Digital Tools for Solar Thermal Plant Monitoring

A Handbook for Plant Operators and Associated Stakeholders

Version 1.0 (June 2024)

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Summary

Background: Large-scale solar thermal plants are a key technology to provide renewable heat in residential, industrial, and district heating applications with substantial growth worldwide in recent years. Increasing availability of data, performance analytics methods and digitalization technologies offer the opportunity to improve quality assurance standards of the technology. An important milestone is the release of ISO 24194 in 2022, which is the first standard of its kind to target the operating phase of solar thermal collector arrays.

Challenge: To ensure high solar energy yields over the lifespan of the plant, digital monitoring solutions which support automated, cost-effective performance benchmarking and optimal system operation are needed. The promising developments in this field are not yet fully seized by the stakeholders, mainly small and medium-sized enterprises who operate solar thermal plants, due to a lack of awareness and accessible, target group specific information.

Aim: This handbook strives to give an overview of digital tools for solar thermal plant monitoring and addresses typical data requirements and evaluation methods. The work focuses on open-source software tools. Open-source tools not only decrease licensing costs for users, but also offer the benefit of traceable and transparent outcomes, e.g., when the software is used to check performance guarantees.

Target group: The handbook mainly targets plant operators of large-scale solar thermal plants, especially small and medium-sized enterprises, and additionally associated stakeholders like system designers, collector manufacturers, quality assurance institutions, investors and heat costumers.

Scope: The presented digital tools are geared towards large-scale applications, mainly for systems using non-concentrating flat plate collectors, with a focus on the collector array (primary loop). One open-source tool, the SunPeek software, is presented in detail. The authors do not claim completeness of the selected tools nor any preference which tools are most suitable.

Previous work: The handbooks integrates on-going work and discussions with experts from IEA SHC Task 68 [1], and strongly builds on the projects HarvestIT [2] and MeQuSo [3].

Structure: The handbook consists of 4 chapters. Chapter **1** summarizes the required measurement setup and data handling. Chapter **2** introduces common methods and key figures used in digital tools, whereas Chapter **3** gives an overview of digital tools and open data sets. Chapter **4** introduces the SunPeek software, which implements the ISO 24194 Power Check.

1 Measurement setup and data handling

This chapter provides recommendations on the required data for the most commonly used performance evaluations done with digital tools for solar thermal plant monitoring.

1.1 Literature review

TABLE 1 lists literature on recommended measurement instrumentation of solar thermal plants.

Table 1. Literature on recommended measurement instrumentation for solar thermal plants. Source: Adapted from [1].

Reference	*Description*
ISO 9806 [4]	An international standard for testing solar collectors, containing requirements for measurement devices and their installation.
ISO 24194 [5]	An international standard to check the performance of collector arrays, containing requirements for measurement devices and their installation.
Guide to ISO 9806 [6]	Guide to ISO 9806, providing tips on how to apply the corresponding standard. It contains information about required sensors, installation conditions, and sensor specifications for testing solar thermal collectors.
Guide to ISO 24194:2022 – Power Check [7]	Guide to the Power Check method of ISO 24194, providing insights how to apply the method in practice. It also contains a chapter about which measurements are required to apply the standard and provide some extensions of the standard, e.g., to multiple collector arrays.
IEA SHC Task 68 [1]	A task report on data gathering, storage, distribution, and validation for solar district heating plants including collector field, heat storage, and heating center up to the interface to the district heating network. The report mainly targets system designers and plant operators, aiming to provide checklists and recommendations on these topics.
IEA SHC Task 45 [8], [9]	Fact sheets on monitoring, listing recommendations for monitoring solar thermal plants. The report contains a list of recommended measurements, installation conditions, and sensor specifications (written in German).
IEA SHC Task 55 Fact sheet B-D.3 [10]	A fact sheet about automated monitoring, listing recommendations for monitoring solar thermal plants. The report contains a list of recommended measurements, installation conditions, and sensor specifications.
Effertz et al. [11]	A research report on measurement and performance testing of solar thermal plants, containing recommendations for sensor specifications and installation.
Faure et al. [12]	An article reviewing dysfunctions of solar thermal plants, containing a description of typical measurements as part of the state-of-the-art section.

Reference	*Description*
Kramer et al. [13]	An article comparing different collector performance tests (ICC, D-CAT, PC), containing a brief overview of required measurements.
Zirkel-Hofer et al. [14]	An article discussing the selection and installation of measurement devices based on uncertainty examination of different sensors, focusing on concentrating collectors.
Solar Heat Data Website [15]	A website showing solar thermal plants and their measurement data. Required measurements are listed as part of the registration process.

1.2 Sensors

Acknowledgment: This chapter contains excerpts (with minor adaptions) of IEA SHC Task 68 report "Efficient Data Management and Validation", Chapter 2.1. [1], relating to collector arrays including the heat exchanger.

This chapter focuses on measurements relating to collector arrays including the heat exchanger connected to the primary circuit, as shown in FIGURE 1.

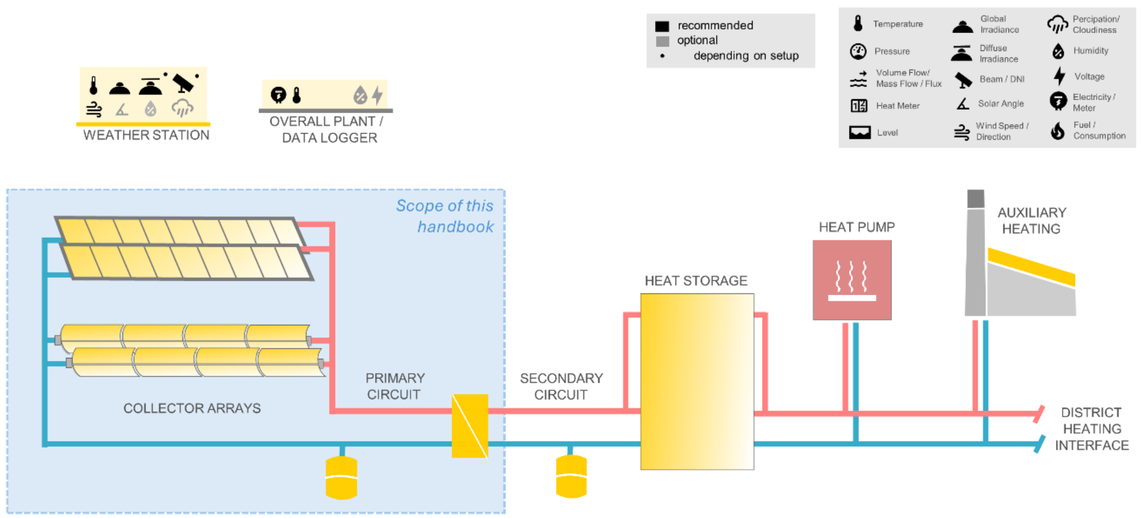


Figure 1. System boundaries for measurements covered in this chapter. Source: Adapted from [1].

The recommended and additional optional sensors are shown in FIGURE 2 and described in more detail below. The following categories are used to loosely group the sensors:

- *Weather Station / Ambient* groups all sensors related to solar radiation and weather.
- *Collector Array* corresponds to measurements at the collector arrays.
- *Primary Circuit* contains all sensors in the primary circuit that are not associated with individual collector loops.

- *Secondary Circuit* contains all measurements in the secondary circuit at the heat exchanger.

Please note that the installation requirements and uncertainty considerations are not in the scope of this handbook. Instead, the interested reader is referred to the cited literature in TABLE 1.

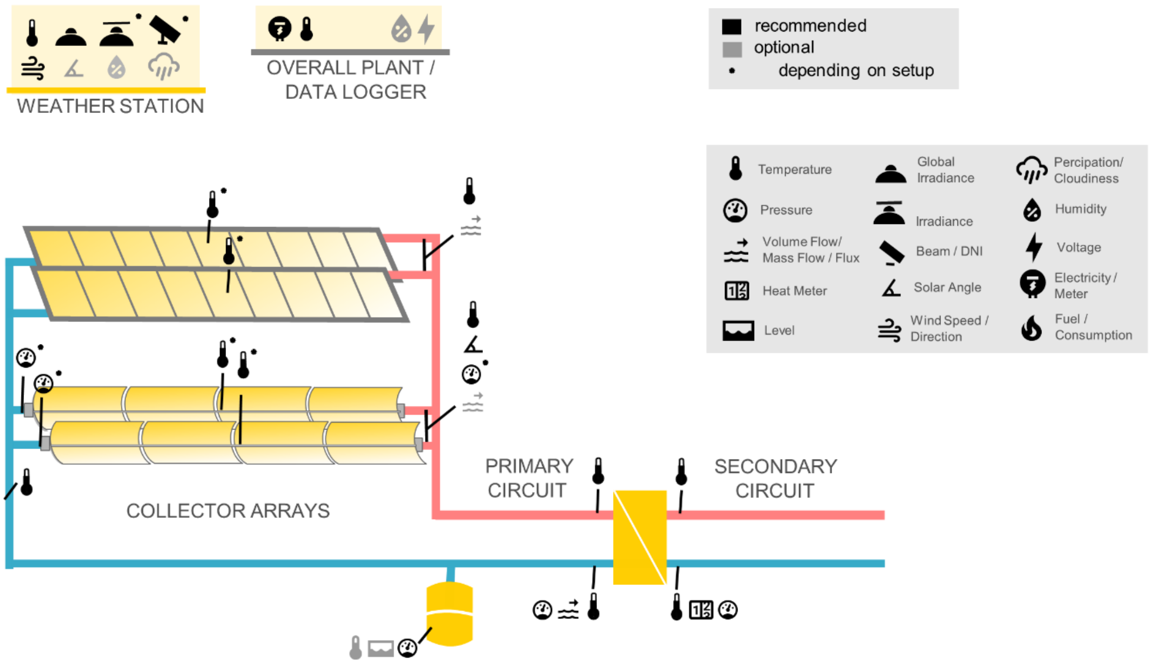


Figure 2. Recommended measurements for collector arrays including the heat exchanger connected to the primary circuit. Source: Adapted from [1].

Weather Station / Ambient

This part comprises measurements related to the weather as shown in TABLE 2. Since solar irradiance is the energy source of solar thermal plants, its measurement data is crucial for monitoring the collectors' efficiency. For example, irradiance data is required to calculate the effective collector efficiency, estimate thermal power according to the collector Keymark equation ISO 9806 [4] and carry out the Power Check as defined by ISO 24194 [5] and the Dynamic Collector Array Test (D-CAT) [3], for details see Chapter 2.1. For non-concentrating collectors, it is often sufficient to measure the *hemispherical solar irradiance* on the collector surface [10], [14], [5]. In contrast, *direct normal irradiance (DNI)* is required for concentrating collectors [4], [5]. For more accurate results, information about the *diffuse solar irradiance* is helpful [4], [5]. However, this quantity is best determined by subtracting measured direct irradiance from measured hemispherical in-plane irradiance since measuring in-plane diffuse irradiance directly is often impractical. Irradiance sensors must be maintained well to prevent systematic errors. As shown, for example by [16] and [3], incorrect measurements might have a substantial influence on efficiency estimates. Based on their results, dirt on the sensors or insufficient sensor accuracy can lead to high systematic errors of 10% or higher. Hence, carefully choosing a proper radiation sensor and periodically cleaning and calibrating the sensor are recommended. In addition, an air shield may help to avoid dirt on a pyrheliometer [17].

The *ambient temperature* is also a crucial measurement, as it allows for estimating heat losses of collectors [12], [13], [14]. Please note that multiple sensors might be needed if the temperature is different at different places of interest (e.g., collector arrays in the field versus pipes inside the control room). As an example, ISO 24194 requires the ambient temperature sensor used for collector evaluations to be shielded from direct sunlight and placed on the field one meter above the ground and not further than 100 meters from the collectors [5]. Shields for ambient temperature sensors should ideally also be equipped with a ventilator, as stagnant air inside the shield enclosure may get heated up and not reflect the actual ambient temperature.

Additional recommended measurements are *wind speed* and *wind direction*, which affect heat losses of the collectors (especially relevant for uncovered collectors). Hence, this data is required, for example, for ISO 24194 [5]. Furthermore, the information about wind is especially important for tracking collectors, for example, for estimating torsion losses, for checking whether safety positions must be applied, and for fault detection in general.

Furthermore, operating experience suggests that measuring the *relative humidity and precipitation* and using *sky cameras* might lead to very useful insights and risk management strategies. For example, knowledge about precipitation might be used to estimate the need for collector cleaning or to indicate whether a draining system is required due to heavy rain. Similarly, information about snow precipitation can be helpful to estimate whether snow covers the collectors in which case tracking collectors might get rid of snow covers by tilting the collectors down. In general, these measurements can help to maintain optimal system efficiency but can also be used for forecasting district heating demand or applying short-term predictive control strategies accounting for cloud movements.

Table 2. Recommended measurements for ambient/weather conditions. Measurements are marked either recommended (R), optional (O), or depending on the setup (*).

Ambient Measurements (Weather Station)		
Measurement	*Required for*	
Hemispherical solar irradiance	Monitoring collector performance (for non-concentrating collectors)	*
Direct normal irradiance (DNI)	Monitoring collector performance (for concentrating collectors)	*
Diffuse horizontal irradiance	Monitoring collector performance	O
Ambient temperature	Calculating heat losses	R
Wind speed	Calculating heat losses, estimating torsion losses, checking the time for safety position	R
Wind direction	Estimating torsion losses, checking the time for safety position (for tracking collectors)	*
Relative humidity	Monitoring condensation, checking plausibility of other weather measurements	O
Precipitation	Estimate collector soiling, evaluate the need for drainage	O
Sky camera	Check cloudiness, short-term forecasting	O

Collector Arrays

This part comprises the collector arrays (or collector loops / rows) installed at the plant (see FIGURE 2). Required measurements may vary depending on the type of thermal collectors used, for an overview see TABLE 3. However, measuring *flow temperatures* for each collector array is common at most plants. For example, the flow temperature allows for detecting "freezing," "stagnation," and "sub-field stagnation" (only a part of the plant is in stagnation) events and for checking that all arrays deliver a similar flow temperature. Similarly, the *return temperature* is also measured at most solar thermal plants, for example, to calculate pipe losses and analyze the temperature increase due to the collectors. Depending on the aim of the measurement, it may suffice to place only one temperature sensor for all arrays. However, pipe losses and pressure drops may lead to a slightly unequal temperature distribution for each loop.

If *volume-* or *mass flows* are measured as well, this even allows the application of the Power Check of ISO 24194, the D-CAT, and similar methods for each individual loop - permitting a more in-depth evaluation of the collector performance of each loop. Due to more focus on quality assurance, recently built plants often install a reference loop for measuring flow- and return temperatures, irradiance, and volume flow for one specific collector loop. This enables a more accurate estimation of collector performance, as pipe distribution losses are limited, and modeling is more straightforward (compared to modeling the whole collector field). The measured collector loop then often serves as a representative of all the collectors of the respective type for defining collector performance guarantees.

Depending on the type of thermal collectors, it is also recommended to measure the *flow-* and *return pressure* for each row, especially in the case of concentrating collectors with high pressure. This allows the monitoring of the pressure drop and can also be used to detect leaks and blockages. For tracking collectors, the *tracking angle* must either be calculated or measured to adjust the tracking actuators for performance optimization and to detect downtime where the collectors are defocused. For large-scale systems with many collectors in a row, it is also recommended to install temperature sensors within the row *(intermediary temperature)* to allow for faster flow control and detection of overheating.

Table 3. Recommended measurements for the collector arrays. Measurements are marked either recommended (R), optional (O), or depending on the setup (*).

Collector Arrays (each)		
Measurement	*Required for*	
Flow temperature	Monitoring collector row performance, detecting "subfield stagnation", anti-freezing, matching flow temperature of different loops, modelling pipe losses.	R
Return temperature	Monitoring collector row performance, anti-freezing, modelling pipe losses.	O
Flow/heat meter	Monitoring collector row performance	O
Return pressure	Pressure-drop monitoring	O
Flow pressure	Pressure-drop monitoring	O
Tracking angle	Adjustment of tracking actuators, performance optimization, detection of downtime/defocusing (for tracking collectors)	*

Collector Arrays (each)		
Measurement	*Required for*	
Intermediary temperature	Faster flow control, detection of overheating	O

Primary Circuit

For the primary circuit (see FIGURE 1), the *flow and return temperatures* should always be measured, as they are often used for system control and can also be used for freezing and stagnation detection, see TABLE 4 for an overview. Combined with a *volume flow* sensor or with a *heat meter*, it allows for monitoring the performance of the whole collector field (e.g., according to ISO 24194) and calculating energy balances. Measuring the *pressure* (e.g., before and after the pump) allows for pump monitoring, leakage detection, and general safety monitoring. In addition, measuring the *expansion vessel level* and *pressure* is recommended for leakage detection and safety monitoring, especially in the case of high-pressure systems. To rule out damages at the expansion vessel due to high fluid temperatures, a *temperature* sensor might be installed at the expansion vessel as well.

Table 4. Recommended measurements for the primary circuit. Measurements are marked either recommended (R) or optional (O).

Primary Circuit		
Measurement	*Required for*	
Flow temperature	Performance monitoring, stagnation detection, check system control	R
Return temperature	Performance monitoring, detect "too little extraction"	R
Flow/heat meter	Performance monitoring, pump monitoring	R
Pressure	Leakage detection, pump monitoring	R
Expansion-vessel pressure	Safety monitoring, process check	R
Expansion-vessel level	Safety monitoring, leakage detection	O
Expansion vessel temperature	Monitoring expansion vessel temperature.	O

Secondary Circuit

The recommended measurements for the secondary circuit are similar to those for the primary circuit, see TABLE 5. However, it is recommended that heat metering is done at the secondary circuit. The reason is that water (typically used in the secondary circuit) has very well-known thermal properties compared to the fluid mixtures (typically anti-freeze glycol mixtures) often used in the primary circuit. Hence, heat calculation is more accurate for the secondary circuit. Apart from that, the recommended measurements are the same.

Table 5. Recommended measurements for the secondary circuit. Measurements are marked either recommended (R) or optional (O).

Secondary Circuit		
Measurement	*Required for*	
Flow temperature	Performance monitoring, stagnation detection, check system control	R
Return temperature	Performance monitoring, detect "too little extraction"	R
Heat meter (incl. flow)	Performance monitoring, pump monitoring	R
Pressure	Leakage detection, pump monitoring	R

Other Measurements

This part lists all measurements that cannot be directly assigned to one of the parts above, see TABLE 6. For example, it is strongly recommended to measure the *electricity consumption* of the plant – either in total or for specific parts of the system. This is needed for an energy balance evaluation, performance monitoring, and accounting. In addition, *webcams* can be installed during construction for security reasons and to check construction progress. During operation, they can also be used to check collector and mirror positions (in the case of tracking collectors), evaluate shading, or detect visible damage or dirt on the collectors. In addition, the *data logger voltage* and *temperature* might be helpful to monitor the data logger. Furthermore, *safety devices* like gas or smoke detectors might also be required for the system for safety reasons.

Table 6. Recommended measurements not connected with a specific part of the plant. Measurements are marked either recommended (R) or optional (O).

Other Measurements		
Measurement	*Required for*	
Electricity meter	Energy balance evaluation, electricity consumption	R
Webcam	Check construction progress, collector positions, and mirrors, visible damage, dirt on collectors, shading	O
Data logger voltage	Feedback on data logger performance	O
Data logger temperature	Feedback on data logger performance	O

1.3 Data gathering

Acknowledgment: This chapter contains excerpts (with minor adaptions) of IEA SHC Task 68 report "Efficient Data Management and Validation", Chapter 3 [1].

Data logging

A summary of the recommended data gathering settings is provided in TABLE 7.

Table 7. Summary of recommendations for data gathering.

Topic	*Recommendation*
Sampling rate	Use ≤ 1-minute intervals for storing measurement data
Time zones	Encode timestamps (preferably in UTC format)
Datetime format	ISO 8601
Encoding	UTF-8 encoding
Language	English if possible

Sampling rate

The sampling rate describes how often data is acquired and stored. While the IEA SHC Task 45 fact sheet recommended a sampling rate of at least 5 minutes [8], the ISO 24194 Power Check method [5] requires a sampling rate of at least 1 minute. Hence, to support the ISO evaluation, a sampling rate of at least 1 minute is recommended by the authors. Even though some methods require even higher sampling rates (e.g., spectral methods from Räber [18] and Grossenbacher [19]), their use is relatively rare. However, if quasi-dynamic collector tests according to ISO 9806 are desired, a sampling rate between 1 and 10 seconds is needed.

Time zones and datetime format

Measurement data always requires information about when the measurement took place to correctly interpret the data (based on the time dependency due to weather and demand). For further processing, the time zone of the timestamps must be correct, e.g., to compute the angle of incidence or run plausibility checks like "no irradiation at night." A lesson learned from the SunPeek project [20] is that storing data in UTC is recommended, as time zones can change and can often lead to bugs [21], especially in the case of timestamps with daylight saving. Thus, the recommendation is to use UTC for storing the data.

In any case, it is recommended to record timestamps with their associated time zone information. It is strongly urged to follow the timestamp conventions specified in ISO 8601. An example time stamp might be 2023-07-18T11:12:27+00:00, where the +00:00 denotes that it is in UTC.

Encoding

Similar to the time zones, another lesson learned from SunPeek [20] is that encoding can be a problem for storing and sharing data. The standard for most applications is the use of UTF-8, whereas less common encodings like "latin1" can sometimes lead to errors and misformatted labels. Hence, we highly recommend using UTF-8.

Language

Ideally, meta-data and sensor names should be in English, as it is the most used language worldwide. In addition, the characters can be easily encoded with UTF-8.

1.4 Data validation

Acknowledgment: This chapter contains excerpts of IEA SHC Task 68 report "Efficient Data Management and Validation", Chapter 4 [1].

For performing analyses, it is essential to work with correct data. Otherwise, the results will not reflect the actual behavior of the plant. Hence, data must be validated, and automated plausibility checks can greatly support users in doing so. **TABLE 8** lists available open-source software that entail common data validation algorithms.

Table 8. Software tools implementing quality and data preprocessing algorithms.

Software	*Description*
SunPeek [20]	Python library and open-source tool implementing the Power Check method of ISO 24194, including some data quality checks as part of data processing. • Link: https://gitlab.com/sunpeek/
PVAnalytics	Python library for analyzing PV plant data, including many useful functions for quality checks for solar irradiance, weather, and general data quality issues. • Link: https://pvanalytics.readthedocs.io
Dronninglund Pit Storage Data	Open-source data about a water pit thermal energy storage, located in Dronninglund, Denmark. The GitHub repository includes a public Python notebook that was used for the data treatment. • Link: https://doi.org/10.1016/j.solener.2022.12.046 [22] • Link: https://github.com/PitStorages/DronninglundData
FHW Arcon South dataset	Open-source measurement data from a collector array located in Graz, Austria. The document includes a description of the preprocessing algorithms used. • Link: https://doi.org/10.1016/j.dib.2023.109224 [23] • Link:https://gitlab.com/sunpeek/zenodo-fhw-arconsouth-dataset-2017

Validation algorithms

Validation algorithms try to analyze whether measurement data is reliable, for example, by spotting statistical outliers or comparing the measurements with physically plausible ranges. Discarding invalid data ensures that the results of further evaluations are correct. A list of common validation algorithms can be seen in **TABLE 9**.

Table 9. Summary of plausibility check algorithms.

Plausibility Checks	
Algorithm	*Short description*
Min-Max-Check	Tests if the sensor value exceeds the min-max boundary and replaces values with NaN or meaningful values [10]. Open source implementations are available in SunPeek [20].
Sensor-Hangs	Test if sensor values are constant for too long, i.e., stuck values, and replace them with NaN values [10]. Open-source implementation available in PVAnalytics [24].

Plausibility Checks	
Algorithm	*Short description*
Irradiance at night	Irradiance during the night can imply that there is a wrong offset in the measurement. Idea from Visplause [25].
Ambient Temperature Offset Detection	Ambient temperature typically does not change rapidly but increases and decreases continuously. Drastic changes can be signs of signal transmission problems or data logging issues for example. Implementation available in PVAnalytics [24].
Heat meter value shift	Heat meter counters are often cumulative, i.e., monotonically increasing. In case the count goes down or experiences large changes (compared with maximum expected yield for example), this can indicate a replacement of the heat meter or other issues.
Step change	Detect unfeasible drastic change in measured values, e.g., irradiance should not change faster than 1000 W/m^2/min [24].
Maximum and minimum feasible values (model-based)	Detect unrealistic or physically impossible values. PVAnalytics [24] has algorithms for checking the plausibility of solar irradiance measurements (e.g., maximum value based on extraterrestrial irradiance) and humidity and temperature (e.g., by comparing with irradiance).
Outlier detection via statistics	For example, by checking for univariate outliers (e.g., single points compared to their typical distribution; too drastic changes of one value to the previous one). Idea from [25] but also implemented by PVAnalytics [24].
Ignored ranges	Exclude user-defined time periods from the data, in case events (e.g., services or faults) have occurred which falsify the data. Typically sets the values to NaN during such periods [20].

2 Methods and key figures

2.1 Methods

Approaches to evaluate solar thermal plants with digital tools can be categorized as follows:

- *Visualization of measurement data channels* in SCADA (Supervisory Control and Data Acquisition) systems or general-purpose tools, see Chapter **3.4** and **3.43.5** for a list of selected tools.
- *Key figures* based on data aggregation or simple formulas, e.g. specific solar yield, see Chapter **2.2** for common examples.
- *Model-based analytics and key figures*, comparing target and measured performance or estimating collector efficiency parameters, using white-box, grey-box or black-box models.

This chapter provides a description of selected methods for model-based analytics with a focus on the ISO 24194 standard.

ISO 9806

The calculation of the target performance for model-based analytics oftentimes builds on the data sheet efficiency parameters of the collectors. The most commonly used procedure to derive these parameters is the Quasi-Dynamic Test (QDT) of ISO 9806 ("Solar energy — Solar thermal collectors — Test methods") [4]. It characterizes the thermal power output $\dot{Q}$ of liquid heating collectors using the following equation (see [4], Eq. (13)):

$$\dot{Q} = A_G\big(\eta_{0,b}K_b(\theta_L,\theta_T)G_b + \eta_{0,b}K_dG_d - a_1(\vartheta_m - \vartheta_a) - a_2(\vartheta_m - \vartheta_a)^2 - a_3u'(\vartheta_m - \vartheta_a) + a_4(E_L - \sigma T_a^4) - a_5(d\vartheta_m/dt) - a_6u'G - a_7u'(E_L - \sigma T_a^4) - a_8(\vartheta_m - \vartheta_a)^4\big)$$

where A_G is the gross area of collector, $\eta_{0,b}$, $K_b(\theta_L,\theta_T)$ and K_d are optical efficiency parameters / functions, a_1, a_2, a_3, a_4, a_6, a_7 and a_8 are loss parameters and a_5 is the effective thermal capacity. Depending on the collector type, only a subset of these coefficients is mandatory, e.g., the use of $\eta_{0,b}$, $K_b(\theta_L,\theta_T)$, K_d, a_1, a_2, and a_5 for collectors with a concentration ration $C_R < 20$.

The original QDT procedure developed by Bengt Peres in the 1990s [26], [27], [28] was intended both for laboratory and in-situ application, but in-situ testing is only allowed since the latest revision of ISO 9806 in 2017. In 2019, a new Appendix P5.5 was added to the Solar Keymark Rules which described the procedure for in-situ certification according to Solar Keymark with the following use case: "In-situ certification is targeting but not limited to collectors which because of their size, power output, weight, operating conditions or on-site production can hardly be tested in a laboratory" [29].

Additional methods related to ISO 9806

The *In-situ Collector Certification (ICC)* is an adaption of the QDT method to test single collectors in a field installation [30]. The method is applicable to all collector types and delivers the same collector parameters as the QDT method for outdoor testing. In comparison to the QDT method, the required boundary conditions regarding volume flow and inlet temperature are relaxed to have less interference with the control system. An overview can be found in [31], a detailed description in the final report of the ZeKon in-situ project (written in German) [32].

The *Dynamic Collector Array Test (D-CAT)* is an in-situ test method applicable to collector arrays with flat plate collectors using measurement data from the normal, fully dynamic plant operation without the need to run special test sequences [3]. The method has a similar physical modeling approach as the QDT test procedure of ISO 9806, with an important extension of the ISO model to collector rows and collector arrays by introducing a new term in the ISO model. Two models are used for dynamic collector arrays, with one of them explicitly modeling the fluid transport along the main flow direction. The parameters are estimated from measurement data. Influencing effects which concern the collector array performance (e.g., soiling, broken insulation, faulty foil tension, etc.) are reflected in the test parameters. For instance, collectors with broken insulation or faulty foil tension will have higher heat loss coefficients compared to data sheet parameters. A modified version of the D-CAT method is currently being implemented in the SunPeek software [20].

Other test methods for collector arrays include the *In-situ Check of Collector Array Performance (ICCP)* [33], *In-situ Solar Collector Field Test (ICFT)* [34] or *In-situ Short Term Testing (ISTT)* method [35].

ISO 24194

ISO 24194 ("Solar energy — Collector fields — Check of performance") [5] is an international standard that focuses on the performance check of solar thermal collector arrays. It was first published in May 2022 and is the first standard of its kind by explicitly targeting collector arrays in operation. The standard is likely to play a key role for on-going operational monitoring and use in guarantee procedures for large-scale installations, strengthening the bankability and trust in the technology. It currently consists of the published ISO 24194:2022 and one amendment, ISO 24194:2022/Amd 1:2024. The standard is applicable to arrays with glazed flat plate collectors, evacuated tube collectors, and concentrating collectors with or without tracking and specifies two methods for comparing measured solar output with target output: the Power Check and the Daily Yield Check.

ISO 24194 Power Check

The overall principle of the Power Check is to check the measured power output with the target (calculated/ estimated) power output, provided that the collector array is running with substantial power output or close to full power. The target power $\dot{Q}_{\mathrm{estimate}}$ is calculated based on the operating conditions (measurement data) and collector parameters of the ISO 9806 QDT test [4] plus some safety factor. The safety factor f_{safe} accounts for pipe and other heat losses, measurement uncertainty and other uncertainties. The equation to calculate the target power is chosen depending on the collector type and solar radiation instrumentation. For non-concentrating collectors "Formula 1", for low-focussing collectors "Formula 2", and for focussing collectors with high concentration ratio "Formula 3" is relevant:

Formula 1:

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

Formula 2:

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

Formula 3:

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

A_{GF} is the gross area of collector array. G_{hem}, G_b and G_d denote the hemispherical, direct and diffuse irradiance in the collector plane, ϑ_m is the mean collector temperature and ϑ_a is the ambient temperature. The collector efficiency factors $\eta_{0,b}$, $K_{hem}(\theta_L,\theta_T)$, $K_b(\theta_L,\theta_T)$, K_d, a_1, a_2, a_5 and a_8 are the data sheet values.

The estimation of the target (estimated) power is done in four main steps as shown in FIGURE 3.

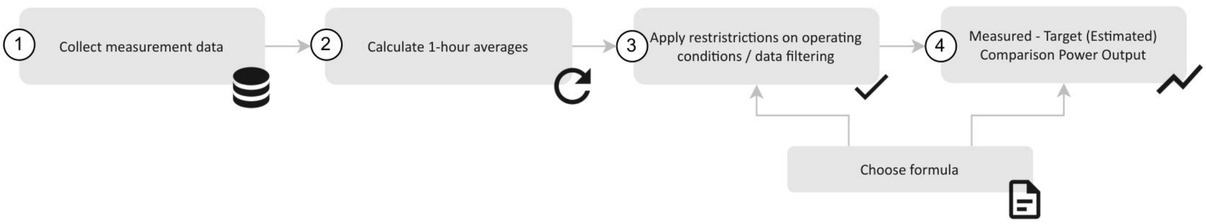
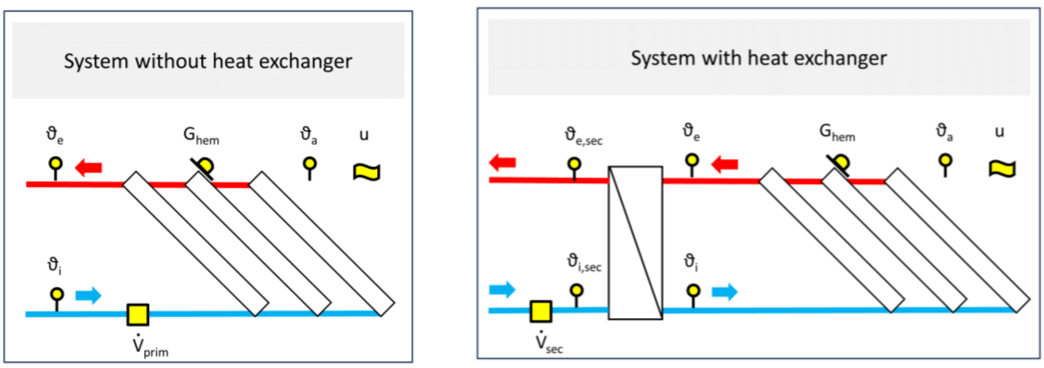


Figure *3*: Power Check procedure of ISO 24194.

For an example of the measured – target (estimated) comparison of the ISO 241914 Power Check see FIGURE 10. Here are some explanations on the steps shown in FIGURE 3:

1. *Collect measurement data*: The necessary measurement instrumentation for the two system configurations described in the standard, namely systems with heat exchanger and without heat exchanger are shown in FIGURE 4. These sensors are included in the recommended measurement instrumentation in Chapter 1, FIGURE 2.



(a) (b)

Figure 4. Required sensors for Power Check for systems (a) without heat exchanger and (b) with heat exchanger.

2. *Calculate 1-hour averages*: The next step in the procedure so to build 1-h average values.
3. *Apply restrictions:* To limit uncertainties, restrictions on operating conditions are given. The standard uses the definitions listed in TABLE 10, depending on the chosen formula.

Table 10. Restrictions on operating conditions for Power Check.

Operation condition	*Formula (1)*	*Limits* *Formula (2)*	*Formula (3)*	*Comments*
Shading		No shadows		
Change in collector mean temperature		≤ 5K		To avoid big change in collector temperature during one hour
Ambient temperature		≥ 5 °C		To avoid snow, ice, condensation on solar radiation sensors
Wind velocity		≤ 10 m/s		Measurement needs to be representative for the wind velocity 1 m to 3 m above highest point of collectors
G_{hem}	≥ 800 W/m²	-	-	
G_b	-	≥ 600 W/m²	≥ 600 W/m²	

4. *Measured – Target (Estimated) Comparison*: The standard compares the average measured power output with the average estimated power output for the valid data records, i.e. 1-h averages (see step 2), which fulfill the restrictions on the operating conditions. At least 20 data records are needed. The estimate is verified the following criteria holds:

$$\text{Average}\ (\dot{Q}_{\text{meas}}) \geq \text{Average}\ (\dot{Q}_{\text{estimate}})$$

ISO 24194 Daily Yield Check

The Daily Yield Check follows a similar approach as the Power Check but compares measured and target daily yields instead of power outputs. In the current version of the standard [5], the Daily Yield Check is defined only for non-tracking and non-concentrating collectors. The target daily yield $Q_{\text{estimate-sys,d}}$ is calculated as follows:

$$Q_{\text{estimate-sys,d}} = \left[\left(\dot{Q}_{\text{estimate-col,d}} - \dot{Q}_{\text{pipe,d}}\right) \cdot (t_e - t_s) - Q_{\text{cap,d}}\right] \cdot f_{\text{safe}}$$

where the daily average power of the collectors $\dot{Q}_{\text{estimate-col,d}}$ minus the daily average heat loss rate of piping $\dot{Q}_{\text{pipe,d}}$ are integrated over the measurement period $(t_e - t_s)$. The daily capacity losses $\dot{Q}_{\text{cap,d}}$ are subtracted. As for the Power Check, the safety factor f_{safe} accounts for pipe and other heat losses, measurement uncertainty and other uncertainties. The average thermal power of the collectors is calculated as follows:

$$\dot{Q}_{\text{estimate-col,d}} = A_{GF} \cdot \left[\eta_{0,\text{hem}} \cdot K_{\text{hem,av}} \cdot f_{\text{sh}} \cdot \overline{G_{\text{hem}}} - a_1 (\overline{\vartheta_m} - \overline{\vartheta_a}) - a_2 (\overline{\vartheta_m} - \overline{\vartheta_a})^2\right]$$

where $K_{\text{hem,av}}$ is the average incidence angle modifier, f_{sh} is an empirical shading factor accounting for internal shading and $\overline{G_{\text{hem}}}$, $\overline{\vartheta_m}$ and $\overline{\vartheta_a}$ are the average hemispherical solar irradiance, average mean collector temperature and average ambient temperature respectively. Note the similarity of the above equation with "Formula 1" of the Power Check.

The estimation of the target (estimated) yield is done in four main steps as shown in FIGURE 5.

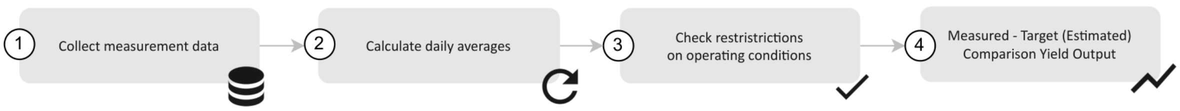


Figure 5. Daily Yield Check procedure of ISO 24194.

The procedure is similar to the Power Check:

1. *Collect measurement data*: same as for Power Check
2. *Calculate daily average*: Daily averages over the measurement period are calculated.
3. *Check restrictions on operating conditions*: The standard uses the restrictions listed in TABLE 11 and states that the measurements are valid only when the collector field can deliver its energy without limitation.

Table 11. Restrictions on operating conditions for Daily Yield Check.

Operation condition	*Limits*	*Comments*
Shadows	Only shading losses of the collector rows considered are permitted.	Shadows of collector rows are considered in the calculation with f_{sh} factor
Daily Irradiation H_{hem}	≥ 5.5 kWh/m²	This restriction prevents invalid points
Total irradiance G_{hem}	≥ 100 W/m²	Lower radiation not relevant

4. *Measured – Target (Estimated) Comparison*: The standard compares the average measured daily yield outputs of the heat meter $\dot{Q}_{HM,\,d}$ with the average target (estimated) daily outputs $\dot{Q}_{estimate\text{-}sys,d}$. Due to capacity and dynamic effects of the solar system during the measurement period, heat metering shall start one hour before and end one hour after the measurement period. At least 5 consecutive valid data points are needed. The estimate is verified if the following criteria holds:

$$\text{Average}\ (\dot{Q}_{HM,\,d}) \geq \text{Average}\ (\dot{Q}_{estimate\text{-}sys,d})$$

Practical application and further developments

Through the first use of ISO 24194 in the solar community, the need for clarification may arise. To this aim, the "Guide to ISO 24194:2022 – Power Check" [7] is currently worked out by scientific and industry experts. The guide provides insights how to apply the Power Check in practice. The Daily Yield Check is not covered by the guide. The document also provides some extensions of the standard, e.g., a detailed description how to apply it to multiple subfields. The final version of the guide will be made available through the IEA SHC Task 68 Website: https://task68.iea-shc.org/publications (planned publication date: Autumn 2024).

Coordinated with the development of these guidelines is the implementation of the Power Check in the SunPeek software described in Chapter 4. SunPeek entails the first open-source implementation of the Power Check, designed to be the reference software implementation by ensuring an open-source, transparent, consistent, readily available and broadly validated implementation. Example use cases of the SunPeek Power Check application can be found in [2].

The development of ISO 24194 involved collaboration between ISO and CEN (European Committee for Standardization) under the Agreement on technical cooperation between the two organizations. 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 have used in Denmark for more than twenty years [36], with IEA SHC Task 45 [37], [38] and IEA SHC Task 55 [39], [16], [40] contributing substantially to its elaboration. An ongoing revision of the standard aims at including an annual yield check method.

ISO 24194 emphasizes the importance of adhering to international standards for ensuring the reliability and durability of solar energy systems. ISO 24194 refers to other important and established standards in the field, such as ISO 9806 (single solar collector laboratory testing), ISO 9060 (instruments for solar radiation), and ISO 9488 (solar vocabulary). Overall, ISO 24194 plays a crucial role in promoting the use of solar energy by setting performance verification standards for solar thermal plants, contributing to simplification and cost reduction of solar energy worldwide.

For solar thermal plant monitoring, it can oftentimes make sense to use several methods in combination. The ISO 24194 Power Check method is very helpful for a quick assessment of the performance but does not allow to estimate collector parameters based on measurement data. This is covered by methods like Dynamic Collector Array Test (D-CAT) or In-situ Check of Collector Array Performance (ICCP), which would allow a more in-depth analysis of possible causes if the plant performes below expectations.

2.2 Key figures

The measurement setup and data handling described in Chapters 1.2, 1.3 and 1.4 allows to calculate the commonly used key figures, such as:

- **Specific Solar Yield** (yield per m² collector area) for a specific plant for different periods, typically daily, monthly, yearly, accumulated yield over the year (see FIGURE 6)
- **Solar Thermal Efficiency** (yield per m² collector area vs. solar irradiance) for a specific plant for different periods, typically daily, monthly, yearly, accumulated yield over the year (see FIGURE 6)
- **Solar Fraction** (solar yield vs. overall heat production) for a specific heat supply system for different periods, typically daily, monthly, yearly, accumulated yield over the year (see FIGURE 7)
- **Input Output Relationship** (irradiance vs. specific solar yield for a whole day) for a specific plant, if available in relation to other systems (see FIGURE 8). This relationship is influenced by

the irradiance levels and operating temperatures as shown in FIGURE 9. For typical systems, the trendline should be approximately linear above the critical radiation level [41].

- **Target-Actual Comparison** (ratio of target vs. measured power output or yield) for a specific plant, as defined in ISO 24194 [5] (see FIGURE 10)
- **Target-Actual Comparison over Time** (ratio target vs. measured power output or yield over time), based on the ISO 24194 [5] (see FIGURE 10)

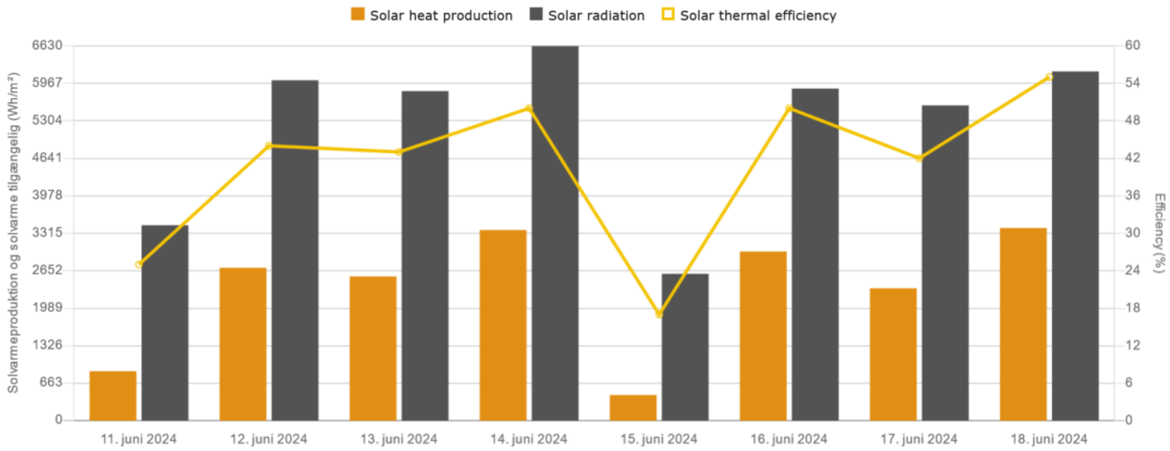


Figure 6. Key figure "Specific Solar Yield" (orange bar) and "Solar Thermal Efficiency" (yellow line). Visualization from solarheatdata.eu [42] for plant "Sandved-Tronemark" (https://solarheatdata.eu/?lid=864#).

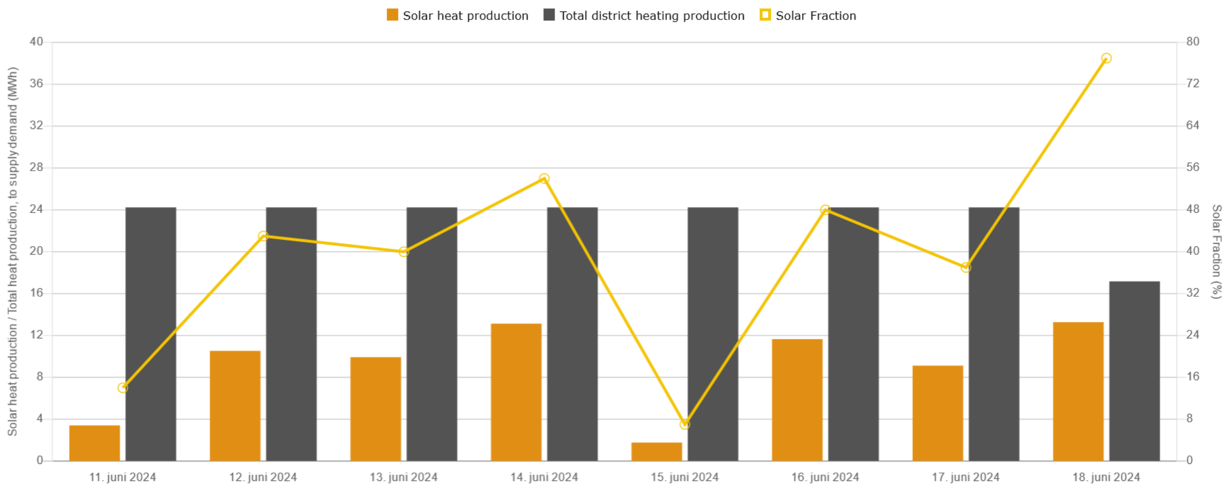


Figure 7. Key figure "Solar Fraction" (yellow line). Visualization from solarheatdata.eu [42] for plant "Sandved-Tronemark" (https://solarheatdata.eu/?lid=864#).

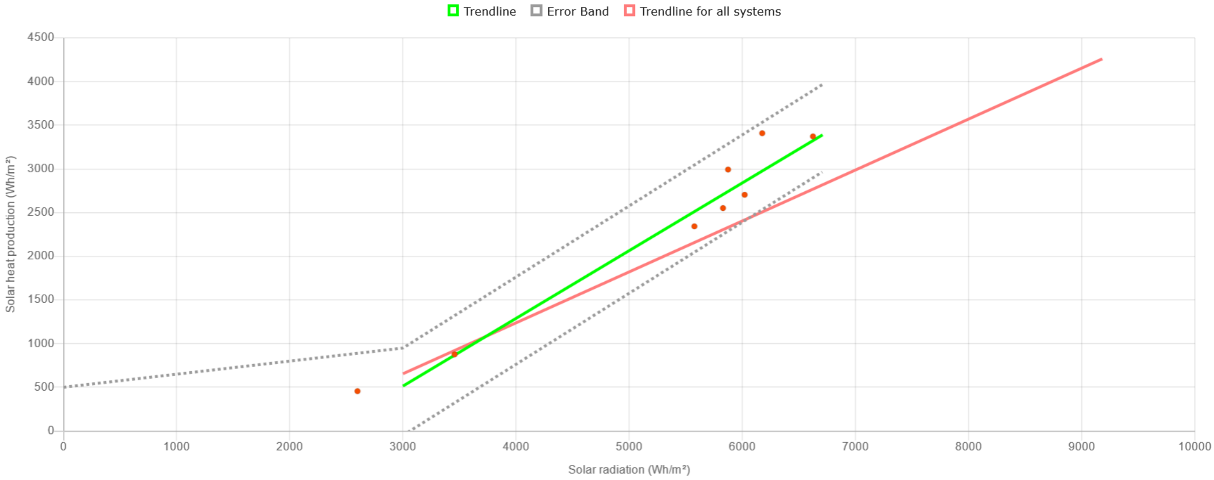


Figure 8. Key figure „Input Output Relationship" with trendlines for one single plants in relation to other systems. Visualization from solarheatdata.eu [42] for plant "Sandved-Tronemark" (https://solarheatdata.eu/?lid=864#).

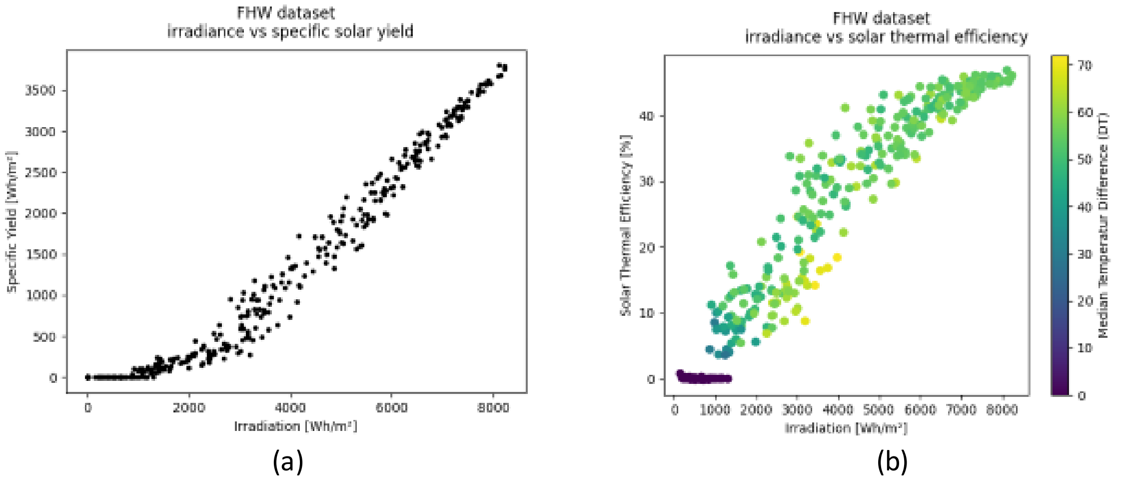


Figure 9. Comparison of key figures (a) „Input Output Relationship" (left) and (b) "Solar Thermal Efficiency" (right). In subplot (b), temperature differences to ambient are shown in the color bar. As shown in subplot (b), the thermal efficiency typically increases with the irradiance level and decreases with the mean temperature difference (for a given irradiance level). Data from plant Fernheizwerk Graz [23].

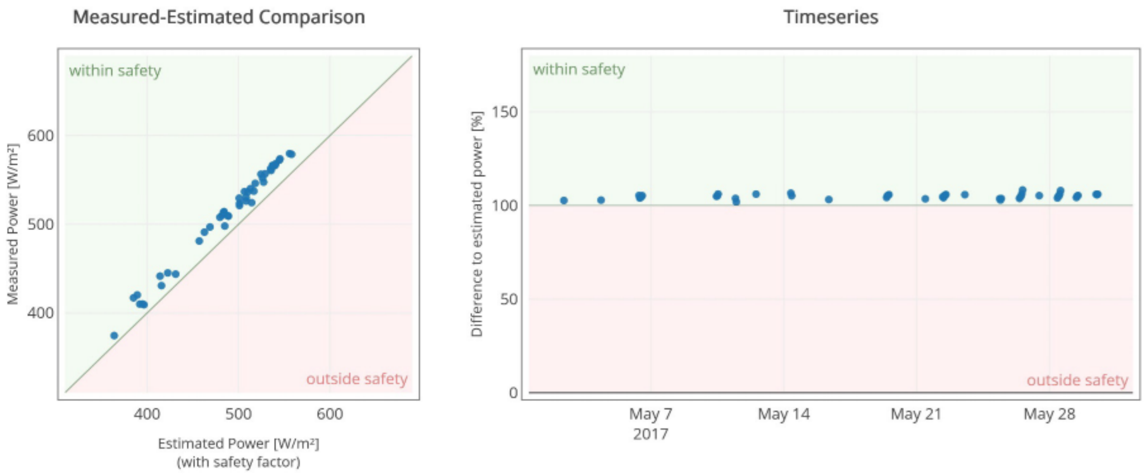


Figure 10. Key figures "Target-Actual Comparison" (left) and "Target-Actual Comparison over Time" (right). Example from SunPeek [20].

3 Software tools and open datasets

This chapter contains an overview of digital tools for solar thermal plants, with a focus on open-source software and open datasets. It lists software tools and methods that can be used for automated plant monitoring, fault detection, and asset management for solar thermal plants. Software tools that only focus on simulation, design, life cycle assessment (LCA), financial analysis, or billing are out of scope and are thus omitted from this collection. Software tools that existed in the past but have been discontinued or are no longer maintained are also excluded from the collection. Note that due to the small number of available software tools, the list also includes some proprietary tools. The open-source licenses are mentioned using common abbreviations (such as BSD, MIT); a good place to learn more about these licenses is the *Open Source Initiative*, https://opensource.org.

3.1 Software tools for solar thermal plants

pvlib	
Tool Name	**pvlib Python**
URL	https://pvlib-python.readthedocs.io/en/stable/ https://github.com/pvlib/pvlib-python
Category & Use Case	Performance Modeling
License	BSD
Description	A Python library for simulating the performance of solar photovoltaic energy systems. It provides a flexible and easy-to-use framework for modeling solar power systems and analyzing their performance. Some of its algorithms can be useful specifically for solar thermal energy, for instance algorithms that focus on solar position and solar irradiance modeling, airmass and atmospheric models, module tracking and shading algorithms.

SunPeek	
Tool Name	**SunPeek**
URL	https://sunpeek.org/ https://docs.sunpeek.org/ https://gitlab.com/sunpeek/
Category & Use Case	Advanced Monitoring
License	LGPL (backend, API); BSD-3-Clause (frontend)

Description	SunPeek is an open-source software designed for performance monitoring and guarantee procedures of large-scale solar thermal plants. It has been successfully deployed to several large-scale solar plants and contains the first open-source implementation of the Power Check method according to ISO 24194:2022. SunPeek's performance analysis includes automatic data analysis of plant measurement data and automatic generation of outputs as pdf reports and graphics via the interactive Web-UI. SunPeek facilitates assessment of present and historical data and offers continuous condition monitoring and assessment of solar thermal plant operation.

SOLARHEATDATA.EU	
Tool Name	**SolarHeatData**
URL	https://solarheatdata.eu/
Category & Use Case	Data Management, Performance Analysis
License	Proprietary
Description	A platform for managing and analyzing data from solar thermal plants. It helps in understanding the performance and efficiency of systems by providing data visualization and reporting tools. Solar thermal plants that are included with SolarHeatData are not required to publicly share their measurement data, but many of them do so. For plants sharing measurement data, people may download historic measurement data and view figures with key performance indicators such as solar energy yield, solar fraction, efficiency, and the input / output of the plant (see also Chapter 2.2 of this document).

Tool Name	**PVAnalytics**
URL	https://github.com/pvlib/pvanalytics
Category & Use Case	Energy Management, Data Analytics
License	MIT
Description	PVAnalytics is a Python library that provides analytics for solar thermal and PV systems, offering quality control, filtering, and other useful tools supporting data analysis and diagnostics. Specifically, PVAnalytics offers algorithms to check the plausibility of measurements like solar irradiance, ambient temperature and humidity, as well as detection of hanging sensors. See Chapter 1.4 of this document for details. PVAnalytics offers analytics to monitor, evaluate, and optimize system performance of mainly PV installations. The tool's functions include data cleaning and transformation, advanced statistical analysis and graphical representations. PVAnalytics aims to support engineers, researchers, and PV

	system operators in identifying performance issues in system efficiency and ensuring the reliability of solar energy production.

Tool Name	**ScenoCalc**
URL	https://solarkeymark.eu/calculation-tools/
Category & Use Case	Energy Yield Simulation
License	Free to download and use; license not specified
Description	A calculation tool developed by the Swedish National Testing and Research Institute RISE in 2019 within the research project QAIST. ScenoCalc is an Excel- and VBA-based tool for calculating the annual energy output of solar thermal collectors under simplified assumptions. The current version of ScenoCalc is 6.2. A rework or update is foreseen with the goal of supporting parabolic trough and Fresnel collectors. ScenoCalc is not a plant monitoring tool and not a system simulation tool for designing solar energy installations. While not strictly being a performance monitoring or data analysis tool, ScenoCalc is included in this list because of its importance with collector testing and standardization. In fact, ScenoCalc is an official SolarKeymark calculation tool, and a well-established and accepted tool in most of the European solar thermal world. ScenoCalc is the tool used to produce the annual solar energy yield figures reported on page 2 of typical SolarKeymark collector datasheets.

Tool Name	**Mondas**
URL	https://mondas-iot.com/
Category & Use Case	Monitoring, Fault Detection
License	Proprietary
Description	Mondas provides a comprehensive platform for monitoring and fault detection for buildings and energy systems, including solar thermal systems. Mondas uses IoT technology to gather and analyze data, helping to optimize system performance and maintenance. Mondas PVisto specifically focuses on monitoring and optimization of photovoltaic plants.

Tool Name	**Synavision**
URL	https://www.synavision.de/

Category & Use Case	Monitoring, Quality Assurance
License	Proprietary
Description	Synavision is a tool for the continuous monitoring and quality assurance of technical systems. Synavision offers a digital quality management platform designed for building performance. It uses digital building models to ensure the operational efficiency and quality of technical systems. This tool is suitable for monitoring solar thermal plants by providing real-time performance analysis and fault detection, ensuring optimal operation and maintenance. Synavision helps in identifying inefficiencies and operational issues, thereby improving the reliability and performance of solar thermal systems.

Tool Name	**ruvi**
URL	https://ruvieos.com/
Category & Use Case	Monitoring, IoT Integration
License	Proprietary
Description	An IoT platform designed for monitoring and controlling solar thermal systems. It offers real-time data acquisition, advanced analytics, and remote management capabilities to optimize system performance.

Note: Beyond the software tools described in the collection above, more general tools and algorithmic approaches exist for the task of human-centered interactive time series data analysis and visual analytics and fault detection. Such tools can in principle also be applied to solar thermal plants, but they are either not specifically designed for and do not make use of domain knowledge of solar thermal energy, or are more in a research state and not available as software yet. Therefore, they are not included in the collection above. This table includes a selection of such tools:

Tool Name	**URL**	**License**
Visplore	https://visplore.com/	Proprietary
Visplause	https://www.vrvis.at/publications/PB-VRVis-2017-056	(Publication)
SunScreen	https://ieeexplore.ieee.org/document/10232874	(Publication)
MTV	https://dl.acm.org/doi/10.1145/3512950	(Publication)

3.2 Open datasets and for solar thermal plants

Basic information on built large-scale solar thermal systems are published in the annual Solar Heat Worldwide report [43] and accessible through the following platforms / databases:

Platform / databases	**URL**
Solar Industry Heating Plants (worldwide)	https://ars.els-cdn.com/content/image/1-s2.0-S0038092X21009476-mmc1.xlsx
SHIP plants (worldwide)	https://energieatlas.aee-intec.at/index.php/view/map?repository=ship&project=ship_edit
Solar District Heating plants (EU) – updated until 2017	https://www.solar-district-heating.eu/en/plant-database/
SolarHeatData (EU, DEN)	http://www.solarheatdata.eu/ https://solvarmedata.dk/
Solar District Heating Plants (GER)	https://www.solare-waermenetze.de/projektbeispiele/projektlandkarte/

Besides the SolarHeatData, these platforms only contain static information and no measurement data. To the best of the authors' knowledge, there are only few datasets of measurement data of solar thermal plants that are publicly available as open datasets, as listed below. Since SolarHeatData is not only a dataset or a platform for data sharing, but also includes monitoring and energy yield assessment, the service is described as a software tool in Chapter **3.1**.

Dataset	**Zenodo FHW ArconSouth Dataset 2017**
URL	https://www.doi.org/10.5281/zenodo.7741083 https://gitlab.com/sunpeek/zenodo-fhw-arconsouth-dataset-2017 https://doi.org/10.1016/j.dib.2023.109224
Category & Use Case	Measurement data of large-scale solar thermal collector array. Open dataset, Gitlab repository and peer-reviewed article.
License	Creative Commons Attribution 4.0 International (CC BY 4.0)
Description	This dataset includes high-precision operational data for one full year (2017) and refers to a real-scale application which is representative of typical large-scale solar thermal plant designs (flat plate collectors, common hydraulic layout). Measurement data are provided in CSV files, sampled at 1-minute intervals with extensive quality assurance measures. Measured data channels include global, beam and diffuse irradiances in horizontal and collector plane. Heat transfer fluid properties were determined in a dedicated laboratory test. Uncertainties of data channels are provided based on data sheet specifications and GUM error propagation. The Gitlab repository is intended as a companion to support the Zenodo repository and includes Python code for data quality assurance, uncertainty calculations, and figure generation.

	A detailed description of the dataset and additional information is provided in a journal article in "Data in Brief", titled "One year of high-precision operational data including measurement uncertainties from a large-scale solar thermal collector array with flat plate collectors in Graz, Austria".

Dataset	**Dronninglund Water Pit Thermal Energy Storage Dataset**
URL	https://github.com/PitStorages/DronninglundData https://doi.org/10.1016/j.solener.2022.12.046
Category & Use Case	Measurement data of a pit thermal energy storage including data of the connected solar heating plant. Open dataset, Gitlab repository and peer-reviewed article.
License	Creative Commons Attribution 4.0 International (CC BY 4.0)
Description	The dataset includes measurement data of the Dronninglund water pit heat storage for the period 2014–2020, including a detailed description of the design, ground conditions, and operating strategy. For the solar thermal collector arrays, inlet and outlet temperatures and produced energy are provided. The dataset has been manually quality-controlled, and erroneous data have been removed with the aim of establishing a high-quality reference dataset.

Dataset	**Thermal Solar Plant Dataset**
URL	https://github.com/stritti/thermal-solar-plant-dataset
Category & Use Case	Thermal solar plant dataset for machine learning
License	MIT
Description	Data are provided as CSV files; a description of the header names and physical units is included. No details concerning the solar thermal plant at which the data were recorded are disclosed. This limits the usefulness of this dataset for monitoring purposes.

Dataset	**PVGIS**
URL	https://pvgis.com/ https://joint-research-centre.ec.europa.eu/photovoltaic-geographical-information-system-pvgis_en
Category & Use Case	Online tool and dataset. Solar resource data, PV performance assessment
License	Free online tool and dataset
Description	PVGIS has been developed by the research center of the Institute for the Environment and Sustainable Development of the European Commission. It provides free access to solar radiation data and tools for estimating the performance of solar energy plants. It includes features for analyzing solar

	potential at different tilt and azimuth angles and calculating expected PV energy output for different system configurations. PVGIS can be used as a web tool and requires no registration and includes an API. While focusing on PV energy, some PVGIS services, such as solar resource data and typical meteorological years, are also useful for solar thermal. The use of PVGIS for plant monitoring is limited by the fact that the provided solar radiation data are long-term averages, not current, nowcast or specific historic data for a specific location.

A dataset with solar irradiance data relating to diffuse irradiance masking for different collector array configurations is described in [44]:

Dataset Name	URL	License
Irradiance measurements of diffuse irradiance masking on tilted planes	https://ars.els-cdn.com/content/image/1-s2.0-S0038092X21009476-mmc1.xlsx	Creative Commons Attribution 4.0 International (CC BY 4.0)

Specifically for PV and general-purpose solar radiation datasets, there are some GitHub repositories providing collections of datasets and resources, including a Kaggle competition:

Dataset Name	URL
National Renewable Energy Laboratory (NREL) Solar Radiation Data	https://data.nrel.gov/search-page/Solar
Global Solar Atlas	https://globalsolaratlas.info/
Kaggle competition and Solar Power Resources	https://github.com/Charlie5DH/Solar-Power-Datasets-and-Resources

AssessingSolar: A special mention shall be given to AssessingSolar, an initiative dedicated to solar resource assessment and quality assurance, including practical guides with Python code snippets and plots. The aim of AssessingSolar is to make it easy to obtain solar radiation data, apply radiation models, and make accurate forecasts. AssessingSolar is a collaborative effort within the IEA Photovoltaic Power Systems Programme (PVPS) Task 16 and is maintained by the same community around pvlib and PVAnalytics. URL: https://assessingsolar.org/

Best Practices Handbook: PVPS Task 16 publishes an important handbook worth mentioning in this context, namely the "Best Practices Handbook for the Collection and Use of Solar Resource Data for Solar Energy Applications" [45], with the third edition published in 2021.

Meteorological Datasets and APIs: Meteorological dataset and especially APIs providing such datasets for specific locations are useful for a variety of data analysis tasks for solar energy monitoring and yield assessment. Here is a brief overview of such services that include free tiers:

Tool Name	URL	License
pvlib forecasting	https://pvlib-python.readthedocs.io/en/v0.4.0/forecasts.html	BSD-3
OpenWeatherMap	https://openweathermap.org/	Various, including free tier
Solar Radiation Database (NSRDB)	https://nsrdb.nrel.gov/	Public domain
Solcast API	https://solcast.com/	Various, including free tier
Weatherbit API	https://www.weatherbit.io/	Various, including free tier
Meteonorm	https://meteonorm.com/	Commercial
Forecast.solar	https://forecast.solar/	Various, including free tier
Solar-Gis	https://solargis.com/	Different tiers, no free tiers
Global Solar Atlas	https://globalsolaratlas.info/	CC BY 4.0

Solar Keymark Database: This freely accessible database comprises information about all valid licenses issued for solar thermal collectors and systems under the Solar Keymark quality label (https://solarkeymark.eu/database/). The database does not contain measurement data, but is an important resource to retrieve collector data sheet parameters for model-based analytics (see Chapter **2.1**).

3.3 Software tools for solar photovoltaic plants

The market for photovoltaic solar energy is much bigger than the market for solar thermal and the market development over recent years has been considerably more dynamic. Hence, a large number of software tools are available when extending the focus from solar thermal to solar PV technology, with a variety of tools for many use cases.

A curated list of open-source tools for PV modeling, partly covering very specific needs, is available at the GitHub project **openpvtools**: https://openpvtools.readthedocs.io.

Here is an overview including some of the main tools that include a focus on monitoring and asset management, not only plant design and sales. Note, though, that most tools in this list are proprietary:

Tool Name	OpenSolar
URL	https://www.opensolar.com/
Category & Use Case	Design, Sales
License	Software is free to use, but not open-source.
Description	A comprehensive asset management platform with real-time monitoring, reporting, and data analytics. Integrates with various third-party systems for seamless data flow and enhanced operational efficiency.

Tool Name	Qantum
URL	https://www.qosenergy.com/
Category & Use Case	Advanced Monitoring, Asset Management
License	Proprietary
Description	A comprehensive asset management platform with real-time monitoring, reporting, and data analytics. Integrates with various third-party systems for seamless data flow and enhanced operational efficiency.

Tool Name	Solar-Log
URL	https://www.solar-log.com/
Category & Use Case	Monitoring, Fault Detection
License	Proprietary
Description	Provides comprehensive monitoring and fault detection for PV plants, focusing on maximizing energy yields and operational efficiency. Suitable for both residential and commercial installations.

Tool Name	VCOM Cloud
URL	https://www.meteocontrol.com/
Category & Use Case	SCADA, Monitoring, Data Management
License	Proprietary
Description	A cloud-based monitoring and control platform for solar plants, offering comprehensive performance analysis, fault detection, and reporting tools.

Tool Name	Ardexa Platform
URL	https://www.ardexa.com/
Category & Use Case	Monitoring, Data Management
License	Proprietary
Description	A global platform for secure data management and control across solar, wind, and hydro energy assets. Emphasizes digital security and modern IT communications.

Tool Name	Solar Monitoring Portal
URL	https://www.azzo.com/
Category & Use Case	Monitoring, Asset Management
License	Proprietary

Description	Combines data from various manufacturers into a single platform for real-time monitoring of power quality and PV performance. Ideal for managing diverse solar portfolios.

Tool Name	SunbaseData
URL	https://www.sunbasedata.com/
Category & Use Case	Business Management
License	Proprietary
Description	A solar business management system that integrates marketing, sales, and operations using workflow automation.

Tool Name	SolarSuccess
URL	https://blubanyan.com/en/solar-solutions/
Category & Use Case	Business Management
License	Proprietary
Description	A cloud-based business management suite optimized for solar installers, integrating accounting, CRM, project management, and more.

Tool Name	HelioScope
URL	https://helioscope.aurorasolar.com/
Category & Use Case	Design & Financial Analysis
License	Proprietary
Description	Combines robust financial modeling with customizable proposals, making it a complete sales solution for solar developers.

3.4 Software tools for SCADA and industrial automation

Beyond software tools focusing on monitoring and assessment of the operation of solar thermal plants, there are a variety of software tools for the general tasks of plant control, automation and SCADA (supervisory control and data acquisition). Here is a brief selection of open-source SCADA and industrial automation systems and software tools.

Tool Name	URL	License
PyScada	https://github.com/pyscada/PyScada https://pyscada.readthedocs.io/en/main/	GNU AGPL v3.0
SCADA-LTS	http://scada-lts.org/	GNU GPL v2.0
Rapid SCADA	https://rapidscada.org/ https://github.com/RapidScada/scada-v6	Apache License 2.0
OpenSCADA	http://oscada.org/	GPL v.2
Schneid SIOCS	https://schneid.at/siocs/	Proprietary

3.5 General visualization, monitoring and IoT platforms

General IoT platforms and time series visualization platforms are another option for visualizing measurement and monitoring data from solar thermal plants. A series of software tools and platforms exist (e.g. OpenNMS, Zabbix), but many are not tailored specifically to time series data. Here is a selection of the most interesting options for the purpose of solar thermal plant monitoring:

ThingsBoard	
Tool Name	**Thingsboard**
URL	https://thingsboard.io/
License	Apache License 2.0 Paid tiers available
Description	Thingsboard is an open-source IoT platform that enables the collection, processing, visualization, and management of data from connected devices. It supports multiple protocols like MQTT, CoAP, and HTTP, making it suitable for integrating various sensors and devices used in solar thermal plant monitoring. Features include real-time monitoring, customizable dashboards, rule engine for data processing, and alarms/alerts for specific events.

Grafana

Tool Name	**Grafana**
URL	https://grafana.com/
License	AGPL v3
Description	Grafana is an open-source platform for monitoring and observability. It allows users to query, visualize, alert on, and understand metrics from multiple data sources, such as Prometheus, InfluxDB, Graphite, Elasticsearch, and more. Grafana excels in creating highly customizable and interactive dashboards, making it ideal for visualizing the performance and operational data of solar thermal plants. It supports alerting based on metrics, which is useful for proactive maintenance and fault detection.

kibana

Tool Name	**Kibana**
URL	https://www.elastic.co/kibana
License	Elastic License 2.0
Description	Kibana is a data visualization and exploration tool used for log and time-series analytics, application monitoring, and operational intelligence use cases. It integrates seamlessly with Elasticsearch and can be used to visualize data collected from solar thermal plants.

Prometheus

Tool Name	**Prometheus**
URL	https://prometheus.io/
License	Apache License 2.0
Description	Prometheus is an open-source system monitoring and alerting toolkit. It is well-suited for monitoring dynamic environments, and when combined with Grafana for visualization, it provides a robust solution for monitoring the performance metrics of solar thermal plants.

Node-RED

Tool Name	**Node-RED**
URL	https://nodered.org/
License	Apache License 2.0
Description	Node-RED is a flow-based development tool for visual programming developed originally by IBM for wiring together hardware devices, APIs, and online services. It's suitable for creating custom monitoring solutions for solar thermal plants, leveraging its integration capabilities and ease of use for data processing and visualization.

4 SunPeek user guide

Acknowledgment: This chapter contains excerpts (with minor adaptions) from “Guide to ISO 24194:2022 – Power Check”, draft version 1.2 [7]. The final version of the guide will be made available through the IEA SHC Task 68 Website: https://task68.iea-shc.org/publications (planned publication date: Autumn 2024).

This chapter contains a brief user guide of the SunPeek software, an open-source tool for performance analytics of solar thermal plants, with a focus on its ISO 24194:2022 Power Check implementation. SunPeek is selected among the tools listed in Chapter **3** for a more thorough coverage, as it provides the first and only open-source implementation of the Power Check, a key method to evaluate solar thermal plants described in Chapter **2.1**. For other use cases, the reader may refer to the tools listed in Chapter **3**.

4.1 What is SunPeek?

SunPeek is a community developed open-source software tool for on-going performance assessment and guarantee procedures of solar thermal plants. The software entails the first open-source implementation of the Power Check of ISO 24194:2022.

SunPeek strives to advance the state-of-the-art of quality assurance and become a versatile platform for new industry-standard solutions in solar thermal plant monitoring. It is designed as a modern, containerized web application, featuring a user-friendly graphical user interface (JavaScript), a web RESTful API, and a backend (Python). This chapter focuses on the Power Check application with the SunPeek Web-UI. Note that there are additional configuration options and algorithms available when using the SunPeek API and backend.

4.2 Quick start

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 Repository	https://gitlab.com/sunpeek/
Python Library	https://pypi.org/project/sunpeek/
Open Dataset (Demo Plant)	https://doi.org/10.5281/zenodo.7741083
Zenodo Community	https://zenodo.org/communities/sunpeek
Contact	support@sunpeek.org

To analyze a plant with the SunPeek open-source software we recommend the following procedure:

- If you are new to SunPeek, try the *public demo* (https://demo.sunpeek.org/), including the built-in *demo plant*.
- Check out the *quick guide* (**FIGURE 11**) for a step-by-step instruction to Power Check evaluations.
- Check out the *SunPeek documentation* (https://docs.sunpeek.org) for additional in-depth information.

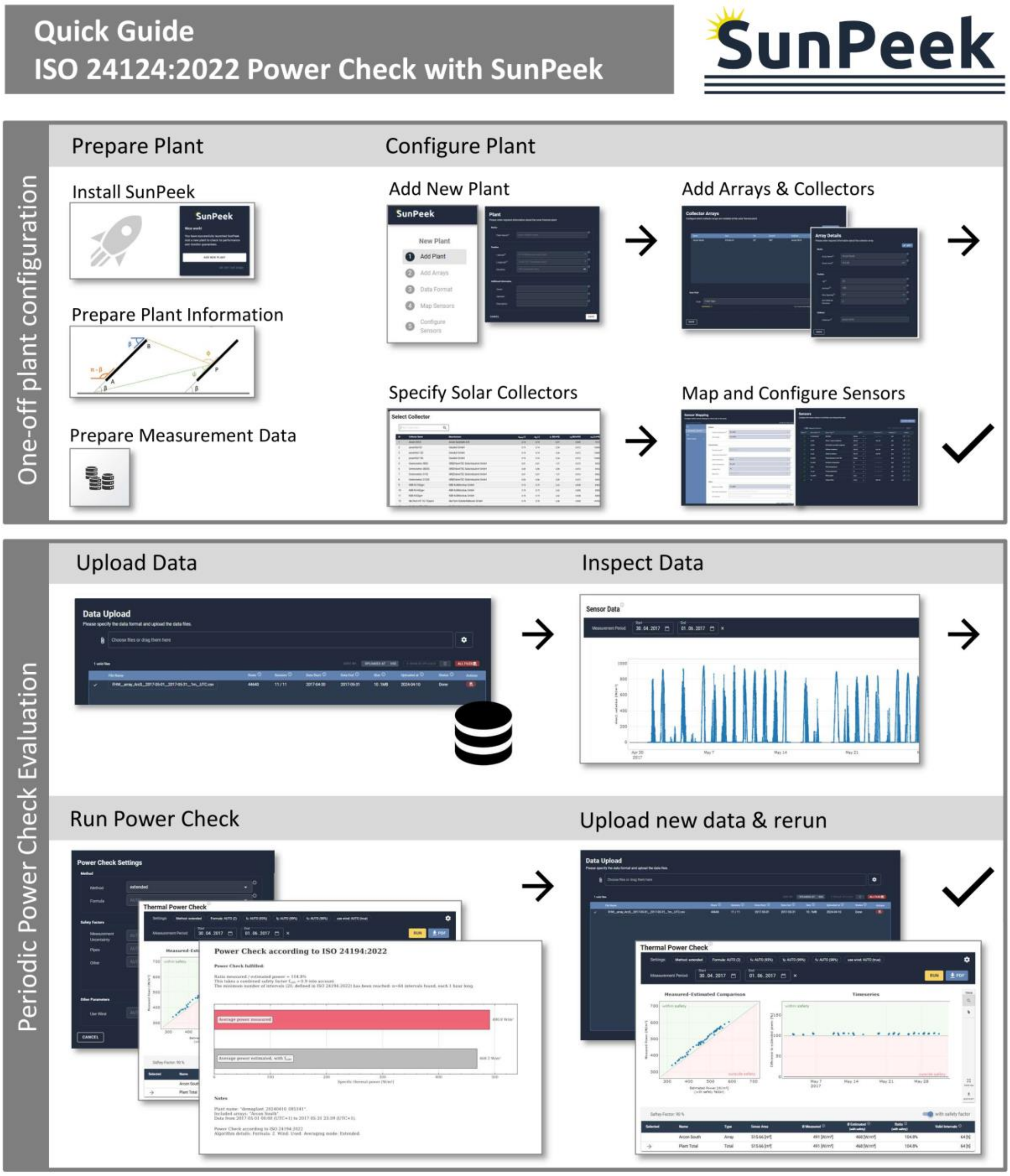


Figure 11: Quick Guide to ISO 24194:2022 Power Check with SunPeek.

4.3 About SunPeek

SunPeek Power Check

SunPeek is designed to be the reference software implementation of the ISO 24194:2022 Power Check by ensuring an open-source, transparent, consistent, readily available and broadly validated implementation. The application of the Power Check to solar thermal collector arrays requires a software implementation for data handling, calculation of measured and estimated power and generation of reports. Specifically, SunPeek has the following goals:

- Make the ISO 24194:2022 Power Check implementation easily accessible and free of charge also for commercial use without the burden that every user needs to design an 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.
- 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.

Licenses

The SunPeek Web-UI has a BSD-3-Clause license (https://opensource.org/license/bsd-3-clause/), the SunPeek Backend has a GNU Lesser General Public license (https://opensource.org/license/lgpl-license-html/). These licenses allow a free commercial use. Note that SunPeek is distributed without any warranty and without even the implied warranty of merchantability or fitness for a particular purpose.

SunPeek Version and Roadmap

The SunPeek documentation at https://docs.sunpeek.org/ covers the main topics about installing and updating SunPeek, licensing, contributing, and the full API documentation. The latest SunPeek source code is available at https://gitlab.com/sunpeek/. This document builds on SunPeek Backend version 0.3.82.

SunPeek strives to improve the user experience and code quality, aligning with further developments of the standard and integrating topics not yet covered, like the Daily Yield Check. The longer-term SunPeek development goals are summarized in a roadmap, as is common for open-source projects. Roadmap: https://gitlab.com/sunpeek/sunpeek-governance/-/wikis/Roadmap.

For installation, see the documentation at https://docs.sunpeek.org/. SunPeek runs on Windows, Mac, Linux, both as Sever and Desktop applications.

SunPeek software features

- Compatibility: SunPeek runs on Windows / Mac / Linux
- Automated calculation and comparison of measured and estimated power output (Power Check according to ISO 24194:2022)
- 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 (CSV, everything pandas can read)
- Option to add custom-defined collectors
- PDF report and CSV export of calculation results
- Automatic conversion between ISO 9806 quasi-dynamic and steady-state collector test certificates
- Automated data pipeline for data cleaning and data calculation, compensating missing sensors
- Fluid properties support, with pre-defined and own fluids, and CoolProp database integration
- Enhanced Power Check applications (e.g., filtering of stagnation events, application to multiple sub-fields, Extended Power Check)
- Standardized interface (RESTful API) for integration into existing software tools and databases

4.4 Plant configuration

After successfully installing SunPeek, you should see the following welcome screen in the web browser running the SunPeek Web-UI (FIGURE 12):

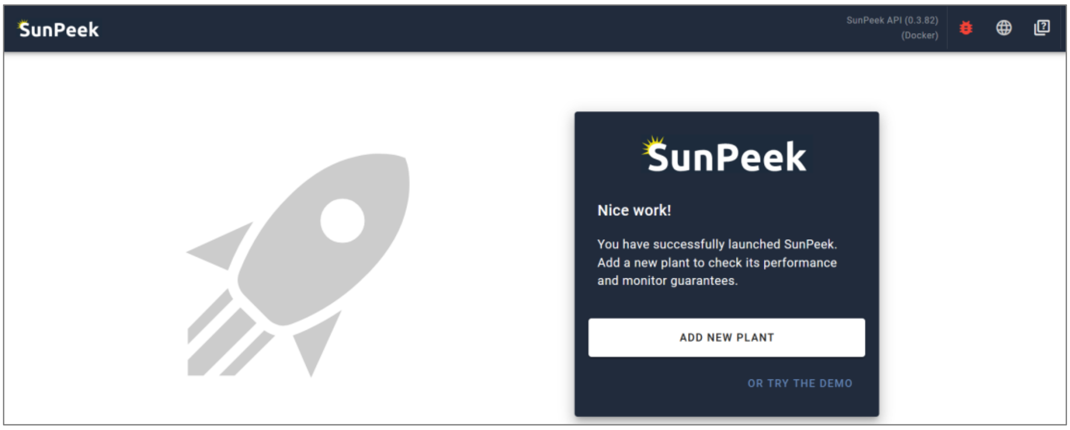


Figure 12: Welcome Screen after successfully launching SunPeek.

To get started, hit „TRY THE DEMO“ to use SunPeek with the pre-configured solar plant "Fernheizwerk Graz" or choose "ADD NEW PLANT" to set up your own solar thermal plant. To set up a solar plant in SunPeek, a one-off configuration is required: The configuration represents all the information needed to run the ISO 24194 Power Check on the plant. This includes things like plant location, collector information, or measurement data.

Plant configuration in five steps

A solar plant in SunPeek consists of the hydraulic and geometric arrangement, the collector arrays, and the measurement setup with the respective data channels. As shown in TABLE 12, plant configuration in SunPeek is done in five steps; SunPeek will guide you through each step.

Table 12. Plant configuration in five steps.

Step	*Page*	*Action*
1	Plant	Enter the parameters which are common for whole the system, e.g. longitude and latitude of the plant location.
2	Arrays	Enter information specific to 1 or many collector arrays and select the collectors used. If power output is not directly measured (only volume or mass flow available), select a fluid to have SunPeek calculate the power output. Note that SunPeek assumes uniformly arranged arrays (same tilt and azimuth angles).
3	Data Channels	Upload a sample data file to provide the names of the measurement data channels, later be used for the Power Check. Also, define the datetime format and time zone of the data.
4	Sensor Mapping	Sensor mapping is the process of linking measurement data channels with input slots for algorithms which have clearly defined meanings in the automated SunPeek evaluations. These meanings are stated in the tooltip description, accessible by clicking on the tooltip icon in the Web-UI. Input slots marked with (*) are required for the Power Check, additional optional inputs can be provided optionally, e.g., "Array is shadowed". SunPeek distinguishes between input slots for plant and collector arrays. The "Plant" holds input slots which are common for the whole plant, like the ambient temperature measurement. The "Array" holds input slots for a specific array, e.g., inlet and outlet temperatures, or irradiance. To allow flexibility regarding measurement setups, SunPeek has a variety of input slots. For example, the thermal power output of a plant can either be provided directly as a measured data channel or be defined as a combination of volume or mass flow, inlet and outlet temperature, and a heat transfer fluid. Note: Data channels can be mapped multiple times. For example, the same temperature sensor can be used as an array inlet temperature, and to calculate the array's thermal power output.
5	Sensors	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.

Configuration for plants with a single collector array

ISO 24194:2022 describes the measurement points of two standard systems with one collector array, i.e. systems without heat exchanger and with heat exchanger respectively (ISO 24194:2022, Figures 5 and 6). SunPeek does not model the heat exchanger explicitly, and instead simply assigns the data channels required for the ISO 24194:2022 Power Check to "Plant" and/or "Array". TABLE 13 lists the required and optional information for the standard systems without and with heat exchanger and shows some exemplary usage for ISO 24194:2022 calculations. FIGURE 13 and FIGURE 14 show the sensor mapping for these two system configurations.

Table 13. Required and optional parameters and sensors for systems without and with heat exchanger and one collector array (see ISO 24194:2022, Figure 5 and 6). Symbols refer to terms and definitions used in ISO 24194:2022.

Configuration page	*Name*	*Symbol*[(1)]	*Required*[(2)]	*Required for/if (examples)*
[Plant]				
Parameter	Plant Name		Y	
	Longitude	L_{loc}	Y	
	Latitude	ϕ	Y	
[Array]				
Paramter	Array Name		Y	
	Gross Area	A_{GF}	Y	
	Tilt	β	Y	Internal shading, incidence angle
	Azimuth	γ	Y	Internal shading, incidence angle
	Row Spacing	S	Y	Internal shading, incidence angle
	Sun Minimal Elevation		(Y)	External shading calculation
Collector	> Choose predefined or add custom collector		Y	
Fluid	> Choose predefined fluid		(Y)	Thermal power calculation if thermal power not measured
[Sensor Mapping]				
Plant	Ambient temperature	ϑ_a	Y	
	Wind speed	u	(Y)	Data filtering if wind speed is considered
	Thermal power (measurement)	$\dot{Q}_{meas}$	(Y)	If no volume flow measurement available
	Thermal power (calculation)			
	Inlet temperature	$\vartheta_i, \vartheta_{i,sec}$	(Y)	If no thermal power measurement
	Outlet temperature	$\vartheta_i, \vartheta_{e,sec}$	(Y)	If no thermal power measurement
	Volume flow	$\dot{V}_{pri}, \dot{V}_{sec}$	(Y)	If no thermal power measurement
	Mass flow	$\dot{m}_{pri}, \dot{m}_{sec}$	(Y)	Alternative measurement instead of volume flow
	Relative humidity		N	For radiation conversion (not yet implemented)
	Dew point temperature		N	For radiation conversion (not yet implemented)

	Air pressure		N	For radiation conversion (not yet implemented)
Array	Inlet temperature	ϑ_i	Y	
	Outlet temperature	ϑ_e	Y	
	Global radiation input	G_{hem}	(Y)	For formula (1) or (2)
	Direct radiation input	G_b	(Y)	For formula (2) or (3) if no I_{DN}
	Diffuse radiation input	G_d	(Y)	For formula (2) if neither G_b or I_{DN}
	DNI radiation input	I_{DN}	(Y)	For formula (2) or (3) if no G_b
	Thermal power	$\dot{Q}_{meas}$	N	Assumed to be same as plant (redundant)
	Volume flow	$\dot{V}_{pri}$	N	Assumed to be same as plant for systems without heat exchanger (redundant)
	Mass flow	$\dot{m}_{pri}$	N	Assumed to be same as plant for systems without heat exchanger (redundant)
	Array is shadowed		(Y)	User defined shading mask for both internal and external shading. Allows using more complex horizons or shading patterns from third-party software.

Y = Yes (required), N = No, (1) According to ISO 24194:2022, Chapter 4, (2) Required for Power Check

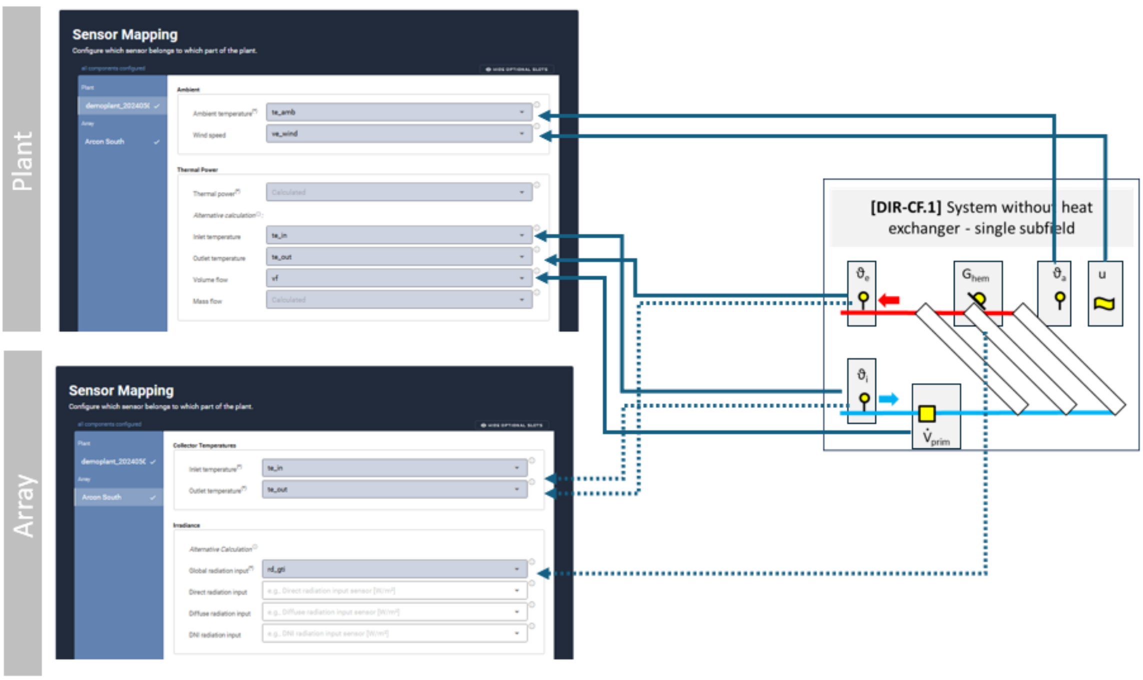


Figure 13. Sensor mapping in SunPeek for system without heat exchanger, plant configuration step #4 (Plant > Configuration > Sensor Mapping > "Plant" / "Array").

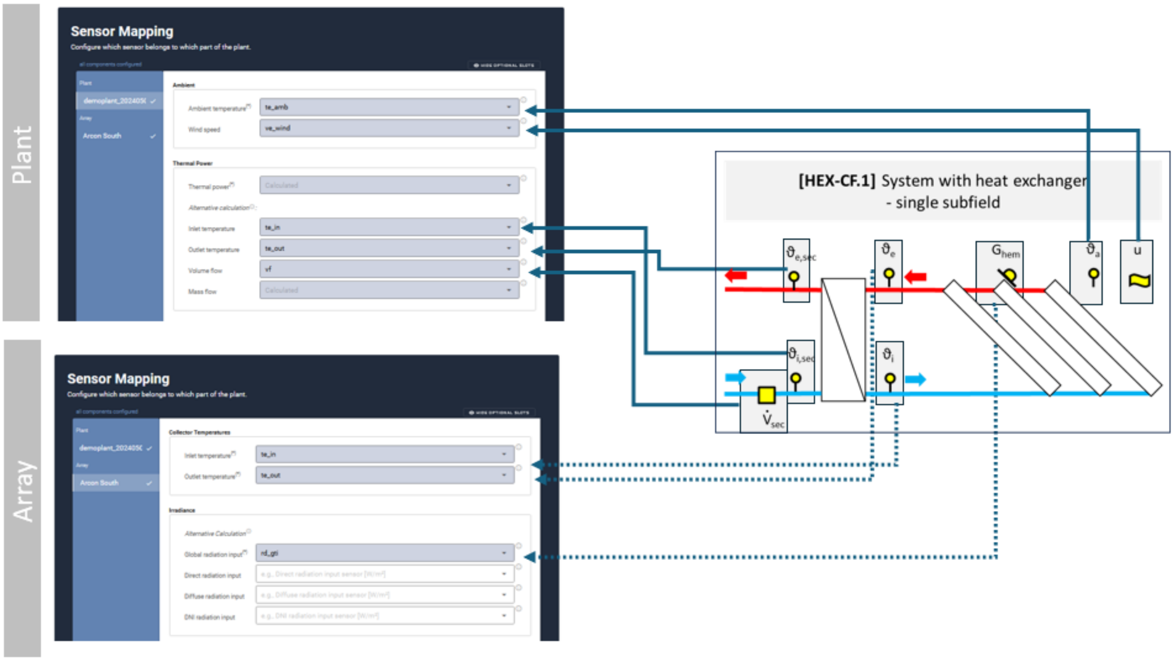


Figure 14. Sensor mapping in SunPeek for system with heat exchanger, plant configuration step #4 (Plant > Configuration > Sensor Mapping > "Plant" / "Array").

Configuration for plants with multiple arrays

In SunPeek, an array is assumed to have exactly one collector model, with a given set of characteristic parameters, and to be uniformly arranged (same tilt and azimuth). For plants with multiple collector models (e.g., flat-plate and concentrating collectors in series) or non-uniformly arranged arrays (e.g., two subarrays with different tilt or azimuth), multiple arrays need to be defined in SunPeek. Although ISO 24194:2022 allows to use representative collector parameters for arrays with similar collector types, it is recommended to define multiple subfields instead. For an example application, see [2]. Currently, the application to multiple arrays is reworked and refined, please consult https://docs.sunpeek.org/ for the most recent update.

Sensor Properties

Prior to data upload, the user needs to confirm the physical unit of each measurement data channel. This is done in the "Sensors" tab during plant configuration, see FIGURE 15. Some channels require specifying additional information, such as tilt and azimuth angles for irradiance sensors.

With this step, the configuration of a solar plant in SunPeek is done, and users may proceed to uploading measurement data and running the Power Check.

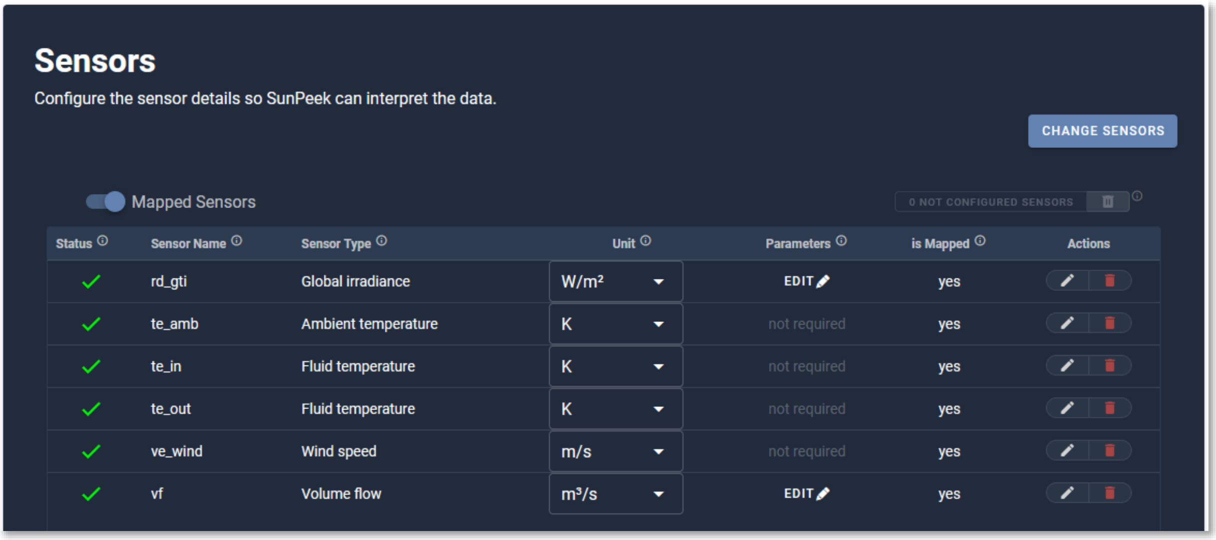


Figure 15. Definition of physical units and other properties for the provided measurement channels in SunPeek, plant configuration step #5 (Plant > Configuration > "Sensor Details" page).

4.5 Data upload and inspection

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 16). Uploaded measurement data will be automatically processed, concatenated, and saved in the internal SunPeek data storage.

In case erroneous data has been uploaded, SunPeek allows deleting either single upload entries, or all uploaded data for the plant. If new data upload overlap in time with already existing data, the new data will overwrite the existing data in the overlapping period.

Uploading data also triggers SunPeek to calculate all "virtual sensors", such as sun position, collector field shading, etc., for the uploaded period.

Figure 16. Data Upload page in SunPeek (Plant > Data Upload).

Visual data inspection

For visual data inspection, SunPeek provides a graphical time-series view of the uploaded measurement data (see FIGURE 17). This view displays the data after all internal quality checks, the same data SunPeek utilizes in its calculations and in the Power Check analysis. Virtual sensors are displayed just like any of the regular data channels.

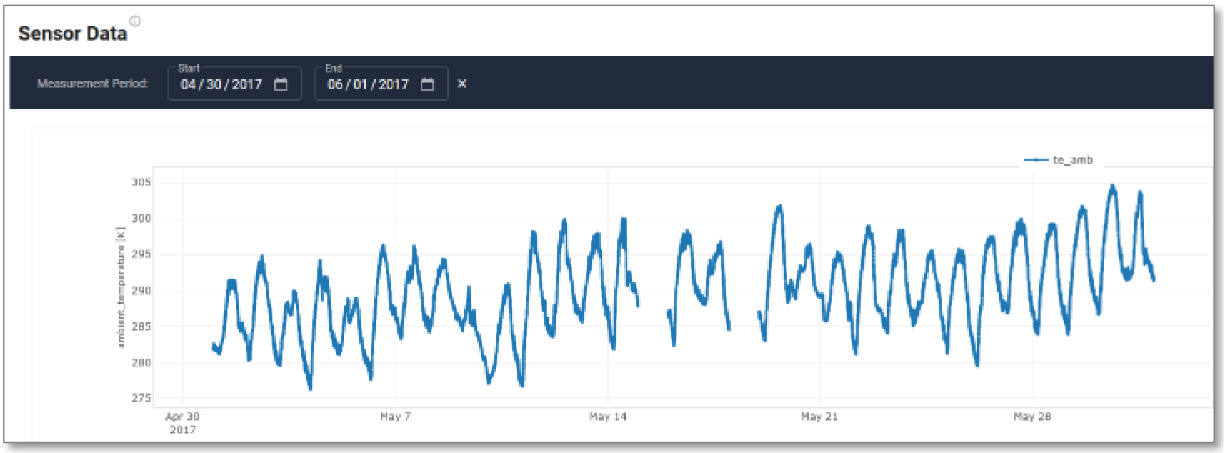


Figure 17. Line plot for visual data inspection in SunPeek (Plant > Sensor Data).

4.6 Power Check application

FIGURE 18 and FIGURE 19 show graphical output of the Power Check in SunPeek's Web-UI. SunPeek displays the "Measured-Estimated Power" (ISO 24194:2022, Figure 3). Additionally, SunPeek shows the "Measured-Estimated Ratio Timeline", which is not mentioned in the standard, but is helpful to detect performance changes over time. Evaluations can be done with or without safety factors, i.e. $f_{safe} = 1$. The SunPeek Power Check PDF report (see

FIGURE *20*) includes additional plots, such as the "Measured-Estimated Ratio" plot (ISO 24194:2022, Figure 4).

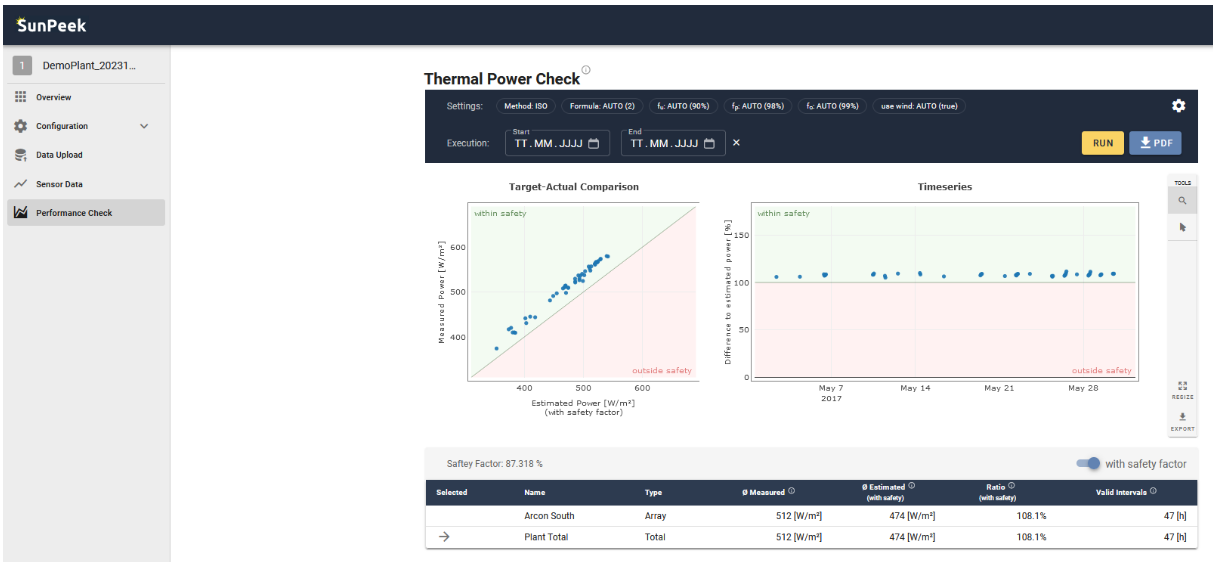


Figure 18. Power Check result page in the SunPeek Web-UI (Plant > Power Check).

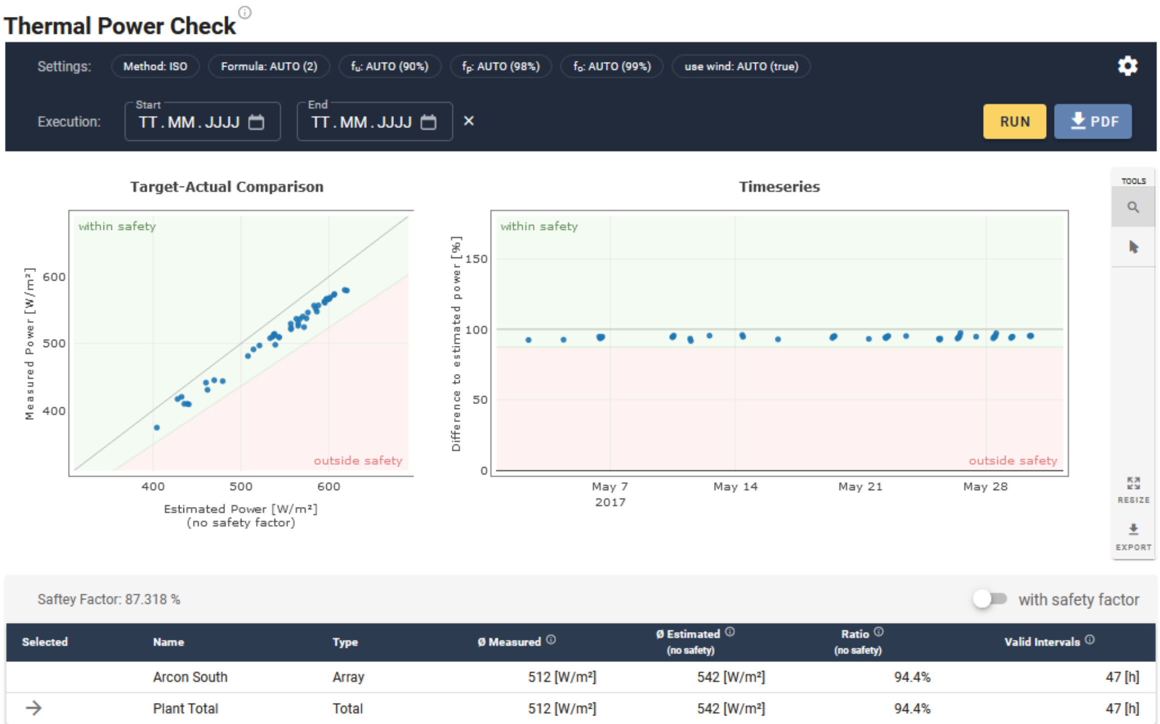


Figure 19. Graphical display of Power Check without safety factor in SunPeek (Plant > Power Check).

These settings can be chosen for the *plant*:

- *Measurement period*: Start and end time of the time interval used for the measured-estimated comparison of the collector array performance.
- *Method*: The user can choose the data averaging method, between "ISO" (the implementation as described in ISO 24194:2022), and "Extended".
- *Use Wind*: Decide if wind speed should be used as a data filtering criterion to check restrictions on operating conditions. If the check is done with wind speed and the data channel is not available, the evaluation throws an error.
- *Formula*: Choice of Formula (1) – (3).
- *Safety Factors*: Safety factors for "Measurement Uncertainty", "Pipes" and "Other".

SunPeek has an *"AUTO" mode* for these settings:

- *Measurement period*: By default, a period that includes all uploaded data is used.
- *Method*: "ISO" is the default option for the data averaging method.
- *Use Wind*: If wind speed measurement is available, use it as a data filtering criterion. If wind is not available, the wind velocity requirement in ISO 24194:2022 Table 1 is ignored.
- *Formula:* For collector type "Flat plate", Formula (2) is chosen if it can be applied (e.g., if beam / DNI irradiance data is available), otherwise Formula (1) is chosen. For collector type "Concentrated", formula (2) is chosen if no concentration ratio is defined ($C_R < 20$).
- *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 $f_0 = 0.98$ for other uncertainties. This results in an overall safety factor $f_{safe} \approx 0.90$. Note that these default values do not indicate recommendations and do not consider accuracy levels.

SunPeek has the following options to *export* the Power Check results:

- Create a *PDF report* which follows the recommendations of ISO 24194:2022 Annex A.
- Create an *extended PDF report*, including line plots for each of the Power Check intervals. Note: This is currently only available via the SunPeek API, not yet in the Web-UI.
- Create a *CSV file* with the numeric calculation results.

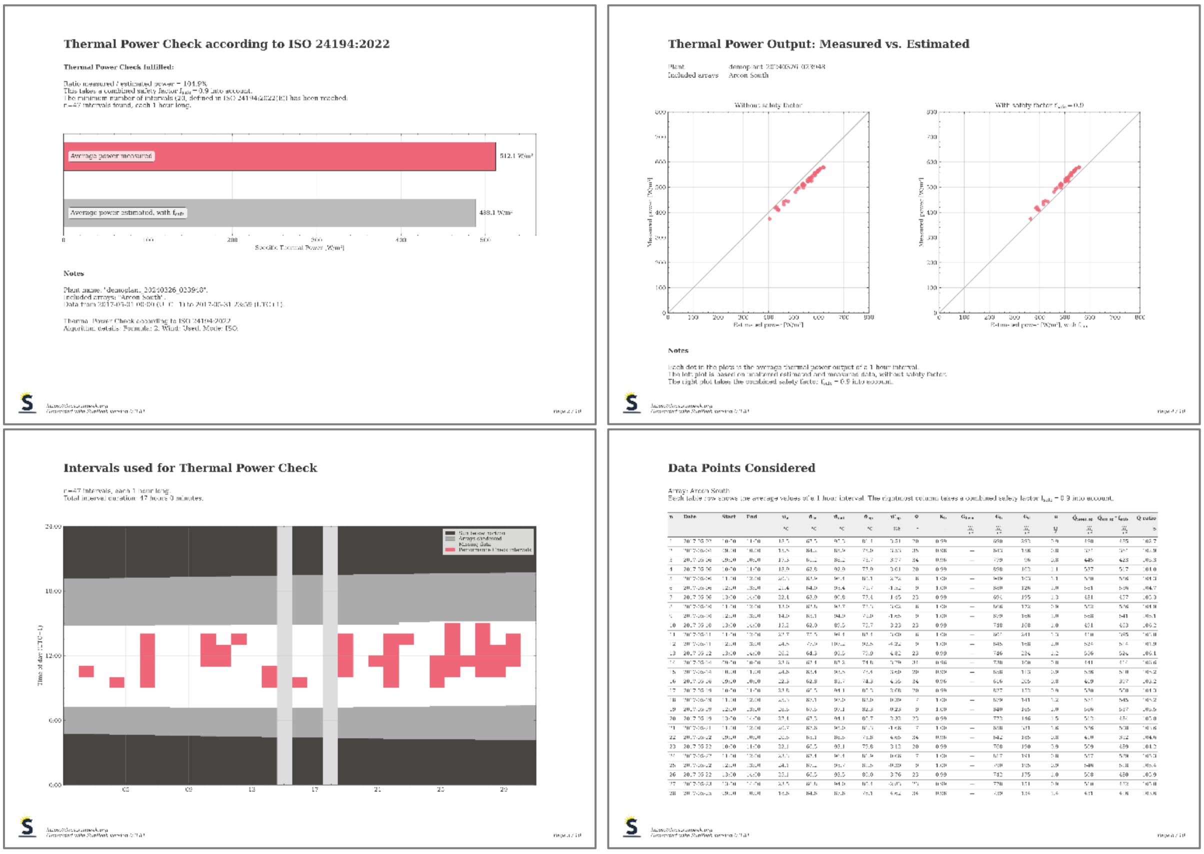


Figure 20. Example pages of Power Check PDF report in SunPeek (Plant > Power Check > Button "PDF").

4.7 Power Check implementation in SunPeek

The SunPeek implementation of the ISO 24194:2022 Power Check closely follows the standard. Nevertheless, compared to the standard, SunPeek has some limitations, adds some modifications and extensions, and automates the data processing and calculation.

Limitations

The following procedures of ISO 24194:2022 are not yet implemented in the SunPeek version described in this chapter. It is foreseen to include these in later versions of SunPeek.

- Power Check Formula (3) for concentrating collectors with high concentration ratio (ISO 24194:2022, Chapter 5.2.2)
- Shadows on one-axis or two-axis tracking collectors in row (ISO 24194:2022, Chapter 5.2.2)
- Daily Yield Check (ISO 24194:2022, Chapter 6)

Extensions

The major conceptual extensions of the SunPeek Power Check compared to ISO 24194:2022 are:

- Systematic approach to apply the Power Check to plants with multiple arrays.

- Automatic calculation of internal (row-to-row) shading.
- Extended Power Check with advanced data filtering.

Modifications

SunPeek introduces the following modifications:

- Additional checks to see if Formula (1) – (2) are applicable.
- Allow evaluation if there is no wind speed measurement.
- Require a minimum number of raw measurements per 1-hour interval. This excludes analyzing plants for only 1-hourly averaged or sampled measurement data are provided.
- Provide a minimum threshold to the thermal power output to treat stagnation cases. Note: This is currently only available via the SunPeek API, not yet in the Web-UI.
- Allow evaluation with less than 20 valid data records but issue a warning in that case.
- Do not check or report accuracy levels and measurement instrumentation. Do not consider accuracy levels in the choice of the default safety factors.
- Exclude external shading to get valid data records, by using the parameter "Sun Minimum Altitude" or by a shading mask provided by the user.

Data processing and calculation procedure

Data handling is only briefly addressed in ISO 24194:2022 and partly lacks consistent terminology. To make data handling and the creation of the Power Check data records more traceable, and to allow additional data quality checks, SunPeek requires users to provide the logged raw data (initial recorded data) and does not allow running the Power Check if only 1-hour data records are provided. The SunPeek data flow and calculation procedure for the Power Check is shown in FIGURE 21 and explained in TABLE 14.

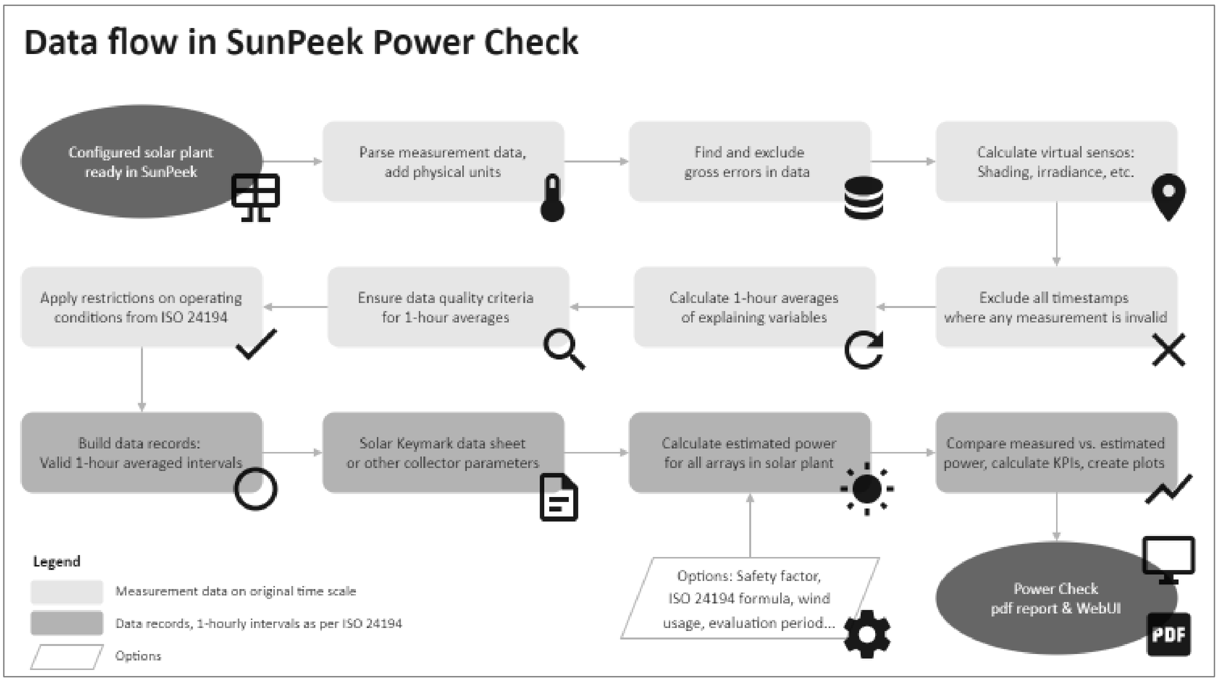


Figure 21. Overview of data processing steps in the SunPeek implementation of the ISO 24194 Power Check. Note: This is a simplified overview and not intended as graphical software documentation.

Table 14. Comments on each data flow step depicted in ***FIGURE 21*** for the SunPeek Power Check.

Step	*Explanation*
	*Configured solar plant ready in SunPeek* This assumes that a real-world solar plant has been prepared for SunPeek, and that the one-off plant configuration has been completed. SunPeek ships with a pre-configured "demo plant" on which you can run the Power Check right away, using the included measurement data.
	*Parse measurement data, add physical units* In this step, SunPeek parses the measurement data of the solar plant provided by the user. • Along with measurement data, also date and time information are parsed. This is a critical step and a frequent cause of problems in practice. • SunPeek internally uses unit-aware quantities, because using explicit physical units help to increase quality of the data processing and avoid unit clash problems. • SunPeek maps the unit-less measurement data to quantities with physical units and utilizes these unit-aware numbers in all calculations. In the SunPeek user interface, users can assign a physical unit to each measurement channel.
	*Find and exclude gross errors in data* Measurement data occasionally may contain untrustworthy data. SunPeek attempts to include only valid data in its calculations. While detailed error analysis of the measurement data is out of scope, SunPeek excludes data that seems untrustworthy or is outside physically possible limits.
	*Calculate virtual sensors: Shading, irradiance, etc.:* Virtual sensors represent quantities that SunPeek requires for its computations yet are not directly measured. Examples of virtual sensors include the solar position, or row-to-row shading of collector

Step	*Explanation*
	rows. Virtual sensor calculation is done in the background and is triggered automatically when new data is uploaded.
	Exclude all timestamps where any measurement is invalid: The "Sensor Data" page in the SunPeek Web-UI shows all sensor data (from both regular and virtual sensors) used for all SunPeek computations, with all error checks and corrections applied. For the Power Check calculation, SunPeek follows a cautious approach and excludes all timestamps where any of the required sensor data is invalid, that is: The computation only includes timestamps for which all sensors have valid data.
	Calculate 1-hour averages of explaining variables: Following the ISO 24194:2022 Power Check method, SunPeek calculates 1-hourly averaged values. In doing so, SunPeek offers two different time averaging methods, namely a fixed-window and a moving-window approach.
	Ensure data quality criteria for 1-hour averages: Due to faulty or missing data, situations may occur where the 1-hour averages are based on only a few measurement data, or where there are long gaps between any valid measurements. SunPeek excludes 1-hour averaged intervals that do not meet certain quality criteria from being included in further computations. For details on these quality criteria, see Chapter **1.4**.
	Apply restrictions on operating conditions from ISO 24194: ISO 24194:2022 Table 1 lists a set of restrictions which must be met within the selected 1-hour intervals, such as minimum solar irradiance levels, or the restriction that there must be no shadows in the selected periods. SunPeek automatically uses the right set of restrictions, depending on the Formula used.
	Build data records: Valid 1-hour averaged intervals: The final data records used by SunPeek in the Power Check are those 1-hour average intervals which fulfill all quality criteria and restrictions described in the previous steps. The numeric and graphical outputs of the Power Check are based on these valid data records.
	Solar Keymark data sheet or other collector parameters: In this step, SunPeek makes sure it has all required collector parameters. • Depending on collector type and formula used for the Power Check, certain collector parameters must be available. • SunPeek automatically converts collector parameters from steady-state and quasi-dynamic collector tests. • Typically, the collector parameters are those reported on Solar Keymark datasheets, but self-defined collectors with own parameters may be used as well.
	Calculate estimated power for all arrays in solar plant: This is the core step of the Power Check, SunPeek uses one of the models defined in ISO 24194:2022 Chapter 5.2 to calculate the expected or estimated power output. If there are multiple arrays in the plant, this step is repeated for each array, and the total estimated power output is summed up from the individual estimates. Each array may use its own Formula in the estimated power computation.
	Options: Safety factor, ISO 24194 formula, wind usage, evaluation period…: Users may define some settings for the Power Check, such as a specific evaluation period, the safety factors used, the specific formula utilized in computation of estimated power, etc. As described in Chapter **4.6**, SunPeek limits the complexity involved in this step by providing sensible default values and "AUTO" settings, where SunPeek attempts to guess the most appropriate values for certain options. See Chapter **4.6** for details on the available options and the "AUTO" mode.

Step	Explanation
	*Compare measured vs. estimated power, calculate KPIs, create plots:* ISO 24194:2022 includes some suggested outputs, plots and report formats including tabular display of numeric outputs. In this step, SunPeek computes the main KPIs required to present the Power Check results in the Web-UI and as a pdf report.
 	*Power Check pdf report & Web-UI:* SunPeek collects the Power Check outputs in a dedicated data structure, which is provided to the Web-UI and used to generate a pdf report. • The SunPeek pdf report follows the recommendations of ISO 24194:2022. • Just like data upload, also the pdf report is available via the SunPeek REST API; this means that once a plant has been configured, the process of adding new data, running the Power Check and getting a summary pdf report can be fully automated.

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