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Confidence interval computation method for dynamic performance evaluations of solar thermal collectors

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ABSTRACT

For the further development and dissemination of solar thermal technology, a continuous demonstration of its reliability is required. For this purpose, meaningful performance and acceptance testing is indispensable. The reliable determination of optical and thermal collector performance parameters involves a suitable testing and evaluation procedure. It additionally requires a dependable quality assessment of the test results. Sophisticated statistical inference calculations, however, are not commonly available in solar thermal collector testing. If applied at all, mostly standardly implemented (linear) confidence interval computations are used.

The present publication proposes an advanced approach of confidence level computation, the so-called bootstrapping technique. It represents a common method in the area of economics and is suited to cope with the complexity of confidence calculations within the context of dynamic performance testing. The basic methodology and specific implementation of the bootstrapping approach are introduced in detail. Since this approach is new in performance evaluation procedures, it is validated with confidence results obtained from an extensive evaluation of a large measurement data basis of a linear Fresnel process heat collector. However, the procedure is equally suited for other collector types as parabolic trough, flat plate, and others. The validation with measurement data reveals the valuable capabilities of the bootstrap procedure. It moreover proves the standard confidence methods to fail, because these provide unrealistically narrow confidence intervals. Comparative results between the different methods are thoroughly discussed. They demonstrate the introduced bootstrapping approach to be a powerful tool, generating considerably more representative and therefore reliable confidence intervals than the customary methods. Consequently, bootstrapping is considered a key feature of an enhanced performance evaluation method, since it may provide improved information concerning parameter distribution, confidence levels, and hence the validity of corresponding test results. Meaningful performance testing represents an essential aspect to further increase the viability and reliability of the solar thermal technology in order to facilitate its easier commissioning and wide acceptance.

1. Introduction

Reliable performance and acceptance testing is considered essential in order to further develop and disseminate concentrating solar thermal technologies. They will play an important role in the future renewable energy mix due to their storage capacities and dispatchability in power generation as well as improved energy efficiency in industrial processes. Performance testing of solar collectors is particularly crucial in the context of certification purposes, since it allows for standardized performance assessments. This enables a proper commissioning of solar fields as well as significant comparisons of different solar collector manufacturers and technologies. Moreover, dependable performance evaluations allow for assessing design improvements in order to increase collector efficiencies and reduce system costs.

A review of solar collector evaluation methods with particular focus on the concentrating solar technology was compiled in Hofer et al. (2016). It revealed an increased popularity and wide application of the quasi-dynamic testing methods according to the current testing standard ISO 9806 (2017). It also showed that for larger systems under test, more advanced evaluation methods with higher flexibility of operating conditions are essential. This flexibility is given by the alternative evaluation approach of a fully dynamic testing approach as introduced by Janotte (2012) or Hofer et al. (2015). It was proven to be an adequate and practical performance test method particularly beneficial for

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Nomenclature

A_{Ap}	aperture area/m^2
C	covariance matrix
CI	confidence interval value
G_{bn}	direct normal irradiance DNI/W/m^2
HL_{100}	reference heat loss value at 100 K fluid temperature difference/W/m
J	Jacobian matrix
K_T/K_L	transversal/longitudinal IAM/–
R	number of bootstrapping replicates/–
S	objective function of optimization procedure/–
T	temperature/°C
X	measurement data matrix
α	percentile
b	block length/–
$\eta_{opt,0}$	optical efficiency at normal incidence/–
e_i	ith normalized bootstrap residual/–
f_{soil}	mirror soiling value/–
$\dot{m}$	mass flow rate/kg/s
n	number of data points/–
p	number of parameters/–
p	pressure/bar
r_i	ith bootstrap residual/–
σ	standard deviation
θ	parameter vector
θ_i	solar incidence angle/°
$\hat{\theta}$	best-fit parameter vector
$\hat{\theta}^*$	bootstrapping best-fit parameter distribution
u_0/u_1	heat loss coefficients
y	objective variable, e.g., T_{out}
y^*	bootstrap replicate of objective variable
BL	Block Length
BS	Bootstrapping
CI	Confidence Interval
DNI	Direct Normal Irradiance
DT	Dynamic Testing
FTC	Flat Plate Collector
IAM	Incidence Angle Modifier
ISE	Institute for Solar Energy Systems
LFC	Linear Fresnel Collector
PTC	Parabolic Trough Collector
QDT	Quasi-Dynamic Testing
RSS	Random Sub-Sampling
iid	identically and independently distributed

larger systems under test, such as installations with line-concentrating solar collectors or complete solar fields of concentrating and non-concentrating collectors (flat plate collectors or others).

Yet, comprehensive performance testing does not only require the availability of a suitable evaluation procedure to be able to determine the performance parameters of a collector. An equally important element for meaningful performance testing represents the quality assessment of the determined parameters with respect to the confidence levels of the test results. It facilitates statements concerning how precise (with how much dispersion) and how accurate (with how much bias) the performance parameters were determined. This dispersion is caused by several uncertainty factors, such as sensor measurement uncertainty, parameter covariance, mirror soiling, tracking inaccuracies, and mirror torsion. These performance uncertainty effects cannot be prevented in collector tests (especially in the case of in situ testing), but need to be considered while reporting meaningful test results. For this reason, derived performance parameters of a thermal test campaign never comprise only one individual value. They rather (and more appropriately) need to be described by an absolute value including a probability distribution instead. These uncertainty bands are commonly reported by means of confidence intervals, which allow to evaluate how much confidence to place in the performance results of the collector testing.

In common thermal collector tests, however, confidence calculations are seldomly addressed. If stated at all, confidence intervals of test results and their computations are given less importance and mostly standard methods are used (see, e.g., ISO 9806, 2017, pp. 113–114). In most cases, these standard confidence methods are based on simple linear-approximation approaches. Particular effects of fitting dynamic time-series data including non-linear simulation models and uncertainty factors such as mirror soiling, tracking errors, and parameter covariance are not considered. As a consequence, for the complex case of dynamic performance testing, the standard confidence methods show limited capacities, since they generate too narrow confidence intervals. With unrealistically narrow confidence results, the reliability of the test results is overestimated, rising the risk of misinterpretation.

For this reason, an alternative approach for the confidence interval computation is proposed in the following. The so-called ‘bootstrapping’ method is particularly used for statistical inference computations in the area of economics (Li and Maddala, 1996, p. 116), and it is consistently gaining popularity in other fields of application as well. Since it is not based on vast simplifications as standard, linear confidence methods, it is able to cope with the complexity given by dynamic performance evaluations. In order to prove its suitability, the introduced bootstrapping procedure for thermal collector tests is validated with real measurement data. Corresponding results reveal the bootstrapping confidence intervals to provide a much more realistic assessment of the test results in comparison to standard methods. On this account, it is considered a powerful tool to reliably and representatively assess and report test results.

Accordingly, the present publication is structured as follows: the basics of performance evaluation methods—in particular of the dynamic testing procedure—are given in Section 2. The fundamental theory and basic approach of standard and alternative confidence interval methods are derived in Section 3. This chapter furthermore explains an empirical approach of validating the proposed bootstrapping technique. Consequently, Section 4 outlines the specifically implemented bootstrapping procedure with its adaptation to the dynamic evaluation procedure of solar thermal collectors. In Section 5 the proposed procedure is verified to real measurement data of a small-scale linear Fresnel process heat collector. The large measurement campaign at this test collector provides a vast measurement data basis, which is necessary in order to validate the newly introduced bootstrapping approach. The implemented methodology for bootstrapping computations is applicable to solar thermal collector testing in general and was already successfully performed for diverse collector tests including different-scale parabolic trough and linear Fresnel collectors. The optical particularities in terms of a two-dimensional incidence angle modifier contribute to the fact that Linear Fresnel Collectors (LFCs) are significantly more challenging to evaluate than other collectors, such as Parabolic Trough Collectors (PTCs) or Flat Plate Collectors (FPCs). For this reason, the new methodology is introduced and verified by means of the most complex case of performance evaluation with an LFC as a reference test collector. This approach allows to demonstrate the overall capabilities of the introduced bootstrapping method, since the suitability for meaningful evaluations of LFCs implies a reliable application to simpler test systems, such as PTCs and other collectors. Finally, overall conclusions concerning confidence interval calculations and an outlook are given in Section 6.