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Specifying Calibration of Energy-Measuring Equipment

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Abstract

Energy-measuring equipment is used to characterize, refine, calibrate, adjust, and monitor equipment associated with energy engineering. Measuring equipment and standards need to be calibrated periodically to ensure that their use yields accurate measurements. Calibration needs, however, vary in sophistication, based on user expectations. This article provides some background on measurement science (i.e., metrology) for context, but more directly pertains to energy engineering by focusing on energy-measuring equipment, the accuracy of which is essential to maximizing energy savings. It reviews calibration terminology and standards, and describes best practices that have been developed for a) calibrating measuring equipment to ensure some known level of accuracy, and b) accrediting calibration laboratories. Calibration is discussed in the context of metrological traceability, and excerpts from laboratory scopes of accreditation are shared to reveal the diversity of terminology and format among them. In an effort to aid those who currently have measuring equipment calibrated or who have new or changing needs for measuring equipment calibration, rationale is provided for why a specification might be used to request calibration services that meet specific test needs. Given the growing interest in using data to manage the energy consumption of systems, and the increasing number and variety of systems (e.g., building, computing) that can report such information, use cases requiring energy data are used to facilitate further discussion and provide examples. Commercially available calibration service providers who are accredited for energy-measuring equipment calibration are compared and contrasted, and a specification template that might be used for requesting this calibration is presented. The specification template should be tailored to meet each user’s needs. To illustrate, an example set of energy-measuring-equipment test conditions (reflecting the planned usage of the device to be calibrated) is used to develop a customized calibration specification, and commercially available service providers are assessed in terms of their qualifications for calibration to that particular implementation of the specification template.

Introduction

Measuring equipment and standards need to be calibrated periodically to ensure that their use yields accurate measurements. Specifically, calibration helps to improve trueness by minimizing systematic error (e.g., due to instrument bias), as opposed to improving precision by minimizing random error (e.g., due to variation attributable to different operators). However, calibration does enable quantification of measurement uncertainty. International Organization for Standardization (ISO) standard 5725-1:1994 provides definitions for accuracy, trueness, precision, and related terms (ISO 1994).

Calibration needs vary in sophistication based on user expectations. At one extreme, the user of a measuring instrument (i.e., measuring equipment) may only want or need a rough sense of a measured quantity, the instrument may exhibit relatively poor resolution and precision, and the user may never have the instrument calibrated. While such a situation might suffice, for example, when a lighting design comfortably meets requirements, it can pose problems when little room is left for error and a code inspection by the local authority having jurisdiction determines that illuminance is noncompliant. At the next level of sophistication, the user may have the instrument calibrated periodically but does not use specifications to ensure that the calibration laboratory (i.e., calibration service provider) is qualified and that the calibration will cover the range of intended use. In this case, the calibration might reduce measurement uncertainty but won't necessarily ensure an established or expected level of measurement trueness. A sophisticated user will develop specifications for calibration that cover the range of intended use but will also ensure that the laboratory is qualified to calibrate the measuring equipment.

Electrical utilities (which must ensure that watthour meters are accurate for billing purposes) and manufacturers of devices that report measured electrical energy are examples of entities that may be more sophisticated in terms of calibration requirements. Such entities may have a small set of devices calibrated periodically to serve as internal reference standards, and then use these to calibrate energy-measuring equipment that will be sold or otherwise put into service, thereby ensuring a degree of accuracy in the field.

Background

In the U.S., calibrations are typically performed relative to National Institute of Standards and Technology (NIST) reference standards (15 CFR 200, 15 U.S.C. 271). NIST leverages the Guide to the Expression of Uncertainty in Measurement (GUM) and the International Vocabulary of Metrology (VIM) to address calibration and other aspects of metrology (Ehrlich 2012, Possolo 2015). These documents were originally developed by ISO Technical Advisory Group 4. The Joint Committee for Guides in Metrology (JCGM) assumed responsibility for them in 1997, publishing the GUM as JCGM 100 and the VIM as JCGM 200. Electronic versions of these publications are available from the JCGM portal on the ISO website, as well as on the websites of other JCGM-supporting organizations, including the International Bureau of Weights and Measures (BIPM). The GUM and VIM have also been adopted as ISO standards by the International Electrotechnical Commission (IEC), designated ISO/IEC Guide 98-3 and ISO/IEC Guide 99, respectively. Similarly, the American National Standards Institute (ANSI) and National Conference of Standards Laboratories (NCSL) standard ANSI/NCSL Z540.2-1997 (R2012) was derived from the GUM and is identical, with the exception of minor editorial changes to facilitate its use in the U.S. (NCSL 2012).

An understanding of the following terms will facilitate interpretation of the VIM definition for calibration:

- **Indication** – quantity value provided by a measuring instrument or a measuring system
- **Measurand** – quantity intended to be measured
- **Measurement result** – set of quantity values being attributed to a measurand, together with any other available relevant information
- **Measurement standard** – realization of the definition of a given quantity, with stated quantity value and associated measurement uncertainty; used as a reference
- **Measurement uncertainty** – non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used
- **Quantity value** – number and reference together expressing the magnitude of a quantity (e.g., 10.1 watts)

Calibration is defined in the VIM as an operation that, under specified conditions:

1. Establishes a relation between the *quantity values* (with measurement uncertainties) provided by *measurement standards* and corresponding *indications* (with associated measurement uncertainties), and
2. Uses this information to establish a relation for obtaining a *measurement result* from an indication.

This is illustrated in Figure 1. Calibration is often perceived as consisting of the first step alone. Similarly, some standards define calibration as including adjustment; for example, although ANSI C12.1-2014 (NEMA 2016) defines "calibration" as comparison of the indication of the instrument under test, or registration of the meter under test (MUT), with an appropriate standard, it specifically defines "watthour-meter calibration" as adjustment to bring the percentage registration of the watthour meter to within specified limits. In contrast, the VIM definition states that calibration is distinct from, and a prerequisite for, the following:

- **Adjustment** – set of operations carried out on a measuring system so that it provides prescribed indications corresponding to given values of a quantity to be measured
- **Verification** – provision of objective evidence that a given item fulfills specified requirements.

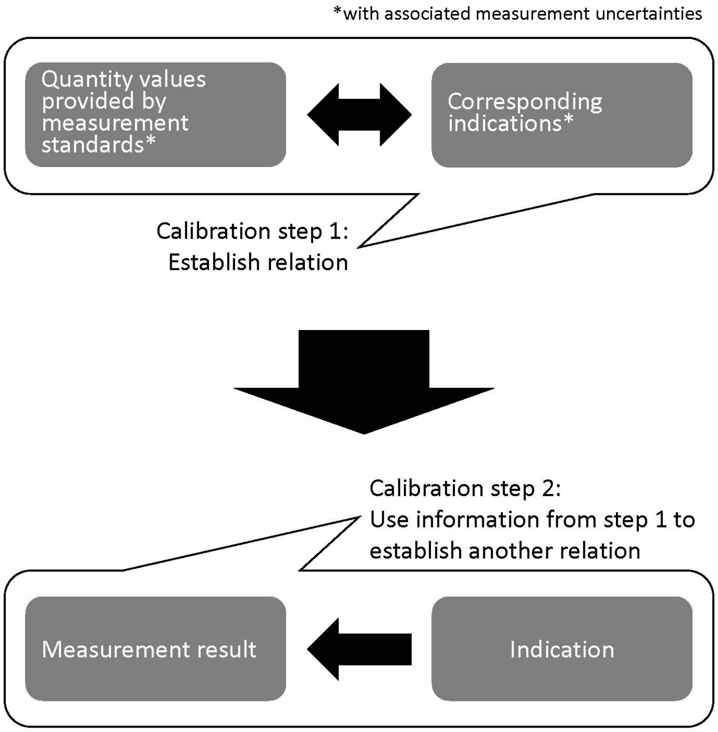

Figure 1. A single calibration, showing necessary versus optional elements.

Development of the current (third) edition of the VIM was motivated in part by the need to incorporate concepts that pertain to metrological traceability and measurement uncertainty. Calibration and traceability have been points of confusion since before the National Bureau of Standards (NBS) was renamed NIST in 1988 (Levin 1982, Gills et al. 2001, Ehrlich 2012, Chow et al. 2013). Indeed, a review of calibration reports or a web search for "NIST traceable" or "traceable to NIST" will yield a variety of claims regarding traceability. For example:

- "All equipment used is certified and fully traceable according to the National Institute of Standards and Technology (NIST)."
- "Validations are performed with reference instrumentation that is certified traceable in accordance with the National Institute of Standards and Technology (NIST)."
- "even with a NIST traceable sensor, it is often important to understand how far removed the sensor is from the actual calibration at NIST."
- "ISO requirements often require that test, measurement and control equipment be traceable to recognized national or international standards."
- "calibrated using measurement standards traceable to the National Institute of Standards and Technology"

Metrological traceability is defined in the VIM as the property of a measurement result (as opposed to a device or material), whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty. Metrological traceability requires an established calibration hierarchy (sequence of calibrations from a reference to the final measuring system, where the outcome of each calibration depends on the outcome of the previous calibration). Traceability therefore enables quantification of measurement uncertainty (Ehrlich 2012). NIST Handbooks 44 (NIST

2018a) and 130 (NIST 2018b), which were developed by the National Conference on Weights and Measures (NCWM), both require traceability to national standards (demonstrated through laboratory accreditation), but adoption of these voluntary standards varies by state, and until recently they did not cover the sale of electricity, which has been controlled by utilities (Gills et al. 2001). Electric vehicle supply equipment (EVSE) is now covered in the 2019 versions of these documents, but no EVSE has been evaluated yet by the National Type Evaluation Program (NTEP). Meanwhile, ANSI C12.1-2014 describes common methods for electric utilities to establish and maintain the traceability of their watthour standards to the International System of Units (SI), and for documenting the relationship between a calibrated revenue meter and the SI.

Although traceability is often stated with reference to NIST, this traceability effectively also indicates traceability to SI units (as illustrated in Figure 2), which are the most basic reference and are defined in the SI brochure published by the BIPM (BIPM 2019a). With the recent changes to several definitions, the seven SI base units (second, meter, kilogram, ampere, kelvin, mole, and candela) are now defined by their corresponding SI constants; these base units correspond to the seven SI base quantities (time, length, mass, electric current, thermodynamic temperature, amount of substance, and luminous intensity). Other SI units (e.g., the volt and ohm) are derived by multiplying together different powers of the base units. However, the practical realization of some base units is actually obtained through realizations of such derived units; for example, accurate realizations of the ampere (A) can be obtained through realizations of the ohm (Ω) and the volt (V), leveraging the relationship $A = V/\Omega$ (BIPM 2019b). Similarly, the watt (W) can be realized by leveraging the relationship $W = V^2/\Omega$, or by other means. Two waveforms can be compared in terms of phase angle (planar angle is the SI-derived unit), expressed in units of radians or degrees; for example, this can be used in calibrating displacement power factor, given sinusoidal voltage and current waveforms of the same frequency that are free of distortion. The practical realization of the second (s) is obtained by finding the duration of an established number of periods of radiation for cesium (of known frequency). The kilowatt-hour (kWh) is accepted as a unit of electrical energy only; the SI unit of energy, the joule, which is equal to the watt-second, is recommended for all applications (IEEE 2011, Butcher et al. 2006). Traceability can be established for all such derived quantities (Liu et al. 2012).

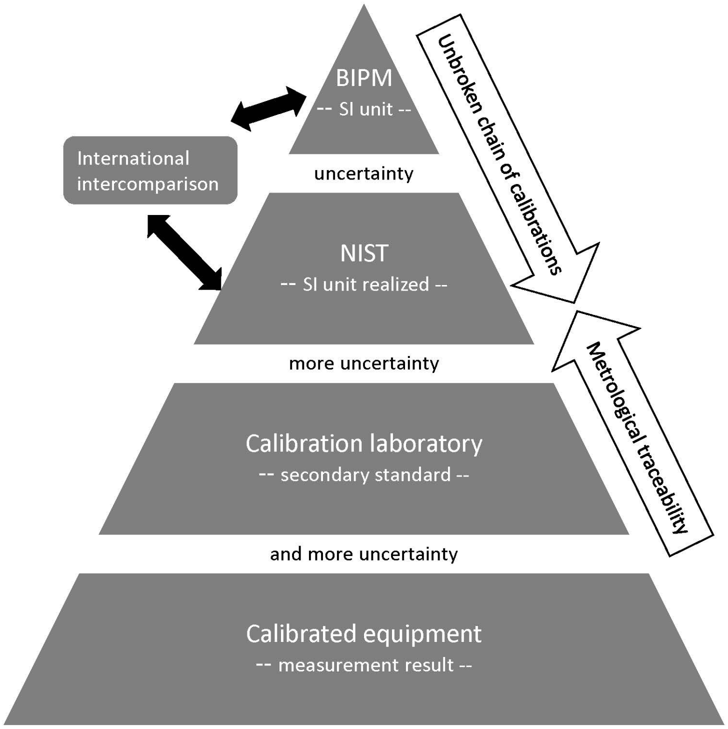

Figure 2. The path of metrological traceability from measurement result to SI unit. Measurement uncertainty increases at each step along the unbroken chain of calibrations.

ISO/IEC 17025 provides general requirements for the competence, impartiality, and consistent operation of calibration laboratories (IEC 2017a). The International Laboratory Accreditation Cooperation (ILAC) became a JCGM-supporting organization in 2005. Accreditation bodies (ABs) that are ILAC Mutual Recognition Arrangement (MRA) signatories have been peer-evaluated in accordance with the requirements of ISO/IEC 17011 (IEC 2017b) to assess and accredit conformity-assessment bodies according to relevant international standards; for example, calibration laboratories are assessed using ISO/IEC 17025. ILAC MRA signatories based in the U.S. include the American Association for Laboratory Accreditation (A2LA), the ANSI National Accreditation Board (ANAB), the International Accreditation Service (IAS), Perry Johnson Laboratory Accreditation (PJLA), and NIST's National Voluntary Laboratory Accreditation Program (NVLAP). Numerous manufacturers offer calibration services; of these, some use equipment calibrated by an accredited laboratory, and fewer are themselves accredited to perform the calibrations.

To meet requirements applicable to certain U.S. customers (in addition to, or in lieu of, international standards), calibration laboratories may also be accredited to ANSI Z540-series standards published by NCSL International. Part 1 of ANSI/NCSL Z540-1-1994 (NCSL 2002), which was based on ISO/IEC Guide 25, was superseded by ANSI/ISO/IEC 17025:2005. However, this NCSL standard is still in use; for example, Annex A in the 2016 edition of NIST HB 150-2 (Belzer et al. 2016) still outlines the general accreditation requirements prescribed in Part 1 of ANSI/NCSL Z540-1-1994 that are not directly addressed in ISO/IEC 17025:2005. Similarly, Part 2 of ANSI/NCSL Z540-1-1994 (which was based on MIL-STD 45662A) was superseded by ANSI/NCSL Z540.3-2006 (NCSL 2013).

ISO/IEC 17011 requires the AB to provide an accreditation certificate to the accredited laboratory, including the standard used for accreditation (e.g., ISO/IEC 17025:2017) and a brief indication of (or reference to) the scope of accreditation. Each calibration laboratory exhibits its accreditation status in its certificate of accreditation, and details corresponding calibration and measurement capabilities (CMCs) in a supplemental document that is usually called a scope of accreditation but is sometimes called a supplement to the certificate of accreditation; the certificate and scope may be contained in separate files. ILAC-P14:01/2013 (ILAC 2013) states that a calibration laboratory's scope of accreditation must express each CMC in terms of measurand or reference material, method/procedure and/or type of instrument/material to be calibrated, range and additional parameters where applicable, and measurement uncertainty (stated as a percentage and/or in units of the quantity). CMC uncertainties are the best (i.e., smallest) achievable by the laboratory; consequently, the uncertainties stated in calibration reports tend to be larger. They are typically based on a coverage factor of 2, with a corresponding confidence level of 95% assuming normally distributed error (A2LA 2014). A calibration laboratory is only accredited for quantities explicitly included in its scope of accreditation; for example, if energy is not explicitly included, it is not implicitly covered via derivation from explicitly included quantities such as power and time. Although ISO/IEC 17025 allows flexible scopes, ILAC G18:04/2010 (ILAC 2010) clarifies that calibration laboratories cannot have flexibility concerning quantities or measurement principles. Some flexibility can be allowed regarding conditions, if the scope of accreditation is explicitly flexible; e.g., as shown in the following footnotes excerpted from selected calibration-laboratory scopes of accreditation:

- "Uncertainties are listed at optimal conditions (PF = 1, Φ = 0º at 10 Hz - 65 Hz). Under different conditions, the uncertainty of the power measurement will vary based on the laboratory's AC voltage and current measurement uncertainties. PFs of less than one will increase the uncertainty of the power measurement, ramping up as PF approaches zero [...] may also report reactive power, apparent power, and power factor under this accreditation. Uncertainties at other conditions can be obtained from the laboratory."
- "The uncertainties shown are for the most favorable conditions. There is an increase in uncertainty that corresponds to the laboratory's AC voltage and current uncertainties at different frequencies other than the ones shown. Power factors (PF) other than the one shown contribute to the power uncertainty. PF is related to the cosine of phase. Therefore, uncertainties track the laboratory's phase uncertainty closely at

> PF near one, but are magnified heavily as PF approaches zero. The lab may also report reactive power, apparent power, and power factor under this accreditation. If needed, contact laboratory for more information regarding uncertainties at frequency and power factor combinations other than the ones shown."

The three-year grace period for laboratory compliance with ISO/IEC 17025:2017 expires in November 2020 (ILAC-ISO 2017). Similarly, the three-year grace period for scopes of accreditation to comply with ISO/IEC 17011:2017 expires in November 2020 (IAF-ILAC 2017). Consequently, some scopes of accreditation updated after November 2017 may not yet reflect compliance with the 2017 versions of these standards. For example, many labs still don't state the method/procedure or calibration equipment in their scope. ILAC-P14:01/2013 states that a scope of accreditation must – for each CMC – state the method/procedure, the calibration equipment, or both. In contrast, ISO/IEC 17011:2017 now requires both of these elements to be present.

As the U.S. National Metrology Institute (NMI), NIST is an International Committee for Weights and Measures (CIPM) MRA signatory. It is recognized by other CIPM MRA signatories in lieu of accreditation, and its CMCs are listed in the BIPM Key Comparison Database (KCDB). It participates in key comparisons (Carranza et al. 2015) among CIPM MRA signatories as well as among other NMIs in its Regional Metrology Organization (RMO), the Inter-American Metrology System (SIM).

Calibration of Energy-Measuring Equipment

The emergence of the Internet of Things (IoT) is resulting in an increased ability of devices and systems to share data. Interest in specific types of data, and the facilitation of the sharing of that data, are typically driven by use cases. For example, building owners and operators strive to optimize the building systems that establish and maintain the building environment (e.g., lighting, heating, ventilation, cooling), so as to balance energy consumption and occupant satisfaction. Increasingly, building systems can report their own energy consumption, thereby facilitating this optimization with actual data, as opposed to using models or rougher estimates. The performance of any data-driven operation, however, is fundamentally a function of the accuracy of the data. Many types of equipment currently measure electrical energy. This includes watthour meters (which are used for utility billing and only report energy), laboratory instruments such as power analyzers and oscilloscopes (which may also report other electrical quantities, such as voltage and power factor), and end-use devices such as computer servers, networking devices, and connected lighting systems (CLS). Depending on their use, any such measuring equipment might need to be calibrated.

Scopes of accreditation for calibration laboratories typically distinguish between calibration of quantity-measuring equipment and calibration of equipment that produces or provides a quantity, but can be difficult to interpret, as the relevant terminology is not harmonized. The words "generate" or "source" are typically used to indicate that the laboratory is accredited for calibration of equipment used to measure electrical quantities (A2LA 2019a, ANAB 2019a, IAS 2019), unless accompanied by a word such as "equipment" (PJLA 2017), in which case the accreditation is for calibration of equipment used to produce electrical quantities. Examples for voltage include "AC Volts True RMS (Source)," AC Voltage – Generate," and "Equipment to Measure AC Voltage." In contrast, "DC Volts – Measure" means that the laboratory can measure the stated voltage with, at best, the claimed level of uncertainty, and can calibrate devices used to source DC voltage. In some cases, explanatory text clarifies whether "AC Power - Low Frequency" means the laboratory is accredited to calibrate power-sourcing equipment, power-measuring equipment, or both; in other cases, this must be inferred based on the equipment used to perform the calibration (as detailed in the scope of accreditation). Similarly, in some cases it is not clear from the scope whether the accreditation covers active power (i.e., real power), apparent power, or both. In addition, some scopes of accreditation use the term "phase" as a synonym for phase angle (a measure of displacement power factor), and express uncertainty for this quantity in terms of degrees (or radians), but then express the corresponding calibration range in hertz (Hz) or amperes.

Excerpts from example scopes of accreditation covering three different quantities (energy, power, and displacement power factor) are shown in Tables 1 through 3 to illustrate the widely varying format and terminology among these documents; one unifying aspect is the use of four similar columns (per ILAC-P14:01/2013), although these are sometimes subdivided. For simplicity, excerpts in these tables exclude superscripts and corresponding footnotes (which provide further clarification) in each scope of accreditation.

Using a variety of keywords (e.g., "AC energy," "watthour," "watt-hour," "kWh," "kW · h") in the Google search engine and in search tools on the websites of the five U.S.-based ILAC MRA signatories, four commercial laboratories in the U.S. were identified as being ILAC MRA signatory-accredited to calibrate energy-measuring equipment. Their relevant accredited CMCs are briefly summarized in Table 4, without any indication of conditions. Rows for related quantities such as voltage and active power are included here to address complete calibration of power analyzers and similar measuring equipment, but may not all be needed for calibration of devices that only measure a subset of these quantities (e.g., watthour meters). Empty fields indicate no accredited coverage for that quantity by the laboratory; the laboratory may be able to calibrate for that quantity, but not within its scope of accreditation. Where coverage of a given quantity is indicated for multiple laboratories, specifics (e.g., range and/or uncertainty) typically vary between laboratories. The adequacy of a given laboratory's capability for a given quantity will depend on the specification used for calibration; additional details for these four laboratories are provided in Tables B7 through B10. Notably, this list may not be exhaustive; for example, some laboratory website search tools lacked necessary features (e.g., phrase search capability), some domains were not searchable using Google (i.e., via "search for a specific site"), and scopes of accreditation for laboratories in the U.S. often do not include "USA" or similar keywords. In addition, the aforementioned tables are based on scopes of accreditation that were current as of September 2019; scope elements (e.g., covered quantities, ranges, uncertainties) can change as scopes of accreditation are periodically updated. The NIST Calibrations Group also offers measurement calibration services for low-frequency power and energy but is excluded here in order to facilitate apples-to-apples comparison.

Table 1. Excerpts from scopes of accreditation that cover calibration of equipment used to measure alternating-current (AC) source energy, illustrating differences in terminology and layout among laboratories (and their ABs). For example, note the differences in column headings, descriptions of quantities or devices covered, and relevant ranges and conditions. Square brackets around ellipses indicate text in report not shown here (for brevity).

Example (AB)	Example column 1	Example column 2	Example column 3	Example column 4
1 (A2LA)	**Electrical – DC/Low Frequency Parameter/Equipment**	**Range**	**CMC (±)**	**Comments**
	AC Energy – Generate @ (47 to 63) Hz (63 to 630) VAC	200 mA to 200 A (0 to 360)° Phase Angle	0.010%	Radian RD-22-331 Watthour Standard and Radian RS-933 Watthour calibration system
2 (A2LA)	**Electrical – DC/Low Frequency Parameter/Equipment**	**Range**	**CMC (±)**	**Comments**
	AC Energy – Generate Watt-Hours	16.7 mWh to 33.3 kWh Over: (120 to 600) V @ 60 Hz (120 to 480) V @ 50 Hz (0.2 to 200) A (-60° to 60°) Phase Angle (5 to 1000) s Test Time (50 to 60) Hz	11 µWh/VAh Alternately: 0.0011% @ 0° Phase Angle 0.0021% @ ± 60° Phase Angle	RS-703-A and RS- 933 calibration systems
3 (ANAB)	**Electrical – DC/Low Frequency Parameter/Equipment**	**Range**	**Expanded Uncertainty of Measurement (+/-)**	**Reference Standard, Method, and/or Equipment**
	Energy - Watt Hour Meters	1.5 W·h to 20.9 kW·h	0.08% of reading	Multifunction Calibrator / Electronic Counter 45 Hz to 65 Hz Power Factor = 1
4 (PJLA)	**Electrical Measured Instrument, Quantity or Gauge**	**Range or Nominal Device Size as Appropriate**	**Calibration And Measurement Capability Expressed as an Uncertainty (±)**	**Calibration Equipment and Reference Standards Used**
	Watt-Hour Standards	0.01 A to 2 A (10 mWh to 2.016 kWh) [...] 5 A to 80 A (5.04 kWh to 80.64 kWh)	18 µWh/VAh [...] 28 µWh/VAh	Fluke 6105A opt 80A TESCO WI: WI-19-10-029; Z540.1

Table 2. Excerpts from scopes of accreditation that cover calibration of equipment used to measure AC source active power, illustrating differences in terminology and layout among laboratories (and their ABs). For example, note the differences in column headings, descriptions of quantities or devices covered, and relevant ranges and conditions. Square brackets around ellipses indicate text in report not shown here (for brevity).

Example (AB)	Example column 1	Example column 2	Example column 3	Example column 4
1 (A2LA)	**Electrical – DC/Low Frequency Parameter/Equipment**	**Range**	**CMC (±)**	**Comments**
	AC Power – Generate Watts	12 W to 120 kW Over: (120 to 600) V @ 60 Hz (120 to 480) V @ 50 Hz (0.2 to 200) A (-60° to 60°) Phase Angle (5 to 1000) s Test Time (50 to 60) Hz	11 µW/VA Alternately: 0.0011% @ 0° Phase Angle 0.0021% @ ± 60° Phase Angle	RS-703A and RS- 933 calibration systems
2 (A2LA)	**Electrical – DC/Low Frequency Parameter/Equipment**	**Range**	**CMC (±)**	**Comments**
	Power – Generate Active Power (0.01 to 0.12) W [...] (1.2 to 2.4) kW	(50 to 60) Hz	0.17% [...] 0.12%	Fluke 5522A
3 (A2LA)	**Electrical – DC/Low Frequency Parameter/Equipment**	**Range**	**CMC (±)**	**Comments**
	Real Power – Measure and Generate Power Factor (0 to 1) Voltage Range (10, 30, 100, 300, 1000) V Current Range (1, 3, 10, 30, 100) A	(50, 60) Hz DC, (40 to 1000) Hz DC, (50, 60) Hz	0.1% rdg + (1 - 0.990 × $e^{1/W}$) where: Verror = % rdg + % rng Ierror = % rdg + % rng	Power factor is computed based on measured real power divided by apparent power. Accuracy is dependant of measured watt Pf = W/VA CMCpower (Watts) = Ireading ×Verror + Vreading × Ierror Line test with N4L PPA530 direct read

4 (ANAB)	**Electrical – DC/Low Frequency Parameter/Equipment**	**Range**	**Expanded Uncertainty of Measurement (+/-)**	**Reference Standard, Method, and/or Equipment**
	AC Power – Source	(1.1 to 3) mW […] (4.5 to 20.9) kW	0.11% of reading […] 0.078% of reading	Multifunction Calibrator 45 Hz to 65 Hz Power Factor = 1
5 (IAS)	**Electrical/DC/Low Frequency Calibration Area**	**Range & Resolution**	**Calibration & Measurement Capability (CMC) (±)**	**Reference Standard/ Equipment**
	AC Power – Generate (330 mV to 1020 V) (45 to 65 Hz)	(3.3 to 8.999) mA […] (90 to 329.99) mA	0.12% […] 0.08%	Fluke 5520A
6 (NVLAP)	**LF Power & Energy (20/E12) Measured Parameter or Device Calibrated**	**Range**	**Uncertainty (k=2)**	**Remarks**
	AC Power – Generate (PF = 1, Φ = 0° at 10 Hz to 65 Hz) 3.3 mA to 9 mA […] 4.5 A to 20.5 A	0.11 mW to 3.0 mW 3.0 mW to 9 W […] 150 mW to 6.7 W 6.7 W to 20 kW	0.13% 0.077% […] 0.17% 0.17%	Fluke 5520A
7 (PJLA)	**Electrical Measured Instrument, Quantity or Gauge**	**Range or Nominal Device Size as Appropriate**	**Calibration and Measurement Capability Expressed as an Uncertainty (±)**	**Calibration Equipment and Reference Standards Used**
	Equipment to Measure AC Power (45 to 65 Hz)	11 µW to 3 000 µW […] 4.5 kW to 20 kW	1.4 mW/W […] 1.0 mW/W	Fluke 5522A

Table 3. Excerpts from scopes of accreditation that cover calibration of equipment used to measure AC load displacement power factor, illustrating differences in terminology and layout among laboratories (and their ABs). For example, note the differences in column headings, descriptions of quantities or devices covered, and relevant ranges and conditions. Square brackets around ellipses indicate text in report not shown here (for brevity).

Example (AB)	Example column 1	Example column 2	Example column 3	Example column 4
1 (A2LA)	**Electrical – DC/Low Frequency Parameter/Range**	**Frequency**	**CMC (±)**	**Comments**
	Phase Angle – (0 to 360)°	(10 to 65) Hz […] (10 to 30) kHz	0.082° […] 7.8°	Fluke 5520A
2 (A2LA)	**Electrical – DC/Low Frequency Parameter/Equipment**	**Range**	**CMC (±)**	**Comments**
	Phase/Power Factor – (10 to 65) Hz PF (0 to 1)	0Φ / PF 1 10Φ / PF 0.985 […] 80Φ / PF 0.174	0.58% […] 1.1%	Fluke 5520A
3 (A2LA)	**Electrical – DC/Low Frequency Parameter/Equipment**	**Range**	**CMC (±)**	**Comments**
	Power – Generate (50 to 60) Hz (cont) Power Factor	± 1 ± (1 to 0.9) […] ± (0.2 to 0.1)	0.065% 0.50% […] 1.4%	Fluke 5522A
4 (ANAB)	**Electrical – DC/Low Frequency Parameter/Equipment**	**Range**	**Expanded Uncertainty of Measurement (+/-)**	**Reference Standard, Method, and/or Equipment**
	Phase Angle - Source	(0 to 360)° (10 to 65) Hz […] (10 to 30) kHz	0.078° […] 7.8°	Multifunction Calibrator
5 (NVLAP)	**Phase (20/E15) Measured Parameter or Device Calibrated**	**Range**	**Uncertainty (k=2)**	**Remarks**
	Phase – Generate	10 Hz to 65 Hz […] 10 kHz to 30 kHz	0.14° […] 12°	Fluke 5520A

6 (PJLA)	Electrical Measured Instrument, Quantity or Gauge	Range or Nominal Device Size as Appropriate	Calibration and Measurement Capability Expressed as an Uncertainty (±)	Calibration Equipment and Reference Standards Used
	Equipment to Measure Phase Angle (at the listed frequencies) 10 Hz to 65 Hz [...] 5 kHz to 10 kHz	0° to 180° [...] 0° to 180°	0.15° [...] 10°	Fluke 5500A

Table 4. Brief summary of capabilities for commercial laboratories in the U.S. identified as being ILAC MRA signatory-accredited to calibrate energy-measuring equipment. Rows for related electrical quantities are included to illustrate gaps in accredited coverage for equipment other than watthour meters (e.g., power analyzers) that may be used to measure quantities including but not limited to energy. Notably, two laboratories accredited to calibrate for a given quantity may have different ranges and/or uncertainties; their relative merits will depend on user requirements (e.g., some users may only need to calibrate for energy). Summarized ranges are followed by corresponding uncertainties (in parentheses). CMCs are valid at 60 Hz and 1.0 power factor, unless noted otherwise. Additional details for these four laboratories are provided in Tables B7 through B10, and readers are encouraged to review the scopes of accreditation directly. The list may not be exhaustive, due to website search limitations, and scopes of accreditation can change as they are periodically updated.

Calibrated quantity	CBRE (ANAB 2019b)	Consumers Energy (A2LA 2018)	Radian Research (A2LA 2019b)	Advent Design / TESCO (PJLA 2019)
AC source frequency	0 to 1050 MHz (4.4 x 10^{-10})	1 mHz to 990 MHz (2.7 parts in 10^{10})		[...] 40 Hz to 10 MHz (100 µHz/Hz)
AC source voltage	[...] 20 to 200 V (2 mV + 85 µV/V) [...]	[...] 22 to 220 V (47 µV/V + 0.60 mV) [...]		[...] 100 to 1000 V (1 200 µV/V + 0.002%)
AC load current	29 to 330 µA (0.08 µA + 0.97%) [...] 11 to 20.5 A (3.9 mA + 0.093%)	Up to 220 µA (0.011% + 8.0 nA) [...] 11 to 20.5 A (0.093% + 1.6 mA)		0 to 100 µA (600 µA/A + 0.03%) [...] 100 mA to 1 A (600 µA/A + 0.02%)
AC load displacement power factor	0 to 360° (0.078°)	0 to 360° (0.082°)		
AC load active power	1.1 to 3 mW (0.11%) [...] 4.5 to 20.9 kW (0.078%)		12 W to 120 kW (11 µW/VA, alternately 0.0011% @ 0° Phase or 0.0021% @ ± 60°)	
AC load energy	1.5 W·h to 20.9 kW·h (0.08%)	63 to 630 VAC 200 mA to 200 A 0 to 360° Phase (0.010%)	16.7 mWh to 33.3 kWh (11 µWh/VAh, alternately 0.0011% @ 0° Phase or 0.0021% @ ± 60°)	0.01 to 2 A 10 mWh to 2.016 kWh (18 µWh/VAh) [...] 5 to 80 A 5.04 to 80.64 kWh (21 µWh/VAh)

Developing Calibration Specifications for Energy-Measuring Equipment

When seeking calibration for equipment that sources or measures electrical energy, specifications should be provided to ensure that the calibration will cover the intended use (quantities, ranges, conditions, required accuracy), and that the laboratory is qualified to perform the calibration with sufficiently low uncertainty. It cannot be assumed that the laboratory will by default calibrate the measuring equipment across its full range of capability. If existing specifications are not sufficient, new specifications should be developed. A complete specification will incorporate the following guidelines:

1. The calibration laboratory should be accredited by an ILAC MRA signatory to relevant standards (e.g., ISO/IEC 17025).

2. The laboratory should be explicitly accredited for each particular quantity of interest. For example, the scope of accreditation should distinguish between AC active power (W) and AC apparent power (VA).

   A. The laboratory should be accredited for the calibration type applicable to the equipment being calibrated. For example, it should be accredited to source AC energy if calibrating energy-measuring equipment, and/or accredited to measure AC energy if calibrating energy-sourcing equipment.

   B. The range of calibration for which the laboratory is accredited should span the range of quantity values for which the calibrated equipment will be used. For example, if AC power measurements using a power analyzer are expected to be in the range of 1 W to 100 W, a laboratory accredited to calibrate from 5 W to 500 W would not be suitable.

   C. The range of relevant conditions for which the laboratory is accredited should span the range of conditions under which the calibrated equipment will be used. For example, if AC power measurements using a power analyzer are expected to be made at AC source (voltage) frequencies ranging from 58.8 Hz to 61.2 Hz, a laboratory only accredited to calibrate at 60 Hz would not be suitable.

   D. The stated uncertainty for each CMC should satisfy applicable requirements. However, because CMC uncertainties are the smallest achievable by the laboratory, the laboratory should be asked to provide an estimate of the expected uncertainty for the specific equipment to be calibrated.

3. The laboratory should understand the equipment to be calibrated (e.g., should be provided with complete make/model information including relevant accessories) and the equipment configuration/settings to be used in calibration.

   A. Some laboratories may only be accredited to calibrate energy-measuring equipment using pulse input (which can facilitate/expedite calibration for energy) as a proxy for direct measurement, but some energy-measuring equipment is not capable of generating pulse output for this purpose. Unfortunately, scopes of accreditation typically do not explicitly state whether pulse input or pulse output are required; however, when specific make/model information is listed for the specific calibration equipment used, product user manuals may clarify relevant equipment limitations.

   B. The equipment range settings should be specified to reflect intended usage. Ideally, range settings should maximize resolution; for example, if the minimum range setting for current is 0.5 A, then a 0.3 A calibration point should use this range in lieu of a 5 A range setting. However, if range settings are not optimized this way in practice, the device should be calibrated accordingly.

C. The desired calibration interval should also be specified so that it can be stated in the calibration report and thereby help in scheduling future recalibration. The appropriate value will depend on several factors, such as applicable requirements for accuracy as well as on ratings for the equipment being calibrated (rated accuracy can be a function of time since last calibration) and the conditions in which it will be used. ANSI C12.1-2014 offers different calibration interval limits depending on watthour meter usage (e.g., secondary standards versus portable standards). Additional guidance is offered in ILAC G24:2007 / OIML D 10:2007 (ILAC-OIML 2007), which is jointly published by ILAC and the International Organization of Legal Metrology (OIML), another JCGM-supporting organization. Similarly, NCSL International provides such guidance in its RP-1 (NCSL 2010).

A specification template for the calibration of energy-measuring equipment is presented in Appendix A, and an example implementation of this specification template is presented in Appendix B. Some aspects of specifying calibration of energy-measuring equipment merit additional consideration:

- Zero values (e.g., corresponding to no-load conditions) can present challenges for calibration. Fundamentally, zero values cannot be realized if negative values are not possible (PJLA 2017). For example, whereas negative values can be realized for temperature units of degrees Celsius, they cannot for units of kelvin. However, it is common to indicate "up to" in lieu of "0 to" on scopes of accreditation (A2LA 2019a, ANAB 2019a, IAS 2019, PJLA 2017). In any case, if a range includes zero, uncertainty cannot be simply expressed as a percentage of reading, because the CMC uncertainty can never be zero (IAS 2019).

- A variety of energy-measuring equipment is available, with a wide range of energy, and (if reported) power and time, resolutions – which can affect the accuracy of energy calculations when energy is not explicitly reported. When establishing test conditions for a device under test (DUT), it is often seen as desirable to use a constant test energy consumption or a constant test time. Both approaches can lead to issues for a DUT with limited resolution. If test energy consumption is fixed at 10 Wh, for example, and the DUT energy resolution is limited to 1 Wh, then the minimum reportable energy increment is 10% of the total, thereby limiting the resolution of calculated error. Further, for low-load conditions, the total test time to generate 100 Wh can be impractical or costly. If test time is instead fixed at 15 minutes, for example, a 10 W load would consume 2.5 Wh of energy, yielding measurements of 2 Wh or 3 Wh (20% error in either direction) at best for a DUT with energy resolution of 1 Wh. If the DUT does not report energy, and energy needs to be calculated by integrating reported power and time, then the accuracy of that integration is always dependent on the power resolution, and depends on time resolution as well, if power is varying over the test. Ideally, a fixed quantity of energy and/or a fixed test time should be defined based on the use case of the energy-measuring equipment. However, at present, use cases beyond electric utility billing purposes and their needs are not well defined. Further, the connected lighting and other IoT devices currently being developed that are capable of reporting their own energy consumption are not being targeted at specific applications that might have defined energy-reporting requirements. DUT resolution needs to be taken into consideration when defining test conditions, which should in turn inform specifications for calibration of energy-measuring equipment.

- Just as illuminance meter accuracy depends on the spectral power distributions (SPDs) of the reference light source and the incident illumination it will be measuring (Levin 1982), energy-measuring equipment accuracy depends on both the waveforms used in calibration and the waveforms encountered during field measurements. Power factor can be compromised by phase modulation, frequency modulation, or a combination of the two (IEC 2016). The specification template currently states that per ANSI C12.1-2014, the third harmonic in the current waveform shall not exceed 0.5% of the fundamental, and other harmonics in the current and voltage waveforms shall not exceed 1.0% of the fundamental. This effectively limits calibration to "perfectly" sinusoidal current and voltage waveforms; although this allows for evaluation of displacement power factor (via phase modulation), it does not address other factors that can compromise power factor in the field (e.g., frequency modulation). In addition, although only current is varied when calibrating for energy in the current version of the specification template, other parameters (e.g., source voltage, frequency, displacement power factor) could also be varied, as is already specified for calibration of active power and other electrical quantities.

- In some cases, there may be no laboratory that is accredited across the needed range for every quantity of interest. In such circumstances, it may be acceptable to include some calibration points outside the scope of accreditation; however, this limitation should be clearly noted when presenting data from energy-measuring equipment that has been calibrated in this manner.

Summary and Recommendations

The emergence of the Internet of Things is resulting in an increased ability of devices and systems to share data. Interest in specific types of data, and the facilitation of the sharing of that data, are typically driven by use cases, and the performance and value of these use cases are dependent to some degree on the accuracy of this data. Users of such data are encouraged to explore the dependency of the use case on data accuracy, and to ensure that the devices and systems leveraged to implement the use case can deliver data of the requisite accuracy.

The accuracy of data-producing devices can be a function of design, component selection, and manufacturing processes – which may include specific steps aimed at compensating for systematic and/or random error. Manufacturers of data-producing devices, as well as end users with particularly stringent needs, may need to validate or characterize the reporting accuracy of manufactured devices. Such validation or characterization is typically achieved by comparing the data produced by a specific device or set of devices against measurements made by a reference instrument with known or reference accuracy. Such equipment typically needs to be calibrated to establish and maintain this reference accuracy. While many commercial laboratories are accredited to perform such calibrations, their scopes of accreditation vary, and as a result, any given laboratory may or may not be suitable for calibrating a particular instrument for specific reference measurement uses. The authors offer the following recommendations accordingly:

- Measuring-equipment owners with calibration needs are encouraged to ensure that the calibration will cover the instrument’s intended use (quantities, ranges, conditions, required accuracy), and that the laboratory is qualified to perform the calibration with sufficiently low uncertainty. If existing calibration specifications are not sufficient, new specifications should be developed.

- Calibration laboratories are encouraged to clearly state scopes of accreditation and, for energy-measuring equipment, to state whether those instruments must emit pulse output in order to be calibrated. Scopes of accreditation should distinguish between active power and apparent power, and between calibration of devices that generate electrical quantities and those that measure electrical quantities. Laboratories are encouraged to harmonize terminology and the organization of content within scopes of accreditation, to facilitate more-efficient review by potential customers. Website searches could also be facilitated by adding the text "USA" to scopes of accreditation for laboratories that are located in the U.S.

- ILAC MRA signatories are encouraged to improve their website search tools and make content accessible via external search engines, to facilitate identification of suitable calibration laboratories.

The authors developed a specification template for calibration of energy-measuring equipment, and provided an example illustrating how it might be tailored to match the range of expected use for a given instrument. Measuring-equipment owners are encouraged to develop such specifications and share them with potential calibration laboratories to ensure that requirements are met. Once a calibration laboratory is selected and the instrument is calibrated, the corresponding calibration report should be reviewed to confirm that each calibration point was covered (with acceptable uncertainty), and to determine whether the equipment was out of tolerance. If adjustment was required, it may be necessary to revisit previously measured values, and it may be appropriate to reduce the interval between calibrations.

The authors intend to further develop the provided specification template as needs dictate, perhaps by addressing distorted current and voltage waveforms by covering calibration of equipment that measures total harmonic distortion (THD) and energy in such non-sinusoidal conditions. Feedback on the existing specification template, and additional suggestions for further development, are encouraged from industry stakeholders with similar needs and interests (email feedback to DOE.SSL.Updates@ee.doe.gov).

Appendices

Appendix A: Calibration Specification Template for Energy-Measuring Equipment

Specifications for calibration of (*provide complete make/model information, including relevant accessories*).

Basic requirements for calibration are as follows:

1. Calibration shall be performed by an ILAC MRA signatory-accredited laboratory and within its scope of accreditation to (specify standard such as ISO/IEC 17025).
2. Report shall include data for each calibration point as detailed in sections 7.8.2 (common requirements for reports) and 7.8.4 (specific requirements for calibration certificates) of ISO/IEC 17025:2017, with conditions readily discernible from text.
3. Report shall indicate (specify)-year calibration interval.
4. Report shall express calibration in the form of a (choose one or more of the following as appropriate: statement, calibration function, calibration diagram, calibration curve, calibration table, additive/multiplicative correction of the indication with associated measurement uncertainty).
5. Verification pass/fail criteria shall be per the calibrated equipment manufacturer's (specify)-month accuracy specifications.
6. If adjustment is required (verify equipment can be adjusted before requesting adjustment), report shall state that adjustment was performed and provide values before/after adjustment.
7. The third harmonic in the current waveform shall not exceed 0.5% of the fundamental, and other harmonics in the current and voltage waveforms shall not exceed 1.0% (per ANSI C12.1-2014).
8. Measuring-equipment settings shall be as follows:
    a. Use crest factor mode = (specify).
    b. Turn frequency filter ON when input signal frequency is (specify).
    c. Use (specify) single-phase two-wire (1P2W) direct input wiring.
    d. Use (specify) integration mode for energy measurement calibration.
9. Energy calibration (specify "shall" or "shall not," as appropriate) require pulse output.
10. Measuring equipment shall be calibrated at the following calibration points, where values for voltage and current are root-mean-square (RMS):
    a. AC source voltage measurement shall be calibrated at 5 points in Table A1.
    b. AC source frequency measurement shall be calibrated at 6 points in Table A2.
    c. AC load displacement power factor measurement shall be calibrated at 3 points in Table A3.
    d. AC load current measurement shall be calibrated at 11 points in Table A4.
    e. AC load active power (W) measurement shall be calibrated at the 10 points in Table A5.
    f. AC load energy (Wh) measurement shall be calibrated at 5 points in Table A6.

Table A1. AC source voltage measurement

Calibration point	Source voltage^1 (V)	Voltage range^2 (V)	Source frequency^3 (Hz)
A	120	150	58.8
B	108	150	60.0
C	120		
D	132		
E	120	150	61.2

Notes (delete this and superscripts after editing values in table as needed)
1. Values are for 120 V nominal and ±10% tolerance. Edit as appropriate.
2. Range setting should be specific to calibrated equipment. Edit as appropriate.
3. Values are for 60 Hz nominal and ±2% tolerance. Edit as appropriate.

Table A2. AC source frequency measurement

Calibration point	Source frequency^1 (Hz)	Source voltage^2 (V)	Load current^2 (A)
A	58.8	120	
B	60.0		
C	61.2		
D	58.8		2.5
E	60.0		
F	61.2		

Notes (delete this and superscripts after editing values in table as needed)
1. Values are for 60 Hz nominal and ±2% tolerance. Edit as appropriate.
2. Value should be near median of expected distribution. Edit as appropriate.

Table A3. AC load displacement power factor measurement

Calibration point	Load power factor^1	Source frequency^2 (Hz)	Source voltage^2 (V)	Voltage range^3 (V)	Load current^2 (A)	Current range^3 (A)
A	0.5 leading	60	120	150	2.5	5
B	0.5 lagging					
C	1.0					

Notes (delete this and superscripts after editing values in table as needed)
1. Values are for 1.0 power factor nominal and ±0.5 power factor tolerance. Edit as appropriate.
2. Value should be near median of expected distribution. Edit as appropriate.
3. Range setting should be specific to calibrated equipment. Edit as appropriate.

Table A4. AC load current measurement

Calibration point	Load current[1] (A)	Current range[2] (A)	Source frequency[3] (Hz)	Source voltage[4] (V)
A B C D	0.005 0.05 0.15 0.5	0.5	60	120
E	2.5	5	58.8	120
F G H	0.5 2.5 5	5	60	120
I	2.5	5	61.2	120
J K	5 10	10	60	120
Notes (delete this and superscripts after editing values in table as needed) *1. Values are for 1.0 power factor nominal and ±0.5 power factor tolerance. Edit as appropriate.* *2. Range setting should be specific to calibrated equipment. Edit as appropriate.* *3. Values are for 60 Hz nominal and ±2% tolerance. Edit as appropriate.* *4. Value should be near median of expected distribution. Edit as appropriate.*				

Table A5. AC load active power (W) measurement

Calibration point	Source frequency[1] (Hz)	Source voltage[2] (V)	Voltage range[3] (V)	Load current (A)	Current range[3] (A)	Load power factor[4]
A B C D	60	120	150	0 0.15 2.5 10	0.5 0.5 5 10	1.0
E F	60	108 132	150	2.5	5	1.0
G H	58.8 61.2	120	150	2.5	5	1.0
I J	60	120	150	2.5	5	0.5 leading 0.5 lagging
Notes (delete this and superscripts after editing values in table as needed) *1. Values are for 60 Hz nominal and ±2% tolerance. Edit as appropriate.* *2. Values are for 120 V nominal and ±10% tolerance. Edit as appropriate.* *3. Range setting should be specific to calibrated equipment. Edit as appropriate.* *4. Values are for 1.0 power factor nominal and ±0.5 power factor tolerance. Edit as appropriate.*						

Table A6. AC energy (Wh) measurement

Calibration point	Load energy (Wh)	Source voltage[1] (V)	Voltage range[2] (V)	Source frequency[1] (Hz)	Load current (A)	Current range[2] (A)	Load power factor[1]
A	1	120	150	60	0.15	0.5	1.0
B					2.5	5.0	
C	10	120	150	60	2.5	5.0	1.0
D					10	10	
E	100	120	150	60	10	10	1.0

Notes (delete this and superscripts after editing values in table as needed)

1. Values are nominal. Edit as appropriate.

2. Range setting should be specific to calibrated equipment. Edit as appropriate.

Appendix B: Example Energy-Measuring Equipment Calibration

The following example illustrates the intended use of the specification template provided in Appendix A.

A set of nine test cases shown in Table B0 defines the range of intended use of a particular reference energy meter.

Given the stated range of intended use, the following specifications were developed for this particular reference energy meter:

1. Equipment to be calibrated is a two-element Yokogawa WT500 (model 760202-D/C7/G5).
2. Calibration shall be within scope of accreditation by ILAC MRA signatory.
3. Report shall include data per sections 7.8.2 and 7.8.4 of ISO/IEC 17025:2017, with conditions readily discernible from text.
4. Report shall indicate one-year calibration interval.
5. Report shall express calibration in the form of a calibration table.
6. Verification pass/fail criteria shall be per the manufacturer’s six-month accuracy specifications.
7. If adjustment is required, report shall state that adjustment was performed and provide values before/after adjustment.
8. The third harmonic in the current waveform shall not exceed 0.5% of the fundamental, and other harmonics in the current and voltage waveforms shall not exceed 1.0% (per ANSI C12.1-2014).
9. Measuring-equipment settings shall be as follows:
    a. Use crest factor mode = 3.
    b. Turn frequency filter ON when input signal frequency is less than or equal to 440 Hz.
    c. Use single-phase two-wire (1P2W) direct-input wiring.
    d. Use "normal" integration mode for energy-measurement calibration.
    e. Use "sold/bought" watthour (Wh) integration method.
10. Energy calibration shall not require pulse output.
11. Measuring equipment shall be calibrated at the following calibration points, where values for voltage and current are root-mean-square (RMS):
    a. AC source voltage measurement shall be calibrated at 5 points (Table B1).
    b. AC source frequency measurement shall be calibrated at 6 points (Table B2).
    c. AC load displacement power factor measurement shall be calibrated at 3 points (Table B3).
    d. AC load current measurement shall be calibrated at 11 points (Table B4).
    e. AC load active power (W) measurement shall be calibrated at 10 points (Table B5).
    f. AC energy (Wh) measurement shall be calibrated at 5 points (Table B6).

Note that because the reference meter being calibrated was not a power source, it was necessary for it to be calibrated for electrical quantities beyond AC energy (e.g., power factor). Also note that limits on uncertainties are not specified. Although calibration point A in Table B5 entails no (zero) load current, a calibration laboratory cannot be accredited to calibrate at zero current, given that zero current cannot be realized.

Four commercial U.S. calibration laboratories with scopes of accreditation that cover calibration of energy-measuring equipment were identified. Tables B7 to B10 illustrate the extent to which each laboratory is accredited to calibrate each of the six quantities addressed in this specification. Although none of the laboratory scopes of accreditation fully satisfied the specification, one (CBRE) came very close, with a floor for energy that was just 0.5 watthours above the specified 1.0 watthour calibration point.

Table B0. Nine test cases in a test method for characterizing the reporting accuracy of energy-measuring equipment.

Test case	Description	Source voltage (V)	Source frequency (Hz)	Load current (A)	Displacement power factor
1	No load	120	60	0	n/a
2	Current variation	120	60	0.15	1.0
3				2.5	
4				≤10	
5	Voltage variation	108	60	2.5	1.0
6		132			
7	Frequency variation	120	58.8	2.5	1.0
8			61.2		
9	Displacement power factor variation	120	60	2.5	0.5 lagging

Table B1. AC source voltage measurement

Calibration point	Source voltage (V)	Voltage range (V)	Source frequency (Hz)
A	120	150	58.8
B	108	150	60.0
C	120		
D	132		
E	120	150	61.2

Table B2. AC source frequency measurement

Calibration point	Source frequency (Hz)	Source voltage (V)	Load current (A)
A	58.8	120	
B	60.0		
C	61.2		
D	58.8		2.5
E	60.0		
F	61.2		

Table B3. AC load displacement power-factor measurement

Calibration point	Load power factor	Source frequency (Hz)	Source voltage (V)	Voltage range (V)	Load current (A)	Current range (A)
A	0.5 leading	60	120	150	2.5	5
B	0.5 lagging					
C	1.0					

Table B4. AC load current measurement

Calibration point	Load current (A)	Current range (A)	Source frequency (Hz)	Source voltage (V)
A	0.005	0.5	60	120
B	0.05			
C	0.15			
D	0.5			
E	2.5	5	58.8	120
F	0.5	5	60	120
G	2.5			
H	5			
I	2.5	5	61.2	120
J	5	10	60	120
K	10			

Table B5. AC load active power (W) measurement

Calibration point	Source frequency (Hz)	Source voltage (V)	Voltage range (V)	Load current (A)	Current range (A)	Load power factor
A	60	120	150	0	0.5	1.0
B				0.15	0.5	
C				2.5	5	
D				10	10	
E	60	108	150	2.5	5	1.0
F		132				
G	58.8	120	150	2.5	5	1.0
H	61.2					
I	60	120	150	2.5	5	0.5 leading
J						0.5 lagging

Table B6. AC energy (Wh) measurement

Calibration point	Load energy (Wh)	Source voltage (V)	Voltage range (V)	Source frequency (Hz)	Load current (A)	Current range (A)	Load power factor
A B	1	120	150	60	0.15 2.5	0.5 5.0	1.0
C D	10	120	150	60	2.5 10	5.0 10	1.0
E	100	120	150	60	10	10	1.0

Table B7. Relevant excerpts from CBRE scope of accreditation (ANAB 2019b). Red font indicates capability does not satisfy specification. Energy-measuring equipment does not need to report via pulse output. Square brackets around ellipses indicate text in report not shown here (for brevity).

Electrical Quantity	Parameter/Equipment	Range	Expanded Uncertainty of Measurement (+/-)	Reference Standard, Method, and/or Equipment	Meets spec
AC source voltage	AC Volts – Source	[...] (22 to 220) V (10 to 20) Hz (20 to 40) Hz 40 Hz to 20 kHz [...]	[...] 4 mV + 240 µV/V 1.5 mV + 90 µV/V 0.6 mV + 240 µV/V [...]	5730A Multifunction Calibrator	Yes
AC source frequency	Frequency Source	(0 to 1 050) MHz	4.4 x 10^{-10}	Signal Generator	Yes?
AC load displacement power factor	Phase Angle - Source	(0 to 360)° (10 to 65) Hz [...]	0.078° [...]	Multifunction Calibrator	Yes
AC load current	AC Current – Source	29 µA to 330 µA (10 to 45) Hz (45 to 1 000) Hz [...] (11 to 20.5) A (45 to 100) Hz (100 to 1 000) Hz (1 to 5) kHz	0.08 nA + 0.16% of reading 0.08 µA + 0.97% of reading [...] 3.9 mA + 0.093% of reading 3.9 mA + 0.12% of reading 3.9 mA + 2.3% of reading	Multifunction Calibrator	Yes
AC load active power	AC Power – Source	(1.1 to 3) mW (3 to 11) mW (11 to 300) mW (300 to 726) mW (0.7 to 1.5) W (1.5 to 6.77) W (0.6 to 92) W (92 to 336) W (336 to 918) W (918 to 2 244) W (2 244 to 4 590) W (4.5 to 20.9) kW	0.11% of reading 0.078% of reading 0.1% of reading 0.08% of reading 0.11% of reading 0.086% of reading 0.093% of reading 0.062% of reading 0.93% of reading 0.07% of reading 0.093% of reading 0.078% of reading	Multifunction Calibrator 45 Hz to 65 Hz Power Factor = 1	Yes
AC load energy	Energy - Watt Hour Meters	1.5 W·h to 20.9 kW·h	0.08% of reading	Multifunction Calibrator / Electronic Counter 45 Hz to 65 Hz Power Factor = 1	No

Table B8. Relevant excerpts from Consumers Energy scope of accreditation (A2LA 2018). Red font indicates capability does not satisfy specification. Note that range for energy (e.g., in watt-hours) is not indicated, preventing direct comparison with the specification. Energy-measuring equipment does not need to report via pulse output. Square brackets around ellipses indicate text in report not shown here (for brevity).

Electrical Quantity	Parameter/Equipment	Range	CMC (±)	Comments	Meets spec
AC source voltage	AC Voltage – Generate (22 to 220) V	40 Hz to 20 kHz	47 µV/V + 0.60 mV	Fluke 5720A	Yes
AC source frequency	Frequency – Measuring Equipment	1 mHz to 990 MHz	2.7 parts in 10^{10}	HP 33250A and 8656A signal generators with 10 MHz distributed signal	Yes
AC load displacement power factor	Phase Angle – (0 to 360)°	(10 to 65) Hz	0.082°	Fluke 5520A	Yes
AC load current	AC Current – Generate Up to 220 µA […] (11 to 20.5) A	40 Hz to 1 kHz […] (45 to 100) Hz	0.011% + 8.0 nA […] 0.093% + 1.6 mA	Fluke 5720A	Yes
AC load active power	(not covered)				No
AC load energy	AC Energy – Generate @ (47 to 63) Hz (63 to 630) VAC	200 mA to 200 A (0 to 360)° Phase Angle	0.010%	Radian RD-22-331 Watthour Standard and Radian RS-933 Watthour calibration system	No

Table B9. Relevant excerpts from Radian Research scope of accreditation (A2LA 2019b). Red font indicates that capability does not satisfy specification. Energy-measuring equipment does not need to report via pulse output.

Electrical Quantity	Parameter/Equipment	Range	CMC (±)	Comments	Meets spec
AC source voltage	(not covered)				No
AC source frequency	(not covered)				No
AC load displacement power factor	(not covered)				No
AC load current	(not covered)				No
AC load active power	AC Power – Generate Watts	12 W to 120 kW Over: (120 to 600) V @ 60 Hz (120 to 480) V @ 50 Hz (0.2 to 200) A (-60° to 60°) Phase Angle (5 to 1000) s Test Time (50 to 60) Hz	11 µW/VA Alternately: 0.0011% @ 0° Phase Angle 0.0021% @ ± 60° Phase Angle	RS-703A and RS- 933 calibration systems	No
AC load energy	AC Energy – Generate Watt-Hours	16.7 mWh to 33.3 kWh Over: (120 to 600) V @ 60 Hz (120 to 480) V @ 50 Hz (0.2 to 200) A (-60° to 60°) Phase Angle (5 to 1000) s Test Time (50 to 60) Hz	11 µWh/VAh Alternately: 0.0011% @ 0° Phase Angle 0.0021% @ ± 60° Phase Angle	RS-703-A and RS- 933 calibration systems	No

Table B10. Relevant excerpts from Advent Design (TESCO) scope of accreditation (PJLA 2019). Red font indicates capability does not satisfy specification. Energy-measuring equipment must report via pulse output. Square brackets around ellipses indicate text in report not shown here (for brevity).

Electrical Quantity	MEASURED INSTRUMENT, QUANTITY OR GAUGE	RANGE OR NOMINAL DEVICE SIZE AS APPROPRIATE	CALIBRATION AND MEASUREMENT CAPABILITY EXPRESSED AS AN UNCERTAINTY (±)	CALIBRATION EQUIPMENT AND REFERENCE STANDARDS USED	Meets spec
AC source voltage	Equipment to Measure AC Voltage (at the listed frequencies) 20 Hz to 100 kHz 20 Hz to 100 kHz	0.01 µV to 100 V 100 V to 1 000 V	1 000 µV/V + 0.05% of range 1 200 µV/V + 0.002% of range	Agilent 3458A opt 001 & opt 002 TESCO WI: WI-19-10-029; Z540.1	Yes
AC source frequency	Equipment to Measure Frequency	1 Hz to 40 Hz 40 Hz to 10 MHz	500 µHz/Hz 100 µHz/Hz	Agilent 3458A opt 001 & opt 002 TESCO WI: WI-19-10-029; Z540.1	Yes
AC load displacement power factor	(not covered)				No
AC load current	Equipment to Measure AC Current (at the listed frequencies) [...] 45 Hz to 100 Hz [...] 45 Hz to 100 Hz [...] 45 Hz to 100 Hz [...]	[...] 0 µA to 100 µA [...] 100 µA to 100 mA [...] 100 mA to 1 A [...]	[...] 600 µA/A + 0.03% of range [...] 600 µA/A + 0.03% of range [...] 600 µA/A + 0.02% of range [...]	Agilent 3458A opt 001 & opt 002 TESCO WI: WI-19-10-029; Z540.1	No
AC load active power	(not covered)				No
AC load energy	Watt-Hour Standards	0.01 A to 2 A (10 mWh to 2.016 kWh) [...] 5 A to 80 A (5.04 kWh to 80.64 kWh)	18 µWh/VAh [...] 28 µWh/VAh	Fluke 6105A opt 80A TESCO WI: WI-19-10-029; Z540.1	Yes

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