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SunPeek Open-Source Software for ISO 24194 Performance Assessment and Monitoring of Large-Scale Solar Thermal Plants

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Abstract. ISO 24194:2022, the first standard specifically designed to assess the operational performance of solar thermal collector arrays, is likely to have substantial impact on the entire solar thermal industry. This standard introduces the Power Check, a method that can be used for monitoring ongoing plant operation and for checking performance guarantees. However, its practical use is presently limited, as initial applications indicate a need for clarification, and it exists as a mere paper description, rendering it less accessible for plant designers and operators. Furthermore, any implementation necessitates practical decisions regarding data handling and algorithm implementation. Closed-source implementations, lacking a traceable and transparent framework, could lead to inconsistent results. To address these issues, this paper introduces SunPeek, an open-source software that provides a reference implementation of the ISO 24194 Power Check. SunPeek is freely accessible for both scientific and commercial purposes. This paper also discusses existing limitations of ISO 24194 and showcases five examples of SunPeek applied to real-life solar thermal plants. This underscores potential practical challenges, such as handling stagnation events, and highlights methodological progress, such as improved data filtering for performance analyses. The findings and applications indicate SunPeek's usability and the high potential for ISO 24194-based performance monitoring of solar thermal plants.

Keywords: Renewable Heat, Quality Assurance, Open-Source Software, Solar Thermal

1. Introduction

Large-scale solar thermal plants (>500 m² collector area or 350 kW_{th}) are a key technology to provide renewable heat in residential, commercial, industrial, and district heating applications, with substantial growth worldwide in recent years [1]. Their heat production costs are stable and competitive (30-60 €/MWh), but only if an optimized operation ensures high energy yields over the lifespan of the plant.

For solar thermal installations, two ISO standards provide a framework for quality control: The well-known ISO 9806 ("Solar energy — Solar thermal collectors — Test methods") [2] addresses the performance of newly produced single collectors under laboratory conditions, generating product data sheets for plant design or simulations; and the ISO 24194 ("Solar energy — Collector fields — Check of performance") [3] introduces the Performance Check for collector arrays. ISO 24194 was published in 2022 and is the first standard of its kind by targeting solar thermal collector arrays. It 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.

ISO 24194 is based on two methods: the Power Check and the Daily Yield Check. The Power Check features a performance number (KPI), defined as the ratio of measured vs. estimated output of a given collector array, corrected for boundary conditions like weather, temperature levels, heat demand, or system control. This KPI is a valuable quality assurance indicator, but the practical application of ISO 24194 faces several challenges:

1. **Consistency:** While the ISO standard describes the Performance Check procedure, implementations done by various parties can lead to disparate results, defeating the goal of having a single source of truth.
2. **Transparency:** As any implementation requires practical choices on data handling and calculation algorithms, closed source implementations do no offer a traceable and transparent framework in case of a dispute of an underperforming plant.
3. **Availability:** Implementing the ISO 24194 methods demand domain knowledge and a deep understanding of the standard, as well as data analysis proficiency. Thus, applying the Performance Check is complex, and resource limitations will effectively impede some parties from using it.
4. **Applicability**: Through the first use of the standard in the solar community, the need for clarification may arise. Collector array configurations and measurement instrumentations vary greatly and not all cases are appropriately covered by the standard, like the application to multiple arrays. Furthermore, different use cases (on-going monitoring vs. guarantee procedures) can have conflicting goals, fostering diverging interpretations of the standard.

To overcome these constraints, the open-source software SunPeek [4] was developed. It contains the first open-source implementation of the Power Check of ISO 24194, designed to be its reference software tool by ensuring an open-source, transparent, consistent, readily available and broadly validated implementation. SunPeek incorporates necessary methodological adaptions and extensions of the standard to enhance its applicability. Coordinated with the SunPeek development, an expert group within IEA SHC Task 68 is currently elaborating the "Guide to ISO 24194:2022" [5] which offers advice on how to apply the Power Check in practice and documents the SunPeek implementation.

This paper outlines limitations of the Power Check of ISO 24194, explicates how the current limitations are addressed in SunPeek, and presents example applications to real-life installations, illustrating challenges and methodological developments. The authors of this paper are developers, maintainers, and early adopters of the SunPeek software as well as contributors to the "Guide to ISO 24194:2022".

2. ISO 24194 Power Check and its limitations

The Power Check is applicable to glazed flat plate collectors, evacuated tube collectors and/or tracking, concentrating collectors used as collectors in arrays. It compares the measured and estimated thermal power output for operating conditions close to full power, which are derived by a set of data filtering criteria (e.g., change in collector mean temperature ≤ 5 K within an hour). The estimated power output is given as a formula depending on the collector parameters according to ISO 9806, a safety factor, and operating conditions. As described in ISO 24194 chapter 5.2, three different formulae are available for the Power Check method, to be chosen depending on the collector type used in a specific collector field.

Applications of the Power Check by the authors of this paper showed the following main challenges and limitations:

1. **Heterogeneous collector arrays**: The standard does not outline in detail how to treat heterogenous collector arrays with combined collector types, but only states the following: "An overall estimate for fields with two or more similar collector types can be given choosing representative collector parameters." and does specify the term "similar types" by way of example (flat plate collectors with single glazing vs. double glazing) [Ch 6.1, p. 14]. This leaves room for interpretation for which array configurations the standard is applicable and how representative parameters are determined.
2. **Non-uniformly arranged arrays and non-standard measurement setups:** The standard lacks elaborations how to apply it to non-uniformly arranged arrays, e.g., with different row spacing and tilts, and non-standard measurement setups, e.g. positioning of an irradiance sensor in the same plane and on top of the collectors.
3. **Multiple collector arrays:** The standard only partially explains how it can be applied to multiple collector arrays and merely states: "If size, inlet and outlet temperatures are available for each field of collectors of same type, estimates can be given for each of these fields." [Ch 6.1, p. 14]. This does not clarify, which inlet and outlet temperature measurements are required for a specific configuration (e.g., does it suffice to have a common outlet temperature measurement for two subfields if good hydraulic balancing is ensured), how restrictions on operating conditions are checked (e.g., valid data recordings may vary between subfields, when shading occurs for one array, but not for the other), and how individual estimations are aggregated for the overall measured-estimated ratio.
4. **Calculation of K_{hem}:** Formula (1) to estimate the power output of non-concentrating collectors [Ch 5.2.2, p. 6] requires the Incidence Angle Modifier (IAM) for hemispherical solar radiation, K_{hem}. This parameter is given for the steady-state test (SST) procedure according to ISO 9806:2017, but not for the common quasi-dynamic test (QDT). The conversion between SST and QDT parameters is not described in ISO 24194 and the procedure explicated in ISO 9806:2017 Annex B seems to aim at the conversion between SST and QDT parameters and leads to conflicting results when applied the other way around.
5. **Radiation conversion**: For non-concentrating collectors, the standard requires a global tilted irradiance measurement coplanar to the collector plane [Ch 7.2.3.1, p. 22]. For non-standard measurement setups, e.g., if one irradiance sensor is used for multiple collector arrays with different tilt and azimuth, radiation conversion is essential. This topic is not covered in the standard.
6. **Wind speed**: WISC (wind and infrared sensitive) collectors are excluded from the Power Check, which might be due to the fact that representative wind speed measurements are hardly impossible for collector arrays. However, the standard requires wind speed measurements to discard operating conditions with high wind speeds > 10 m/s [Ch 5.4, p. 8]. Many installations in low-wind locations do not have a wind sensor installed which may imply that the standard is not applicable.

7. **External shading**: The standard only addresses internal (row-to-row) shading [Ch. 5.5]. It must be assumed that conditions with external shading are also to be excluded, but this is not clearly stated.
8. **Data filtering for operating conditions:** Although ISO 24194 states that only measurement points should be considered for the measured-estimated comparison when the collector array is close to stable full power operation [Ch 5.4, p. 7], data filtering criteria do neither enforce that the pump is running nor that the array is not in stagnation.
9. **Data quality issues and data aggregation**: The standard uses a two-step approach to deal with measurement data, where the initial raw data with logging time ≤ 1 min are averaged to hourly data records used for further calculations. Data records represent average values from the last full hour, e.g., from 11:00 to 12:00, 12:00 to 13:00, etc. [Ch. 7.2.2, p. 21]. The standard does not specify any data quality checks (e.g., outlier detection) nor how to treat missing data (e.g., some share of missing data within a 1-hour interval) and reduces the valid data records by sticking to fixed starting and end points (full hour) when creating hourly mean values.
10. **Safety factor**: The safety factor is essential for guarantee procedures, as it specifies the safety retention for the estimated power output and therefore influences if the measured-estimated ratio is above the 100 % threshold. The standard distinguishes safety factors for heat losses from pipes, measurement uncertainty and other uncertainties such as non-ideal flow distribution and uncertainties in the model/procedure itself [Ch. 5.2.2, pp. 6-7]. The standard defines three accuracy levels for measurement instrumentation, but does no outline in detail, how accuracy levels translate to safety factors and does not provide guidelines how to set typical safety factors.

3. SunPeek software and the Power Check implementation

SunPeek is a community developed open-source software tool designed as a modern web application, featuring a user-friendly graphical user interface (JavaScript), a web API, and a backend (Python) [4]. The software is freely available on GitLab [6] since February 2023 and distributed under open-source licenses that explicitly endorse commercial usage (Backend: GNU LGPL; Frontend: BSD-3-Clause). The software can be run on different platforms using Docker. The current version (v 0.3.80) is close to a Beta Release.

SunPeek entails the first open-source implementation of the Power Check of ISO 24194, designed to be the reference implementation for the solar community. SunPeek can also serve as a framework for other data-driven performance evaluations, quality analysis, and modelling of solar plants in operation. In addition to the Power Check, SunPeek contains an innovative procedure to check the solar energy yield, called Dynamic Collector Array Test (D-CAT), using on a dynamic simulation to obtain a solar yield estimation [7]. The software has a preconfigured demo plant, featuring a full year of open-access measurement data of the subfield “Arcon South” of the solar plant “Fernheizwerk” in Graz, Austria [8]. A public demo of SunPeek based on this dataset is available online [9]. Importantly, using SunPeek is possible on-premises without sharing measurement data with third parties. The software does not interfere with system control, facilitating a comprehensive assessment of both present and past system performance.

With reference to the Power Check limitations described in Chapter 2, Table 1 gives an overview how the current SunPeek implementation addresses these limitations and sketches possible further developments which are discussed within the “Guide to ISO 24194:2022”. The current Power Check implementation is applicable to typical plant designs and measurement setups of large-scale solar thermal plants. A screenshot of the Power Check Web-UI page is shown in Figure 1. The software allows the automated generation of a PDF report, as illustrated in Figure 2.

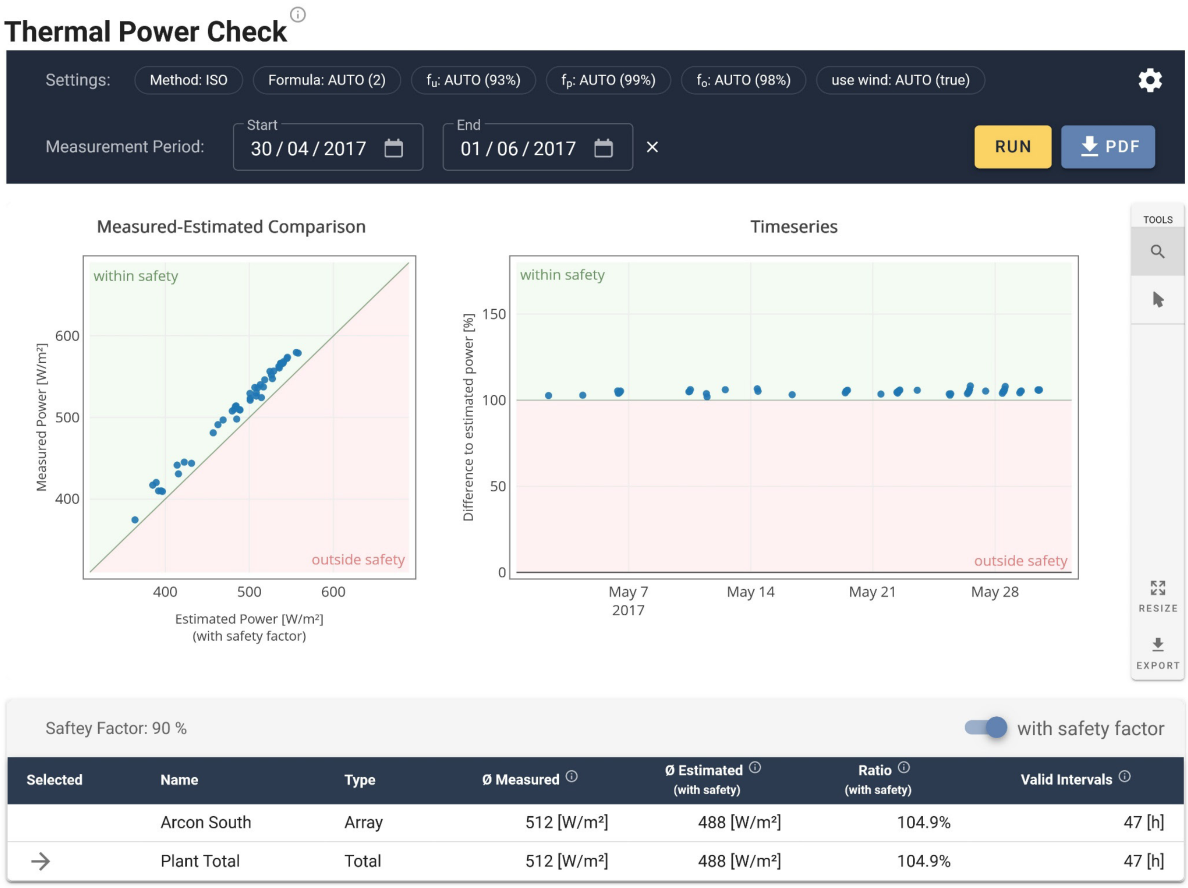
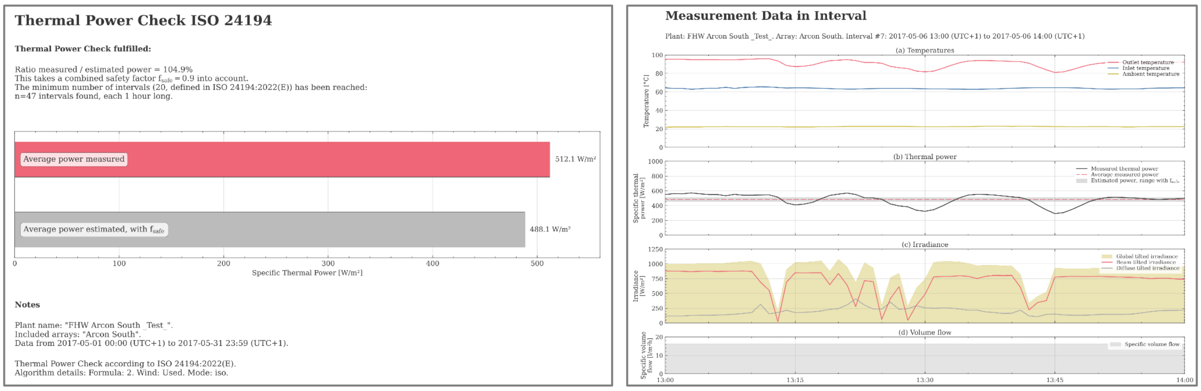


***Figure 1**. Screenshot of the SunPeek Web-UI with results of the ISO 24194 Power Check using the public dataset "Fernheizwerk" . The left plot illustrates a comparison between measured and estimated hourly performance values; the right plot depicts the evolution of performance values over time.*



(a) (b)

***Figure 2:** SunPeek PDF report with ISO 24194 Power Check results from public demo dataset "Fern-heizwerk" plant in Graz, Austria. The left plot (a) shows the measured-estimated ratio for the whole measurement period; the right plot (b) depicts measurement data for a 1-hour interval.*

***Table 1**. Limitations of the Power Check method (see Chapter 2) and development work in SunPeek to address these challenges.*

#	Limitation	SunPeek, "Guide to ISO 24194:2022"
1	Heterogeneous collector arrays	SunPeek allows custom-defined collectors with representative parameters. In the "Guide to ISO 24194:2022", heterogeneous collector arrays are conceptually treated like subfields (case #3).
2	Non-uniformly arranged arrays and non-standard measurement setups	SunPeek has pre-defined input slots for different setups (e.g., volume flow, inlet and outlet temperature, fluid properties vs. thermal power measurement), which allows some flexibility regrading measurement setups. Future SunPeek releases aim at increasing the flexibility, especially regarding radiation measurements (case #5). The "Guide to ISO 24194:2022" entails recommendations how to treat non-uniformly arranged arrays, e.g., using the most restrictive settings regarding collector row spacing, tilt and azimuth to assure that no part of the collector field is shaded. Additional use cases are needed to provide more comprehensive recommendations.
3	Multiple collector arrays	SunPeek allows to specify multiple collector arrays with their respective parameters (collector, gross area, tilt, azimuth, row spacing, sun elevation angle for internal shading calculation, etc.) and measurement data. If inlet and outlet temperatures and irradiance measurements are given for each array, SunPeek selects intervals where the data filtering criteria fulfilled for all arrays simultaneously, calculates the estimated power for each array and aggregates these values for the measured-estimated comparison for the plant (typically, thermal power is only available for the whole plant). For an example see Chapter 4.30. The "Guide to ISO 24194:2022" entails a classification of hydraulic setups and entails recommendations how to apply the standard to these configurations, which will be integrated in future SunPeek releases.
4	Calculation of K_{hem}	SunPeek entails a conversion procedure between SST and QDT collector data sheets, see Appendix, which is also documented in the "Guide to ISO 24194:2022".
5	Radiation conversion	SunPeek entails some radiation conversion algorithms (e.g., from titled to horizontal irradiance). Future releases aim at providing a generic framework for radiation conversion, also considering diffuse irradiance masking [10].
6	Wind speed	SunPeek allows to compute the Power Check with and without using wind measurements for data filtering. The "Guide to ISO 24194:2022" recommends that for low-wind locations, a wind speed sensor is not necessary, but further clarification is needed to operationalize this criterion.
7	External shading	SunPeek allows to exclude external shading by discarding operating conditions below a minimum sun elevation angle (Θ_{min}). Additionally, a shading mask can be provided, which allows to use external programs for detailed shading calculations.
8	Data filtering for operating conditions	SunPeek follows the standard by not checking that the pump is running nor that the array is not in stagnation. To ensure that the plant is in operation (and thus avoid stagnation), an option could be added to SunPeek backend to set a minimum thermal power output. For an analysis how this affects the outcome see Chapter 4.2

#	Limitation	SunPeek, “Guide to ISO 24194:2022”
		The “Guide to ISO 24194:2022” does not yet contain a final recommendation on this subject, as there are underlying conflicting interests, i.e., that for guarantee procedures it should be assured that the plant is in operation, and that for on-going monitoring, detection of stagnation might be useful.
9	Data quality issues and data aggregation	SunPeek entails data quality checks (Min-Max outlier detection, sensor hangs, etc.) and allows for some missing data when building 1-hour averages. The “Extended Power Check” allows advanced data filtering by selecting the “best” 1-hour intervals with moving averaging, not limited to start and end points on the full hour. For an example see Chapter 4.5.
10	Safety factor	SunPeek allows to input the three safety factors (i.e., heat losses, measurement uncertainty, other uncertainties). How to determine these values and to check sensor accuracies are out of scope for SunPeek, although uncertainty information and propagation might be incorporated in future releases. Practical recommendations to determine safety factors are not given in the “Guide to ISO 24194” and require further analysis.

4. Applications and Practical Experiences

SunPeek is already being used successfully for 10-20 large-scale solar thermal installations. Example applications include several Austrian plants within the HarvestIT project [9], the Austrian “Begleitforschung Solare Großanlagen” [8], the EU-funded IndHeap project (with a planned application to concentrating collectors), the Applied CPS project [11] and in-house applications of the compagnies SOLID, GASOKOL and Schneid. The software has also been used to evaluate large-scale, evacuated tube collector arrays within the HP-BIG project at ISFH [7], and an academic thesis studied the effect of stagnation events the SunPeek results. Further use cases with SunPeek are foreseen at ISFH within monitoring projects, especially for heat pipe collectors.

SunPeek has also been applied to SolarCADII, a solar district heating project in Geneva, using evacuated flat plate collectors manufactured by TVP Solar SA. SolarCADII was monitored by the HEIG-VD Institute in the framework of a research project funded by the Swiss Federal Office of Energy, validating SunPeek with in-house scripts based on 1-minute sampled data. This chapter presents selected example applications, illustrating challenges and methodological developments.

4.1 Performance degradation due to soiling

Background: In extension to ISO 24194, SunPeek provides the user with a measured-estimated comparison of the collector array performance over time. This allows detecting time-related performance degradations, e.g., due to ageing or soiling of the collectors. By focusing on relative changes of the measured-estimated ratio, modelling distortions might be reduced, e.g., if heat losses or diffuse irradiance masking affect the performance similarly over time.

Use Case: The district heating plant Fernheizwerk Graz in Styria Austria is the largest testing field for solar-thermal collectors, containing collectors from various manufacturers and different collector types (concentrating, flat-plate, evacuated tubes). It was installed in 2007 by SOLID Solar Energy Systems and since then has been extended multiple times. Today, 8216 m² of collector area is installed and the heat is supplied to the local district heating network (see Figure 3). To test the monitoring capabilities of SunPeek, the software was applied to data of one of the collector arrays. Due to pollution from the adjacent gas heating plant, an adjacent recycling center, and trees directly behind the array, the collector array is subject to considerable soiling especially in spring (as shown in Figure 4, top right) resulting in performance degradation. The aim of the analysis was to investigate the effects of a cleaning event that took place in Mid-June during the investigation period and whether the performance change can be identified using SunPeek.

Results: The results obtained with SunPeek are shown in Figure 4, depicting the measured-estimated ratio of the collector performance over time. Before the cleaning event, the datapoints show a slight downward trend, indicating the collector degradation due to the accumulating pollution. However, a drastic pattern change can be seen after the cleaning event in Mid-June. After that, the measured-estimated ratio of the collectors is drastically increased and stable, indicating that the performance of the collectors was restored.

Recommendations: In this example, the performance changes of the collector array could be well identified, as the filtering criteria of the ISO 24194 enable a stable comparison of measured and estimated performance and boundary conditions such as weather and operating temperatures are excluded from the evaluation. Hence, influences on the collector performance can be identified faster than compared to e.g. comparing solar yield and irradiation, which does not take different operating conditions into account. In addition, the ISO procedure also enables a clearer cost-benefit analysis of the cleaning, as the effect on the collector performance can be assessed more easily.

Figure 3. *Image of the solar district heating plant Fernheizwerk located in Graz, Austria, showing one part of the installed collectors. Source: SOLID.*

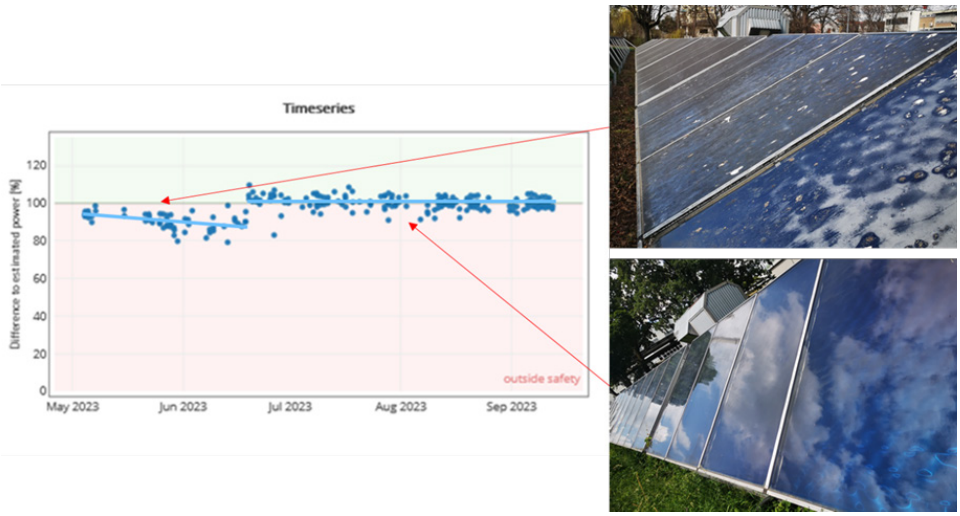


Figure 4. *Screenshot of SunPeek, illustrating the ratio of hourly measured to estimated performance values over time (left). A noticeable pattern shift can be seen around Mid-June 2023, due to cleaning the collectors. The right plot shows the collectors before (upper) and after the cleaning (lower part).*

4.2 Influence of stagnation periods

Background: The investigations were done in the scope of the project “Reduction of the heat price of large-scale solar thermal systems with heat pipe vacuum tube collectors” HP-BIG (reference number 03EN6011A-C).

Use Case: A solar thermal collector array with approximately 6 000 m² of vacuum tubes supplies a district heating network with a solar fraction of about 15% in Germany. Various causes (e.g., low summer heat demand, non-ideal load management with other suppliers in the grid) lead to significant stagnation days (almost 40 d in the whole year 2022). The period of consideration for the Power Check is based on approximately two months of summer 2022 in the first year after commissioning. The data show some downtime days, especially in June, which is the reason for beginning the SunPeek evaluation after that. The remaining downtime days were eliminated to obtain unbiased Power Check results. The measurement setup used does not allow a separation between direct and diffuse solar irradiance, so that the Power Check is carried out with global irradiance on the collector plane by using Formula (1) according to ISO 24194. The influence of wind speed was not considered, because no such sensors are available. Due to using vacuum tube collectors the influence of wind speed can be neglected. The Safety Factor was assumed by 90 %, which mainly includes heat losses as well as measurement uncertainties and represents the default settings in SunPeek.

Results: The evaluation of the summer period shows a significant influence by stagnation events on the SunPeek results, even after discarding downtimes. Figure 5 illustrates the results, whereby the valid intervals of SunPeek and their performance ratio were classified in these three categories: (a) data with downtimes (grey), (b) data without downtimes, influenced by stagnation (red) and (c) data without stagnation periods, means typical collector operation (blue). The flow rate in the collector circuit and the temperature (outlet) were used as criteria to identify stagnation events. Downtimes usually show a different temperature behavior and have been confirmed by the plant operator. As expected, the results for the typical collector operation without stagnation periods are around the 100 %-line (with acceptable deviations). The downtime periods do not have a thermal power output, the stagnation periods generate results between zero and the 100 %-line, depending on the individual stagnation event. For example, the identified power on the 14th of August is about 39 % of the estimated power.

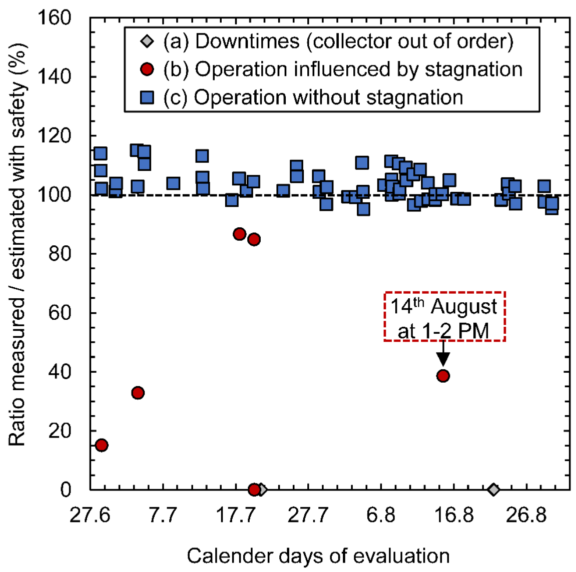


Figure 5. *Ratio of the measured versus estimated power in SunPeek for (a) data with downtimes as grey diamonds, (b) data without downtimes, influenced by stagnation as red circles and (c) data without stagnation periods (typical operation) as blue squares using one-hour intervals.*

Figure 6 shows the collector temperatures (outlet and return), flow rate and global irradiance for this day. The hour from 1-2 PM was affected by beginning stagnation and was recorded as a valid data interval. Table 2 shows the outputs of SunPeek for the three different categories of data selection. The Power Check is only fulfilled (reaching 100 %) if, in addition to downtimes, stagnation periods are also removed from the measurement data.

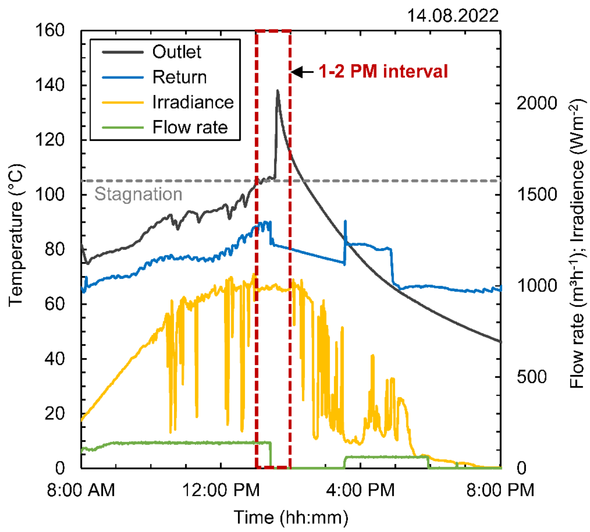


Figure 6. *Collector temperatures (outlet and return), flow rate and global irradiance for August 14th, 2022, with stagnation at the 1-2 PM interval.*

Table 2*. Power Check results for different data selection procedures.*

Used data	Ø Power (measured)	Ø Power (estimated)	Safety Factor	Ratio	Valid Intervals	Power Check
All data, with downtimes	398 W/m²	452 W/m²	90 %	88.1 %	77 h	not fulfilled
Data without downtimes	438 W/m²	449 W/m²	90 %	97.6 %	70 h	not fulfilled
Data without downtimes and stagnation	459 W/m²	446 W/m²	90 %	102.9 %	62 h	fulfilled

Recommendations: SunPeek is well suited for checking the collector array performance and enables an efficient identification of faulty operating scenarios or downtimes. Several stagnation events are automatically filtered out by SunPeek, because of the lack of conformity with the data filtering criteria according to ISO 24194. However, some stagnation events are included in SunPeek as hourly performance values and are difficult to identify, which results in reduced performance. The overall result can be influenced by stagnation events, especially regarding the question of whether the target value is fulfilled or not, as the example shows. In the future, higher solar thermal fractions in large-scale systems are expected, such that stagnation must be taken into account as a possible operating state in the Power Check evaluation. Therefore, it is recommended to implement this option also in the graphical user interface of SunPeek (this option is already available in the Python environment).

4.3 Multiple collector arrays

Background: The ISO standard 24194 is mainly targeted at plants with only one type of collector installed (ref chapter 2). However, there exist a vast number of plants that utilize more than one collector array, for example due to plant extensions, cost and risk optimization, optimization of efficiency by combining low temperature and high temperature collectors, or due to testing different collectors in a similar environment. Hence, SunPeek was designed to be applied on plants with multiple collector types as well.

Use Case: One example of a plant with multiple types of collectors is the district heating plant Mürzzuschlag in Styria, Austria. It was installed by SOLID Solar Energy Systems in 2020 and has been extended in 2023 due to its successful operation. In total, the plant spans 6850 m² of collector gross area, consisting of three different collector types (5290m² KBB K5Giga+, 814m² Gasokol PowerSol136, and 744m² ENSOL DIS 150 collectors). For quality assurance, heat meters are installed for the total collector field on the primary and secondary side, and additional heat meters are installed at two measurement lines at Gasokol and ENSOL as part of collector guarantees (see Figure 7).

Results: Figure 8 shows how the situation can be modelled using SunPeek, by using five different arrays. The first SunPeek Array comprises the KBB collectors (5290m²) which does not have a dedicated heat meter installed. However, temperature measurements for the array exist allowing to compute the estimated yield for the collector array. The second SunPeek Array models the Gasokol collectors which are directly measured by heat meter (81m²). As such, both a estimated and measured yield is available for this collector row. However, all other Gasokol collectors (734m²) are not directly measured via a heat meter and hence only estimated yield can be calculated. The same is true for the ENSOL collectors, which also was divided into a measured row (93m²) and the remaining part without dedicated heat meter measurements (651m²). Using SunPeek, this enables three different evaluations: First, it is possible to compare the measurement and estimations of only the Gasokol measured row (81m²). Second, the same can be done for the ENSOL measurement row (93m²). And finally, the total plant can be analyzed, by summing up the estimates from the individual collector types and comparing with the measured power of the heat meter for the total field. In every case, only 1-hour timestamps which are valid for all collector arrays were considered.

Recommendations: The example shows that SunPeek allows to intuitively evaluate the performance of plants with multiple collectors installed, and also enables analysis of single arrays as long as measurement data is available. Some limitations in the current SunPeek implementation (e.g., applying different formulas for different types of collectors) will hopefully be developed in the future.

***Figure 7**: Picture of district heating plant in Mürzzuschlag showing the different collector fields and the installed heat meters. Source:SOLID.*

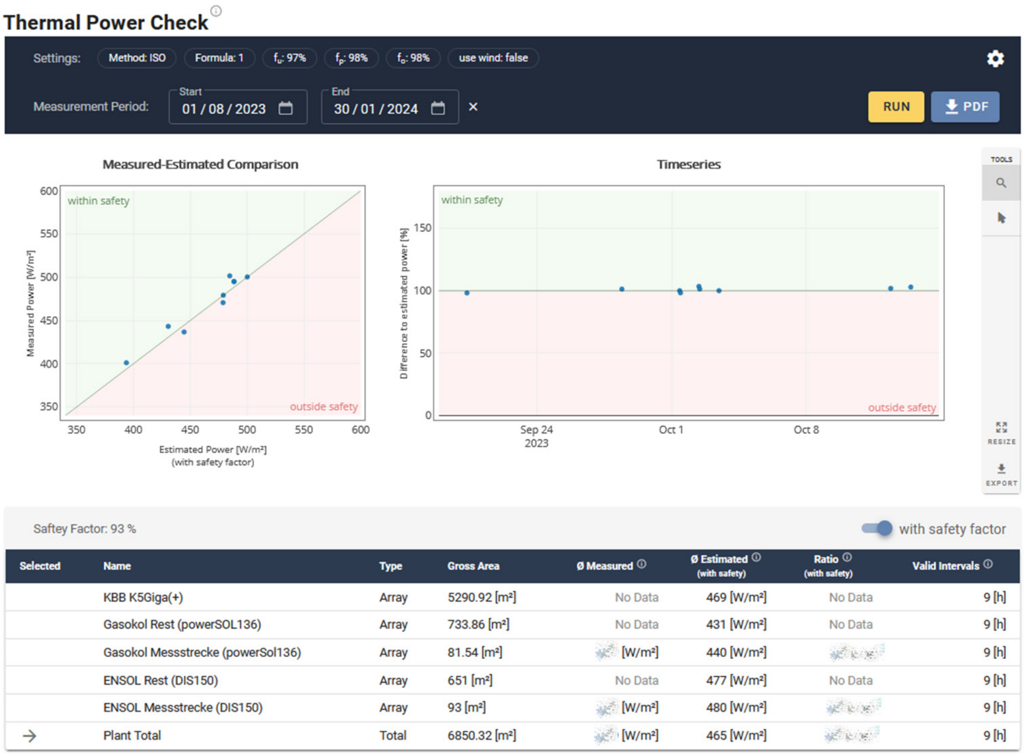


***Figure 8**. Screenshot of SunPeek depicting the results of ISO 24194 for Mürzzuschlag (measured results are anonymized). Using this setup, the Power Check can be applied for (i) the Gasocol measurement row, (ii) the ENSOL measurement row, and (iii) the total plant (currently selected).*

4.4 Checking collector vacuum integrity

Background: The utility company in the Geneva canton, known as Service Industriels de Genève (SIG), manages significant portfolios of District Heating Networks (DHN). The main DHN, the CADSIG, features an energy mix composed mainly by heat generated by a large Municipal Waste Incineration Plant (MWI) and a natural gas boiler. With a forward temperature fluctuating between 115°C (winter) and 90°C (summer) and a return temperature of 72°C +/- 2°C all year round, this DHN can be classified as a second generation DHN.

Switzerland-based company TVP Solar has pioneered the development of an efficient Evacuated Flat Plate collector (EFP), primarily designed for industrial process heat and DHN applications. This collector stands among the earliest commercially available EFPs. Notably, its efficiency surpasses that of alternative technologies when the temperature difference between ambient and solar collector exceeds 50K [12] and in case of low solar irradiance.

In 2019, SIG decided to assess the solar thermal technology as a source of renewable heat for their DHN portfolio in a pilot plan connected to the DHN CADSIG. Since this latter operates at relatively high temperatures, it was decided to use the TVP EFPC technology, able to maintain high conversion efficiency at these temperatures. The TVP collectors were integrated into an 800 m^2 solar thermal plant named SOLARCADII and the collected solar heat injected into the return pipe of the CADSIG DHN. This solar installation marked one of the pioneering uses of EFP technologies at this plant scale. Since its commissioning in January 2021, the solar thermal plant performances have been monitored in the framework of a collaboration agreement among SIG, TVP Solar and the HEIG-VD university, fostered by the Swiss Federal Office of Energy (SFOE) [13].

Use Case: In order to evaluate the solar thermal field performance compared to a single collector, monitoring data recorded in July 2022 were used to perform a power check with the SunPeek application. This evaluation holds a significant importance for this plant, given its utilization of a recently developed collector technology. Any compromise in the vacuum integrity of the collector could potentially lead to a substantial decrease in performance. Currently the collector vacuum integrity is checked with an infrared camera and by measuring surface temperature. This method is very efficient but time consuming.

Results: The graph below (Figure 9) compares the expected power calculated with SunPeek to the monitored thermal power. The analysis confirms that the efficiency of the solar field aligns closely with the Solar Keymark efficiency standards, incorporating a 0.9 safety margin. Notably, it appears that the integrity of the TVP vacuum has been maintained following a year of operational usage, as corroborated by on-site inspections utilizing an infrared (IR) camera and surface temperature measurements.

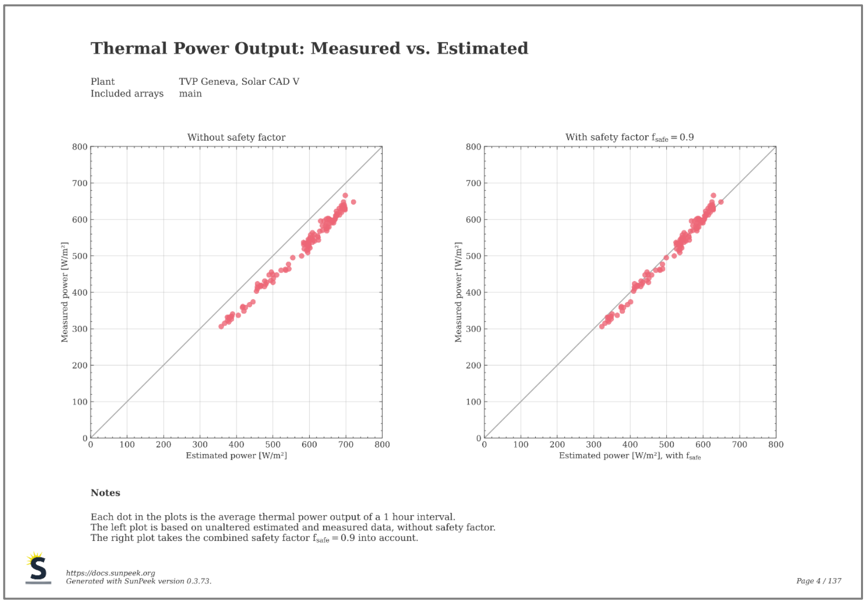


***Figure 9**. Results of the Power Check with SunPeek with data recorded in July 2021.*

Recommendations: SunPeek is well suited to detect collector vacuum integrity losses automatically. This method is easier and faster to implement than the onsite method. Nevertheless, the onsite method is more efficient to detect vacuum losses in a small number of collectors. For this new technology, both methods will be used in the near future to confirm the ability of the TVP collector to maintain vacuum over the years.

4.5 Extended Power Check Method

Background: The ISO 24194:2022 [3] Power Check method utilizes 1-hour averages of measurement values. The default method, as outlined in the ISO standard, requires intervals to start and end at full hours (e.g., 11:00, 12:00, 13:00, etc.), an approach that owes to practical constraints of spreadsheet-based data analysis. However, confining interval limits to full hours is not imperative for obtaining 1-hour averages and may not yield the most useful results. To address this limitation, an innovative implementation of the Power Check has been developed in SunPeek, referred to as the “Extended” method.

Just like the default Power Check method, also the Extended method employs 1-hour averages of measurement data, but without restricting interval limits to full hours. For example, with the Extended method, a 1-hour interval could span from 10:24 to 11:24. Importantly, the Extended method adheres to the same criteria as the default method for selecting and filtering measurement data. This ensures that all 1-hour intervals resulting from the Extended method meet all data requirements of ISO 24194:2022, such as the restrictions on operating conditions defined in Table 1 (chapter 5.4) of the ISO standard.

Implementation: SunPeek leverages state-of-the-art data analysis packages like pandas, which provide efficient solutions to overcome the full-hour limitation. The Extended method is implemented using a moving-window approach, powered by pandas "rolling" function. Figure 10 compares the different data averaging methods of the default and the Extended method. The moving-window averaging generates a set of "candidate" intervals that satisfy all data filtering criteria of the ISO 24194 Power Check. Therefore, a technique is required to select the best among all candidate intervals. To do so, SunPeek's Extended method implements a minimum-noise criterion for interval selection, i.e., a score calculated as minimum relative standard deviation of the thermal power. This implies that preference is given to intervals with steady thermal power output conditions. Once a candidate interval is selected, overlapping intervals are discarded from the candidate set (see Figure 10), and the next best interval is chosen. The source code of the Extended method[1], like all SunPeek, is publicly accessible.

In summary, the main methodological differences between the Extended and the default Power Check method are: 1) The Extended method employs a moving-window resampling instead of fixed-hour resampling. As a result, the 1-hour data intervals used for the Power Check analysis are not restricted to full hours. 2) The Extended method uses a minimum-noise criterion to select among overlapping interval candidates.

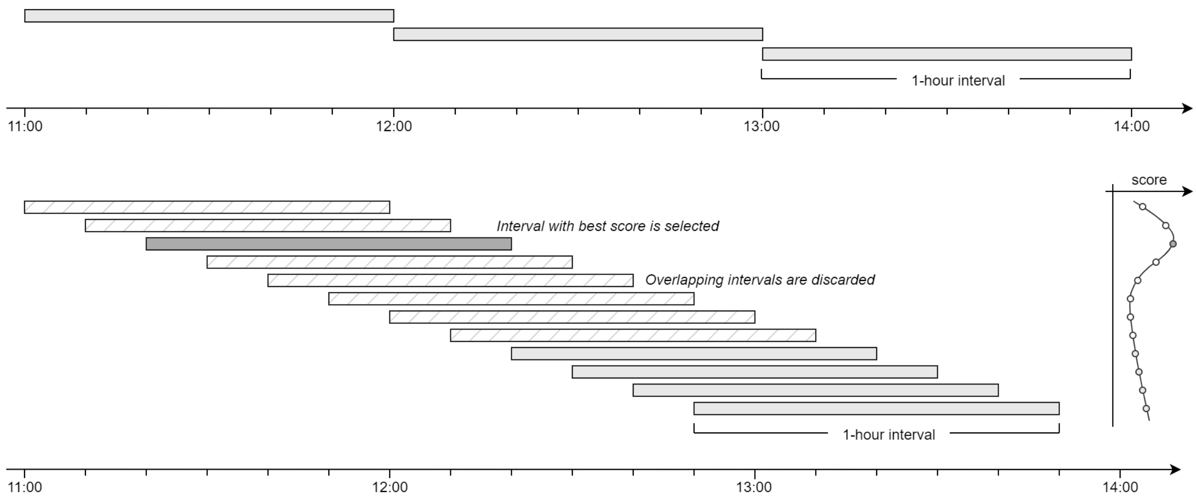


***Figure 10**. Comparison of the averaging methods in the two SunPeek ISO 24194:2022 Power Check implementations: The default method (top) is limited to intervals confined by full hours. The Extended method (bottom) is based moving-window resampling and selects intervals based on a score metric.*

Results: Based on the "Fernheizwerk" open dataset [9], a numerical comparison between the default and the Extended methods has been conducted. Table 3 provides an overview of the results obtained from applying both methods to one month of measurement data (May 2017). As illustrated in Figure 11 (a) and (b), both methods yield nearly identical overall scores (power ratio 104.9% vs 104.8%). However, the Extended method identifies more intervals (64 vs 47), thereby reducing the time required to achieve 20 intervals (as mandated by ISO 24194:2022 chapter 5.9 for a valid Power Check). This suggests that in real-world applications, the Extended method will be quicker in producing a valid check. Figure 11 (c) and (d) depict the distribution of the 1-hour intervals identified by Extended and default method. For a specific day (2017-05-02), Table 4 compares the interval limits identified by the two methods.

[1] https://gitlab.com/sunpeek/sunpeek/-/blob/main/sunpeek/core_methods/pc_method/main.py

***Table 3**. Comparison of numerical results of default and Extended Power Check methods. This analysis is based on data from May 2017, using the "Fernheizwerk" open dataset [9].*

	Default method	**Extended method**
Ratio of measured / estimated power (averaged over all intervals, including a 90% safety factor)	104.9%	104.8%
Number of intervals found	47	64 (+36%)
Measured power range of the 1-hour intervals	374 to 580 W/m²	340 to 605 W/m²
Number of days to find 20 intervals	19	12

***Table 4**. Comparison of the Power Check intervals found with default and Extended methods. Note the different number of intervals and the Extended method intervals not being limited by full hours.*

Interval number	**Default method**	**Extended method**
1	2017-05-02 10:00 - 11:00	2017-05-02 08:41 - 09:41
2		2017-05-02 10:09 - 11:09
3		2017-05-02 11:17 - 12:17
4		2017-05-02 13:47 - 14:47

(a) Default method: summary

(b) Extended method: summary

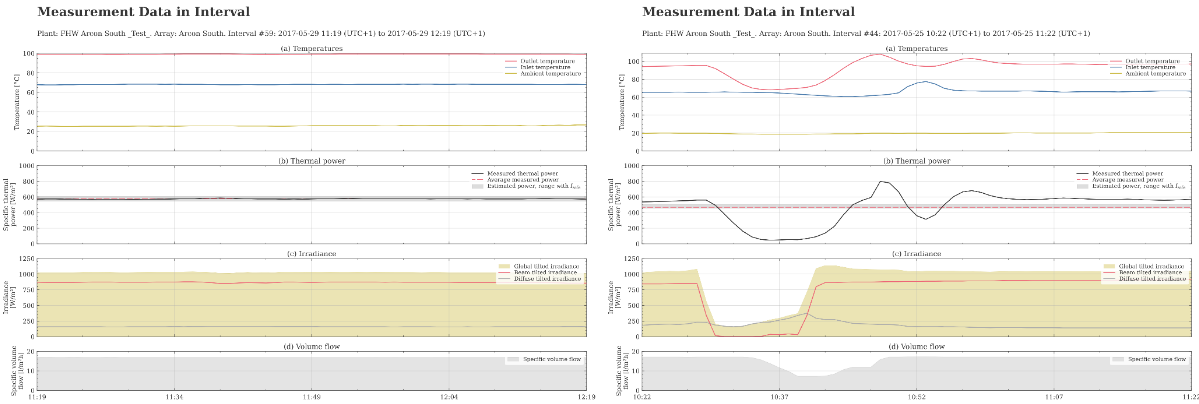
(c) Default method: intervals

(d) Extended method: intervals

***Figure 11**. Comparison of selected ISO 24194 Power Check outputs for the default and Extended methods, for May 2017. Figures (a) and (b) show a summary page of the pdf report; figures (c) and (d) show the distribution of intervals over time. Analysis based on the "Fernheizwerk" open dataset [9].*

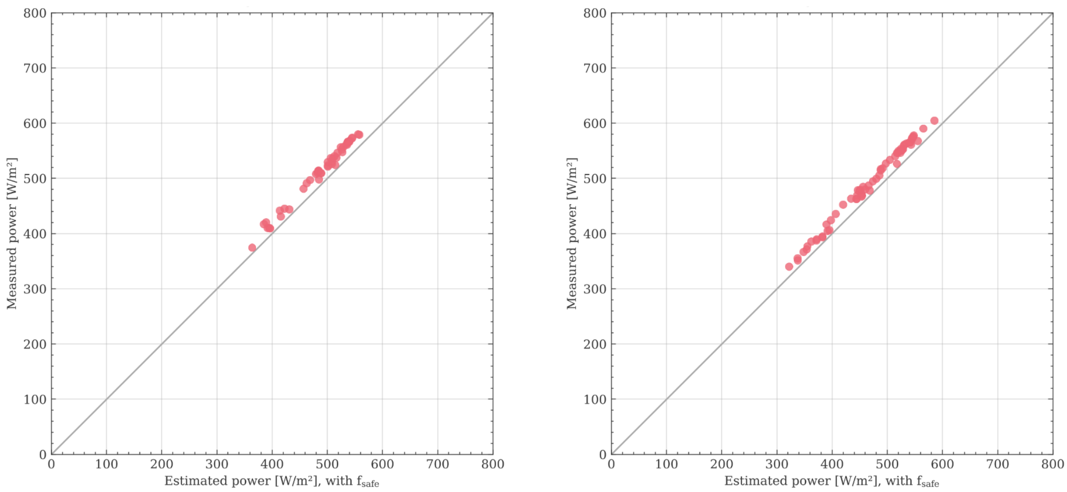
Figure 12 demonstrates the effect of the Extended method's interval scoring: The highest-scoring interval (a) has one hour of nearly perfect steady-state operating conditions, while thermal power in the lowest-scoring interval (b) shows considerable variability. Overall, the Extended method covers a broader power range, with the lowest interval starting already at 340 W/m² (vs 374 W/m² for the default method) and the highest value reaching 605 W/m² (vs 580 W/m²), as depicted in Figure 13. These results suggest that while producing a comparable overall score, the Extended method yields numerically broader results that better represent a plant's operating conditions in a given time range.

Recommendations: The Extended Power Check method has been applied to several solar thermal plants, and the results have been compared to those of the default method. These experiences suggest that the Extended method tends to produce more intervals, while the main Power Check KPI, the ratio of measured vs estimated power, remains comparable. The Extended method provides a more flexible Power Check implementation, covering a wider range of operating conditions, contributing to somewhat more insightful results. The authors are looking forward to discussing these findings within the community and consider the Extended Power Check method for future revisions of the ISO 24194:2022.



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

***Figure 12**. Highest scoring interval (a) and lowest scoring interval (b) selected by the Extended method, for May 2017. Analysis based on the "Fernheizwerk" open dataset [9].*



(a) Default method *(f) Extended method*

***Figure 13**. ISO 24194 Power Check results comparing measured and estimated 1-hourly averages for default and Extended method, for May 2017. Analysis based on the "Fernheizwerk" open dataset [9].*

5. Discussion and Outlook

ISO 24194 is likely to play a key role for large-scale solar thermal plants in the foreseeable future. First applications of SunPeek indicate a good usability and practical use, e.g. to evaluate soiling effects or identify stagnation events. The software has been found to ensure reproducibility of results and show a high potential to become the industry-wide reference for ISO 24194 based performance monitoring.

To further enhance the applicability of the ISO standard, methodological developments, applications to more use cases, and extensions of the SunPeek functionality should go hand in hand and foster each other. The “Guide to ISO 24194:2022” which is currently developed within IEA SHC Task 68 will offer advice on how to apply the method, and bundle experiences and requirements of the community to be considered in future revisions of the standard.

A future goal is for SunPeek to become a versatile platform, integrating more sophisticated methodologies like energy yield checks or advanced irradiance conversions between differently aligned arrays. Options include possible extensions to related technologies like photovoltaic thermal hybrid solar collector fields (PVT) or including methods towards predictive maintenance. More research is required to implement these methods, compare their advantages and disadvantages, and assess their practical applicability. As a community developed tool, SunPeek invites stakeholders to download and use the software, define SunPeek’s roadmap, contribute algorithms and code, share open-access data, and take part in the steering committee.

Data availability statement

The data from the demo collector array “Arcon South” of the “Fernheizwerk” plant is described in a journal article [8] and is freely available under a CC BY-SA 4.0 license on Zenodo [14]. A GitLab repository intended to facilitate maintenance of the associated Python code is provided along with the data [15]. Additional plant data used in this article is not publicly available.

Author contributions

Daniel Tschopp & Philip Ohnewein – Conceptualization, Data curation, Formal analysis, Software, Validation, Writing – original draft, Writing – review & editing; Marnoch Hamilton-Jones, Peter Zauner, Lukas Feierl, Maria Moser, Michael Zellinger, Christian Kloibhofer, Martin Koren, Stefan Mehnert, Alexis Duret, Xavier Jobard, Stefano Pauletta, Federico Giovannetti & Bert Schiebler – Data curation, Formal analysis, Software, Validation, Writing – review & editing.

Competing interests

The authors declare that they have no competing interests.

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Appendix

The calculation procedure for the Incidence Angle Modifier (IAM) for hemispherical solar radiation, K_{hem}, is summarized in Table 5. Please note that the conversion from SST to QDT parameters follows ISO 9806:2017, whereas the conversion from QDT to SST parameters "interprets" the standard.

***Table 5**. Parameter conversion from QDT to SST and SST to QDT test procedures.*

Initial test procedure; equations	**Source**
QDT (Quasi-dynamic test)	
Given parameter: $\eta_{0,b}, K_b, K_d$	
Derived parameter: $\eta_{0,hem}, K_{hem}$	
$\eta_{0,hem} = \eta_{0,b}(0.85 + 0.15\,K_d)$	ISO 9806:2017 Annex B, Formula (B.2), (B.5)
$K_{hem}(\theta_L,\theta_T) = \frac{\eta_{0,b}}{\eta_{0,hem}}(0.85K_b\,(\theta_L,\theta_T) + 0.15\,K_d)$	Derived from ISO 9806:2017 Annex B, Formula (B.2), (B.5)
SST (Steady-state test)	
Given parameter: $\eta_{0,hem}, K_{hem}$	
Derived parameter: $K_b, K_d, \eta_{0,b}$	
$K_b(\theta_L,\theta_T) = K_{hem}(\theta_L,\theta_T)$	ISO 9806:2017 Annex B, Formula (B.1)
$K_d = \frac{1}{W}\sum_{\theta,\gamma=0^o}^{90^o} K_b(\theta,\gamma)\,sin(\theta)\,cos(\gamma)$ $W = \sum_{\theta,\gamma=0^o;\ steps=10^o}^{90^o} sin(\theta)\,cos(\gamma)$	ISO 9806:2017 Annex B, Formula (B.3), (B.4)
$\eta_{0,b} = \frac{\eta_{0,hem}}{0.85 + 0.15\,K_d}$	ISO 9806:2017 Annex B, Formula (B.5)

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