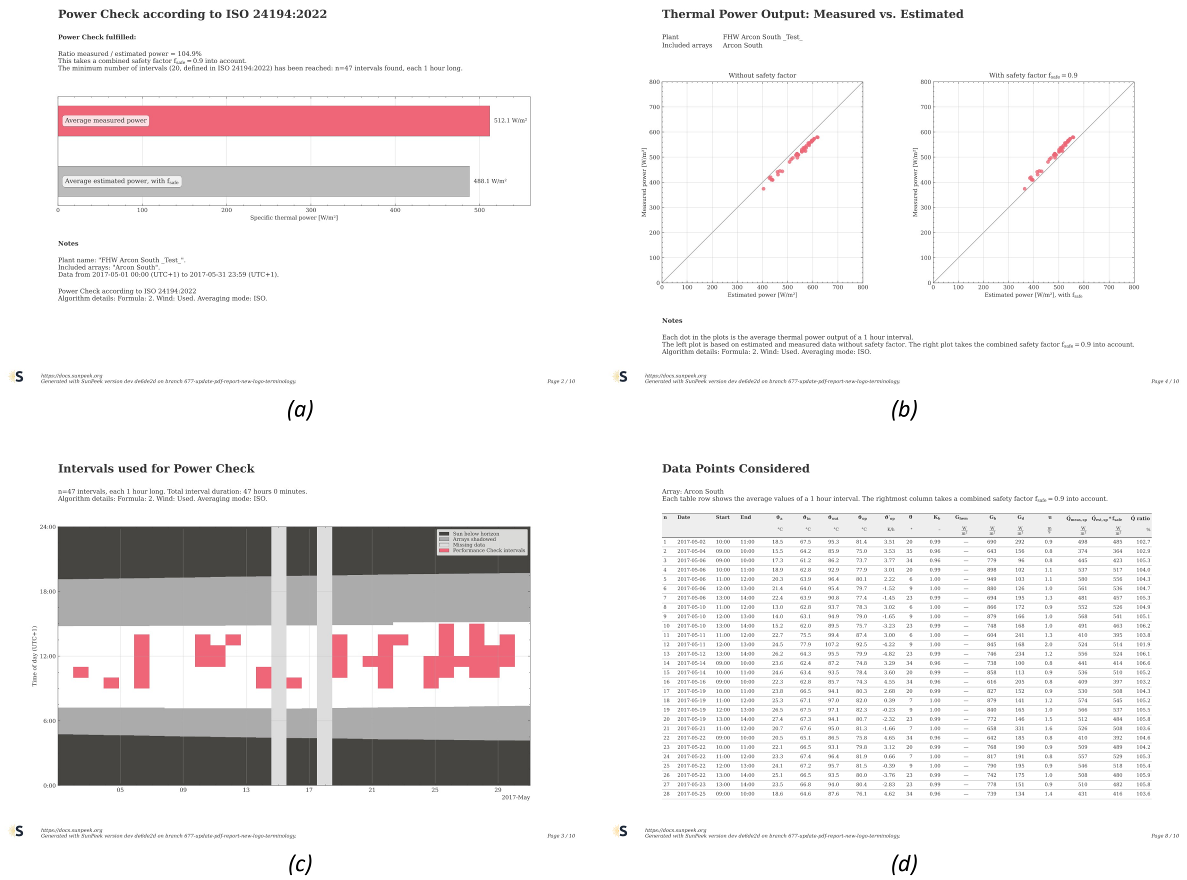


Figure 37. Example pages of Power Check PDF report in SunPeek: (a): Average measured and estimated power output (averaged over all valid data records), similar to Figure 4 in ISO 24194; (b): Measured vs. estimated power output for valid intervals, without safety factor (left) and with safety factor (right), similar to Figure 3 in ISO 24194; (c): Distribution of valid data records (intervals), no similar figure in ISO 24194; (d): Numeric calculation results for valid data records, extension of the “Data points considered” table in ISO 24194 Annex A.

C.6. Power Check implementation

The SunPeek implementation closely follows the standard and the recommendations of Chapter **A**. Nevertheless, compared to the standard, SunPeek has some limitations, adds some modifications and extensions, and automates the data processing and calculation.

Limitations

The following specifications of ISO 24194 are not yet implemented in the SunPeek version described in this document. These are expected to be included in the future, see SunPeek Roadmap in Section **E.4**:

- Daily Yield Check (ISO 24194, Chapter 6), for details see Section **A.9**.
- Power Check Formula 3 for concentrating collectors with high concentration ratio (ISO 24194, Section 5.2.2).
- Shadows on one-axis or two-axis tracking collectors in a row.

Extensions

The major conceptual extensions of the SunPeek implementation compared to ISO 24194 are:

- An approach for applying Power Check to plants with multiple and heterogeneous collector fields. The current SunPeek version supports a limited number of plant configurations (see Section **B.2**), more complex cases will be added in an improved implementation.

- Automatic calculation of internal (row-to-row) shading, assuming rectangular and regular collector fields, and extending the formulas to collectors mounted on sloped ground. To exclude external shading: option to include a constant horizon profile, in terms of a minimum sun altitude (horizon) or a user-provided shading mask.
- Extended Power Check (see Section **B.1**) with a moving-window ("rolling") data filtering.
- Minimum average power output as additional restriction on operating conditions (see Section **A.5**) to ensure that the plant is in operation.

Modifications

SunPeek introduces the following modifications:

- Requiring *a minimum number of measured values* per 1-hour interval. This excludes applying Power Check to plants if only 1-hour averaged measurement data are provided. For details, see Section **C.7**.
- Allowing Power Check results to be provided with *less than 20 valid data records*, issuing a warning in that case.
- Allowing calculation of Power Check even if there is *no wind speed* measurement (see Section **A.7**).
- *No check or reporting of accuracy levels* of measurement instrumentation. Does not consider accuracy levels in the choice of the default safety factor.
- *Interpretation of the "change in mean temperature"* restriction on operating conditions so as to avoid significant heat up / cool down phases over an interval, i.e., $\left|\overline{d\vartheta_m / dt}\right| \leq 5\ \mathrm{K}$ within one hour (see Section **A.5**).

Data flow and calculation procedure

Data processing for Power Check is only briefly addressed in ISO 24194, and the terminology used is not always consistent. To enhance traceability in data handling and creation of data records, and to allow additional data quality checks, SunPeek requires users to provide the logged raw measurement data (initial recorded data) and does not accept only 1-hour data records. The SunPeek data flow and Power Check calculation procedure are illustrated in **Figure 38** and explained in **Table 12**. Further details can be found in Section **C.7**.

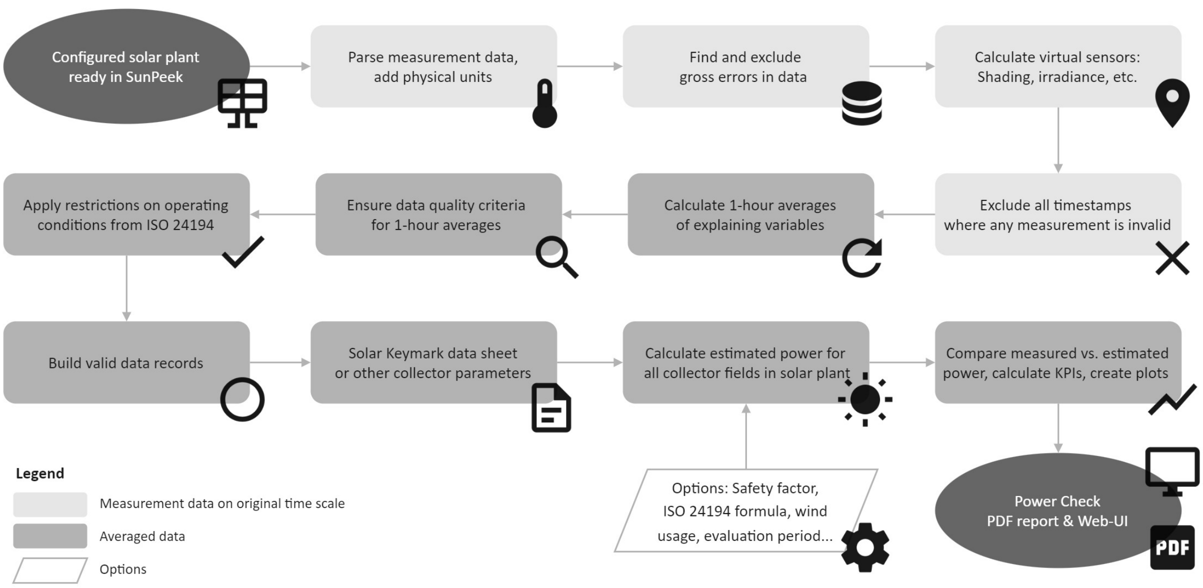


Figure 38. Overview of data processing steps in the SunPeek implementation of the ISO 24194 Power Check. This is a simplified overview and not intended as graphical software documentation.

Table 12. Comments on each data flow step depicted in **Figure 38** for the SunPeek Power Check.

Step	*Explanation*
	Configured solar plant ready in SunPeek: This assumes that the plant configuration in SunPeek has been completed. • For the *plant configuration*, see Section **C.3**. • SunPeek ships with a pre-configured “demo plant” which allows users to run Power Check right away, using the included measurement data, see Section **D.2**.
	Parse measurement data, add physical units: In this step, SunPeek parses the measurement data provided by the user. • Alongside the measurement data, date and time information are also parsed. In practice, this is a critical step and a frequent source of issues, see Section **C.7** for more information. • SunPeek uses unit-aware quantities internally, because using explicit physical units helps to improve data processing quality and avoid unit clashes. It maps unitless measurement data to unit-aware quantities with physical units, and uses these in internal calculations (for details, see Section **C.8**. Users can assign physical units to measurement channels in the SunPeek Web-UI, see Section **C.3**.
	Find and exclude gross errors in data: Measurement data may occasionally contain unreliable or invalid entries. • SunPeek attempts to use only valid and reliable data. While detailed error analysis of the measurement data is out of scope, SunPeek excludes data that are outside physical limits. • For details on these gross error checks, see Section **C.7**.
	Calculate virtual sensors: Shading, irradiance, etc.: Virtual sensors represent quantities required for computations but are not directly measured. • Examples include the solar position, or row-to-row shading of collector rows. Virtual sensor calculations are triggered when new data is uploaded. • Virtual sensors are calculated at data upload. Recalculating virtual sensors might become necessary due to changes in the plant configuration (e.g., sensor mapping, or assigning a different physical unit to a sensor). SunPeek warns when such a recalculation is necessary. Recalculation is computationally expensive; therefore, it is not triggered automatically. • For more details on virtual sensors, see Section **C.8**.
	Exclude all timestamps where any measurement is invalid: The “Sensor Data” page in the SunPeek Web-UI shows all sensor data (both regular and virtual sensors) as used in computations, with all error checks and corrections applied. For Power Check calculation, SunPeek is cautious and excludes all timestamps where *any* of the required sensor data is invalid, ensuring that only timestamps with valid data for all sensors are included.
	Calculate 1-hour averages of explaining variables: Following the ISO 24194 standard, SunPeek calculates 1-hour averaged values (data records), offering two averaging methods, namely a fixed-window and a moving-window approach. For details on these averaging methods, see Sections **A.5** and **B.1**.
	Ensure data quality criteria for 1-hour averages: Faulty or missing data can lead to 1-hour averages based on limited measurements or long gaps between measurements. SunPeek excludes 1-hour intervals that do not meet quality criteria. SunPeek does not require a 1-minute sampling rate (logging time) as ISO 24194 does but makes the process of building 1-hour averages traceable. For details on these quality criteria, see Section **C.7**.
	Apply restrictions on operating conditions from ISO 24194: ISO 24194 Table 1 lists restrictions for the data records (1-hour intervals), such as minimum solar irradiance, or no shadows. SunPeek automatically applies the right set of restrictions, depending on the formula used. See Section **A.5** for more details.

Step	*Explanation*
	Build valid data records: The valid data records that SunPeek uses for Power Check are those 1-hour averaged intervals which meet all quality criteria and restrictions described in the previous steps. Numeric and graphical outputs of Power Check are based solely on these valid data records.
	Solar Keymark data sheet or other collector parameters: SunPeek makes sure it has all required collector parameters. • Depending on the formula used for Power Check (see Section **A.3**), certain collector parameters are required. • SunPeek automatically converts collector parameters from SST (steady-state) and QDT (quasi-dynamic) collector tests, if necessary. See Section **A.3** for details. • Typically, these collector parameters are from Solar Keymark datasheets, but self-defined collectors with custom parameters can also be used.
	Calculate estimated power output for all collector fields in a solar plant: In this core step, SunPeek uses one of the power output models (Formulas 1–3 in ISO 24194 Section 5.2) to compute the estimated power output. For plants with multiple arrays, this step is repeated for each array or field, and the total estimated power outputs are summed up.
	Options: Safety factor, ISO 24194 Formula, wind usage, evaluation period / measurement period: Users can define some Power Check settings, such as evaluation period / measurement period, safety factors, and the formula for computing estimated power output. As described in Section **C.5**, SunPeek simplifies this process by providing sensible default values and "AUTO" settings.
	Compare measured vs. estimated power output, calculate KPIs, create plots: ISO 24194 suggests outputs, plots and report formats, including tabular display of numeric results. SunPeek computes the main KPIs from Power Check results.
	Power Check PDF report & Web-UI: SunPeek compiles Power Check results into a data structure for the Web-UI and PDF report. The PDF report follows the recommendations of ISO 24194 and is available via the Web-UI and SunPeek REST API. Once a plant is configured, this allows full automation of Power Check process: adding new data, running Power Check analysis, and generating a PDF report.

C.7. Data handling and quality checks

This section describes how SunPeek handles a variety of timestamp formats and implements data quality checks to allow for an automated Power Check application for real-world plants. An overview of the SunPeek procedure to compute valid Power Check data records is shown in **Figure 38** in the previous section.

Timestamps

Since the quantitative Power Check results depend on solar position and related information (e.g., angle of incidence, calculated shading, etc.), it is crucial that time zone information is parsed correctly. The main practical issues are incorrect time zones or misspecified timestamp formats.

SunPeek does not follow the concept of a sampling rate or logging time. Measurement data can be provided by users with arbitrarily sampled timestamps; specific criteria apply to decide if data chunks are good enough to build 1-hour average data records, as explained later in this section. SunPeek does not interpolate or resample data to a default time grid. This causes the limitation that SunPeek currently cannot combine data channels from different sources with possibly different timestamps. To use several data sources, users are required to sample data to common timestamps before using that data in SunPeek. In other words, for each time interval for which measurement data is provided the respective data file needs to cover all data channels.

To avoid ambiguities, SunPeek recommends providing *time zone aware timestamps* and *not* using daylight saving time (DST), as also recommended by ISO 24194**Error! No bookmark name given.**. SunPeek recommends using the timestamp formats following ISO 8601-1:2019 [33] with a clear time zone indication: **Table 13** contains example data in a format complying with ISO 8601 without time zone, and **Table 14** has an example with time zone-aware timestamps, as recommended.

In practice, specifying the wrong time zone is a common issue. That said, and since data in real life often do not comply with these recommendations, SunPeek provides a variety of options to specify custom time zones. Here are the main ones:

1) *"UTC offset included in data":* For measurement data that contain time zone information as a UTC offset, timestamps would look like this: "2023-10-04T11:14:00+01:00" or "2023-10-04 11:14:00+01:00", see **Table 14**.
2) *"Plant local time zone with DST":* For measurement data recorded in the same time zone where the plant is located, including the DST changeover (from / to summertime).
3) *"Plant local time zone without DST":* Like 2), but without DST changeover. This is often the way data loggers record data.
4) *Any other time zone:* Any time zone can be selected, such as UTC or "Europe/Vienna". Note that many time zones based on place names assume a DST changeover.

SunPeek parses timestamps based on this time zone information, and internally always uses time zone aware timestamps. This avoids ambiguity and allows conversion to any time zone for display. By default, SunPeek outputs (plots, reports) display timestamps in ISO 8601 format in the “local time zone”, an automatically determined time zone of the plant location (latitude, longitude), without DST changeover. For example, for most of central Europe, this is “UTC+1”. Using such local time zones with fixed UTC offset also facilitates interpretation of results, as solar radiation and solar thermal power patterns match with this time zone, unlike DST-affected time zones like “Europe/Vienna”.

Table 13. Default data format “YYYY-MM-DD hh:mm:ss” according to ISO 8601-1:2019 **[31]** without time zone information. In SunPeek, the “Time zone / UTC offset” needs to be defined in the “Data Upload” page or API endpoint.

```
timestamps; data_channel_01; data_channel_02; data_channel_03
2025-01-01 10:00:00; 14.72; 13.47; 1.4
2025-01-01 10:01:00; 15.72; 14.89; 1.5
```

Table 14. Default data format with time zone information. Extended format “YYYY-MM-DDThh:mm:ss±hh:mm” according to ISO 8601-1:2019 **[31]**. In SunPeek, the corresponding “Data Upload” setting is “UTC offset included in data”.

```
timestamps; data_channel_01; data_channel_02; data_channel_03
2025-01-01T10:00:00+01:00; 14.72; 13.47; 1.4
2025-01-01T10:01:00+01:00; 15.72; 14.89; 1.5
```

Data storage

After parsing the provided measurement data and computing virtual sensors (see **Figure 38**), SunPeek stores the raw (uncorrected) measurement data as time series. In practice, data volumes can become large, with numerous sensors per plant, and plants being monitored over many years. SunPeek uses file-based Parquet[10] data storage for efficient storage and retrieval of data. Individual sensor data, for both measured and virtual sensors, can be fetched from Parquet. To deal with large data volumes, data is fetched in-memory for specific time intervals, when necessary for specific computation. For details on the SunPeek software architecture, see **[30]**.

SunPeek also provides options to batch delete all uploaded data, and to delete single uploaded data files. When new data is uploaded, overlapping existing data is overwritten. This enables users to upload new data in case erroneous data has previously been uploaded. Some of these features extend the feature set of classical Parquet packages and have therefore been implemented in Python in a custom parquet-datastore-utils package[11], published on PyPi[12] and available under a BSD-3 license .

Data quality checks

SunPeek excludes physically impossible values from being used in analysis and Power Check computations. For example, a solar irradiance measurement of $2000\ \mathrm{W/m^2}$ is considered erroneous. As illustrated in **Figure 39**, SunPeek rejects values outside valid ranges and sets them to NaN (not-a-number) and corrects values slightly outside physically possible limits. Data quality checks are implemented as follows:

- *Sensor type:* SunPeek assigns a sensor type in the sensor mapping process (see Section **C.3**). For example, when a data channel is mapped as “inlet temperature” of a collector field, its sensor type is automatically set to “Fluid temperature”. Available sensor types for data channels related to Power Check are listed in **Table 15**.
- *Physical units:* A sensor type determines the allowed physical units for a data channel. For example, for power measurements, the units W, kW and MW are accepted, but kWh or K are not.
- In practical data acquisition, measurement values slightly outside physically possible limits can occur due to measurement uncertainties. To deal with this case, SunPeek provides a “tolerance range” where data are replaced by physically meaningful values. For instance, slightly negative radiation values (such as $-3\ \mathrm{W/m^2}$) appear frequently in radiation measurements; such values are replaced by the value $0\ \mathrm{W/m^2}$. Values outside the tolerance range (e.g. $-50\ \mathrm{W/m^2}$) are set to NaN. See **Table 15** for a list of all SunPeek sensor types and the respective data replacement schemes.
- SunPeek does data check corrections on the fly. No raw data is ever overwritten. The Parquet file storage (see above) keeps original, raw data, as parsed. Data check settings can be changed at any time and will be effective immediately.

[10] https://parquet.apache.org/
[11] https://gitlab.com/sunpeek/parquet-datastore-utils
[12] https://pypi.org/project/parquet-datastore-utils/

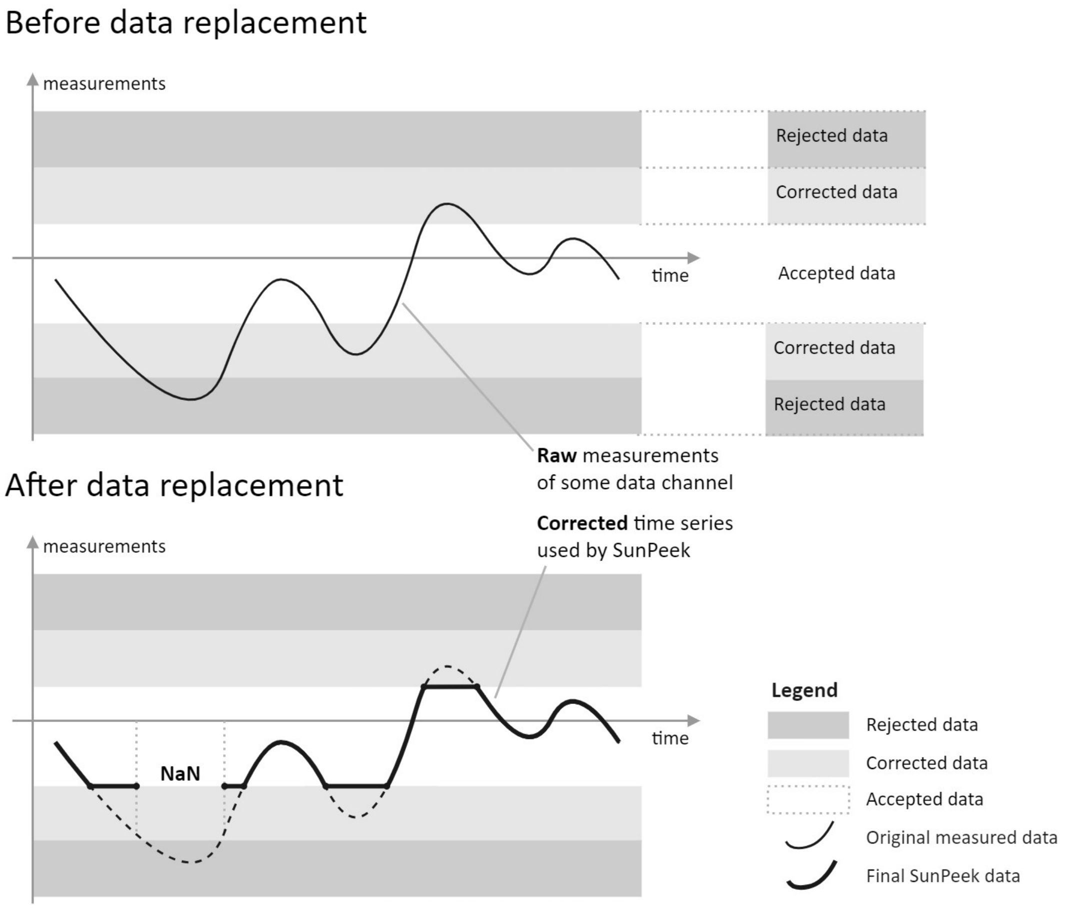


Figure 39. Data quality checks in SunPeek for treating gross errors.
Values inside a “tolerance range” are corrected, values outside are set to NaN.

Table 15. SunPeek sensor types and data replacement schemes.

Sensor type	*Compatible unit* [1]	*Measurement data channel*	*Set to NaN below*	*Replace with 0 within range*	*Set to NaN above*
Fluid temperature	°C	ϑ_i, ϑ_e	-20	–	200
Ambient temperature	°C	ϑ_a	-30	–	60
Global radiation [2]	W/m²	G_{hem}	-10	[-10, 0]	1700
Direct radiation	W/m²	G_{b}	-10	[-10, 0]	1400
Diffuse radiation	W/m²	G_{d}	-10	[-10, 0]	1110
DNI	W/m²	DNI	-10	[-10, 0]	1400
Thermal power	W	$\dot{Q}_{\mathrm{pri}}, \dot{Q}_{\mathrm{sec}}$	-10	[-10, 0]	–
Mass flow	kg/s	$\dot{m}_{\mathrm{pri}}, \dot{m}_{\mathrm{sec}}$	-100	[-100, 0]	–
Volume flow	m³/s	$\dot{V}_{\mathrm{pri}}, \dot{V}_{\mathrm{sec}}$	-0.1	[-0.1, 0]	–
Wind speed	m/s	u	-1	[-1, 0]	–
Temperature derivative	K/s	$d\vartheta_m / dt$	-100	–	100
Angle	°	$\theta_{\mathrm{L}}, \theta_{\mathrm{T}}$	-90	–	90

[1] Physical unit of measurement data channel assigned to the sensor type must be convertible to this unit.
[2] The term “Global radiation” is used for both hemispherical irradiance (in tilted plane) and horizontal irradiance.

Building data records

In practical data acquisition, perfect, flawless data does not exist. Therefore, clear criteria should specify what is acceptable. When building Power Check data records (the 1-hour averages), SunPeek allows for some share of bad (missing or invalid) individual measured values. To ensure the quality of data records, SunPeek defines 3 criteria for quality assurance, as detailed in **Table 16**.

- For a given timestamp, SunPeek checks if all relevant data channels are available and meets all quality requirements for individual measurements, as described above. SunPeek follows a strict approach, excluding all timestamps where one or multiple measurements are invalid (NaN).
- Next, SunPeek computes the 1-hour averages. To be considered for Power Check analysis, data records must meet the 3 quality criteria in **Table 16**: 1) A data record must have a minimum percentage of available data (`max_nan_density`). 2) Gaps between individual measurements are allowed but must be short (`max_gap_in_interval`). 3) Each data record must be based on a minimum number of individual measurements (`min_data_in_interval`).
- These criteria might seem tricky to grasp at first, but they offer the advantage of being easily applicable to varying sampling rates and intervals lengths. As a result, a wide range of data scenarios (data logging and acquisition, sampling rates, data quality issues, etc.) can be handled using the same criteria set. Nevertheless, to meet specific needs in certain cases, the SunPeek API allows for customization of these criteria for valid data records.
- The resulting data records will be used to run Power Check. Power Checks imposes restrictions on operating conditions (see Section **A.5**), so only a part of these data records may be considered "valid data records" in the terminology of ISO 24194 (see **Figure 38** for an overview on data processing steps).

Some numeric issues involved in computing data records are worth noting:

- ISO 24194 includes an operating condition restriction that involves the change of the mean collector temperature over time. This criterion allows several interpretations, SunPeek uses the interpretation that aims to filter out significant heat up / cool down phases over an interval, i.e. $\left| d\vartheta_m / dt \right| \leq 5 \ K$ (see Section **A.5**). Calculating derivatives of noisy measured data is known to be very delicate, if based on unfiltered raw and possibly irregularly sampled data. To obtain reliable values for $\left(d\vartheta_m / dt \right)$, SunPeek uses a numerically stable approach based on SciPy's implementation of the Savitzky-Golay filter **[32]**.
- Power Check Formulas (see Section **A.3**) are based on hourly-averaged values of individual measurements (e.g. hourly-averaged irradiance, ambient temperature etc.). The hourly averages are calculated first (data records) and are then used in one formula to compute the estimated power output. This process order is fine if the involved terms are linear. However, some terms in the formulas are nonlinear, namely $\left(\vartheta_m - \vartheta_a \right)^2$ and $\left(\vartheta_m - \vartheta_a \right)^4$. Non-linear terms should be calculated on the initial time grid first and only then averaged to build data records.
- As mentioned in Section **A.6**, valid data records must not contain any shaded timestamps. That is, a valid data record is considered as having "no shadows" if there is no internal and no external shading for any timestamp within the 1-hour period.

Table 16. Data quality criteria for building data records (1-hour intervals) utilized for Power Check in SunPeek.

Name	*Default value*
`max_nan_density`	$10\,\%$
Missing or invalid data are encoded in SunPeek as NaN (not-a-number). The percentage of NaN data compared to the total data is termed "NaN density". This criterion defines the maximum allowed NaN density, within a	

Name	*Default value*
1-hour interval. For example, for measurement data recorded with a 1-minute sampling rate, a 1-hour interval should have 60 values. In this case, no more than 6 timestamps with NaN data are allowed.	
`min_data_in_interval`	10
Minimum number of non-NaN measurement values required in a 1-hour-interval. The 1-hour intervals are meant to be averages over several single measurement values. It might happen that a 1-hour interval contains only a few individual measurements. The intention of this criterion is to exclude intervals with too few measurements. For example, a 10-minute sampling rate results in only 6 values per 1-hour-interval.	
`max_gap_in_interval`	10 minutes
Even if an interval has enough individual measurements per 1-hour interval, those records might have gaps between them. For example, measurements might be clustered at the beginning or end of the interval. The intention of this criterion is to avoid having 1-hour intervals with large gaps between measurements.	

C.8. Virtual sensors and other calculations

Virtual sensors

Virtual sensors are much like regular, measured sensors, but they are not given directly as measurement data channels. Instead, virtual sensors are calculated based on other sensors and optionally on parameters. Virtual sensors exist on the same time grid as regular sensors.

Typical examples for virtual sensors are the solar position, or internal (row-to-row) shading of collector rows. Another important example for a virtual sensor is a plant's thermal power output if it is not available as a sensor measurement. In this case, SunPeek allows thermal power to be calculated, based on measured volume or mass flow, inlet and outlet temperatures, and fluid properties.

SunPeek calculates virtual sensors automatically at data upload, after applying data quality checks to regular, measured sensors (see **Figure 38**, **Table 12**). SunPeek then applies data quality checks to the calculated values of the virtual sensors themselves, just like regular sensors. Users can also trigger recalculation at any time (e.g., after a change in plant configuration), on the "Sensor Data" page in the Web-UI (see **Figure 40**). The "Sensor Data" page also lists all the virtual sensors available in a plant.

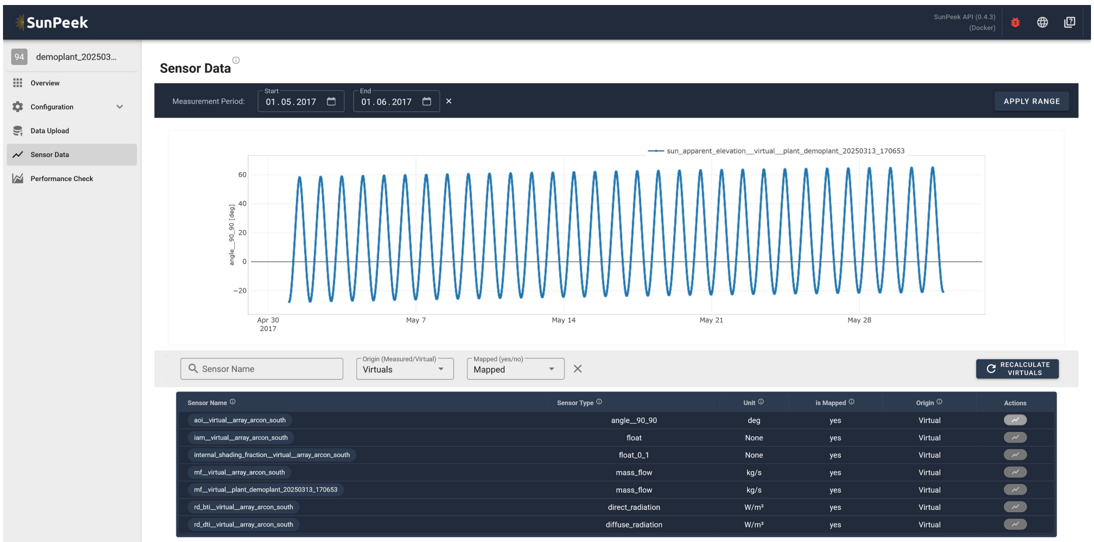


Figure 40. Screenshot of Virtual Sensors in the "Sensor Data" page.
The page offers filtering for "Virtuals" and "Recalculate Virtuals".

Heat transfer fluids

Fluid properties (density, heat capacity) are required to calculate power output from volume flow or mass flow (see Section **A.7**). SunPeek integrates CoolProp [33], a well-established C++ library with a fully featured Python wrapper[13]. CoolProp includes a library of common solar fluids (e.g., brands like Antifrogen, Pekasol and Zitrec) and standardized fluids (e.g., ASHRAE glycols). In the SunPeek Web-UI, users can select a fluid and specify the concentration (volumetric percentage).

Additionally, the SunPeek backend allows users to define custom fluids, both pure and concentration-dependent, provided that density and heat capacity data are available from datasheets, characteristic curves, or lab tests. Fluid property information is often available in graphical charts, and SunPeek follows this procedure to incorporate such information:

1) *Digitize charts:* Use WebPlotDigitizer[14] to digitize the density and heat capacity charts and export a CSV file with fluid property tables. If charts are available for different fluid concentrations, digitize each concentration curve into the same CSV file.
2) *Train models:* Use SunPeek's fluid package to train interpolation models. Once trained, these models allow for temperature- and concentration-dependent fluid property calculations.
3) *Transfer to database:* Add the trained, custom fluid to the SunPeek fluid database.

Shading calculation

SunPeek assumes uniformly arranged arrays and models them as shown in **Figure 4** with the same tilt β, azimuth γ, collector length L, row spacing S. These parameters are used to calculate row-to-row shading. Through the Python API, row-to-row shading calculation for collector fields mounted on sloped ground is also available. Shading for one- and two-axis tracking collectors is not yet implemented. The optional parameter minimum sun altitude / horizon ($\theta_{\min}$) is used to check for external shading. The effect of view obstructions of the front collector in reducing the incident radiation from the sky and altering reflection patterns is not considered (see Section **A.6** for further discussions).

Radiation conversion

Radiation conversion between collector fields of different tilt and azimuth is desirable, as well as radiation decomposition which allows splitting hemispherical irradiance into its beam and diffuse parts. This feature is not yet implemented in SunPeek. Once implemented, it will allow calculating irradiance for arrays without their own radiation sensor, based on one or more irradiance sensors existing elsewhere in the plant (see Section **F.7** for further discussions).

Conversion of collector parameters

In SunPeek, solar collector parameters can be given either as QDT (quasi-dynamic) or SST (steady-state) test procedures and referencing the collector's gross or aperture area. As required by ISO 24194 (section 5.2.1), SunPeek always uses collector parameters related to gross collector area. If necessary, SunPeek converts these parameters in accordance with ISO 9806, as outlined in Section **A.3**.

Unit conversion

SunPeek internally utilizes unit-aware quantities, based on the python packages *pint* and *pint-pandas*. Dealing with explicit physical units enhances the quality of data processing and mitigates issues related to unit clashes.

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[13] http://www.coolprop.org
[14] https://automeris.io

External calculations

SunPeek utilizes the pvlib package **[34]** to leverage existing functionality, specifically for collector incidence angle modifiers (IAM) and for solar radiation calculations. The *pvlib.iam* module is used for the ASHRAE IAM model. For the common case where longitudinal and transversal IAM values are known for a collector (e.g., if the Solar Keymark data sheet is provided), SunPeek extends *pvlib.iam.interp* to support longitudinal and transversal IAM, whereas *pvlib.iam.interp* only works for symmetric collector IAMs. Additionally, SunPeek employs pvlib to calculate solar position (azimuth, elevation etc.) and angle of incidence. Future enhancements of SunPeek involving radiation modeling are anticipated to rely more heavily on *pvlib.irradiance*, along with self-developed algorithms.

C.9. Solar Keymark Collector Database integration

The Solar Keymark is the main quality label for solar thermal products and is widespread in the European market and beyond. Its certification scheme for collectors builds on ISO 9806. Among other things, the Solar Keymark database **[3]** lists the certified collectors and their technical parameters, see **Figure 41** for an example.

SunPeek uses the collector efficiency parameters and dimensions to run Power Check (see Section **C.3**). To ease the configuration and ensure that the correct parameters are used, the "SunPeek Collector Package" is currently being created in collaboration with the Solar Keymark Network and Solar Heat Europe. The package is planned to be released and integrated into the main SunPeek Web-UI in 2025; for the current status, please check **[35]**.

The "SunPeek Collector Package" is a Python package containing performance parameters and other data of all collectors certified according to Solar Keymark. The package will be synchronized regularly with the Solar Keymark database, adding newly certified collectors and dropping collectors that lost certification. The package will also be available for general use, as a stand-alone without using the main SunPeek package. In addition to this Solar Keymark interface, users can also define and use custom collectors in SunPeek as described in Section **C.3**. This might be useful for applications with experimental or uncertified collectors.

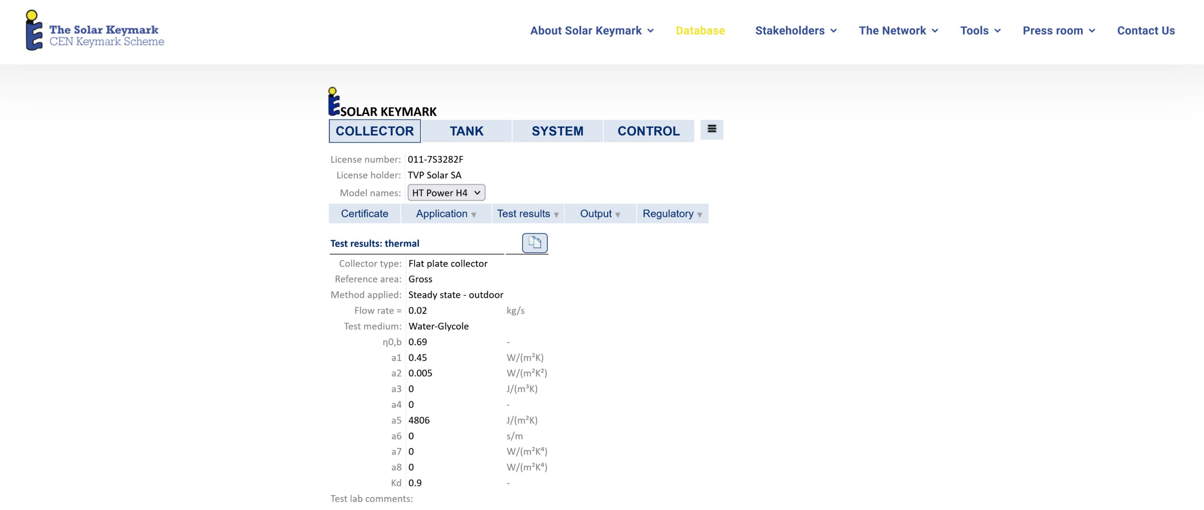


Figure 41. Example of thermal test result entries for collectors in Solar Keymark database. Source: [3].

D Applications and usage

This section elaborates different uses of Power Check and contains example applications to large-scale solar thermal plants using the SunPeek open-source software. The aim of this chapter is to make Power Check results more accessible to the solar community, deepen methodological understanding, and show the variety of practical use cases of the SunPeek software:

- Section **D.1**: Discusses three main uses of Power Check results.
- Section **D.2**: Presents the SunPeek Demo Plant, a large solar plant located in Austria, for which accurate measurement data is publicly available, and shows the influence of various Power Check settings on the outcome, including the Extended Power Check.
- Section **D.3**: Treats the question of the influence of soiling on collector performance, using SunPeek and Power Check in a monitoring setting.
- Section **D.4**: Shows how Power Check can be applied to multiple fields as discussed in Section **B.2**.
- Section **D.5**: Shows how stagnation events affect Power Check results, providing empirical material to the discussions in Section **B.3**.
- Section **D.6**: Presents an application to evacuated flat-plat collectors.

D.1. Usage of Power Check results

Power Check can be applied to three main use cases.

1) Plant power performance verification: Power Check can be used to verify plant performance a posteriori (over a defined time interval), for example, to demonstrate and verify compliance with funding agency requirements. The typical KPI is the Performance Verification Criterion (PVC, average measured vs. estimated power output) as defined in Section **A.3** and shown in **Figure 46**.

2) Power performance guarantee: While ISO 24194 does not explicitly define a procedure for performance guarantees, stakeholders can agree to take the Performance Verification Criterion (PVC) or specific (averaged) results of the measured-estimated power ratio when setting power performance guarantees, such as in contractual agreements. These performance guarantees can be given for plant commissioning, the initial operating period (typically 1–3 years) or any other fixed reference period. This use case is similar to performance verification, but as failing to fulfill guarantee contracts may result in substantial fees, the procedure may be “stricter”.

3) Ongoing performance monitoring: Regular application of Power Check, e.g. with daily updates, enables early detection of performance deviations, such as those caused by soiling or degradation. Ongoing monitoring can be beneficial over the whole plant lifetime, also for plants built before ISO 24194 was published. One possible approach is to continuously update a KPI such as the average measured-estimated power ratio averaged over 20 data records. This KPI could be used to monitor plant performance and to anticipate maintenance needs (see **Figure 48** as an example).

Safety factor: The importance of a “true” safety factor value depends on the intended use of Power Check results. For ongoing monitoring, one may mostly look for relative performance changes, thus f_{safe} is less important. For power performance guarantees, the safety factor is oftentimes directly linked to the fulfillment of the guarantee and thus comes under the scrutiny of contractual negotiations, although it is meant to be a purely technical parameter. For scientific analysis, in-depth modeling of individual safety factors can provide additional insights. Experience from practical applications of

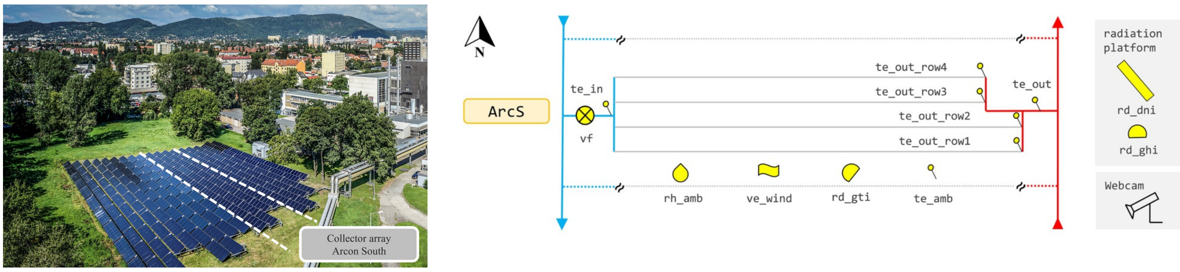
Power Check with the SunPeek software has shown that an f_{safe} in the range of 0.85 to 0.95 is common.

Remark: It is beneficial to distinguish these use cases and be aware of how they influence the importance of the safety factor. To further clarify the situation, an “acceptance threshold” should be introduced in revisions of ISO 24194, to clearly distinguish technical and non-technical aspects of safety retentions (see Section **F.9** for further discussion).

D.2. SunPeek Demo Plant

Use case and data

SunPeek comes with a preconfigured demo plant with a collector field of the “Fernheizwerk” installation in Graz, Austria. **Figure 42** shows a plant picture and the measurement setup for included “Arcon South” field, a flat-plate collector field representative for the layout of many large installations. The demo plant comes with open-access measurement data: A full year of operational measurement data is available for download on Zenodo **[36]** and can be used under a Creative Commons license. Basic information of the plant is listed in **Table 17**.



(a) *(b)*

Figure 42. SunPeek Demo Plant (“Fernheizwerk”, field “Arcon South”), located between the white dashed lines, at time of data recording in 2017. View from the southeast. Source: https://www.picfly.at Thomas Eberhard.

Table 17. Basic information of SunPeek Demo Plant (“Fernheizwerk”, field “Arcon South”)

Item	*Value, Source*
Plant location	Graz, Austria
Collector Area	516 m^2 or 361 kW (field for demo dataset), 8206 m^2 or 5.7 MW (total plant)
Application	Solar District Heating (SDH) for the Graz District Heating network
Operator	solar.nahwaerme.at Energiecontracting GmbH
Public Demo	https://demo.sunpeek.org/
Open Dataset	https://doi.org/10.5281/zenodo.7741083
Journal Article	https://doi.org/10.1016/j.dib.2023.109224

The dataset was acquired in a research project and is also described in a journal article [9]. It features one calendar year of 1-minute sampled, quality-checked measurement data, including irradiance data for DNI, G_{hem} (in collector plane), and global horizontal irradiance, and lab-tested density and heat capacity of the solar fluid. Measurement uncertainty is provided for all data channels, including Python code for the GUM error propagation. For the SunPeek Demo Plant, the data are used to test, validate, and demonstrate Power Check. Beyond SunPeek, the dataset supports scientific progress and collaborative initiatives for open-source software.

SunPeek configuration

The demo plant can be accessed in two ways: a) via the public SunPeek demo[15], b) via the Web-UI in a custom SunPeek installation. To create a demo plant, click on "TRY THE DEMO" on the welcoming screen or "ADD DEMO PLANT" on the Plant Overview page, where one can also access already created demo plants (see Figure 43). Since both hemispherical, beam tilted and diffuse tilted irradiance are available, the demo plant can be evaluated with both Power Check Formula 1 and 2.

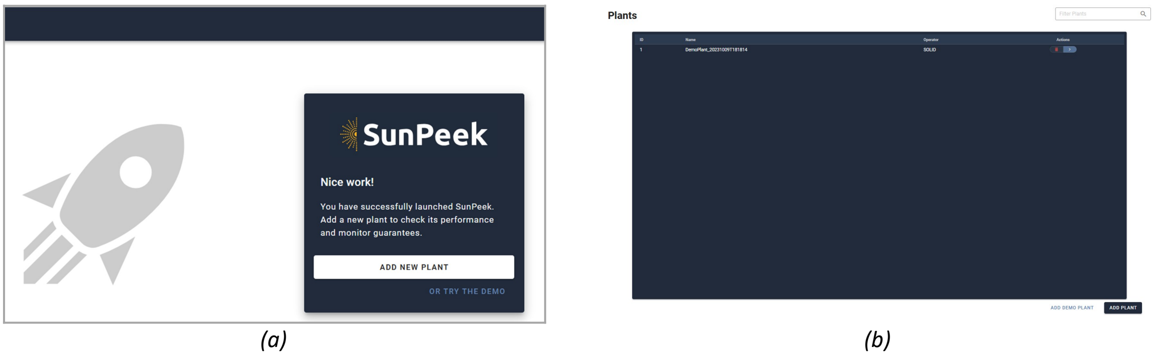


Figure 43. Creation of a demo plant with "TRY THE DEMO" on the welcoming screen (left), access to demo plant on the Plant Overview page or creation of additional demo plant with "ADD DEMO PLANT" (right).

Results

On the next pages, the results of the ISO 24194 Power Check applied to the demo plant are demonstrated using SunPeek. The results are presented graphically and summarized numerically. The plots are grouped by the following use cases:

- Power Check strictly following ISO 24194
- Extended Power Check with shorter averaging intervals
- Extended Power Check's impact on selection of valid intervals
- Power Check with different settings (Formula 1 vs. 2, data averaging methods, interval length, wind influence)

Power Check exactly following ISO 24194

The following results for the full year 2017 are presented:

- Figure 44 and Figure 45: Collector field shading, indicating unshaded periods where Power Check could produce valid data records, and distribution of valid data records (1-hour intervals) within the feasible area of the operational year.
- Power Check results for 2017 for the "Fernheizwerk" plant yield a total of 270 valid data records. For the full year, the check is fulfilled as shown in the bar plot in Figure 46.
- Figure 47 displays the measured vs. estimated comparison for all valid data records.
- The measured-estimated power ratio is shown in a time-based plot in Figure 48, alongside a histogram showing the distribution of data records over the year.

[15] https://demo.sunpeek.org/

- Sometimes, it is interesting to know what exactly happened inside a Power Check data record. **Figure 49** has an example for a selected data record, showing time-series plots of various data channels, on original timestamps.
- All plots in this section are generated with Formula 2, data averaging as in ISO 24194, considering the wind sensor in the data restrictions and safety factor $f_{safe} = 90\,\%$.

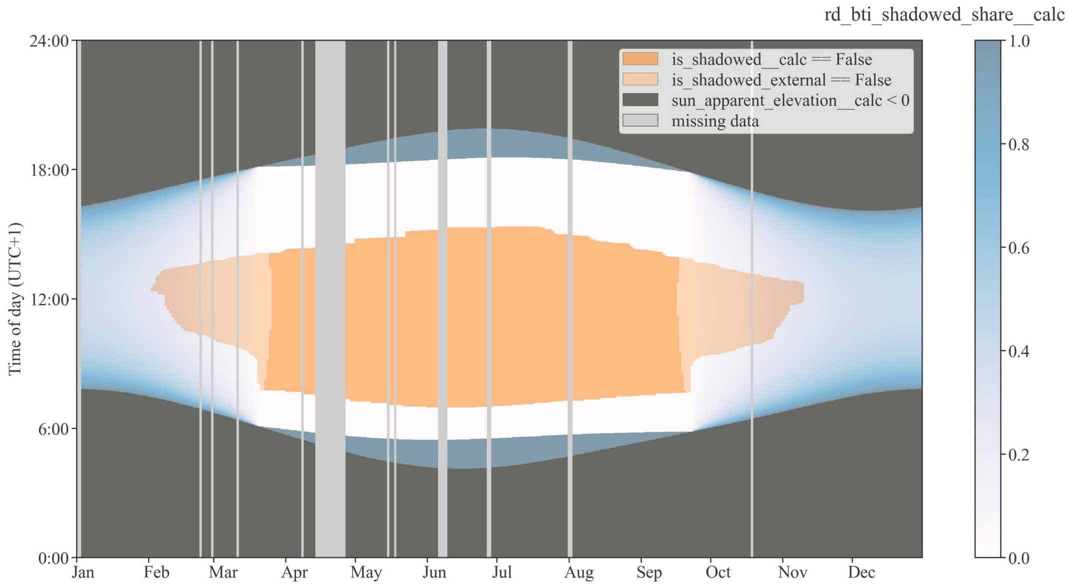


Figure 44. Collector field shading: Internal shading (calculated in SunPeek) and external shading (calculated with external tool) for the full demo plant period. Orange: Unshaded periods. Bright orange: Periods with no external shading. Color bar: fraction of row-to-row beam shading. Vertical grey lines: missing data. Source: [28].

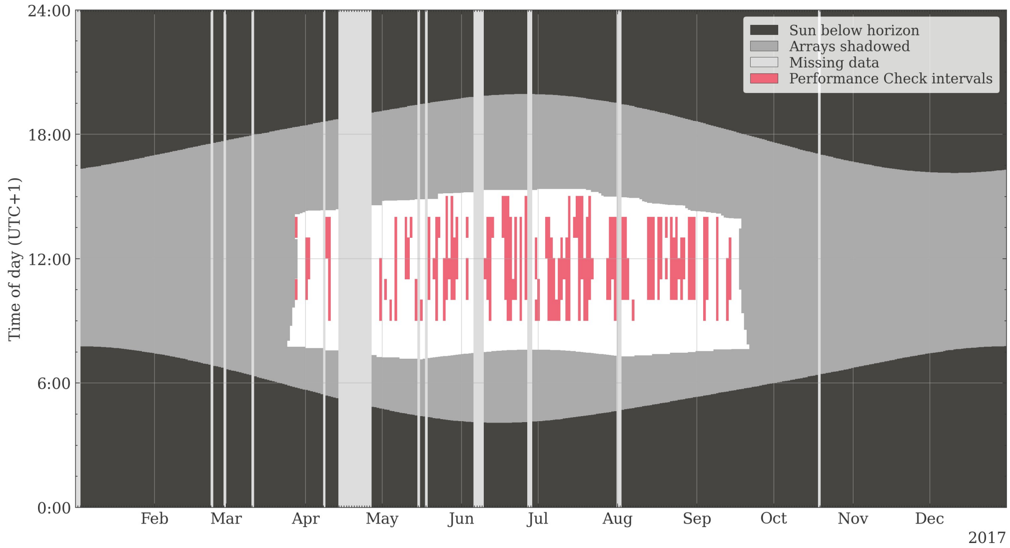


Figure 45. Distribution of the 270 valid data records (1-hour intervals) for the demo plant for 2017. White and red areas are periods without shading. Shading in this plot is computed automatically by SunPeek (in contrast to **Figure 44**). Details: Formula 2, data averaging as in ISO 24194, wind considered.

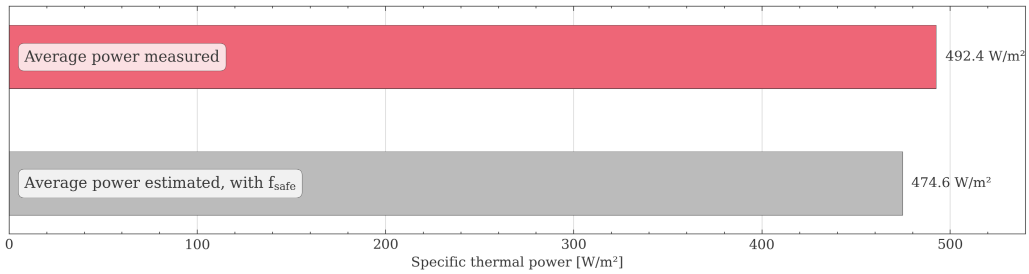


Figure 46. Overall Power Check results for the demo plant for full-year 2017: Measured and estimated specific power, averaged over all 270 valid data records. Average power ratio: 103.7% (Power Check fulfilled).
Details: Formula 2, data averaging as in ISO 24194, wind speed considered, $f_{safe} = 90\,\%$.

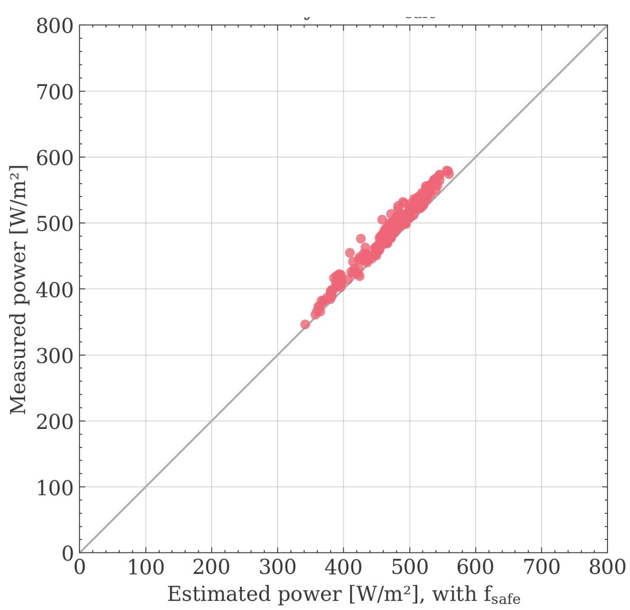


Figure 47. Measured vs. estimated power of all 270 valid data records in 2017.
Details: Formula 2, data averaging as in ISO 24194, wind considered, $f_{safe} = 90\,\%$.

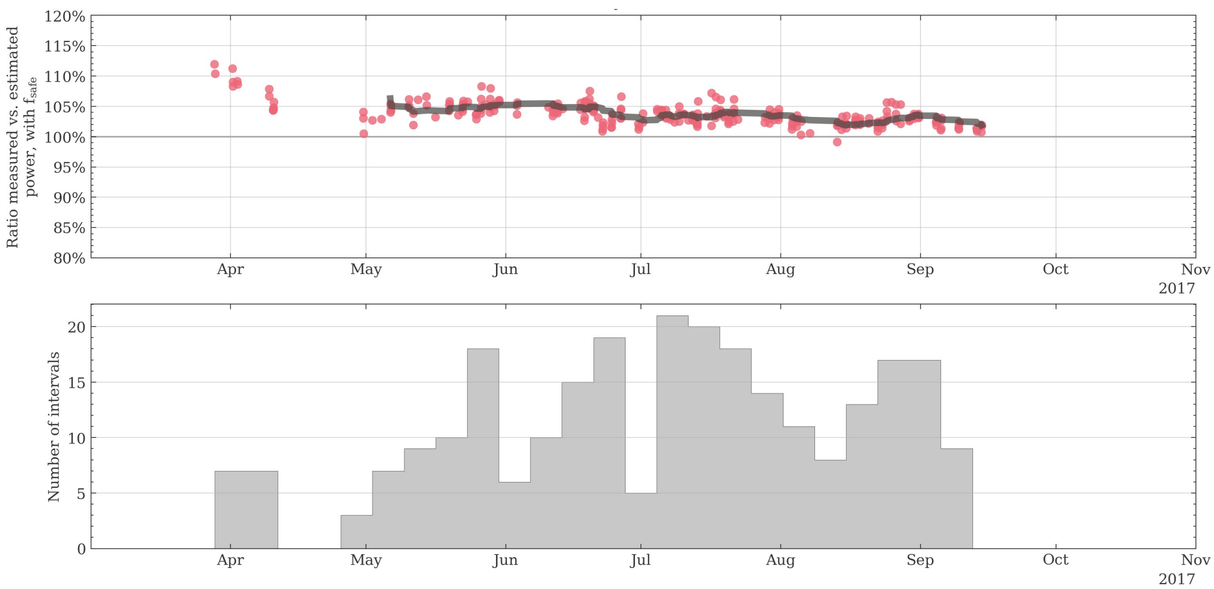


Figure 48. Top: Measured-estimated power ratio, for all valid data records in 2017.
Black line: a running average of 20 data records. Bottom: Histogram of valid data records, bin width is one week.
Details: Formula 2, data averaging as in ISO 24194, wind considered, $f_{safe} = 90\,\%$.

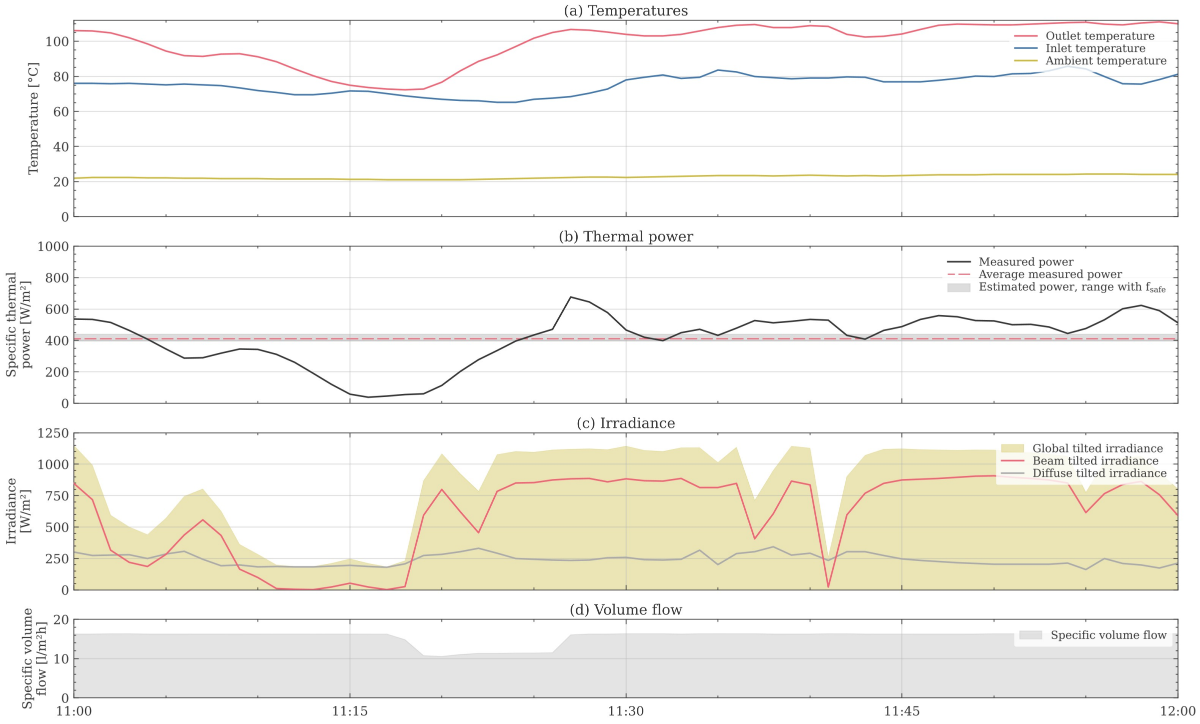


Figure 49. Time-series plot for an example valid data record: Subplot (a) shows collector field inlet / outlet and ambient temperatures, (b) measured and estimated power output, (c) hemispherical, beam, and diffuse irradiance, and (d) specific volume flow. Details: Formula 2, data averaging as in ISO 24194, wind considered, $f_{safe} = 90\,\%$.

Extended Power Check with 45 min. interval length

Figure 50 shows the valid data records when shortening the interval length to 45 minutes and using the Extended data averaging (see Section **B.1**). **Figure 51** displays the measured-estimated power ratio with shorter interval length. Compared to the regular 1-hour interval length (**Figure 48**), the variation of the measured-estimated power ratio is not substantially increased. The Extended Power Check finds 379 valid data records (compared to 270 with full-hour intervals) with a total duration of 284 hours (compared to 270 hours). As shown in **Table 20**, the average power ratio only changes by $0.2\,\%$ compared to the default setting.

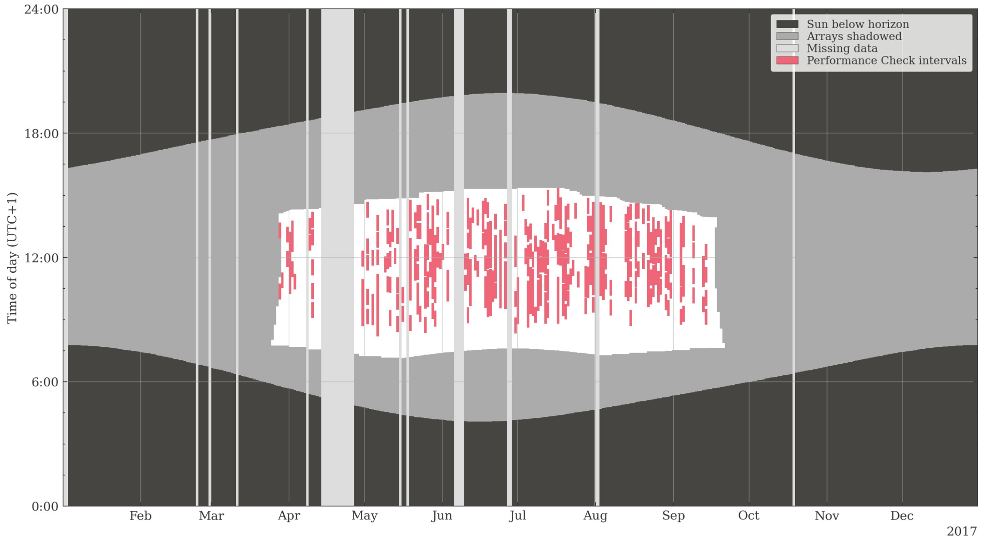


Figure 50. Same as **Figure 45**, but for 45-minute intervals: Distribution of the 379 valid intervals (data records) in the year 2017. Details: Formula 2, Extended data averaging, wind considered.

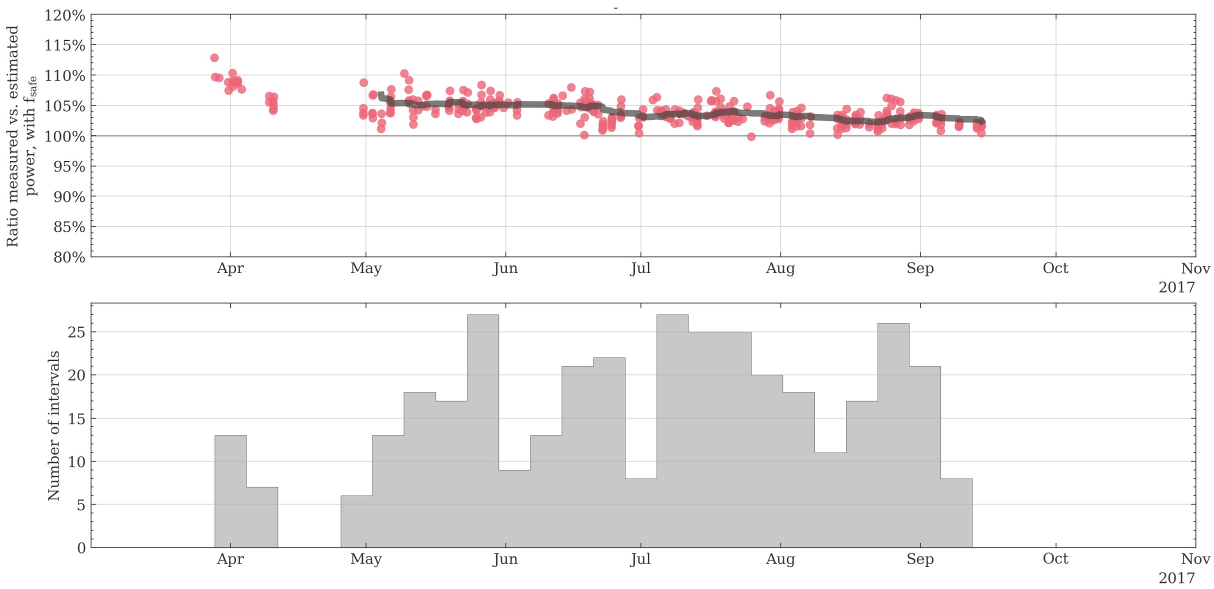


Figure 51. Same as **Figure 48**, but for 45-minute-long intervals and Extended data averaging. Thick line: a running average of 30 data records (~22 hours). Details: Formula 2, Extended data averaging, wind considered, $f_{safe} = 90\,\%$.

Interval selection with Extended Power Check

The ISO 24194 Power Check and the Extended Power Check (see Section **B.1**) have different data averaging methods, which are discussed here by applying both methods on one month of measurement data (May 2017). Numeric results of the two methods are shown in **Table 18**. As listed, both methods yield nearly identical overall scores (power ratio $104.9\,\%$ vs. $104.8\,\%$), but the Extended data averaging identifies more intervals (64 vs. 47). The Extended method also covers a broader power range, with the lowest interval starting at $340\ \mathrm{W/m^2}$ (vs. $374\ \mathrm{W/m^2}$) and the highest value reaching $605\ \mathrm{W/m^2}$ (vs. $580\ \mathrm{W/m^2}$). The number of days to find 20 intervals is substantially shorter (12 vs. 19). This is also highlighted by **Table 19**, where the intervals found for a specific day (2017-05-02) are shown.

The measured vs. estimated plot of the valid data records is shown in **Figure 54** (next section). **Figure 52** (a) and (b) depict the distribution of the valid data records. It shows that the Extended Power Check finds additional intervals towards the start and end of the day, as well as on days where the default method does not find any intervals. These results suggest that while producing a comparable overall score, the Extended Power Check yields numerically broader results that represent a plant's operating conditions better and reduces the time required to achieve the mandated 20 intervals.

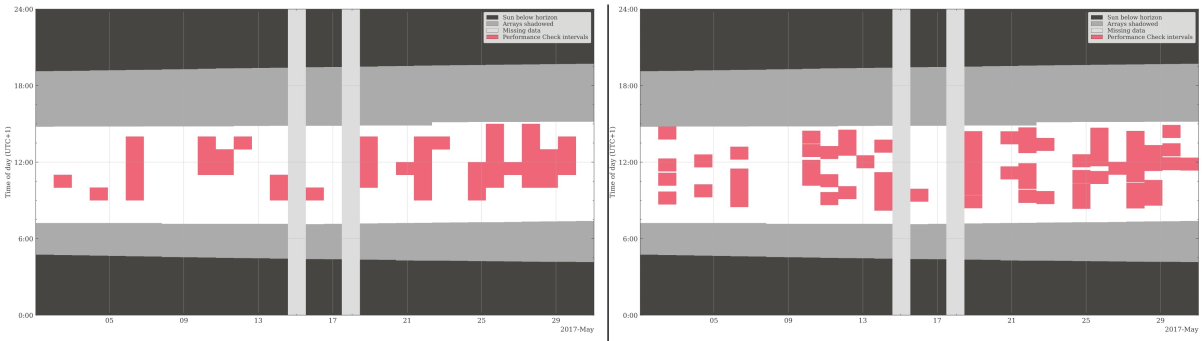
Table 18. Comparison of numerical results of default and Extended Power Check. Data from May 2017. Details: Formula 2, wind considered, $f_{safe} = 90\,\%$.

Item	*ISO 24194 Power Check*	*Extended Power Check*
Average power ratio (averaged over all valid intervals)	$104.9\,\%$	$104.8\,\%$
Valid intervals / data records found	47	64
Power range in valid intervals / data records	374 to 580 $\mathrm{W/m^2}$	340 to 605 $\mathrm{W/m^2}$
Number of days to find 20 valid intervals / data records	19	12

Table 19. Comparison of valid intervals (data records) found with default and Extended Power Check for one day (2017-05-02). The Extended Power Check finds more intervals, as it is not limited to full hours. Details: Formula 2, wind considered.

Interval number	*ISO 24194 Power Check*	*Extended Power Check*
1	2017-05-02 10:00 - 11:00	2017-05-02 08:41 - 09:41

Interval number	ISO 24194 Power Check	Extended Power Check
2		2017-05-02 10:09 - 11:09
3		2017-05-02 11:17 - 12:17
4		2017-05-02 13:47 - 14:47



(a) ISO 24194 Power Check intervals

(b) Extended Power Check intervals

Figure 52. Comparison of valid intervals (data records) found with (a) ISO 24194 Power Check and (b) Extended Power Check. Data from May 2017. Details: Power Check Formula 2, wind considered, $f_{safe} = 90\%$.

Power Check settings

Several computational options are compared regarding their effect on the measured vs. estimated power for one month of data (May 2017):

- **Figure 53**: Comparison of Formula 1 and 2.
- **Figure 54**: Data averaging with full-hour intervals (as in ISO 24194) compared to Extended (moving-window) averaging, which delivers improved Power Check results.
- **Figure 55**: Effect of different interval lengths on Power Check data records.

Additionally, the effect of using wind speed as a data filtering criterion is investigated for a full year of data (2017):

- **Figure 56**: Comparison with / without using wind speed measurement.

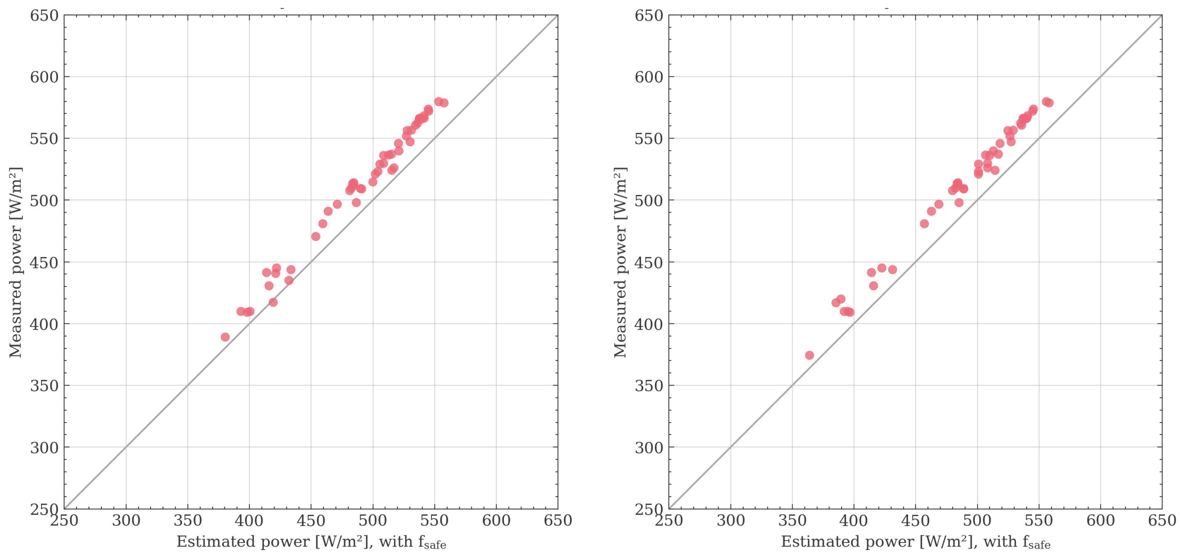
Table 20 provides the key numeric outcomes for the settings shown in these figures as well as additional settings. The following conclusions can be drawn from these investigations (numbers refer to "Case" column in **Table 20**):

- Overall, the average power ratio does not change significantly between various settings (choice of formula, averaging method, data record duration), i.e. between $0 - 0.3\%$ for the full year analysis (Cases 1a–6a), and between $0 - 0.9\%$ for the May 2017 analysis (Cases 1b-6b).
- The average power ratio is slightly, but not substantially higher for May 2017 (Cases 1b-6b) than for the full year 2017 (Cases 1a-6a). Outcome variations for different evaluation periods deserve further investigation, as they could be due to procedural uncertainties of Power Check, or due to actual performance changes over time.
- The inclusion / exclusion of the wind speed filtering criteria has no influence on the demo plant results (Cases 2a vs. 3a, 2b vs. 3b). However, as the plant is in a low-wind location, and the employed flat-plate collectors are not very wind-sensitive, these results are hard to generalize.
- The Extended data averaging with the same 1-hour interval lengths tends to find more intervals (Cases 3a and 4a, 3b and 4b). Results also cover a broader power range and reduce the time to achieve the number of required intervals (see previous section). Given that the average

power ratio remains stable, this method seems to be an improvement to the overall procedure.

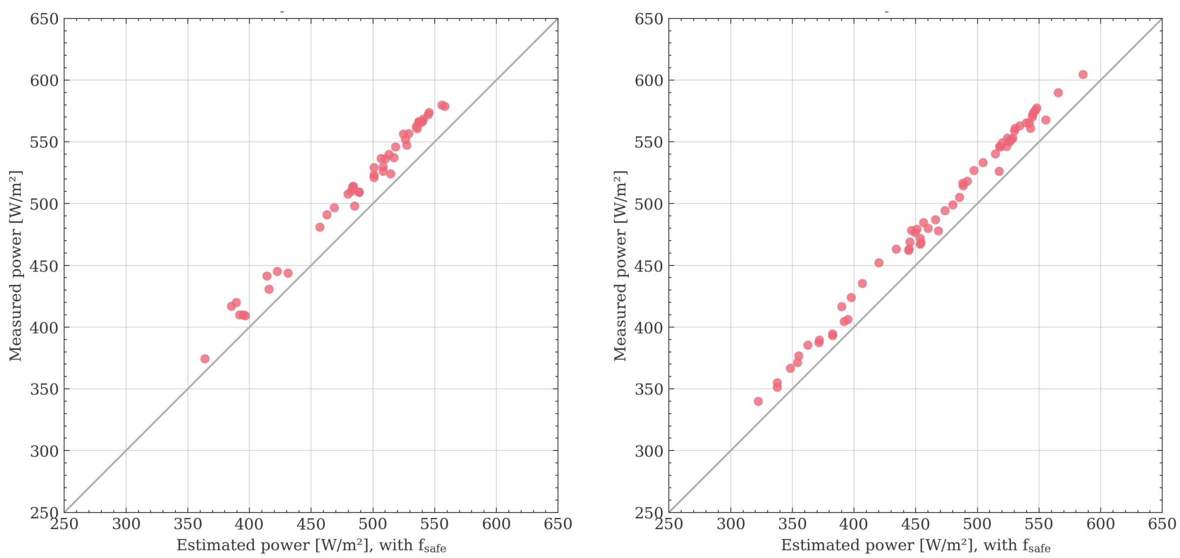
- Using shorter interval lengths of 30 or 45 minutes (Cases 5a, 6a, 5b, 6b) increases the number of found intervals, but not the total duration of all valid data records combined. This is caused by SunPeek using a minimum-noise criterion for interval selection (see **Figure 6**), selecting the best interval among the overlapping candidate intervals. This can lead to gaps between intervals. The selection criterion may be changed to maximize the number of intervals, with a possible cost to increase the noise within an interval.

Applications to additional installations may be necessary to generalize these results.



(a) Formula 1 *(b) Formula 2*

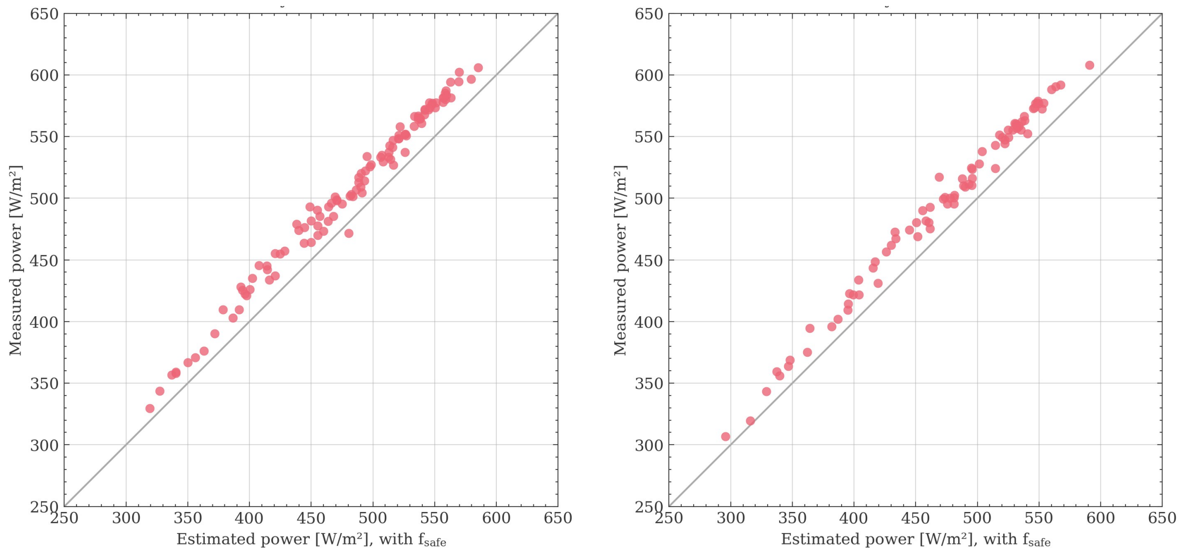
Figure 53. Effect of Power Check Formula: (a) Formula 1 (50 valid data records) and (b) Formula 2 (47 valid data records). Data: May 2017. Details: Power Check Formula 1 and 2, data averaging as in ISO 24194, wind considered, $f_{safe} = 90\,\%$. Numeric results in **Table 20**: (a) Case 1a, (b) Case 1b.



(a) ISO 24194 averaging *(b) Extended averaging*

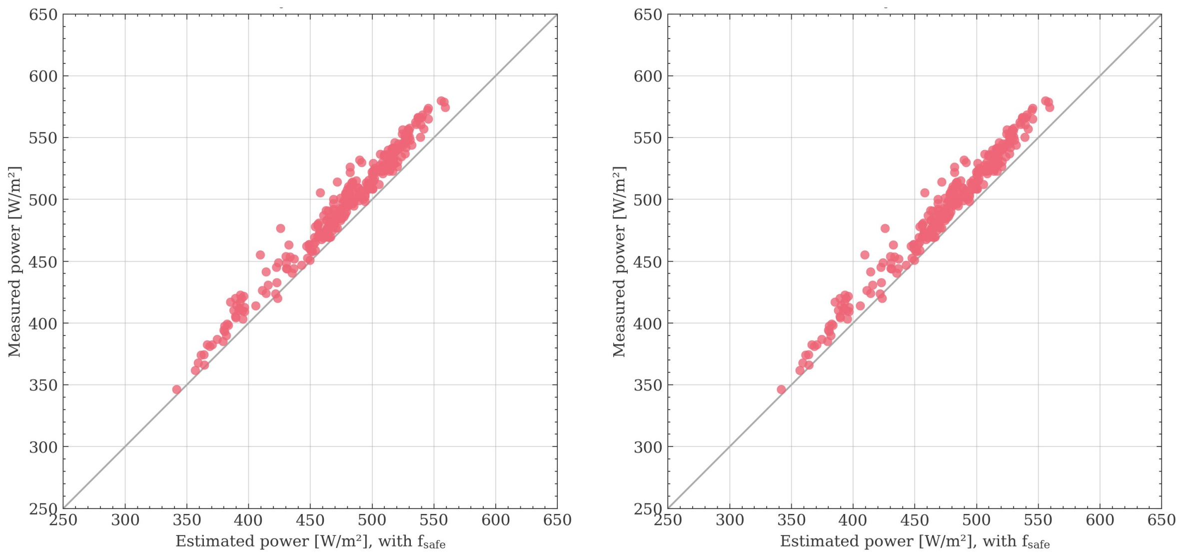
Figure 54. Effect of data averaging (see Section **B.1**): (a) Data averaging as in ISO 24194 (47 valid data records, average power ratio $104.9\,\%$), (b) Extended data averaging (64 valid data records, $104.8\,\%$). While numeric results are very similar,

the Extended averaging covers a wider power range and finds more data records. Data: May 2017.
Details: Power Check Formula 2, wind considered, $f_{safe} = 90\,\%$. Numeric results in **Table 20**: (a) Case 2b, (b) Case 2c.



(a) 30 min. *(b) 45 min.*

Figure 55. Effect of different interval lengths: (a) 30 min. intervals (110 valid data records, 55 hours in total, average power ratio $105.2\,\%$), (b) 45 min. intervals (81 valid data records, 60, hours, $105.1\,\%$). Compare with **Figure 54** (b) for extended data averaging with 60 min. interval length (64 valid data records, 64 hours, $104.8\,\%$). Data: May 2017. Details: Power Check
Formula 2, Extended data averaging, wind considered, $f_{safe} = 90\,\%$. Numeric results in **Table 20**: (a) Case 6b, (b) Case 6a.



(a) Wind considered *(b) Wind not considered*

Figure 56. Effect of wind restrictions (see Section **A.5**): (a) Wind considered in data filtering, (b) wind not considered. The retrieved valid intervals (270) coincide for both cases, wind has no effect. Data: full year 2017. Details: Power Check Formula 2, data averaging as in ISO 24194, $f_{safe} = 90\,\%$. Numeric results in **Table 20**: (a) Case 2a, (b) Case 2b.

Table 20. Power Check results for the SunPeek Demo Plant, comparing the effect of various calculation settings.

Case	*Used data*	*Power Check settings*				*Power Check results*					*Figure*
		Formula	*Averaging method* [1]	*Data record duration* [min]	*Wind considered*	*Number of records* [–]	*Total record duration* [h]	*Average power measured* [W/m²]	*Average power estimated* [2] [W/m²]	*Average power ratio* [3] [%]	
1a	Year 2017	1	ISO	60	Yes	294	294	492	475	103.7	
2a	Year 2017	2	ISO	60	Yes	270	270	492	475	103.7	**Figure 56** (a)
3a	Year 2017	2	ISO	60	No	270	270	492	475	103.7	**Figure 56** (b)
4a	Year 2017	2	Ext.	60	Yes	293	293	486	468	103.8	
5a	Year 2017	2	Ext.	45	Yes	379	284	487	469	103.9	
6a	Year 2017	2	Ext.	30	Yes	548	274	490	471	104.0	
1b	May 2017	1	ISO	60	Yes	50	50	511	489	104.3	**Figure 55** (a)
2b	May 2017	2	ISO	60	Yes	47	47	512	488	104.9	**Figure 55** (b)
3b	May 2017	2	ISO	60	No	47	47	512	488	104.9	
4b	May 2017	2	Ext.	60	Yes	64	64	491	468	104.8	**Figure 54** (b)
5b	May 2017	2	Ext.	45	Yes	81	60	497	473	105.1	**Figure 55** (b)
6b	May 2017	2	Ext.	30	Yes	110	55	506	481	105.2	**Figure 55** (a)

[1] ISO: full-hour averaging (as in ISO 24194), Ext.: Extended (moving-window) averaging, as in Section **B.1**.

[2] Estimated power output considers safety factor $f_{\text{safe}} = 90\,\%$.

[3] Average power ratio (averaged over all valid data records) and considering $f_{\text{safe}} = 90\,\%$.

D.3. Performance degradation due to soiling

Background

One possible application of Power check is for ongoing monitoring, where the collector field performance is monitored continuously during the operating phase to detect and quantify performance degradations. In addition to the suggested graphs in the standard, SunPeek provides the user with a measured-estimated power comparison of the collector array performance over time. This allows easier detecting of time-related performance degradations, e.g., due to ageing or soiling of the collectors. By focusing on relative changes of the measured-estimated power ratio, modelling distortions might be reduced, e.g., if heat losses or diffuse irradiance masking affect the performance similarly over time.

Use Case

To showcase the use of Power Check for ongoing monitoring, SunPeek was applied to one (undisclosed) collector field of the “Fernheizwerk” plant of which one subarray was described in Section **D.2**. Due to pollution from the adjacent gas heating plant, an adjacent recycling center, and leaves and needles from trees directly behind the array, the collector array was subject to considerable soiling especially in spring resulting in performance degradation. The aim of the analysis was to investigate the effects of a cleaning event that took place in Mid-June during the investigation period and whether the performance change could be identified using SunPeek.

Results

The results obtained with SunPeek are shown in **Figure 57**, depicting the measured-estimated power ratio of the collector performance over time. Before the cleaning event, the datapoints show a slight downward trend, indicating the collector degradation due to the accumulating pollution. However, a drastic pattern change can be seen after the cleaning event in Mid-June. After that, the measured-estimated power ratio of the collectors is drastically increased and stable, indicating that the performance of the collectors was restored. This example shows that the performance changes of the collector array could be well identified by Power Check, as the filtering criteria of the ISO 24194 enable a stable comparison of measured and estimated performance, while boundary conditions such as weather and operating temperatures are compensated, in the evaluation.

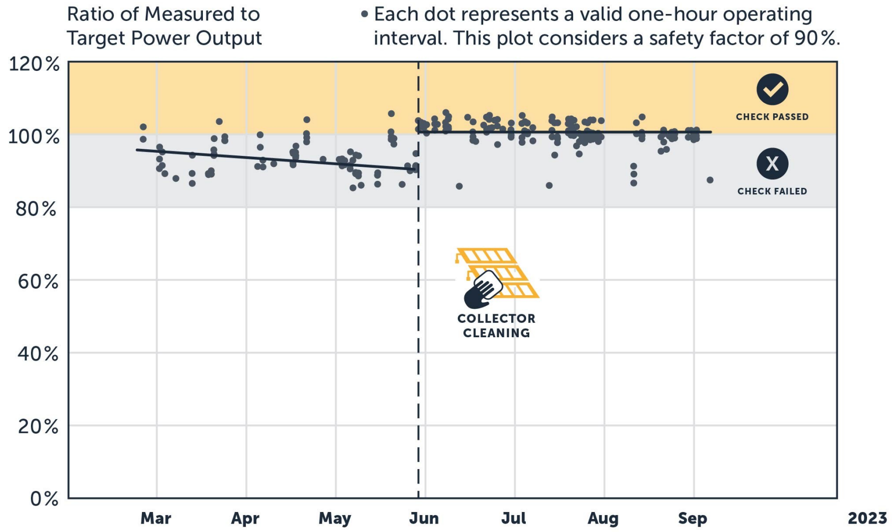


Figure 57. SunPeek screenshot, showing the measured-estimated power ratio over time. A pattern shift happens around Mid-June 2023, after collector cleaning. The figure shows real measurement data but has been graphically enhanced to better highlight the collector cleaning and pattern change.

D.4. Multiple collector fields

Background

As described in Section **B.2**, ISO 24194 mainly targets plants with only one collector model and lacks systematic treatment of plants with multiple fields. However, there exist a vast number of plants that utilize more than one collector field, for example due to plant extensions, cost and risk optimization, optimization of efficiency by combining low temperature and high temperature collectors, or due to benchmarking different collectors in a similar environment. The current SunPeek version supports some configurations of the proposed methodology to evaluate plants with multiple and heterogenous fields (see Section **B.2** and **C.3**).

Use Case

One example of a plant with multiple collector types is the Solar District Heating plant Mürzzuschlag in Styria, Austria as depicted in **Figure 59**. It was designed and built by SOLID Solar Energy Systems. The plant was put into operation in 2020 and has been extended in 2023 due to its successful operation. In total, the plant spans a gross collector gross area of $6850\,\mathrm{m}^2$, consisting of three different collector types ($5290\,\mathrm{m}^2$ KBB K5Giga+, $814\,\mathrm{m}^2$ Gasokol PowerSol136, and $744\,\mathrm{m}^2$ ENSOL DIS 150 collectors). For quality assurance, heat meters are installed on the primary and secondary side which measure the whole field, and for one collector row (measuring track) inside the Gasokol and ENSOL collector fields to check collector guarantees ("guarantee row"). The measurement setup is shown in **Figure 58**.

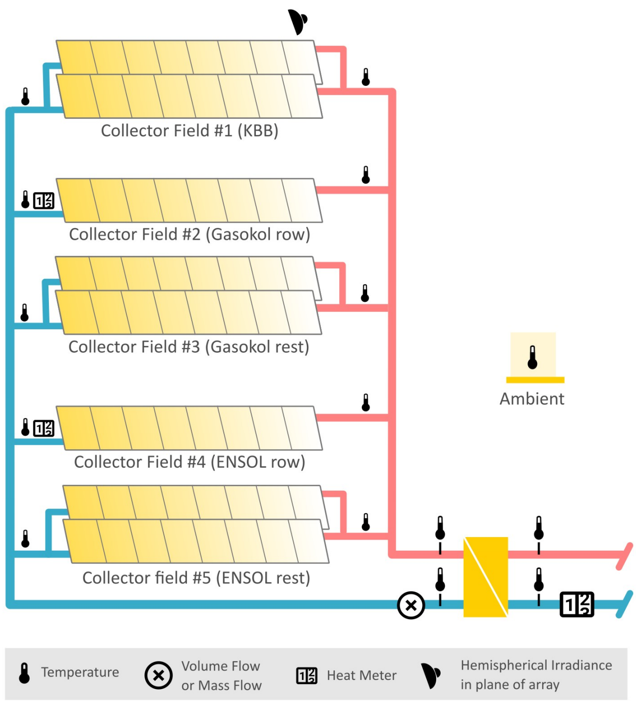


Figure 58. Measurement setup for Solar District Heating plant Mürzzuschlag. Heat meters are installed for the whole plant (primary side and secondary side) and in one row ("guarantee row") of the Gasokol and ENSOL collector fields. The collector orientation (tilt, azimuth) is the same for all fields, therefore a single radiation sensor is sufficient.

Figure 59. Picture of Solar District Heating plant in Mürzzuschlag showing the different collector fields and the installed heat meters. Source: SOLID.

Results

Figure 60 shows how the situation can be modeled using SunPeek, by using five different collector fields. The collector fields are arranged in parallel as in **Figure 12** b:

- *Collector field #1 (KBB)*: The first SunPeek Array comprises the KBB collector field ($5290\,m^2$) which does not have a dedicated heat meter installed. However, inlet and outlet temperatures exist for this field, allowing computation of the estimated power output of the field.
- *Collector field #2 (Gasokol row)*: The second SunPeek Array models the Gasokol collector row which is measured separately by a heat meter ($81\,m^2$). As such, both measured and estimated power are available for this collector row.

- *Collector field #3 (Gasokol rest)*: However, all other Gasokol collectors ($734\ \mathrm{m}^2$) are not directly measured via a heat meter and hence only estimated power can be calculated.
- *Collector field #4 (ENSOL row)*: In a similar fashion, the fourth SunPeek Array models the ENSOL collectors which are directly measured by a heat meter ($93\ \mathrm{m}^2$).
- *Collector field #5 (ENSOL rest)*: The last field includes the remaining ENSOL collectors without dedicated heat meter measurements ($651\ \mathrm{m}^2$).

Using SunPeek, this enables three different evaluations:

1) First, it is possible to compare the measurements and estimations of only the Gasokol guarantee row ($81\ \mathrm{m}^2$).
2) Second, the same can be done for the ENSOL guarantee row ($93\ \mathrm{m}^2$).
3) And finally, the total plant can be analyzed, by summing up the estimates from all individual fields and comparing them with the measured power of the heat meter for the whole field.

In all cases, only 1-hour data records valid for all collector arrays at the same time were considered.

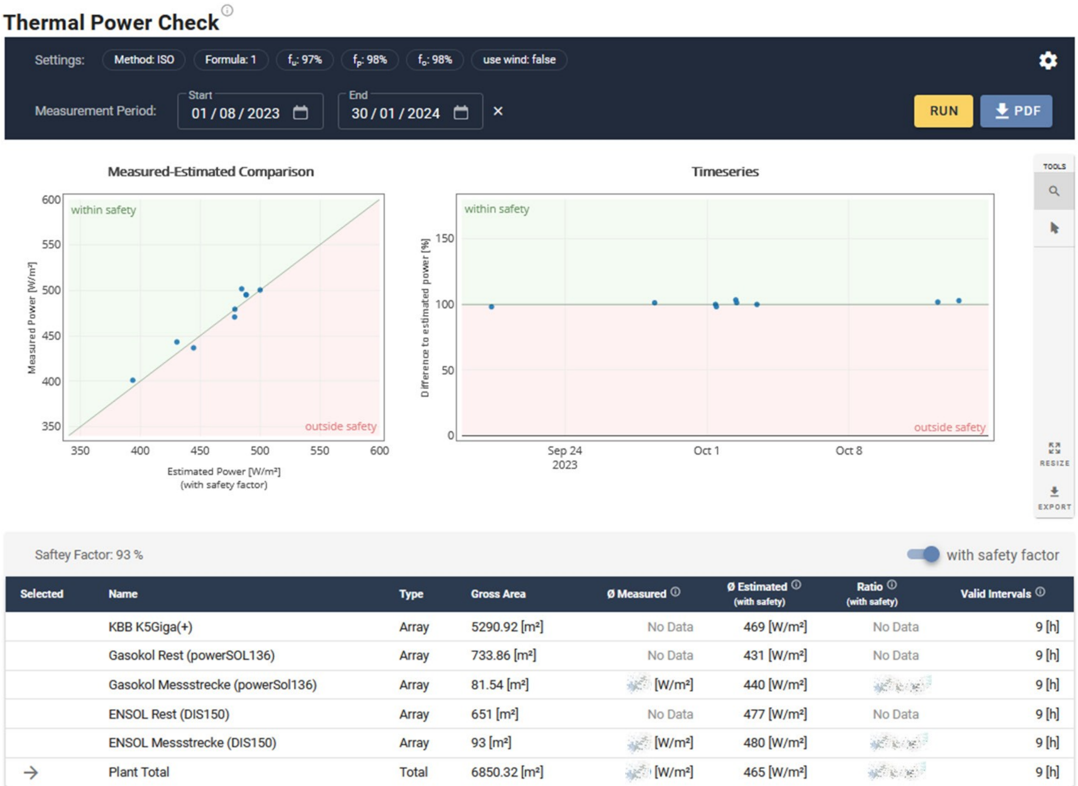


Figure 60. Screenshot of SunPeek depicting Power Check results for Solar District Heating plant Mürzzuschlag (measured results are anonymized). Using this setup, Power Check can be applied to the i) Gasokol guarantee row (measuring track), ii) ENSOL guarantee row (measuring track) and iii) total plant (selected in the Web-UI and graphically depicted).

D.5. Stagnation events

Background

As described in Section **A.5** and **B.3**, the restrictions on operating conditions do not ensure that stagnation events are discarded from valid data records. The use case presented below aims to exemplify the influence of stagnation events on Power Check results.

Use Case

A collector field with approximately $6000\ \mathrm{m}^2$ of vacuum tube collectors supplies a district heating network in Germany, with a solar fraction of about $15\,\%$. Various causes (e.g., low summer heat demand, non-ideal load management in the grid) lead to significant stagnation days (almost 40 days in 2022). Power Check has been applied to two months of summer 2022, the first year after commissioning.

The measurement setup provides only hemispherical irradiance in collector plane, beam and diffuse irradiance are not measured separately. Hence, Power Check is carried out using Formula 1. The influence of wind speed was not considered, because no such sensors are available, but wind influence is negligible due to using vacuum tube collectors. The safety factor was set at $90\,\%$, using the SunPeek default value, and mainly accommodates for heat losses and measurement uncertainties.

Results

The evaluation of the summer period shows that stagnation events have a significant influence on Power Check outcomes, even after periods of downtime are discarded. **Figure 61** illustrates the results, whereby the valid intervals and their measured-estimated power ratio were classified in three categories: a) data with downtimes (grey), b) data without downtimes, influenced by stagnation (red), c) data without stagnation periods, i.e. typical collector operation (blue). **Table 21** shows numerical results for the three different categories. Power Check is only fulfilled (average power ratio $\geq 100\,\%$) if, in addition to downtime, stagnation periods are removed from the measurement data.

Two criteria were used to distinguish normal plant operation from stagnation: a) a minimum specific volume flow rate in the collector circuit (see Eq. **(25)**) and b) the maximum allowed outlet temperature as defined for the plant control. Downtimes have been confirmed by the plant operator and usually show a different temperature behavior. As expected, the results for the normal operation (no stagnation) are around the $100\,\%$ line (with small, acceptable deviations). The downtime periods do not have a measured thermal power output. Stagnation events within 1-hour intervals generate results somewhere between $0\,\%$ and $100\,\%$, depending on the duration of the stagnation: For example, the measured power output on August 14th is about $39\,\%$ of the estimated power output.

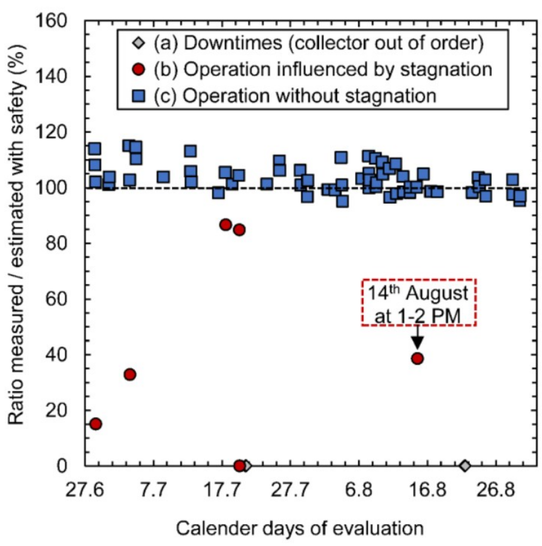


Figure 61. Influence of downtimes and stagnation events on Power Check results for a Solar District Heating plant with approximately $6000\ m^2$ collector area. The plot shows the measured-estimated power ratio for 1-hour intervals:
a) data with downtimes (grey diamonds), b) data without downtimes, influenced by stagnation (red circles), and
c) typical operation without stagnation (blue squares).
Source: ISFH.

Table 21. Influence of downtimes and stagnation events on Power Check results.
Power Check is only fulfilled if downtimes and stagnation are excluded.

Used data	*Valid data records* $[h]$	*Average measured power* $[W/m^2]$	*Average estimated power* [1] $[W/m^2]$	*Average power ratio* $[\%]$	*Power Check performance verification*
All data, with downtimes	77	398	452	88.1	Not fulfilled
Data without downtimes	70	438	449	97.6	Not fulfilled

Used data	*Valid data records* $[h]$	*Average measured power* $[W/m^2]$	*Average estimated power* [1] $[W/m^2]$	*Average power ratio* $[\%]$	*Power Check performance verification*
Data without downtimes and stagnation	62	459	446	102.9	Fulfilled

[1] Including a safety factor $f_{\text{safe}} = 90\,\%$.

D.6. Application to evacuated flat-plate collectors

Background

Power Check applies to several collector technologies thanks to the availability of different formulas discussed in Section **A.3**. In general terms, Formulas 1 and 2 can be applied to vacuum technology, based on the available data. This section covers the application to evacuated flat-plate collectors.

Use Case

One example of a plant equipped with evacuated flat-plate collectors is the pilot Solar District Heating plant SolarCADII in Geneva, Switzerland, shown in **Figure 62**. The plant, owned and operated by the local utility service company (Services Industriels de Geneve), was commissioned in 2021 and has been in operation since. The collector field has a gross area of $784\ \mathrm{m}^2$, consisting of 50 rows connected in parallel with each row having 8 TVP Solar collectors installed in series. For heat metering purposes, an Aquametro heat meter is installed at the injection point on the district heating network side, while on the solar side, flow rate and temperature measurements allow estimating the solar field yield. Sensor locations are shown in the simplified diagram of **Figure 63**. A combined hemispherical / diffuse radiation meter (i.e., SPN1 by Delta-T devices) allows the acquisition of hemispherical and diffuse irradiance values on the POA (plane of array) of the collector field.

Figure 62. Image of the Solar District Heating plant in Geneva. Source: SIG.

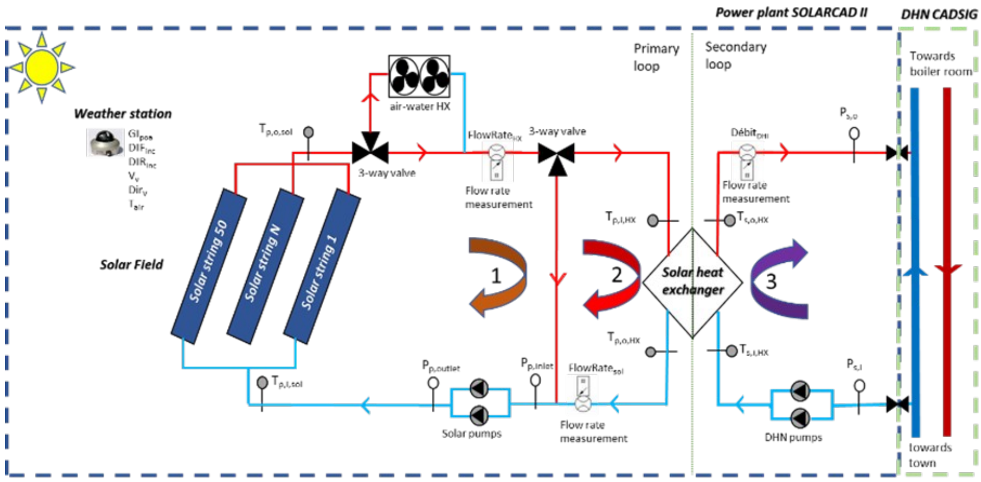


Figure 63. Simplified hydraulic flow diagram of the SolarCADII Solar District Heating plant, indicating sensor locations.

Results

Figure 64 shows the results of Power Check computed by SunPeek for the SolarCADII plant. Computations use data from July 2022 and are based on Formula 1, considering only the hemispherical irradiance on the plane of array and without using wind speed measurements. **Figure 65** shows the valid data records used for the calculations, while in **Figure 66**, the measured and estimated power with and without safety factors are shown. The analysis confirms that the efficiency of the collector field aligns closely with the Solar Keymark efficiency standards, incorporating a safety factor of $90\,\%$.

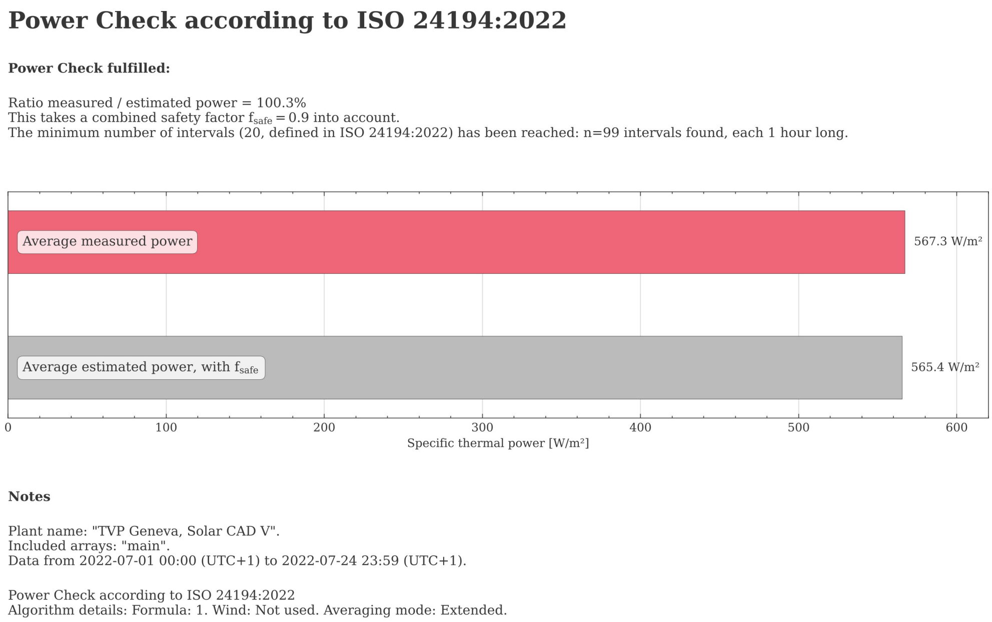


Figure 64. Power Check results for SolarCADII Solar District Heating plant. The average power ratio is $100.3\,\%$ (Power Check fulfilled), 99 valid data records found. Data: July 2022.
Details: Formula 1, Extended data averaging, wind speed not considered, $f_{\text{safe}} = 90\,\%$.

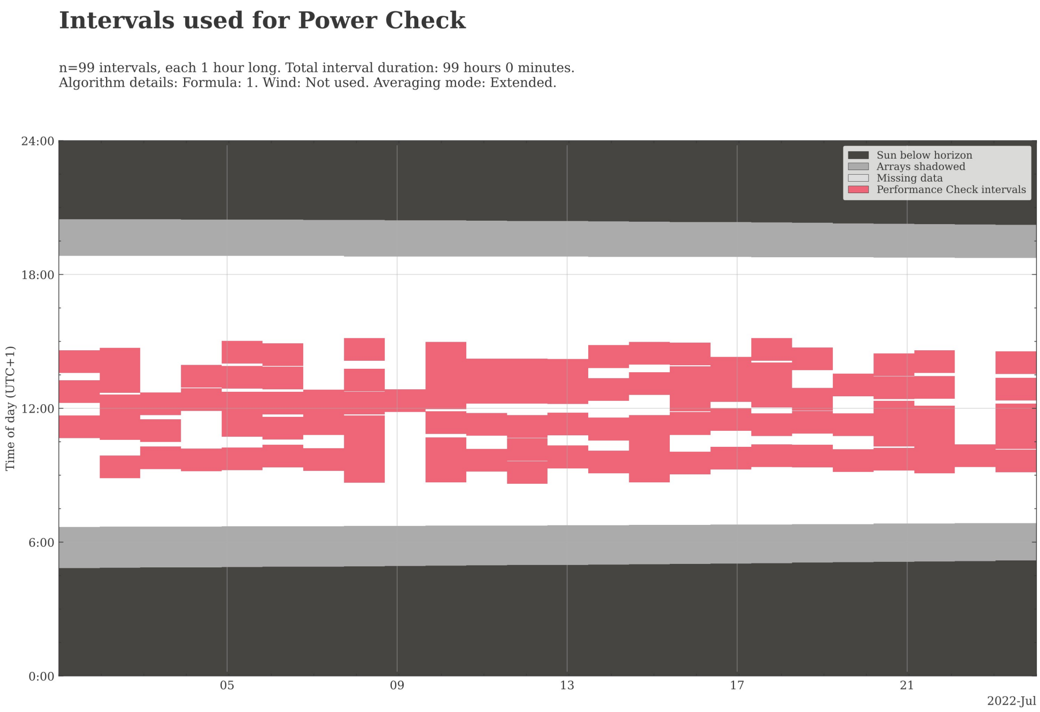
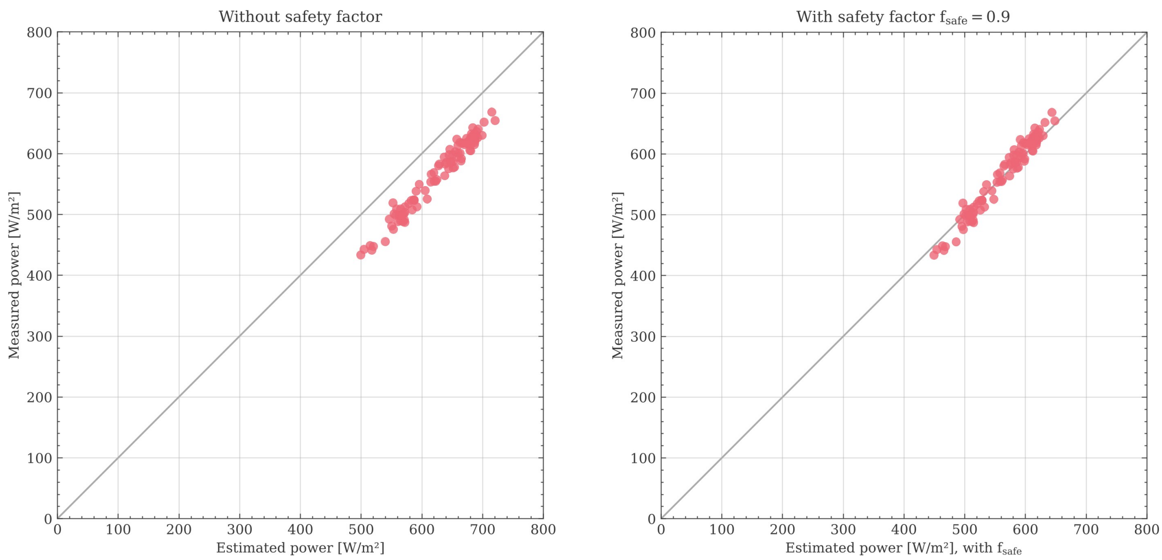


Figure 65. Valid data records (intervals) for Power Check of SolarCADII Solar District Heating plant. Data: July 2022. Details: Formula 1, Extended data averaging, wind speed not considered.



(a) Without safety factor *(b) With safety factor*

Figure 66. Power Check results for SolarCADII Solar District Heating plant (a) without safety factor, (b) with safety factor $f_{safe} = 90\,\%$. Omitting the safety factor shifts data records to the left. Data: July 2022. Details: Formula 1, Extended data averaging, wind speed not considered.

E Discussion

This chapter summarizes a list of key discussion points and ideas regarding the further development of Power Check, which could serve as an input for revisions of ISO 24194, SunPeek developments and future research activities. A concept for a major rework of the modeling framework (Harmonized Power Check) is outlined in Chapter F.

E.1. Applicability and usage

Collector types

A) *Concentrating collectors*: Although the standard is applicable to concentrating collectors with or without tracking, there is lack of specifications for specific challenges, such as phase changes in the heat transfer medium, structure deformation due to wind effect, or tracking accuracy. Also, the treatment of circumsolar radiation for fair Power Check applications to concentrating collectors is an open issue; see also [5].

B) *WISC*: In revisions of the standard, WISC collectors should be included if both wind speed data measured on the collector plane and longwave radiation data are available, although such data may be rarely available in practical applications, see Section F.2.

C) *Exclusion of co-generating / PVT collectors*: With the current ISO 9806:2017 [2] test procedures, these collectors should also be excluded in revisions of ISO 24194. The reason is that their thermal performance in real-world operation depends on the operation of the electrical part: If the electrical part is switched off, limited, or curtailed for any reason, while the thermal part remains active, this would lead to an overestimation of the thermal power output, based on performance parameters determined under MPP conditions (maximum electrical power generation), as specified in ISO 9806.

D) *Exclusion of solar air heating collectors (SAHC)*: These collectors should remain excluded due to the complexity of accurately assessing their performance.

Use cases

E) *Differentiation of use cases*: Predecessor procedures of Power Check were mainly used for performance guarantee purposes, but monitoring is another important use case, see Section D.1. It is beneficial to distinguish use cases and be aware of how they influence the importance of the safety factor. For ongoing monitoring, one may mostly look for relative performance changes, whereas for power performance guarantees, the safety factor is oftentimes directly linked to the fulfillment of the guarantee. In this case, it may come under the scrutiny of contractual negotiations, although it is meant to be a purely technical parameter.

F) *Number of valid data records*: The standard requires 20 valid data records for performance verification. It should be examined how the reliability of the results corresponds to the number of found intervals.

G) *Performance benchmarking*: Power Check results can be used to benchmark the performance across multiple plants, similar to the solarheatdata.eu platform [37]. Power Check factors out location-dependent conditions such as irradiance levels, heat demand, and weather influences. Although power or yield output cannot be compared directly, comparisons could identify good system designs and choice of collectors which meet the expected output, compare collector degradations and the effectiveness of maintenance measures.

H) *Guarantee row*: To reduce measurement, heat losses and modeling uncertainties, some recent installations deploy "guarantee rows" to apply Power Check. A guarantee row is a dedicated collector row with a heat meter that represents the whole plant, an example is shown in Section **D.4**. This use case should be discussed within the community and potentially be clarified in revisions of the standard.

I) *Iterative application*: Power Check could be applied iteratively, e.g., once a month over a 1-year evaluation period, or daily, with a moving average of the last 20 Power Check data records (see **Figure 57**). Such iterative Power Check applications probably bear reasonable information to assess the solar yield, extrapolating the measured-estimated power ratios to measured-estimated ratios for solar yield. The usefulness of this KPI needs to be explored further. A figure with the development of the measured-estimated power ratio over time should be added to the recommended reporting formats.

J) *Safety factor*: Setting the combined safety factor for the measured vs. estimated power comparison is a key question for guarantee procedures based on Power Check. Revisions of ISO 24194 should give recommendations for indicative safety factor ranges for heat losses from pipes, measurement uncertainty and other uncertainties for typical use cases. How accuracy levels (I–III) translate to measurement uncertainty safety factor ranges should be elaborated. Such ranges require more theoretical analysis and insights from practical experience. Also, the interpretation of safety factors as a purely technical parameter must be clear, and risk and practical considerations should be treated separately in contractual negotiations (see Section **F.9**).

K) *Incentives for less accurate measurement equipment:* If the safety factor is linked to contractual negotiations, less accurate and poorly maintained measurement devices may give the guarantor leverage to argue for a higher measurement uncertainty safety factor, which makes it easier to fulfill guarantees. Fulfillment of guarantees can occur if the measured values are biased positively, i.e. the uncertainty distribution is on its upper tail, although the collectors may in fact underperform. Incentives should be given for more accurate devices, e.g., by setting the measurement uncertainty safety factor a priori, before the sensors are chosen and installed.

E.2. Data handling and measurement setup

Data handling

L) *Requirement of raw data usage:* The standard prescribes a logging time ≤1 minute for raw data but uses averaged values (data records) with recording time ≤1 hour to compute Power Check. This practice leads to accuracy loss, obscures possible data pre-treatment (e.g., filling gaps within a 1-hour interval, outlier detection), applies non-linear transformations (in Formulas 1–3, see Section **C.7**) to previously averaged values, impedes detecting stagnation events, impedes advanced data filtering such as needed for the Extended Power Check, and impedes selecting shorter averaging intervals. SunPeek requires raw data and sets minimum thresholds for data availability within 1-hour intervals (see Section **C.7**). Typical minimum sampling rates should be around 1 to 5 min., resulting in data volumes that modern data analytics tools can handle without issues. Data averaging should be done by arithmetic mean.

M) *Data quality assurance:* Revision of ISO 24194 should include recommendations on necessary data quality checks and allowance on data gaps and missing data. SunPeek offers some simple, yet effective checks such as lower-upper-bound replacements (see Section **C.7**).

N) *Extended Power Check:* Section **B.1** and **D.2** propose and discuss an enhanced data averaging method. This Extended Power Check improves data selection by employing a moving-window averaging instead of fixed-hour resampling. This improvement should be included in revisions of ISO 24194 due to the benefits of this method (more valid data records, covering broader power range, reduced time to achieve number of required intervals) and no significant change to the average power ratio.

O) *Duration of averaging intervals*: Preliminary tests indicate that running Power Check with shorter averaging intervals (e.g., 30 or 45 min. instead of 1 hour) appears to deliver comparable outcomes, while requiring fewer data to obtain 20 data records. Shorter intervals would also include more partial load conditions and conditions with lower incidence angles, see Section **D.2**. The required interval duration could also be related to the traveling time and sampling rate to control delay effects.

Restrictions on operating conditions

Power Check restrictions on operating conditions (see Section **A.5**) involve a tradeoff between narrow boundaries (to reduce uncertainties) and wide boundaries (to cover a wider operational range). Other boundary values should be investigated, such as:

P) *Internal shading:* Internal shading for uniformly arranged collector fields can be modeled with minimal effort. Allowing an internal shading fraction of up to approx. $50\,\%$ would enhance Power Check by providing insights into partial load conditions, and by extending the method's coverage during winter months.

Q) *External shading*: Revisions of ISO 24194 should explicitly address how to treat external shading, e.g., by the procedure implemented in SunPeek, see Section **A.6**.

R) *Irradiance:* The standard sets high irradiance levels for data filtering: $G_{\text{hem}} \geq 800\ W/m^2$ and $G_b \geq 600\ W/m^2$. Easing this restriction and considering lower irradiance thresholds would allow coverage of more partial load operation conditions. Cosine effects also play a role. As an example, collector fields in high-latitude locations with north-south axis tracking can have large cosine effects even at noon, especially in spring and autumn, making it challenging to find valid intervals.

S) *Changes in collector mean temperature:* The intention of the current restriction can be interpreted as: avoiding significant heat-up / cool-down phases; or significant deviations compared to the mean temperature of the interval; or significant temperature peaks / dips within an interval. All these interpretations have their pros and cons and need further investigation.

T) *Wind speed*: Many solar plants, especially in low-wind locations, typically have no on-site wind speed sensors. The authors recommended making wind speed an optional measurement, required only if the result is expected to be wind dependent. If both wind-related collector parameters (a_3, a_6) are zero, Power Check should also be applicable without wind speed data, and the wind criterion may be omitted in Power Check data filtering.

U) *Wind speed limits*: ISO 9806 sets the wind speed limit for test condition limit at $4\ \text{m/s}$ on the collector plane, while the ISO 24194 Power Check allows wind speeds up to $10\ \text{m/s}$, measured 1 to 3 meters above the highest collector point. The correlation between the two criteria should be investigated further to make sure that collector parameters are not used outside their validity range.

V) *Maximum angle of incidence*: The standard does not specify a maximum angle of incidence (AOI), whereas SunPeek uses a maximum AOI of $80°$ to reduce uncertainties. The required irradiance levels may filter out conditions with high AOI, but it is nevertheless recommended to investigate and use sensible boundaries.

W) *Plant in operation*: The standard does not explicitly check that the collector field is operational. For example, tracking collectors can deliberately go out of tracking to avoid overheating. Revisions of ISO 24194 should include a criterion, such as a minimum average specific power output, to ensure the collector field is operational.

X) *Stagnation*: The standard does not explicitly mention stagnation. Filtering out stagnation seems to align with the intention of the standard that the valid data records represent the normal plant behavior. Revisions of ISO 24194 should include a criterion to filter out stagnation, see Section B.3. To ensure that stagnation does not go unnoticed, a summary of stagnation events should be documented in Power Check outputs.

Measurement setup specifications

Y) *Fluid properties*: In some circumstances, it is necessary to measure thermal power in the primary loop, or based on measured volume or mass flow, which makes it necessary to use fluid density and heat capacity; see Section A.7. For non-water fluids it is highly recommended to determine fluid properties by measurement, at least once at the start of recording measurements, as fluid properties can be unreliable. The standard should provide guidelines on how to treat such cases and include them in the accuracy level definitions.

Z) *DNI measurement for concentrating collectors*: Typical modern pyrheliometers have a Field of View (FOV) of $5°$ following the recommendation of the World Meteorological Organization (WMO) [38]. The acceptance angle for concentrating collectors depends on the collector technology, tracking accuracy, distribution of the circumsolar radiation, etc., but is typically much smaller. For concentrating collectors, this introduces a systematic bias in Power Check analysis. However, as this bias is hard to model and quantify, it is recommended to use measured, uncorrected values of pyrheliometers with a $5°$ FOV, until further research may lead to improved procedures.

AA) *Accuracy levels:* Recommendations on sensors and required data quality are important parts of the standard. However, the defined accuracy levels (I–III) should be refined. For most installations meeting all requirements is unlikely, making their practical relevance questionable. Also, accuracy levels should be linked to safety factors (see above).

BB) *Documentation of measurement setup*: Revisions of ISO 24194 should recommend a reporting format for the sensors used, their associated uncertainties, details about the measurement chain, including those components that mainly drive the uncertainty of logged data, and a logbook of significant plant events. The documentation should also include any information needed for data interpretation, such as sensor mounting or orientation.

E.3. Advances in methodology

Nomenclature

CC) *Consistent and clear terminology*: The standard lacks a clear definition and consistent use of terminology for data handling expressions such as “valid data”, “data records”, “valid data records", "data points", "valid points". Also, the main KPIs should have defined names, such as Performance Verification Criterion (PVC). See Section G.1 for suggestions.

Collector field modeling

DD) *Collector field model:* The standard uses three formulas to calculate the collector field output. Revisions of ISO 24194 should better align the modeling to ISO 9806, using only one formula as outlined see Section F.2.

EE) *Multiple and heterogenous fields:* In Section B.2 a procedure is outlined how to apply Power Check to plants with multiple and heterogenous collector fields, Section D.4 contains a practical application. This methodologically sound approach allows treating more complex hydraulic and geometric plant layouts, thus extending practical applicability of Power Check. Revisions of ISO 24194 should include this extension.

FF) *Missing sensors:* Revisions of ISO 24194 should specify how to treat cases with missing sensors, see Section B.2 and F.7. This is relevant for thermal power calculations, collector field temperatures (e.g., how to compute inter-field temperatures for serially connected arrays) and radiation data. The concept of "Virtual Sensors" used in SunPeek allows a straightforward representation of different measurement setups.

Radiation data and modeling

Irradiance measurements are typically the largest contributions to uncertainty of Power Check outcomes, and the standard should specify radiation data and modeling in more detail.

GG) *Use of satellite data / weather station data*: The standard allows using satellite-based irradiance data. The implied additional uncertainty should be analyzed for typical cases. Satellite data could be used to cross-check local measurements.

HH) *Radiation conversion*: For plants where the collector orientation differs from the irradiance sensor (e.g., if global horizontal irradiance is measured or G_{hem} for only one array orientation), radiation conversion is necessary to apply Power Check. The standard should clarify the situation regarding radiation conversion procedures, see Section F.7.

II) *Radiation decomposition*: Radiation decomposition models could be used to split hemispherical irradiance into beam and diffuse parts [43]. This allows using the more accurate Formula 2 instead of Formula 1 for non- or low-concentrating collectors. The used radiation models and their uncertainties should be documented.

JJ) *Diffuse irradiance masking*: Within collector field arrangements, diffuse sky radiation is reduced along the collector height, due to view obstructions of the front collector row. Measurements on top of collectors introduce a systematic bias (exaggerating the estimated power output). Revisions of ISO 24194 should make note of this issue.

Power Check and Yield Check

KK) *Power Check coverage*: Power Check "coverage" can be defined as the share of the solar energy yield covered by Power Check data records, compared to the total energy yield in the same period. This "coverage" gives an indication on the generalizability of the results; the usefulness of this KPI should be explored further. A higher "coverage" translates to increased usefulness of Power Check results in the realm of solar energy yield assessment.

LL) *Power Check vs. Daily Yield Check*: ISO 24194 also includes a Daily Yield Check (see Section A.9). A systematic comparison of the outcomes of Power and Daily Yield checks for different use cases would allow new insights and highlight the strengths and weaknesses of each method.

E.4. Community based development and SunPeek open-source software

Revisions of the ISO 24194 Power Check should be broadly discussed with relevant stakeholders and developed within a community-based approach. How to contribute:

1) *Use Cases:* Contribute real-world use cases and example applications for Power Check application; for inspiration, see examples in Chapter **D**.
2) *Open data:* Developing open-source software like SunPeek is only possible with publicly available datasets of plant operation. Such datasets are used for testing, validation and demonstration purposes. However, publicly available datasets are scarce; for an overview, see **[40]**. Open data repositories such as Zenodo make data sharing with the community very straightforward.
3) *Modeling*: Advances in modeling and further investigations require expert contributions, particularly from academia.
4) *Software*: SunPeek as the reference implementation for the ISO 24194 Power Check is actively seeking contributions; see below.
5) *Standard Committee and Tasks*: Conditional on approval, experts from industry and academia may directly participate in the technical committee ISO/TC 180, Solar energy, Subcommittee (SC) 4. Follow-up activities of IEA SHC Task 68 should continue to collaborate with the standard development. SolarPACES Task IV have regular expert exchanges on standard developments.

SunPeek strives to enhance its methods, the user experience and code quality. Also, SunPeek aims to align with further developments of the ISO 24194 standard and integrate topics not yet covered. **Table 22** summarizes features planned to be implemented in later versions of SunPeek. The longer-term SunPeek development goals are summarized in a Roadmap[16], as is common for open-source projects.

SunPeek Contributing
To contribute, interested users and software developers are encouraged to contact the development team at sunpeek@sunpeek.org.
SunPeek follows an open-innovation approach; new features and methodological details are discussed using git issues. Contributions are welcome in the form of feature requests, discussion inputs in issues, code, and reports of real-world applications of the software.
To contribute, please check out the SunPeek Contributing Guidelines: https://docs.sunpeek.org/contributing/index.html

Table 22. SunPeek Roadmap relevant for ISO 24194, at publication time of the present document.

Topic	*Implementation*
Power Check ISO 24194	• Update to the newest ISO 24194 **[41]**, under committee review (stage 40.20) at the time of writing of this document. • Shadows on one-axis or two-axis tracking collectors in a row
Yield Check ISO 24194	• Annual Yield Check procedure (as soon as part of ISO 24194 revision) • Daily Yield Check procedure
Power Check enhancement	• Full coverage of “Multiple Fields” case (Section **B.2**)

[16] https://sunpeek.org/resources/roadmap

	• Full coverage of “Stagnation events” case (Section **B.3**)
Automation	• Enable automated use of SunPeek, including automated data upload and auto-scheduling of Power Check evaluations
Cloud solution	• Enable a cloud version of SunPeek with public demo cases

F Towards a Harmonized Power Check framework

This chapter streamlines the insights presented in the previous chapters regarding Power Check modeling and results, proposing a new unified “Harmonized Power Check” framework which could serve as an input for revisions of ISO 24194, for SunPeek developments, and for future research activities.

F.1. Introduction

The Harmonized Power Check framework is considered a major rework of Power Check procedure, aiming at improved consistency between ISO 24194 and ISO 9806. It suggests a modular approach, starting with a baseline setup, followed by “what-to-do-if” instructions on how to adapt the procedure to hydraulic and measurement setups with increasing complexity and lack of measurement data.

Figure 67 gives an overview of the main processing steps of the Harmonized Power Check framework. For comparison with the existing Power Check see **Figure 1**. The following sections elaborate the new modeling approach (Sections **F.2** to **F.8**), as well as usage and interpretation of results (Section **F.9**). Section **F.10** compares the ISO 24194 Power Check and the Harmonized Power Check framework.

F.2. Collector output model

The modeling approach is based on the ISO 9806 collector model (Eq. 13 in ISO 9806:2017 **[2]**) as the single model for collector power output. It is recommended to use collector parameters obtained through the ISO 9806 test or equivalent procedures.

$$\begin{aligned}\dot{Q}_{\mathrm{QDT}} = A_{\mathrm{G}} \cdot [\eta_{0,\mathrm{b}}\ K_{\mathrm{b}}(\theta_{\mathrm{T}},\theta_{\mathrm{L}}) G_{\mathrm{b}} + \eta_{0,\mathrm{b}}\ K_{\mathrm{d}} G_{\mathrm{d}} - a_1(\vartheta_m - \vartheta_a) - a_2(\vartheta_m - \vartheta_a)^2 - a_3 u(\vartheta_m - \vartheta_a) \\ + a_4\left(E_{\mathrm{L}} - \sigma T_a^{\ 4}\right) - a_5(d\vartheta_m/dt) - a_6 u\left(K_{\mathrm{b}}(\theta_{\mathrm{T}},\theta_{\mathrm{L}}) G_{\mathrm{b}} + K_{\mathrm{d}} G_{\mathrm{d}}\right) - a_8(\vartheta_m - \vartheta_a\end{aligned} \qquad (26)$$

Mandatory parameters: As outlined in ISO 9806, certain parameters are mandatory, depending on collector concentration ratio and testing options. It should not be permitted to drop mandatory parameters from the above equation.

Zero collector parameters: Certain collector parameters in the above model may be zero, effectively neglecting specific effects. This is permissible if the guidelines of ISO 9806 are followed. Under ISO 9806, a parameter value of zero means that the parameter was either identified to be statistically insignificant or deliberately set to zero under specific conditions. ISO 9806 also specifies in detail when parameter values can be set to zero prior or during data analysis.

Missing model parameters: If collector parameters to apply ISO 9806 are missing, e.g., because only SST (steady-state) test data are given, the model parameters should be derived following recommendations of ISO 9806 and the Guide to Standard ISO 9806 **[6]**, as outlined in Chapter **A.3**.

Validity of collector parameters: ISO 9806 allows using collector parameters only for temperature differences between mean fluid and ambient temperatures up to a maximum of 30 K exceeding the temperatures during testing. When applying Power Check, attention should be paid to not significantly exceed this threshold. Additional validity limitations, usually detailed in the respective test documentation, may apply to specific collectors and should be regarded.

Limitations regarding collector types: Given the above approach, WISC collectors can be included if both wind speed data measured on the collector plane and measured longwave radiation data are available. Nevertheless, collectors co-generating thermal and electrical power and solar air heating collectors (SAHC) should be explicitly excluded for the reasons stated in Section A.1.

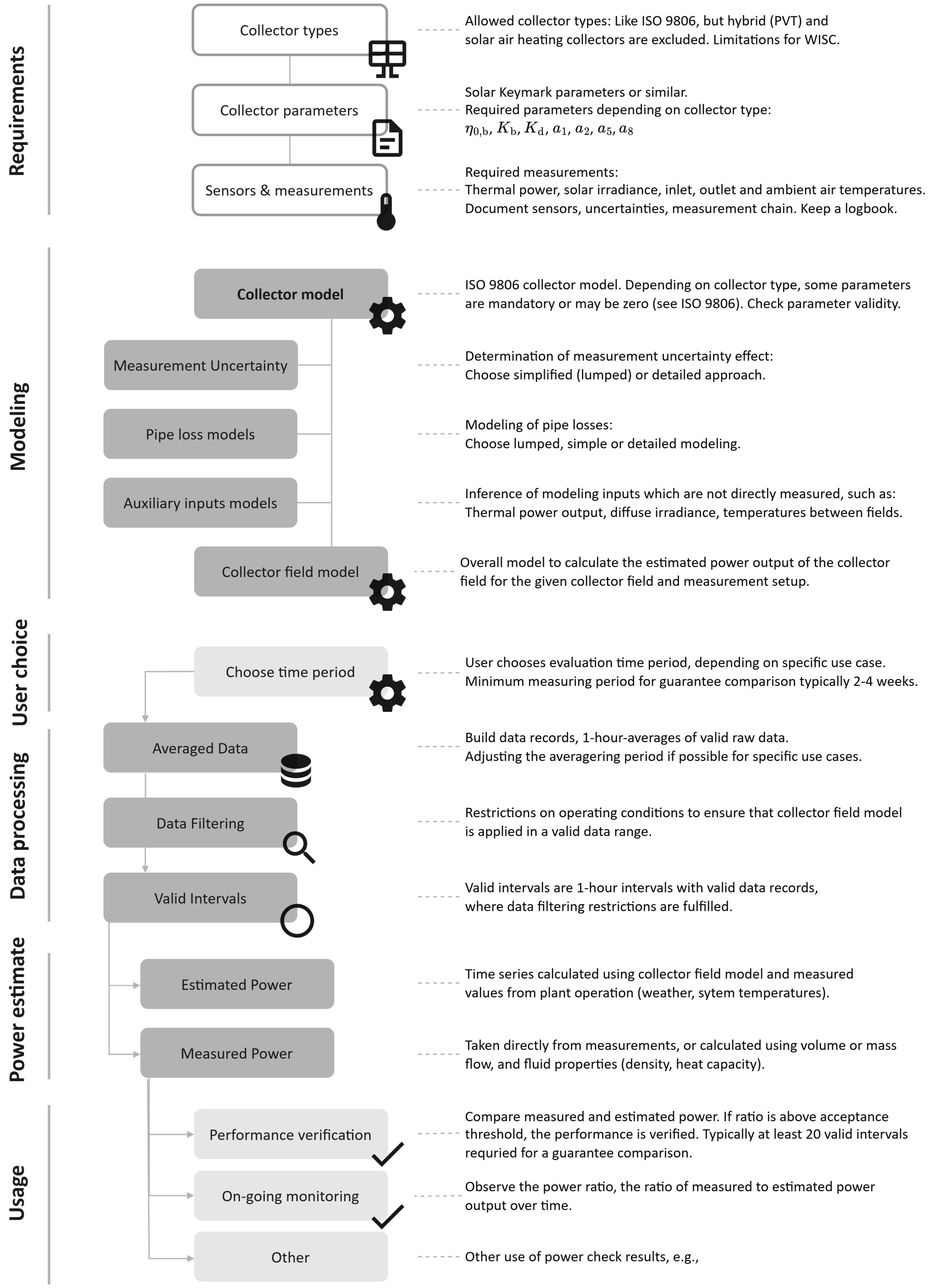


Figure 67. Step-by-step procedure of Harmonized Power Check framework.

F.3. Collector field output model

The Harmonized Power Check model is designed to compute an estimated power output for a collector field. It is based on the collector output model (see previous Section) and includes adjustments to account for effects on collector field level, and for common practical constraints such as missing input data. The estimated power output for a collector field is modeled as follows:

$$\dot{Q}_{\text{estimated}} = \left(1 - f_{\text{uncertainty}}\right) \cdot \left(1 - f_{\text{model}}\right) \left(A_{\text{GF}} \cdot \dot{Q}_{\text{QDT}} / A_{\text{G}} - \dot{Q}_{\text{pipe}}\right) \quad (27)$$

where $\dot{Q}_{estimated}$ is the collector field's estimated power output, A_{GF} is the gross collector field area, $f_{\text{uncertainty}}$ is a factor accounting for measurement uncertainty, f_{model} is a factor accounting for model uncertainty, $\dot{Q}_{QDT}$ the power output based on Eq. (13) in ISO 9806 (see Section **F.2**), and $\dot{Q}_{pipe}$ is the power loss in piping per square meter collector area.

Model interpretation: The collector field output model **(27)** uses the collector parameters from the ISO 9806 test of equivalent procedures and is hence based on performance parameters of new, "off the shelf" collectors. By design, the model does not include effects which accrue to the collectors as a component, like soiling, aging or degradation, even if they might be relevant. Such effects are accounted for by the acceptance threshold, see Section **F.9**. On the other hand, measurement uncertainty, model uncertainty, and pipe losses, which accrue to the collector field, are accounted for. The model aims to describe the expected extracted power output of the collector field from a technical perspective, excluding risk assessment and other practical considerations which might be relevant for performance verification or for guarantee procedures.

Documentation: Generally, plant-specific assumptions and chosen modeling options should be documented in all Power Check outputs (e.g., reports).

F.4. Measurement uncertainty

The factor $f_{\text{uncertainty}}$ in Eq. **(27)** represents the impact of measurement uncertainty (as opposed to modeling uncertainty and systematic effects) on the estimated power output. Its purpose is to ensure that $\dot{Q}_{estimate}$ represents the lower bound of a confidence interval around the unknown true value of $\dot{Q}_{estimate}$, assuming no measurement errors. The factor $f_{\text{uncertainty}}$ represents the uncertainty of whole measurement chains and data recording procedures, including uncertainty of single sensors, cables, and data logging. Measurement uncertainty can be incorporated in the following ways:

(i) Detailed modeling: The effect of measurement uncertainty could, in principle, be modeled in detail, by applying e.g. GUM **[42]** or other uncertainty quantification methods, using documented uncertainty information for sensors and measurement chains. In such case, $f_{\text{uncertainty}}$ can and should be applied individually to each logged data measurement value, as measurement uncertainty in general depends on the absolute measured values.

(ii) Lumped factor: The detailed uncertainty modeling described above seems too cumbersome for widespread practical application. As an alternative, a single lumped factor $f_{\text{uncertainty}}$ can be used. Revised versions of ISO 24194 should give clear guidelines and indicate ranges for choosing $f_{\text{uncertainty}}$, based on measurement accuracy levels (see Section **A.8**). Such ranges require more theoretical analysis and insights from practical experience. As an example, a way to present such ranges is presented in **Table 23**; see also new values in the updated ISO/CD 24194 **[41]**:

Table 23. Indicative ranges for $f_{\text{uncertainty}}$.

Accuracy level	$f_{\text{uncertainty}}$ indicative range
I	$0.02\ -\ 0.07$
II	$0.05\ -\ 0.10$
III	$0.10\ -\ 0.15$

F.5. Model uncertainty

The factor f_{model} accounts for model imperfections and unmodeled effects, such as delay effects or detailed dynamic responses (see Section **F.8** for further discussions). As such, f_{model} accounts for uncertainties of the collector output model (Section **F.2**), pipe model (Section **F.6**), and auxiliary models to calculate model inputs (Section **F.7**), where each auxiliary model comes with additional model uncertainty. Typically, f_{model} is very small, with a recommended range of $f_{model} \in [0,\ 0.02]$. The choice of larger values should be explained.

F.6. Pipe losses

Pipe losses refer to power losses from connection pipes, covering the distance between the location of the inlet and outlet temperature measurements and the collector field. Pipe losses (or in general non collector component-related losses) are an integral part of the plant design. They should therefore not be lumped in “safety factors” in the sense of ISO 24194 but rather be treated by an adaptation of the collector field output model. Pipe losses may be connected more intuitively to the plant temperatures than to power output. Pipe losses within fields are typically negligible.

Pipe losses $\dot{Q}_{pipe}$ can be estimated using one of the following approaches:

(i) Lumped pipe model: Use a lumped reduction factor f_{pipe} on the modeled collector power output:

$$\dot{Q}_{\text{pipe}} = f_{\text{pipe}} \cdot \dot{Q}_{\text{QDT}} \tag{28}$$

Values of f_{pipe} differ from plant to plant, depending mainly on pipe lengths and diameters, operating temperatures, and local climate. Typical values are $f_{pipe} \in [0,\ 0.05]$. The lumped pipe model is equivalent to using the safety factor for heat losses from pipes f_P in ISO 24194 (see Section **A.4**).

(ii) Simple pipe model: Use the following simple pipe loss model:

$$\dot{Q}_{\text{pipe}} = q_{\text{pipe}} \cdot L_{\text{pipe}} \cdot (\vartheta_{\text{op}} - \vartheta_{\text{loss}}) \tag{29}$$

This model is based on Eq. 22 of ISO 24194:2022, slightly modified to allow setting ϑ_{loss} to the respective heat loss temperature (ambient air, ground). The heat loss coefficient q_{pipe} can be computed using Eq. 23 of ISO 24194:2022:

$$q_{\text{pipe}} = 0.32 \cdot \left(\frac{V_{\text{pipe}}}{L_{\text{pipe}}} \right)^{0.22} \tag{30}$$

If pipe losses to both ground and air are relevant, or if inlet and outlet pipe lengths differ significantly, the pipe loss formula can be applied analogously to each part.

Example: **Table 24** shows an example for the simple pipe model, based on the example in ISO 24194, Section 6.7:

Table 24. Example to calculate pipe models.

Item	*Value*
Volume of piping	$V_{\text{pipe}} = 15000 \ \text{l}$
Length of piping	$L_{\text{pipe}} = 700 \ \text{m}$
Specific heat loss	$q_{\text{pipe}} = 0.628 \ \frac{\text{W}}{\text{m K}}$
Mean operating temperature	$\vartheta_{\text{op}} = 80 \ °\text{C}$
Ambient / ground temperature	$\vartheta_{\text{loss}} = 10 \ °\text{C}$
Pipe losses (calculated)	$\dot{Q}_{\text{pipe}} = 30.8 \ \text{W}$

(iii) Detailed pipe model: If a more detailed model for pipe heat losses is used, modeling details should be documented in Power Check outputs.

F.7. Auxiliary input models and treatment of irradiance

Power Check can only be applied if data for all explanatory model variables are available. This includes all terms in the model with non-zero collector parameters, and thermal power output. However, due to practical limitations, required measurements are often not available. The following recommendations for specific cases should be used.

Thermal power output

$\dot{Q}_{measured}$ can be inferred in three ways:

(i) Direct measurement, e.g. via heat meter.
(ii) Computation using measured mass flow: $\dot{Q}_{\text{measured}} = \dot{m} \cdot c_p(\vartheta_{\text{m}}) \cdot (\vartheta_{\text{in}} - \vartheta_{\text{out}})$
(iii) Computation using measured volume flow: $\dot{Q}_{\text{measured}} = \dot{V} \cdot \rho(\vartheta) \cdot c_p(\vartheta_{\text{m}}) \cdot (\vartheta_{\text{in}} - \vartheta_{\text{out}})$, where $\rho(\vartheta)$ must be evaluated at the temperature where $\dot{V}$ is measured.

Fluid properties (heat capacity and/or density) must be known for approaches 2) and 3). This is unproblematic if water is used as a heat transfer fluid. For other fluids, this can be problematic, and it is highly recommended to determine fluid properties by measurement, at least once at the start of recording, even if this can be costly (see Section A.7). It is important that the fluid properties are evaluated at the correct temperatures. For mixed fluids, also fluid concentration must be known.

Collector field temperatures

Measured inlet and outlet temperature of a collector field must be available to run Power Check. However, these temperatures may be missing if the procedure is applied to heterogenous or multiple collector fields. For such cases, the Harmonized Power Check framework recommends following the guidelines of Section B.2 of this Guide to calculate the missing temperatures.

Irradiance inputs

The irradiance term in the ISO 9806 model equation, $K_b(\theta_T, \theta_L) \cdot G_b + K_d \cdot G_d$, is one of the principal inputs for the Power Check model. The irradiances G_b and G_d represent the POA (plane of array) beam and diffuse irradiances for the collector field. The following scenarios outline how to handle specific cases. Each of these cases comes with additional model uncertainty, which should be accounted for in the model uncertainty factor, f_{model}.

(i) Only G_{hem} available: Due to practical difficulties of measuring G_{b} and G_{d}, such as technical complexity or high cost, a common practical case is to have only G_{hem} (POA hemispherical irradiance) available. In this case, either of the following approaches can be used; modeling assumptions must be documented in Power Check outputs.

- *"Blue sky" assumption:* The "blue sky" assumption of ISO 9806 is: $G_{\mathrm{b}}=0.85 \cdot G_{\mathrm{hem}}$ and $G_{\mathrm{d}}=0.15 \cdot G_{\mathrm{hem}}$. This is equivalent to using Formula 1 of ISO 24194 and the ISO 9806 methodology to compute K_{hem} from K_{b} and K_{d}, if measured irradiance data is unavailable (see Section **A.7**).
- *Irradiance model:* Using a more realistic radiation model for "reverse transposition" and decomposition. For an overview of the topic, see PVPS Handbook 2024 **[39]**. Models are available in pvlib **[34]**, based on Driesse et al. **[43]** and Marion **[44]**.

(ii) Only G_h available: If only global horizontal irradiance is available, use a radiation decomposition and transposition model to estimate G_{b} and G_{d}. A recommended state-of-the-art transposition model is the Perez 1990 model **[45]**.

(iii) Only G_{hem} available, but on a plane with different orientation: The approach outlined above ("Only G_{hem} available – Irradiance model") can be used to calculate G_{b} and G_{d}, which are then used to model G_{b} and G_{d} on a plane with different orientation. This works well when the orientation difference is small, but there are limits to how large an orientation difference is acceptable while maintaining an accurate method. Further research into this question is needed, and the authors cannot currently give a specific recommendation.

POA corrections

If the measured or modeled G_b and G_d values refer to the top of the collector, the POA G_{b} and G_{d} values used as model inputs may be adjusted to account for ground-reflected irradiance and diffuse irradiance reduction due to masking (part of the sky diffuse irradiance blocked by adjacent collector rows, for fixed mounted fields). Not applying such POA corrections overestimates POA irradiance, hence the Power Check model would systematically overestimate a collector field's power output.

POA correction model choices and assumptions should be documented. State-of-the-art implementations for such adjustments exist, see e.g. pvlib **[34]**. For the discussion on the magnitude of the effects for typical configurations, see **[14]**.

F.8. Modeling limits and unmodeled effects

Validity limits

Generally, the ISO 24194 Power Check model is subject to the validity limits of collector parameters, derived from the ISO 9806 model, see Section **F.2**. Additional limitations are usually documented in collector data sheets. Consequently, Power Check data filtering must ensure it stays within the validity range of the collectors used. Inaccuracies can arise if the operating conditions in the collector field (e.g., absolute volume flow rate) significantly differ from the test conditions under which the collector efficiency parameters were obtained. ISO 24194 takes the collector parameters as point values (deterministic assumption) and does not account for uncertainty information of collector parameters (standard deviations, covariance, see also ISO 9806 Annex B).

Soiling

Soiling reduces the collector's optical efficiency and is an operationally important effect for the power output of solar thermal plants. The Power Check model refers to the power output of new collectors, as tested, and soiling is deliberately not included in the Power Check model. However, comparing measured and estimated power output may provide insight into the degree of soiling on plant performance.

Delay effects

The ISO 9806 model does not account for delay effects caused by the transit time of the heat transfer fluid through the collector field and potentially through pipes. This transit time can range from approximately 5 to 30 minutes, and its effects are clearly observable in collector field data **[7]**. For Power Check, the impact of not modeling delay effects is somewhat mitigated by the averaging process used in building data records. However, it cannot be excluded that delay effects may lead to increased model error in certain intervals, see discussion in Section **A.5**. Generally, model validity decreases when the instantaneous collector inlet and outlet temperatures are not representative of the internal temperature state of the collector field.

Natural extensions of the ISO 9806 model to collector fields exist, which explicitly take fluid transport effects through the collector field into account, while still being based on the original collector parameters (see, e.g., the D-CAT model **[7]**). However, this step considerably increases model and analysis complexity because it turns the model into a partial differential equation.

Uneven flow distribution

Uneven flow distribution is known to impact the power output of a collector field to a very small degree, except in extreme cases that indicate very poor system design. For practical purposes, the effect of uneven flow distribution can be considered negligible (see e.g. **[29]**).

Tracking accuracy

This applies only to tracking collectors. The Power Check model assumes optimal tracking, which is considered to be desirable collector field behavior. Deviations due to suboptimal tracking accuracy are not considered in the model.

DNI correction

This applies only to collectors with a high concentration ratio $C_R > 20$. There might be a mismatch between the acceptance angles of measured DNI (typically $5°$ field of view) and those of the used concentrating collector technology (typically smaller field of view). This is a constructive effect and does not represent suboptimal operation of a collector field; therefore, beam irradiance may be corrected for the different fields of view, and the reduced G_b can be used as model input. This DNI correction is optional, as it is not yet standard practice. If applied, it must be documented in Power Check outputs. For more details, see also .

F.9. Usage and acceptance threshold

The Harmonized Power Check aims to clearly differentiate between the outputs of Power Check and its usage. For a chosen evaluation period $[t_1, t_2]$ Power Check produces a time series of valid data records with measured and estimated power outputs and their power ratios:

$$\begin{aligned} \dot{Q}_{\text{measured}}([t_1, t_2]) &= \dot{Q}_{\text{measured},1} \ , \ \dot{Q}_{\text{measured},2} \ , \ \dot{Q}_{\text{measured},3} \ , \ldots \\ \dot{Q}_{\text{estimate}}([t_1, t_2]) &= \dot{Q}_{\text{estimate},1} \ , \dot{Q}_{\text{estimate},2} \ \dot{Q}_{\text{estimate},3} \ , \ldots \end{aligned} \tag{31}$$

$$\dot{Q}_{\text{ratio}}([t_1, t_2]) = \frac{\dot{Q}_{\text{measured},1}}{\dot{Q}_{\text{estimate},1}}, \frac{\dot{Q}_{\text{measured},2}}{\dot{Q}_{\text{estimate},2}}, \frac{\dot{Q}_{\text{measured},3}}{\dot{Q}_{\text{estimate},3}}, \ldots$$

For Power Check according to ISO 24194, at least 20 consecutive valid data records are required, and an estimate is verified if the following criterion holds (see Section **A.2**).

$$\text{Average}(\dot{Q}_{\text{measured}}) \geq \text{Average}(\dot{Q}_{\text{estimated}}) \quad (32)$$

The collector field output model aims to describe the power output assuming new, "off the shelf" collectors. While the model is set up once (except for changes in the plant configuration), the measured- and estimated power output can be continuously updated with new data. Section **D.1** outlines different usages of Power Check results. The Harmonized Power Check framework addresses these uses cases as follows:

Power performance verification / Power performance guarantee: For these use cases, Power Check should introduce an acceptance threshold or minimum performance target, considering risk assessment and practical safety considerations. The acceptance criterion can be expressed as:

$$\frac{\text{Average}(\dot{Q}_{\text{measured}})}{\text{Average}(\dot{Q}_{\text{estimated}})} \geq \text{acceptance\_threshold} \quad (33)$$

The acceptance threshold may vary over time due to factors such as soiling or collector aging that vary with time, and the acceptance threshold is in general a subject of negotiations. Introducing an acceptance threshold cuts the direct link of the safety factor with the Performance Verification Criterion (PVC), allowing a clear interpretation of the safety factor as a purely technical parameter and avoiding contractual discussions.

Ongoing performance monitoring: Applying Power Check regularly, e.g., with daily updates, enables early detection of performance deviations, such as those caused by soiling or degradation. One possible option is a visual approach by plotting the measured-estimated power ratio over time or to continuously update a KPI such as the power output ratio averaged over 20 data records. Such KPIs could be used to monitor plant performance and to anticipate maintenance needs. Absolute values and relative changes, making systematic modeling biases less problematic, are both of interest.

F.10. Comparison of ISO 24194 Power Check and Harmonized Power Check framework

In the previous sections, the modeling approach of Harmonized Power Check framework has been outlined. Additional adaptations and improvements to Power Check as summarized in Chapter **E** should also be included in the framework, notably:

- Data averaging of Extended Power Check (Section **B.1**)
- Methodology for the treatment of multiple and heterogeneous collector fields (Section **B.2**)
- Exclusion of stagnation events (Section **B.3**)

These changes are not linked to the modeling approach of the Harmonized Power Check framework per se and are compatible both with the existing and new Power Check framework. **Table 25** provides a comparison between the two procedures.

Table 25. Comparison of ISO 24194 Power Check and Harmonized Power Check framework.

Item	*ISO 24194 Power Check*	*Harmonized Power Check*
Applicable collector types	Glazed flat-plate, evacuated tube, concentrating / tracking collectors	Most collector types of ISO 9806; exclusion of co-generating / PVT collectors, solar air

Item	*ISO 24194 Power Check*	*Harmonized Power Check*
	(air heating collectors not explicitly excluded)	heating collectors; WISC allowed under some circumstances
Collector field model	Formula 1–3 depending on collector type and available measurements; parameter conversion between SST and QDT procedure may be necessary	Collector model of ISO 9806. Parameters may be set to zero or dropped following the guidelines of ISO 9806; consideration of validity limits of collector parameters
Interpretation of collector field model	Presumably the same as for Harmonized Power Check framework, but not explicitly stated	Performance of new, “off the shelf” collectors, not accounting for effects that accrue to the collectors as a component, but for effects relating to the whole field
Safety factor	Overall safety factor f_{safe}, compromised of f_P for heat losses from pipes, f_U for measurement uncertainty and f_O for other uncertainties	Safety factor $f_{\text{uncertainty}}$ for measurement uncertainty, f_{model} for model uncertainty; no overall safety factor
Determination of safety factors	Constant values	Fixed value for f_{model}, lumped or detailed modeling for $f_{\text{uncertainty}}$
Pipe losses	Covered by safety factor f_{P} (constant values)	Various modeling options (lumped, simple and detailed pipe model), some models depending on operating conditions
Missing sensors	Choice of Formula 1 or 2 depending on irradiance input, no systematic treatment of missing sensors	Systematic treatment and modeling options for missing sensors (thermal power output, collector field temperatures, irradiance inputs)
Acceptance threshold	No acceptance threshold for power performance verification	Explicit threshold for power performance verification considering collector degradation, risk assessment, practical safety considerations, etc.
Open-source implementations	SunPeek [30]	None yet

G Appendix

G.1. Terms and Definitions

Table 26 contains terms and definitions used in this document. The column “Basis” indicates where the term was originally introduced or is prominently used (“Guide” refers to this document). Wherever possible, the definitions and explanations follow ISO 24194. But as ISO 24194 does not contain a comprehensive terms and definitions section, some of these terms remain undefined or are used ambiguously. Revisions of ISO 24194 should extend the terms and definitions section and strictly adhere to it.

Table 26. Terms and Definitions used in this guide. The column “Basis” indicates the origin of the term (“Guide” refers to this document).

Term	*Definition, explanation*	*Basis*
AOI	Angle of Incidence, i.e. the angle between the beam radiation on a surface (typically the collector plane) and the normal to that surface.	Guide
Average estimated power output	Average of estimated power output for all valid intervals of Power Check.	Guide
Average measured power output	Average of measured power output for all valid intervals of Power Check.	Guide
Average power ratio	Average of estimated power output divided by average of measured power output (for all valid intervals of Power Check).	Guide
Collector array	Defined in ISO 9488:2022 [16] as a group of solar collectors that are closely connected in series, in parallel or in combination of both modes, with one hydraulic input and one hydraulic output.	ISO 9488
Collector field	This term is not explicitly defined in ISO 24194 but presumably used synonymously to collector array. For the ISO 24194 Power Check, a collector field is the technical object for which Power Check is performed. This requires a common power measurement either on the primary or secondary side. This document distinguishes between uniform collector fields, where the application of Power Check is straightforward, and heterogenous collector fields, which are not covered in ISO 24194. SunPeek uses the term (collector) array instead of collector field.	ISO 24194
Collector model	A collector with distinct name and dimensions, and one set of collector performance parameters listed in the data sheet (if tested according to a standard or quality assurance scheme like Solar Keymark).	Guide
Collector type	As collector types, ISO 9488:2022 [16] lists, among other, flat-plate, evacuated tubular, concentrating and WISC (wind and infrared sensitive collector) collectors. ISO 24194 mentions single- and double-glazed flat-plate collector types.	ISO 9488/ ISO 24194
Cosine effect	Reduction of the receiving area for beam / direction radiation caused by the cosine angle θ formed between the beam solar radiation and the normal of the collector plane: $G_b = DNI \cdot \cos(\theta)$	Guide
Data channel	Collection of measured or calculated values associated with a specific quantity / measurand. For Power Check, all data channels are given as time series data where each measured value has an associated timestamp. In CSV (Comma-separated Values) files, the name of a data	Guide

Term	*Definition, explanation*	*Basis*
	channel is usually the column head (e.g., Hemispherical Irradiance, Collector Field Inlet Temperature, Angle of Incidence).	
Data record	Hourly-mean values of a specific 1-hour interval, containing all data channels relevant for the measured-estimated comparison (e.g., G_{hem}, ϑ_a, ϑ_i, ϑ_e,...). To make Power Check traceable, the authors of this guide recommend including measured variables, e.g., G_{hem}, and calculated variables, e.g., θ_L, θ_T, and explanatory variables, e.g., $K_{\text{hem}}(\theta_L, \theta_T)$, when reporting the (valid) data records, see **Figure 37**.	ISO 24194
Evaluation period	Period from which the valid intervals of Power Check are selected, equal or a subinterval of the measurement period.	Guide
Heterogenous collector field	A heterogenous collector field is more complex than a uniform collector field, e.g., due to using multiple collector types, having multiple subgroups of collectors connected in parallel or serial, irregular row spacing, irregular mounting angles, etc. Such cases are not covered in the ISO 24194 Power Check.	SunPeek
Hourly-mean data	Arithmetic averages of (valid) raw data over 1-hour intervals. The ISO 24194 Power Check requires intervals to start and end at full hours (e.g., 11:00, 12:00, 13:00, etc.) and assigns the last timestamp of the averaging interval to the hourly-mean data (e.g., the timestamp 12:00 represents measurements from 11:00 to 12:00 on that day).	ISO 24194
IAM	Incidence Angle Modifier	ISO 9806
Measured-estimated power ratio	Estimated power output divided by measured power output of a Power Check interval.	Guide
Measured value (MV)	Quantity value representing a measurement (GUM **[42]**).	GUM
Measurement data	(Raw) data obtained by a measurement device.	Guide
Measurement data channel	Data channel originating from a measurement, containing measured values.	Guide
Measurement period	Period for which data of an installation is logged.	Guide
PVC	Performance Verification Criterion, comparing average estimated power output to average measured power output as defined in Eq. **(2)** for all valid data records.	Guide
Plant	System using solar energy for the delivery of thermal energy (ISO 9488:2022 **[16]**). System and installation are used as synonyms for plant. A plant can have one or multiple collector fields, which can be uniform or heterogenous.	ISO 9488
POA	Plane of Array, as in POA irradiance: Solar irradiance measured or modeled in the plant of the collector field.	Guide
QDT	Quasi-dynamic test (QDT) procedure according to ISO 9806.	ISO 9806
Raw data	Data at original sampling rate as recorded from measurement device (e.g., hemispherical irradiance measured by a pyranometer) or calculated (e.g., angle of incidence, temperature difference mean collector temperature and ambient air). Some data loggers include basic data quality checks.	Guide
Sampling rate	Length of time interval for which the data is acquired and stored (logging time).	ISO 24194
Sensor	Element of a measuring system that is directly affected by a phenomenon, body, or substance carrying a quantity to be measured (GUM **[42]**).	GUM

Term	*Definition, explanation*	*Basis*
	A sensor is typically associated with a data channel but may require additional sensor properties to make use of the measured value.	
Sensor mapping	Linking measurement data channels with input slots for computations as part of the SunPeek plant configuration.	SunPeek
Sensor properties	Specifications of a Sensor, e.g., tilt and azimuth of an irradiance sensor, to interpret / process its measured values.	SunPeek
Sensor type	Sensor category associated with a measurement data channel in SunPeek, determines allowed physical units and data replacement scheme.	SunPeek
Uniform collector field	Collector field consisting of one collector model with a geometrically uniform arrangement, i.e. same mounting (tracked or fixed with constant tilt and azimuth) and row spacing with a rectangular shape on a plane. If no external shading occurs, collectors within rows can be assumed to receive similar irradiance levels. For the ISO 24194 Power Check, uniform collector fields have one set of efficiency parameters to be used in Formulas 1–3. The application of ISO 24194 is straightforward in this case. This term “uniform collector field” can be used as a modeling abstraction. For example, a heterogenous collector field where the collectors have different mounting angles could be split into two uniform collector fields.	SunPeek
Valid interval / Valid data record	Data record fulfilling the data filtering criteria of Power Check.	ISO 24194
Valid data point	In ISO 29194, this term is presumably used synonymous with “valid data record”. The authors of this guide suggest depreciating this term.	ISO 24194
Valid raw data	Raw data after applying data quality checks. SunPeek excludes physically impossible values and replaces measurement values sightly outside physically possible limits that might occur due to measurement uncertainties.	Guide
Virtual Sensor	Similar to a Sensor but not related to a measuring system. Its values are calculated based on other (virtual) sensors and optionally on parameters. Used in SunPeek to replace missing sensors or calculate required inputs for subsequent analysis like solar position, or internal (row-to-row) shading of collector rows.	SunPeek
SST	Steady-state test (SST) procedure according to ISO 9806.	ISO 9806
WISC	Wind and infrared sensitive collector. WISC refers to a collector type that is particularly sensitive to wind and/or infrared radiation like uncovered co-generating / PVT and solar air heating collectors (as opposed to flat-plate, evacuated tubular, concentrating collectors).	ISO 9488 / ISO 9806

G.2. List of symbols

Where available, the symbols follow the conventions in ISO 24194:2022 [1], ISO 9806:2017 [2] and ISO 9488:2022 [16]. The amendment ISO 24194/Amd 1:2024 [46] corrects incorrect symbols from ISO 24194:2022; the corrected symbols are used here. Explanations and deviations in the description are marked in square brackets to improve readability. The column "Basis" in Figure 27 indicates where the term was originally introduced or where it is prominently used ("Guide" refers to this document).

Table 27. List of Symbols used in this guide.

Symbol	*Description*	*Basis*	*Unit*
A_{Ap}	Aperture area of collector as defined in ISO 9488	ISO 9844 / ISO 9806	m^2
A_{G}	Gross area of collector	ISO 24194	m^2
A_{GF}	Gross area of collector field	ISO 24194	m^2
a_1	Heat loss coefficient at (ϑ_m - ϑ_a) = 0 [Denoted $a_{1,\Delta Q}$ in ISO 24194]	ISO 24194	$\frac{\mathrm{W}}{\mathrm{m}^2\cdot\mathrm{K}}$
a_2	Temperature dependence of the heat loss coefficient [Denoted $T_{\Delta Q}$ in ISO 24194]	ISO 24194	$\frac{\mathrm{W}}{\mathrm{m}^2\cdot\mathrm{K}^2}$
a_3	Wind speed dependence of the heat loss coefficient [Denoted $v_{\Delta Q}$ in ISO 24194]	ISO 24194	$\frac{\mathrm{J}}{\mathrm{m}^3\cdot\mathrm{K}}$
a_4	Sky temperature dependence of the heat loss coefficient [Denoted T_S in ISO 24194]	ISO 24194	–
a_5	Effective thermal capacity. In some literature and data sheets denoted as C_{eff} with unit $kJ/(m^2\cdot K)$.	ISO 24194	$\frac{\mathrm{J}}{\mathrm{m}^2\cdot\mathrm{K}}$
a_6	Wind speed dependence of the zero-loss efficiency [Denoted v in ISO 24194]	ISO 24194	s/m
a_7	Wind speed dependence of IR radiation exchange [Denoted v_{IR} in ISO 24194]	ISO 24194	$\frac{\mathrm{W}}{\mathrm{m}^2\cdot\mathrm{K}^4}$
a_8	Radiation losses dependence	ISO 24194	$\frac{\mathrm{W}}{\mathrm{m}^2\cdot\mathrm{K}^4}$
c_{f}	Specific heat capacity of heat transfer fluid	ISO 24194	$\frac{\mathrm{J}}{\mathrm{kg}\cdot\mathrm{K}}$
C_{R}	Geometric concentration ratio	ISO 24194	–
DNI	Direct Normal Irradiance [denoted I_{DN} in ISO 24194]	ISO 24194	$\mathrm{W/m}^2$
E_{L}	Longwave irradiance ($\lambda > 3\ \mu\mathrm{m}$)	ISO 9806	$\mathrm{W/m}^2$
f_{model}	Factor accounting for model uncertainty in Harmonized Power Check Model	Guide	–
f_{O}	Safety factor for other uncertainties, e.g., non-ideal conditions such as non-ideal flow distribution and unforeseen heat losses – and uncertainties in the model / procedure itself.	ISO 24194	–
f_{P}	Safety factor for heat losses from pipes etc. in the collector loop	ISO 24194	–
f_{safe}	Mathematical product based on the individual safety factors f_{P}, f_{U}, f_{O}	ISO 24194	–
f_{U}	Safety factor for measurement uncertainty	ISO 24194	–

Symbol	*Description*	*Basis*	*Unit*
$f_{uncertainty}$	Factor accounting for measurement uncertainty in Harmonized Power Check Model	Guide	–
G_b	Direct solar irradiance (beam irradiance) on the plane of collector	ISO 24194	W/m^2
G_d	Diffuse solar irradiance on the plane of collector	ISO 24194	W/m^2
G_h	Hemispherical solar irradiance on a horizontal plane	ISO 9488	W/m^2
G_{hem}	Hemispherical solar irradiance on the plane of collector	ISO 24194	W/m^2
$K_b(\theta_L, \theta_T)$	Incidence angle modifier for direct solar irradiance	ISO 24194	–
K_d	Incidence angle modifier for diffuse solar radiation	ISO 24194	–
$K_{hem}(\theta_L, \theta$	Incidence angle modifier for hemispherical solar radiation	ISO 24194	–
L	Length of a collector [from bottom to top as stated in ISO 9488, in contrast to Figure 1 in ISO 24194]	ISO 9488 / ISO 24194	m
L_{pipe}	Overall Length of the pipe system without collectors	ISO 29194	m
q_{pipe}	Empirical specific heat losses per m pipe	ISO 24194	W/m
$\dot{Q}$	Power output (of a collector field)	Guide	W
$\dot{Q}_{estimated}$	Estimated power output (of a collector field)	ISO 24194	W
$\dot{Q}_{measured}$	Measured power output (of a collector field)	ISO 24194	W
$\dot{Q}_{pipe}$	Power losses in piping in Harmonized Power Check model	Guide	W
$\dot{Q}_{QDT}$	Power output of collector of single collector	Guide	W
$\dot{Q}_{sp,min}$	Minimum measured specific power output (assuming normal operational behavior) relative to gross area of collector field A_{GF}	Guide	W/m^2
$\dot{Q}_{tot}$	Total measured power output for plants with multiple collector fields, i.e. $\dot{Q}_{tot} = \dot{Q}_1 + \dot{Q}_2$	Guide	W/m^2
S	Collector row spacing: Distance between bottom of collectors of adjacent rows [ISO 24194: Spacing center to center in between adjacent rows]	ISO 24194	m
t	Time	ISO 24194	s
t_{end}	Start of interval (first timestamp with measurement data)	ISO 24194	s
t_{start}	End of interval (last timestamp with measurement data)	ISO 24194	s
T_a	Absolute ambient temperature	ISO 9806	K
u	Surrounding air speed (wind speed). Measured 1 to 3 meters above highest point of collector field in ISO 24194, measured in collector plane in ISO 9806	ISO 24194 / ISO 9806	m/s
$\dot{V}$	Volumetric flow rate	ISO 24194	m^3/s
V_{pipe}	Volume of piping	Guide	m^3
α	Weight to calculate unknown temperature within heterogeneous collector fields	Guide	–
β	Collector (field) tilt angle: Angle between the horizontal plane and the collector plane [ISO 24194: Slope (or tilt), the angle between the plane of the collector and the horizontal]	ISO 24194	°
γ	Collector (field) azimuth angle [ISO 24194: 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]	ISO 24194	°

Symbol	*Description*	*Basis*	*Unit*
ε	Volumetric concentration of anti-freeze heat transfer fluid	Guide	%vol
$\eta_{0,b}$	Peak collector efficiency (η_b at $\vartheta_m - \vartheta_a$ = 0 K) based on beam irradiance G_b	ISO 24194	—
$\eta_{0,hem}$	Peak collector efficiency ($\eta_{0,hem}$ at $\vartheta_m - \vartheta_a$= 0 K) based on hemispherical irradiance G_{hem}	ISO 24194	—
θ	Angle of incidence	ISO 24194	—
θ_L	Longitudinal angle of incidence: angle between the normal to the plane of the collector and incident sunbeam projected into the longitudinal plane	ISO 24194	°
θ_{min}	Threshold for sun elevation where external shading occurs	Guide	°
θ_{sun}	Sun elevation (sun altitude angle)	Guide	°
θ_T	Transversal angle of incidence: angle between the normal to the plane of the collector and incident sunbeam projected into the transversal plane	ISO 24194	°
ϑ	Temperature	Guide	°C
ϑ_a	Ambient air temperature	ISO 24194	°C
ϑ_i	Collector [field] inlet temperature	ISO 24194	°C
ϑ_e	Collector [field] outlet temperature	ISO 24194	°C
ϑ_{loss}	Reference temperature for pipe losses (ambient air, ground).	Guide	°C
ϑ_m	Mean temperature of heat transfer fluid in collector loop	ISO 24194	°C
ϑ_{op}	Mean operating temperature relevant for pipe losses	Guide	°C
ϑ_x	Collector field temperature at position x within array or inter-field multiple arrays	Guide	°C
ρ	Density of heat transfer fluid [at measurement position]	Guide	m^3/s
σ	Stefan-Boltzmann constant	ISO 9806	$\frac{W}{m^4 K^4}$

G.3. List of figures

G.4. List of tables

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