Final report of the EURAMET.EM-K5.2018 comparison on AC power

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Draft B
March 2026

1 INTRODUCTION

The Mutual Recognition Arrangement (MRA) requests that the metrological equivalence of national measurement standards is determined by a set of key comparisons organised by the Consultative Committees of the CIPM working closely together with the Regional Metrology Organisations (RMO).

Recently, the international key comparison CCEM-K5.2017 of 50/60 Hz standards was organized under the auspices of the Consultative Committee of Electromagnetism (CCEM). As a follow-up, the regional key comparison EURAMET.EM-K5.2018 has been conducted between the participating National Metrology Institutes (NMIs) and Designated Institutes (DIs). Most of the participating NMIs/DIs are members of EURAMET but one NMI from COOMET also participated.

In this EURAMET.EM-K5.2018 comparison the comparability of power measurements between the participants was assessed. The aim of the comparison was to determine the participants‘ Degrees of Equivalence (DoE) referred to the linked key comparison reference value of the related CCEM key comparison CCEM-K5.2017. The comparison protocol was based on the procedures used during the CCEM-K5.2017 comparison and followed the CCEM Guidelines for Planning, Organizing, Conducting and Reporting Key, Supplementary and Pilot Comparisons [1].

This report presents the outcomes of the EURAMET.EM-K5.2018 key comparison. The analysis of the comparison results with respect to the CMC claims of the participating institutes and the measures to be taken in the case of inconsistencies are not within the scope of this report.

2 PARTICIPANS AND ORGANISATION

In total 22 laboratories participated in the comparison. The coordination was shared by four NMIs: VSL, PTB, NPL, and LNE. VSL was responsible for the general coordination, the analysis and the reporting, PTB performed the stability measurements for both standards, LNE was responsible for the practical organisation of the comparison, and NPL assisted in the reporting.

The comparison was organised in two parallel loops, referred to as A and B. Four weeks were allowed for each participant including transportation time to the next participant. However, due to the COVID-19 pandemic, it was not possible to keep to the original schedule due to laboratory closures and local restraints imposed on the laboratories. Nevertheless, the measurements by all 22 participants were completed in a time frame of less than two years. No technical issues occurred with any of the transfer standards.

The full list of participants is presented in alphabetical order in Table 1.

Table 1 - Participants of the comparison

BEV	Bundesamt für Eich- und Vermessungswesen	Austria
BIM	Bulgarian Institute of Metrology	Bulgaria
CEM	Centro Español de Metrología	Spain
CMI	Ceský Metrologický Institut	Czech Republic
EIM	Hellenic Institute of Metrology	Greece
GUM	Glówny Urzad Miar	Poland
INM	Institutul Național de Metrologie	Romania
INRIM	Istituto Nazionale di Ricerca Metrologica	Italy
JV	Justervesenet	Norway
LNE	Laboratoire National de Métrologie et d'Essais	France
METAS	Federal Institute of Metrology	Switzerland
METROSERT	AS Metrosert	Estonia
MIKES VTT	Centre for Metrology of the Technical Research Centre of Finland	Finland
MIRS/SIQ	Metrology Institute of the Republic of Slovenia / Slovenian Institute of Quality and Metrology	Slovenia
NPL	National Physical Laboratory	United Kingdom
PTB	Physikalisch-Technische Bundesanstalt	Germany
RISE	Research Institutes of Sweden	Sweden
SMU	Slovenský Metrologický Ústav	Slovakia
TRESCAL	Trescal Denmark	Denmark
TUBITAK UME	Ulusal Metroloji Enstitüsü	Turkey
UMTS	State Enterprise "Ukrmetrteststandard"	Ukraine
VSL	VSL B.V.	Netherlands

3 TRANSFER STANDARDS

3.1 DESCRIPTION OF THE TRAVELLING STANDARDS

Two travelling standards of the type RADIAN RD-22-332S were used in this key comparison in two parallel loops. These standards were adapted to measure active power at 120 V and 240 V and 5 A with outstanding stability in time. PTB provided travelling standard with serial number S/N 207172 that was used in loop A and VSL provided travelling standard with serial number S/N 208014 that was used in loop B.

The standards and accompanying accessories (connectors and power supplies) were provided with an individual rugged plastic container, suitable for shipping the standards by air. The standards were packaged with a temperature/humidity miniature logger. During measurements at the participant's laboratory, the logger remained on the top surface of the travelling standard, mainly close to the backlit LCD of the travelling standard, in order to log measurements of ambient temperature and humidity. The logging data were downloaded and monitored by PTB in order to keep track of the changes of temperature or humidity which may have occurred during transportation or while staying at the participating laboratory.

The reference standards were provided with a 24 V DC power supply, which was connected to the mains at 240 V, 50 Hz. The auxiliary power to the travelling standard was to be applied at least 4 hours before starting the tests.

3.2 QUANTITY TO BE MEASURED

The participating laboratories reported a single power measurement for each of the 10 possible combinations of voltage, current, and power factor referred to in Table 2. In this Table, "lead" is defined as the current phase leading the voltage phase, and "lag" as the current phase lagging the voltage phase. The measurement result reported was the calibration error of the travelling standard, defined as the difference between the value of the measured quantity indicated by the travelling standard and the applied value as determined by the participating laboratory, and divided by the nominal apparent power in VA. The value and uncertainty of the calibration were expressed in the unit µW/VA. The error is defined positive if the travelling standard's indication is larger than the applied value as determined by the participating laboratory.

Table 2 - Parameters for the measurement of active power

Parameter	**Value**
RMS voltage	120 V, 240 V
RMS current	5 A
Power factor	1.0, 0.5 lead, 0.5 lag, 0 lead, 0 lag
Frequency	53 Hz

3.3 Circulation scheme

The circulation scheme and time schedule are shown in Table 3 (Loop A) and Table 4(Loop B).

Table 3 – Travelling schedule of loop A

NMI/DI	Country	Start date	End date	Duration (calendar days)
PTB	Germany		04/02/2019	
GUM	Poland	04/02/2019	28/02/2019	24
PTB	Germany	04/03/2019	08/03/2019	4
CMI	Czech Republic	15/03/2019	16/04/2019	32
SMU	Slovakia	16/04/2019	22/05/2019	36
BEV	Austria	22/05/2019	24/06/2019	33
INM	Romania	26/06/2019	26/08/2019	61
PTB	Germany	29/08/2019	30/09/2019	32
UME	Turkey	04/11/2019	15/11/2019	11
MIRS/SIQ	Slovenia	06/12/2019	16/01/2020	41
INRIM	Italy	17/01/2020	24/02/2020	38
BIM	Bulgaria	27/02/2020	11/06/2020	105
EIM	Greece	12/06/2020	13/07/2020	31
PTB	Germany	10/08/2020	14/08/2020	4
UMTS	Ukraine	06/11/2020	10/12/2020	34
PTB	Germany	17/12/2020	06/01/2021	20

Table 4 – Travelling schedule of loop B

NMI/DI	Country	Start date	End date	Duration (calendar days)
PTB	Germany		04/02/2019	
TRESCAL	Denmark	05/02/2019	05/03/2019	28
PTB	Germany	11/03/2019	14/03/2019	3
RISE	Sweden	18/03/2019	23/04/2019	36
MIKES VTT	Finland	24/04/2019	24/05/2019	30
METROSERT	Estonia	27/05/2019	21/06/2019	25
VSL	Netherlands	26/06/2019	26/08/2019	61
PTB	Germany	27/08/2019	30/09/2019	34
JV	Norway	01/11/2019	02/12/2019	31
METAS	Switzerland	13/01/2020	17/03/2020	64
CEM	Spain	18/05/2020	18/06/2020	31
LNE	France	26/06/2020	04/08/2020	39
PTB	Germany	18/08/2020	21/08/2020	3
NPL	United Kingdom	08/09/2020	23/11/2020	76
PTB	Germany	30/11/2020	18/12/2020	18

4 MEASUREMENT DESCRIPTION

4.1 METHOD OF MEASUREMENT OF ACTIVE POWER

The participating laboratories followed their usual measurement procedure to achieve their best measurement capabilities within the allowed time frame for the comparison. Measurement results of individual laboratories were accompanied by a description of the method used and a layout of the primary current circuit with dimensions. The individual participants' measurement results are summarized in Appendix A, the data used for the calculations is provided as a separate digital supplement with a detailed explanation in Appendix B, and the participants' reports are shown in Appendix C.

The measurement setups used by the participants in this comparison show great similarities. The calibration signals are generated using a phantom power approach, generating voltage and current in two separate circuits. This is done using a power calibrator or a function generator with transimpedance and transconductance amplifiers. The calibration signals are applied simultaneously to the device(s) under test and the reference setup, which typically consists of either voltage and current scaling devices in combination with two sampling voltmeters or a commercial reference power meter. The phase relation between voltage and current measurement is defined using an external trigger. Voltage scaling is done using a resistive divider or an inductive voltage divider. Current to voltage conversion is done using a current shunt or a current transformer together with a current shunt.

4.2 MEASUREMENT CONDITIONS

The travelling standard was kept in the laboratory before the measurements for a period of time such that it reached stable temperature. The temperature and relative humidity were reported in the individual results. The value and uncertainty of the ambient temperature and relative humidity of the laboratory were reported. The travelling standard was de-energized between each set of measurements for 1 minute, followed by a warm up period of at least 15 minutes.

Voltage and current sources were set to 53 Hz with voltage and current magnitudes within 0.2 % of the values shown in Table I. At every power factor, the required number of measurements were taken as stated in the procedures of the calibration laboratory. Readings of active power, voltage, current, power factor and frequency displayed on the backlit LCD of the travelling standard were recorded. The average of at least five sets of measurements was computed.

4.3 UNCERTAINTY OF MEASUREMENT

All participants provided their results with the associated measurement uncertainty and a complete uncertainty budget including the Type A and Type B evaluations of the uncertainty of the NMI/DI's calibration system. The expanded uncertainty was calculated for a level of confidence of 95.45 %, corresponding to $k = 2$ for a normal distribution. The measurement uncertainty was determined according to the ISO Guide to the Expression of Uncertainty in Measurement (GUM). All participants supplied a statement of traceability to SI units.

5 RESULTS OF MEASUREMENT

5.1 DATA ANALYSIS

As stated by the CIPM MRA, “RMO key comparisons must be linked to the corresponding CIPM key comparisons by means of joint participants” and “only key comparisons carried out by a Consultative Committee or the BIPM lead to a key comparison reference value”. For a key comparison carried out by a regional metrology organization the link to the key comparison reference value is obtained by reference to the results from those institutes which have also taken part in the CIPM key comparison.” In this RMO key comparison the following approach has been employed for each of the compared quantities:

1. An internal RMO reference value has been calculated based on the submitted results by the participants of the Euramet comparison only, as well as degrees-of-equivalence.
2. For the laboratories participating both in the CIPM and in the Euramet comparison, a comparison of the degrees-of-equivalence obtained in each of the comparisons has been made, resulting in a linking correction.
3. This linking correction can be used to calculate an updated, linked RMO reference value, as well as updated, linked degrees of equivalence.

In the next sections these steps will be presented in more detail. First, the calculation of the internal RMO reference value for the Euramet.EM-K5.2018 comparison is explained. This calculation will be performed following the mainstream approach presented in [2] extended to the general, multi-dimensional case in [3], as there are two loops in the comparison. After this, the calculation of the linking correction will be presented in more detail, after which the computed numerical values for the linked degrees of equivalence will be presented. The analysis finishes with a brief discussion.

5.2 SYMBOLS AND ABBREVIATIONS

In order not to make the notation too complex the test point is not explicitly indexed as a parameter in the notation. The mathematical model and analysis process has been repeated for each of the ten test points which are specified by the required voltage, current and PF values. Where relevant, the loop is indicated with superscript A or B. The notation is introduced in Table 5 for loop A; the notation for loop B is defined in an analogous way.

Table 5 - Symbols and abbreviations. The notation for loop B is defined in an analogous way as that for loop A.

MRA	Mutual Recognition Agreement
CIPM	International Committee of Weights and Measures
CCEM	Consultative Committee for Electricity and Magnetism
RMO	Regional Metrology Organization
Euramet	RMO for Europe
TS	Travelling Standard: artefact that has been sent around
PL	Pilot Laboratory: laboratory where the standards have been repeatedly measured (in this case PTB)
REF	RMO comparison reference value
KCRV	Key Comparison Reference Value of the CIPM comparison to which this comparison links
LKCRV	Linked Key Comparison Reference Value, the updated REF after linking it to the CIPM comparison based on the results of the linking laboratories

RDOE	RMO Degree of Equivalence, calculated with respect to REF
DOE	Degree Of Equivalence, calculated with respect to the LKCRV
y_0^A	true value of loop A: the unknown value of the calibration error of TS A
y_{ref}^A	RMO reference value in loop A, the best estimate of y_0^A based on the provided measurement results of the measurements performed within the RMO comparison only
y_{lkcrv}^A	LKCRV in loop A
ℓ	correction term for linking the CIPM KCRV to the RMO REF value and similarly for linking the DOEs
y_i	measured value by laboratory i, whereby the index i implicitly specifies if TS A or TS B has been measured. The PL has two indices, one for each TS.
$y_{i,j}$	j-th repetition of measured value by laboratory i (only relevant for the PL)
δ_i^A	instrument instability of TS A measured at laboratory i
η_i	measurement error of laboratory i
u_i	standard uncertainty of η_i provided by laboratory i
r	correlation coefficient of the measurement error for any laboratory when performing repeated measurements (relevant for the PL and for the linking laboratories)
u_{TS}^A	standard uncertainty of δ_i^A (value independent of laboratory i)
$u(y_i)$	standard uncertainty of y_i, combining u_i and u_{TS}^A (or u_{TS}^B)
n^A	number of participating laboratories in loop A
m	number of repetitions at the PL for each test point
i_{PL}^A	index of the PL in loop A
k	coverage factor for the expanded uncertainty
d'_i	RMO degree of equivalence of laboratory i (i.e. with respect to REF)
E'_i	normalized RDOE of laboratory i (i.e. with respect to REF)
d_i	degree of equivalence of laboratory i with respect to LKCRV
E_i	normalized DOE of laboratory i (i.e. with respect to LKCRV)

5.3 Assumptions

Some of the modelling assumptions and choices that have been used to solve the mathematical model are listed below. The pertinence of the assumptions has been verified by means of the data wherever possible.

- The uncertainties of all laboratories are considered independent.
- For repetitive measurements, the uncertainty of individual laboratories is assumed to be largely systematic, i.e. the measurement uncertainties for the same laboratory have correlation coefficient $r = 0.8$.
- The PL has participated with the average result of the 5 repeated stability measurements. In view of the assumed correlation, the PL laboratory uncertainty for the mean equals $u\sqrt{(1+4r)/5} = 0.92\,u$, whereby u is the uncertainty provided for each of the five measurements. The additional random uncertainty due to the TS will average out by a factor $1/\sqrt{5}$.
- Although the PL is assumed to have some random uncertainty, the observed variation in the repeated stability measurement results by the PL is entirely attributed to the instabilities of

the two TSs in order not to underestimate the TS uncertainty if the assumed correlation coefficient r would be too low.

- The instrument instabilities are fully random, no drift correction over time is needed. (This has been verified by fitting a line to the repeated stability measurements at the PL, and verifying that the slope coefficient of the line is not statistically different from zero.)
- The link with the related CCEM-K5.2017 comparison (KCRV) is based on the calculation of a correction term to the degrees of equivalence in this Euramet RMO comparison (RDOEs) in order to establish linked degrees of equivalence (LDOEs). This procedure can also be interpreted as the calculation of new linked reference values for the Euramet.EM-K5.2018 comparison. The correction term due to the link turned out to be insignificant in view of its uncertainty, but can nevertheless be used to align the realized DOEs in both comparisons as much as possible.

A more detailed discussion of the instrument instabilities based on the results of the repeated measurements at the PL can be found in section 5.6.

5.4 Mathematical model

The measured value y_i^A (i.e., the calibration error) of TS A by laboratory i at a specific test point can be modelled as a sum of the true value y_0^A, the (mean-zero) instrument instability δ_i^A, and the (mean-zero) measurement error η_i of the laboratory in the following way (similarly for TS B):

$$y_i = y_0^A + \delta_i^A + \eta_i \qquad 1 \le i \le n^A \qquad (1)$$

$$y_i = y_0^B + \delta_i^B + \eta_i \qquad n^A + 1 \le i \le n^A + n^B \qquad (2)$$

where the laboratories with indices 1 to n^A have measured TS A in loop A and the laboratories with indices $n^A + 1$ to $n^A + n^B$ TS B in loop B. As the PL has measured both TSs, it has two corresponding indices denoted by i_{PL}^A and i_{PL}^B. As the measurement error of the PL is assumed to be correlated between various measurements, the correlation between $\eta_{i_{PL}^A}$ and $\eta_{i_{PL}^B}$ can be used to connect the results of loops A and B with each other. In this analysis it is assumed that the errors are largely correlated, i.e.,

$$r\left(\eta_{i_{PL}^A}, \eta_{i_{PL}^B}\right) = 0.8 \qquad (3)$$

The standard uncertainty u_i of the measurement error η_i is provided by laboratory i itself:

$$u(\eta_i) = u_i$$

The standard uncertainties u_{TS}^A and u_{TS}^B of the travelling standards are determined based on the $m = 5$ repeated measurements by the PL and are the same for each laboratory. This calculation is presented in section 5.6. These values only depend on the TS and not on the laboratory i:

$$u(\delta_i^A) = u_{\mathrm{TS}}^A$$

$$u(\delta_i^B) = u_{\mathrm{TS}}^B$$

The combined uncertainty $u(y_i)$ of the measurements y_i follows from combining the laboratory uncertainty u_i with the instrument instability uncertainty u_{TS}^A or u_{TS}^B. For the laboratories which measured the standard once (all but the PL), this yields:

$$u(y_i) = \sqrt{u_i^2 + {u_{TS}^A}^2} \qquad 1 \leq i \leq n^A, \qquad i \neq i_{PL}^A \tag{4}$$

$$u(y_i) = \sqrt{u_i^2 + {u_{TS}^B}^2} \qquad n^A + 1 \leq i \leq n^A + n^B, \qquad i \neq i_{PL}^B \tag{5}$$

The PL has measured both standards five times. It is assumed that the PL laboratory uncertainties are correlated for different measurements with correlation coefficient r according to equation (3), whereas the instrument stability uncertainty is random, and is averaged over the five measurements. The reported values $y_{i_{PL}^A}$ and $y_{i_{PL}^B}$ are the mean values over all repeated measurements. The combined uncertainties in loop A and B for the PL are now given by

$$u(y_{i_{PL}^A}) = \sqrt{(u_{i_{PL}^A}^2 (1 + 4r) + {u_{TS}^A}^2)/5} \tag{6}$$

$$u(y_{i_{PL}^B}) = \sqrt{(u_{i_{PL}^B}^2 (1 + 4r) + {u_{TS}^B}^2)/5}\,. \tag{7}$$

The equations (1) and (2) above can be written in matrix notation in the following form:

$$\boldsymbol{y} = X\, \boldsymbol{y}_0 + \boldsymbol{\delta} + \boldsymbol{\eta} \tag{8}$$

with

$$\boldsymbol{y} = \begin{pmatrix} y_1 \\ \vdots \\ y_{n^A} \\ y_{n^A+1} \\ \vdots \\ y_{n^A+n^B} \end{pmatrix}, \quad X = \begin{pmatrix} 1 & 0 \\ \vdots & \vdots \\ 1 & 0 \\ 0 & 1 \\ \vdots & \vdots \\ 0 & 1 \end{pmatrix}, \quad \boldsymbol{y}_0 = \begin{pmatrix} y_0^A \\ y_0^B \end{pmatrix}, \quad \boldsymbol{\delta} = \begin{pmatrix} \delta_1^A \\ \vdots \\ \delta_{n^A}^A \\ \delta_{n^A+1}^B \\ \vdots \\ \delta_{n^A+n^B}^B \end{pmatrix}, \quad \boldsymbol{\eta} = \begin{pmatrix} \eta_1 \\ \vdots \\ \eta_{n^A} \\ \eta_{n^A+1} \\ \vdots \\ \eta_{n^A+n^B} \end{pmatrix}$$

and associated covariance matrix of $\boldsymbol{\delta} + \boldsymbol{\eta}$ given by

$$V_{\boldsymbol{y}} = \begin{pmatrix} v_{1,1} & \cdots & v_{1,n^A+n^B} \\ \vdots & \ddots & \vdots \\ v_{n^A+n^B,1} & \cdots & v_{n^A+n^B,n^A+n^B} \end{pmatrix}. \tag{9}$$

The only non-zero entries $v_{i,j}$ of the covariance matrix $V_{\boldsymbol{y}}$ are given by the diagonal entries $v_{i,i}$ and the entries resulting from the covariance of the measurements by the PL:

$$v_{i,i} = u^2(y_i)$$

$$v_{i_{PL}^A, i_{PL}^B} = v_{i_{PL}^B, i_{PL}^A} = r\, u_{i_{PL}^A} u_{i_{PL}^B}\,.$$

Note that even in the case of $r = 1$, the variables $y_{i_{PL}^A}$ and $y_{i_{PL}^B}$ would not be fully correlated due to the random uncertainties of the TSs.

The solution of the weighted least squares problem corresponding to (8) and (9) follows from minimizing the function

$$\boldsymbol{a} \mapsto (\boldsymbol{y} - X\boldsymbol{a})^{\mathrm{T}} V_{\boldsymbol{y}}^{-1} (\boldsymbol{y} - X\boldsymbol{a}).$$

The solution $\widehat{\boldsymbol{a}} = \boldsymbol{y}_{\mathrm{ref}}^{AB} = \left(y_{\mathrm{ref}}^{A}, y_{\mathrm{ref}}^{B}\right)^{\mathrm{T}}$ and associated covariance matrix $V_{\widehat{\boldsymbol{a}}}$ are given by

$$\boldsymbol{y}_{\mathrm{ref}}^{AB} = V_{\boldsymbol{y}_{\mathrm{ref}}^{AB}}^{-1} X^{\mathrm{T}} V_{\boldsymbol{y}}^{-1} \boldsymbol{y} \qquad \text{and} \qquad V_{\boldsymbol{y}_{\mathrm{ref}}^{AB}} = \left(X^{\mathrm{T}} V_{\boldsymbol{y}}^{-1} X\right)^{-1}.$$

In section 0, y_{ref}^{A} will be referred to by REF-A, and y_{ref}^{B} by REF-B.

The RMO degrees of equivalence (RDOE) d'_i are defined by

$$d'_i = y_i - y_{\mathrm{ref}}^{A} \qquad \text{for } 1 \le i \le n_A \tag{10}$$

$$d'_i = y_i - y_{\mathrm{ref}}^{B} \qquad \text{for } n_A + 1 \le i \le n_A + n_B \tag{11}$$

or in vector notation

$$\boldsymbol{d}' = \boldsymbol{y} - \boldsymbol{y}_{\mathrm{ref}} \quad \text{with} \quad \boldsymbol{y}_{\mathrm{ref}} = X\, \boldsymbol{y}_{\mathrm{ref}}^{AB}$$

The uncertainty of the DOEs are given by the covariance matrix

$$V_{\boldsymbol{d}'} = V_{\boldsymbol{y}} - V_{\boldsymbol{y}_{\mathrm{ref}}} \qquad \text{where} \qquad V_{\boldsymbol{y}_{\mathrm{ref}}} = X\, V_{\boldsymbol{y}_{\mathrm{ref}}^{AB}}\, X^{\mathrm{T}}$$

See [3] for the details of the computation.

Component-wise this corresponds to

$$u(d'_i) = \sqrt{u^2(y_i) - u^2(y_{\mathrm{ref}}^{A})} \quad \text{for } 1 \le i \le n^A$$

$$u(d'_i) = \sqrt{u^2(y_i) - u^2(y_{\mathrm{ref}}^{B})} \quad \text{for } n^A + 1 \le i \le n^A + n^B$$

where $u^2\left(y_{\mathrm{ref}}^{A}\right)$ and $u^2(y_{\mathrm{ref}}^{B})$ are given by entries (1,1) and (2,2) of the 2 × 2 matrix $V_{\widehat{\boldsymbol{a}}}$.

The (signed) normalized RDOE E'_i equals d'_i normalized by $k\, u(d'_i)$ where k denotes a coverage factor, usually $k = 2$. The expression for E'_i is then given by

$$E'_i = \frac{d'_i}{2\, u(d'_i)}$$

For PTB two RDOEs, $d'_{i_{PL}^{A}}$ and $d'_{i_{PL}^{B}}$, are available corresponding to the measurement of the two TSs. These DOEs can be combined into a single RDOE d'_{PL} by computing their uncertainty weighted average in the following way, where $\boldsymbol{e} = (1{,}1)^{\mathrm{T}}$, $\boldsymbol{d}'_{\mathrm{PL}} = (d'_{i_{PL}^{A}}, d'_{i_{PL}^{A}})^{\mathrm{T}}$ and $V_{\boldsymbol{d}'_{\mathrm{PL}}}$ denotes the covariance matrix of $\boldsymbol{d}'_{\mathrm{PL}}$:

$$u(d'_{\mathrm{PL}}) = \left(\boldsymbol{e}^{\mathrm{T}}\, V_{\boldsymbol{d}'_{\mathrm{PL}}}{}^{-1}\, \boldsymbol{e}\right)^{-1/2} \tag{12}$$

$$d'_{\mathrm{PL}} = (\boldsymbol{e}^{\mathrm{T}}\, V_{\boldsymbol{d}'_{\mathrm{PL}}}{}^{-1} \boldsymbol{d}'_{\mathrm{PL}})\, u^2(d'_{\mathrm{PL}}) \tag{13}$$

The normalized RDOE E'_{PL} then follows from $E'_{\mathrm{PL}} = d'_{\mathrm{PL}} \,/\, (2\, u(d'_{\mathrm{PL}}))$.

5.5 LARGEST SUBSET OF CONSISTENT VALUES AND DETERMINATION OF THE RMO REFERENCE VALUE

There are various methods for assessing if the results provided by the laboratories are consistent. In [2] and [3] a chi-squared test is proposed. This test provides valid results (i.e., with a correct significance level) regarding the consistency of the measured values by the laboratories if the uncertainties provided by all laboratories are appropriate. If some laboratories overestimated and others underestimated their uncertainties, the chi-squared test may not have the desired significance level. The test may indicate consistency in a situation where there actually is a problem and where further analysis is required. Furthermore, in the case one laboratory underestimates its uncertainty this may result in a shift of the reference value resulting in unreasonably high E'_i values for other laboratories. This may not be fair to these other laboratories and it may not give a proper representation of the capabilities of the participants of the comparison.

ISO 17043 [4] suggests that

- $|E'_i| \leq 1$ indicates "satisfactory" performance and generates no signal;
- $|E'_i| > 1$ indicates "unsatisfactory" performance and generates an action signal.

In this report this latter approach has been followed in the following way: for every test point the reference value is calculated using the results of all laboratories and the E'_i values for all laboratories are calculated. If one or more laboratories have a value with $|E'_i| > 1$, the laboratory with the highest absolute value is excluded from contributing to the calculation of the reference value and the evaluation of the mathematical model is repeated without the measurement result of that laboratory. If there are still laboratories with $|E'_i| > 1$ the process is repeated again by excluding one additional lab, and this iteratively continues until all laboratories contributing to the reference value for a specific test point have $|E'_i| \leq 1$. After establishing the reference value the degrees of equivalence for the excluded laboratories can be calculated using

$$u(d'_i) = \sqrt{u^2(y_i) + u^2(y^A_{\mathrm{ref}})} \quad \text{if } 1 \leq i \leq n^A \text{ and laboratory } i \text{ not contributing to } y^A_{\mathrm{ref}}$$

$$u(d'_i) = \sqrt{u^2(y_i) + u^2(y^B_{\mathrm{ref}})} \quad \text{if } n^A + 1 \leq i \leq n^A + n^B \text{ and laboratory } i \text{ not contributing to } y^B_{\mathrm{ref}}$$

Note the plus sign in the equations above which is due to the fact that y_i and y^A_{ref} resp. y^B_{ref} are now independent. The normalized error values with respect to the RMO reference value for these laboratories can be calculated in the usual way by means of $E'_i = d'_i/(2\,u(d'_i))$.

Bilateral DOEs d'_{ij} between laboratories i and j and their uncertainties $u(d'_{ij})$ can now be calculated using the vector $\boldsymbol{e}_{ij} = (0, \ldots, 0, 1, 0, \ldots, 0, -1, 0, \ldots 0)^{\mathrm{T}}$, whereby the 1 is at position i and the -1 is at position j, in the following way:

$$d'_{ij} = \boldsymbol{e}^{\mathrm{T}}_{ij}\,\boldsymbol{d}' = d'_i - d'_j \tag{14}$$

$$u(d'_{ij}) = \sqrt{\boldsymbol{e}^{\mathrm{T}}_{ij}\, V_{\boldsymbol{d}'}\, \boldsymbol{e}_{ij}} = \sqrt{u^2(d'_i) + u^2(d'_j) - 2\,u(d'_i, d'_j)}, \tag{15}$$

where $u(d'_i, d'_j)$ denotes the covariance between d'_i and d'_j, corresponding to entry (i, j) from $V_{\boldsymbol{d}'}$.

The bilateral DOEs have not been reported in this document, but are part of the digital supplement (that is considered Appendix D of this report, not printed out in this document, but with a read-me as Appendix B of this document).

5.6 CALCULATION OF THE TRAVELING STANDARD INSTABILITIES

As overall (single) reported values from the PL for each loop the mean values of the $m = 5$ repeated measurements $y_{i_{PL}^A,j}$ and $y_{i_{PL}^B,j}$ $(1 \le j \le 5)$ are used:

$$y_{i_{PL}^A} = \frac{1}{5}\sum_{j=1}^{5} y_{i_{PL}^A,j}$$

$$y_{i_{PL}^B} = \frac{1}{5}\sum_{j=1}^{5} y_{i_{PL}^B,j}$$

The standard uncertainties $u_{\mathrm{TS}}^A = u(\delta_i^A)$ and $u_{\mathrm{TS}}^B = u(\delta_i^B)$ due to the instabilities of the traveling standards are calculated from the standard deviation of the repeated measurements:

$$u_{\mathrm{TS}}^A = \sqrt{\frac{1}{4}\sum_{j=1}^{5}\left(y_{i_{PL}^A,j} - y_{i_{PL}^A}\right)^2}$$

$$u_{\mathrm{TS}}^B = \sqrt{\frac{1}{4}\sum_{j=1}^{5}\left(y_{i_{PL}^B,j} - y_{i_{PL}^B}\right)^2}$$

The resulting values for the standard uncertainty of TS A and B can be found in Table 6.

Table 6 - Calculated standard uncertainty u_{TS}^A and u_{TS}^B for instrument instability per test point expressed in ppm.

Test point	120 V 5 A PF = 1	120 V 5 A 0.5 lead	120 V 5 A 0 lead	120 V 5 A 0.5 lag	120 V 5 A 0 lag	240 V 5 A PF = 1	240 V 5 A 0.5 lead	240 V 5 A 0 lead	240 V 5 A 0.5 lag	240 V 5 A 0 lag
u_{TS}^A [ppm]	2.4	1.4	1.2	1.8	0.9	2.8	1.2	1.2	1.7	0.7
u_{TS}^B [ppm]	0.6	0.7	1.1	0.2	0.4	1.4	0.9	0.7	1.0	0.6

In appendix A all measurement data is listed and plotted, including the repeated measurements by the PTB. From these plots it becomes clear that no systematic drift is present, which has been confirmed by a statistical test for the significance of the fitted slope.

5.7 LINKING PROCEDURE

In order to link this RMO (Euramet) comparison to the worldwide CIPM (CCEM) comparison, the results of the four linking laboratories LNE, PTB, RISE and VSL in both comparisons have been considered. Let $d_i^{(\mathrm{CIPM})}$ denote the degree of equivalence of laboratory i in the CIPM comparison and d_i its degree of equivalence in the RMO comparison after correction of d_i' by means of the linking procedure. In view of the mean zero measurement errors for all laboratories, and in the case of consistent measurements, it should hold in particular for the DOEs of linking laboratories that

$$d_k^{(\mathrm{CIPM})} \approx d_k \tag{16}$$

whereby inequality can be due to the uncertainties in all of the considered measurements as well as the behaviour of the TSs. The goal of the linking procedure is to determine a linking correction ℓ that can be used to compute linked DOEs d_i for the laboratories not participating in the CIPM comparison based on the RMO DOE d'_i. This will be done according to

$$d_i = d'_i + \ell \tag{17}$$

If the model including all reported and calculated uncertainties and assumed correlations appropriately fits the data, the linking correction value ℓ will be insignificantly different from 0 in view of its uncertainty. Still this DOE correction can be used to align the realized CIPM and RMO DOEs as much as possible.

Note that equation (17) can also be interpreted as the computation of an updated reference value for the RMO comparison, that is called in this report the 'linked key comparison reference value' (LKCRV), by writing

$$d_i = d'_i + \ell = y_i - y_{\mathrm{ref}} + \ell = y_i - (y_{\mathrm{ref}} - \ell),$$

indicating that the LKCRV can be defined by

$$y_{\mathrm{lkcrv}} = y_{\mathrm{ref}} - \ell \tag{18}$$

such that $d_i = y_i - y_{\mathrm{lkcrv}}$. This computation can be performed for both loop A and B.

Writing $d_k^{(\mathrm{CIPM})} = y_k^{(\mathrm{CIPM})} - y_{\mathrm{kcrv}}^{(\mathrm{CIPM})}$ and $d_k = y_k - y_{\mathrm{lkcrv}}$, equation (16) can be transformed into

$$y_{\mathrm{lkcrv}} \approx y_{\mathrm{kcrv}}^{(\mathrm{CIPM})} - y_k^{(\mathrm{CIPM})} + y_k$$

showing that the estimate of the LKCRV does not depend on the RMO internal reference value y_{ref}.

The difference in all these formulations and possible definitions of a linking correction term is how the contributions of the individual linking laboratories will be weighted when computing the overall estimate of the link and its uncertainty.

In this report the linking correction ℓ has been defined by equation (17). Based on the measurement results of each linking laboratory and equations (16) and (17) estimates ℓ_k of ℓ can be calculated by means of

$$\ell_k = d_k^{(\mathrm{CIPM})} - d'_k \tag{19}$$

The evaluation of the uncertainties of the ℓ_k is more complicated than the calculation of the values ℓ_k, as the underlying terms are correlated. Calling the (drift corrected) measurement data of the CIPM comparison $\boldsymbol{x}$ and its full uncertainty matrix $V_{\boldsymbol{x}}$ and introducing

$$\boldsymbol{z} = \begin{pmatrix} \boldsymbol{x} \\ \boldsymbol{y} \end{pmatrix} \quad \text{and} \quad V_{\boldsymbol{z}} = \begin{pmatrix} V_{\boldsymbol{x}} & (\mathrm{cov}) \\ (\mathrm{cov}) & V_{\boldsymbol{y}} \end{pmatrix},$$

the correlations between the measurements in the CIPM and in the RMO comparison can now be integrated by inserting appropriate covariance terms in the matrix $V_{\boldsymbol{z}}$ in the submatrices indicated by (cov). This has been done by means of the same procedure used for constructing $V_{\boldsymbol{y}}$ above (and $V_{\boldsymbol{x}}$ in the CIPM analysis), using the same correlation coefficient from equation (3). By stacking all linear transformations described in this report and similarly for the CIPM analysis, sensitivity matrices $C^{(\mathrm{CIPM})}$ and $C^{(\mathrm{RMO})}$ can be calculated such that

$$\boldsymbol{d}^{(\mathrm{CIPM})} = C^{(\mathrm{CIPM})}\,\boldsymbol{x} \quad \text{and} \quad \boldsymbol{d}' = C^{(\mathrm{RMO})}\,\boldsymbol{y}$$

Note that $\boldsymbol{x}$, $V_{\boldsymbol{x}}$ and $C^{(\mathrm{CIPM})}$ have all been made digitally available in the digital supplement to the report of the CCEM-K5.2017 comparison which is related this Euramet.EM-K5.2018 comparison. Let $C_{\mathrm{link}}^{(\mathrm{CIPM})}$ contain only the rows of $C^{(\mathrm{CIPM})}$ that correspond to linking laboratories, and similarly for $C_{\mathrm{link}}^{(\mathrm{RMO})}$. By defining

$$C_{\mathrm{link}} = \begin{pmatrix} C_{\mathrm{link}}^{(\mathrm{CIPM})} & 0 \\ 0 & C_{\mathrm{link}}^{(\mathrm{RMO})} \end{pmatrix} \quad \text{and} \quad F = \begin{pmatrix} 1 & 0 & 0 & -1 & 0 & 0 \\ 0 & \ddots & 0 & 0 & \ddots & 0 \\ 0 & 0 & 1 & 0 & 0 & -1 \end{pmatrix}$$

the vector $\boldsymbol{\ell}$ containing the estimates ℓ_k and their associated covariance matrix $V_{\boldsymbol{\ell}}$ can be computed from

$$\boldsymbol{\ell} = F\,C_{\mathrm{link}}\,\boldsymbol{z} \quad \text{and} \quad V_{\boldsymbol{\ell}} = F\,C_{\mathrm{link}}\,V_{\boldsymbol{z}}\,C_{\mathrm{link}}{}^{\mathrm{T}}F^{\mathrm{T}}.$$

The uncertainty-weighted estimate of the linking correction ℓ of equation (17) and its uncertainty $u(\ell)$ can now be computed in a similar way as what was done in equations (12) and (13). However, in order to assure that the computed uncertainty $u(\ell)$ is not unrealistically low compared to the observed dispersion of the ℓ_k, a chi-squared test of the consistency of the entries of $\boldsymbol{\ell}$ in view of the covariance matrix $V_{\boldsymbol{\ell}}$ was performed at a 95 % confidence level. It was seen as inappropriate to exclude any linking laboratory from contributing to the computation of the linking correction, as the individual analyses of the CCEM and Euramet comparisons had not excluded any of these results either. In the case of inconsistency, an additional uncertainty term $\delta\ell_k$ was added to equation (17) for the linking laboratories with an uncertainty just large enough to make the consistency test pass, i.e.

$$d_k = d'_k + \ell + \delta\ell_k \tag{20}$$

The uncertainties $u^2(\delta\ell_k)$ have been chosen identical for each linking laboratory, which will be called $u^2(\delta\ell)$. This procedure corresponds to adding a diagonal matrix $V_{\boldsymbol{\delta\ell}}$ with entries $u^2(\delta\ell)$ on the diagonal to $V_{\boldsymbol{\ell}}$ before calculating the weighted average. Denoting the vector with calculated weights $\boldsymbol{g}$, it is found that

$$\ell = \boldsymbol{g}^{\mathrm{T}}\boldsymbol{\ell}$$

$$u^2(\ell) = \boldsymbol{g}^{\mathrm{T}}(V_{\boldsymbol{\ell}} + V_{\boldsymbol{\delta\ell}})\,\boldsymbol{g} = \boldsymbol{g}^{\mathrm{T}}V_{\boldsymbol{\ell}}\,\boldsymbol{g} + \boldsymbol{g}^{\mathrm{T}}V_{\boldsymbol{\delta\ell}}\,\boldsymbol{g} = \boldsymbol{g}^{\mathrm{T}}V_{\boldsymbol{\ell}}\,\boldsymbol{g} + (\boldsymbol{g}^{\mathrm{T}}\boldsymbol{g})u^2(\delta\ell) = \boldsymbol{g}^{\mathrm{T}}V_{\boldsymbol{\ell}}\,\boldsymbol{g} + u^2(\widetilde{\delta\ell})$$

where $u^2(\widetilde{\delta\ell}) = (\boldsymbol{g}^{\mathrm{T}}\boldsymbol{g})u^2(\delta\ell)$. The uncertainty $u(\widetilde{\delta\ell})$ is the uncertainty that is quadratically added to the uncertainty of ℓ and it is roughly about a factor 2 smaller than the added uncertainty $u(\delta\ell)$ to the results of the individual linking laboratories, which is due to the averaging effect of using four linking laboratories. The uncertainty $u(\widetilde{\delta\ell})$ is also used in the uncertainty calculation of the LKCRV of equation (18), i.e.:

$$u^2(y_{\mathrm{lkcrv}}) = u^2(y_{\mathrm{ref}} - \ell) + u^2(\widetilde{\delta\ell}) \tag{21}$$

The points with increased linking uncertainty were: point 1 ($u(\widetilde{\delta\ell}) = 2.1$ ppm), point 4 ($u(\widetilde{\delta\ell}) = 1.2$ ppm), point 9 ($u(\widetilde{\delta\ell}) = 1.1$ ppm) and point 10 ($u(\widetilde{\delta\ell}) = 0.04$ ppm). The finally obtained values and uncertainties of the linking value can be found in Table 7. Note that the absolute value of each linking correction is smaller than twice its standard uncertainty which indicates that there is no significant difference between the CIPM DOEs and the Euramet DOEs.

Table 7 - Linking values and their expanded uncertainties (k = 2) of the Euramet comparison with the CIPM comparison for each of the ten test points.

Test point	120 V 5 A PF = 1	120 V 5 A 0.5 lead	120 V 5 A 0 lead	120 V 5 A 0.5 lag	120 V 5 A 0 lag	240 V 5 A PF = 1	240 V 5 A 0.5 lead	240 V 5 A 0 lead	240 V 5 A 0.5 lag	240 V 5 A 0 lag
ℓ $(2u(\ell))$	-4.6 (6.3)	-1.3 (3.9)	1.1 (3.5)	-3.2 (4.7)	-1.1 (3.4)	-3.6 (4.5)	-2.2 (3.8)	2.4 (3.4)	-3.4 (4.4)	-1.2 (3.3)

Using a similar matrix-based approach as above, the uncertainty $u(d_i)$ of the linked DOE d_i of equation (20) can be computed in a way that respects all involved covariances, as well as the calculated additional uncertainty $u(\widetilde{\delta\ell})$ of the link.

Finally, note that the linking procedure does not affect the value and uncertainty of the bilateral DOEs between the RMO partners as the linking term ℓ does not affect the difference between DOEs. Thus we have for the DOEs d_{ij} after linking

$$d_{ij} = d'_{ij}$$

6 RESULTS OF THE COMPARISON

6.1 RMO REFERENCE VALUES AND LINKED KEY COMPARISON REFERENCE VALUE

In Table 8 and Table 9, respectively, for each test point the linked key comparison reference values y^A_{lkcrv} resp. y^B_{lkcrv} with expanded uncertainty ($k = 2$), the RMO reference values y^A_{ref} and y^B_{ref} with expanded uncertainty ($k = 2$) and the reported values by each laboratory for loop A resp. B are shown, together with the expanded combined uncertainty $2\,u(y_i)$ calculated using equations (3), (4), (5) and (6) and the values in Table 7. Measurement results not contributing to the calculation of the RMO reference value have been marked with an asterisk. Graphs with a visual representation of the measured values and reported expanded laboratory uncertainties $2\,u_i$ can be found in appendix A.

Table 8 - LKCRV and RMO reference values and reported values with expanded combined uncertainties (k = 2) in parentheses for loop A. The results marked with an asterisk (*) have not contributed to the calculation of the RMO reference value.

Test point / Lab	120 V 5 A PF = 1	120 V 5 A 0.5 lead	120 V 5 A 0 lead	120 V 5 A 0.5 lag	120 V 5 A 0 lag	240 V 5 A PF = 1	240 V 5 A 0.5 lead	240 V 5 A 0 lead	240 V 5 A 0.5 lag	240 V 5A 0 lag
LKCRV-A	14.2 (7.4)	5.7 (5.1)	-0.9 (4.7)	7.2 (5.7)	-1.1 (4.6)	20.8 (6.0)	11.1 (5.1)	-1.8 (4.7)	11.5 (5.6)	-1.4 (4.6)
REF-A	9.6 (5.4)	4.4 (4.8)	0.3 (4.2)	4.0 (4.9)	-2.2 (4.1)	17.1 (5.4)	8.9 (4.9)	0.5 (4.2)	8.1 (5.0)	-2.6 (4.2)
GUM	-8.0 (53.2)	-1.0 (32.1)	3.0 (32.1)	-7.0 (32.2)	-3.0 (32.1)	4.0 (53.3)	5.0 (32.1)	4.0 (32.1)	-2.0 (32.2)	-4.0 (32.0)
CMI	6.2 (24.5)	6.2 (14.3)	1.9 (8.5)	1.6 (14.5)	-4.4 (8.4)	18.0 (24.7)	12.2 (14.2)	3.8 (8.5)	5.5 (14.4)	-6.0 (8.3)
SMU	-1.5 (61.4)	2.8 (71.9)	4.2 (71.8)	-4.9 (71.6)	-5.6 (73.0)	11.7 (65.6)	8.9 (74.8)	4.4 (75.7)	1.6 (71.1)	-5.8 (77.8)
BEV	-5.5 (58.9)	-0.0 (56.3)	-4.1 (53.8)	0.5 (55.9)	1.7 (54.3)	6.6 (58.1)	6.4 (55.0)	3.6 (53.8)	3.0 (55.6)	11.4 (55.0)
INM	18.0 (54.2)	3.0 (58.1)	-	16.0 (64.1)	-	21.0 (52.3)	12.0 (58.1)	-	16.0 (52.1)	-
TUBITAK	-8.7* (17.4)	-5.4 (14.0)	-0.1 (12.6)	-2.3 (14.2)	-0.5 (12.5)	5.7 (19.0)	4.5 (15.2)	2.4 (14.0)	-0.1 (15.4)	-3.6 (13.9)
PTB	10.6 (9.4)	3.4 (9.3)	-3.8 (9.2)	6.9 (9.3)	1.8 (9.2)	21.3 (9.5)	7.7 (9.2)	-5.4 (9.2)	13.9 (9.3)	3.5 (9.2)
SIQ	-1.2 (25.4)	-1.2 (25.2)	0.4 (25.1)	-0.6 (25.3)	-0.5 (25.1)	0.5 (25.6)	-3.1 (25.1)	-4.1 (25.1)	2.1 (25.2)	1.6 (25.0)
INRIM	1.6 (15.9)	-0.8 (13.9)	-0.1 (13.2)	-0.4 (14.1)	-2.7 (13.1)	11.9 (17.0)	7.2 (14.3)	3.2 (13.6)	2.8 (14.5)	-5.5 (13.5)
BIM	-15.8* (14.6)	32.8* (24.2)	2.2 (24.0)	-48.8* (24.3)	-12.8 (24.0)	-7.3* (15.2)	40.5* (24.3)	5.7 (24.2)	-48.1* (24.4)	-16.1 (24.1)
EIM	8.0 (117.1)	11.3 (107.6)	1.3 (103.6)	-12.3 (106.7)	-18.3 (103.6)	18.1 (116.8)	16.8 (107.5)	21.8 (104.3)	-7.9 (107.2)	-17.1 (104.9)
UMTS	4.1 (18.8)	3.3 (26.6)	4.4 (23.5)	-1.5 (26.5)	-0.3 (23.5)	2.5 (19.0)	2.4 (26.5)	3.7 (23.3)	-0.4 (26.6)	-2.0 (23.2)

Table 9 - LKCRV and RMO reference values and reported values with expanded combined uncertainties (k = 2) in parentheses for loop B. The results marked with an asterisk (*) have not contributed to the calculation of the RMO reference value.

Test point / Lab	120 V 5 A PF = 1	120 V 5 A 0.5 lead	120 V 5 A 0 lead	120 V 5 A 0.5 lag	120 V 5 A 0 lag	240 V 5 A PF = 1	240 V 5 A 0.5 lead	240 V 5 A 0 lead	240 V 5 A 0.5 lag	240 V 5A 0 lag
LKCRV-B	2.8 (6.1)	3.5 (3.7)	0.7 (3.4)	1.8 (4.4)	-2.4 (3.2)	2.6 (4.6)	2.9 (3.7)	-2.9 (3.3)	2.1 (4.4)	-0.9 (3.3)
REF-B	-1.8 (3.8)	2.1 (3.9)	1.8 (3.5)	-1.4 (4.1)	-3.5 (3.4)	-1.0 (3.9)	0.6 (4.1)	-0.5 (3.4)	-1.3 (4.2)	-2.1 (3.4)
Trescal	27.0 (32.0)	29.0* (22.0)	18.0 (18.1)	-2.0 (23.0)	-21.0 (19.0)	27.0 (33.1)	30.0* (24.1)	13.0 (18.0)	1.0 (23.1)	-19.0 (18.0)
RISE	2.7 (11.1)	3.8 (10.1)	5.2 (10.2)	-0.5 (10.0)	-6.5 (10.0)	6.2 (11.3)	7.6 (10.1)	-6.2 (10.1)	0.4 (10.2)	-1.4 (10.1)
VTT	-4.4 (6.1)	12.0 (11.1)	16.7* (13.2)	-16.7* (11.0)	-18.6* (13.0)	-1.5 (6.6)	15.8* (11.1)	19.0* (13.1)	-17.8* (11.2)	-21.1* (13.1)
Metrosert	-7.2 (44.6)	-5.5 (23.9)	-4.4 (10.1)	-1.8 (23.9)	1.7 (9.9)	-5.2 (44.7)	-5.3 (24.0)	-5.9 (10.0)	0.6 (24.0)	3.3 (10.0)
VSL	5.0 (11.1)	3.0 (8.1)	0.0 (6.4)	3.0 (8.0)	-2.0 (6.0)	0.0 (11.3)	-2.0 (7.2)	-3.0 (6.1)	2.0 (8.2)	0.0 (6.1)
JV	-8.5 (28.0)	1.0 (28.0)	5.6 (28.1)	-10.2 (28.0)	-8.9 (28.0)	-4.2 (32.1)	4.6 (32.0)	7.4 (32.0)	-9.5 (32.1)	-10.1 (32.0)
PTB	-4.1 (9.2)	-2.4 (9.2)	-2.0 (9.2)	-1.6 (9.2)	0.0 (9.2)	-1.5 (9.2)	-2.4 (9.2)	-4.7 (9.2)	1.6 (9.2)	2.4 (9.2)
METAS	0.5 (15.1)	2.4 (15.1)	2.4 (15.2)	-2.2 (15.0)	-4.7 (15.0)	4.8 (15.2)	8.5 (15.1)	7.1 (15.1)	-4.0 (15.1)	-9.1 (15.0)
CEM	-4.4 (49.0)	3.9 (44.2)	20.7 (42.1)	-2.5 (42.0)	20.6 (47.0)	-3.5 (49.2)	-4.4 (43.0)	9.5 (45.0)	4.2 (43.0)	41.1 (50.0)
LNE	6.0 (25.9)	4.0 (17.1)	0.1 (12.0)	2.3 (17.1)	-3.6 (11.9)	-2.7 (26.0)	3.4 (17.1)	3.1 (11.9)	0.1 (17.2)	-6.2 (11.9)
NPL	18.6 (25.9)	31.3 (40.7)	18.6 (21.0)	6.2 (40.7)	-15.3 (20.9)	3.7 (26.0)	30.7 (40.8)	18.9 (20.8)	-20.1 (40.8)	-30.5* (20.9)

6.2 DEGREES OF EQUIVALENCE WITH THE RMO REFERENCE VALUE

For each test point and each laboratory, the degree of equivalence d'_i with respect to the RMO reference values is shown in Table 10. For PTB a combined DOE was calculated based on the two DOEs for the two TSs.

Table 10 - DOEs with respect to the RMO reference values with expanded combined uncertainties (k = 2). The measurement results marked with an asterisk (*) have not contributed to the calculation of the RMO reference values.

Test point / Lab	120 V 5 A PF = 1	120 V 5 A 0.5 lead	120 V 5 A 0 lead	120 V 5 A 0.5 lag	120 V 5 A 0 lag	240 V 5 A PF = 1	240 V 5 A 0.5 lead	240 V 5 A 0 lead	240 V 5 A 0.5 lag	240 V 5A 0 lag
GUM	-17.61 (52.93)	-5.36 (31.77)	2.74 (31.81)	-11.03 (31.83)	-0.79 (31.79)	-13.15 (53.02)	-3.85 (31.72)	3.46 (31.81)	-10.12 (31.79)	-1.36 (31.75)
CMI	-3.45 (23.85)	1.81 (13.46)	1.64 (7.43)	-2.46 (13.62)	-2.23 (7.32)	0.82 (24.05)	3.31 (13.35)	3.26 (7.42)	-2.62 (13.50)	-3.36 (7.18)
SMU	-11.16 (61.14)	-1.61 (71.70)	3.92 (71.72)	-8.92 (71.43)	-3.42 (72.91)	-5.47 (65.42)	0.01 (74.68)	3.89 (75.62)	-6.54 (70.90)	-3.14 (77.70)
BEV	-15.09 (58.67)	-4.39 (56.10)	-4.32 (53.61)	-3.57 (55.70)	3.86 (54.14)	-10.50 (57.86)	-2.43 (54.82)	3.09 (53.63)	-5.08 (55.38)	14.05 (54.84)
INM	8.39 (53.93)	-1.36 (57.87)	-	11.97 (63.92)	-	3.85 (52.03)	3.15 (57.85)	-	7.88 (51.87)	-
TUBITAK	-18.31* (18.20)	-9.76 (13.14)	-0.36 (11.91)	-6.33 (13.31)	1.71 (11.83)	-11.45 (18.17)	-4.35 (14.40)	1.86 (13.35)	-8.22 (14.54)	-0.96 (13.22)

Test point / Lab	120 V 5 A PF = 1	120 V 5 A 0.5 lead	120 V 5 A 0 lead	120 V 5 A 0.5 lag	120 V 5 A 0 lag	240 V 5 A PF = 1	240 V 5 A 0.5 lead	240 V 5 A 0 lead	240 V 5 A 0.5 lag	240 V 5A 0 lag
PTB	1.09 (7.67)	-1.76 (7.86)	-3.97 (8.12)	1.88 (7.84)	3.83 (8.12)	3.48 (7.81)	-1.52 (7.80)	-5.35 (8.11)	5.00 (7.80)	5.62 (8.10)
SIQ	-10.81 (24.86)	-5.56 (24.70)	0.14 (24.76)	-4.63 (24.79)	1.71 (24.72)	-16.65 (25.05)	-11.95 (24.64)	-4.64 (24.76)	-6.02 (24.73)	4.24 (24.68)
INRIM	-8.01 (14.91)	-5.11 (13.05)	-0.33 (12.54)	-4.38 (13.18)	-0.51 (12.48)	-5.25 (16.09)	-1.67 (13.48)	2.70 (12.97)	-5.32 (13.63)	-2.87 (12.83)
BIM	-25.37* (15.61)	28.45* (24.64)	1.95 (23.63)	-52.80* (24.76)	-10.63 (23.59)	-24.44* (16.16)	31.67* (24.79)	5.11 (23.81)	-56.23* (24.89)	-13.42 (23.73)
EIM	-1.62 (116.95)	6.96 (107.45)	0.99 (103.49)	-16.37 (106.57)	-16.07 (103.51)	0.98 (116.64)	7.99 (107.41)	21.21 (104.22)	-16.06 (107.06)	-14.45 (104.82)
UMTS	-5.51 (18.00)	-1.06 (26.12)	4.14 (23.14)	-5.53 (26.00)	1.91 (23.11)	-14.65 (18.27)	-6.45 (26.06)	3.16 (22.94)	-8.52 (26.14)	0.64 (22.86)
Trescal	28.80 (31.80)	26.86* (22.39)	16.18 (17.80)	-0.61 (22.63)	-17.47 (18.71)	28.02 (32.88)	29.36* (24.40)	13.53 (17.72)	2.32 (22.70)	-16.93 (17.71)
RISE	4.54 (10.41)	1.69 (9.29)	3.37 (9.64)	0.88 (9.12)	-2.99 (9.44)	7.23 (10.64)	6.93 (9.29)	-5.65 (9.50)	1.71 (9.29)	0.67 (9.47)
VTT	-2.62 (4.84)	9.86 (10.36)	14.93* (13.63)	-15.33* (11.75)	-15.09* (13.45)	-0.50 (5.31)	15.15* (11.86)	19.49* (13.50)	-16.45* (11.93)	-18.99* (13.50)
Metrosert	-5.40 (44.46)	-7.64 (23.61)	-6.22 (9.53)	-0.41 (23.55)	5.23 (9.34)	-4.18 (44.51)	-5.94 (23.61)	-5.37 (9.39)	1.92 (23.61)	5.37 (9.36)
VSL	6.80 (10.41)	0.86 (7.10)	-1.82 (5.37)	4.39 (6.87)	1.53 (5.02)	1.02 (10.64)	-2.64 (5.93)	-2.47 (5.12)	3.32 (7.09)	2.07 (5.06)
JV	-6.71 (27.78)	-1.17 (27.76)	3.75 (27.87)	-8.81 (27.70)	-5.39 (27.81)	-3.23 (31.88)	3.98 (31.78)	7.91 (31.85)	-8.22 (31.78)	-8.04 (31.84)
METAS	2.34 (14.58)	0.29 (14.54)	0.54 (14.76)	-0.85 (14.43)	-1.16 (14.64)	5.84 (14.74)	7.90 (14.53)	7.61 (14.67)	-2.70 (14.53)	-7.03 (14.65)
CEM	-2.60 (48.90)	1.76 (44.02)	18.88 (41.91)	-1.11 (41.80)	24.13 (46.88)	-2.48 (49.07)	-5.04 (42.84)	10.03 (44.89)	5.52 (42.84)	43.17 (49.90)
LNE	7.81 (25.66)	1.85 (16.66)	-1.72 (11.54)	3.69 (16.56)	-0.08 (11.38)	-1.73 (25.75)	2.72 (16.65)	3.65 (11.42)	1.40 (16.65)	-4.12 (11.40)
NPL	20.45 (25.59)	29.12 (40.55)	16.74 (20.69)	7.62 (40.52)	-11.78 (20.65)	4.70 (25.68)	30.06 (40.55)	19.42 (20.57)	-18.81 (40.55)	-28.43* (21.15)

6.3 NORMALIZED DEGREES OF EQUIVALENCE WITH RESPECT TO RMO REFERENCE VALUE

The (signed) normalized degrees of equivalence with respect to the RMO reference value for all test points and laboratories in both loops are shown in Table 11. The entries that have an absolute value larger than 1 have been printed in bold. It turned out that these entries exactly correspond to those who were earlier on excluded from contributing to the calculation of the RMO reference value.

Table 11 - Normalized errors per laboratory and test point. Normalized DOEs with absolute value greater than 1 have been printed in bold.

Test point / Lab	120 V 5 A PF = 1	120 V 5 A 0.5 lead	120 V 5 A 0 lead	120 V 5 A 0.5 lag	120 V 5 A 0 lag	240 V 5 A PF = 1	240 V 5 A 0.5 lead	240 V 5 A 0 lead	240 V 5 A 0.5 lag	240 V 5 A 0 lag
GUM	-0.33	-0.17	0.09	-0.35	-0.02	-0.25	-0.12	0.11	-0.32	-0.04
CMI	-0.14	0.13	0.22	-0.18	-0.30	0.03	0.25	0.44	-0.19	-0.47
SMU	-0.18	-0.02	0.05	-0.12	-0.05	-0.08	0.00	0.05	-0.09	-0.04
BEV	-0.26	-0.08	-0.08	-0.06	0.07	-0.18	-0.04	0.06	-0.09	0.26

Test point / Lab	120 V 5 A PF = 1	120 V 5 A 0.5 lead	120 V 5 A 0 lead	120 V 5 A 0.5 lag	120 V 5 A 0 lag	240 V 5 A PF = 1	240 V 5 A 0.5 lead	240 V 5 A 0 lead	240 V 5 A 0.5 lag	240 V 5 A 0 lag
INM	0.16	-0.02	-	0.19	-	0.07	0.05	-	0.15	-
TUBITAK	**-1.01**	-0.74	-0.03	-0.48	0.14	-0.63	-0.30	0.14	-0.57	-0.07
PTB	0.14	-0.22	-0.49	0.24	0.47	0.44	-0.20	-0.66	0.64	0.69
SIQ	-0.44	-0.23	0.01	-0.19	0.07	-0.66	-0.48	-0.19	-0.24	0.17
INRIM	-0.54	-0.39	-0.03	-0.33	-0.04	-0.33	-0.12	0.21	-0.39	-0.22
BIM	**-1.63**	**1.15**	0.08	**-2.13**	-0.45	**-1.51**	**1.28**	0.21	**-2.26**	-0.57
EIM	-0.01	0.06	0.01	-0.15	-0.16	0.01	0.07	0.20	-0.15	-0.14
UMTS	-0.31	-0.04	0.18	-0.21	0.08	-0.80	-0.25	0.14	-0.33	0.03
Trescal	0.91	**1.20**	0.91	-0.03	-0.93	0.85	**1.20**	0.76	0.10	-0.96
RISE	0.44	0.18	0.35	0.10	-0.32	0.68	0.75	-0.59	0.18	0.07
VTT	-0.54	0.95	**1.10**	**-1.30**	**-1.12**	-0.10	**1.28**	**1.44**	**-1.38**	**-1.41**
Metrosert	-0.12	-0.32	-0.65	-0.02	0.56	-0.09	-0.25	-0.57	0.08	0.57
VSL	0.65	0.12	-0.34	0.64	0.30	0.10	-0.45	-0.48	0.47	0.41
JV	-0.24	-0.04	0.13	-0.32	-0.19	-0.10	0.13	0.25	-0.26	-0.25
METAS	0.16	0.02	0.04	-0.06	-0.08	0.40	0.54	0.52	-0.19	-0.48
CEM	-0.05	0.04	0.45	-0.03	0.51	-0.05	-0.12	0.22	0.13	0.87
LNE	0.30	0.11	-0.15	0.22	-0.01	-0.07	0.16	0.32	0.08	-0.36
NPL	0.80	0.72	0.81	0.19	-0.57	0.18	0.74	0.94	-0.46	**-1.34**

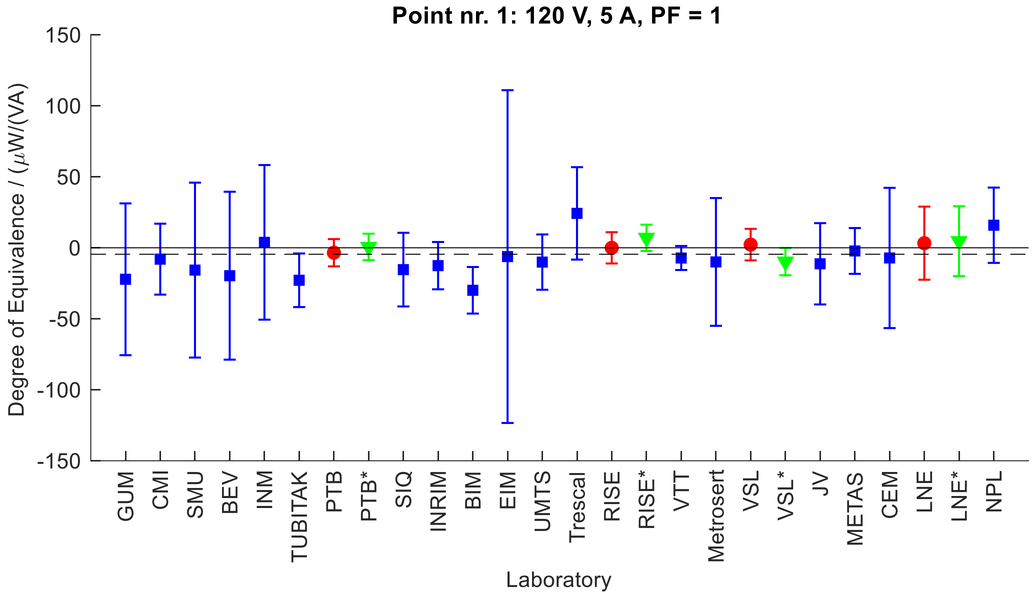
6.4 DEGREES OF EQUIVALENCE WITH RESPECT TO THE LINKED KEY COMPARISON REFERENCE VALUES

For each test point and each laboratory, the degree of equivalence d_i with respect to the linked CCEM key comparison reference values is shown in Table 12. This also includes the four laboratories that took part in the CCEM key comparison themselves. A plot of these results is shown in Figure 1.

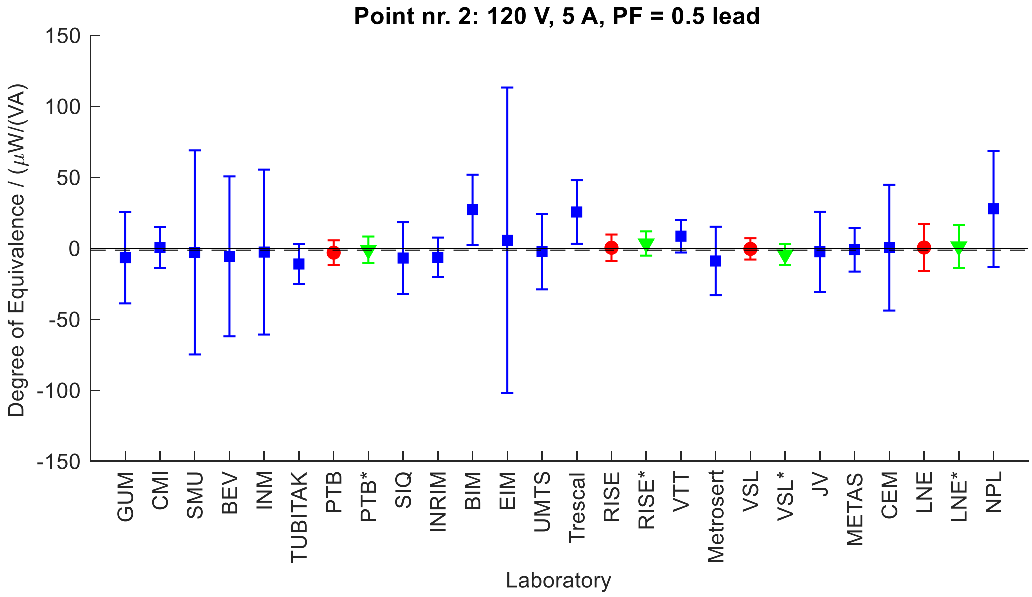
Table 12 - DOEs with respect to the LKCRVs with expanded combined uncertainties (k = 2) per test point for all laboratories, including the laboratories that took part in the CCEM comparison.

Test point / Lab	120 V 5 A PF = 1	120 V 5 A 0.5 lead	120 V 5 A 0 lead	120 V 5 A 0.5 lag	120 V 5 A 0 lag	240 V 5 A PF = 1	240 V 5 A 0.5 lead	240 V 5 A 0 lead	240 V 5 A 0.5 lag	240 V 5A 0 lag
GUM	-22.19 (53.45)	-6.68 (32.15)	3.87 (32.09)	-14.20 (32.32)	-1.94 (32.05)	-16.78 (53.37)	-6.10 (32.11)	5.84 (32.08)	-13.54 (32.26)	-2.58 (32.02)
CMI	-8.03 (24.98)	0.48 (14.35)	2.77 (8.56)	-5.63 (14.72)	-3.38 (8.38)	-2.81 (24.80)	1.07 (14.26)	5.64 (8.51)	-6.04 (14.59)	-4.58 (8.30)
SMU	-15.74 (61.59)	-2.93 (71.87)	5.05 (71.84)	-12.09 (71.64)	-4.57 (73.02)	-9.10 (65.70)	-2.24 (74.85)	6.27 (75.73)	-9.96 (71.12)	-4.36 (77.81)
BEV	-19.67 (59.14)	-5.71 (56.32)	-3.19 (53.78)	-6.74 (55.98)	2.71 (54.30)	-14.13 (58.17)	-4.68 (55.05)	5.48 (53.79)	-8.50 (55.66)	12.84 (55.00)
INM	3.81 (54.44)	-2.68 (58.09)	-	8.80 (64.16)	-	0.22 (52.37)	0.90 (58.06)	-	4.46 (52.16)	-
TUBITAK	-22.89 (18.88)	-11.08 (14.06)	0.77 (12.64)	-9.50 (14.43)	0.56 (12.52)	-15.08 (19.14)	-6.60 (15.24)	4.24 (13.99)	-11.64 (15.55)	-2.18 (13.86)
PTB	-3.49 (9.60)	-3.09 (8.66)	-2.84 (8.65)	-1.29 (9.06)	2.68 (8.60)	-0.16 (8.63)	-3.77 (8.61)	-2.97 (8.59)	1.59 (8.95)	4.40 (8.58)
SIQ	-15.39 (25.95)	-6.88 (25.20)	1.27 (25.12)	-7.80 (25.41)	0.56 (25.06)	-20.28 (25.77)	-14.20 (25.15)	-2.26 (25.10)	-9.44 (25.34)	3.02 (25.03)

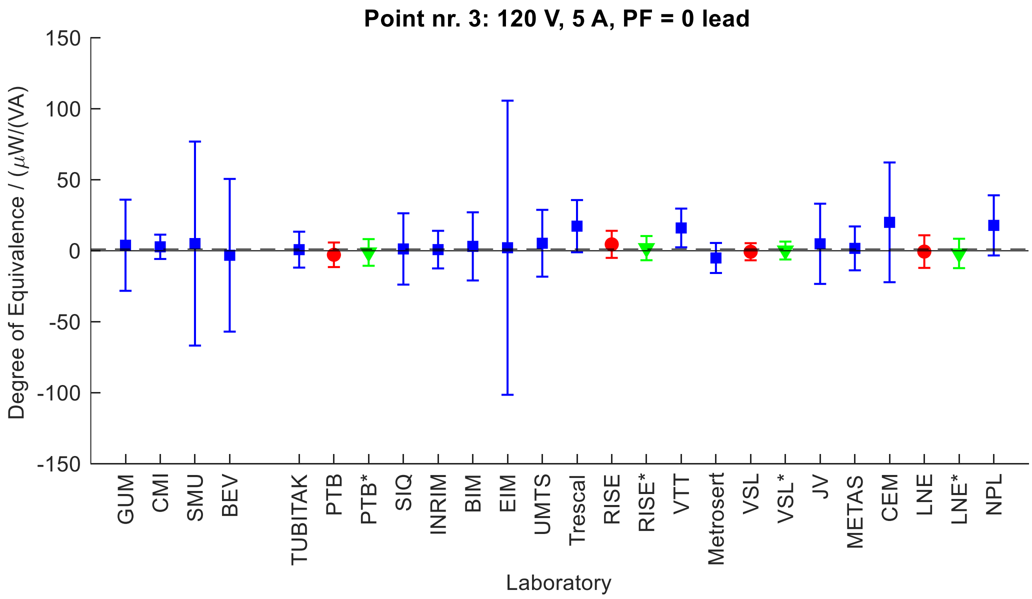
Test point / Lab	120 V 5 A PF = 1	120 V 5 A 0.5 lead	120 V 5 A 0 lead	120 V 5 A 0.5 lag	120 V 5 A 0 lag	240 V 5 A PF = 1	240 V 5 A 0.5 lead	240 V 5 A 0 lead	240 V 5 A 0.5 lag	240 V 5A 0 lag
INRIM	-12.59 (16.66)	-6.44 (13.97)	0.80 (13.25)	-7.55 (14.32)	-1.66 (13.13)	-8.88 (17.18)	-3.91 (14.38)	5.08 (13.62)	-8.73 (14.71)	-4.09 (13.49)
BIM	-29.95 (16.41)	27.13 (24.70)	3.08 (24.01)	-55.97 (24.93)	-11.78 (23.94)	-28.07 (16.37)	29.42 (24.83)	7.49 (24.17)	-59.65 (25.03)	-14.64 (24.09)
EIM	-6.20 (117.19)	5.64 (107.57)	2.12 (103.57)	-19.54 (106.71)	-17.22 (103.59)	-2.65 (116.79)	5.74 (107.52)	23.59 (104.30)	-19.48 (107.20)	-15.67 (104.91)
UMTS	-10.09 (19.48)	-2.38 (26.59)	5.27 (23.53)	-8.70 (26.59)	0.76 (23.47)	-18.28 (19.24)	-8.70 (26.54)	5.54 (23.31)	-11.94 (26.72)	-0.58 (23.23)
Trescal	24.22 (32.55)	25.54 (22.35)	17.32 (18.38)	-3.79 (23.35)	-18.62 (19.23)	24.38 (33.35)	27.11 (24.34)	15.91 (18.29)	-1.09 (23.42)	-18.15 (18.28)
RISE	-0.04 (11.01)	0.36 (9.31)	4.51 (9.54)	-2.29 (9.56)	-4.14 (9.40)	3.60 (10.25)	4.69 (9.34)	-3.26 (9.43)	-1.71 (9.61)	-0.55 (9.43)
VTT	-7.20 (8.46)	8.54 (11.53)	16.06 (13.62)	-18.51 (11.86)	-16.24 (13.42)	-4.14 (7.70)	12.91 (11.72)	21.88 (13.48)	-19.87 (12.00)	-20.20 (13.47)
Metrosert	-9.98 (45.00)	-8.96 (24.15)	-5.08 (10.58)	-3.59 (24.24)	4.08 (10.34)	-7.82 (44.86)	-8.19 (24.17)	-2.99 (10.42)	-1.49 (24.30)	4.15 (10.40)
VSL	2.22 (11.11)	-0.46 (7.49)	-0.68 (6.02)	1.21 (7.93)	0.38 (5.62)	-2.62 (10.15)	-4.89 (6.57)	-0.09 (5.54)	-0.09 (7.61)	0.85 (5.57)
JV	-11.29 (28.63)	-2.49 (28.21)	4.89 (28.25)	-11.98 (28.29)	-6.53 (28.16)	-6.86 (32.36)	1.74 (32.20)	10.29 (32.16)	-11.64 (32.30)	-9.25 (32.16)
METAS	-2.24 (16.14)	-1.04 (15.39)	1.68 (15.45)	-4.03 (15.54)	-2.30 (15.29)	2.21 (15.76)	5.66 (15.42)	9.99 (15.35)	-6.11 (15.63)	-8.25 (15.34)
CEM	-7.18 (49.39)	0.44 (44.31)	20.02 (42.16)	-4.29 (42.19)	22.98 (47.09)	-6.12 (49.39)	-7.29 (43.15)	12.41 (45.12)	2.11 (43.22)	41.95 (50.10)
LNE	3.23 (25.74)	0.52 (16.69)	-0.59 (11.49)	0.52 (16.67)	-1.23 (11.37)	-5.36 (25.75)	0.47 (16.72)	6.04 (11.58)	-2.02 (16.83)	-5.34 (11.39)
NPL	15.86 (26.52)	27.79 (40.87)	17.88 (21.19)	4.45 (40.92)	-12.93 (21.12)	1.07 (26.28)	27.82 (40.88)	21.81 (21.06)	-22.22 (40.96)	-29.65 (21.13)



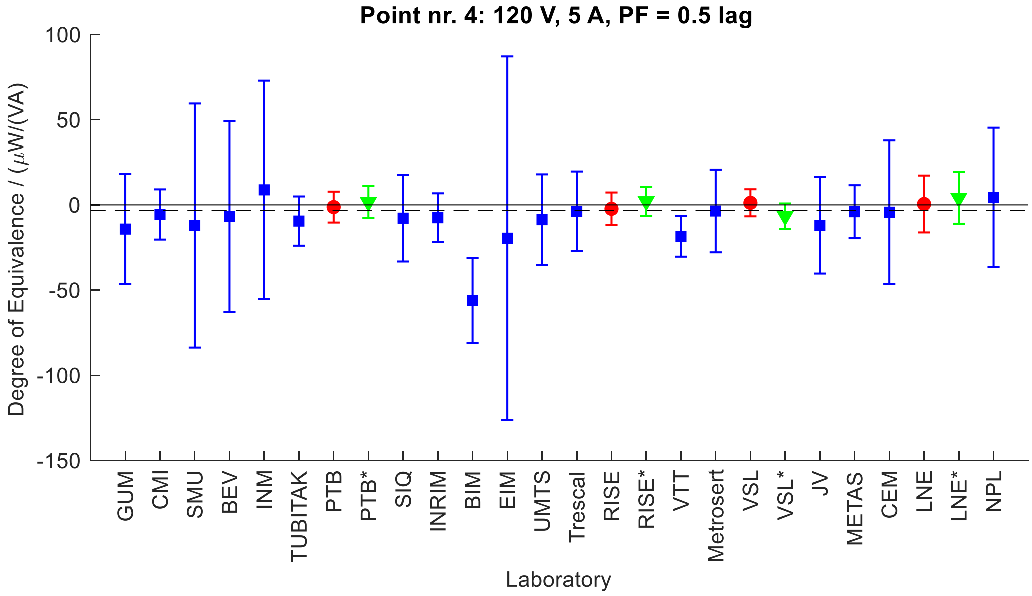
Point nr. 1: 120 V, 5 A, PF = 1
Degree of Equivalence / (μW/(VA)
150
100
50
0
-50
-100
-150
GUM
CMI
SMU
BEV
INM
TUBITAK
PTB
PTB*
SIQ
INRIM
BIM
EIM
UMTS
Trescal
RISE
RISE*
VTT
Metrosert
VSL
VSL*
JV
METAS
CEM
LNE
LNE*
NPL
Laboratory



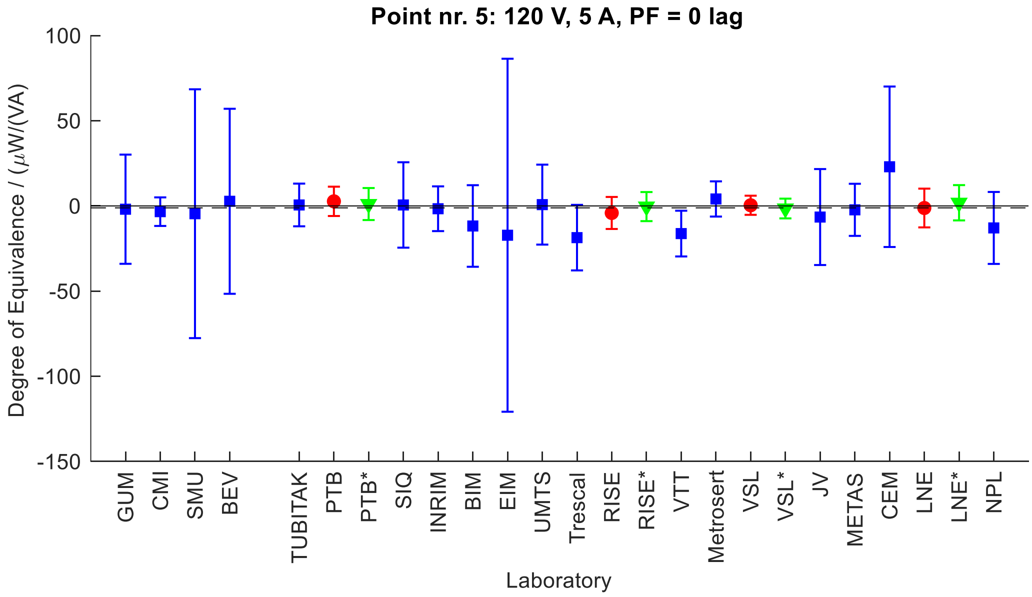
Point nr. 2: 120 V, 5 A, PF = 0.5 lead
Degree of Equivalence / (μW/(VA)
150
100
50
0
-50
-100
-150
GUM
CMI
SMU
BEV
INM
TUBITAK
PTB
PTB*
SIQ
INRIM
BIM
EIM
UMTS
Trescal
RISE
RISE*
VTT
Metrosert
VSL
VSL*
JV
METAS
CEM
LNE
LNE*
NPL
Laboratory



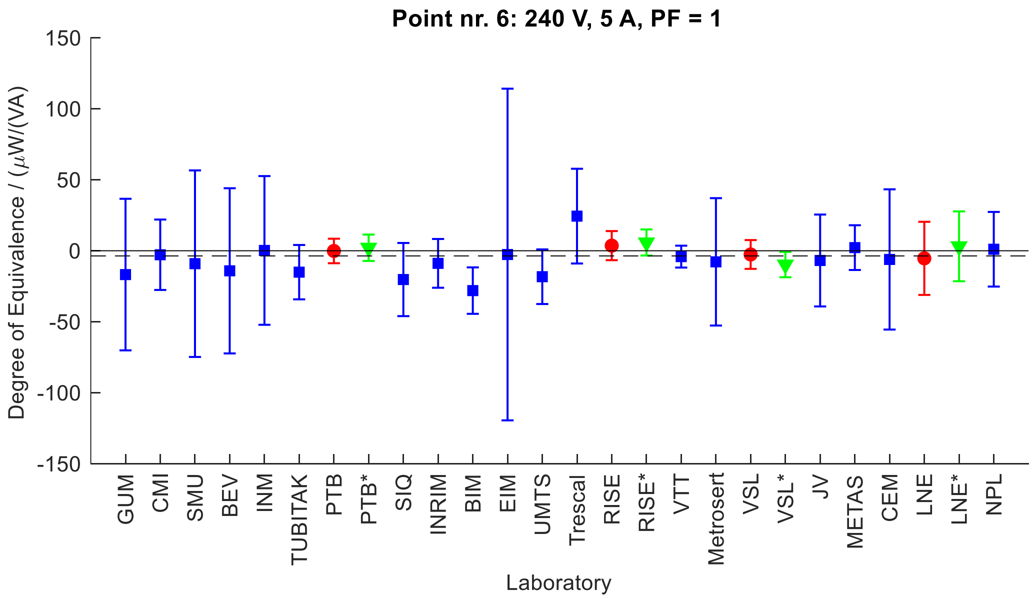
Point nr. 3: 120 V, 5 A, PF = 0 lead
Degree of Equivalence / (μW/(VA)
150
100
50
0
-50
-100
-150
GUM
CMI
SMU
BEV
TUBITAK
PTB
PTB*
SIQ
INRIM
BIM
EIM
UMTS
Trescal
RISE
RISE*
VTT
Metrosert
VSL
VSL*
JV
METAS
CEM
LNE
LNE*
NPL
Laboratory



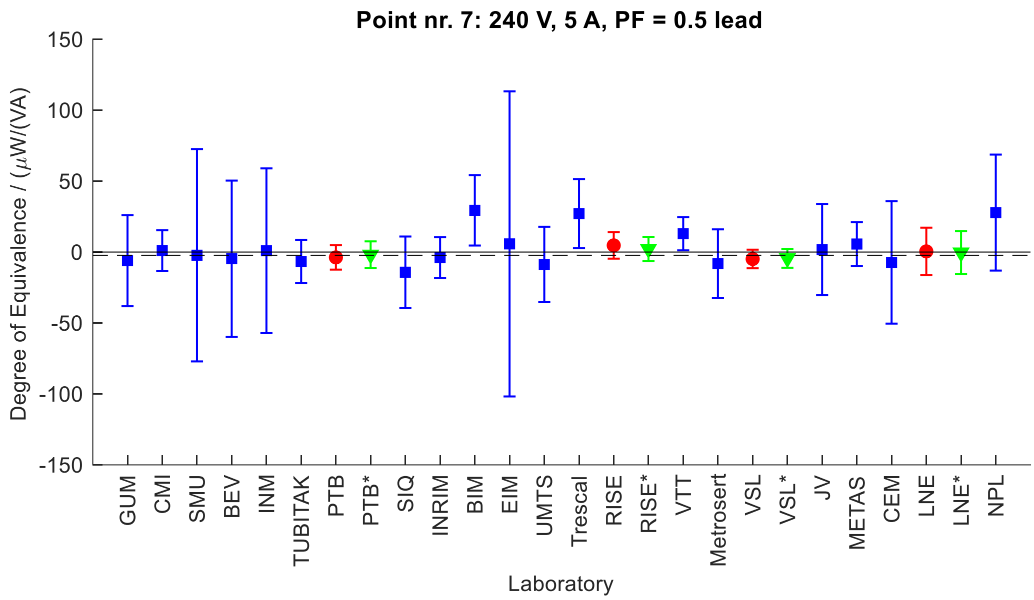
Point nr. 4: 120 V, 5 A, PF = 0.5 lag
Degree of Equivalence / (μW/(VA))
100
50
0
-50
-100
-150
GUM
CMI
SMU
BEV
INM
TUBITAK
PTB
PTB*
SIQ
INRIM
BIM
EIM
UMTS
Trescal
RISE
RISE*
VTT
Metrosert
VSL
VSL*
JV
METAS
CEM
LNE
LNE*
NPL
Laboratory

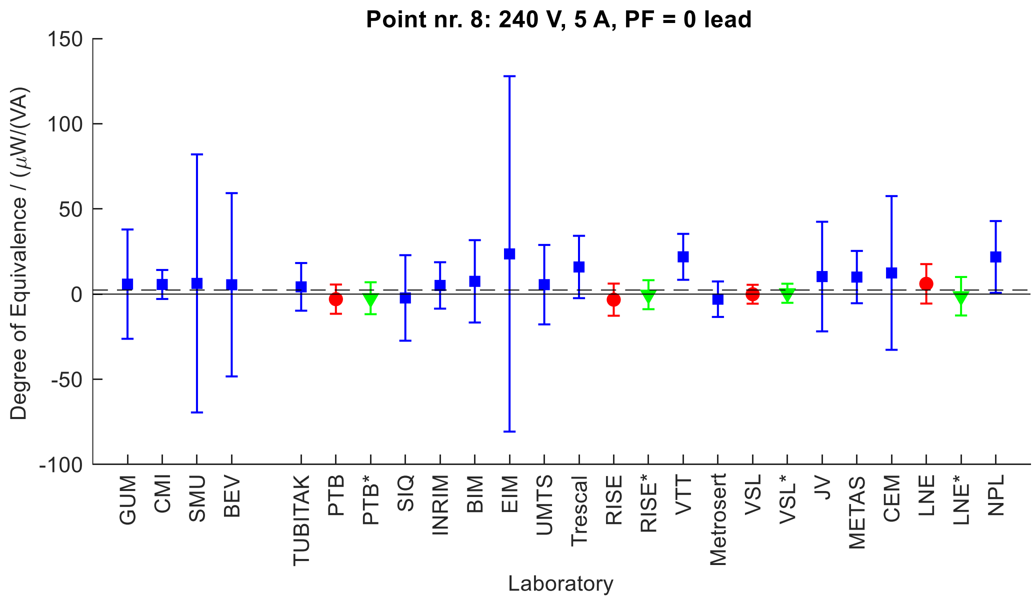


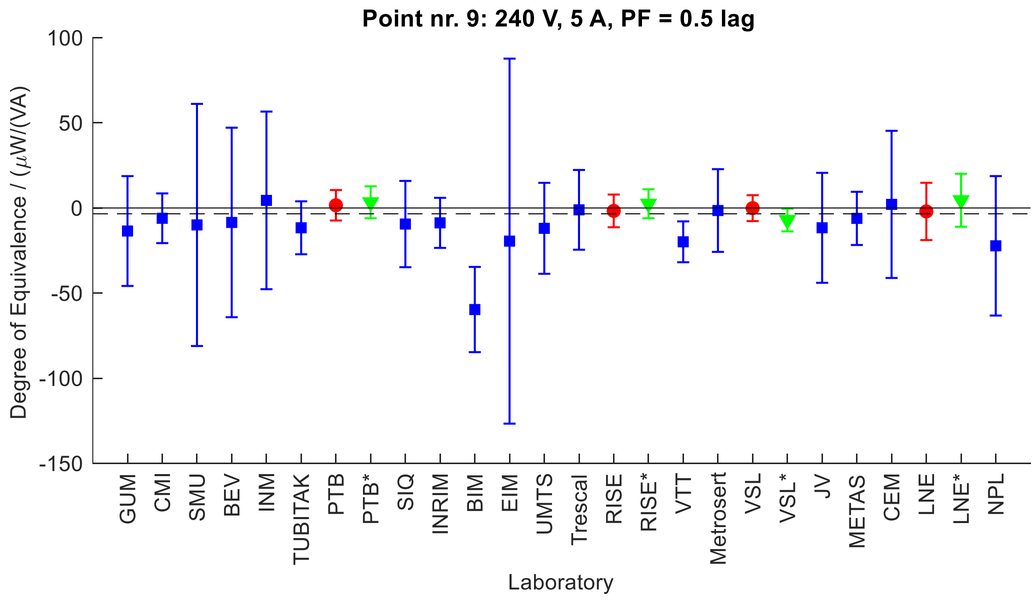
Point nr. 5: 120 V, 5 A, PF = 0 lag
Degree of Equivalence / (μW/(VA))
100
50
0
-50
-100
-150
GUM
CMI
SMU
BEV
TUBITAK
PTB
PTB*
SIQ
INRIM
BIM
EIM
UMTS
Trescal
RISE
RISE*
VTT
Metrosert
VSL
VSL*
JV
METAS
CEM
LNE
LNE*
NPL
Laboratory



Point nr. 6: 240 V, 5 A, PF = 1
Degree of Equivalence / (μW/(VA))
150
100
50
0
-50
-100
-150
GUM
CMI
SMU
BEV
INM
TUBITAK
PTB
PTB*
SIQ
INRIM
BIM
EIM
UMTS
Trescal
RISE
RISE*
VTT
Metrosert
VSL
VSL*
JV
METAS
CEM
LNE
LNE*
NPL
Laboratory


Point nr. 7: 240 V, 5 A, PF = 0.5 lead
Degree of Equivalence / (μW/(VA)
Laboratory
GUM
CMI
SMU
BEV
INM
TUBITAK
PTB
PTB*
SIQ
INRIM
BIM
EIM
UMTS
Trescal
RISE
RISE*
VTT
Metrosert
VSL
VSL*
JV
METAS
CEM
LNE
LNE*
NPL


Point nr. 8: 240 V, 5 A, PF = 0 lead
Degree of Equivalence / (μW/(VA)
Laboratory
GUM
CMI
SMU
BEV
TUBITAK
PTB
PTB*
SIQ
INRIM
BIM
EIM
UMTS
Trescal
RISE
RISE*
VTT
Metrosert
VSL
VSL*
JV
METAS
CEM
LNE
LNE*
NPL


Point nr. 9: 240 V, 5 A, PF = 0.5 lag
Degree of Equivalence / (μW/(VA)
Laboratory
GUM
CMI
SMU
BEV
INM
TUBITAK
PTB
PTB*
SIQ
INRIM
BIM
EIM
UMTS
Trescal
RISE
RISE*
VTT
Metrosert
VSL
VSL*
JV
METAS
CEM
LNE
LNE*
NPL

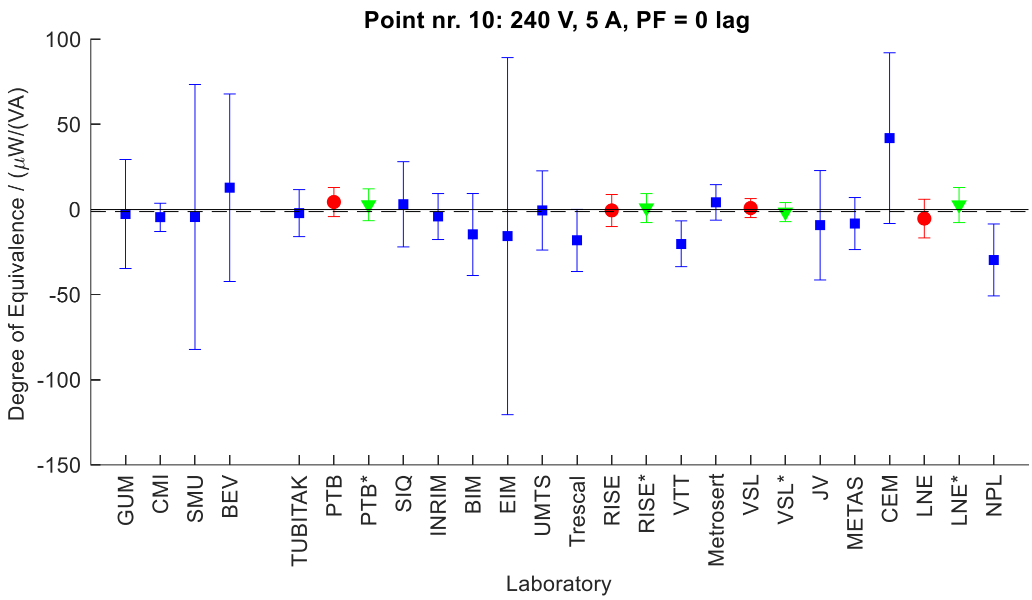


Figure 1: Degrees of equivalence with respect to the linked KCRV of the CCEM comparison. For the linking laboratories the linked DOEs of the Euramet comparison are plotted with red circles, whereas the DOEs of the CCEM are printed with green triangles and to the corresponding laboratory names an asterisk has been added. The dashed horizontal line corresponds to the Euramet internal reference value.

6.5 Normalized degrees of equivalence with respect to linked key comparison reference value

The (signed) normalized degrees of equivalence with respect to the linked key comparison reference value for all test points and laboratories are shown in Table 13. This also includes the four laboratories the took part in the CCEM comparison themselves. In comparison with Table 11, NPL has obtained an additional result with absolute En-value larger than 1.

Table 13 - Normalized linked DOEs per test point for all laboratories, including the laboratories that took part in the CCEM comparison. Normalized linked DOEs with absolute value greater than 1 have been printed in bold.

Test point / Lab	120 V 5 A PF = 1	120 V 5 A 0.5 lead	120 V 5 A 0 lead	120 V 5 A 0.5 lag	120 V 5 A 0 lag	240 V 5 A PF = 1	240 V 5 A 0.5 lead	240 V 5 A 0 lead	240 V 5 A 0.5 lag	240 V 5 A 0 lag
GUM	-0.42	-0.21	0.12	-0.44	-0.06	-0.31	-0.19	0.18	-0.42	-0.08
CMI	-0.32	0.03	0.32	-0.38	-0.40	-0.11	0.08	0.66	-0.41	-0.55
SMU	-0.26	-0.04	0.07	-0.17	-0.06	-0.14	-0.03	0.08	-0.14	-0.06
BEV	-0.33	-0.10	-0.06	-0.12	0.05	-0.24	-0.08	0.10	-0.15	0.23
INM	0.07	-0.05	-	0.14	-	0.00	0.02	-	0.09	-
TUBITAK	**-1.21**	-0.79	0.06	-0.66	0.04	-0.79	-0.43	0.30	-0.75	-0.16
PTB	-0.36	-0.36	-0.33	-0.14	0.31	-0.02	-0.44	-0.35	0.18	0.51
SIQ	-0.59	-0.27	0.05	-0.31	0.02	-0.79	-0.56	-0.09	-0.37	0.12
INRIM	-0.76	-0.46	0.06	-0.53	-0.13	-0.52	-0.27	0.37	-0.59	-0.30
BIM	**-1.83**	**1.10**	0.13	**-2.24**	-0.49	**-1.71**	**1.19**	0.31	**-2.38**	-0.61
EIM	-0.05	0.05	0.02	-0.18	-0.17	-0.02	0.05	0.23	-0.18	-0.15
UMTS	-0.52	-0.09	0.22	-0.33	0.03	-0.95	-0.33	0.24	-0.45	-0.03
Trescal	0.74	**1.14**	0.94	-0.16	-0.97	0.73	**1.11**	0.87	-0.05	-0.99
RISE	-0.00	0.04	0.47	-0.24	-0.44	0.35	0.50	-0.35	-0.18	-0.06
VTT	-0.85	0.74	**1.18**	**-1.56**	**-1.21**	-0.54	**1.10**	**1.62**	**-1.66**	**-1.50**
Metrosert	-0.22	-0.37	-0.48	-0.15	0.39	-0.17	-0.34	-0.29	-0.06	0.40

Lab \ Test point	120 V 5 A PF = 1	120 V 5 A 0.5 lead	120 V 5 A 0 lead	120 V 5 A 0.5 lag	120 V 5 A 0 lag	240 V 5 A PF = 1	240 V 5 A 0.5 lead	240 V 5 A 0 lead	240 V 5 A 0.5 lag	240 V 5 A 0 lag
VSL	0.20	-0.06	-0.11	0.15	0.07	-0.26	-0.74	-0.02	-0.01	0.15
JV	-0.39	-0.09	0.17	-0.42	-0.23	-0.21	0.05	0.32	-0.36	-0.29
METAS	-0.14	-0.07	0.11	-0.26	-0.15	0.14	0.37	0.65	-0.39	-0.54
CEM	-0.15	0.01	0.47	-0.10	0.49	-0.12	-0.17	0.28	0.05	0.84
LNE	0.13	0.03	-0.05	0.03	-0.11	-0.21	0.03	0.52	-0.12	-0.47
NPL	0.60	0.68	0.84	0.11	-0.61	0.04	0.68	**1.04**	-0.54	**-1.40**

6.6 FURTHER ANALYSES

Some further analyses have been performed that have not been described in detail in this report.

A check has been performed regarding correlation between the reported calibration error and the realized value of the nominal quantities specifying each test point (voltage amplitude, current amplitude, phase difference, frequency) resp. the realized ambient conditions (temperature, pressure). No significant correlation has been found, indicating that the error of the travelling standards is not sensitive to small variations of the test point and to fluctuations of the ambient conditions.

When combining the two DOEs of PTB it has been verified if the individual DOEs are consistent in view of the assumed uncertainties and correlation. This turned out to be the case except for test point 2 and test point 6. It was not possible to find the root cause for this small inconsistency, and no action was taken.

7 COMMENTS ON SPECIFIC NMI RESULTS

The comments in sections 7.1 and 7.2 were provided by BIM and Trescal, respectively.

7.1 BIM RESULTS

After the Draft A report was distributed to the participants, BIM has performed an extensive evaluation of the comparison results. For the purpose of this comparison an Excel file was used especially prepared for calculation of the comparison results. We found an incorrect formula in the Excel file (from 2020), were the reference value and the measured value were swapped. After the corrections were made, we calculated the corresponding values of En and found that part of our new results are in line with the LCKRV results for the instrument/traveling standard RD 207172 that we measured. However, for some results the uncertainty was increased from 24 to 35 ppm in order to obtain En values smaller than 1. As a result of participating in the comparison for PF = 0.5 lead/lag, the uncertainty of our CMCs registered in KCDB will be increased by 10 ppm.

LKCRV and RMO reference values and reported values with expanded combined uncertainties (k = 2)

Test point / Lab	120 V 5 A PF = 1	120 V 5 A 0.5 lead	120 V 5 A 0 lead	120 V 5 A 0.5 lag	120 V 5 A 0 lag	240 V 5 A PF = 1	240 V 5 A 0.5 lead	240 V 5 A 0 lead	240 V 5 A 0.5 lag	240 V 5A 0 lag
LKCRV-A	14.2 (7.4)	5.7 (5.1)	-0.9 (4.7)	7.2 (5.7)	-1.1 (4.6)	20.8 (6.0)	11.1 (5.1)	-1.8 (4.7)	11.5 (5.6)	-1.4 (4.6)
BIM	15 (14)	-19 (35)	-7 (24)	+38 (35)	-13 (24)	18 (14)	-22 (35)	6 (24)	44 (35)	-9 (24)

DOEs with respect to the LKCRVs with expanded combined uncertainties (k = 2) per test point

Test point / Lab	120 V 5 A PF = 1	120 V 5 A 0.5 lead	120 V 5 A 0 lead	120 V 5 A 0.5 lag	120 V 5 A 0 lag	240 V 5 A PF = 1	240 V 5 A 0.5 lead	240 V 5 A 0 lead	240 V 5 A 0.5 lag	240 V 5A 0 lag
BIM	0.8 (15.8)	-24.7 (35.4)	-6.2 (24.5)	30.8 (35.5)	-11.9 (24.4)	-2.7 (15.2)	-33.1 (35.4)	7.9 (24.5)	32.5 (35.5)	-7.6 (24.4)

Normalized linked DOEs per test point

Test point / Lab	120 V 5 A PF = 1	120 V 5 A 0.5 lead	120 V 5 A 0 lead	120 V 5 A 0.5 lag	120 V 5 A 0 lag	240 V 5 A PF = 1	240 V 5 A 0.5 lead	240 V 5 A 0 lead	240 V 5 A 0.5 lag	240 V 5A 0 lag
BIM	0.05	-0.70	-0.25	0.87	-0.49	-0.18	-0.94	0.32	0.92	-0.31

These results allow us to verify the measurement capabilities of BIM at a significantly better level than the official comparison.

7.2 TRESCAL RESULTS

As our results are not in good agreement with the majority of the participants, we have tried to identify some possible sources for this:

1. At the end our report we added the following note:
   “3) Shortly after the completion of the intercomparison measurements and after the travelling standard was sent to the next participant, an issue with the Fluke 52120A current amplifier was observed. During a final check a change in output was detected depending on the presence or

absence of a Low to Ground connection on the amplifier. This prompted a correction of –19 ppm of all 5 A reference current measurements, and this is included in all the reported measurement results. For reasons unknown later measurements failed to reproduce this rather large difference. This and the fact that the travelling standard had already been sent to the next participant means that it is not entirely clear whether this issue was significant during the time of the intercomparison measurements.
This has not changed, so we have recalculated all measurement results by removing the correction of –19 ppm.

2. In our report we stated that the influence of the asymmetric nature of the set-up due to the current Tee could be neglected at low frequencies. We have now put this to the test by investigating the influence of our current Tee on the phase by using two NI PXI-5922 digitizers in differential mode. Each side of the current Tee is measured independently against a reference signal (voltage channel), with the side of the current Tee not used shorted. The result of this is a difference between the high and the low side of the current Tee of –0.00008° at 53 Hz, which is a correction to be added to the reference phase measurements.

3. With the same set-up a further possible influence, not previously considered, was investigated by connecting the SP 120 V and 240 V resistive voltage dividers to the voltage channel as well, including the capacitive loads and the NMIA buffer amplifiers. In this case the low side of the current Tee was measured both with and without the dividers connected. The result is a correction of –0.00014° with the 120 V divider and –0.00009° with the 240 V divider, also to be added to the reference phase measurements.

Both measurement results and uncertainties have been recalculated by applying these corrections, and an uncertainty component of ±0.0003° due to the influence on phase has also been added.

The results of these corrections are shown in the table below as “Reevaluated” next to the original “Reported” numbers.

Nominal set points					Results: Reported / Reevaluated	
Voltage	Current	Power Factor	Phase Angle	Frequency	Error Value	Expanded Uncertainty
V	A		deg	Hz	µW/VA	µW/VA
120	5	1	0	53	27 / 8	32 / 32
120	5	0,5 lead	60	53	29 / 17	22 / 24
120	5	0 lead	90	53	18 / 15	18 / 20
120	5	0,5 lag	-60	53	-2 / -8	23 / 24
120	5	0 lag	-90	53	-21 / -17	19 / 20
240	5	1	0	53	27 / 8	33 / 33
240	5	0,5 lead	60	53	30 / 18	24 / 24
240	5	0 lead	90	53	13 / 10	18 / 19
240	5	0,5 lag	-60	53	1 / -6	23 / 24
240	5	0 lag	-90	53	-19 / -16	18 / 19

8 DISCUSSION AND SUMMARY

In this comparison two standards for power measurement have been circulated in two parallel loops. In loop A, 12 laboratories participated, whereas 11 laboratories participated in loop B. Each participant calibrated the standard at 10 test points and the results were reported to VSL. PTB participated in both loops and measured the standards five times in order to assess the stability of the standards. The standards turned out to possess no systematic drift. Random standard uncertainties due to instrument instability were determined in the range of 0.2 to 2.8 ppm, depending on the test point and the standard. The laboratory uncertainty of the PL was assumed to be substantially correlated and this was used to connect both loops to each other.

The comparison results were linked to the CIPM comparison results by means of the results of four laboratories participating in both comparisons. Both RMO reference values, RMO degrees of equivalence and normalized RMO degrees of equivalence, as well as linked key comparison reference values, linked degrees of equivalence and normalized linked degrees of equivalence were calculated.

In the calculation of the RMO reference results, provided measurement results with an absolute value of the normalized error exceeding 1 were excluded from contributing to the RMO reference value in an iterative way. It turned out that 17 of the 22 laboratories were fully consistent with each other for all 10 test points.

Linking the RMO results to the CIPM comparison results did not significantly change the observations. Due to small changes in calculated En-values, one laboratory obtained an additional test point with absolute En-value larger than 1.

9 REFERENCES

[1] *CCEM Guidelines for Planning, Organizing, Conducting and Reporting Key, Supplementary and Pilot Comparisons*. CCEM, 21 March 2007

[2] M G Cox, *The evaluation of key comparison data*, Metrologia 39, 589, 2002

[3] L Nielsen, *Evaluation of measurement intercomparisons by the method of least squares*, DFM Technical Report, 2000, DOI: 10.13140/RG.2.2.12239.02728

[4] ISO/IEC 17043:2010, *Conformity assessment - General requirements for proficiency testing*, Switzerland, 2010

APPENDIX A: REPORTED MEASUREMENT VALUES

In Table 14 and Table 15 the reported values y_i and reported expanded uncertainties $2u_i$ are shown for loop A and loop B, whereas a graphical representation is presented in Figures 2 and 3.

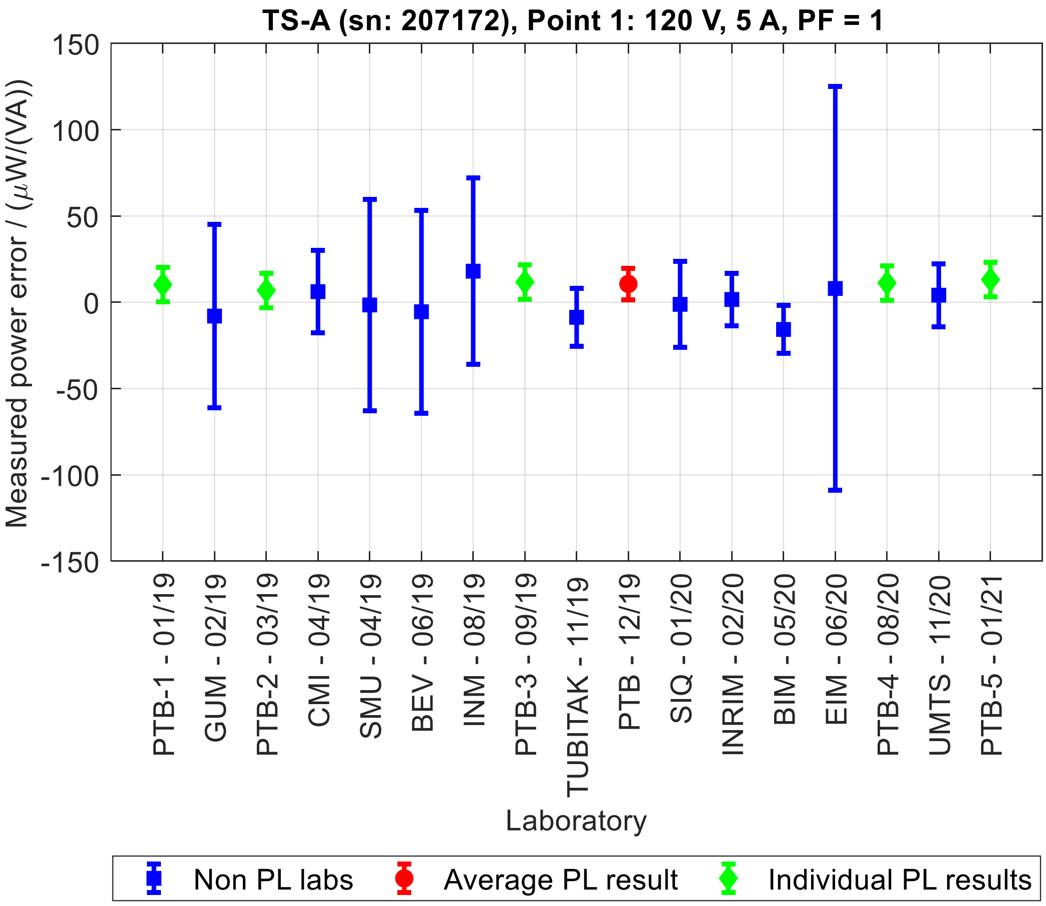
Table 14 - Reported measurement values with reported expanded uncertainties (k = 2) for loop A.

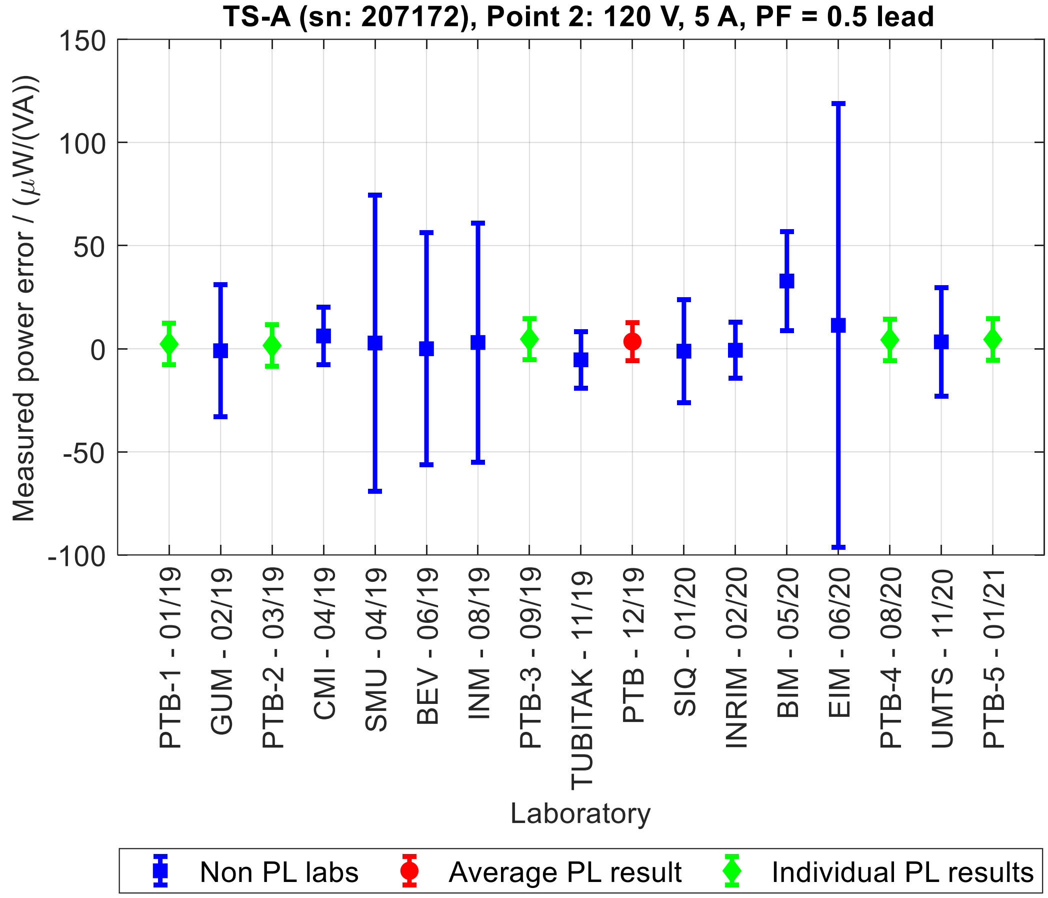
Laboratory name	Approximate measurement date	120 V 5 A PF = 1	120 V 5 A 0.5 lead	120 V 5 A 0 lead	120 V 5 A 0.5 lag	120 V 5 A 0 lag	240 V 5 A PF = 1	240 V 5 A 0.5 lead	240 V 5 A 0 lead	240 V 5 A 0.5 lag	240 V 5 A 0 lag
PTB-1	30-1-2019	10.2 (10.0)	2.3 (10.0)	-5.2 (10.0)	8.2 (10.0)	3.1 (10.0)	21.6 (10.0)	7.0 (10.0)	-6.7 (10.0)	15.0 (10.0)	4.5 (10.0)
GUM	8-2-2019	-8.0 (53.0)	-1.0 (32.0)	3.0 (32.0)	-7.0 (32.0)	-3.0 (32.0)	4.0 (53.0)	5.0 (32.0)	4.0 (32.0)	-2.0 (32.0)	-4.0 (32.0)
PTB-2	7-3-2019	6.8 (10.0)	1.5 (10.0)	-2.4 (10.0)	3.8 (10.0)	1.3 (10.0)	16.5 (10.0)	5.9 (10.0)	-3.7 (10.0)	11.6 (10.0)	3.2 (10.0)
CMI	3-4-2019	6.2 (24.0)	6.2 (14.0)	1.9 (8.2)	1.6 (14.0)	-4.4 (8.2)	18.0 (24.0)	12.2 (14.0)	3.8 (8.2)	5.5 (14.0)	-6.0 (8.2)
SMU	26-4-2019	-1.5 (61.2)	2.8 (71.8)	4.2 (71.8)	-4.9 (71.5)	-5.6 (73.0)	11.7 (65.4)	8.9 (74.8)	4.4 (75.7)	1.6 (71.0)	-5.8 (77.8)
BEV	5-6-2019	-5.5 (58.7)	-0.0 (56.2)	-4.1 (53.7)	0.5 (55.8)	1.7 (54.3)	6.6 (57.8)	6.4 (55.0)	3.6 (53.7)	3.0 (55.5)	11.4 (55.0)
INM	1-8-2019	18.0 (54.0)	3.0 (58.0)	-	16.0 (64.0)	-	21.0 (52.0)	12.0 (58.0)	-	16.0 (52.0)	-
PTB-3	18-9-2019	11.8 (10.0)	4.6 (10.0)	-3.5 (10.0)	7.2 (10.0)	1.2 (10.0)	22.4 (10.0)	8.6 (10.0)	-5.0 (10.0)	13.2 (10.0)	3.0 (10.0)
TUBITAK	13-11-2019	-8.7 (16.7)	-5.4 (13.7)	-0.1 (12.4)	-2.3 (13.7)	-0.5 (12.4)	5.7 (18.1)	4.5 (15.0)	2.4 (13.8)	-0.1 (15.0)	-3.6 (13.8)
SIQ	14-1-2020	-1.2 (25.0)	-1.2 (25.0)	0.4 (25.0)	-0.6 (25.0)	-0.5 (25.0)	0.5 (25.0)	-3.1 (25.0)	-4.1 (25.0)	2.1 (25.0)	1.6 (25.0)
INRIM	20-2-2020	1.6 (15.1)	-0.8 (13.6)	-0.1 (13.0)	-0.4 (13.6)	-2.7 (13.0)	11.9 (16.0)	7.2 (14.1)	3.2 (13.4)	2.8 (14.1)	-5.5 (13.4)
BIM	27-5-2020	-15.8 (13.8)	32.8 (24.0)	2.2 (23.9)	-48.8 (24.0)	-12.8 (23.9)	-7.3 (14.2)	40.5 (24.2)	5.7 (24.1)	-48.1 (24.2)	-16.1 (24.1)
EIM	29-6-2020	8.0 (117.0)	11.3 (107.5)	1.3 (103.5)	-12.3 (106.6)	-18.3 (103.6)	18.1 (116.6)	16.8 (107.5)	21.8 (104.3)	-7.9 (107.1)	-17.1 (104.9)
PTB-4	12-8-2020	11.2 (10.0)	4.3 (10.0)	-3.1 (10.0)	6.7 (10.0)	0.9 (10.0)	22.6 (10.0)	8.5 (10.0)	-5.1 (10.0)	13.8 (10.0)	2.9 (10.0)
UMTS	29-11-2020	4.1 (18.2)	3.3 (26.4)	4.4 (23.4)	-1.5 (26.2)	-0.3 (23.4)	2.5 (18.2)	2.4 (26.4)	3.7 (23.2)	-0.4 (26.4)	-2.0 (23.2)
PTB-5	5-1-2021	13.2 (10.0)	4.5 (10.0)	-4.7 (10.0)	8.5 (10.0)	2.3 (10.0)	23.6 (10.0)	8.6 (10.0)	-6.3 (10.0)	15.8 (10.0)	3.9 (10.0)

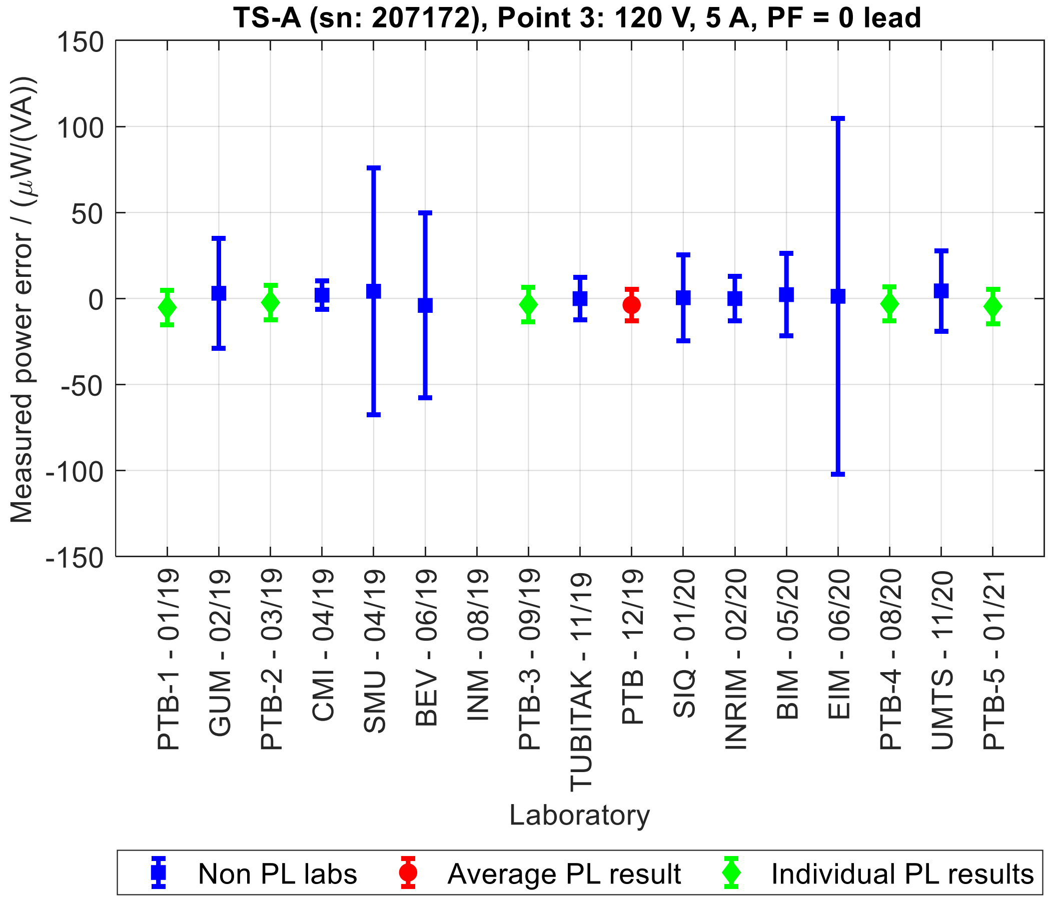
Table 15 - Reported measurement values with reported expanded uncertainties (k = 2) for loop B.

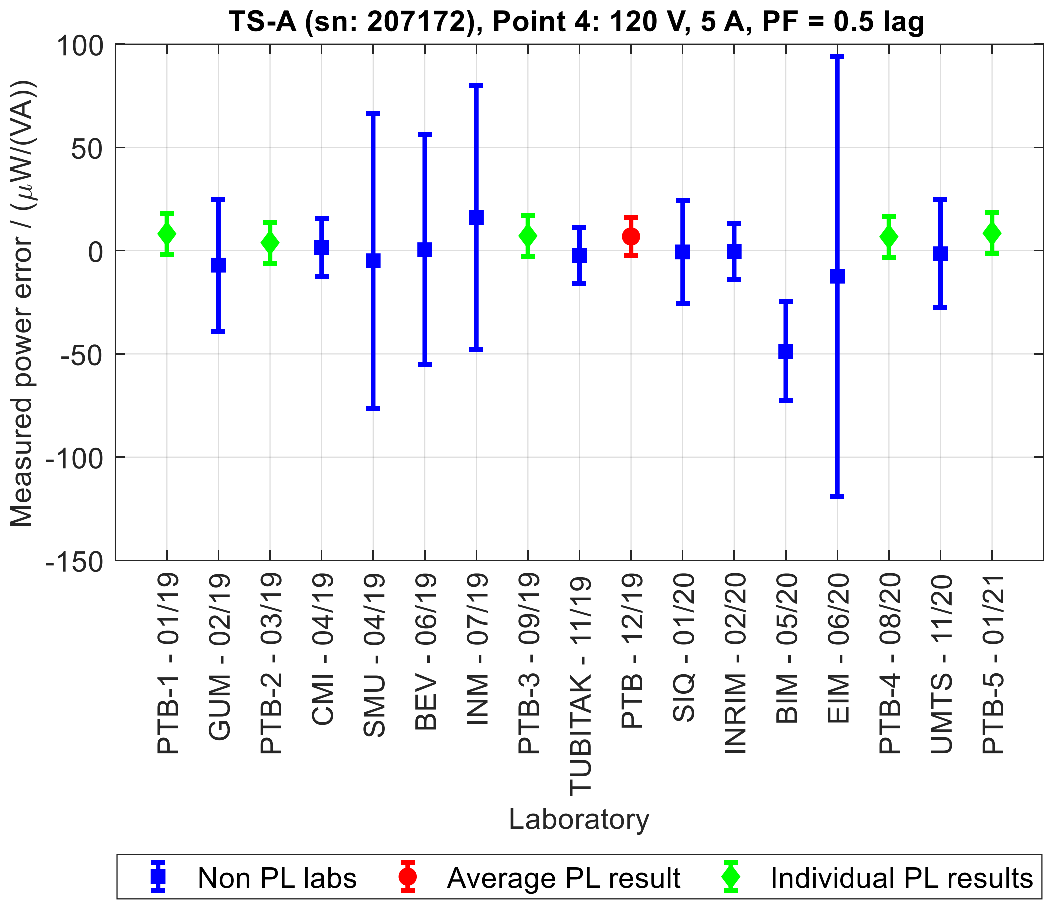
Laboratory name	Approximate measurement date	120 V 5 A PF = 1	120 V 5 A 0.5 lead	120 V 5 A 0 lead	120 V 5 A 0.5 lag	120 V 5 A 0 lag	240 V 5 A PF = 1	240 V 5 A 0.5 lead	240 V 5 A 0 lead	240 V 5 A 0.5 lag	240 V 5 A 0 lag
PTB-1	30-1-2019	-4.5 (10.0)	-2.5 (10.0)	-2.8 (10.0)	-1.5 (10.0)	0.4 (10.0)	-0.5 (10.0)	-2.8 (10.0)	-5.5 (10.0)	2.5 (10.0)	3.1 (10.0)
Trescal	4-3-2019	27.0 (32.0)	29.0 (22.0)	18.0 (18.0)	-2.0 (23.0)	-21.0 (19.0)	27.0 (33.0)	30.0 (24.0)	13.0 (18.0)	1.0 (23.0)	-19.0 (18.0)
PTB-2	13-3-2019	-4.3 (10.0)	-3.2 (10.0)	-0.3 (10.0)	-1.6 (10.0)	-0.1 (10.0)	-2.7 (10.0)	-2.6 (10.0)	-4.5 (10.0)	-0.1 (10.0)	2.0 (10.0)
RISE	5-4-2019	2.7 (11.0)	3.8 (10.0)	5.2 (10.0)	-0.5 (10.0)	-6.5 (10.0)	6.2 (11.0)	7.6 (10.0)	-6.2 (10.0)	0.4 (10.0)	-1.4 (10.0)
VTT	23-5-2019	-4.4 (6.0)	12.0 (11.0)	16.7 (13.0)	-16.7 (11.0)	-18.6 (13.0)	-1.5 (6.0)	15.8 (11.0)	19.0 (13.0)	-17.8 (11.0)	-21.1 (13.0)
Metrosert	7-6-2019	-7.2 (44.6)	-5.5 (23.9)	-4.4 (9.9)	-1.8 (23.9)	1.7 (9.9)	-5.2 (44.6)	-5.3 (23.9)	-5.9 (9.9)	0.6 (23.9)	3.3 (9.9)

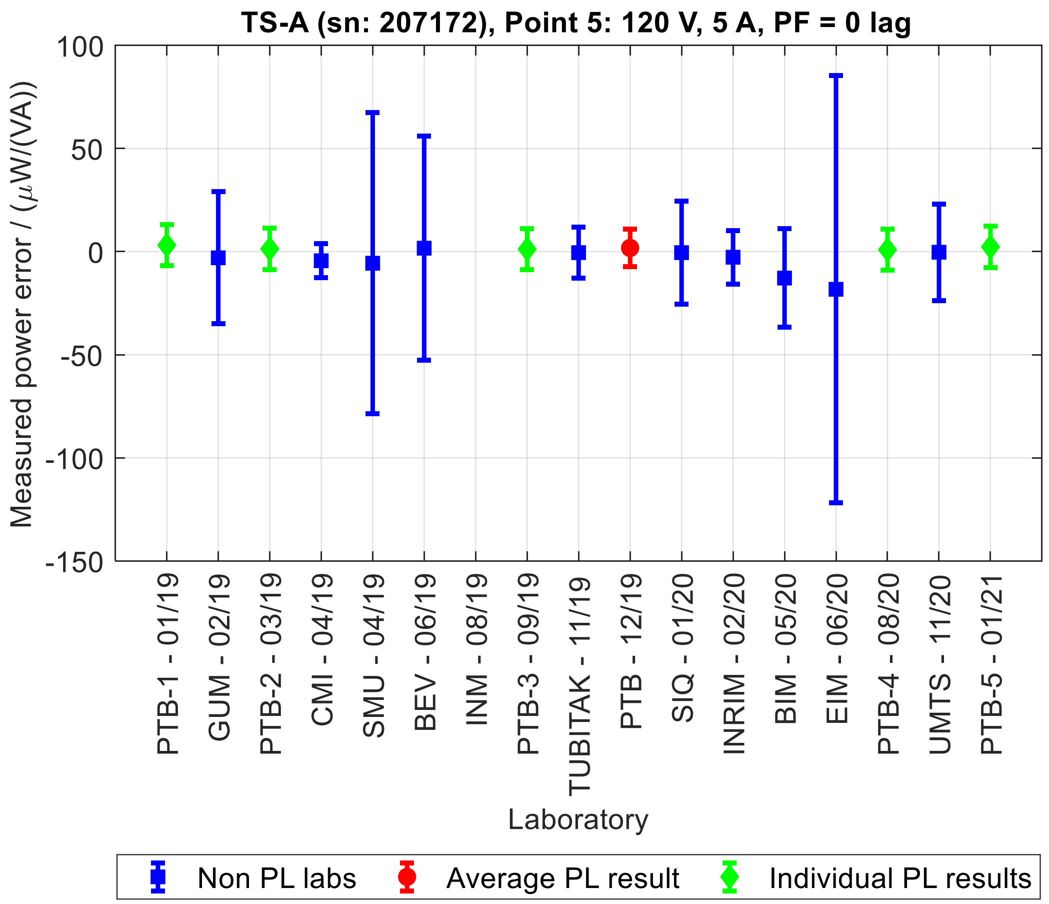
Laboratory name	Approximate measurement date	120 V 5 A PF = 1	120 V 5 A 0.5 lead	120 V 5 A 0 lead	120 V 5 A 0.5 lag	120 V 5 A 0 lag	240 V 5 A PF = 1	240 V 5 A 0.5 lead	240 V 5 A 0 lead	240 V 5 A 0.5 lag	240 V 5 A 0 lag
VSL	4-8-2019	5.0 (11.0)	3.0 (8.0)	0.0 (6.0)	3.0 (8.0)	-2.0 (6.0)	0.0 (11.0)	-2.0 (7.0)	-3.0 (6.0)	2.0 (8.0)	0.0 (6.0)
PTB-3	18-9-2019	-4.5 (10.0)	-2.6 (10.0)	-2.7 (10.0)	-1.6 (10.0)	0.1 (10.0)	-3.2 (10.0)	-2.9 (10.0)	-4.8 (10.0)	1.7 (10.0)	2.6 (10.0)
JV	27-11-2019	-8.5 (28.0)	1.0 (28.0)	5.6 (28.0)	-10.2 (28.0)	-8.9 (28.0)	-4.2 (32.0)	4.6 (32.0)	7.4 (32.0)	-9.5 (32.0)	-10.1 (32.0)
METAS	15-3-2020	0.5 (15.0)	2.4 (15.0)	2.4 (15.0)	-2.2 (15.0)	-4.7 (15.0)	4.8 (15.0)	8.5 (15.0)	7.1 (15.0)	-4.0 (15.0)	-9.1 (15.0)
CEM	13-6-2020	-4.4 (49.0)	3.9 (44.2)	20.7 (42.0)	-2.5 (42.0)	20.6 (47.0)	-3.5 (49.2)	-4.4 (43.0)	9.5 (45.0)	4.2 (43.0)	41.1 (50.0)
LNE	22-7-2020	6.0 (25.9)	4.0 (17.1)	0.1 (11.8)	2.3 (17.1)	-3.6 (11.8)	-2.7 (25.9)	3.4 (17.1)	3.1 (11.8)	0.1 (17.1)	-6.2 (11.8)
PTB-4	18-8-2020	-3.0 (10.0)	-1.3 (10.0)	-1.5 (10.0)	-1.9 (10.0)	-0.6 (10.0)	-0.3 (10.0)	-0.9 (10.0)	-3.6 (10.0)	1.6 (10.0)	1.6 (10.0)
NPL	9-11-2020	18.6 (25.8)	31.3 (40.7)	18.6 (20.9)	6.2 (40.7)	-15.3 (20.9)	3.7 (25.8)	30.7 (40.7)	18.9 (20.8)	-20.1 (40.7)	-30.5 (20.8)
PTB-5	2-12-2020	-4.1 (10.0)	-2.5 (10.0)	-2.8 (10.0)	-1.5 (10.0)	0.2 (10.0)	-0.8 (10.0)	-2.9 (10.0)	-4.9 (10.0)	2.0 (10.0)	2.7 (10.0)




TS-A (sn: 207172), Point 2: 120 V, 5 A, PF = 0.5 lead
Measured power error / (µW/(VA))
150
100
50
0
-50
-100
PTB-1 - 01/19
GUM - 02/19
PTB-2 - 03/19
CMI - 04/19
SMU - 04/19
BEV - 06/19
INM - 08/19
PTB-3 - 09/19
TUBITAK - 11/19
PTB - 12/19
SIQ - 01/20
INRIM - 02/20
BIM - 05/20
EIM - 06/20
PTB-4 - 08/20
UMTS - 11/20
PTB-5 - 01/21
Laboratory
Non PL labs
Average PL result
Individual PL results


TS-A (sn: 207172), Point 3: 120 V, 5 A, PF = 0 lead
Measured power error / (µW/(VA))
150
100
50
0
-50
-100
-150
PTB-1 - 01/19
GUM - 02/19
PTB-2 - 03/19
CMI - 04/19
SMU - 04/19
BEV - 06/19
INM - 08/19
PTB-3 - 09/19
TUBITAK - 11/19
PTB - 12/19
SIQ - 01/20
INRIM - 02/20
BIM - 05/20
EIM - 06/20
PTB-4 - 08/20
UMTS - 11/20
PTB-5 - 01/21
Laboratory
Non PL labs
Average PL result
Individual PL results


TS-A (sn: 207172), Point 4: 120 V, 5 A, PF = 0.5 lag
Measured power error / (μW/(VA))
100
50
0
-50
-100
-150
PTB-1 - 01/19
GUM - 02/19
PTB-2 - 03/19
CMI - 04/19
SMU - 04/19
BEV - 06/19
INM - 07/19
PTB-3 - 09/19
TUBITAK - 11/19
PTB - 12/19
SIQ - 01/20
INRIM - 02/20
BIM - 05/20
EIM - 06/20
PTB-4 - 08/20
UMTS - 11/20
PTB-5 - 01/21
Laboratory
Non PL labs
Average PL result
Individual PL results


TS-A (sn: 207172), Point 5: 120 V, 5 A, PF = 0 lag
Measured power error / (μW/(VA))
100
50
0
-50
-100
-150
PTB-1 - 01/19
GUM - 02/19
PTB-2 - 03/19
CMI - 04/19
SMU - 04/19
BEV - 06/19
INM - 08/19
PTB-3 - 09/19
TUBITAK - 11/19
PTB - 12/19
SIQ - 01/20
INRIM - 02/20
BIM - 05/20
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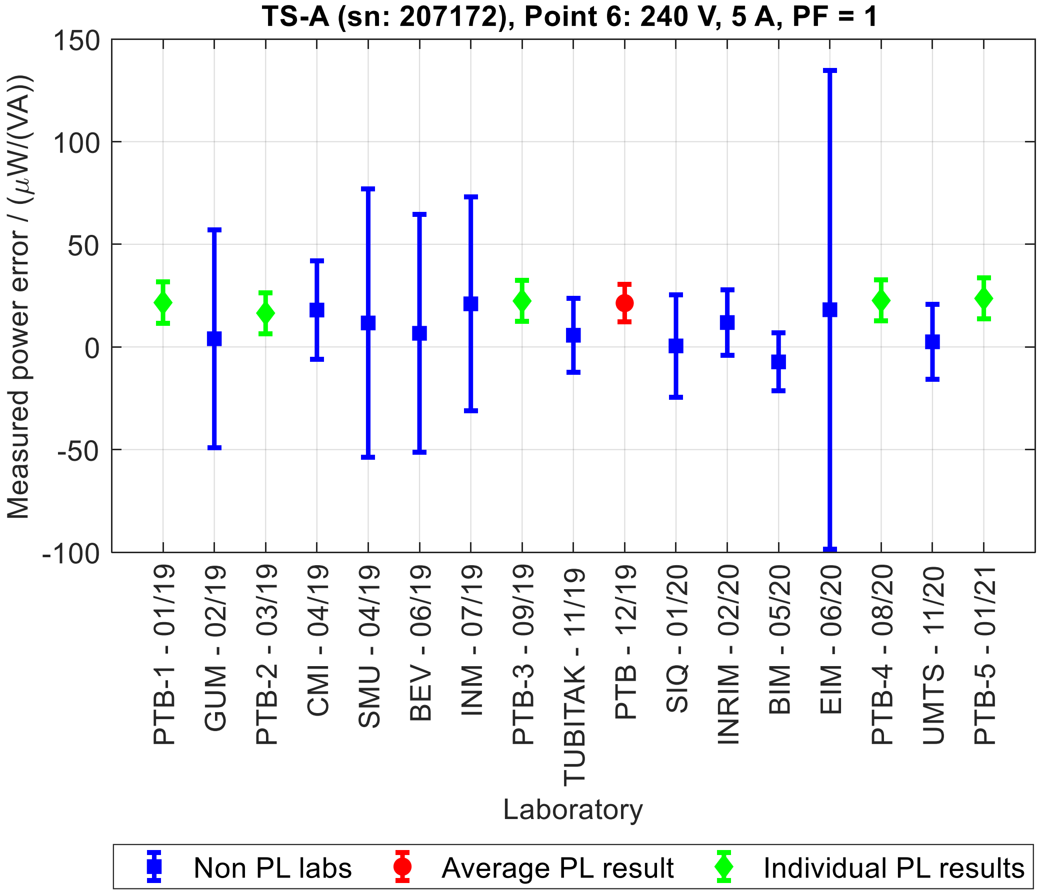
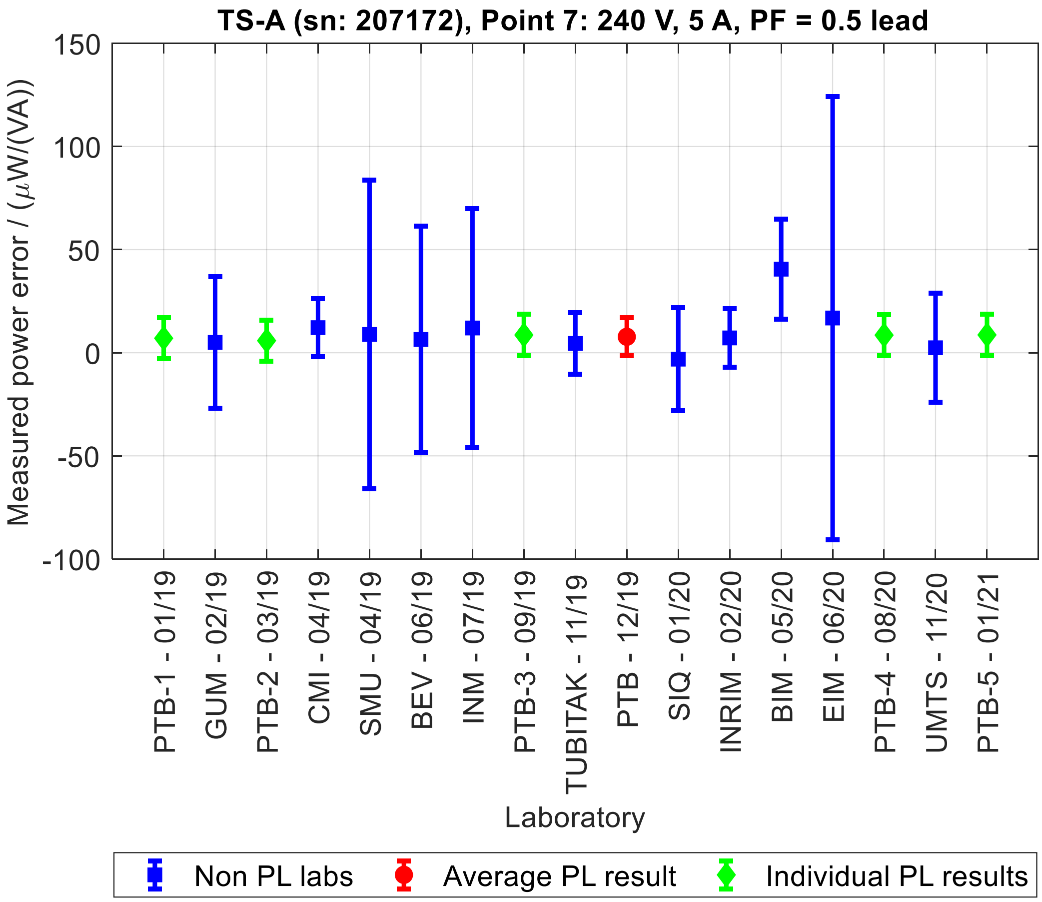
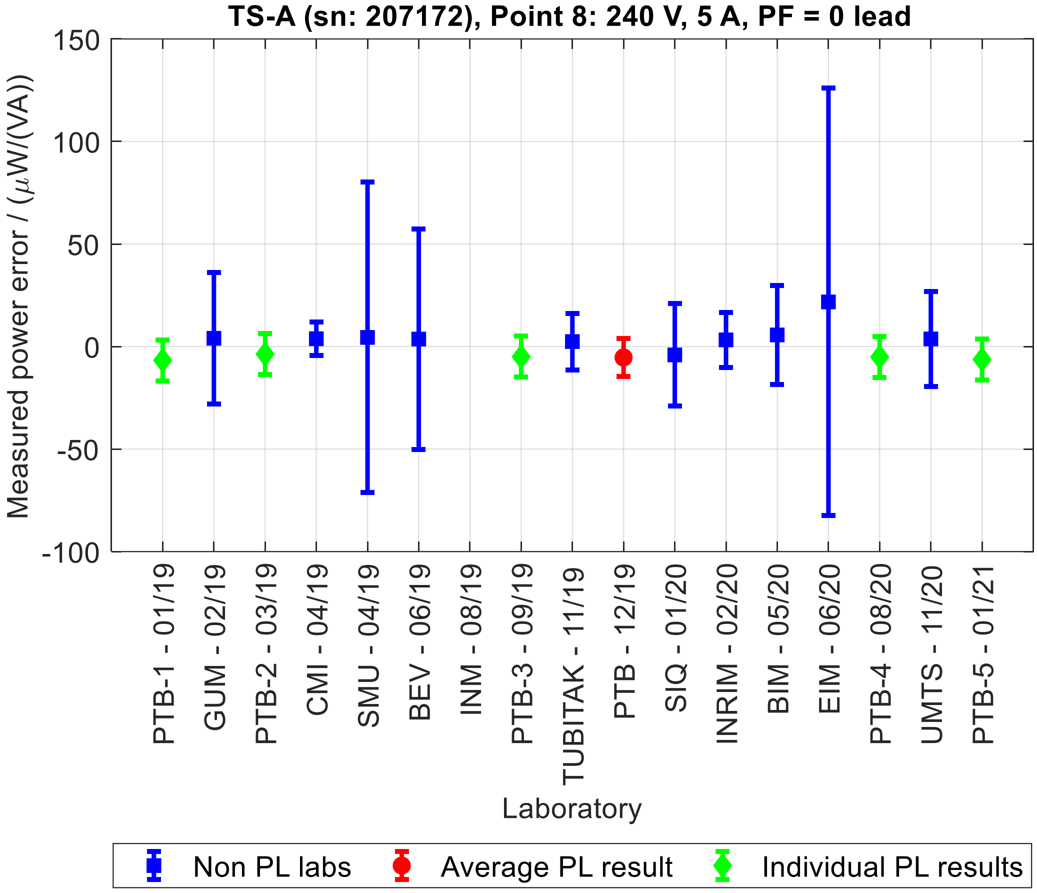
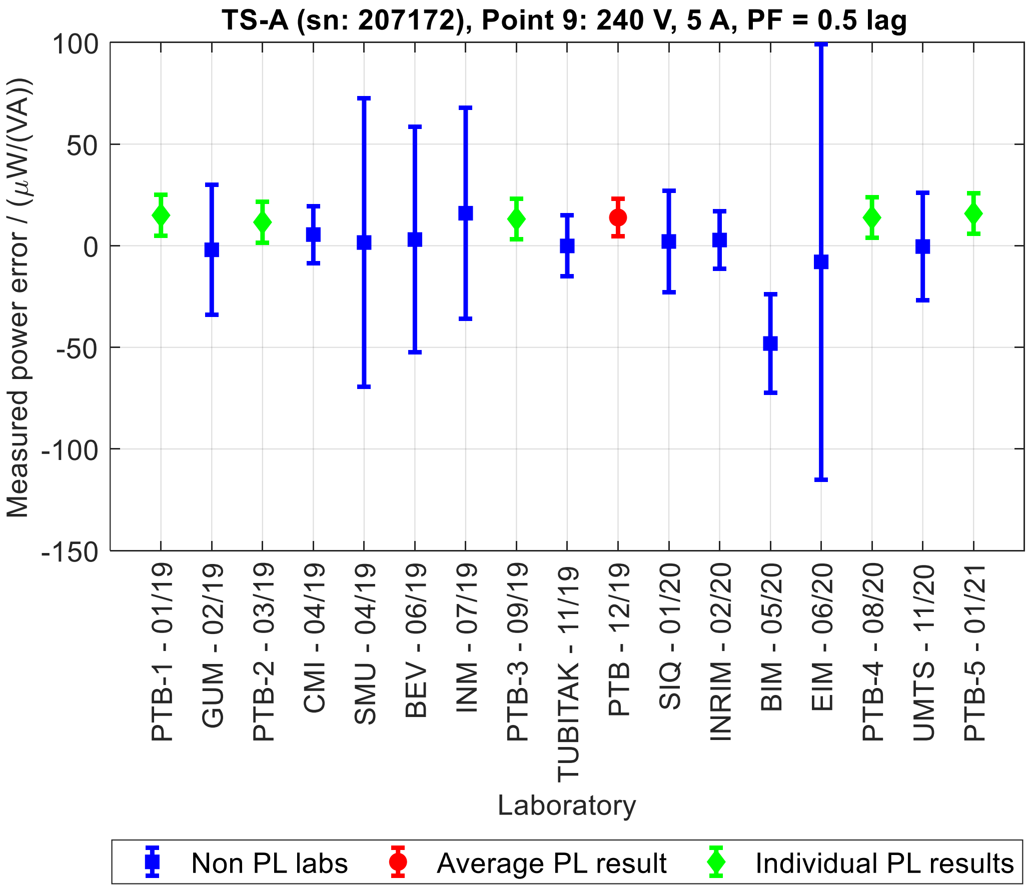
PTB-5 - 01/21
Laboratory
Non PL labs
Average PL result
Individual PL results


TS-A (sn: 207172), Point 6: 240 V, 5 A, PF = 1
Measured power error / (μW/(VA))
150
100
50
0
-50
-100
PTB-1 - 01/19
GUM - 02/19
PTB-2 - 03/19
CMI - 04/19
SMU - 04/19
BEV - 06/19
INM - 07/19
PTB-3 - 09/19
TUBITAK - 11/19
PTB - 12/19
SIQ - 01/20
INRIM - 02/20
BIM - 05/20
EIM - 06/20
PTB-4 - 08/20
UMTS - 11/20
PTB-5 - 01/21
Laboratory
Non PL labs
Average PL result
Individual PL results


TS-A (sn: 207172), Point 7: 240 V, 5 A, PF = 0.5 lead
Measured power error / (μW/(VA))
150
100
50
0
-50
-100
PTB-1 - 01/19
GUM - 02/19
PTB-2 - 03/19
CMI - 04/19
SMU - 04/19
BEV - 06/19
INM - 07/19
PTB-3 - 09/19
TUBITAK - 11/19
PTB - 12/19
SIQ - 01/20
INRIM - 02/20
BIM - 05/20
EIM - 06/20
PTB-4 - 08/20
UMTS - 11/20
PTB-5 - 01/21
Laboratory
Non PL labs
Average PL result
Individual PL results


TS-A (sn: 207172), Point 8: 240 V, 5 A, PF = 0 lead
Measured power error / (μW/(VA))
150
100
50
0
-50
-100
PTB-1 - 01/19
GUM - 02/19
PTB-2 - 03/19
CMI - 04/19
SMU - 04/19
BEV - 06/19
INM - 08/19
PTB-3 - 09/19
TUBITAK - 11/19
PTB - 12/19
SIQ - 01/20
INRIM - 02/20
BIM - 05/20
EIM - 06/20
PTB-4 - 08/20
UMTS - 11/20
PTB-5 - 01/21
Laboratory
Non PL labs
Average PL result
Individual PL results


TS-A (sn: 207172), Point 9: 240 V, 5 A, PF = 0.5 lag
Measured power error / (μW/(VA))
100
50
0
-50
-100
-150
PTB-1 - 01/19
GUM - 02/19
PTB-2 - 03/19
CMI - 04/19
SMU - 04/19
BEV - 06/19
INM - 07/19
PTB-3 - 09/19
TUBITAK - 11/19
PTB - 12/19
SIQ - 01/20
INRIM - 02/20
BIM - 05/20
EIM - 06/20
PTB-4 - 08/20
UMTS - 11/20
PTB-5 - 01/21
Laboratory
Non PL labs
Average PL result
Individual PL results

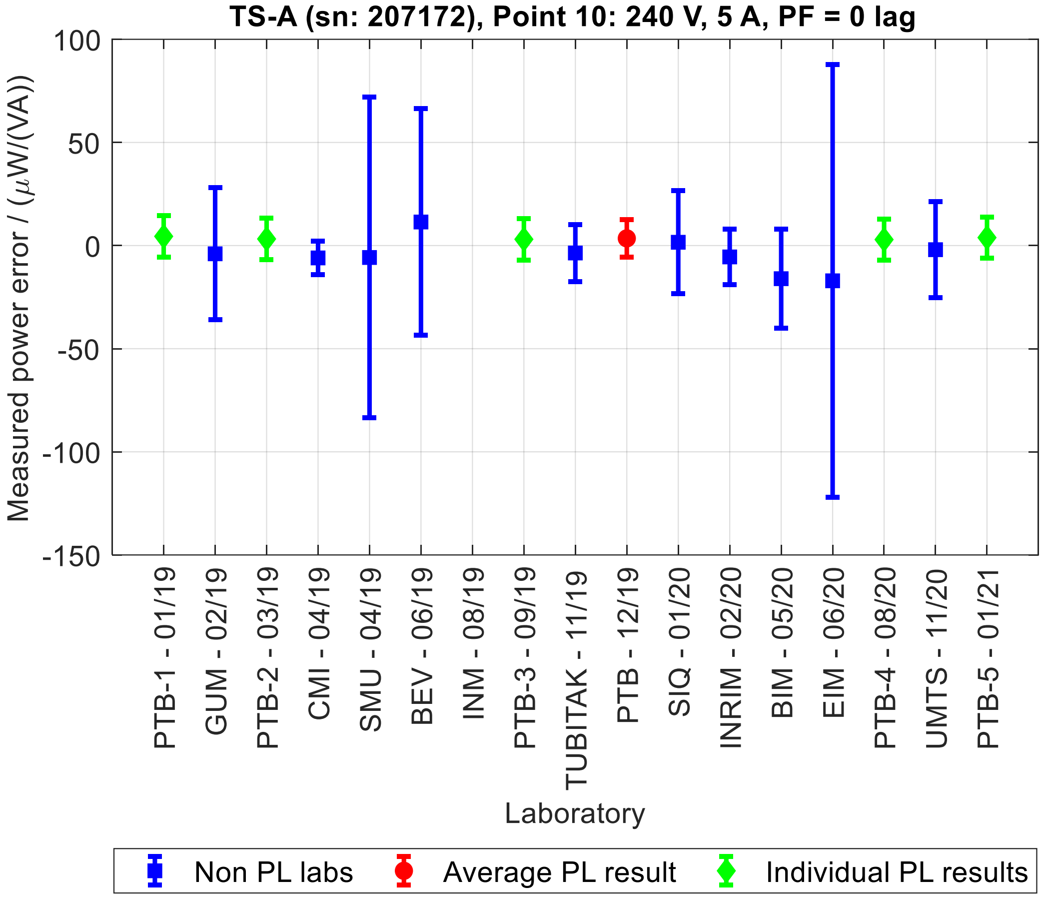
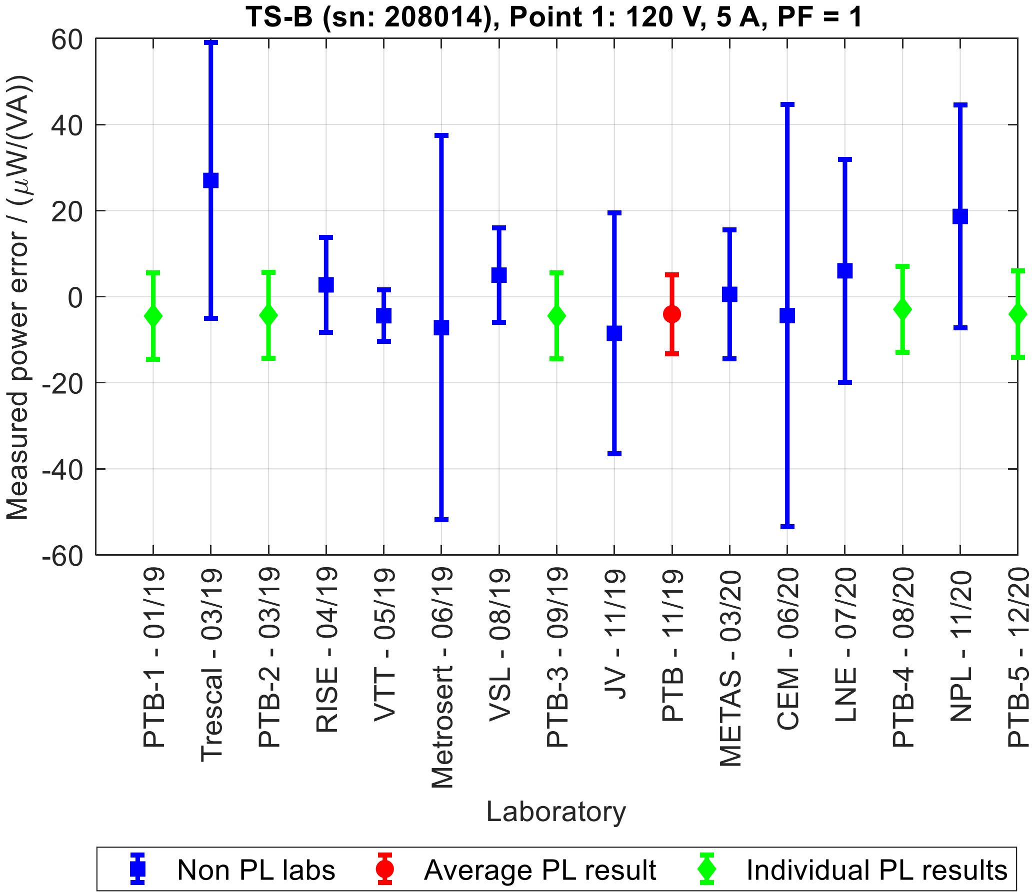
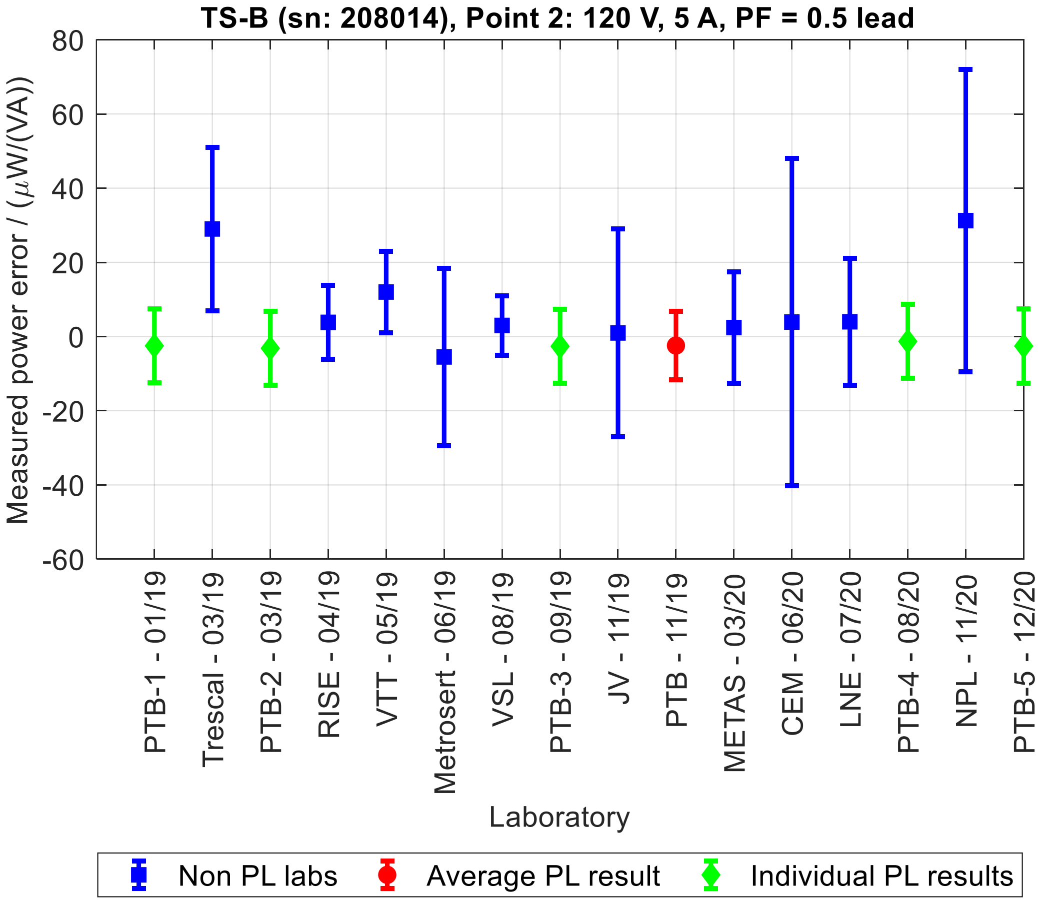
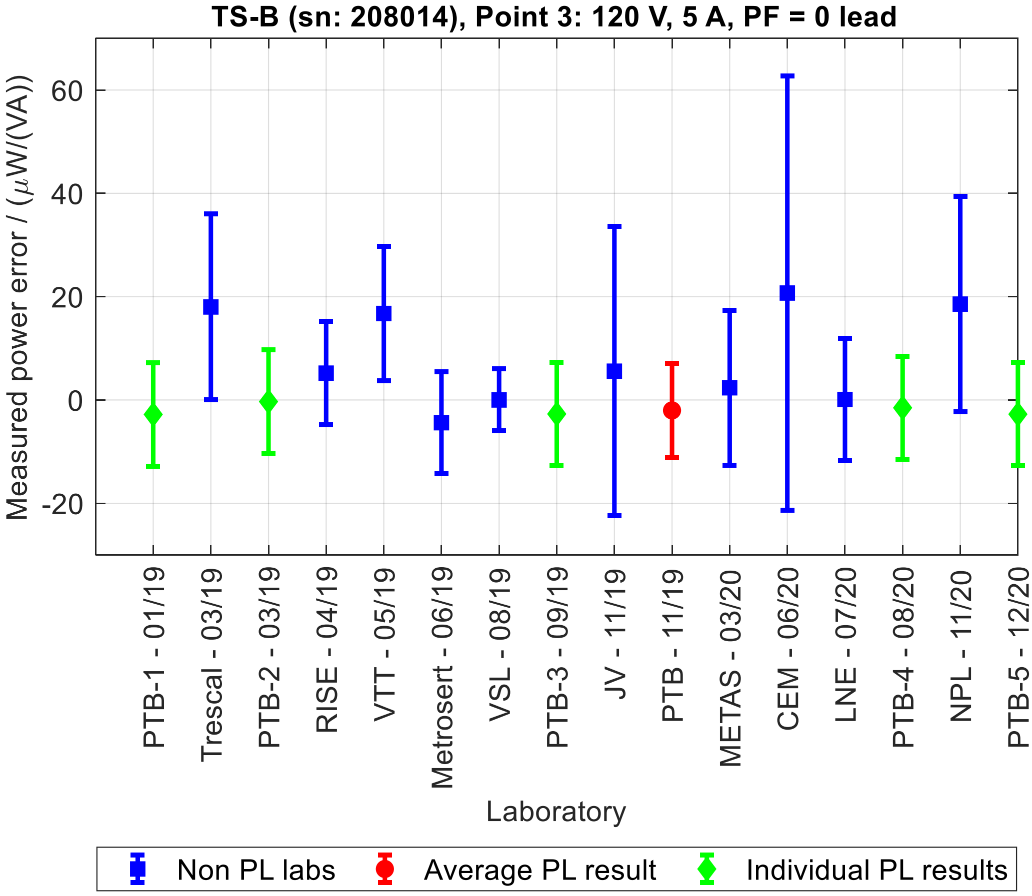
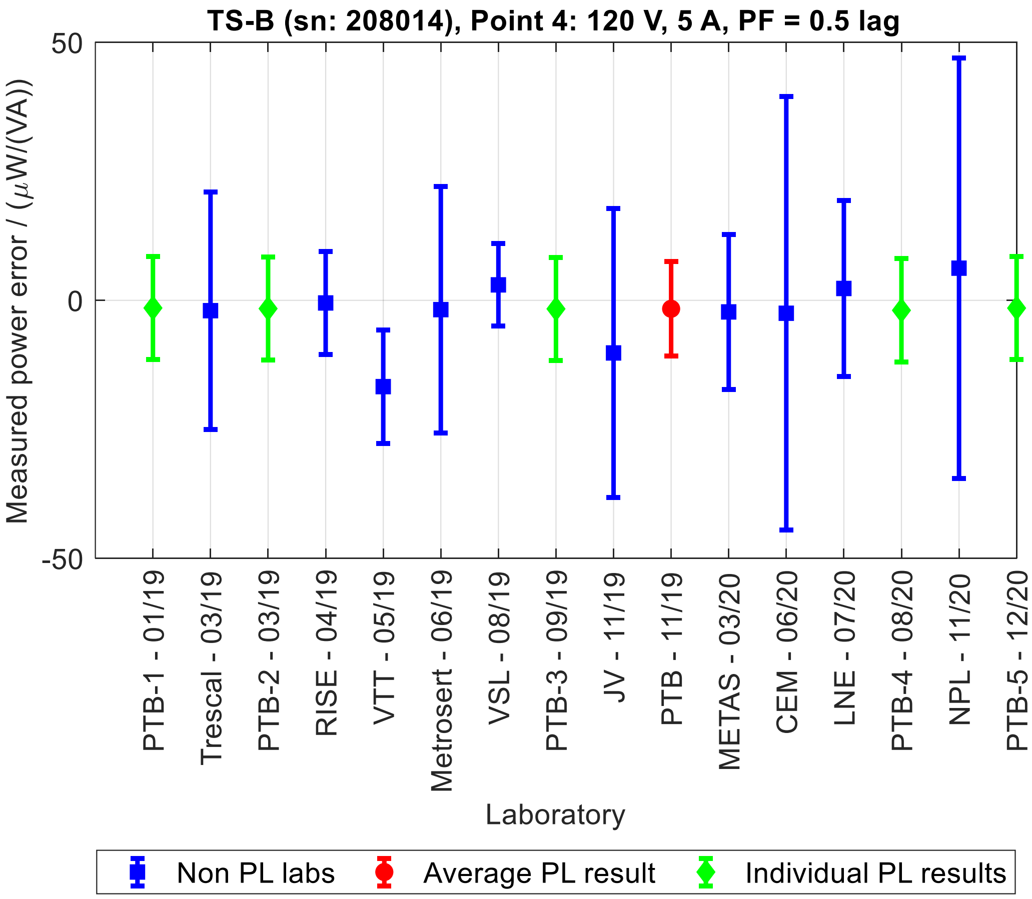


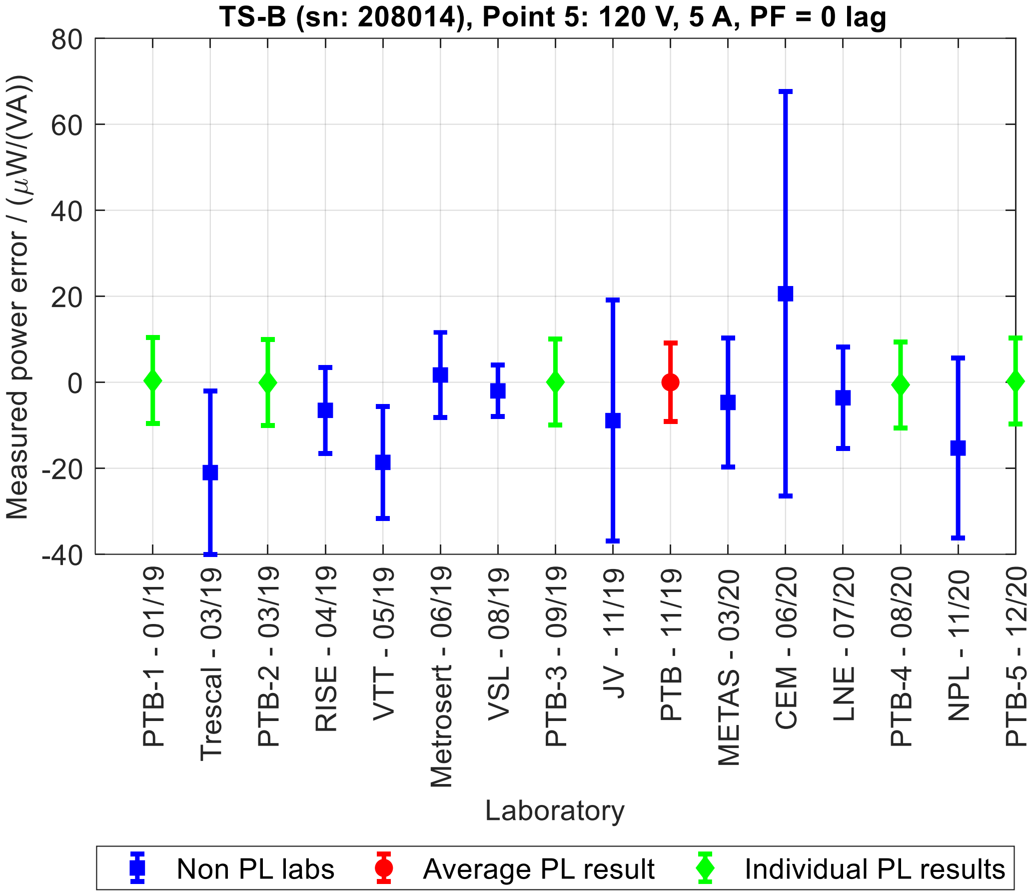
Figure 2: Plot of the measurement results with expanded uncertainties (k = 2) as provided by the laboratories for loop A.

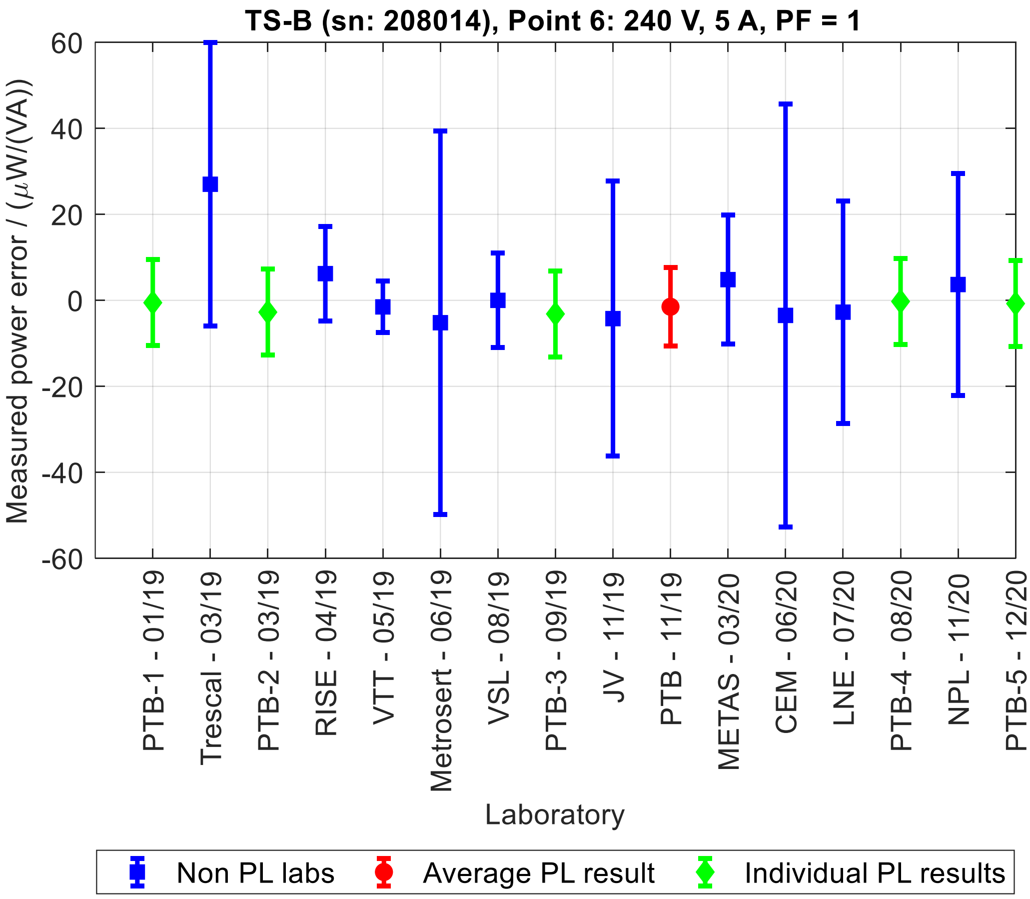

TS-B (sn: 208014), Point 1: 120 V, 5 A, PF = 1
Measured power error / (μW/(VA))
60
40
20
0
-20
-40
-60
PTB-1 - 01/19
Trescal - 03/19
PTB-2 - 03/19
RISE - 04/19
VTT - 05/19
Metrosert - 06/19
VSL - 08/19
PTB-3 - 09/19
JV - 11/19
PTB - 11/19
METAS - 03/20
CEM - 06/20
LNE - 07/20
PTB-4 - 08/20
NPL - 11/20
PTB-5 - 12/20
Laboratory
Non PL labs
Average PL result
Individual PL results

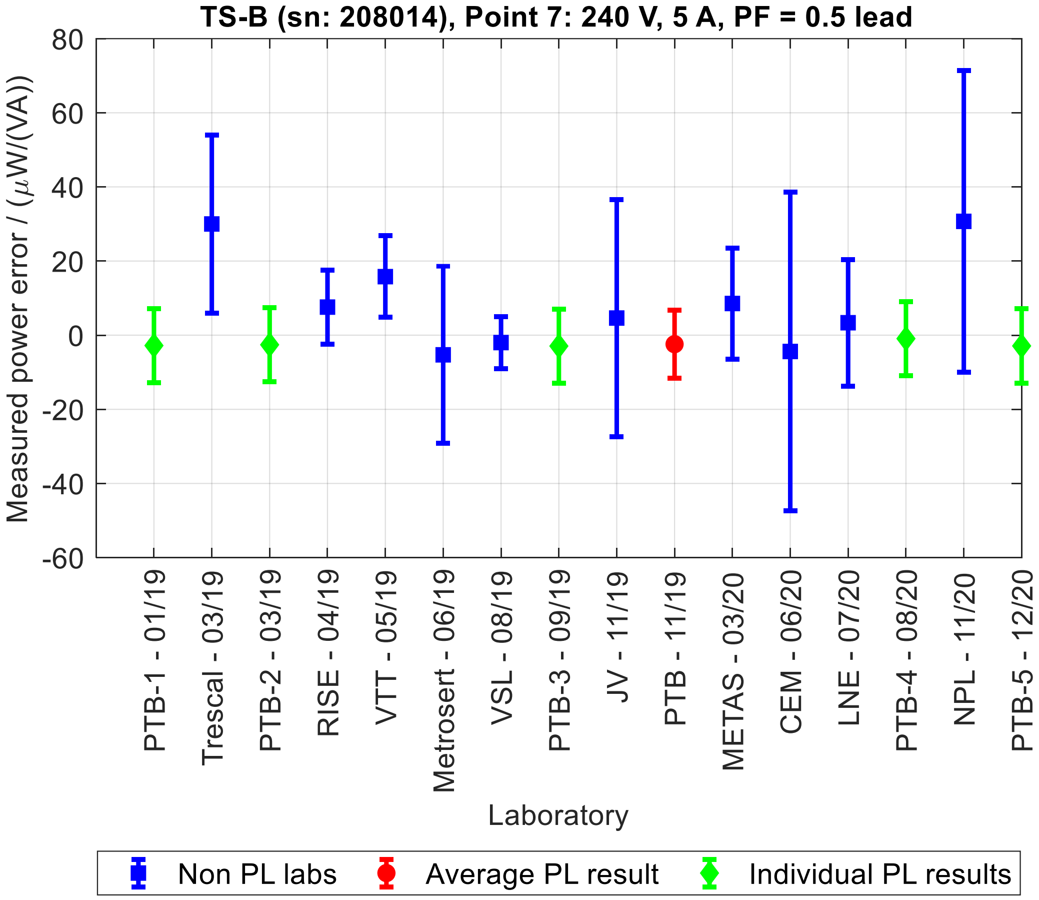

TS-B (sn: 208014), Point 2: 120 V, 5 A, PF = 0.5 lead
Measured power error / (μW/(VA))
80
60
40
20
0
-20
-40
-60
PTB-1 - 01/19
Trescal - 03/19
PTB-2 - 03/19
RISE - 04/19
VTT - 05/19
Metrosert - 06/19
VSL - 08/19
PTB-3 - 09/19
JV - 11/19
PTB - 11/19
METAS - 03/20
CEM - 06/20
LNE - 07/20
PTB-4 - 08/20
NPL - 11/20
PTB-5 - 12/20
Laboratory
Non PL labs
Average PL result
Individual PL results

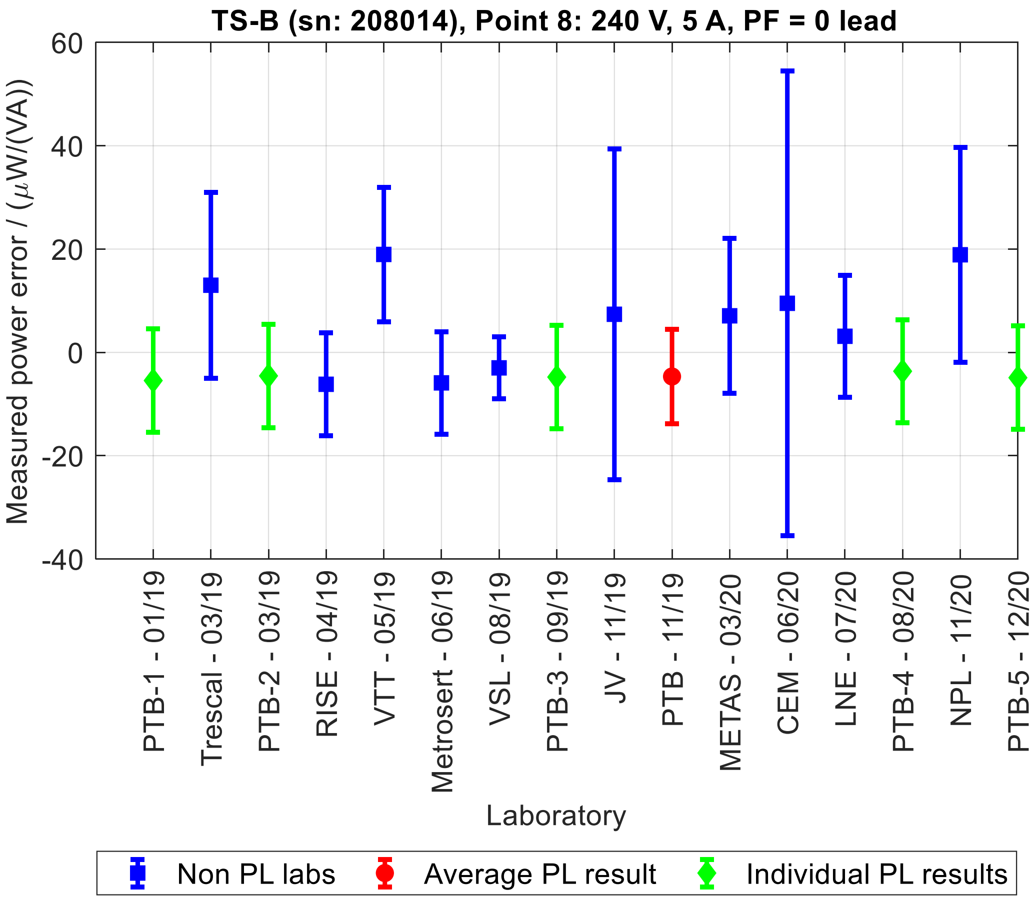

TS-B (sn: 208014), Point 3: 120 V, 5 A, PF = 0 lead
Measured power error / (μW/(VA))
60
40
20
0
-20
PTB-1 - 01/19
Trescal - 03/19
PTB-2 - 03/19
RISE - 04/19
VTT - 05/19
Metrosert - 06/19
VSL - 08/19
PTB-3 - 09/19
JV - 11/19
PTB - 11/19
METAS - 03/20
CEM - 06/20
LNE - 07/20
PTB-4 - 08/20
NPL - 11/20
PTB-5 - 12/20
Laboratory
Non PL labs
Average PL result
Individual PL results

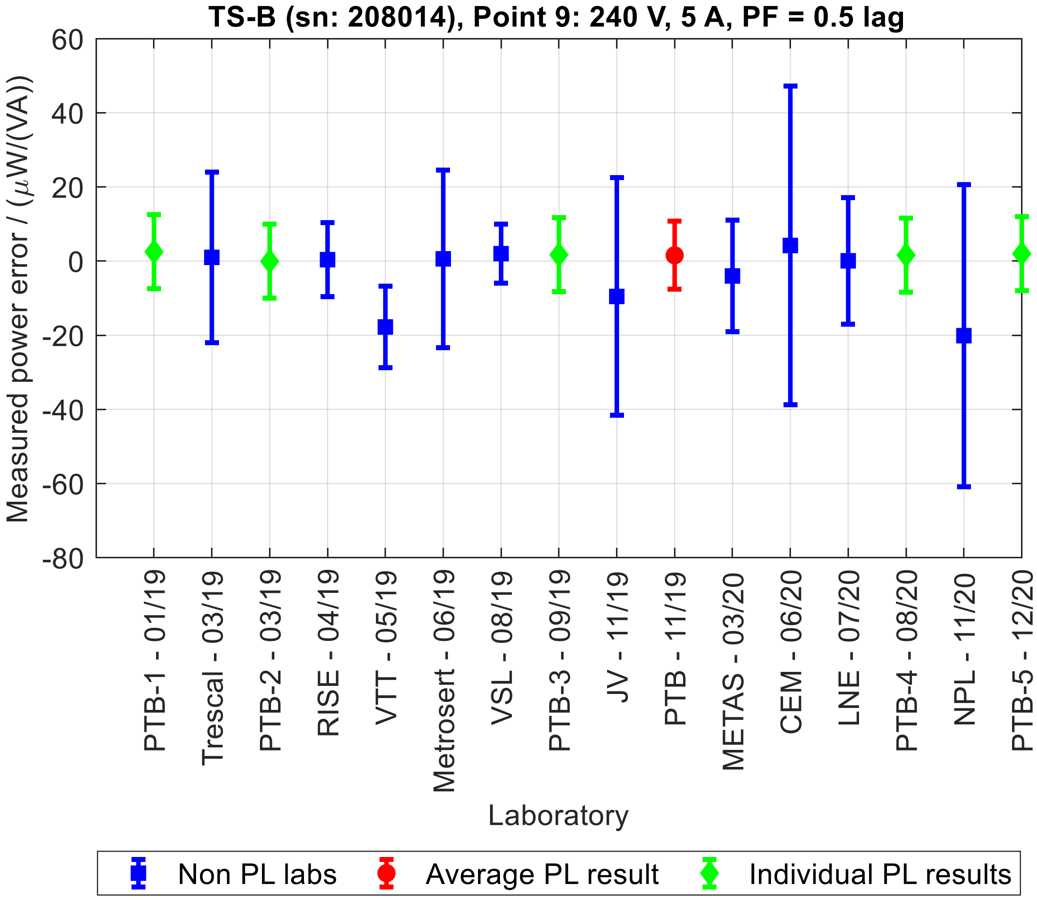

TS-B (sn: 208014), Point 4: 120 V, 5 A, PF = 0.5 lag
Measured power error / (μW/(VA))
50
0
-50
PTB-1 - 01/19
Trescal - 03/19
PTB-2 - 03/19
RISE - 04/19
VTT - 05/19
Metrosert - 06/19
VSL - 08/19
PTB-3 - 09/19
JV - 11/19
PTB - 11/19
METAS - 03/20
CEM - 06/20
LNE - 07/20
PTB-4 - 08/20
NPL - 11/20
PTB-5 - 12/20
Laboratory
Non PL labs
Average PL result
Individual PL results


TS-B (sn: 208014), Point 5: 120 V, 5 A, PF = 0 lag
Measured power error / (μW/(VA))
80
60
40
20
0
-20
-40
PTB-1 - 01/19
Trescal - 03/19
PTB-2 - 03/19
RISE - 04/19
VTT - 05/19
Metrosert - 06/19
VSL - 08/19
PTB-3 - 09/19
JV - 11/19
PTB - 11/19
METAS - 03/20
CEM - 06/20
LNE - 07/20
PTB-4 - 08/20
NPL - 11/20
PTB-5 - 12/20
Laboratory
Non PL labs
Average PL result
Individual PL results


TS-B (sn: 208014), Point 6: 240 V, 5 A, PF = 1
Measured power error / (μW/(VA))
60
40
20
0
-20
-40
-60
PTB-1 - 01/19
Trescal - 03/19
PTB-2 - 03/19
RISE - 04/19
VTT - 05/19
Metrosert - 06/19
VSL - 08/19
PTB-3 - 09/19
JV - 11/19
PTB - 11/19
METAS - 03/20
CEM - 06/20
LNE - 07/20
PTB-4 - 08/20
NPL - 11/20
PTB-5 - 12/20
Laboratory
Non PL labs
Average PL result
Individual PL results


TS-B (sn: 208014), Point 7: 240 V, 5 A, PF = 0.5 lead
Measured power error / (μW/(VA))
80
60
40
20
0
-20
-40
-60
PTB-1 - 01/19
Trescal - 03/19
PTB-2 - 03/19
RISE - 04/19
VTT - 05/19
Metrosert - 06/19
VSL - 08/19
PTB-3 - 09/19
JV - 11/19
PTB - 11/19
METAS - 03/20
CEM - 06/20
LNE - 07/20
PTB-4 - 08/20
NPL - 11/20
PTB-5 - 12/20
Laboratory
Non PL labs
Average PL result
Individual PL results


TS-B (sn: 208014), Point 8: 240 V, 5 A, PF = 0 lead
Measured power error / (μW/(VA))
60
40
20
0
-20
-40
PTB-1 - 01/19
Trescal - 03/19
PTB-2 - 03/19
RISE - 04/19
VTT - 05/19
Metrosert - 06/19
VSL - 08/19
PTB-3 - 09/19
JV - 11/19
PTB - 11/19
METAS - 03/20
CEM - 06/20
LNE - 07/20
PTB-4 - 08/20
NPL - 11/20
PTB-5 - 12/20
Laboratory
Non PL labs
Average PL result
Individual PL results



TS-B (sn: 208014), Point 9: 240 V, 5 A, PF = 0.5 lag
Measured power error / (µW/(VA))
60
40
20
0
-20
-40
-60
-80
PTB-1 - 01/19
Trescal - 03/19
PTB-2 - 03/19
RISE - 04/19
VTT - 05/19
Metrosert - 06/19
VSL - 08/19
PTB-3 - 09/19
JV - 11/19
PTB - 11/19
METAS - 03/20
CEM - 06/20
LNE - 07/20
PTB-4 - 08/20
NPL - 11/20
PTB-5 - 12/20
Laboratory
Non PL labs
Average PL result
Individual PL results

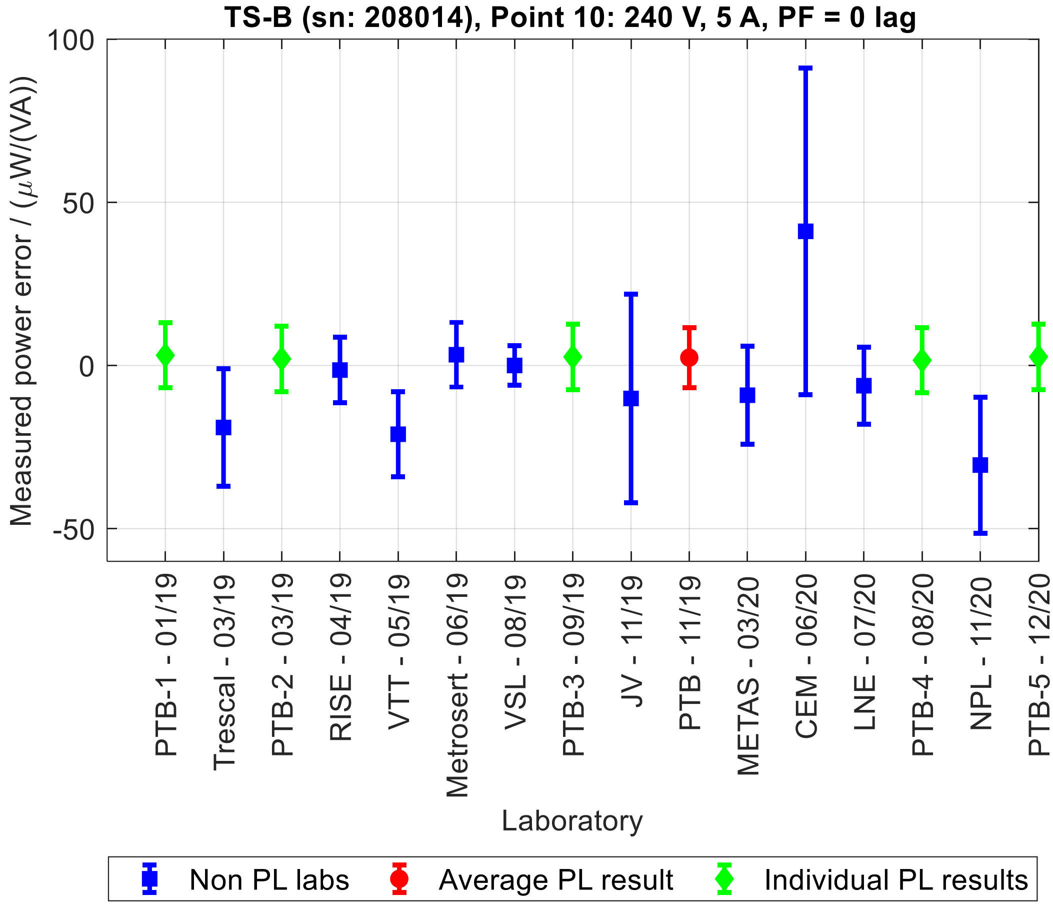


Figure 3: Plot of the measurement results with expanded uncertainties (k = 2) as provided by the laboratories for loop B.

APPENDIX B: READ-ME FILE TO DIGITAL SUPPLEMENT

In order to facilitate further analysis and uptake of the intercomparison measurement data and computed results, the main parts of this analysis have been made available in the form of a digital, machine-readable supplement. The main data structures of interest have been encoded in JSON format which is available in the form of .json file as supplementary file. This also includes the bilateral degrees of equivalence d'_{ij} and the uncertainties $u(d'_{ij})$ which have not been presented in this report. The values of d'_{ij} are stored in the variable Calc.bildoe_per_lab_lab_pnt, whereas the values of $u(d'_{ij})$ are stored in the variable Calc.ubildoe_per_lab_lab_pnt. As the linking procedure only adds a constant term ℓ to all RMO degrees of equivalence d'_i, there is no difference between RMO degrees of equivalence $d'_{ij} = d'_i - d'_j$ and the linked degrees of equivalence $d_{ij} = d_i - d_j$.

Furthermore, the full covariance matrices of the corrected measurement results and of the DoEs are given as well as matrices with sensitivity coefficients, which can be of use when linking complementary comparisons to this regional (RMO) comparison.

The data structure is split into three parts:

- 'Gen' contains some general variables;
- 'Stab' contains the measurement results of the stability measurements;
- 'Meas' contains the provided measurement results by the participating laboratories;
- 'Calc' contains the computed results as explained in the main part of this document.
- 'Link' contains an additional set of computed results as explained in the main part of this document.

A detailed explanation of all variable names contained in the digital supplement can be found in Table 16.

Table 16: Explanation of the variable names contained in the digital supplement

Variable name	**Explanation**	**Reference in report**
General variables (Gen)		
• n_pnts	Number of test points (= 10)	Table 2
• n_labs	Number of participating laboratories (= 22, PTB is counted once)	Table 3 and Table 4
• n_ts	Number of travelling standards (= 2)	Section 3.1
• meas_pnt_defs_per_pnt	Definition of test points	Table 2
• laboratory_name_per_lab	Names of the participating laboratories	Table 3 and Table 4
• extended_laboratory_name_ per_labext	Names of the participating laboratories with an additional postfix -A or -B depending on the travelling standard being reported on	Table 3 and Table 4
• rho_measurement_uncertainty	Assumed correlation coefficient between provided measurement results by the same laboratory for the same nominal quantity (= 0.8)	Equation (3)
Stability measurement data (Stab)		

Variable name	Explanation	Reference in report
• lab_name	The name of the laboratory performing the stability measurements (= PTB)	Section 2
• date_per_rep_ts_pnt	The measurement dates of the stability measurements for each repeated measurement, traveling standard and test point	Table 14 and Table 15
• y_per_rep_ts_pnt	The measured values of the stability measurements	Table 14 and Table 15
• uy_per_rep_ts_pnt	The standard uncertainties of the stability measurements	Table 14 and Table 15
Provided measurement data (Meas)		
• date_per_labext_pnt	Matrix containing the measurement dates for each laboratory (with postfixes -A and -B) and each test point	Table 14 and Table 15
• y_per_labext_pnt	Matrix containing the provided measurement values for each laboratory (with postfix -A or -B) and each test point	Table 14 and Table 15
• uy_per_labext_pnt	Matrix containing the provided standard uncertainty for each laboratory (with postfix -A or -B) and each test point	Table 14 and Table 15
Calculated results (Calc)		
• ycor_per_labext_pnt	Measured values after correction for drift per laboratory and test point. Identical to y_per_labext_pnt in this comparison.	Not applicable
• vycor_per_labext_labext_pnt	Covariance matrix with squared standard uncertainties of the provided values augmented with TS uncertainty for each pair of laboratories per test point.	Equation (9)
• ref_per_ts_pnt	Matrix containing the computed REFs for each of the TSs for each test point	$\boldsymbol{y}_{\text{ref}}$
• vref_per_ts_ts_pnt	3D-matrix whereby each 2D-slice (per test point, 3rd dimension) contains the covariance matrix of the computed REFs for each pair of TSs	$V_{\boldsymbol{y}_{\text{ref}}}$
• sens_ref_ycor_per_ts_labext_pnt	3D-matrix whereby each 2D-slice (per test point, 3rd dimension) contains the sensitivity coefficients or weights for each of the REFs w.r.t. each of the provided measurement values	formula for $\boldsymbol{y}_{\text{ref}}$
• rdoe_ts_per_labext_pnt	Matrix containing the RDOEs before merging for each laboratory (with postfix -A or -B) and for each test point	Equation (10) and (11)
• vrdoe_ts_per_labext_labext_pnt	3D-matrix whereby each 2D-slice (per test point, 3rd dimension) contains the covariance matrix of the RDOEs for each pair of laboratories (with postfix -A or -B)	$V_{\boldsymbol{d}'}$

Variable name	Explanation	Reference in report
• sens_rdoe_ts_per_labext_labext_pnt	3D-matrix whereby each 2D-slice (per test point, 3rd dimension) contains the sensitivity coefficients of the RDOE for each of the laboratories w.r.t. each of the provided measurement values	Based on calculations for $\boldsymbol{d}'$
• rdoe_per_lab_pnt	Matrix containing the merged RDOEs for each laboratory (only relevant for PTB)	Equation (13)
• urdoe_per_lab_pnt	Standard uncertainties of the merged RDOEs per laboratory and test point	$u(d'_i)$ and Equation (12)
• vrdoe_per_lab_lab_pnt	3D-matrix whereby each 2D-slice (per test point, 3rd dimension) contains the covariance matrix of the merged RDOEs for each pair of laboratories (only relevant for PTB)	modified version of $V_{\boldsymbol{d}'}$
• sens_rdoe_ycor_per_lab_labext_pnt	3D-matrix whereby each 2D-slice (per test point, 3rd dimension) contains the sensitivity coefficients of the RDOE for each of the laboratories w.r.t. each of the provided measurement values (only relevant/ different for PTB)	Based on calculations for $\boldsymbol{d}'$
• bilrdoe_per_lab_lab_pnt	3D-matrix whereby each 2D-slice (per test point, 3rd dimension) contains the bilateral DOEs for each pair of laboratories	Equation (14)
• ubilrdoe_per_lab_lab_pnt	3D-matrix whereby each 2D-slice (per test point, 3rd dimension) contains the standard uncertainty of the bilateral DoEs for each pair of laboratories	Equation (15)
Calculated results w.r.t. linking (Link)		
• link_per_pnt	value of the link between the RMO REF value and the CIPM KCRV per test point	ℓ
• ulink_per_pnt	uncertainty of the link between the RMO REF value and the CIPM KCRV per test point	$u(\ell)$
• ylkcrv_per_ts_pnt	LKCRV: updated reference value of the RMO comparison after linking with the CIPM comparison per TS and per test point	Equation (18)
• uylkcrv_per_ts_pnt	standard uncertainty of the LKCRV	Equation (21)
• ldoe_per_lab_pnt	Matrix containing the DOEs for each laboratory after linking with the CIPM key comparison	Equation (17)
• uldoe_per_lab_pnt	Matrix containing the standard uncertainty of the DOEs for each laboratory after linking with the CIPM key comparison	$u(d_j)$
• vldoe_per_lab_lab_pnt	3D-matrix whereby each 2D-slice (per test point, 3rd dimension) contains the covariance matrix of the linked DOEs for each pair of laboratories after linking with the CIPM key comparison	$V_{\boldsymbol{d}}$

APPENDIX C: PARTICIPANT REPORTS