TECHNICAL
COOPERATION

Expert Report

Expert Report

Quality Infrastructure for Energy Efficiency and Renewable Energy in Latin America and the Caribbean
95309

Technical Cooperation with **Solar und Wärmetechnik Stuttgart**
Country | region: Latin America and the Caribbean
Objective: Support for an evaluation of an inter-laboratory comparison test
City | country: Stuttgart/Germany and Cuernavaca /Mexico
Duration: 11 July 2017 – 31 December 2019

Reporter: Stephan Fischer
Function: External Expert / 4500108714
Date: 05.03.2020

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Abbreviations | Explanation of terms used

ICE	Instituto Costarricense de Energía
IEC	International Electrotechnical Commission
INTI	Instituto Nacional de Tecnología Industrial
IPT	Instituto de Pesquisas Tecnológicas
ISFH	Institut für Solarenergieforschung in Hameln
ISO	International Standardisation Organisation
LES	Laboratorio de Energía Solar
PTB	Physikalisch-Technische Bundesanstalt
SWT	Solar und Wärmetechnik Stuttgart
UNAM	Universidad Nacional Autónoma de México

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1. Introduction

In 2017 - 2019, Solar und Wärmetechnik Stuttgart (SWT) supported an inter-laboratory comparison test for solar thermal collectors which was organized in the framework of the PTB Projekt “Quality Infrastructure for Energy Efficiency and Renewable Energy in Latin America and the Caribbean”. 5 laboratories from Latin America participated in this inter-laboratory comparison.

The support was given in four different fields:

1. Test protocol and report sheets: A test protocol and a corresponding report sheet was elaborated and discussed with the participants and representatives of PTB. After the discussion and some iterations, the test protocol and report sheet were finalised and distributed.
2. Test samples: Suitable solar thermal collectors were identified and offers were organised from different manufacturers
3. Evaluation of test results of reference laboratory: The test results of the reference laboratory which tested all solar thermal collectors before the shipment were assessed.
4. Evaluation of the final results: The final results for the participants were assessed.

This inter-laboratory test was planned, carried out, assessed and documented in this report on the basis of ISO/IEC 17043 “Conformity assessment – General requirements for proficiency testing” [1] by Solar und Wärmetechnik Stuttgart. The purpose of this report is the presentation of results and performance of the participants.

2. Program

2.1 Test procedure

The tests should be performed according to ISO 9806 [2]. Complete test protocol is listed in Annex 7.1. A collector from GREENoneTEC was purchased by PTB and used. The collectors were send to the laboratories in 2019, the test period was approximately 6 months.
Solar und Wärmetechnik Stuttgart main part was to support the test, to collect the data and evaluate and asses them.

2.2 Participants

The inter-laboratory comparison test was exclusively done for the participants of the PTB Projekt “Quality Infrastructure for Energy Efficiency and Renewable Energy in Latin America and the Caribbean” (see table 1).

Table 1: Participants of the inter-laboratory comparison test

Participant	Country	Test method used
Instituto Costarricense de Energía (ICE)	Costa Rica	Steady state test indoor (ssti)
Universidad Nacional Autónoma de México (UNAM)	Mexico	Steady state test indoor (ssti) + outdoor (ssto)
Instituto Nacional de Tecnología Industrial (INTI)	Argentina	Steady state test outdoor (ssto)
Laboratorio de Energía Solar (LES)	Uruguay	Steady state test outdoor (ssto) + quasi-dynamic testing outdoor (qdto)
Instituto de Pesquisas Tecnológicas (IPT)	Brazil	Steady state test indoor (ssti)

2.3 Homogeneity Testing

To check for the homogeneity of the purchased collectors all collectors have been tested by the Institut für Solarenergieforschung in Hameln (ISFH), Germany before they were sent to the participants. The homogeneity testing showed a good homogeneity of the test samples and qualified the test samples for the inter-comparison test.

3. Statistical design

The statistical design is based on ISO 13528 [3] and ISO/IEC 17043 [1]. The deviation of laboratory's mean MW_{LAB} value from the assigned value X was evaluated

3.1 Determination of assigned value

The assigned value X is determined as a consensus value of the results of all participating laboratories. It is calculated as a robust mean value. For each test parameter an assigned value was calculated. The respective assigned value X is the median of all laboratories results MW_{LAB}.

The normalised interquartile range (nIQR) is used as standard deviation for the proficiency assessment σ(nIQR):

$$nIQR = 0{,}7413\ (Q3\text{-}Q1) \qquad (1)$$

75 % of all values are lower than Q3, 25 % of all values are lower than Q1. (Q3-Q1) is called interquartile range (IQR). The factor 0,7413 derives from the standard normal distribution, which has a mean of zero and a standard deviation equal to one. The width of the interquartile range of such a distribution is 1,34898 and results to 1/1,34898 = 0,7413. Multiplying IQR by this factor makes it comparable to a standard deviation [4].

The results of this proficiency test are assessed with the help of a Z-score that is calculated for each laboratory and each test parameter according to equation (2):

$$Z = (MW_{LAB} – X)/ \sigma \quad (2)$$

According to ISO/IEC 17043 the following judgements will be made:

- $|Z| \leq 2$ satisfactory participated
- $|Z| \geq 3$ unsatisfactory participated
- $2 < |Z| < 3$ result questionable.

Table 2 gives a review of the respective assigned values X and the standard deviations for proficiency assessment σ that were used in equation (2) of each element.

For a better view the results are rounded to the last digit.

Table 2: Compilation of assigned values X and standard deviations of proficiency test σ

Parameter	**X**	σ	**Z = - 3**	**Z = -2**	**Z = 2**	**Z = 3**
Gross area [m²]	2.02	0.01	2.00	2.01	2.03	2.04
$\eta_{0,hem}$ [-]	0.729	0.009	0.701	0.710	0.748	0.757
a(50K) [W/(m²K)]	4.360	0.251	3.608	3.859	4.861	5.112
K_d [-]	0.91	0.02	0.84	0.87	0.95	0.98
0°K* (1000 W/m²) [W]	1462	55	1296	1351	1572	1627
20°K* (1000 W/m²) [W]	1297	55	1131	1187	1407	1462
40°K* (1000 W/m²) [W]	1111	66	913	979	1243	1308

60°K* (1000 W/m²) [W]	903	78	669	747	1059	1137
0°K** (700 W/m²) [W]	1013	53	855	907	1119	1171
20°K** (700 W/m²) [W]	848	50	699	749	947	997
40°K** (700 W/m²) [W]	662	59	483	543	781	840
60°K** (700 W/m²) [W]	454	82	207	289	619	702
0°K*** (400 W) [W]	572	46	432	479	665	711
20°K*** (400 W) [W]	404	45	270	315	494	538
40°K*** (400 W) [W]	214	55	50	105	323	378
60°K*** (400 W) [W]	8	70	-203	-133	149	219
$K_b(20°)$ [-]	1.00	0.01	0.98	0.99	1.01	1.02
$K_b(30°)$ [-]	0.99	0.01	0.973	0.979	1.001	1.007
$K_b(40°)$ [-]	0.97	0.01	0.95	0.96	0.98	0.99
$K_b(50°)$ [-]	0.95	0.02	0.894	0.913	0.987	1.006
$K_b(60°)$ [-]	0.91	0.02	0.84	0.86	0.96	0.98
T_{stag} [°C]	200	2	193	196	204	207

*Power output at 1000 W/m² (G_b = 850 W/m², G_d = 150 W/m²) for dT = xx K

**Power output at 700 W/m² (G_b = 440 W/m², G_d = 260 W/m²) for dT = xx K

***Power output at 1000 W/m² (G_b = 400 W/m², G_d = 0 W/m²) for dT = xx K

4. Results

The results of this proficiency test are summarized in Table 3 and graphically presented in appendix 7.2. In Table analysis with questionable or unsatisfactory results are summarised.

Table 3: Summary of results

Parameter	**Number of results**	**Number |Z| <= 3**	**Number 2<|Z|<3**
Gross area [m²]	8	0	0
$\eta_{0,hem}$ [-]	8	0	0
a(50K) [W/(m²K)]	8	0	0
K_d [-]	6	0	1
0°K* (1000 W/m²) [W]	8	0	0
20°K* (1000 W/m²) [W]	8	0	0
40°K* (1000 W/m²) [W]	8	0	0
60°K* (1000 W/m²) [W]	8	0	0

0°K** (700 W/m²) [W]	8	0	0
20°K** (700 W/m²) [W]	8	0	0
40°K** (700 W/m²) [W]	8	0	0
60°K** (700 W/m²) [W]	8	0	0
0°K*** (400 W) [W]	8	0	0
20°K*** (400 W) [W]	8	0	0
40°K*** (400 W) [W]	8	0	0
60°K*** (400 W) [W]	8	0	0
$K_b(20°)$ [-]	6	0	0
$K_b(30°)$ [-]	6	0	0
$K_b(40°)$ [-]	6	0	0
$K_b(50°)$ [-]	6	0	0
$K_b(60°)$ [-]	6	0	0
T_{stag} [°C]	8	2	0

*Power output at 1000 W/m² (G_b = 850 W/m², G_d = 150 W/m²) for dT = xx K

**Power output at 700 W/m² (G_b = 440 W/m², G_d = 260 W/m²) for dT = xx K

***Power output at 1000 W/m² (G_b = 400 W/m², G_d = 0 W/m²) for dT = xx K

Table 4 shows all laboratories which had a questionable or unsatisfactory result for at least one Parameter. Laboratories not present in Table 4 have completed all parameter satisfactory. There was done no overall assessment by the organizer. If a laboratory received more than 25 % unsatisfactory results per collector / system and year, it should start corrective actions to find the reason for this deviation.

Table 4: Questionable and unsatisfactory result

Parameter	LES	ICE	INTI
K_d [-]	O		
T_{stag} [°C]		X	X

X Analysis with a Z-Score $|Z|\geq3$
O Analysis with a Z-Score $2<|Z|<3$

5. Summary

5 laboratories from 5 Latin-American countries participated in the laboratory inter-comparison test of solar collectors in 2019 which was evaluated by Solar und Wärmetechnik Stuttgart (SWT) in Stuttgart, Germany. The results submitted were evaluated on basis of a robust statistical method, in order to minimize the influence of outliers regarding individual laboratory mean values. The total results show very good results. Although the tasks were very complex, the results were close together. The result of the inter-laboratory comparison is as good as similar comparison test done previously in Europe e. g. within the QAiST project (2011 and 2012) or the ECOTEST project (2018) The number of unsatisfactory results is clearly lower. This shows a

very good quality of work in the participating laboratories. It gives a conclusion of the high level of training of personnel and the high quality of the standards used.

6. Literature

[1] ISO/IEC 17043:2010, Conformity assessment - General requirements for proficiency testing. International Organisation for Standardization, Genève, February 2010.

[2] ISO 9806:2017, Solar energy — Solar thermal collectors — Test methods; ISO, Geneva, Switzerland, 2017.

[3] ISO 13528:2005, Statistical methods for use in proficiency testing by interlaboratory comparisons. International Organisation for Standardization, Genève, September 2005.

[4] PTPM 1.1, Guide to Proficiency Testing Australia, PTA. Australia, April 2008.

7. Appendix to expert report

7.1 Test protocol

Procedure for the collector Round Robin Test conducted within the LACRE3 project

1 Introduction

A round robin test with the following participants will be carried out:

ICE, UNAM, INTI, MEXOLAB, LES-UR, IPT and a so called reference test laboratory.

Subject of the round robin will be 7 flat plate collectors of the same type and from the same batch of production.

Before the collectors will be sent to Latin America all 7 collectors will be tested by the reference test laboratory in Germany. Afterwards 6 collectors will be sent Latin America, one to each participating test laboratory and be tested during the year 2018. The 7th collector will remain at the reference test laboratory and will be used for the evaluation of the stability of the set of collectors used in this Round Robin Test when required (see section 8).

The reference test laboratory will be selected by PTB from the Solar Keymark recognised test laboratories (http://www.estif.org/solarkeymarknew/contacts/recognised-test-labs). To ensure a high experience of the reference test laboratory it shall have conducted a minimum of 15 Solar Keymark tests during the last 24 months and must be accredited according to ISO/IEC 17025 [1] for conducting tests according to ISO 9608:2017 [2].

The round robin is supervised and evaluated by SWT (Stephan Fischer) acting as third party.

2 Objective

The following are the objectives of the Round Robin Test

- Comparison of results derived from indoor and outdoor measurements
- Comparison of results gained by different test labs using the same test procedure
- Comparison of results gained by all participating test labs to check the competence of the test labs
- Learning and gaining experience
- Input for accreditation

3 Collectors

As decided during the workshop held in July 2017 at ICE, Costa Rica, the collector will have the following basic specifications:

- Tempered glass (float glass)
- Selective coating (Alanod/Tinox Almeco)
- Size approx. 1 m x 2 m
- Vertical

- Harp (risers and manifolds)
- 4 connections, ¾" outer thread
- Ultrasonic / laser welded absorber

The collectors will be purchased by PTB[1] with the support from Stephan Fischer (SWT).

The collectors would have to belong to the same batch of production.

4 Transportation

The collectors purchased will be delivered from the manufacturer to the reference test laboratory (cost included in collector costs). The reference test laboratory must inform PTB and SWT within 2 weeks after receiving the collectors and deliver a time schedule for the tests.

After having been tested from the reference test laboratory the 6 collectors for the participating Latin American test laboratories will be packed in 6 single boxes, appropriate for sending the collectors in such a way that no damage occurs, and sent to PTB which will send the boxes to the 6 participating Latin America test laboratories.

Responsible for packing and organising the transport to PTB will be the reference test laboratory. Costs for packing and transport will be covered by PTB. The reference test laboratory will inform PTB and SWT about the date of pickup and scheduled arrival at PTB. Afterwards PTB will inform SWT and the participating Latin American test laboratories of the date of pickup and the scheduled arrival at the participating Latin American test laboratories.

5 Communication

During the Round Robin Test no communication is allowed between the participating test laboratories related to the Round Robin Test or the collectors involved. Sole person for questions will be Stephan Fischer (SWT) who will decide if the possible question can be answered without influencing the Round Robin Test. In case an answer can be given it will be given to all participating test laboratories.

All participating test laboratories will supply PTB and SWT with complete contact details of the person(s) in charge of the Round Robin Test and the delivery address before the collectors will be purchased.

6 Supervision an evaluation of the round robin

The round robin is supervised and evaluated by SWT (Stephan Fischer) acting as third party.

7 Responsibilities and test protocol for the reference test laboratory

Upon arrival of the test collectors the reference test laboratory will inform PTB and SWT and deliver the time schedule for the testing.

[1] The reference test laboratory will have to compensate PTB for the collector costs

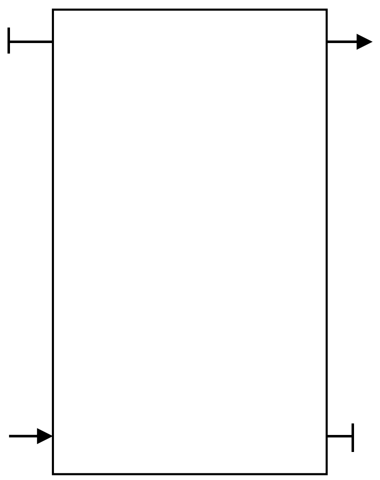
Within 5 days after arrival the reference test laboratory will perform an incoming inspection consisting of

- Visible inspection of the collectors including outer appearance, corners of collector box, sealing of pipes and glass cover, homogeneity of the absorber, distance between absorber and glass cover, location of the absorber within the collector box. All 7 collectors shall have, within typical production tolerance a similar appearance.
- Photographic documentation of the collector including front view, back view, side views, collector label, collector corners and any peculiarities according to the list above.

In case of any obvious possibility that the delivered collectors do not fulfil the requirements for the Round Robin Test PTB and SWT have to be informed immediately. PTB and SWT will examine the possible problem and decide on the following steps.

After the decision that the collectors can be used for the Round Robin Test the preconditioning of all the collectors according to ISO 9806:2017, clause 23.2 will be carried out. In case no obvious peculiarities are visible after the preconditioning the test samples can be prepared for testing. Otherwise PTB and SWT have to be informed immediately. PTB and SWT will examine the possible problem and decide on the following steps.

Before testing, all test samples shall be prepared as followed: The inlet shall be at the bottom left, outlet at the top right (seen from the front of the collector) and be insulated according to ISO 9806:2017. The remaining two connections shall be closed and shall not be insulated.



All 7 collectors shall be subject to an indoor performance test according to ISO 9806:2017 using a tilt angle of 45°. One selected collector shall be in addition subject to an outdoor performance test to determine the incidence angle modifiers for hemispherical and diffuse irradiance. Here the test of one collector is sufficient due to the dependency of the optical properties of the used components (absorber and glass cover) and the geometry of the collector casing. The homogeneity of the first is checked during the indoor performance test and the second by the initial inspection.

Water shall be used as heat transfer medium.

Collector parameters to be determined according to section 12.

Reporting see section 13.

8 Homogeneity and stability

Homogeneity can be assumed if the collectors are purchased from a high quality manufacturer using absorbers and glass covers from the same batch for the 7 collectors to be produced. In addition, homogeneity is assessed during the indoor performance test performed by the reference test laboratory. Measures for the homogeneity are the collector power at a temperature difference between mean fluid temperature and ambient temperature of 0 K and 50 K. Both quantities shall not deviate more than ± 1.5 %[2] from the mean value of the 7 measurements.

After the report of the reference test laboratory to PTB and SWT the results will be evaluated and the homogeneity will be confirmed before shipping of the collectors.

Stability is not an issue if the collectors are not damaged or subject to extensive stagnation or water ingress. However, in case the Round Robin Test shows some unexpected deviations the collector(s) in question can be shipped back to the reference test laboratory to prove the stability by a retest of the collector. Measures for the stability are the collector power at a temperature difference between mean fluid temperature and ambient temperature of 0 K and 50 K. If both quantities do not deviate more than ± 2 %[3] from the initial values stability is given.

In case of a higher deviation than ± 2 % the result cannot be considered within the Round Robin Test. An additional collector for retest will not be provided.

9 Handling and storage of the collector before and after testing

Upon arrival of the test collectors the Latin American test laboratory will inform PTB and SWT and deliver the time schedule for the testing.

Within 5 days after arrival the test laboratory will perform an incoming inspection consisting of

- Visible inspection of the collectors including outer appearance, corners of collector box, sealing of pipes and glass cover, homogeneity of the absorber, distance between absorber and glass cover, location of the absorber within the collector box. All 7 collectors shall have, within typical production tolerance a similar appearance.
- Photographic documentation of the collector including front view, back view, side view, collector label, collector corners and any peculiarities according to the list above.

In case of any damage of the delivered collector PTB and SWT have to be informed immediately. PTB and SWT will examine the possible problem and decide on the following steps.

After the initial inspection the collector shall not be exposed outdoors but stored in a dry and clean place until the test starts.

After the test the collector shall not be exposed outdoors but stored in a dry and clean place until the project is terminated and further instruction will be delivered by PTB[4].

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[2] The limit of ± 1.5 % is based on the experience of similar homogeneity measurements.

[3] The limit of ± 2 % is based on the overall measurement uncertainty given by the ISO 9807:2017.

[4] After the end of the project the collectors will be donated to the Latin American test laboratories for further use as reference collector which can be used for quality assurance purpose.

10 Photographs to be taken

Photos shall be taken from the test sample and test sample installation and shall be stored by the testing laboratory for further use in case of questions during the evaluation. These photos shall include at least the following:

1. Front view
2. Rear view
3. Each connection to the collector when installed
4. Front view mounted collector under test

An example of these photos will be sent before the interlaboratory comparison begins.

11 Cleaning during testing

When outdoor testing is carried out the collector shall be cleaned every morning.

12 Test methods

Both the indoor and outdoor steady state method according to ISO 9806:2017 can be applied. If time and equipment allows both test methods shall be used. In case of outdoor testing the collector can either be tracked or installed on a fixed test rig. The tilt of the collector shall be adjusted according to the latitude. In case of indoor testing the tilt shall be adjusted to 45°.

Water shall be used as heat transfer medium. In case the water available at the Latin American test laboratory has a high content of minerals so that calcification can occur demineralised water shall be used.

The two connections not used as inlet and outlet shall not be insulated.

Collector parameters to be determined are:

A_G Gross area of collector as defined in the ISO 9488, m^2

η_{hem} Collector efficiency based on hemispherical irradiance G_{hem}, -

a_1 Heat loss coefficient at $(\vartheta_m - \vartheta_a) = 0$, W/(m^2·K)

a_2 Temperature dependence of the heat loss coefficient, W/(m^2·K^2)

$K_{hem}(\theta_L,\theta_T)$ Incidence angle modifier for hemispherical solar radiation (measured at incident angles of 40° and 60°), -

K_d Incidence angle modifier for diffuse solar radiation (calculated from $K_{hem}(\theta_L,\theta_T)$), –

From the above listed collector parameters the following quantities shall be calculated:

ϑ_{stg} Standard stagnation temperature, °C

and the collector output according the following table

$(\vartheta_m - \vartheta_a)$	G_b = 850 W/m² + G_d = 150 W/m²	G_b = 440 W/m² + G_d = 260 W/m²	G_b = 0 W/m² + G_d = 400 W/m²
0			
20			

40			
60			
Max. tested temperature difference + 30 K			

13 Report sheets

The template (LACRE3 RR 9806 Report sheet final.xlsx) shall be used as report sheet. The format shall not be changed. After completion of the test the report sheet shall be sent to fischer@itw.uni-stuttgart.de with a copy to imilce.zuta@gmail.com and Niklas.cramer@ptb.de.

14 Statistical design

The statistical design is based on ISO 13528 [3] and ISO/IEC 17043 [4]. The deviation of laboratory's mean MW_{LAB} value from the assigned value *X* will evaluated.

The assigned value X will be determined as a consensus value of the results of all participating laboratories. It is calculated as a robust mean value. For each test parameter an assigned value will be calculated. The respective assigned value X is the median of all laboratories results MW_{LAB}.

The normalised interquartile range (nIQR) is used as standard deviation for the proficiency assessment σ(nIQR):

$$nIQR = 0{,}7413\ (Q3-Q1) \quad (1)$$

75 % of all values are lower than Q3, 25 % of all values are lower than Q1. (Q3-Q1) is called interquartile range (IQR). The factor 0,7413 derives from the standard normal distribution, which has a mean of zero and a standard deviation equal to one. The width of the interquartile range of such a distribution is 1,34898 and results to 1/1,34898 = 0,7413. Multiplying IQR by this factor makes it comparable to a standard deviation [6]. The statistical design is based on ISO 13528 [5] and ISO/IEC 17043 [1]. The deviation of laboratory's mean MW_{LAB} value from the assigned value X will be evaluated.

The results of this proficiency test are assessed with the help of a Z-score that is calculated for each laboratory and each test parameter according to equation (2):

$$Z = (MW_{LAB} - X)/\ \sigma \quad (2)$$

According to ISO/IEC 17043 the following judgements will be made:

- $|Z| \leq 2$ satisfactory participated
- $|Z| \geq 3$ unsatisfactory participated
- $2 < |Z| < 3$ result questionable.

Measurement uncertainties are given by the ISO 9806 standard. The participating test laboratories must comply to the given measurement uncertainties.

15 Final report

After evaluation of all results a final report will be prepared by SWT and sent out to the participants. A preliminary report will not be issued.

16 Schedule of activities

What	Who	Deadline
Purchase of collectors	PTB with support from SWT	15.02.2018
Subcontracting reference test laboratory	PTB with support from SWT	15.02.2018
Delivery of collectors to reference test laboratory	Collector manufacturer	28.02.2018
Initial collector testing	Reference test laboratory	31.03.2018
Evaluation of Initial collector testing	SWT	15.04.2018
Delivery of collector (test item) to participating Latin American test laboratories	Reference test laboratory with support from PTB	30.05.2018
Testing at participating Latin American test laboratories	ICE, UNAM, INTI, MEXOLAB, LES-UR, IPT	01.06.18 to 30.04.19
Report of results to PTB and SWT	ICE, UNAM, INTI, MEXOLAB, LES-UR, IPT	30.04.2019
Evaluation of test results and preparing of report	SWT	31.05.2019

17 Literature

[1] EN ISO/IEC 17025:2005, General requirements for the competence of testing and calibration laboratories - trilingual version. Beuth Verlag, Berlin, April 2005.

[2] Solar energy — Solar thermal collectors — Test methods, International Organisation for Standardization, Genève, September 2017.

[3] ISO 13528:2005, Statistical methods for use in proficiency testing by inter-laboratory comparisons. International Organisation for Standardization, Genève, September 2005.

[4] ISO/IEC 17043:2010, Conformity assessment - General requirements for proficiency testing. International Organisation for Standardization, Genève, February 2010.

Stephan Fischer

20.01.2018

7.2 Graphical presentations of results

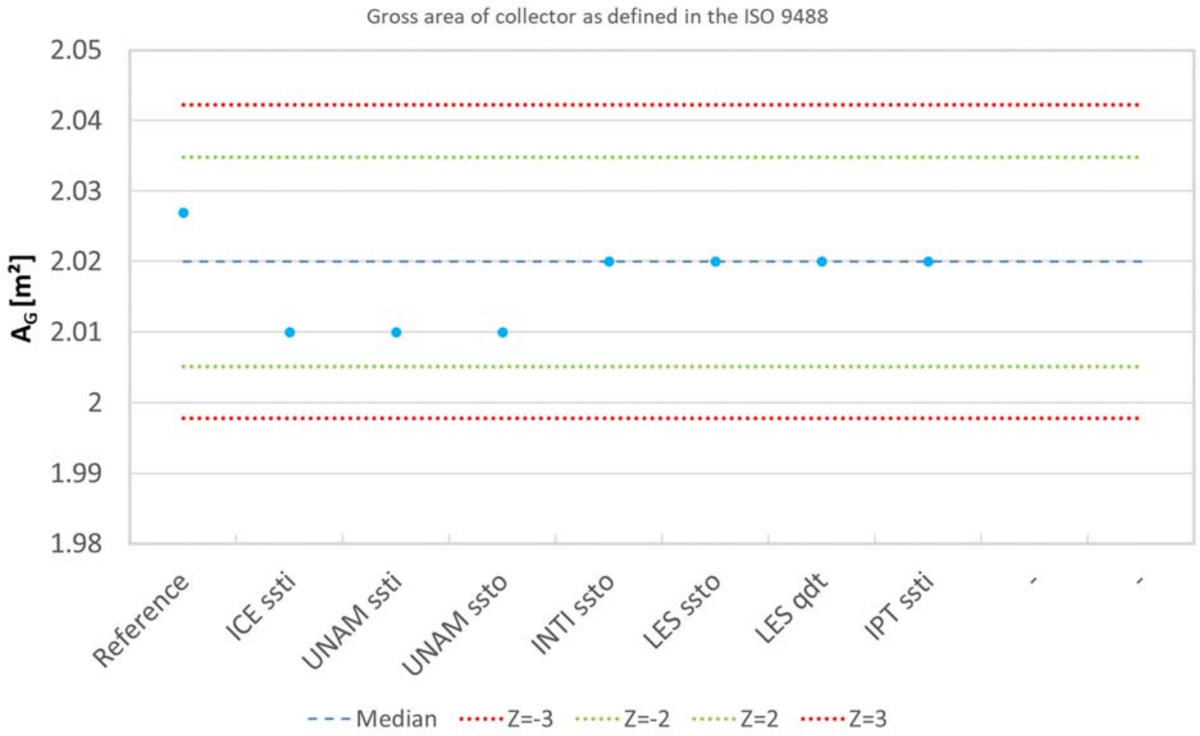

Figure 1: Gross area of collector as defined in the ISO 9488

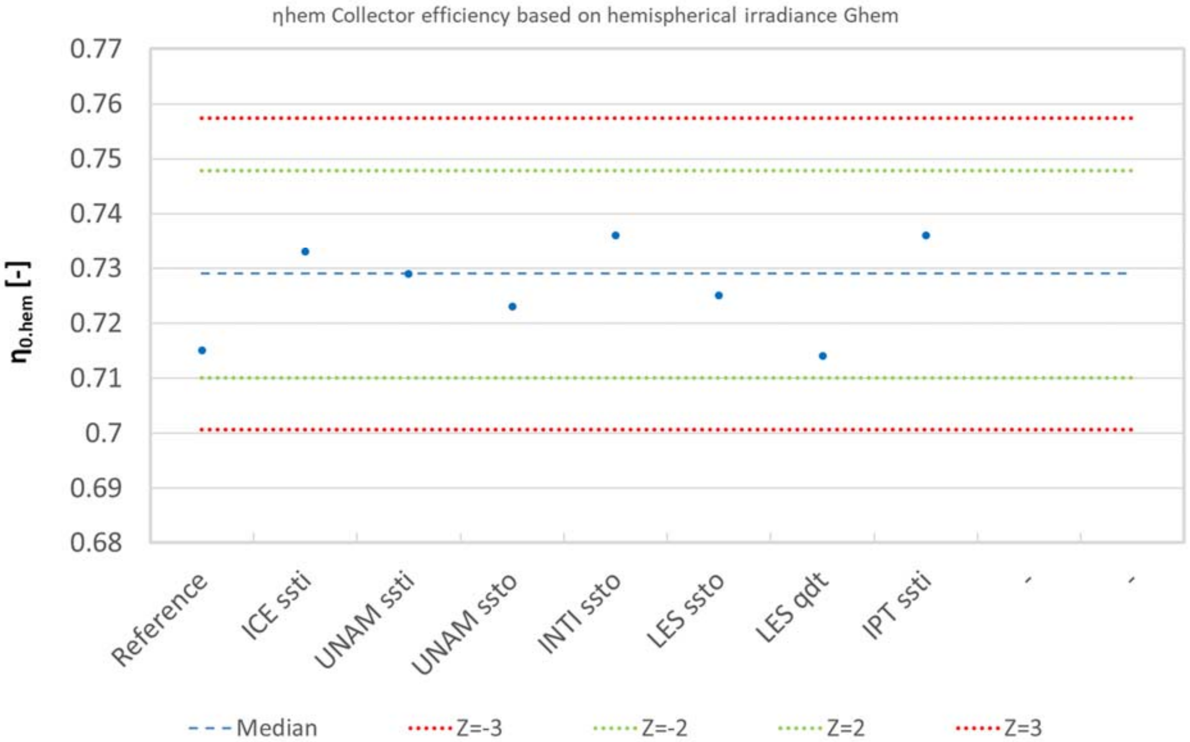

Figure 2: η_{hem} Collector efficiency based on hemispherical irradiance G_{hem}

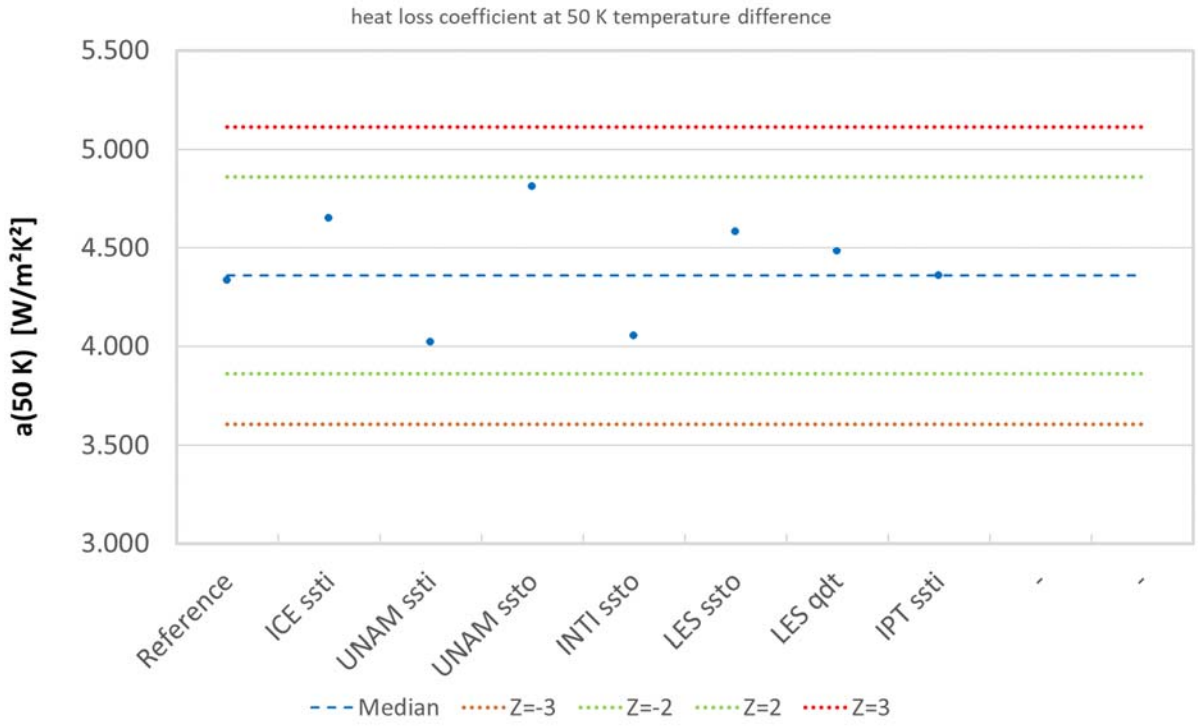

Figure 3: Heat loss coefficient at 50 K temperature difference

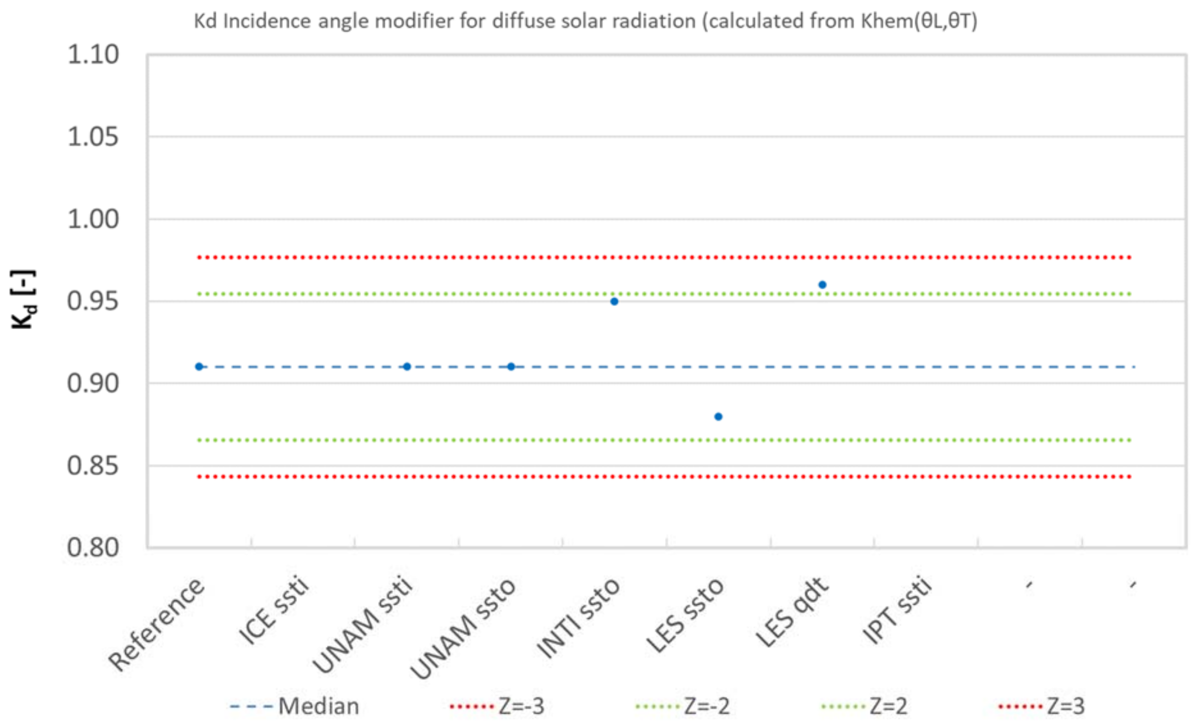

Figure 4: K_d Incidence angle modifier for diffuse solar radiation (calculated from Khem(θ_L,θ_T)

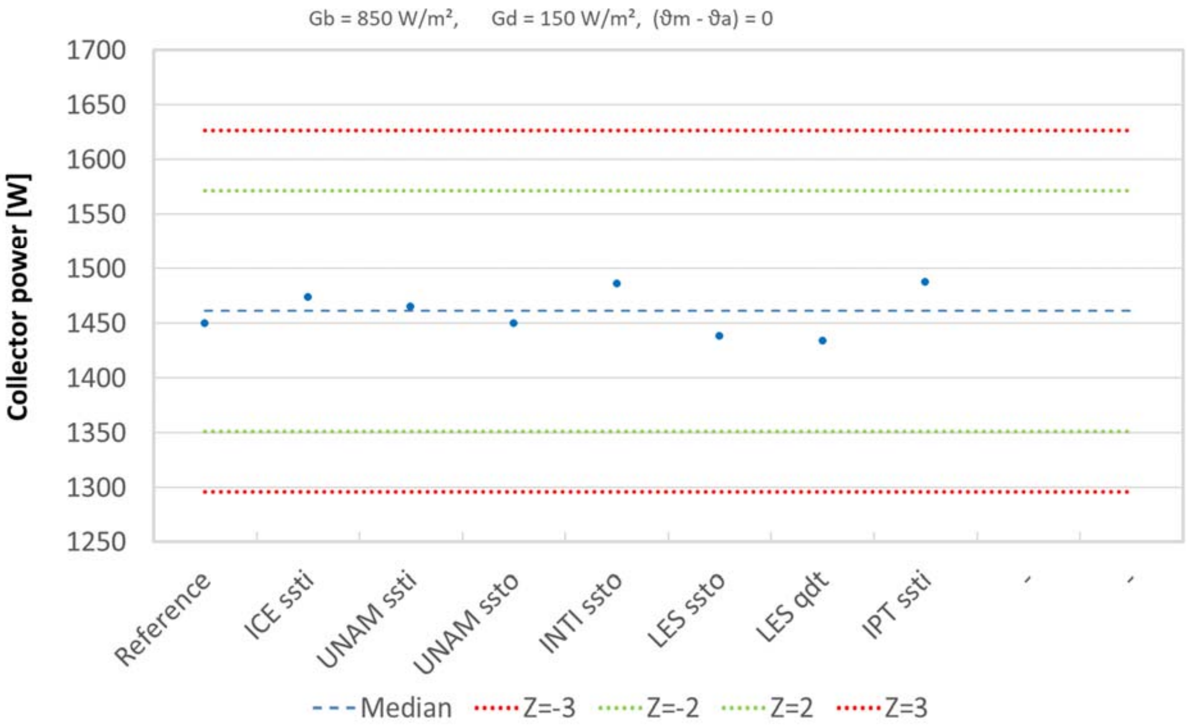

Figure 5: Collector power for G_b = 850 W/m², G_d = 150 W/m², (ϑ_m - ϑ_a) = 0 K

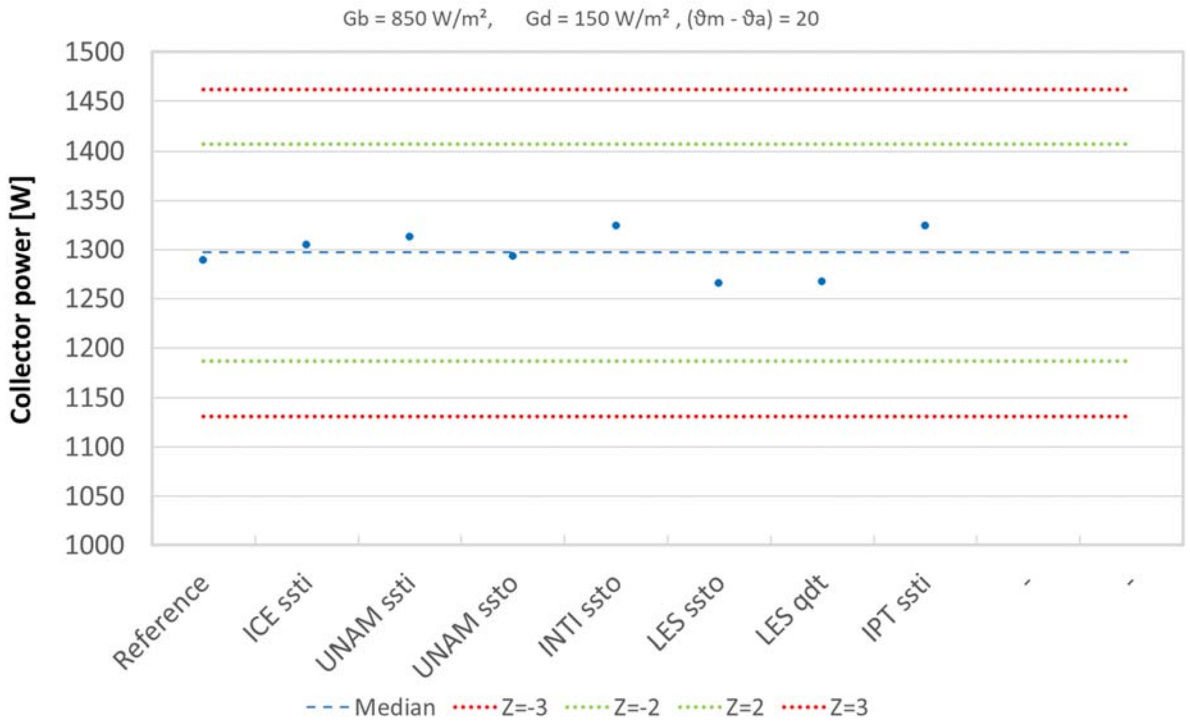

Figure 6: Collector power for G_b = 850 W/m², G_d = 150 W/m², (ϑ_m - ϑ_a) = 20 K

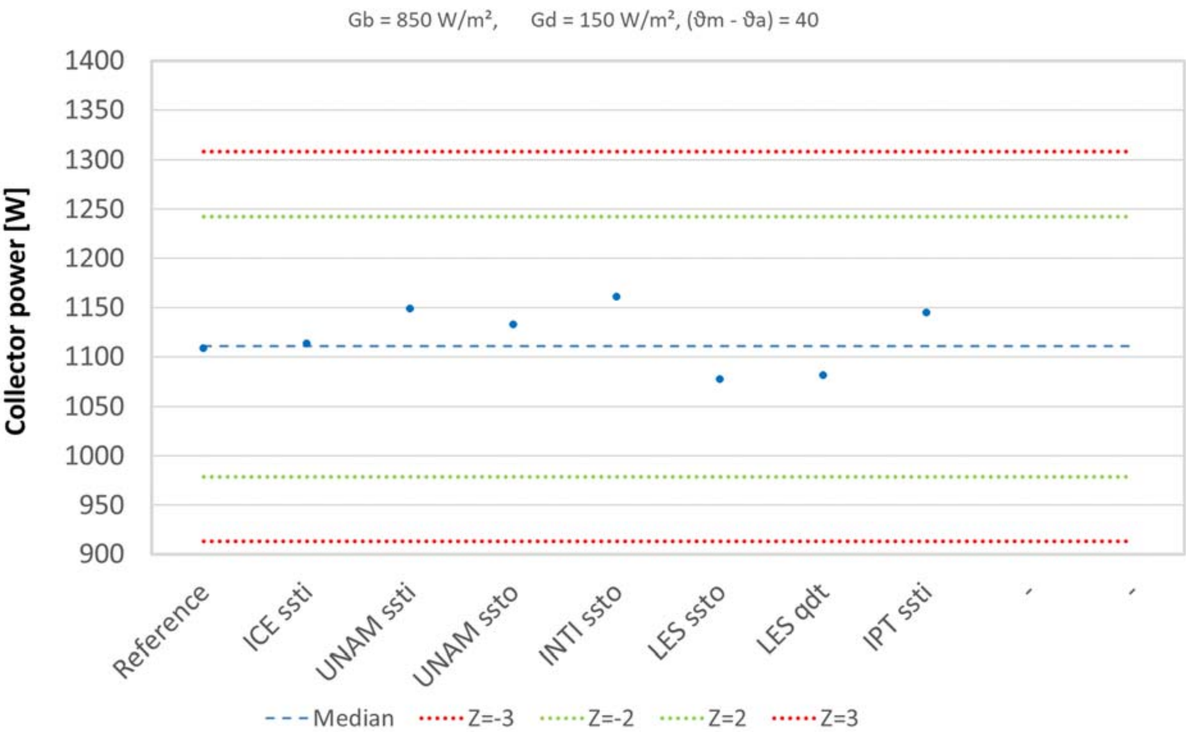

Figure 7: Collector power for G_b = 850 W/m², G_d = 150 W/m², (ϑ_m - ϑ_a) = 40 K

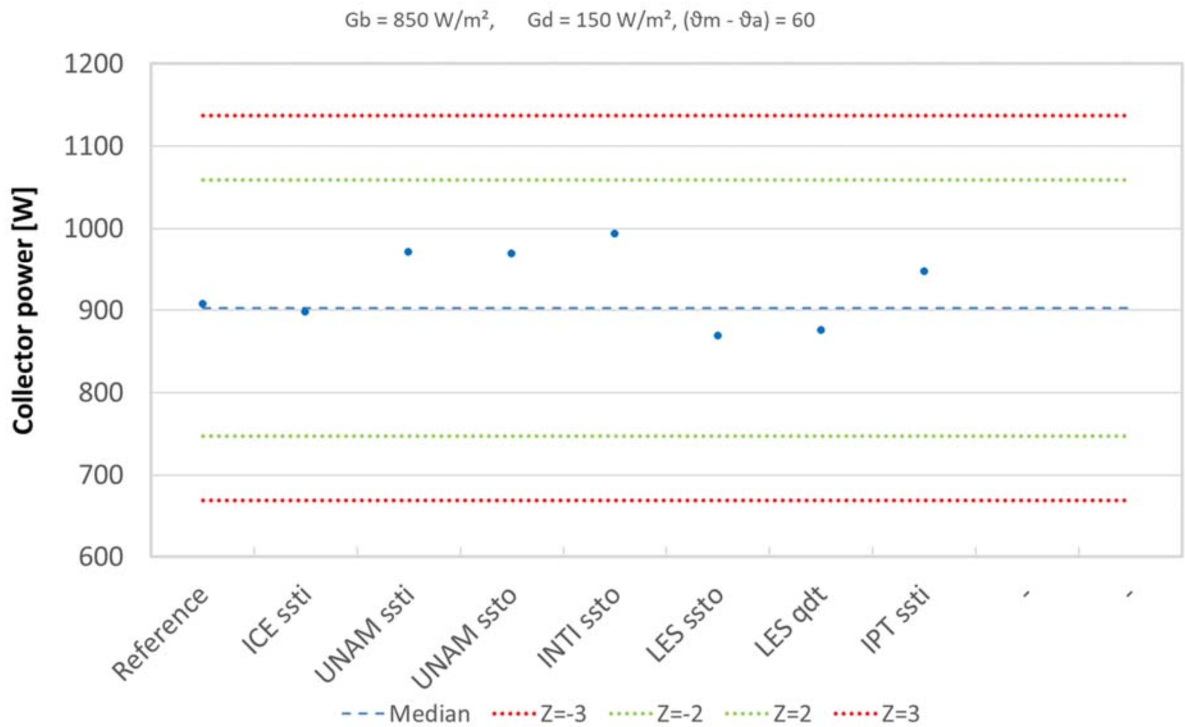

Figure 8: Collector power for G_b = 850 W/m², G_d = 150 W/m², (ϑ_m - ϑ_a) = 60 K

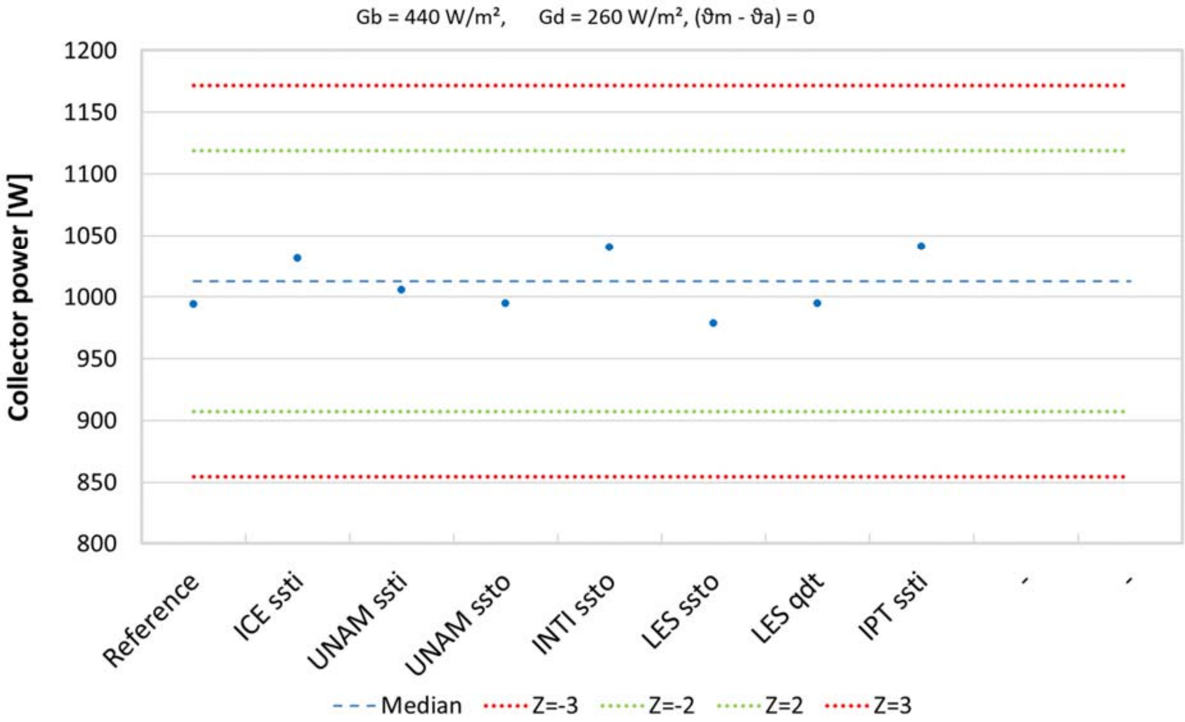

Figure 9: Collector power for G_b = 440 W/m², G_d = 260 W/m², (ϑ_m - ϑ_a) = 0 K

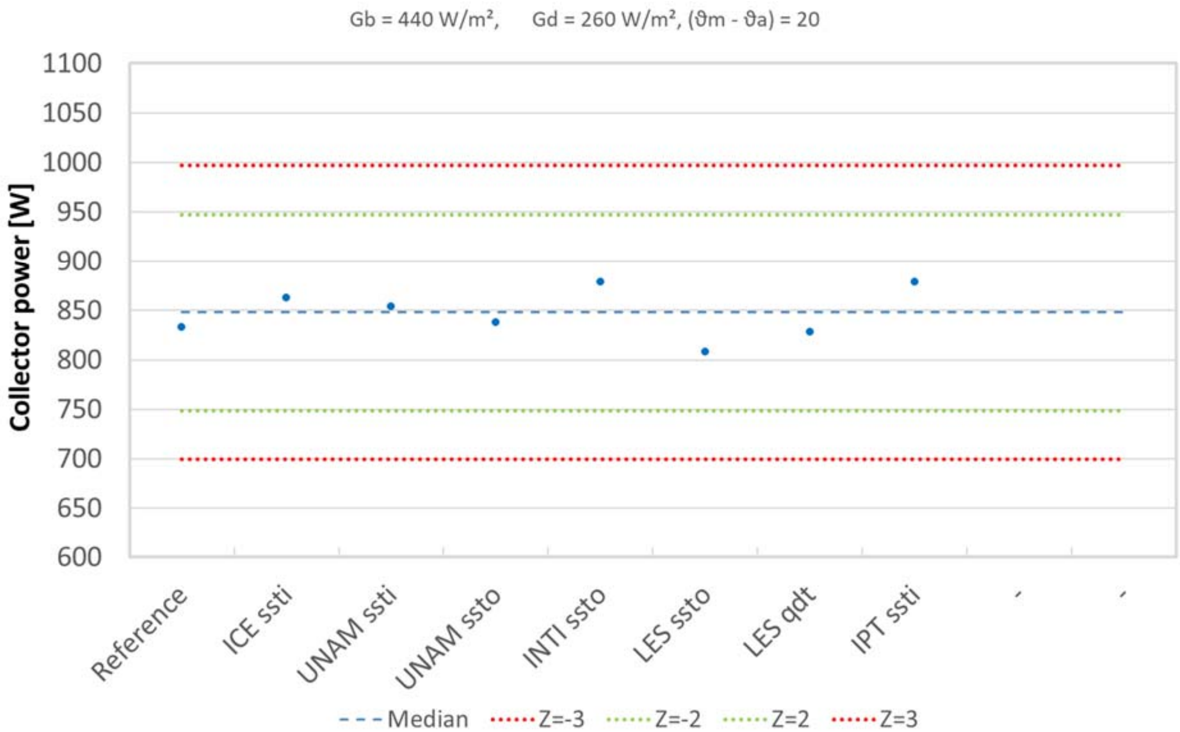

Figure 10: Collector power for G_b = 440 W/m², G_d = 260 W/m², (ϑ_m - ϑ_a) = 20 K

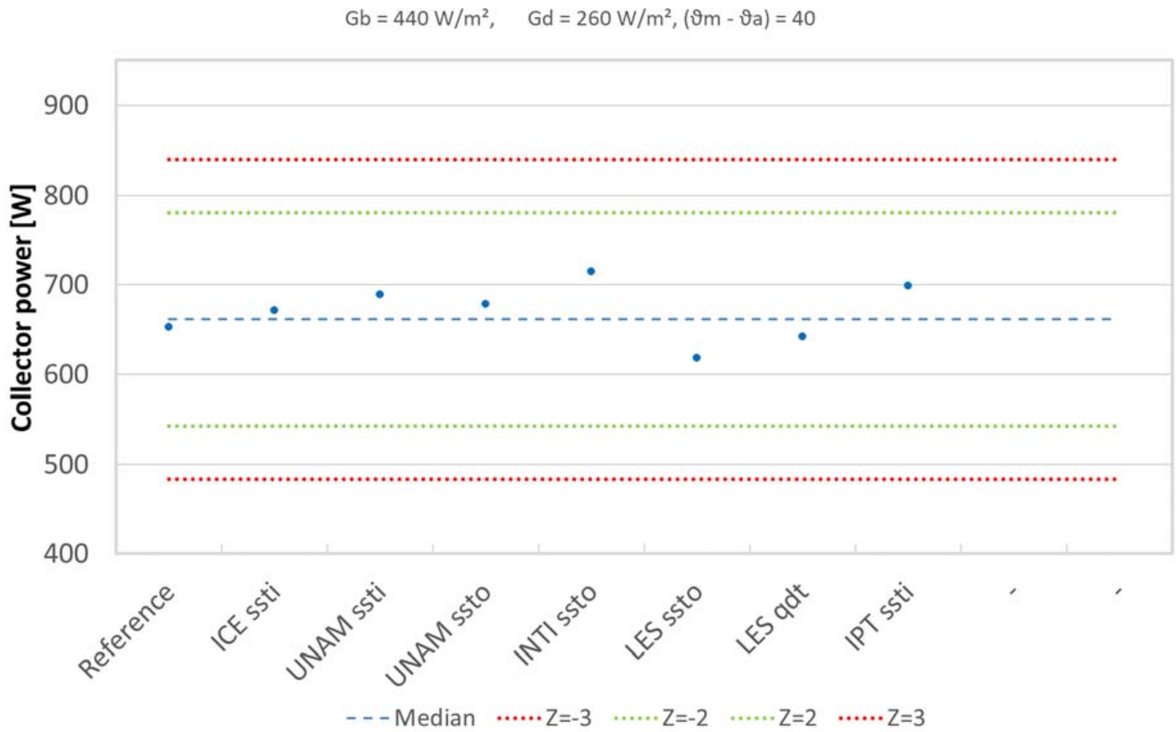

Figure 11: Collector power for G_b = 440 W/m², G_d = 260 W/m², (ϑ_m - ϑ_a) = 40 K

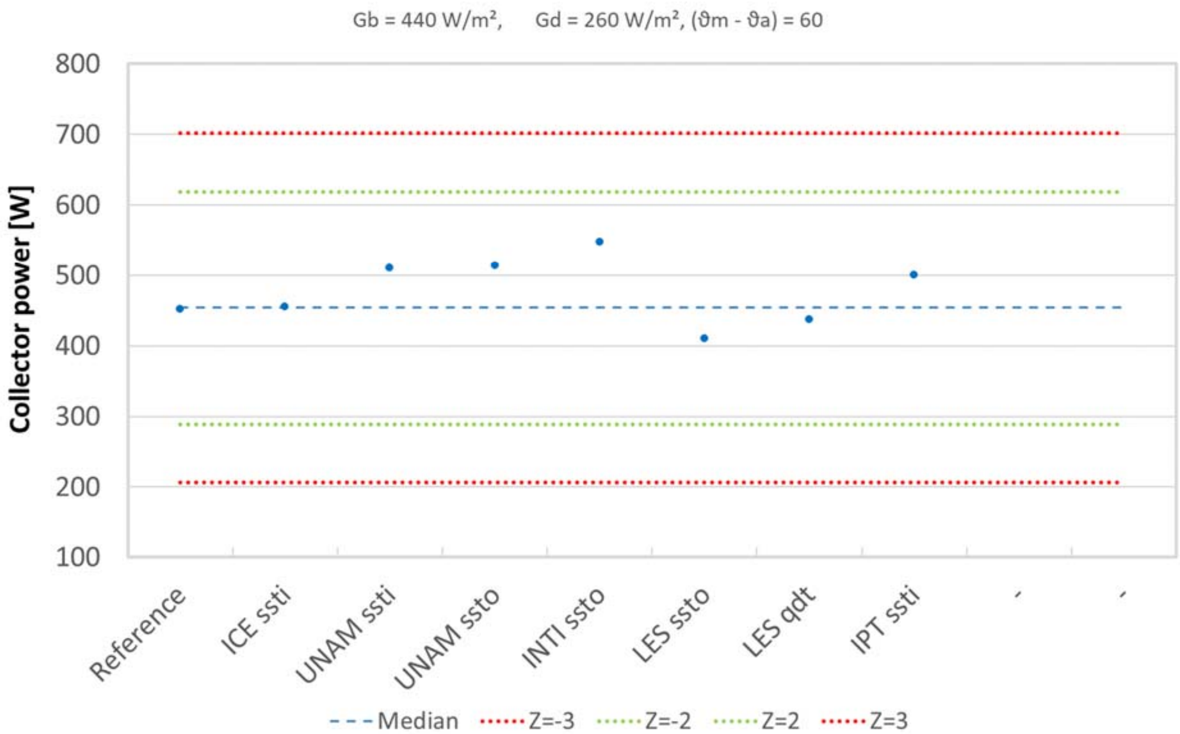

Figure 12: Collector power for G_b = 440 W/m², G_d = 260 W/m², (ϑ_m - ϑ_a) = 60 K

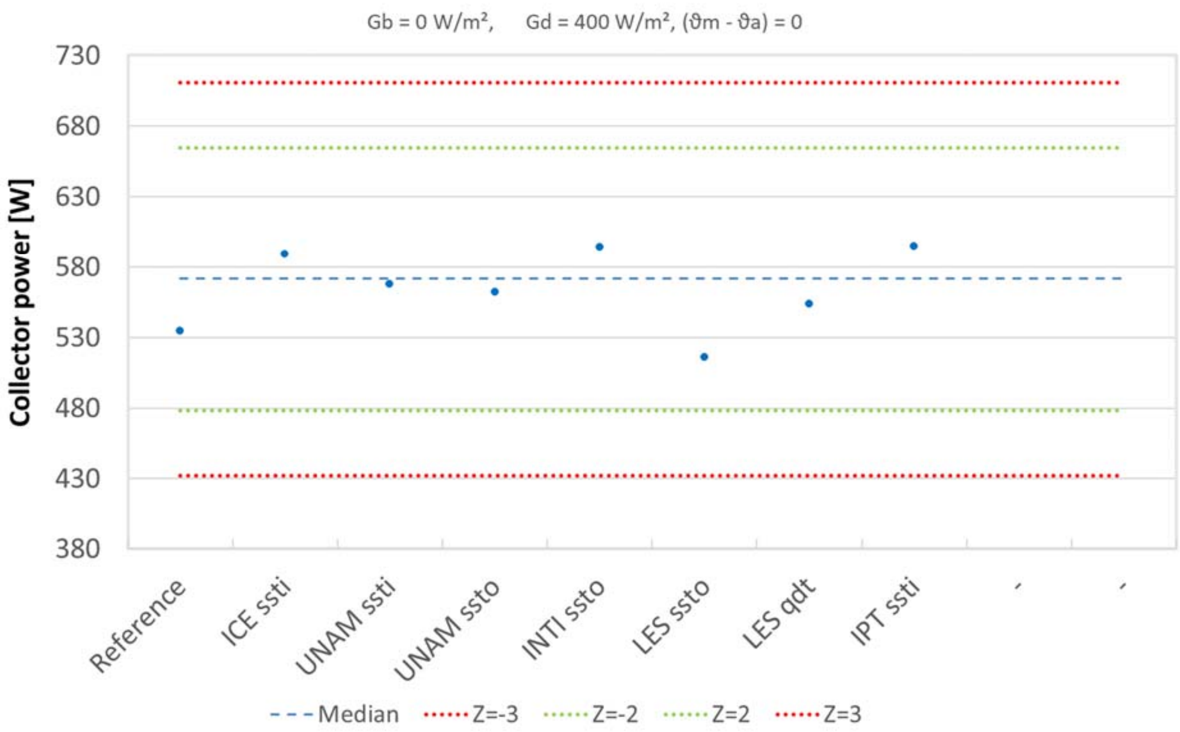

Figure 13: Collector power for G_b = 0 W/m², G_d = 400 W/m², (ϑ_m - ϑ_a) = 0 K

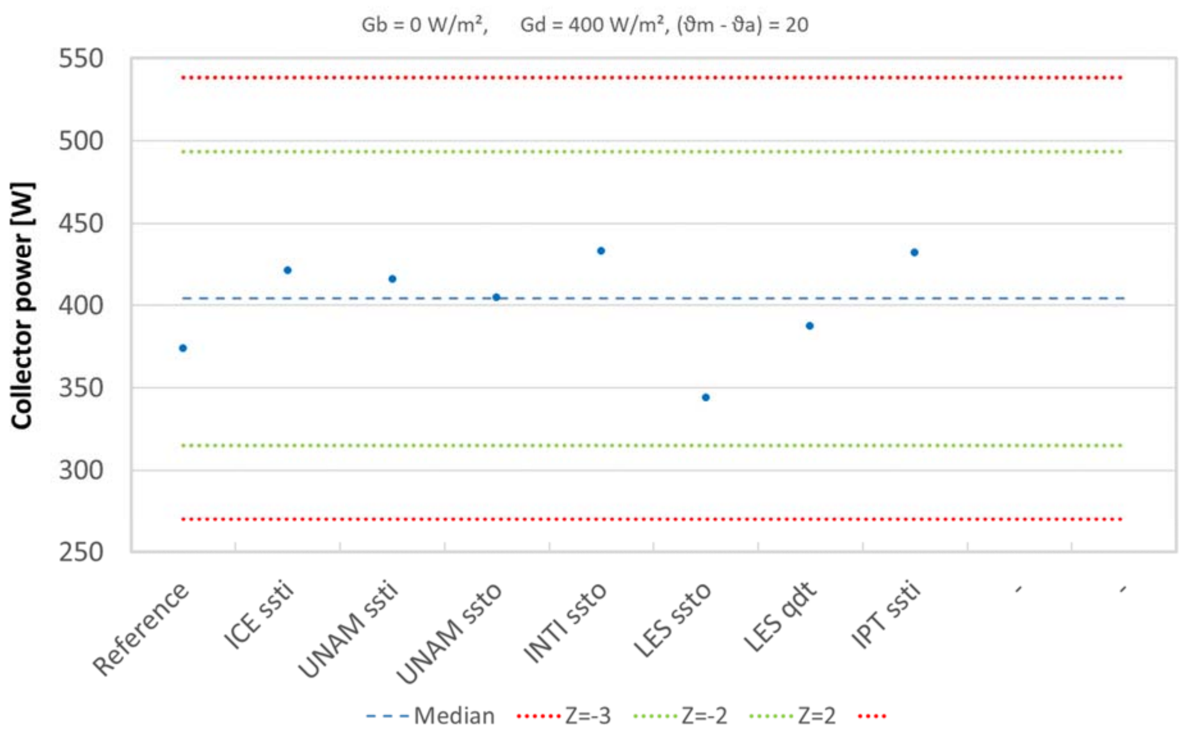

Figure 14: Collector power for G_b = 0 W/m², G_d = 400 W/m², (ϑ_m - ϑ_a) = 20 K

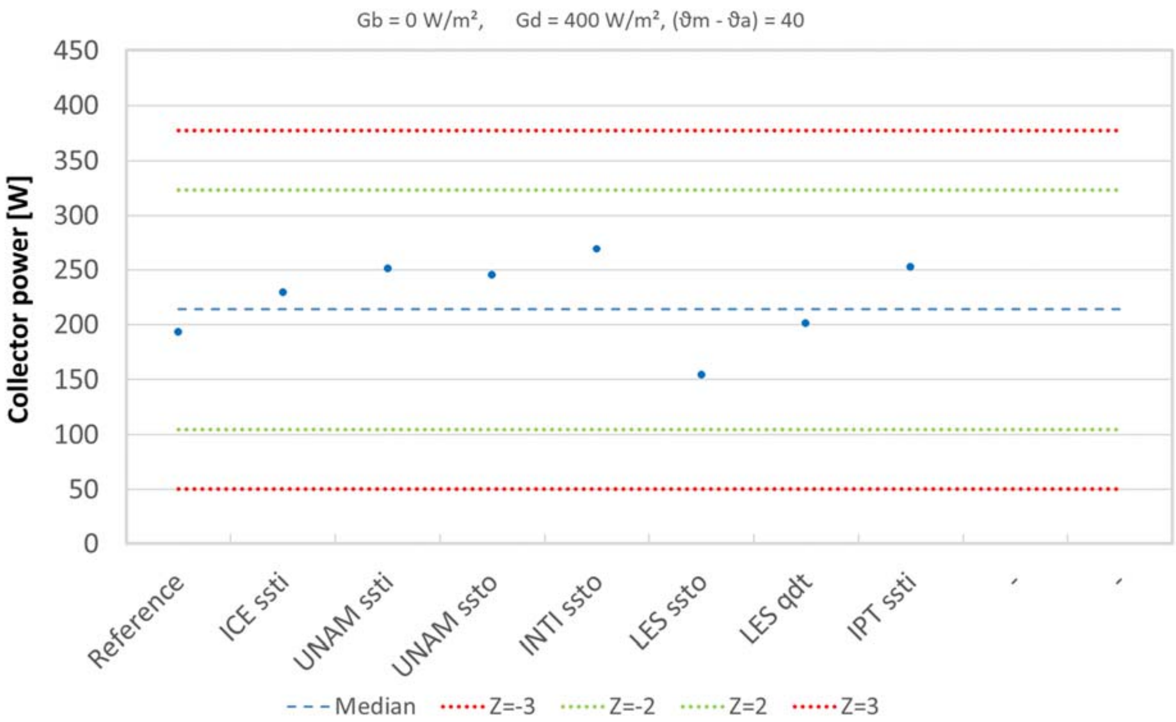

Figure 15: Collector power for G_b = 0 W/m², G_d = 400 W/m², (ϑ_m - ϑ_a) = 40 K

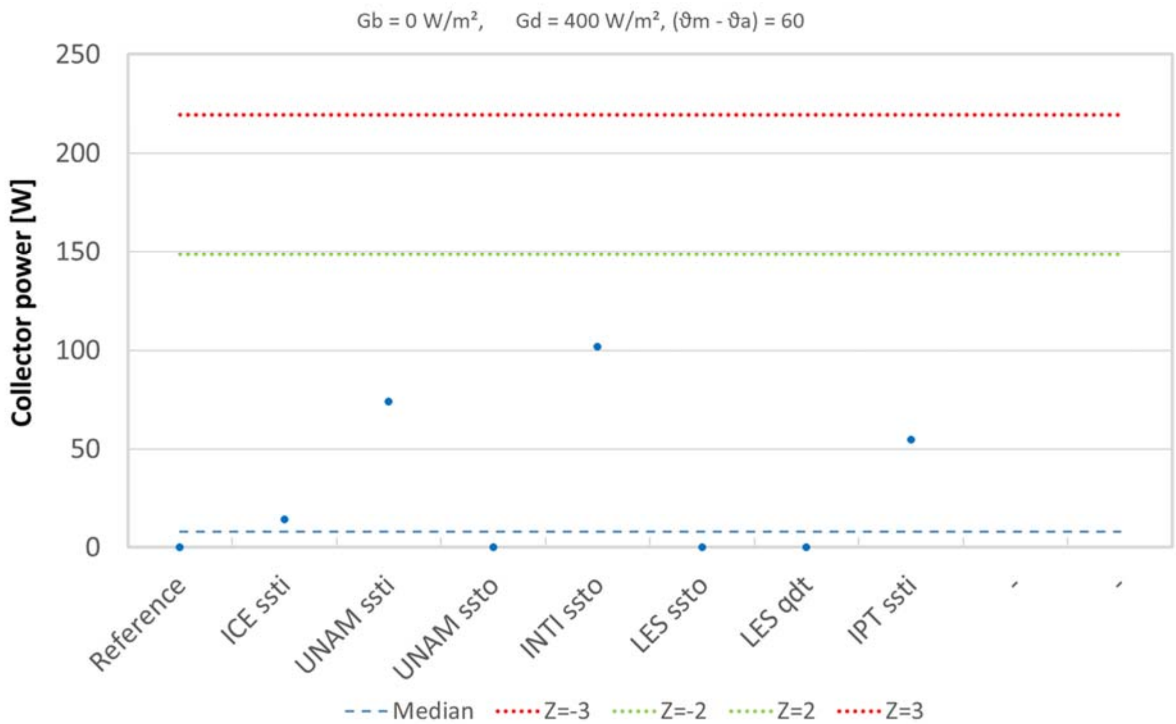

Figure 16: Collector power for G_b = 0 W/m², G_d = 400 W/m², (ϑ_m - ϑ_a) = 60 K

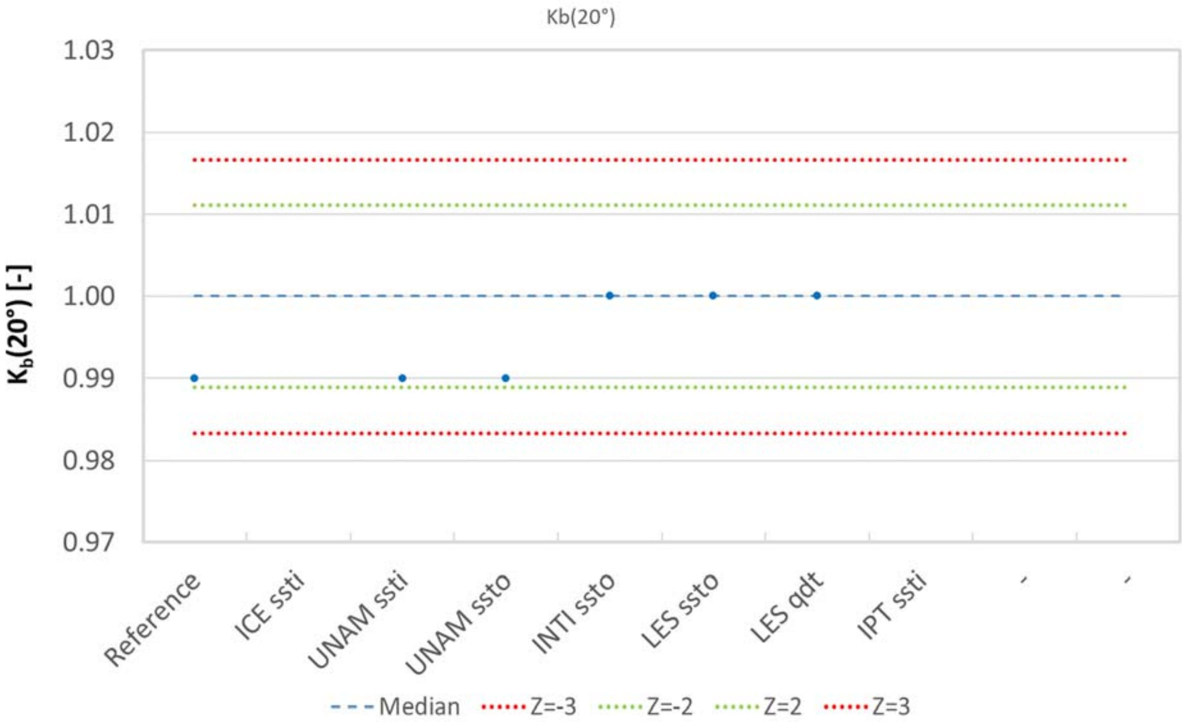

Figure 17: Incidence angle modifier for beam irradiance and 20° K_b (20°)

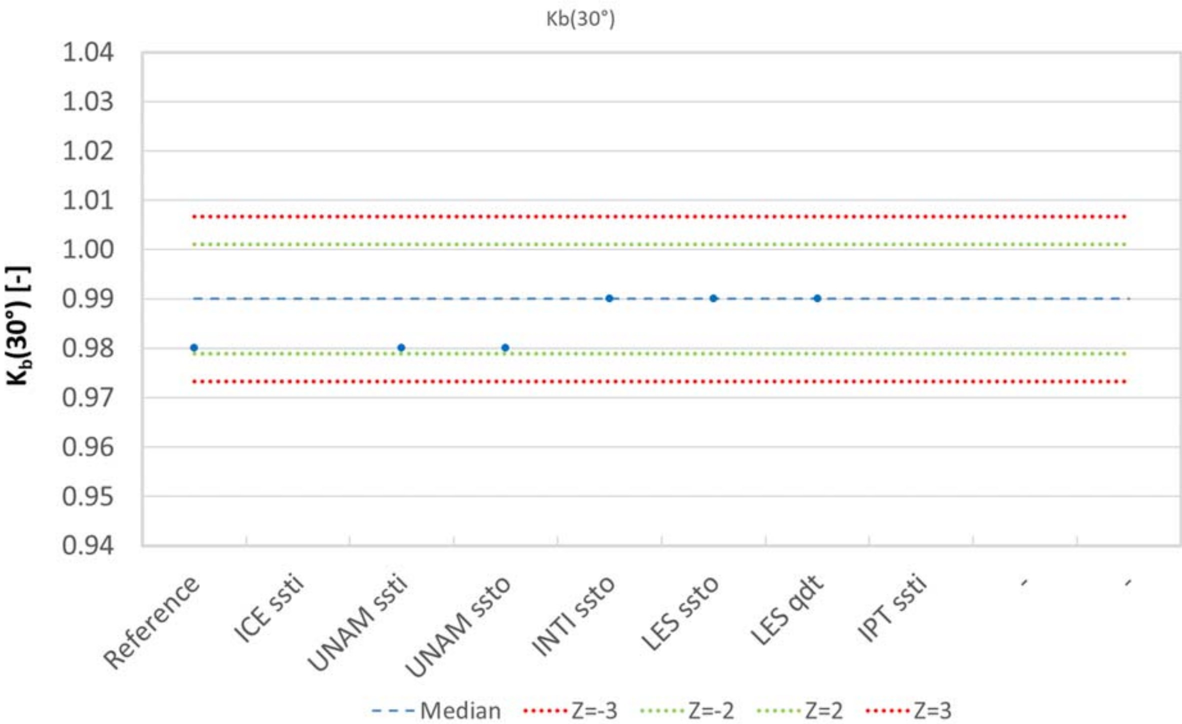

Figure 18: Incidence angle modifier for beam irradiance and 30° K_b (30°)

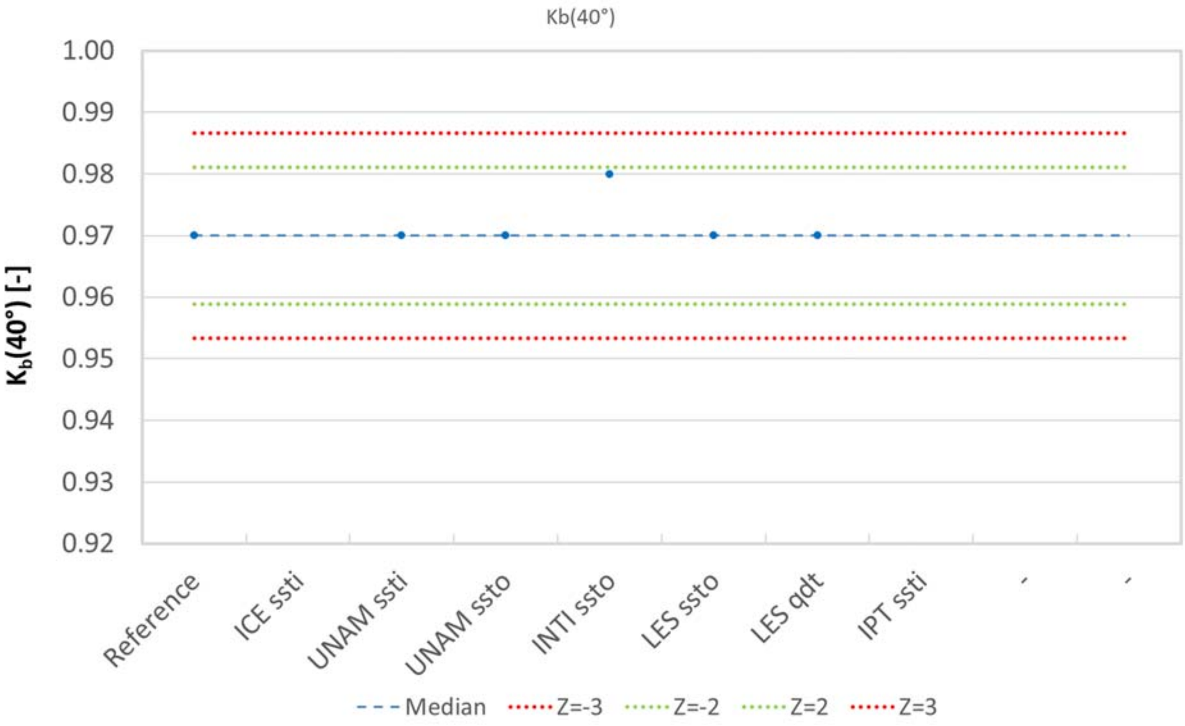

Figure 17: Incidence angle modifier for beam irradiance and 40° K_b (40°)

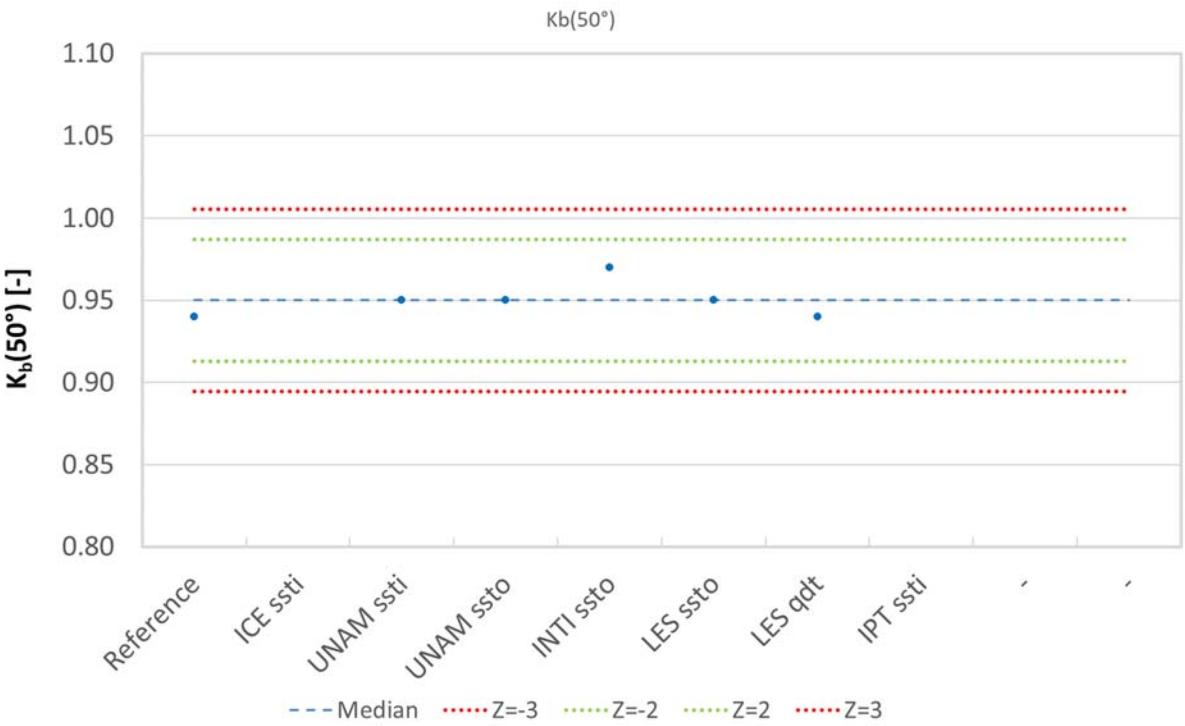

Figure 18: Incidence angle modifier for beam irradiance and 50° K_b (50°)

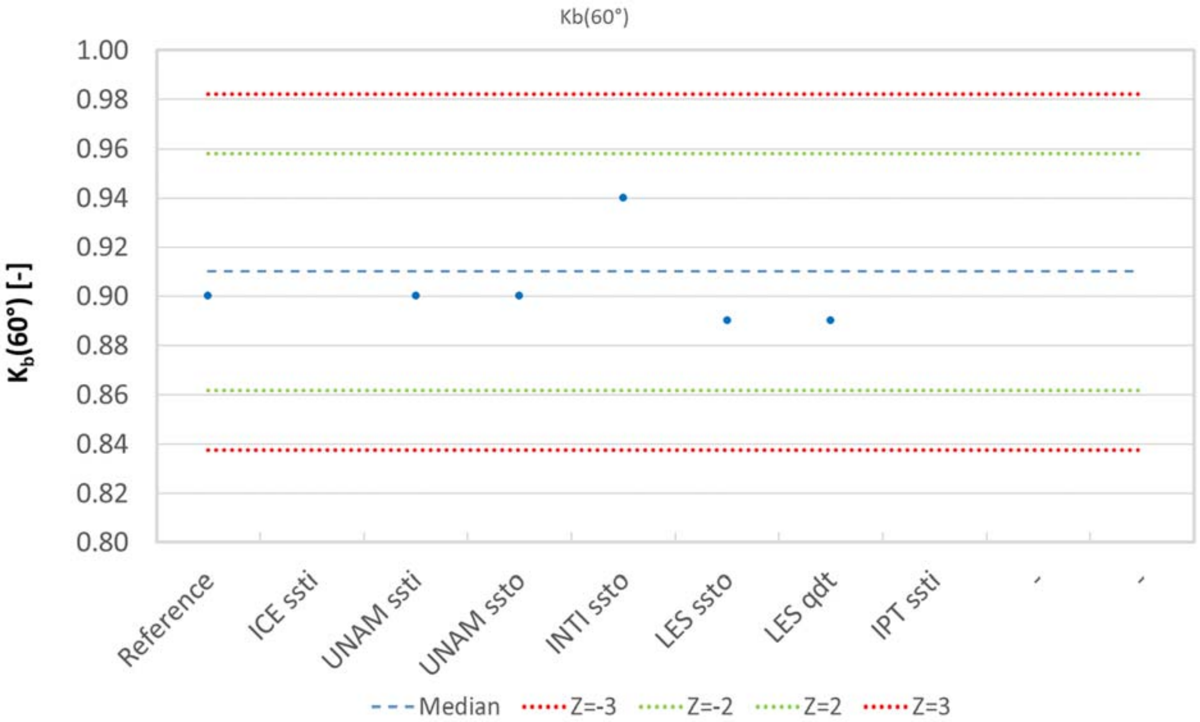

Figure 17: Incidence angle modifier for beam irradiance and 60° K_b (60°)

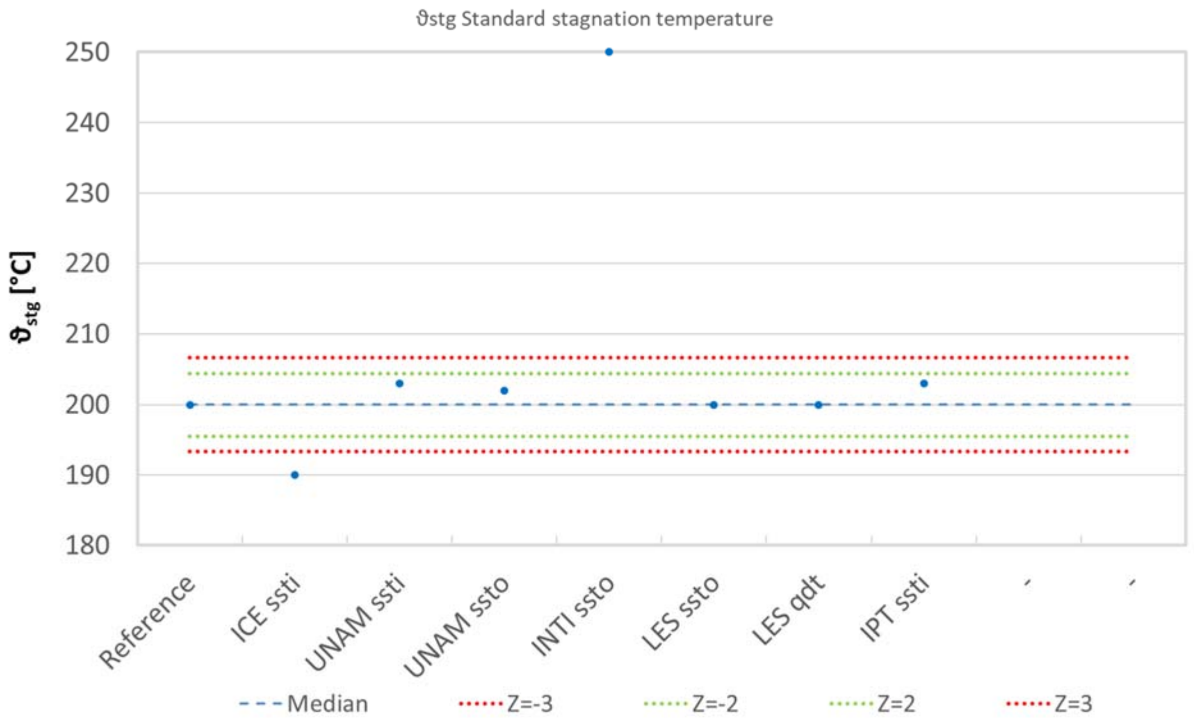

Figure 18: Standard stagnation temperature ϑ_{stg}