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# Improved in situ performance testing of line-concentrating solar collectors: Comprehensive uncertainty analysis for the selection of measurement instrumentation

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## HIGHLIGHTS

- Guideline for the proper selection of measurement instrumentation is presented.
- Results assure representative performance testing of concentrating collectors.
- Detailed methodology is proposed and applied to exemplary uncertainty case study.
- Complete range of different collector types and operating conditions is studied.
- One relevant gap of current testing standard for line-concentrating collectors is closed.

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## ABSTRACT

Accurate and complete performance evaluation is playing a major role in the further development of concentrating solar collectors. To ensure dependable test results, an appropriate testing and evaluation procedure is required. Moreover, the selection and installation of suitable measurement instrumentation are essential for obtaining reliable data for the performance evaluation. The quality of the measurement instrumentation greatly influences the representativeness of the test results. Details on the measurement instrumentation recommended for the testing of low-temperature solar collectors have already been provided in the testing standard EN ISO 9806:2013. Due to the larger dimensions of concentrating collectors and thus different working temperatures and mass flow rates, these recommendations cannot be directly applied for the testing of concentrating solar collectors. A good selection of measurement instrumentation will always be a trade-off between feasibility, cost of the instrumentation and its associated uncertainties. For this reason, it is crucial for every testing and certification institution to assess the quality of measurement data during the instrumentation selection process. Until now, this aspect has been sparsely addressed in the relevant literature concerning collector testing procedures. However, uncertainty examinations have become particularly relevant for in situ testing, in which the choice of measurement instrumentation has to be adapted to the specific measurement situation on-site. In situ testing is considered to be particularly beneficial (if not even indispensable) for concentrating collectors in terms of cost effectiveness and feasibility.

With the objective of simplifying the selection of measurement instrumentation, we present an elaborate methodology and comprehensive case study concerning the uncertainty calculation of line-concentrating solar collectors. The assessment of the suitability of measurement instrumentation is conducted based on two operational reference cases. These cases adequately cover the complete range of collector types and operating conditions typically involved in the field of line-concentrating solar collectors. The analysis is designed such that the results are also transferable to other testing situations, which are not specifically studied within this publication. The presented systematic uncertainty case study thus serves as a guideline for the selection of appropriate measurement instrumentation, providing useful indications for every testing and certification entity dedicated to the planning and execution of significant and reliable collector performance testing. The associated risk decrease of performance testing is essential for the further development and economic aspects of concentrating solar technology.



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**Nomenclature**

| | |
|---|---|
| $A_{Ap}$ | collector aperture area ($m^2$) |
| $c_p$ | specific heat capacity ($kJ\,kg^{-1}\,K^{-1}$) |
| $\Delta T$ | temperature difference (K) |
| $\eta$ | collector efficiency (–) |
| $G_b$ | direct normal irradiance ($W\,m^{-2}$) |
| $k$ | coverage factor |
| $k_c$ | normally distributed random variable representing the uncertainty of the heat capacity $c_p(T_m)$ |
| $k_\rho$ | normally distributed random variable representing the uncertainty of the fluid density $\rho(T_m)$ |
| $\dot{m}$ | mass flow rate ($kg\,s^{-1}$) |
| $Q$ | collector output power (W) |
| $\rho$ | fluid density ($kg\,m^{-3}$) |
| $T$ | temperature (°C) |
| $T_m$ | mean fluid temperature (°C) |
| $U(X)$ | overall/expanded standard uncertainty of measurand $X$ |
| $u(X)$ | standard uncertainty of a measurand $X$ |
| $U_c(Y)$ | overall/expanded combined uncertainty of an objective function $Y$ |
| $u_c(Y)$ | combined standard uncertainty of an objective function $Y$ |
| $\dot{V}$ | volume flow rate ($m^3\,s^{-1}$) |
| $v$ | fluid velocity ($m\,s^{-1}$) |
| $X$ | measurand (random variable) |
| $Y$ | calculated measurand (random variable) depending on measurands $X_i$ |
| $y$ | estimate of measurand $Y$, result of a measurement |
| COP21 | United Nations Framework Convention on Climate Change, 21st Conference of the Parties |
| DNI | Direct Normal Irradiance |
| GUM | Guide to the Expression of Uncertainty in Measurement |
| LFC | Linear Fresnel Collector |
| PTC | Parabolic Trough Collector |
| RMS | Root Mean Square |
| pts | points |

## 1. Introduction

To meet the current EU and national targets of limiting global warming and mitigating climate change according to the Paris Agreement of the UN Climate Conference (COP21), renewable energy resources will play an important role in the world's future energy mix. Due to its dispatchability in power generation and increased energy efficiency in industrial process heat, concentrating solar thermal energy is able to strongly contribute to the reduction of global $CO_2$ emissions [1]. To legitimize investments within this sector, it is crucial to be able to reliably compare different alternatives for heat and power generation. This is only guaranteed by a viable and dependable testing of the systems in question to ensure a realistic performance prediction. Adequate testing becomes additionally relevant for the commissioning phase of newly constructed commercial systems. To this end, installed measurement instrumentation and its uncertainties represent important aspects, which are often neglected compared to other more apparent factors such as data evaluation procedures and test planning. Thus, the deliberate selection of measurement instrumentation will be specifically addressed within this publication, which has not previously been studied to this wide of an extent.

### 1.1. Motivation

A thorough testing procedure lays the foundation for a significant and comparable determination of the performance parameters of concentrating solar collectors. Representative performance parameters, such as optical efficiency and heat loss coefficients, are essential for the further development of concentrating solar collectors because they provide both indicators for meaningful comparisons between collectors and the means for performing a cost-benefit analysis of design improvements. Due to their dimensions, line-concentrating collectors can hardly be tested in laboratories and are rather tested outdoors. Larger modules, collector loops, and complete solar fields are preferentially and more appropriately tested at the production site of the manufacturer or at the final installation site of the end user, requiring in situ measurements.

Due to the absence of a laboratory facility for in situ testing, the operating conditions of the collector under test cannot be controlled because heat dissipating capacities are generally not available. This situation may require a more flexible evaluation of measurement data. Several research institutes and companies are currently investigating adequate testing and evaluation methods for line-concentrating collectors, pursuing different approaches of steady-state testing [2], quasi-dynamic testing [3] or dynamic testing [4,5]. A review on current testing procedures has jointly been published by experts within this working field (for an overview and details on the testing procedures, see Hofer et al. [6]), revealing a lack of standardized, flexible and applicable testing procedures for concentrating solar collectors. Therefore, national and international standardization efforts (ISO TC 180, IEC TC 117, and AENOR) are being devoted to make performance evaluation for line-concentrating collectors more comparable and reliable, which are considered to substantially contribute to the further development and market penetration of this emerging technology.

Moreover, the lack of laboratory conditions during in situ measurements does not permit the use of standardly installed laboratory instrumentation. The sensors have to be selected according to the testing situation on-site. Differences in heat transfer media, fluid temperatures and mass flow rates should be considered for the selection of appropriate instrumentation. Additionally, specific access to the hydraulic circuit, as well as the piping material and geometry, influences the choice of suitable sensors.

The performance parameters of a collector determined from thermal measurements can only be as good as the quality of the measurement data (i.e., of the installed measurement instrumentation). The performance of a collector is recorded via measurements of, e.g., inlet and outlet temperatures of the collector, mass flow rate and ambient conditions such as direct solar irradiance and ambient temperature. The error of the test results depends on the error propagation law on the error (i.e., uncertainties) of every measurement instrument installed. Measurement instrumentation and its associated uncertainties therefore greatly influence the representativeness of the test results.

For low-temperature collectors (such as flat plate or vacuum tube collectors) tested in an indoor or outdoor laboratory (with heating and cooling capacities), recommendations for appropriate measurement instrumentation are elaborately provided in the relevant testing standard EN ISO 9806:2013 [7]. An assessment of the quality of the measurement data (i.e., of the representativeness of