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Characterization and Analysis of the Energy-Reporting Accuracy of Connected Devices

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Abstract

Emerging energy-efficient building systems increasingly exhibit greater functionality, often requiring multiple operating modes (e.g. white-tunability for lighting products and data traffic for devices with networked, integrated sensors). This increased functionality makes energy consumption estimates more complex. Given that these functions consume energy, the energy performance of such building systems is dependent on what operating modes they use and how much time they spend in each mode. Devices and systems that can report their own energy consumption mitigate this energy-performance uncertainty.

This study explores the energy-reporting accuracy of market-available connected electrical outlets. The study considers two residential-market products (five units each, one outlet per unit) and three commercial-market products (two units each, 18 to 24 outlets per unit) with the ability to report power drawn and/or energy consumed by devices connected to their receptacles. The products were purchased through typical market channels. Pacific Northwest National Laboratory (PNNL) conducted testing in December 2018 at its Connected Lighting Test Bed (CLTB), using a custom-developed test setup and method adapted from industry standards. The setup collected energy-consumption data reported by the outlet devices under test (DUTs) at one-minute intervals and compared that data with measurements taken by a reference meter over a range of test conditions. The residential products reported power draw but not interval or cumulative energy consumption. The commercial products reported both power draw and cumulative energy consumption. Relative reporting error (RRE) was calculated for all measurements, and analysis of the results revealed variations across devices and test conditions. The total number of measurements (50 for each residential product, 60 for each commercial product) offers an appreciable comparison of performance at the make/model level.

The average RRE of the residential products derived from reported power draw was -0.02% and -1.20%. The average RRE for two of the three the commercial products derived from reported power draw was worse than those of the residential products (-2.40%, -2.72%, -0.36%). The internal integration of power over time, used to calculate cumulative energy consumption, typically occurs at current and voltage sampling rates much higher than once per minute. This suggests that the average commercial-product RRE derived from reported energy consumption should be very consistent and better than performance based on reported power draw. However, the RRE derived from reported energy consumption varied significantly across the three makes of commercial-market products and was uniformly less accurate than performance based on reported power draw. Subsequent analysis identified a number of root causes for this decrease in performance, most of which were related to reporting resolution.

The goals of this study are to generate awareness of building systems capable of reporting their own energy consumption, further interest in the value of energy data for a variety of uses, draw attention to how the accuracy of reported metrics can be characterized, and quantify the performance variation found in market-available products. The results of this study and subsequent related work may be relevant to stakeholders in industry-specification and standards-development organizations. The methods this study employs could inform test and measurement procedures and performance classifications for connected outlets, lighting products, and other building systems capable of reporting their own energy consumption. The study concludes with stakeholder recommendations, including the following:

- Energy-reporting device and system manufacturers developing products that report energy consumption should characterize the accuracy of reported metrics using a reference meter calibrated by an independent laboratory that was accredited by an ILAC MRA signatory (and whose scope of accreditation explicitly covers energy measurement), and should include this information on product data sheets.

- Standards and specification development organizations should develop application-specific performance classifications that end users can understand and relate to their energy-data use needs

(e.g., 2% accuracy class for utility streetlight energy billing needs, or 10% accuracy class for ESCO performance verification needs).

- Current or potential owners, operators, and specifiers of energy-reporting building systems should rigorously analyze the dependency of current and planned energy-data use cases on accuracy, noting in particular the dependence (or lack thereof) on relative vs. absolute accuracy, and on trueness vs. precision (i.e., repeatability), and should communicate use-case needs to industry standards and specification organizations.

Introduction

Emerging energy-efficient building systems (e.g., lighting, HVAC) increasingly have greater functionality, which often requires additional operating modes. This increased functionality makes energy consumption more complex, as system energy performance is increasingly dependent on what operating modes they use and how much time they spend in each mode. The lighting industry is undergoing particularly significant change in this regard. LED technology has steadily improved energy efficiency and control of light intensity, spectrum, and directionality in an increasing number of lighting applications. Connected lighting systems (CLS) – comprised of intelligent LED lighting devices with one or more network interfaces and one or more sensors – offer features and capabilities beyond what has historically been achieved by pairing luminaires with conventional lighting controls. The impact of the light spectrum on human, animal, and plant physiology (subjects of ongoing research in many respects) is driving interest in spectrally tunable light sources. Microelectronic technology readily facilitates the integration of new capabilities into products, and allows them to take advantage of technology evolution and cost reductions that are driven by other applications (e.g. computing, networking, mobile device). As a result, the lighting industry is increasingly exploring the integration of sensors and modern network interfaces into lighting products.

This increased functionality makes lighting energy consumption estimates significantly more difficult. Lighting energy consumption has historically been modeled by utilizing a combination of manufacturer-reported power draw during nominal conditions (e.g., full output), estimations of power at other conditions (e.g., 50% power at 50% output for LED), assumptions about hours-of-use for various applications, and generalizations about how much energy can be saved by various lighting control strategies (e.g. task tuning, occupancy, daylight compensation). However, the number of functional states (and associated power draws) in which LED devices operate increases rapidly as a function of a) the ability to deliver variable luminous intensity and variable spectrum, and b) the integration of network interfaces, sensors, and data processors. The energy impact of the requisite integrated network communication interfaces, sensors, and data processors is largely unknown and may vary by application, use case, system architecture, and core technology.

Increased uncertainty about energy performance can be largely mitigated, however, if devices and systems can accurately report their own energy consumption. Many emerging CLS already offer some form of this capability. The availability of actual consumption data can facilitate the implementation of data-driven energy management methodologies that adapt to changing conditions over time. The data can facilitate pay-for-performance energy-efficiency incentives that bridge the gap to demand response and true real-time pricing schemes. CLS that report their own energy use can also reduce the cost of verification for energy service companies (ESCOs) that offer financing options and can manage the installation, configuration, and operation of complex systems. Many challenges remain before this vision can become reality, including a lack of appropriate standardized test methods for characterizing reporting accuracy, a lack of classifications for specifying performance, and a lack of information models for reported data.

As an initial foray into exploring the performance of building systems that can report their own energy consumption, this study explores the reporting accuracy of connected electrical outlets. While connected electrical outlets are not inherently components of typical building systems (e.g., lighting, HVAC), they can be used to report the energy consumed by cord-and-plug lighting products (e.g., table lamps, desk lamps, undercabinet luminaires, and furniture-integrated task-ambient lighting systems) as well as other building devices that do not inherently report their own energy consumption (e.g., computers, office equipment). Further, while the microelectronic technology that is often used to implement the energy-reporting capability is load-size dependent (e.g., may be different for 10W loads as compared to 10kW loads), it is not application-dependent. That is, the technology used to measure the consumption of a 10W device plugged into a connected outlet is likely to be very similar to that used to measure the self-consumption of a 10W lighting or computing product.

Background

Although its usage varies in practice, the term "accuracy" broadly refers to the extent to which a given measure agrees with a defined true or reference value (ANSI 2014). The measure may reflect a single observation or a set of observations (e.g., as the average value). A set of observations is considered accurate when it is both true (corresponding to low systematic error or bias) and precise (corresponding to low random error) (ISO, BIPM). Whereas trueness describes the closeness of a set of measurement results to the actual (i.e., true or reference) value, precision describes the closeness as a set of results to each other (without regard for the true value), as illustrated in Figure 1.

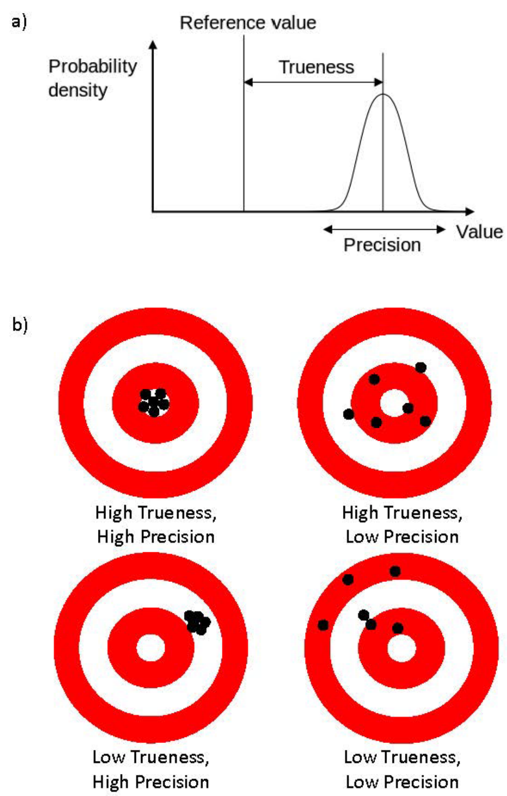

Figure 1: The two key aspects of accuracy (trueness and precision), as shown by a) a probability density plot (Source-Wikimedia), and b) bullseye plots.

Precision can be further resolved into:

- Repeatability – the variation arising when all efforts are made to keep conditions constant by using the same instrument and operator within a short time period; and
- Reproducibility – the variation arising using the same measurement process at different times and across different instruments, operators, and locations.

The accuracy requirements for energy meters used by electric utilities to bill their customers, along with the test methods for demonstrating whether devices meet those requirements, are well-defined and regulated in existing standards such as ANSI C12.1 (ANSI 2014) and ANSI C12.20 (ANSI 2015). The accuracy requirements for energy reports from building devices is not well-established, however, and are likely to be less stringent than those required for creating electric utility bills. Further, while the test method principles described in the existing standards apply to any electronic device that produces estimates of energy consumption, the test procedures do not, or might not, directly apply. For example, the existing standards describe how to characterize the accuracy of a meter – a device that monitors an unknown load – while building end-use devices might report their own energy consumption, for which the load is known. Further, the load levels and ranges for such devices are typically much smaller than those described in the existing standards.

The performance requirements described in the existing standards apply to every recorded data element from every device; that is, they do not specify requirements with some statistical representation (i.e., average accuracy of a set of multiple measurements), or from a set of multiple devices. Every measurement data point must meet the performance requirements. Such stringent requirements might not make sense for building-equipment devices, given that the accuracy of a specific measurement from a specific device is unlikely to ever be of paramount interest for many use cases, as decisions are usually made based on the average value.

Scope

This study explores the reporting accuracy of market-available electrical outlets with the ability to report their own energy consumption. The study tested both residential-market, single-outlet products and commercial-market, multiple-outlet power distribution units (PDUs). Reporting accuracy was evaluated under a total of 10 environmental input and load conditions, consisting of introduced variations in source AC voltage and frequency, and load current and power factor. Each condition was evaluated once. Electrical transients (e.g., sag, swell, surge) as well as environmental test conditions (e.g., temperature, humidity) were not developed here or evaluated for this study.

Given the preliminary nature of this investigation, accuracy was explored in a simplistic way. The limited number of units and outlets facilitates a limited and not statistically significant ability to characterize error sources as a function of unit or device. The limited number of evaluations per environmental condition (i.e., one evaluation per condition) further offered no ability to characterize repeatability or reproducibility. However, when the number of test conditions were considered, a total of 50 measurements were made for each of the residential make/models (5 units x 1 outlet/unit x 10 tests), and a total of 60 measurements were made for each of the commercial make/models (2 units x 3 outlets/unit x 10 tests), thereby offering an appreciable ability to compare performance at the make/model level. Each measurement yielded a relative reporting error (RRE), and energy-reporting accuracy was characterized for each make/model in the form of average RRE across all test conditions and devices-under test (DUT); variation of average RRE across test conditions, as derived from reported power or reported energy; and variation of average RRE across DUTs, derived from reported power/reported energy. Fitting the relationship between reported and reference measurements to a simple linear model and evaluating the randomness of the residuals separated systematic error sources from random error sources.

Test Setup and Implementation

A test setup consisting of a programmable AC source, a programmable AC load, and a reference power analyzer was used to characterize the reporting accuracy of the DUT (i.e., the electrical outlets). The programmable AC source supplies input power to the DUT and implements variations in AC input voltage and frequency. The programmable load defines the load current level and characteristics (e.g., power factor) drawn through the DUT. During testing, the power analyzer monitors DUT voltage and current, and calculates power factor on both the line (AC source) side and the load (AC load) side of the DUT. Energy consumption was calculated by the reference meter at both the line and load side of the DUT by integrating the measured power over a defined measurement interval.

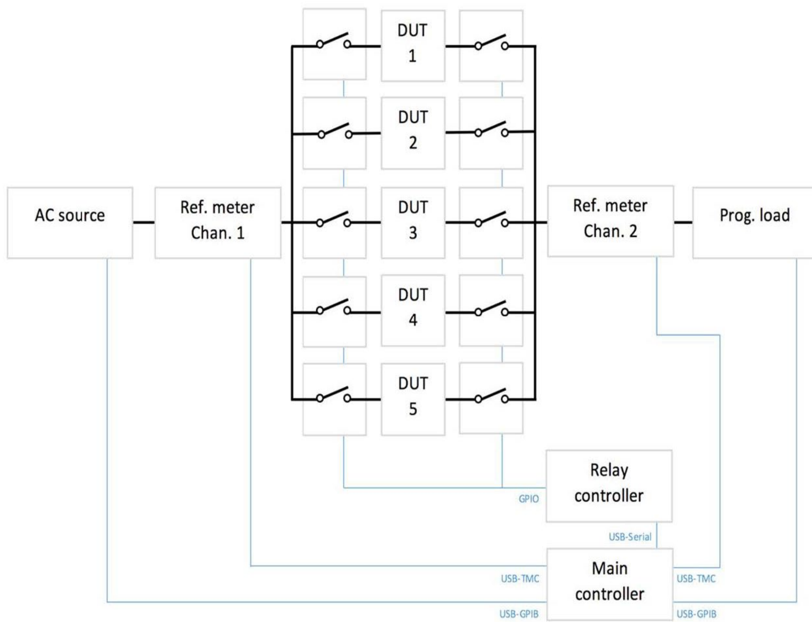

Figure 2: Block diagram of the test setup implementation.

The high-level architecture of the test setup implementation is shown in Figure 2. An array of software-controlled relays allows up to five DUTs to be evaluated sequentially, to reduce human intervention and increase testing throughput. Three relays per DUT were utilized: one on the load side, one on the line side, and one additional relay per DUT on the line side to switch the neutral connection. Residential products were found to measure current on the neutral (as opposed to line) wire during preliminary testing. The additional relay was used to prevent multiple neutral return paths for DUTs that measure current on the neutral wire. The relays were controlled using the general-purpose input/output (GPIO) pins of an Arduino Uno and serial-over-USB communications with the main software.

Electrical losses in cords and relays utilized in the test setup implementation were mathematically compensated for by measuring the resistance between each energy-monitoring point and the DUTs on both the line and load side. These measurements were taken prior to the evaluation of each set of DUTs, using a python script. Energy values were calculated as shown below:

$Lineside\ Energy = refLinesideEnergy - (LinesideRes*I^{2}*t)$

$Loadside\ Energy = refLoadsideEnergy + (LoadsideRes*I^{2}*t)$

Where

refLinesideEnergy = Reference meter lineside energy measurement (Wh)

refLoadsideEnergy = Reference meter loadside energy measurement (Wh)

LinesideRes = Measured lineside resistance values (Ω)

LoadsideRes = Measured loadside resistance values (Ω)

I = Test condition current (A)

t = Time (hour)

a)

b)

c)

Figure 3: Primary test setup equipment, including (a) a Chroma 61604 Programmable Power Supply, b) a Chroma 63802 Programmable Load, and c) a Yokogawa WT500 Power Analyzer, which served as the Reference Meter.

This test setup was primarily implemented (Figure 3) in the Pacific Northwest National Laboratory (PNNL) Connected Lighting Test Bed (CLTB) via a Chroma 61604 programmable AC source, a Chroma 63802 programmable load, and a Yokogawa WT500 power analyzer that served as the reference meter for accuracy calculations. Shunts were used instead of probes to measure current. Key specifications for these three primary pieces of equipment are provided in Table 1. In order to minimize testing time, the test execution and data acquisition was semi-automated. A python script was written to control and monitor the programmable power supply, the programmable load, and the power analyzer. Prior to the start of a given test, the script set the programmable power supply AC voltage and frequency; the programmable load current level, power factor, and impedance; and the power analyzer integration time and measurement range. The script then connected the load, initiated the power integration, and collected data supplied by the power analyzer. Separately, time-stamped data reported by the DUT was retrieved via an application programming interface (API) using a GET method. For the residential products, the API provided by the manufacturer was utilized (Table 2). For the commercial PDUs, outlet data was collected via Sunbird Power IQ software, and the data was accessed via the Sunbird Power IQ API (Table 3).

Table 1: Key test setup equipment and specifications.

Chroma 61604 Programmable Power Supply	Maximum Output: 2000VA Voltage: 0 - 300V AC, 0.2% + 0.2% FS accuracy with 1V resolution Frequency: 15Hz - 1kHz, 0.15% accuracy with 10 Hz resolution Distortion: 0.3% at 50/60Hz Line Regulation: 0.1% Load Regulation: 0.2%
Chroma 63802 Programmable Load	Power: 1800W Voltage: 50 - 350V RMS Frequency: 45 - 440Hz Constant Current: 0 - 18A RMS, 0.1% + 0.2% FS accuracy with 2 mA resolution Power Factor: 0 - 1, 1% FS accuracy with 0.005 resolution
Yokogawa WT500 Power Analyzer (Reference Meter)	Voltage Range: 0 - 1kV Current Range: 0 - 40A Sample Rate: 100kS/s Power Accuracy at (50-70Hz): 0.2% of reading + 0.2% of range Power Integration accuracy: + 0.02% of apparent power amount

Table 2: Python scripts used to access data from the two residential products.

D-Link python script

```
try:
    req =
requests.post("http://"+ipAddr+"/my_cgi.cgi?"+str(random.random()),
    timeout=10, data={'request':'create_chklst'})
  except requests.exceptions.RequestException as err:
       return {'ts':timestamp,'w':None}
  for line in req.text.split("\n"):
    if line.startswith("Meter Watt:"):
      try:
        power = float(line.split()[-1])
      except ValueError:
        print("Error on string '%s', keeping previous reading" % line)
  return {'ts':timestamp,'w':power}
```

TP-Link python script

```
sock_tcp = socket.socket(socket.AF_INET, socket.SOCK_STREAM)
  sock_tcp.connect((ipAddr, 9999))
  sock_tcp.send(encrypt('{"emeter":{"get_realtime":{}}}'))
  data = json.loads(decrypt(sock_tcp.recv(2048)[4:]))
  sock_tcp.close()
  return
{'ts':timestamp,'v':float(data["emeter"]["get_realtime"]["voltage"]),
'i':float(data["emeter"]["get_realtime"]["current"]),
'w':float(data["emeter"]["get_realtime"]["power"])}
```

Table 3: Python scripts used to access data from the three commercial products.

Commercial PDU python script

```
  req = requests.get("http://"+ipaddress+"/api/v2/pdus/1/outlets",
timeout=10, verify=False, auth=HTTPBasicAuth('admin', 'sunbird'))
  data = req.json()
  power = data['outlets'][address]['reading']['active_power']
  energy = data['outlets'][address]['reading']['watt_hour']
  current = data['outlets'][address]['reading']['current']
```

Reference Meter Calibration

The reference meter was calibrated in January 2019 by an independent laboratory that was accredited by an International Laboratory Accreditation Cooperation (ILAC) Mutual Recognition Arrangement (MRA) signatory to calibrate electrical measurement equipment of this type. PNNL staff instructed the laboratory to calibrate both sensing elements in the reference meter in two ways:

1. Using a laboratory-defined default set of calibration points, corresponding to the set of performance specifications published by the meter manufacturer in the user manual. This approach is typically used when customers do not provide custom calibration specifications. For example, the reference meter's published accuracy for voltage measurements between 45 Hz and 66 Hz is ±(0.1% of reading + 0.1% of range), so the calibration included points at 150 Vrms (top of range for nominal 120 Vrms measurements) and 1.5 Vrms (where the corresponding lower bound is slightly negative).

2. Using a custom set of calibration points defined by PNNL, corresponding to the set of test conditions defined in the test method used in this study. This approach helps to ensure linearity across measurements. For example, root-mean-square (RMS) voltage calibration included one point at 120 Vrms and 60.0 Hz, two points at 120 Vrms and varied frequency (58.8 and 61.2 Hz), and two points at 60.0 Hz and varied voltage (108 and 132 Vrms). Other single-phase AC parameters specified included frequency, displacement power factor, RMS current, active power, and energy. The full set of calibration points is provided in Appendix B.

The calibration laboratory confirmed that all calibration points were covered by its scope of accreditation to ISO/IEC 17025:2005, and determined that the reference meter's performance was within manufacturer stated tolerance and therefore did not require any adjustment. However, PNNL staff subsequently determined (via correspondence with the five U.S.-based ILAC MRA signatories) that only quantities that were explicitly included in the scope of accreditation were covered. Consequently, although calibration for voltage, current and power were covered by the laboratory's scope of accreditation, calibration for frequency and energy were not covered, because they were not explicitly included in the scope of accreditation. Given the energy-reporting focus of this investigation, and the use of the reference meter energy measurement to calculate the key metric (i.e., RRE), the reference meter should – in an ideal world – be calibrated by a laboratory whose scope of accreditation explicitly covers energy measurement.

Test Method

Prior to the evaluation of each set of DUTs, a set of measurements were taken to evaluate and compensate for electrical losses in the cables and relays, as discussed previously. All units to be tested were then plugged into the line-side relay box, and the cords from the load-side relay box were connected to the DUT receptacles (up to five at a time). The DUTs and all test equipment were allowed to operate for a minimum of 30 minutes and thereby reach thermal equilibrium with the ambient environment prior to the initiation of data collection. A Python 2.7 script based on the PyVISA (1.8), numpy (1.12.0), and pyserial (3.2.1) libraries was executed to communicate with the AC source, AC load, and reference meter in order to establish a specific test condition. The test method implemented 10 test conditions by varying load current (noload, curr_##), source AC voltage (volt_##), source AC frequency (freq_##), and load power factor (pfact_##, pulse), as shown in Table 4. The test conditions were adapted from ANSI C12.1 (ANSI 2014) conditions, with a focus on evaluating electrical loads that might be presented by real-world lighting devices, and limiting test time to a reasonable level. The script subsequently communicated with the relay controller to electrically connect a single DUT and establish a single path for current to flow through the test setup.

Table 4: The 10 environmental test conditions used to characterize the energy reporting accuracy of the DUTs.

Test Condition	Source AC Voltage (Vrms)	Source AC Frequency (Hz)	Load Current (A)	Load Power Factor	Reference Meter Voltage Range (Vrms)	Reference Meter Current Range (A)	Energy (Watt-hours)	Test Time (Minutes)
noload	120.00	60.00	0.00	1.000	150	0.5	N/A	10
curr_0.15	120.00	60.00	0.15	1.000	150	0.5	100	333.34
curr_2.5	120.00	60.00	2.50	1.000	150	5	100	20
curr_10	120.00	60.00	10.00	1.000	150	10	300	15
volt_108	108.00	60.00	2.50	1.000	150	5	100	22.23
volt_132	132.00	60.00	2.50	1.000	150	5	100	18.18
freq_58.8	120.00	58.80	2.50	1.000	150	5	100	20
freq_61.2	120.00	61.20	2.50	1.000	150	5	100	20
pfact_0.5	120.00	60.00	2.50	0.500	150	5	100	40
pulse[1]	120.00	60.00	2.50	0.555	150	5	100	36.03

The total time required to execute all 10 tests for each DUT was nine hours. At the end of each test, relative reporting error was calculated and recorded. After looping through all 10 tests for a given DUT, the relay controller opened the active relays and closed the next pair of relays to initiate testing of the next DUT, until all connected DUTs were characterized.

[1] The pulse test condition results in a load current with high harmonic content. A detailed explanation of this test condition, and its implementation via the programmable AC load, is provided in Appendix A. The specific configuration parameters for the Chroma 63802 utilized in the test setup implementation to create the pulse test condition are C = 9999 µ F and RL = 169 Ω.

Test Devices

Two residential-market products (five units each, one outlet per unit, shown in Figure 4) and three commercial-market PDUs (two units each, 18 to 24 outlets per unit, shown in Figure 5) that claimed the ability to report the energy flowing through their outlets were purchased through typical market channels. Each PDU had three blocks, or groupings, of outlets. One outlet was randomly selected from each block for testing, which was conducted at the PNNL CLTB in December 2018. The two commercial Vertiv units that were received had different user interface panel colors and different serial numbers (Y17C_ versus Y18A_). Key characteristics for all products are shown in Table 5. The reporting interval for the residential products was fixed by the manufacturer at one minute, while the commercial products had configurable reporting intervals that were set to one minute. Only one of the products was capable of producing time-stamped data (i.e., associating real-time, for a given time-zone, with a single reported parameter or set of them); however, even this product did not have an internal real-time clock and required time to be set manually or via a network time server. The residential products did not make accuracy claims, while the commercial products made claims between 1% and 2% with varying caveats, as shown in Table 5.

Figure 4: The two residential-market, single-outlet products that were tested (one unit of each shown here).

Figure 5: The three commercial-market, multiple-outlet PDUs that were tested (two units of each shown here).

Table 5: Key characteristics for all characterized products.

Type	Make, Model	Outlets per Unit, Minimum/Maximum Load Rating (A)	Reporting Interval	Data time stamp	Accuracy Claims
Residential	D-Link, DSP-W215	1, unspecified/15	Fixed, 1 minute	No	No claim
Residential	TP-Link, HS110	1, unspecified/15	Fixed, 1 minute	No	No claim
Commercial	Chatsworth Products, P6-1C0A5	24, 0.5/16	Configurable, 1 minute	Yes, but must be set manually or via a network time server.	"*±1% metering accuracy at each breaker*"
Commercial	Eaton, EMA114-10 and EMA6MD15ALG87AC	24, 0.025/16	Configurable, 1 minute	No	"*One percent revenue-grade power monitoring*"
Commercial	Vertiv, MPHR1403 and MPH2-NRV_L5-20P_18A	18, 0.05/16	Configurable, 1 minute	No	"*±1 % + 0.1 VAC*" and "*±1.5 % + 0.01 A FROM 1 % TO 10 % OF UNIT RATING; ±1 % + 0.01 A FROM >10 % TO 125 % OF UNIT RATING*"

The residential products reported a limited set of parameters: The D-Link just reported power, while the TP-Link product reported current, voltage, and power. Notably, neither of the residential products report interval or cumulative energy consumption; consequently, energy consumption could only be estimated by performing a numerical integration on the reported power data. The commercial PDUs reported an expanded set of parameters over multiple user interfaces, including a unit display, manufacturer-provided software, and API. The reporting availability and resolution of five key parameters (energy, power, current, voltage, power factor) are summarized for each the commercial products in Table 6. One commercial product did not report output voltage, and another did not report power factor via any mechanism. The resolution for reported parameters was not specified in product marketing or technical literature for any of the products. In some cases, apparent resolution could be discerned from graphics in instruction manuals, but even in such instances, the apparent resolution did not always match the observed resolution. The minimum reporting resolution for energy consumption varied significantly across the three commercial products, from 1 Wh to 100 Wh. For two of the products – Chatsworth and Eaton – the resolution available from the software interface was higher (i.e., worse) than that from the API. This relationship was not consistent, however, as the resolution of other parameters reported by one of these products was lower (i.e., better) when retrieved from the software interface than from the API. Reporting resolution is an important factor in the design of test conditions and the evaluation of error and accuracy. If one desires to evaluate relative reporting error of, for example, a 100 Wh measurement to the nearest 1%, then a minimum resolution of 1 Wh is required, and ideally, a resolution 10 times smaller than the minimum (i.e., 0.1 Wh) would be utilized. Notably, the test method for this study was designed around a common 100 Wh evaluation. One product reported energy in 100 Wh increments, and therefore its relative reporting error for energy consumption could not be directly evaluated, thereby limiting evaluation to the energy consumption calculated via the integration of reported power.

Table 6: Reported parameter availably and resolution, as provided via three different user interfaces, for the three commercial products.

Make	Parameter Resolution (Unit display, Software interface, API)				
	Energy (Wh)	Power (W)	Current (A)	Voltage (V)	Power Factor
Chatsworth	N/A, 10, 1	N/A, 10, 0.1	0.01, 0.01, 0.01	N/A, 0.1, 0.1	N/A, N/A, N/A
Eaton	N/A, 10, 1	1, 0.1, 1	0.001, 0.001, 0.01	N/A, N/A, N/A	0.001, 0.001, 0.01
Vertiv	N/A, 100, 100	N/A, 0.1, 1	N/A, 0.01, 0.01	0.1, 0.1, 0.1	N/A, 0.01, 0.01

Results

Test results and analysis are presented anonymously for both the residential (henceforth referred to as R1 and R2) and commercial (henceforth referred to as C1, C2, and C3) products. The 10 test conditions were successfully applied to all five R1 units (one outlet each), as well as to all six commercial units (two units, three outlets each for C1, C2, and C3 products). One R2 unit failed to connect to the ethernet communication network while testing; consequently, measurement results were only collected for four out of the five R2 units. For the curr_0.15 test condition, C1 DUTs were tested at 0.55 A instead of 0.15 A, because of the minimum load current limitations.

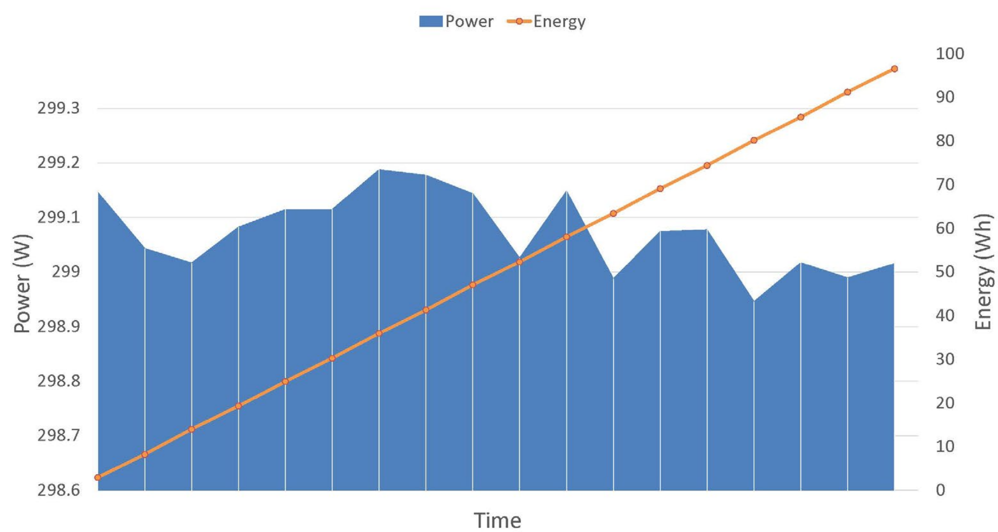

Figure 6: Sample calculation of energy via the integration of power over time, using the trapezoidal rule.

In addition to the reported energy data, cumulative energy consumption was calculated for all DUTs from reported power data, because the residential units did not report energy and the commercial products had varying energy resolution – which might have compromised a comparison of their performance. The power data were collected at one-minute intervals, and the energy was calculated by integrating power over reporting time using the Trapezoidal rule, as shown in Figure 6. As the resolution of data from the reference meter was always higher than that of the reported energy data, reference meter data were rounded to the resolution of data from each DUT, such that they both had same number of decimal places. The energy consumption derived from reported power and reported energy from each DUT was compared with the reference meter measurements by calculating relative reporting error for each DUT and test condition:

U = the energy consumption reported by the DUT, either directly or calculated from reported power (Wh)

Q = the energy consumption reported by the reference meter (Wh)

Relative reporting error (RRE %) = (U-Q) / Q * 100

Average reporting error was calculated for each make and model, across all DUTs and test conditions, weighted equally:

$$\frac{\sum_{i=1}^{l}\sum_{j=1}^{m}\sum_{k=1}^{n} Relative\ Reporting\ Error_{i,j,k}}{l * m * n}$$

where

l = number of units per make/model

m = number of DUTs each unit

n = number of test conditions

Analysis

Residential-Market Products

For a given test condition, the relative reporting error (RRE) was calculated for each residential-market DUT, as shown in the previous section. R2 (red) DUTs reported more consistently for a given test condition than did R1 (blue) DUTs, as shown in Figure 7. On the other hand, average RRE across DUTs was fairly constant across test conditions for R1 and varied by ~4% for R2, mostly due to the high current condition. Even though four out of five R1 DUTs showed less than 1% variation in RRE for any given test condition, variation in the average RRE among the five DUTs was ~4.5%, as shown in Figure 8. The RRE for four of five R1 DUTs were consistent across test conditions but inconsistent in comparison with each other; while, on the other hand, the RRE for R2 DUTs were consistent among themselves but varied across test conditions.

The average internal power draw for R1 was ~1.25 W across all load conditions, while the draw for R2 increased from 1.75 W at 0.15 A to 2.75 W at 10 A, as shown in Figure 9. If R2 was used to monitor an 18 W resistive load (120 V, 0.15 A, 1 PF), this 1.75 W comprised 10% of the total load. On the other hand, if R2 was used to monitor a 1200 W resistive load (120 V, 10 A, 1 PF), the 2.75 W internal draw comprised only 0.2% of the total load. If this product is used to monitor and control very low loads, its internal power draw could significantly compromise any energy savings that might be derived from such monitoring and control. The average no-load (i.e., standby) power draw was 1.31 W for R1 and 1.95 W for R2.

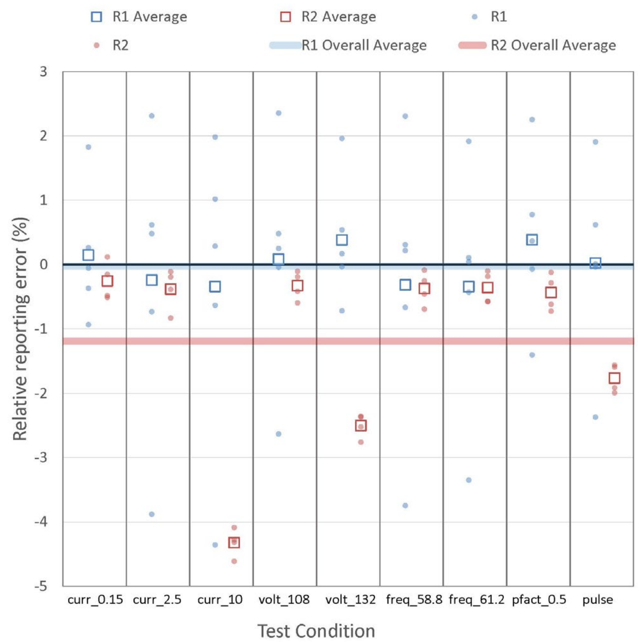

Figure 7: Relative reporting error for the residential products, per test condition. Each plotted point represents a DUT. Each square represents an average for a given make/model across all DUTs.

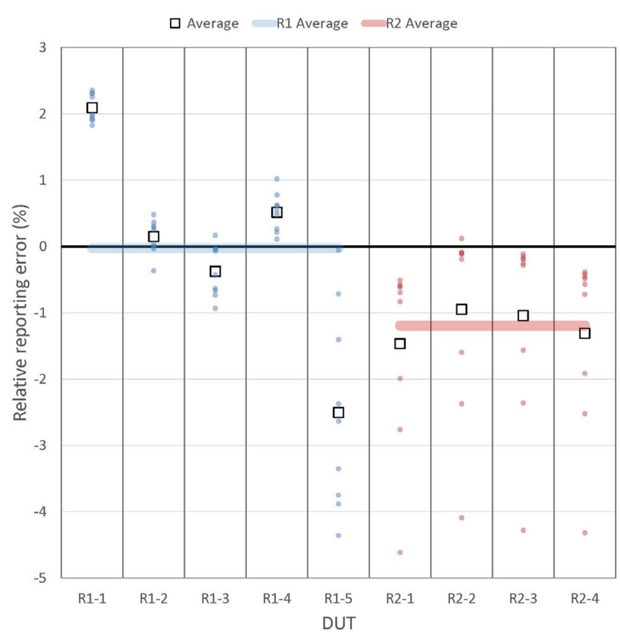

Figure 8: Relative reporting error for the residential products, per DUT. Each plotted point represents a test condition. Each square represents an average for a given DUT across all test conditions.

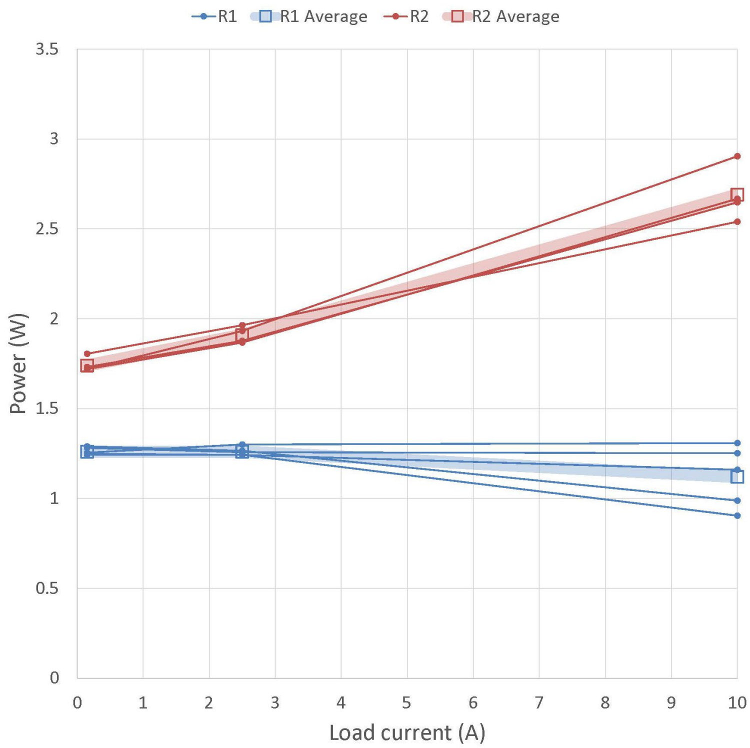

Figure 9: DUT power draw vs. load current for the residential products.

Commercial-Market Products

For a given test condition, RRE was calculated for each commercial-market DUT using two methods, first from the cumulative energy calculated from reported power and second from reported energy data. RRE in both cases was a comparison between these energy values and the energy data from reference meter. An evaluation of RRE based on cumulative energy calculated from reported power showed that all three makes/models on average underreported, as shown in Figure 10. An initial evaluation of RRE based on reported energy (Figure 11) showed little variation across test condition, with the notable exception of the pfact_0.5 and pulse conditions for certain products. C1 significantly overreported for the pfact_0.5 and pulse test conditions, while C2 significantly underreported when subjected to the pfact_0.5 test condition. The reasons for this significant under- and overreporting were completely different. The magnitude of overreporting by C1 suggested that it did not account for power factor correctly. On the other hand, the evaluation of C2 under the pfact_0.5 test condition was compromised by its limited resolution, rendering calculation of RRE for small loads or short reporting intervals not representative of its capabilities under other conditions. A closer look at the data (Figure 12) showed that C1 and C3 products tended to underreport slightly. At first glance, RRE for C2 appeared to be zero for most of these test conditions, but these results were again compromised by C2's limited resolution. This analysis showed how low resolution can give false accuracy performance for insufficient load levels or durations. An analysis of RRE across DUTs, based on cumulative energy calculated from reported power (Figure 13) and based on reported energy (Figure 14), clearly showed little dependence on DUT or unit, and showed the same anomalies for the pfact_0.5 and pulse test conditions. If these two conditions were removed from the analysis, the variation of average RRE for a given DUT was less than ~2.5%, as shown in Figures 15 and 16.

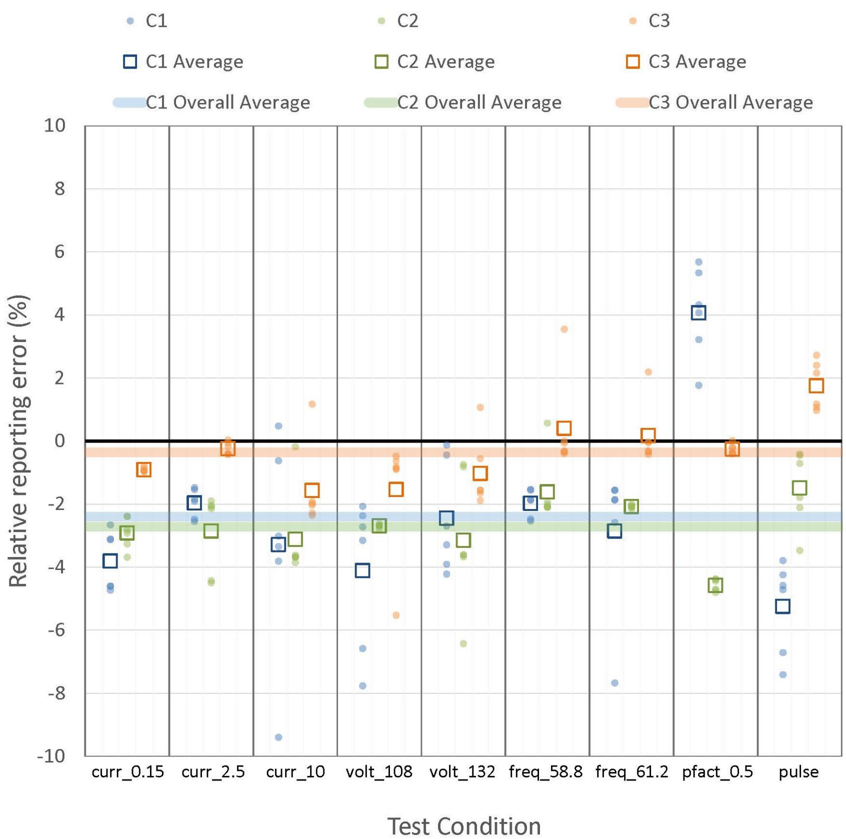

Figure 10: Relative reporting error for the commercial products, per test condition; derived from reported power. Each plotted point represents a DUT. Each square represents an average for a given make/model across all DUTs.

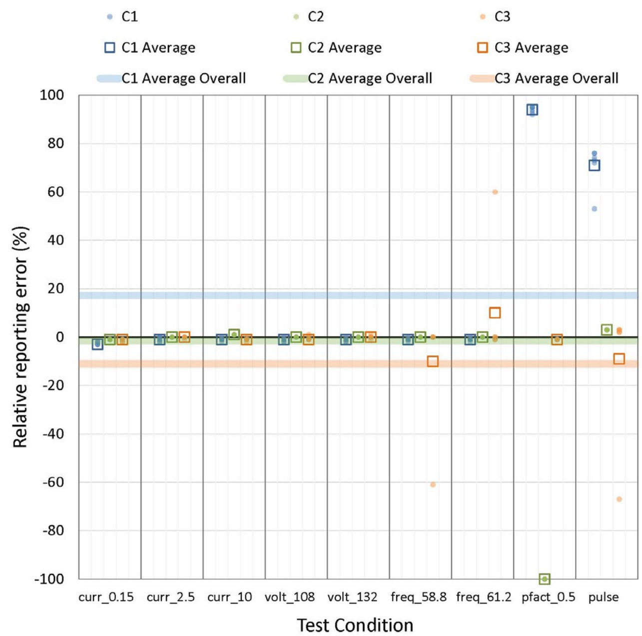

Figure 11: Relative reporting error for the commercial products, per test condition; derived from reported energy. Each plotted point represents a DUT. Each square represents an average for a given make/model across all DUTs.

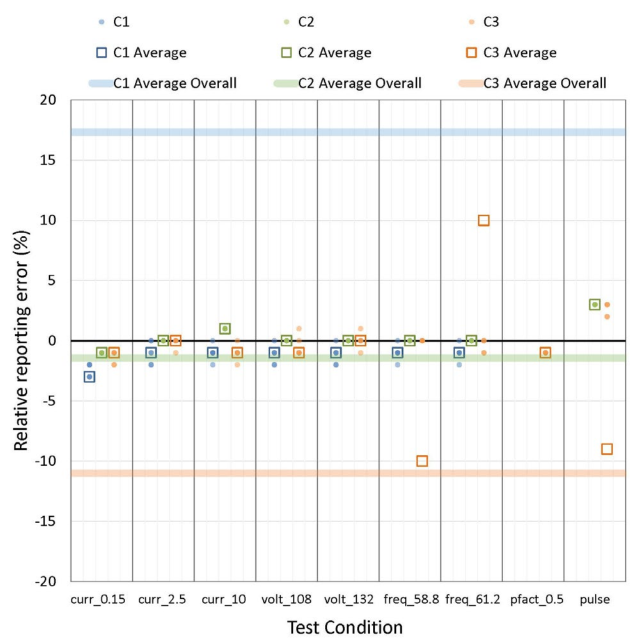

Figure 12: Relative reporting error for the commercial products, per test condition; derived from reported energy. Each plotted point represents a DUT. Each square represents an average for a given make/model across all DUTs.

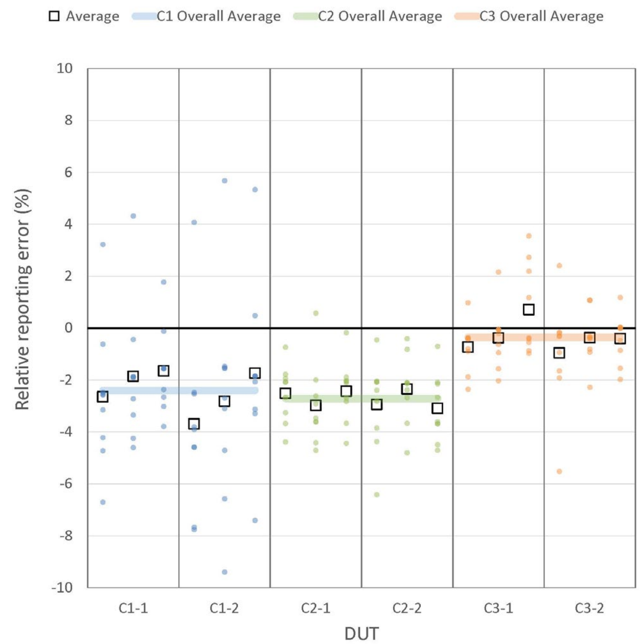

Figure 13: Relative reporting error for the commercial products, per DUT; derived from reported power. Each plotted point represents a test condition. Each square represents an average for a given DUT across all test conditions.

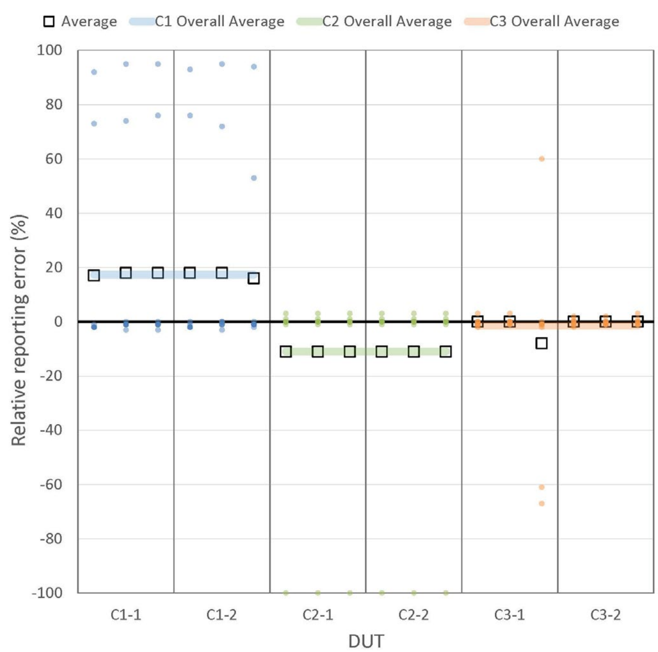

Figure 14: Relative reporting error for the commercial products, per DUT; derived from reported energy. Each plotted point represents a test condition. Each square represents an average for a given DUT across all test conditions.

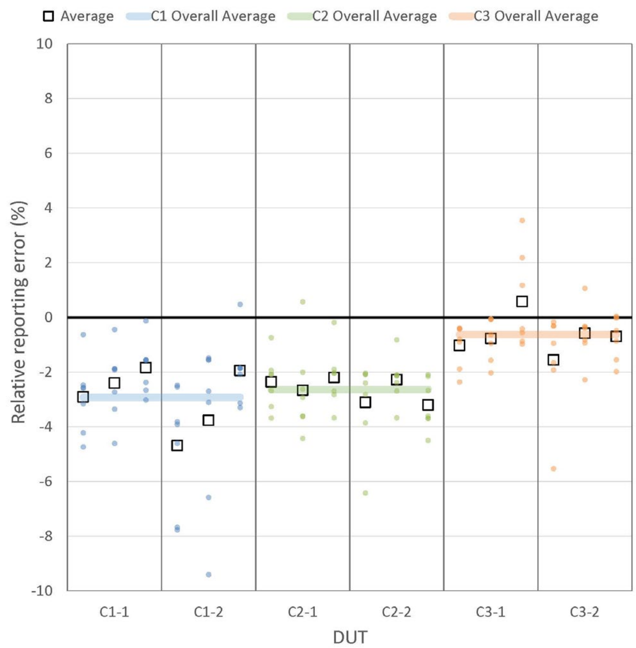

Figure 15: Relative reporting error for the commercial products, per DUT; derived from reported power. Each plotted point represents a test condition. Each square represents an average for a given DUT across seven test conditions.

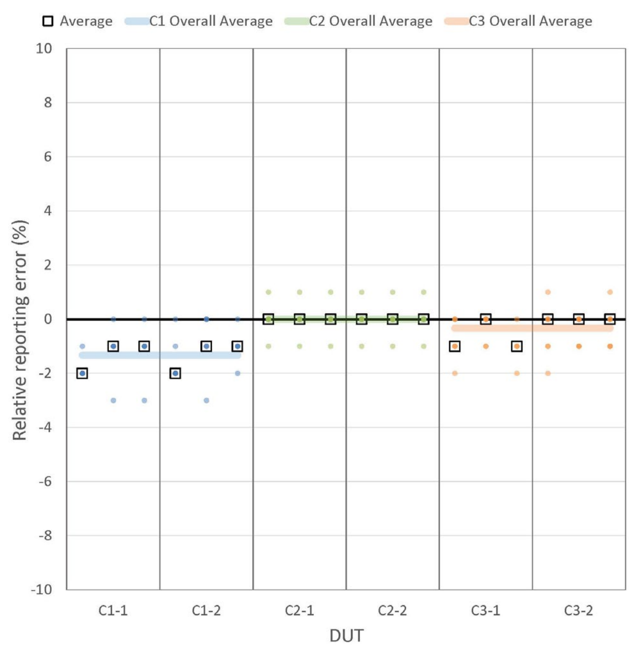

Figure 16: Relative reporting error for the commercial products, per DUT; derived from reported energy. Each plotted point represents a test condition. Each square represents an average for a given DUT across seven test conditions.

The internal power draw by the three commercial units varied by make/model and the load current that they were controlling and monitoring, as shown in Figure 17. C1 and C2 drew a minimum of ~5 watts, and at 10 amps drew an average 12.6 watts and 18.2 watts, respectively – representing a significant (>150%) increase. C3 drew a minimum of 19.2 watts, and at 10 amps drew an average of 25.4 watts, representing a >32% increase. If C1, C2, and C3 were used to monitor an 18 W resistive load (120V, 0.15A, 1 PF), their respective power draw would comprise 27%, 27%, and 106% of the total load, respectively. On the other end of the spectrum, if the same three commercial make/model units were used to monitor a 1200 W resistive load (120V, 10A, 1 PF), their respective power draws would comprise 1.05%, 1.51%, and 2.11% of the total load, respectively. The average no-load (i.e., standby) power draw was 5.13 W for C1, 5.72 W for C2, and 20.50 W for C3.

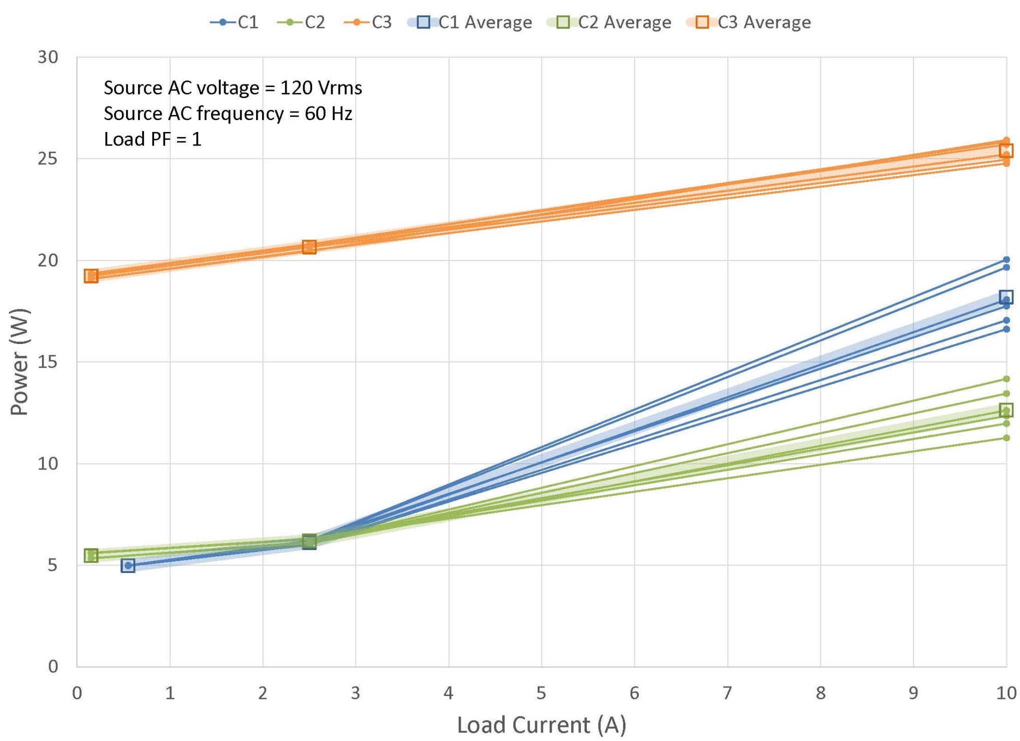

Figure 17: DUT power draw vs. load current for the commercial products.

Normality Analysis

Histograms of the RRE for all makes/models were created in an attempt to understand the statistical nature of the data collected (Figure 18). A normally distributed histogram is a good indicator that the measured values only contain random errors. While R1 and C2B had distributions that were approaching normal, the remaining products did not. Many products (e.g., C2A and C3B) had distributions which were clearly skewed left, indicating a systematic offset error. Some products (e.g., C1A and C1B) appeared to also have secondary peaks, thereby indicating a second systematic error source. While the number of evaluated samples was not sufficient to definitively characterize statistical distributions, these histograms nevertheless appeared to provide some reasonable insight.

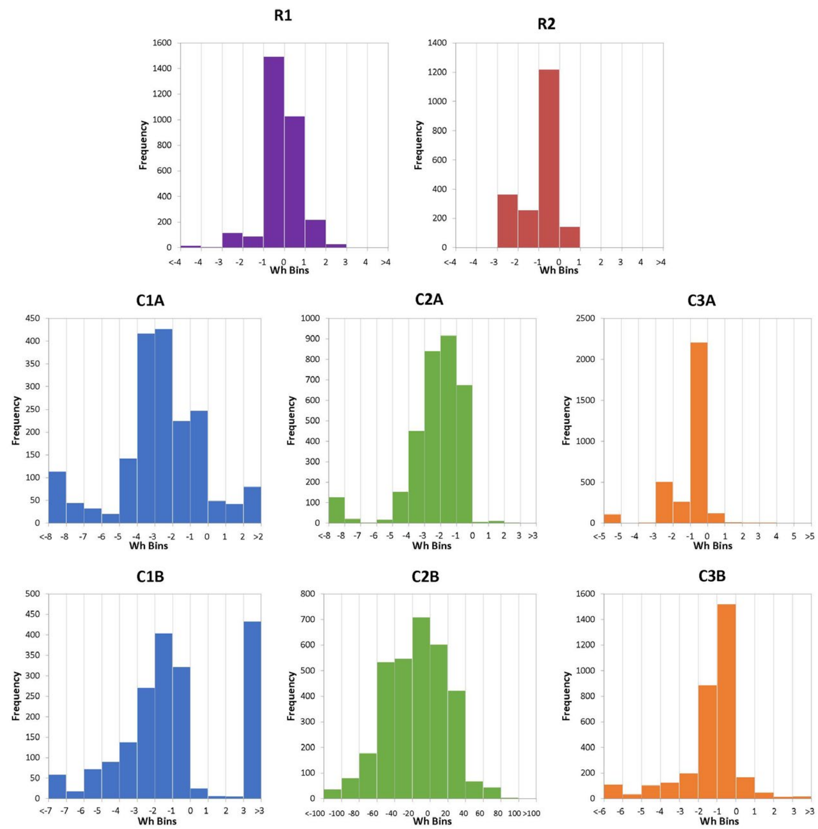

Figure 18: Histograms of the RRE as derived from reported power for all products (R1, R2, C1A, C2A, C3A) and as derived from reported energy for the commercial products (C1B, C2B, C3B).

Linear Regression Analysis

In a simple attempt to separate systematic errors from random errors for each product, a linear regression analysis was performed on the calculated and reported energy data for all products. An example regression, performed on a plot of reported energy consumption vs. reference energy consumption, is shown in Figure 19. This regression used a simple linear predictive model. Residuals from linear regression analysis, which were calculated as the difference between calculated or reported energy consumption data as produced by the DUT and the energy consumption "predicted" by the linear model for a given reference energy reading, represented a RRE for energy data that had been transformed or "corrected" by the linear model. The residuals were plotted against the predicted energy readings, or "fitted values," producing what is referred to in the statistical world as a "residuals vs. fits" plot, as shown in Figure 20. Calculated or reported energy consumption data that only contain random errors should produce a residual plot with values that are randomly distributed around zero, and a horizontal bandwidth that depicts the amount of random error.

The lines that appeared to form in some of the residual vs. fits plots (e.g., C1B, C2B, C3B) were indicative of cases where the reported value resolution was higher (i.e., worse) than the reference value resolution, revealing one form of systematic error. The residual vs. fits plots also showed systematic errors that were unique to each DUT and some test conditions (e.g., R2, R1). Most of the residual bands had a positive slope, which was indicative of a systematic error that was a function of calculated or reported energy. Most plots had more negative residuals than positive, which was consistent with the previous conclusions that these products tended to underreport.

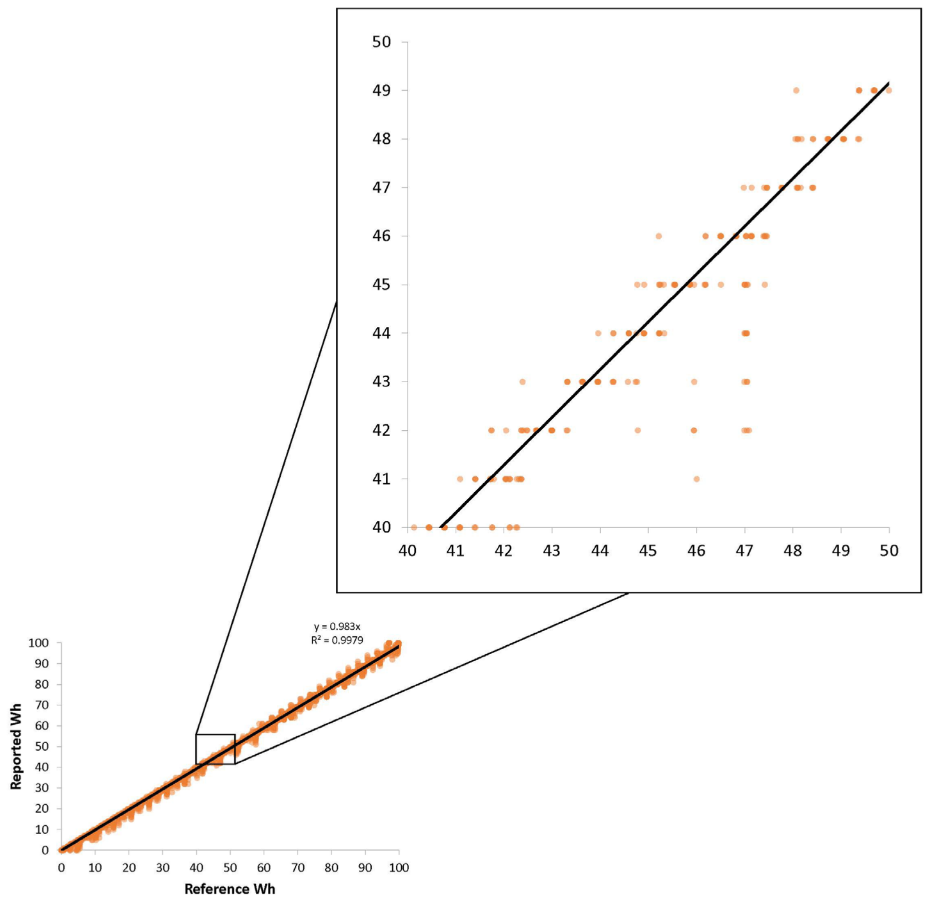

Figure 19: Example linear regression performed on the C3 reported energy data.

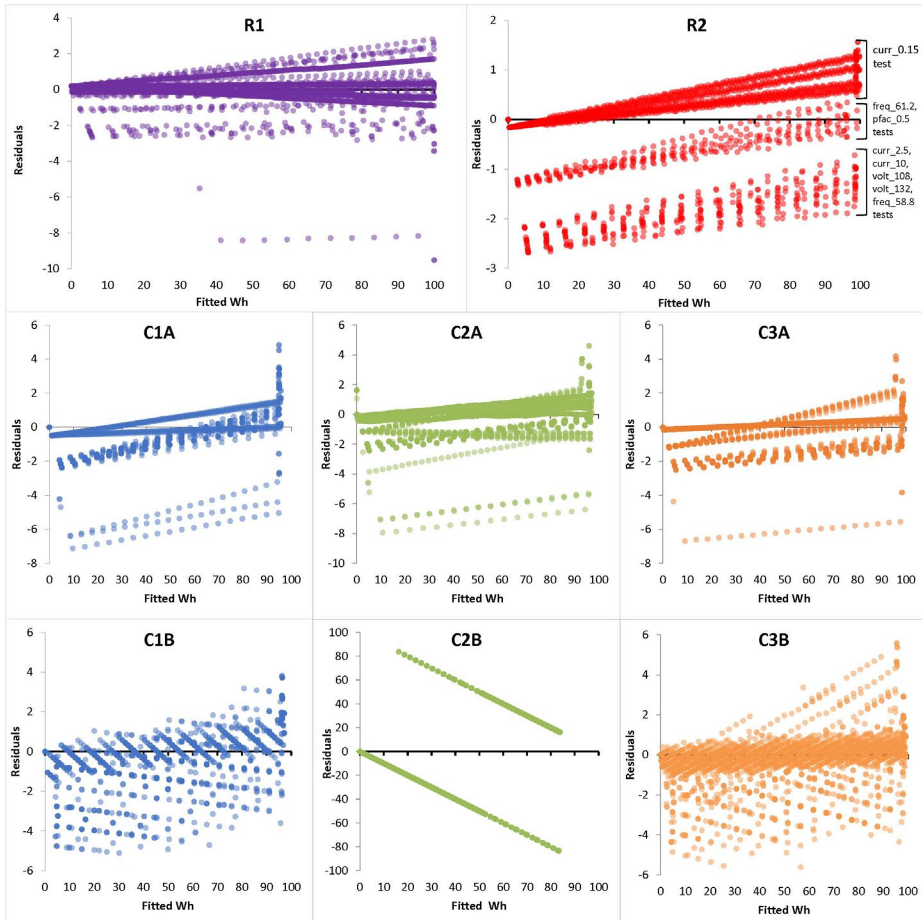

Figure 20: Residuals vs predicted energy for the linear regression analysis performed on calculated energy data, as derived from reported power, for all products (R1, R2, C1A, C2A, C3A) and performed on reported energy data, for the commercial products (C1B, C2B, C3B).

Histograms of the residuals were created to explore how well the linear regression analysis was able to separate the systematic errors from the random errors (Figure 21). Once again, a normally distributed histogram was a good indicator that the residuals only contained random errors. The linear regression model appeared to have been partially successful, in that it had removed the offset and secondary peaks for many of the products. However, some of the distributions were still skewed left (e.g., R2, C1B, C3A), and one of the distributions (C2B) then appeared bifurcated. These results suggested that some of the products appeared to have more than one systematic error source.

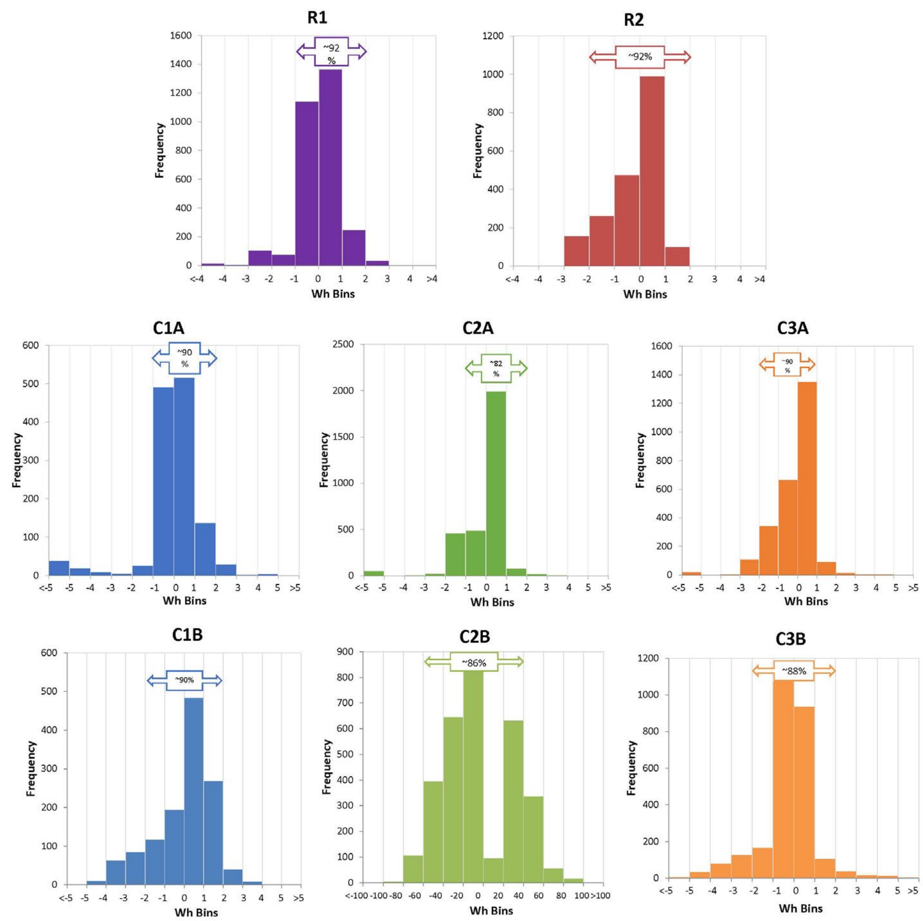

Figure 21: Histograms of the RRE residuals produced by linear regression performed on RRE as derived from reported power for all products (R1, R2, C1A, C2A, C3A) and on RRE as derived from reported energy for the commercial products (C1B, C2B, C3B).

Summary, Next Steps, and Recommendations

Based on the limited testing done in this study, it was found that the RRE for connected outlet products can vary significantly with AC source and load condition, as well as across different units of the same make/model. For residential units, R1 showed very little dependence on test conditions, but the RRE varied significantly across its DUTs, as shown in Table 7. On the other hand, R2 showed very little dependence on DUT, but the RRE varied across test conditions. Variation in average RRE was more dependent on test condition than on DUT, for all the commercial products. The average RRE derived from reported cumulative energy for the three commercial products (17%, -10.78%, -1.5%) varied significantly and was worse than the average RRE derived from a numerical integration of reported power (-2.40%, -2.72%, -0.36%). The average RRE for residential products derived from numerical integration (-0.02%, -1.20%) was surprisingly better than that for commercial products. Commercial-product performance typically exceeds the performance of similar residential products. While the tested commercial products contain many more monitored outlets (18-24) than the residential product (1), this difference is not expected to have an impact on performance, as each of the monitored outlets in the commercial products was claimed to be individually monitored and capable of meeting stated performance, independent of whether or to what degree other outlets were loaded. The residential units did not make accuracy claims that could be compared with their characterized performance. Comparing the performance of the commercial units against their claims, which were generally between 1%

and 2% with varying caveats, is complicated by the significant variation seen between the two reporting conditions (i.e., cumulative energy vs. energy derived from numerical integration of power). The accuracy of directly reported cumulative energy consumption for one of the commercial units was in the vicinity of its claim, while the other two were significantly worse. The same commercial product performed well within its claims when energy consumption was derived from numerical integration of power, while the other two were slightly worse.

The energy consumption of these products can vary significantly with the connected load. All makes/models showed very little dependence on DUT, but the energy consumption of commercial units varied significantly across load conditions (Table 8). The average power draw for the three commercial units (9.76 W, 8.10 W, 21.76 W) was significantly higher than the average power draw of the residential units (1.21 W, 2.11 W). The average no-load power draw for the three commercial units (5.13 W, 5.72 W, 20.50 W) was also significantly higher than the average power draw of the residential units (1.31 W, 1.95 W).

Table 7: Energy reporting accuracy for each make/model, across all test conditions and DUTs.

Make/Model	Average RRE across all test conditions and DUTs, as derived from reported power/reported energy	Variation of average RRE across test conditions, as derived from reported power/reported energy	Variation of average RRE across DUTs, as derived from reported power/reported energy
R1	-0.02 / NA	-0.34 to 0.38 / NA	-2.50 to 2.09 / NA
R2	-1.20 / NA	-4.32 to -0.25/ NA	-1.46 to -0.94 / NA
C1	-2.40 / 17	-5.24 to 4.06 / 94 to -3	-3.69 to -1.65 / 16 to 18
C2	-2.72 / -10.78	-4.57 to -1.48 / 3 to -100	-3.09 to -2.34 / -11
C3	-0.36 / -1.5	-1.56 to 1.75 / 10 to -10	-0.95 to 0.71 / -8 to 0

Table 8: Average power draw for each make/model, across all test conditions and DUTs.

Make/Model	Average power draw across all test conditions and DUTs	Variation of average power draw across test conditions	Variation of average power draw across DUTs
R1	1.21	1.12 to 1.26	1.13 to 1.29
R2	2.11	1.74 to 2.69	2.09 to 2.19
C1	9.76	4.99 to 18.2	9.20 to 10.41
C2	8.10	5.47 to 12.64	7.73 to 8.30
C3	21.76	19.25 to 25.4	21.45 to 21.98

The variations observed in average RRE across test conditions suggests that end users may see different performance in different applications. Similarly, the variations in average RRE across DUT suggests that end users may see different performance from different units used for the same application. The average RRE for two out of three commercial products was not necessarily representative of the product's capabilities under all circumstances. For example, the high average RRE observed for C2 was in large part the result of its low resolution relative to the 100Wh test duration. For longer test durations, the performance of C2 would have been expected to be more aligned with the RRE derived from calculated cumulative energy data. The high average RRE observed for C1 was in large part the result of C1's inability to account for sub-unity power factor. Due to API limitations, all PDU outlets were active (i.e., capable of delivering power to the connected load) during testing, even when no load was connected. The internal power draw of any of these commercial products might have been lower when only loaded outlets were active.

The normality analysis shows that all products appeared to have systematic and random error sources. An attempt to separate systematic error from random error using a simple linear regression model was partially successful. For example, the linear regression clearly appeared to separate a systematic offset for some products. However, even in such instances, the residuals from the linear regression did not appear to be normally distributed, suggesting that additional systematic errors were still present.

While the number of evaluated samples was not sufficient to characterize statistical distributions, it is important to note that the performance of these devices was a function of more than just product design. Manufacturers usually only specify a single value for accuracy and do not provide any details about how it varies with connected load. Also, they do not provide any information about the expected variation across DUTs, which is important because the range of variation of average RRE across DUTs can be significant (Table 7). It is anticipated that future phases of this study will allow for the collection of more data – including units per make/model and more measurements per DUT– and thereby facilitate a more robust characterization of trueness and precision.

Next Steps

This study is the first in a planned series of investigations into the device-level energy-reporting accuracy of connected outlets and connected lighting systems. PNNL plans to further improve the test setup and method, and to conduct at least one follow-up study about energy-reporting accuracy of commercial PDUs, and a series of studies focused on the energy-reporting accuracy of connected lighting devices and systems. Ideas presently under consideration include:

- Improvement of the test setup and method by incorporating additional test conditions that might, for example, create a time-varying load, which would enable the exploration of performance under dynamic load conditions.
- For connected outlets, characterization of all the outlets of C3 PDUs, to enable a better statistical exploration of error sources as a function of unit; characterization of the same three DUTs over multiple iterations, to explore measurement repeatability; characterization of additional make/model PDUs with a reported energy resolution of 1 watt-hour or better, to better explore performance across makes/models with similar capabilities.
- For connected lighting systems, characterization of streetlight controllers and Power over Ethernet systems.

Recommendations

This study yielded recommendations potentially relevant to energy-reporting product manufacturers, standards and specification developers, and building-system owners, operators, and specifiers. Key takeaways for these various stakeholder groups are as follows:

Energy-reporting device and system manufacturers that develop products reporting energy consumption should:

- Characterize the accuracy of reported metrics using a reference meter calibrated by an independent laboratory that was accredited by an ILAC MRA signatory (and whose scope of accreditation explicitly covers energy measurement), and include this information on product data sheets.
- Clearly document resolution for all reported metrics, via all reporting interfaces (e.g., hardware display, software user interface, data exports, API), on product data sheets.

- Contribute to the development of industry-standard test methods for characterizing energy-reporting accuracy, such as those underway in the ANSI C136 – Standards for Roadway and Area Lighting Equipment (ANSIC136) and ANSI C137 – Standards for Lighting Systems (ANSIC137) committees.
- Develop product designs that enable efficient characterization of reporting accuracy by independent laboratories and other interested parties.
- Report the internal power draw of energy-reporting devices and systems under well-defined conditions (e.g., minimum, maximum, no-load), and contribute to the development of industry-standard power-draw limits.
- Implement vendor-neutral common REST APIs for common product types/applications, as has been done for some commercial PDUs.
- Report energy data using industry-standard information and semantic models, and contribute to the ongoing development of these models, such as those underway in ASHRAE AP Working Group, the Open Connectivity Foundation, or the ZigBee Alliance.

Standards and specification development organizations should:

- Develop application-specific performance classifications that end users can understand and relate to their energy-data use needs (e.g., 2% accuracy class for utility streetlight energy billing needs, or 10% accuracy class for ESCO performance verification needs).
- Develop test methods to verify whether energy-reporting devices and systems comply with established application-specific performance classifications.
- Develop internal power-draw limits for energy-reporting devices and systems under well-defined operating conditions.
- Develop test methods to verify whether energy-reporting devices and systems comply with established internal power-draw limits.

Current or potential owners, operators, and specifiers of energy reporting building systems should:

- Rigorously analyze the dependency of current and planned energy-data use cases on accuracy, noting in particular the dependence (or lack thereof) on relative vs. absolute accuracy, and on trueness vs. precision (i.e., repeatability), and should communicate use-case needs to industry-standards and specification organizations.
- Support or require relevant industry standards and specifications in requests for information, proposals, and quotes.

Appendices

Appendix A: Pulse Current Waveform

Switched-mode power supplies, which are found in LED luminaire drivers as well as most consumer electronics products, draw current from the AC line in short pulses. As a result, their input current has high harmonic content. Most programmable loads are not capable of simulating such nonlinear conditions through harmonic waveform synthesis (i.e., the ability to specify load current waveforms in terms of the sum of their harmonic coefficients). Many, however, provide the ability to specify circuit element parameters for a rectified load equivalent circuit (Figure A1). The allowed circuit element set points for the Chroma 63802 are shown in Table A1.

The diode bridge in this equivalent circuit rectifies the entire sinusoidal AC source input. During the positive half-cycle, current flows from the positive terminal of the AC source through the forward-biased diodes D_1 and D_2. During the negative half-cycle, current flows from the negative terminal of the AC source through the forward-biased diodes D_3 and D_4. The shunt capacitor allows some of the energy to be stored and discharged between pulses, effectively smoothing out the output voltage waveform. The source will only conduct during a portion of each half-cycle (conduction angle) to recharge the capacitor to the peak value of the supply voltage (Figure A2). Sizing the capacitor presents a design tradeoff – a larger capacitor reduces ripple more and produces a steadier DC output, but draws higher peak currents from the AC input source. The series inductor prevents current peaks from building up and coming down too quickly, effectively smoothing out the current waveform. With a large-enough inductor, current will become more continuous and constant, but the peak voltage will not be reached.

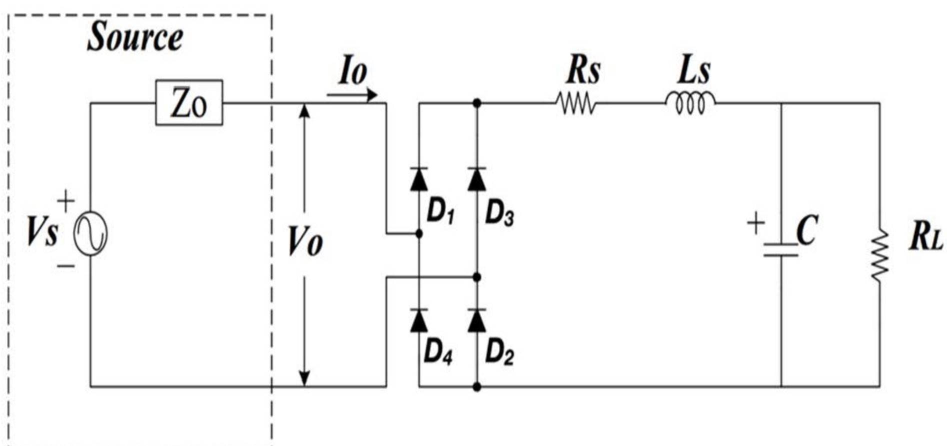

Figure A1. A rectified load equivalent circuit capable of drawing current with high harmonic content.

Table A1. Chroma 63802 allowed set points for the rectified load equivalent circuit.

Circuit Element	Allowed set points
Operating Frequency	45Hz - 70Hz
R_S	0 – 9.999Ω
L_S	0 – 9.999mH
C	100uF – 9.999mF
R_L	2.77Ω – 9.999kΩ

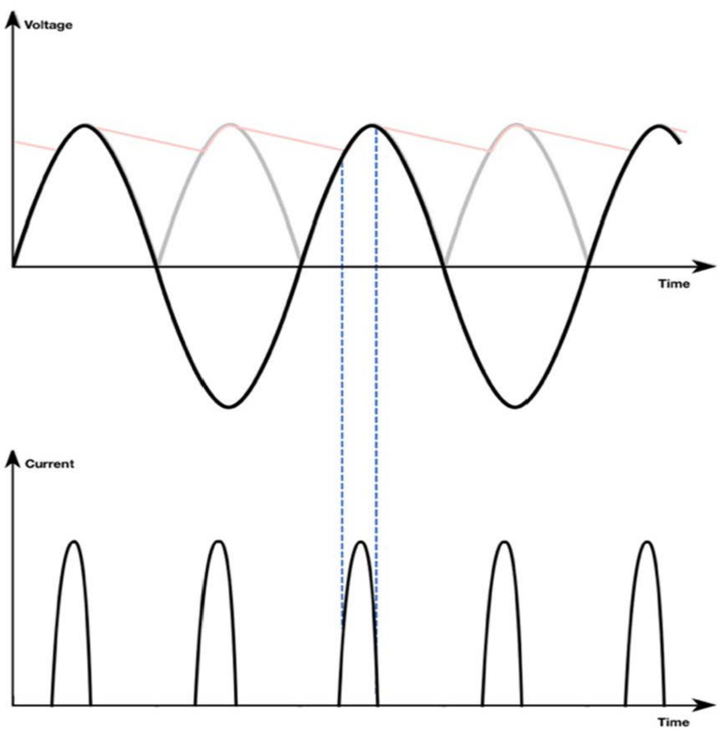

Figure A2. Example voltage and current waveforms for the rectified load.

Appendix B: Custom Reference Meter Calibration

Basic Requirements

1. Calibration shall be within scope of accreditation by ILAC MRA signatory
2. Report shall include ISO/IEC 17025 data, with conditions readily discernable from text
3. Report shall indicate 1-year calibration interval
4. Pass/fail shall be per the manufacturer's 6-month accuracy specifications
5. No distortion shall be present on source voltage or load current waveforms
6. Measuring equipment settings shall be as follows (specific to Yokogawa WT500 the is being calibrated)
   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" watt-hour (Wh) integration method
7. Measuring equipment shall be calibrated at the standard calibration points used and recommended by the manufacturer, as well as the following supplemental custom calibration points:
   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)

Table B1. AC source voltage measurement.

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

Table B2. AC source frequency measurement.

Calibration point	Source frequency (Hz)	Source voltage (V)	Load current (A)
A B C	58.8 60.0 61.2	120	2.5
D E F	58.8 60.0 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 B C	0.5 leading 0.5 lagging 1.0	60	120	150	2.5	5

Table B4. AC load current measurement.

Calibration point	Load current (A)	Current range (A)	Source frequency (Hz)	Source voltage (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

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 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

Table B6. AC energy (Wh) measurement.

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

Appendix C: Test Results

This section shows results for all DUTs (for each model, there are multiple units in a sample, and typically at least two outlets per unit) across individual test conditions. Each table for residential outlets shows the calculated energy (from measured power, sampled every 60 seconds), accuracy, and power consumption corresponding to each test condition. The results for commercial outlets show energy measurements (calculated and reported), corresponding accuracy, and power usage.

Table C1: R1 Results

Model-Unit	Test Condition	Average DUT Power (W)	Energy (Wh), as calculated from reported DUT power data	Reporting Error (%)
R1-1	noload	1.27	0	N/A
R1-1	curr_0.15	1.26	102.798371	1.82
R1-1	curr_2.5	1.30	102.53244	2.31
R1-1	curr_10	1.31	305.389966	1.98
R1-1	volt_108	1.26	102.553549	2.35
R1-1	volt_132	1.28	102.11186	1.96
R1-1	freq_58.8	1.27	102.518452	2.30
R1-1	freq_61.2	1.27	102.151341	1.92
R1-1	pfact_0.5	1.26	103.179741	2.25
R1-1	pulse	1.27	99.509423	1.91
R1-2	noload	1.33	0	N/A
R1-2	curr_0.15	1.29	100.587376	0.37
R1-2	curr_2.5	1.27	100.789314	0.48
R1-2	curr_10	0.99	300.502667	0.29
R1-2	volt_108	1.27	100.528348	0.25
R1-2	volt_132	1.27	100.184012	0.03
R1-2	freq_58.8	1.27	100.599826	0.31
R1-2	freq_61.2	1.26	100.362377	0.04
R1-2	pfact_0.5	1.25	101.369195	0.37
R1-2	pulse	1.28	97.734289	0.006
R1-3	noload	1.34	0	N/A
R1-3	curr_0.15	1.28	99.982778	0.93
R1-3	curr_2.5	1.26	99.598786	0.73
R1-3	curr_10	1.25	297.715326	0.63

R1-3	volt_108	1.29	100.242047	0.04
R1-3	volt_132	1.30	100.384696	0.17
R1-3	freq_58.8	1.30	99.61269	0.67
R1-3	freq_61.2	1.30	99.87074	0.43
R1-3	pfact_0.5	1.29	100.912729	0.07
R1-3	pulse	1.29	97.366078	0.03
R1-4	noload	1.27	0	N/A
R1-4	curr_0.15	1.24	101.11881	0.26
R1-4	curr_2.5	1.24	100.896591	0.61
R1-4	curr_10	0.90	302.473523	1.02
R1-4	volt_108	1.22	100.739187	0.48
R1-4	volt_132	1.24	100.742359	0.53
R1-4	freq_58.8	1.23	100.487055	0.22
R1-4	freq_61.2	1.23	100.398803	0.11
R1-4	pfact_0.5	1.22	101.799101	0.78
R1-4	pulse	1.24	98.492072	0.62
R1-5	noload	1.36	0	N/A
R1-5	curr_0.15	1.25	100.921909	0.05
R1-5	curr_2.5	1.24	96.42493	3.88
R1-5	curr_10	1.16	286.363445	4.35
R1-5	volt_108	1.25	97.643344	2.63
R1-5	volt_132	1.31	99.504451	0.72
R1-5	freq_58.8	1.26	96.517807	3.74
R1-5	freq_61.2	1.27	96.934499	3.35
R1-5	pfact_0.5	1.26	99.578098	1.40
R1-5	pulse	1.23	95.098982	2.37

Table C2: R2 Results

Model-Unit	Test Condition	Average DUT Power (W)	Energy (Wh), as calculated from reported DUT power data	Reporting Error (%)
R2-1	noload	1.99	0	N/A
R2-1	curr_0.15	1.80	100.373563	0.51
R2-1	curr_2.5	1.96	99.359851	0.83
R2-1	curr_10	2.54	285.302366	4.61
R2-1	volt_108	1.91	99.55153	0.60
R2-1	volt_132	1.94	97.3568	2.76
R2-1	freq_58.8	1.96	99.480545	0.69
R2-1	freq_61.2	1.96	99.622328	0.58
R2-1	pfact_0.5	1.90	100.270532	0.62
R2-1	pulse	1.92	95.849674	1.99
R2-2	noload	1.94	0	N/A
R2-2	curr_0.15	1.73	101.061424	0.12
R2-2	curr_2.5	1.88	100.087314	0.19
R2-2	curr_10	2.65	287.044664	4.09
R2-2	volt_108	1.84	100.127399	0.10
R2-2	volt_132	1.86	97.819216	2.37
R2-2	freq_58.8	1.87	100.172217	0.08
R2-2	freq_61.2	1.87	100.180139	0.10
R2-2	pfact_0.5	1.82	100.859637	0.12
R2-2	pulse	1.82	96.034824	1.59
R2-3	noload	1.93	0	N/A
R2-3	curr_0.15	1.72	100.796203	0.15
R2-3	curr_2.5	1.87	100.168582	0.11
R2-3	curr_10	2.67	286.42151	4.28
R2-3	volt_108	1.85	100.033176	0.19
R2-3	volt_132	1.87	97.821839	2.36
R2-3	freq_58.8	1.87	99.999945	0.25
R2-3	freq_61.2	1.87	100.090847	0.18
R2-3	pfact_0.5	1.81	100.689589	0.28

R2-3	pulse	1.81	95.794912	1.56
R2-4	noload	1.94	0	N/A
R2-4	curr_0.15	1.72	100.403544	0.48
R2-4	curr_2.5	1.93	99.851901	0.39
R2-4	curr_10	2.90	286.271297	4.32
R2-4	volt_108	1.84	99.78872	0.42
R2-4	volt_132	1.86	97.647179	2.52
R2-4	freq_58.8	1.86	99.776794	0.46
R2-4	freq_61.2	1.86	99.689117	0.57
R2-4	pfact_0.5	1.80	100.278746	0.72
R2-4	pulse	1.76	95.169956	1.91

Table C3: C1-1 Results

Model-Unit-Outlet	Test Condition	Average DUT Power (W)	E1 (Wh), as calculated from reported DUT power	Reporting Error (%), based on E1	E2 (Wh), as reported by the DUT	Reporting Error (%), based on E2
C1-1-6	noload	5.14	0	N/A	0	N/A
C1-1-6	curr_0.15	4.97	95.775432	4.73	99	1.52
C1-1-6	curr_2.5	6.01	97.401974	2.55	98	1.96
C1-1-6	curr_10	16.61	294.881482	0.62	291	1.93
C1-1-6	volt_108	5.84	96.718448	3.15	98	1.87
C1-1-6	volt_132	5.84	95.722105	4.22	98	1.94
C1-1-6	freq_58.8	5.91	97.499334	2.47	99	0.97
C1-1-6	freq_61.2	5.90	97.413452	2.58	98	2.00
C1-1-6	pfact_0.5	5.77	104.039766	3.22	194	92.47
C1-1-6	pulse	5.68	89.946794	6.71	166	72.17
C1-1-15	noload	5.12	0	N/A	0	N/A
C1-1-15	curr_0.15	4.97	95.898317	4.61	98	2.52
C1-1-15	curr_2.5	6.01	98.032978	1.91	99	0.95
C1-1-15	curr_10	17.05	286.658095	3.35	294	0.87
C1-1-15	volt_108	5.92	97.156799	2.73	99	0.88

C1-1-15	volt_132	6.01	99.439852	0.44	100	0.12
C1-1-15	freq_58.8	6.06	98.030007	1.88	99	0.90
C1-1-15	freq_61.2	6.07	98.052647	1.87	99	0.93
C1-1-15	pfact_0.5	5.95	105.091804	4.32	197	95.55
C1-1-15	pulse	5.75	92.562458	4.24	169	74.83
C1-1-23	noload	5.13	0	N/A	0	N/A
C1-1-23	curr_0.15	4.98	97.844364	2.66	98	2.50
C1-1-23	curr_2.5	6.08	98.378657	1.54	100	0.08
C1-1-23	curr_10	18.06	287.37612	3.02	294	0.78
C1-1-23	volt_108	5.95	97.505362	2.37	99	0.87
C1-1-23	volt_132	5.95	99.762098	0.13	99	0.89
C1-1-23	freq_58.8	6.02	98.364114	1.56	99	0.92
C1-1-23	freq_61.2	6.02	98.378594	1.57	99	0.94
C1-1-23	pfact_0.5	5.87	102.517463	1.77	197	95.56
C1-1-23	pulse	5.85	93.223714	3.79	171	76.48

Table C4: C1-2 Results

Model-Unit-Outlet	Test Condition	Average DUT Power (W)	E1 (Wh), as calculated from reported DUT power	Reporting Error (%), based on E1	E2 (Wh), as reported by the DUT	Reporting Error (%), based on E2
C1-2-1	noload	5.17	0	N/A	0	N/A
C1-2-1	curr_0.15	4.99	95.928859	4.59	99	1.54
C1-2-1	curr_2.5	6.21	97.426612	2.48	98	1.90
C1-2-1	curr_10	17.75	285.093595	3.81	295	0.47
C1-2-1	volt_108	5.88	92.156717	7.77	98	1.92
C1-2-1	volt_132	5.87	96.030183	3.91	98	1.94
C1-2-1	freq_58.8	5.94	97.429925	2.54	98	1.97
C1-2-1	freq_61.2	5.94	92.31779	7.67	99	0.99
C1-2-1	pfact_0.5	5.80	104.935664	4.07	195	93.40
C1-2-1	pulse	5.78	92.774237	4.58	171	75.88
C1-2-16	noload	5.12	0	N/A	0	N/A
C1-2-16	curr_0.15	4.98	97.423289	3.10	98	2.53

C1-2-16	curr_2.5	6.17	98.425802	1.48	100	0.10
C1-2-16	curr_10	19.66	268.039636	9.40	294	0.63
C1-2-16	volt_108	6.03	93.274292	6.58	100	0.16
C1-2-16	volt_132	6.02	97.185149	2.69	99	0.87
C1-2-16	freq_58.8	6.08	98.367041	1.53	100	0.10
C1-2-16	freq_61.2	6.09	98.367699	1.55	99	0.92
C1-2-16	pfact_0.5	5.94	106.49554	5.68	197	95.49
C1-2-16	pulse	5.85	92.18235	4.71	167	72.62
C1-2-23	noload	5.13	0	N/A	0	N/A
C1-2-23	curr_0.15	4.99	97.378989	3.13	99	1.52
C1-2-23	curr_2.5	6.21	98.034813	1.85	99	0.88
C1-2-23	curr_10	20.04	297.166892	0.48	293	0.93
C1-2-23	volt_108	6.07	97.76006	2.07	99	0.83
C1-2-23	volt_132	6.08	96.562893	3.30	99	0.85
C1-2-23	freq_58.8	6.13	98.026775	1.86	99	0.88
C1-2-23	freq_61.2	6.13	98.051084	1.86	100	0.10
C1-2-23	pfact_0.5	5.98	106.124868	5.33	196	94.54
C1-2-23	pulse	5.90	89.575492	7.41	148	52.98

Table C5: C2-1 Results

Model-Unit-Outlet	Test Condition	Average DUT Power (W)	E1 (Wh), as calculated from reported DUT power	Reporting Error (%), based on E1	E2 (Wh), as reported by the DUT	Reporting Error (%), based on E2
C2-1-2	noload	5.65	0	N/A	0	N/A
C2-1-2	curr_0.15	5.35	97.528657	3.26	100	0.81
C2-1-2	curr_2.5	6.08	98.018721	2.08	100	0.10
C2-1-2	curr_10	12.62	286.854639	3.68	300	0.74
C2-1-2	volt_108	6.01	97.344339	2.68	100	0.02
C2-1-2	volt_132	6.01	99.292166	0.74	100	0.03
C2-1-2	freq_58.8	6.06	98.135996	1.94	100	0.08
C2-1-2	freq_61.2	6.05	98.012565	2.08	100	0.10
C2-1-2	pfact_0.5	5.91	96.413214	4.39	0	100.00

C2-1-2	pulse	5.86	95.321376	1.79	100	3.04
C2-1-11	noload	5.57	0	N/A	0	N/A
C2-1-11	curr_0.15	5.34	97.971285	2.92	100	0.91
C2-1-11	curr_2.5	6.12	95.628841	4.42	100	0.06
C2-1-11	curr_10	13.45	286.770693	3.62	300	0.83
C2-1-11	volt_108	6.05	97.369956	2.62	100	0.01
C2-1-11	volt_132	6.05	96.379639	3.61	100	0.01
C2-1-11	freq_58.8	6.10	100.60921	0.57	100	0.04
C2-1-11	freq_61.2	6.10	98.057437	2.00	100	0.06
C2-1-11	pfact_0.5	5.94	96.057566	4.72	0	100.00
C2-1-11	pulse	5.86	93.508241	3.47	100	3.23
C2-1-17	noload	5.55	0	N/A	0	N/A
C2-1-17	curr_0.15	5.34	97.98155	2.82	100	0.82
C2-1-17	curr_2.5	6.13	98.180245	1.90	100	0.08
C2-1-17	curr_10	14.17	296.89864	0.18	300	0.86
C2-1-17	volt_108	6.11	97.29461	2.69	100	0.01
C2-1-17	volt_132	6.11	96.335251	3.67	100	0.01
C2-1-17	freq_58.8	6.15	98.02723	2.03	100	0.06
C2-1-17	freq_61.2	6.15	98.034149	2.05	100	0.08
C2-1-17	pfact_0.5	6.01	96.370716	4.45	0	100.00
C2-1-17	pulse	5.93	94.878009	2.11	100	3.17

Table C6: C2-2 Results

Model-Unit-Outlet	Test Condition	Average DUT Power (W)	E1 (Wh), as calculated from reported DUT power	Reporting Error (%), based on E1	E2 (Wh), as reported by the DUT	Reporting Error (%), based on E2
C2-2-5	noload	5.90	1.632765	N/A	0	N/A
C2-2-5	curr_0.15	5.61	98.427529	2.40	100	0.84
C2-2-5	curr_2.5	6.30	98.127635	2.04	100	0.18
C2-2-5	curr_10	11.26	286.792502	3.86	300	0.57
C2-2-5	volt_108	6.18	97.327013	2.82	100	0.15
C2-2-5	volt_132	6.19	93.689694	6.42	100	0.12

C2-2-5	freq_58.8	6.23	98.089605	2.08	100	0.18
C2-2-5	freq_61.2	6.23	98.120418	2.08	100	0.20
C2-2-5	pfact_0.5	6.06	96.433424	4.38	0	100.00
C2-2-5	pulse	6.02	96.720671	0.46	100	2.92
C2-2-11	noload	5.83	0	N/A	0	N/A
C2-2-11	curr_0.15	5.59	98.514907	2.38	100	0.91
C2-2-11	curr_2.5	6.28	98.019535	2.14	100	0.17
C2-2-11	curr_10	11.97	287.16758	3.67	300	0.63
C2-2-11	volt_108	6.23	97.416691	2.69	100	0.11
C2-2-11	volt_132	6.23	99.273995	0.82	100	0.09
C2-2-11	freq_58.8	6.27	98.035599	2.11	100	0.15
C2-2-11	freq_61.2	6.28	98.058669	2.11	100	0.17
C2-2-11	pfact_0.5	6.10	96.059186	4.81	0	100.00
C2-2-11	pulse	6.09	96.978737	0.41	100	2.69
C2-2-17	noload	5.82	0	N/A	0	N/A
C2-2-17	curr_0.15	5.59	97.216889	3.68	100	0.93
C2-2-17	curr_2.5	6.29	95.697802	4.50	100	0.20
C2-2-17	curr_10	12.34	287.107952	3.69	300	0.63
C2-2-17	volt_108	6.29	97.451929	2.67	100	0.13
C2-2-17	volt_132	6.29	96.492495	3.61	100	0.10
C2-2-17	freq_58.8	6.33	98.059062	2.10	100	0.16
C2-2-17	freq_61.2	6.34	98.024328	2.15	100	0.18
C2-2-17	pfact_0.5	6.18	96.092076	4.71	0	100.00
C2-2-17	pulse	6.13	96.47819	0.71	100	2.92

Table C7: C3-1 Results

Model-Unit-Outlet	Test Condition	Average DUT Power (W)	E1 (Wh), as calculated from reported DUT power	Reporting Error (%), based on E1	E2 (Wh), as reported by the DUT	Reporting Error (%), based on E2
C3-1-8	noload	20.93	0	N/A	0	N/A
C3-1-8	curr_0.15	19.09	100.027168	0.80	99	1.82
C3-1-8	curr_2.5	20.49	99.706397	0.41	100	0.12

C3-1-8	curr_10	24.76	291.280004	2.36	295	1.11
C3-1-8	volt_108	20.34	99.151153	0.90	99	1.05
C3-1-8	volt_132	20.40	98.155892	1.89	100	0.04
C3-1-8	freq_58.8	20.64	99.698775	0.39	100	0.09
C3-1-8	freq_61.2	20.65	99.693873	0.42	99	1.11
C3-1-8	pfact_0.5	20.06	100.482275	0.37	100	0.85
C3-1-8	pulse	20.01	98.484559	0.97	101	3.55
C3-1-14	noload	20.19	0	N/A	0	N/A
C3-1-14	curr_0.15	19.32	99.871129	0.95	100	0.82
C3-1-14	curr_2.5	20.79	100.027319	0.06	100	0.09
C3-1-14	curr_10	25.83	292.023633	2.03	296	0.70
C3-1-14	volt_108	20.59	99.388983	0.63	100	0.02
C3-1-14	volt_132	20.51	98.456503	1.57	100	0.03
C3-1-14	freq_58.8	20.75	100.002605	0.07	100	0.07
C3-1-14	freq_61.2	20.76	100.038871	0.06	100	0.10
C3-1-14	pfact_0.5	20.16	100.631915	0.21	100	0.84
C3-1-14	pulse	20.12	99.869496	2.16	101	3.31
C3-1-18	noload	20.21	0	N/A	0	N/A
C3-1-18	curr_0.15	19.08	99.8706	0.98	100	0.85
C3-1-18	curr_2.5	20.45	99.690202	0.42	99	1.11
C3-1-18	curr_10	25.92	301.5331	1.17	292	2.02
C3-1-18	volt_108	20.31	99.160617	0.87	99	1.03
C3-1-18	volt_132	20.35	99.482401	0.56	100	0.04
C3-1-18	freq_58.8	20.59	103.636432	3.55	39	61.03
C3-1-18	freq_61.2	20.60	102.296526	2.19	160	59.83
C3-1-18	pfact_0.5	20.02	100.470458	0.38	100	0.84
C3-1-18	pulse	19.90	99.895277	2.72	32	67.10

Table C8: C3-2 Results

Model-Unit-Outlet	Test Condition	Average DUT Power (W)	E1 (Wh), as calculated from reported DUT power	Reporting Error (%), based on E1	E2 (Wh), as reported by the DUT	Reporting Error (%), based on E2
C3-2-3	noload	21.04	0	N/A	0	N/A
C3-2-3	curr_0.15	19.23	99.880107	0.94	99	1.82
C3-2-3	curr_2.5	20.65	99.939245	0.17	100	0.11
C3-2-3	curr_10	24.96	292.585811	1.92	296	0.78
C3-2-3	volt_108	20.46	94.51577	5.53	101	0.96
C3-2-3	volt_132	20.52	98.387898	1.65	99	1.04
C3-2-3	freq_58.8	20.74	99.768483	0.32	100	0.09
C3-2-3	freq_61.2	20.75	99.80179	0.31	100	0.11
C3-2-3	pfact_0.5	20.16	100.626266	0.20	100	0.82
C3-2-3	pulse	20.14	99.998913	2.40	100	2.40
C3-2-16	noload	20.29	0	N/A	0	N/A
C3-2-16	curr_0.15	19.35	99.887005	0.93	100	0.82
C3-2-16	curr_2.5	20.75	99.715805	0.39	100	0.11
C3-2-16	curr_10	25.21	291.473019	2.28	296	0.76
C3-2-16	volt_108	20.61	99.219407	0.82	99	1.04
C3-2-16	volt_132	20.50	101.105905	1.07	100	0.04
C3-2-16	freq_58.8	20.74	99.75146	0.33	100	0.09
C3-2-16	freq_61.2	20.75	99.770227	0.34	100	0.11
C3-2-16	pfact_0.5	20.16	100.421962	0.42	100	0.84
C3-2-16	pulse	20.13	98.563389	1.07	100	2.55
C3-2-19	noload	20.31	0	N/A	0	N/A
C3-2-19	curr_0.15	19.36	99.944655	0.86	100	0.81
C3-2-19	curr_2.5	20.80	100.143042	0.04	100	0.10
C3-2-19	curr_10	25.70	292.245468	1.98	297	0.39
C3-2-19	volt_108	20.64	99.539529	0.48	99	1.02
C3-2-19	volt_132	20.53	98.481705	1.55	101	0.97
C3-2-19	freq_58.8	20.78	100.080637	0.01	100	0.07
C3-2-19	freq_61.2	20.79	100.076438	0.02	99	1.10
C3-2-19	pfact_0.5	20.20	100.841543	0.01	100	0.82
C3-2-19	pulse	20.17	98.589337	1.17	100	2.62

Appendix D: List of Acronyms

A	Ampere
CLTB	Connected Lighting Test Bed
PNNL	Pacific Northwest National Laboratory
DUT	Device under test
RRE	Relative reporting error
LED	Light-emitting diode
CLS	Connected lighting systems
DOE	U.S. Department of Energy
ESCO	Energy service companies
W	Watts
ANSI	American National Standards Institute
ISO	International Organization for Standardization
BIPM	International Bureau of Weights and Measures
IoT	Internet of Things
VIM	International Vocabulary of Metrology
PDU	Power distribution unit
AC	Alternating current
GPIO	General purpose input output
Wh	Watt-hour
API	Application programming interface
ILAC	International Laboratory Accreditation Cooperation
MRA	Mutual recognition arrangement
RMS	Root mean square
V	Voltage
IEC	International Electrotechnical Commission
PF	Power factor

References

ANSI 2014: ANSI C12.1-2014, American National Standard for Electric Meters—Code for Electricity Metering

ANSI 2015: ANSI C12.20-2015, American National Standard for Electric Meters for Electricity Meters – 0.1, 0.2 and 0.5 Accuracy Classes

ANSIC136: ANSI C136 – Standards for Roadway and Area Lighting Equipment, https://www.nema.org/Technical/Pages/ANSI-C136-Series-Standards-for-Roadway-and-Area-Lighting-Equipment.aspx

ANSIC137: ANSI C137 – Standards for Lighting Systems, https://www.nema.org/Technical/Pages/ANSI-C137-Lighting-Systems-Committee.aspx

BIPM: BIPM VIM3, International Vocabulary of Metrology, VIM definitions with informative annotations, https://www.bipm.org/en/publications/guides/vim.html

ISO: ISO 5725-1, "Accuracy (trueness and precision) of measurement methods and results - Part 1: General principles and definitions.", p.1 (1994), https://www.iso.org/obp/ui/#iso:std:iso:5725:-1:ed-1:v1:en (last amended in 1998)

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