

Connected Lighting Systems Efficiency Study

PoE Cable Energy Losses, Part 2

September 2018

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PoE Cable Energy Losses, Part 2

Prepared in support of the DOE Solid-State Lighting Technology program

Study Participants:
Pacific Northwest National Laboratory
U.S. Department of Energy

Jason Tuenge
Karsten Kelly
Yan Chen
Anay Waghale
Michael Poplawski

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Pacific Northwest National Laboratory
Richland, Washington 99352

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Preface

The U.S. Department of Energy's Solid-State Lighting (SSL) program documents the performance of SSL products and systems based on standardized laboratory test results, additional specialized testing, mock-up studies, and real-world field evaluations. This information is provided publicly for several purposes: 1) to track SSL technology performance improvement over time; 2) to identify technology challenges that impact performance and application of SSL; 3) to spur continued advancements in SSL technology, product design, and application; and 4) to maximize energy efficiency and decrease U.S. energy use, while improving lighting quality. DOE does not endorse any commercial product or in any way provide assurance that other users will achieve similar results through use of these products. SSL technology continues to evolve quickly, so evaluation results should always be understood in the context of the timeframe in which products were acquired, tested, installed, and operated. Especially given the rapid development cycle for SSL products, specifiers and purchasers should always seek current information from manufacturers when evaluating such products.

The U.S. Department of Energy (DOE) is interested in feedback or comments on all aspects of this study. Please write to DOE.SSL.UPDATES@ee.doe.gov and include the study title in the subject line of your email.

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Nomenclature or List of Acronyms

A	ampere(s)
AC	alternating current
ANSI	American National Standards Institute
ASTM	American Society for Testing and Materials
AWG	American Wire Gauge
CLTB	Connected Lighting Test Bed
DC	direct current
DCR	DC resistance
Ø	diameter
DOE	U.S. Department of Energy
F/UTP	foil (surrounding) unscreened twisted pairs
ft	foot, or feet
I ² R	current squared times resistance
IEEE	Institute of Electrical and Electronics Engineers
in	inch(es)
LAN	local area network
LED	light-emitting diode
LPS	Limited Power Source
m	meter(s)
NEC	National Electrical Code
NFPA	National Fire Protection Association
Ω	ohm(s)
PD	powered device
PNNL	Pacific Northwest National Laboratory
PoE	Power over Ethernet
PSE	power sourcing equipment
SSL	solid-state lighting
TIA	Telecommunications Industry Association
UPOE	Universal Power Over Ethernet
UTP	unshielded twisted pair
U/UTP	unshielded (and unscreened) twisted pair
V	volt(s)
W	watt(s)

Executive Summary

Power over Ethernet (PoE) technology offers the ability to provide both low-voltage direct current (DC) power and communication over a standard Ethernet cable—also referred to as a local area network (LAN) cable or Category cable. Light-emitting diode (LED) technology has reduced the power required for lighting applications, while advances in PoE standards and technology have yielded substantial increases in the amount of power that can be delivered to a networked device over a single cable. As a result, PoE technology is emerging in lighting and many other applications beyond its historical foothold in telephony and networking equipment. Several major LED luminaire manufacturers have introduced PoE connected lighting systems in recent years, making this a potentially disruptive technology.

PoE lighting systems can offer improved efficiency relative to traditional line voltage alternating current (AC) systems, because AC-DC power conversion losses can be reduced if this work is consolidated among one or more PoE switches, rather than being distributed among a greater number of smaller LED drivers. However, this effect can be offset to some extent by increased losses associated with an increased voltage drop in the low-voltage Ethernet cabling. In fact, these losses could exceed 15% in poorly designed systems. Aspects of cable design that can affect cable energy performance include American Wire Gauge (AWG), Category (e.g., 5e), shielding, and fire rating (e.g., CMP). Installation practices (e.g., bending, bundling, conduit) can also affect cable performance. Although cable energy losses can be predicted with knowledge of conductor DC resistance (DCR), and DCR can be estimated based on rated AWG, most product datasheets state maximum DCR—or reference standards that specify DCR limits—in lieu of nominal DCR.

DOE published a report in November 2017 (herein referred to as “Part 1”) summarizing the results of an exploratory study investigating power losses in Ethernet cables used between PoE switches and luminaires in PoE connected lighting systems. Testing was conducted at the Pacific Northwest National Laboratory (PNNL) Connected Lighting Test Bed (CLTB) in September 2017. The results were analyzed to explore the impact of cable selection on PoE lighting system energy efficiency, as well as the effectiveness of guidelines published by the American National Standards Institute (ANSI) C137 Lighting Systems Committee in 2017. The guidance offered in ANSI C137.3-2017 was found to be effective in limiting cable power losses to 5% of PoE switch output in PoE lighting applications, provided that the average cable length on a project does not exceed 50 m.

This Part 2 report summarizes the results of a continued investigation of the power losses in Ethernet cables used between PoE switches and luminaires in PoE connected lighting systems. Testing was conducted at the PNNL CLTB in July–August 2018. A test setup comprising a PoE switch, a set of luminaires, and a reference meter was again used to test multiple cable models of varying design. The results were analyzed to explore the impact of cable selection and installation practices on PoE lighting system energy efficiency, as well as the effectiveness of the ANSI C137.3 guidelines. Notably, three cables—two of which were shielded in design—were previously excluded from the Part 1 study due to compatibility issues. All three cables were included in this Part 2 study. In addition, whereas no patch cords were used in Part 1, patch cords were used in some Part 2 testing. The key study findings are as follows:

- The ANSI C137.3 guidance was again shown to effectively limit power losses to less than 5% in the cables tested (varying in AWG, Category, shielding, and manufacturer). However, these findings should not be construed as being representative of all cable models and installation practices. For example, power losses would be greater when cables are connected to patch cords, bundled in conduit, and loaded with powered devices (PDs) approaching 90 W input power.
- Cable losses decreased with increasing conductor diameter (i.e., numerically smaller AWG), as would be expected based on the corresponding improvements to conductor DCR. No appreciable difference was observed for the other characteristics; however, considering the study limitations (e.g., the set of cables tested), this does not mean these parameters do not affect cable losses.

- With 44 W luminaires as PDs and room ambient temperatures below 30°C, cable power losses were not substantially increased by cable bending or bundling in uninsulated conduit. However, environments with higher ambient temperatures will have greater power losses due to increased conductor DCR. In addition, product selection and installation practices will have increased importance as PDs approaching 90 W input power—conveyed by a single Ethernet cable—are introduced following publication of the recently approved Institute of Electrical and Electronics Engineers (IEEE) Standard 802.3bt.

The following recommendations, stemming from the study findings, are offered to help streamline the adoption of PoE technology in lighting applications:

- ANSI C137.3 should be revised or amended to clarify whether shielded cabling is included in its scope.
- PoE lighting system specifiers should state that minimum AWG must be per ANSI C137.3 guidance, or specify minimum AWG directly if a limit below 5% is desired or average cable length exceeds 50 m.
- Manufacturers of cabling (e.g., cables, patch cords, connectors) should state nominal DCR on product datasheets to further enable the design of energy-efficient PoE systems.
- PoE lighting system specifiers/suppliers/installers should publish statistics on PoE cable lengths used for each project (e.g., minimum, maximum, mean, median), along with information on each model used (e.g., AWG, Category, shielding, fire rating).
- Lighting industry stakeholders should provide input to DOE on whether additional or new cable models or types are likely to perform differently from the ones already tested in Parts 1 and 2 of this study, and whether DOE testing results would be valuable.
- Lighting industry stakeholders should provide input to DOE on cabling configurations and installation practices that best reflect real-world PoE lighting applications, whether they are likely to perform differently from the scenarios already tested in Parts 1 and 2 of this study, and whether DOE testing results would be valuable.

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1 Introduction

Power over Ethernet (PoE) technology offers the ability to provide low-voltage direct current (DC) power and communication over a standard Ethernet cable—also referred to as a local area network (LAN) cable or Category cable. Light-emitting diode (LED) technology has reduced the power required for lighting applications, while advances in PoE standards and technology have yielded substantial increases in the amount of power that can be delivered to a networked device over a single cable. As a result, PoE technology is emerging in lighting and many other applications beyond its historical foothold in telephony and networking equipment. Several major LED luminaire manufacturers have introduced PoE connected lighting systems in recent years, making this a potentially disruptive technology (DOE 2017b).

PoE lighting systems can offer improved efficiency relative to traditional line voltage alternating current (AC) systems, because AC-DC power conversion losses can be reduced if this work is consolidated among one or more PoE switches, rather than being distributed among a greater number of smaller LED drivers. However, if the system is poorly designed, this effect can be offset to some extent by increased losses associated with increased voltage drop in the low-voltage Ethernet cabling (e.g., cables and connectors). Such losses are commonly referred to as I^2R losses, because the power dissipated by an imperfect conductor is the product of its resistance (R) and the square of the current (I) it conveys.

Clause 33 of Institute of Electrical and Electronics Engineers (IEEE) Standard 802.3-2015 specifies the use of twisted pair Ethernet cables for PoE applications, where each cable is composed of eight conductors (i.e., four pairs). The standard references Telecommunications Industry Association (TIA) standards for cabling requirements. IEEE 802.3 permits a Class 4 powered device (PD) to sink up to 25.5 W from a Type 2 power sourcing equipment (PSE), which is capable of sourcing up to 30 W over two of the four conductor pairs (2-pair PoE). In contrast, PSEs implementing Cisco's Universal Power Over Ethernet (UPOE) technology can source up to 60 W over all four conductor pairs (4-pair PoE), effectively doubling the capacity of a Type 2 PSE and supporting 51 W PDs. IEEE 802.3bt leverages 4-pair PoE at power levels approaching 90 W while continuing to comply with Limited Power Source (LPS) restrictions; the amendment was approved in September 2018 (Ethernet Alliance 2018a) and is expected to be published in late 2018 (Ethernet Alliance 2018b).

To simplify the design of PoE lighting systems and limit cable losses to less than 5% of PSE output power¹ over an assumed average cable length of 50 m, the American National Standards Institute (ANSI) recently published ANSI C137.3-2017, which specifies minimum AWG for unshielded twisted pair (UTP) Ethernet cables as a function of power dissipated by the PD (ANSI 2017).² The standard bases its guidance on an included table of nominal DCR values derived from data published in American Society for Testing and Materials (ASTM) B258-14 (which does not specify tolerances) for straight solid conductors at 20°C (ASTM 2014). Notably, standards published by IEEE and TIA limit DCR largely for performance; safety limits are given in the National Electric Code (NEC), published by the National Fire Protection Association (NFPA) as NFPA 70 (NFPA 2017).

DOE published a report in November 2017 (herein referred to as “Part 1”) summarizing the results of an exploratory study investigating power losses in Ethernet cables used between PoE switches and luminaires in PoE connected lighting systems (DOE 2017a). Testing was conducted at the Pacific Northwest National Laboratory (PNNL) Connected Lighting Test Bed (CLTB) in September 2017. The results were analyzed to

¹ According to the Forward to ANSI C137.3, “The commercially available gauge sizes specified by the standard have been chosen to result in average resistive line losses of less than 5% of total power delivered across typical installations assuming an average cable length of 50 m.” We interpret the 5% as applying to PSE output, rather than PD input, given that cable efficiency is calculated as cable output (PD input) divided by cable input (PSE output).

² Use of patch cords is permitted, but 26 AWG is limited to 5 m total length. Losses in cables from PD to any indirect PoE loads are excluded.

explore the impact of cable selection on PoE lighting system energy efficiency, as well as the effectiveness of the ANSI C137.3 guidelines.

This Part 2 report summarizes the results of a continued investigation of power losses in Ethernet cables used between PoE switches and luminaires in PoE connected lighting systems. Testing was conducted at the PNNL CLTB in July–August 2018. A test setup comprising a PoE switch, a set of luminaires, and a reference meter was again used to test multiple cable models of varying design. The results were analyzed to explore the impact of cable selection and installation practices (e.g., cable bending, cable bundling, and installation in conduit) on PoE lighting system energy efficiency, as well as the effectiveness of the ANSI C137.3 guidelines.

2 Scope

The goal of the investigation documented herein was to explore the impact of cable selection and installation variables on PoE lighting system energy efficiency, while also evaluating the effectiveness of the ANSI C137.3 guidance.

- Section 3 of this report addresses ANSI C137.3-related testing conducted as a continuation of Part 1. Testing included one new unshielded 24 AWG Category 5e cable, plus three cables that were previously acquired for Part 1 but excluded from testing in that study due to compatibility issues. In addition, whereas no patch cords were used in Part 1, one cable was tested with patch cords in Part 2.
- Section 4 addresses bundle testing, which is new in Part 2, to evaluate the effect of temperature rise on cable power losses when bundled cables are operated in conduit.
- Section 5 addresses bend testing, which is also new in Part 2, to evaluate the effect of multiple small-radius bends on cable power losses.

The Part 2 investigation sought to answer the following research questions:

1. Does the guidance in ANSI C137.3 ensure power losses in a 50 m Ethernet cable do not exceed 5% of PSE output?
2. To what extent do losses vary between models of cable differing in AWG, Category, shielding, and manufacturer?
3. To what extent do field installation variables (e.g., bending, bundling, conduit) affect power losses?
4. What knowledge gaps remain to be filled by future PoE cable energy losses research?

As in Part 1, all testing conducted in this study was exploratory in nature. Findings were limited by the small number of evaluated cable models, small sample size for each model, non-random sample collection, measurement resolution, uncontrolled ambient temperature, and other factors. Test results are intended to inform future testing, which will incorporate improved test setup implementation and higher power products that nominally comply with IEEE 802.3bt and stress PoE cabling to its full capacity. It is also hoped that study findings will fuel conversation with specifiers and standards development organizations.

3 ANSI C137.3 Cable Selection Guidance

The following sections detail testing conducted in accordance with Part 1 of the study. The intent was again to evaluate the utility of the ANSI C137.3 guidance, this time by resuming and completing tests of three cable models that had previously been excluded due to compatibility issues, while adding a new model to the set that was acquired and tested for this purpose.

3.1 Test Setup

The functional test setup for measuring power losses in Ethernet cables was the same for Part 2 as in Part 1. See the Part 1 report for details.

3.2 Test Setup Implementation

The test setup was implemented using the same equipment as in Part 1, except that only luminaire A was used, and the damaged switch was replaced with another unit of the same model. See the Part 1 report for equipment specifications and other details.

3.3 Test Method and Calculations

The test method and calculations for Part 2 were the same as for Part 1, except as noted below.

PoE switch output power was recorded automatically at 5 minute intervals using the recurring command plugin available with a full Tera Term installation. In Part 1, timestamped power measurements were recorded manually at these intervals via keyboard commands.

In Part 2, Ethernet cables were tested in one or more of the following configurations, as illustrated in Figure 1.

- Cables were field-terminated with RJ45 plugs, as in Part 1. Cable lengths were 1.5 m and 49 m.
- The cable termination method used in Part 1 was approximated by using a short 24 AWG patch cord (which had a factory-terminated RJ45 plug at one end and a 110-style connector at the other end that accepts an unterminated cable) in lieu of field-terminated RJ45 plugs at each end of cable. Cable lengths were 1.5 m and 49 m. Each patch cord had a nominal length of 18 inches (approximately 0.5 m), and an estimated³ DCR of $0.08\ \Omega$ at 20°C (the product datasheet does not state rated DCR).⁴ The difference in power dissipated by two of these patch cords when used with 1.5 m versus 49 m lengths of cable is assumed negligible for the purposes of this study.
- The cable was field-terminated with RJ45 jacks that were then connected to 26 AWG patch cords with factory-terminated RJ45 plugs. Cable length was 45 m; each patch cord had a nominal length of 7 feet (approximately 2.1 m), and an estimated⁵ DCR of $0.33\ \Omega$ at 20°C (the product datasheet does not state rated DCR). Rather than determining PD input power by extrapolating from 1.5 m to 0 m (as in Part 1), the average extrapolated value from the configuration A tests was used.

³ Assuming 18 inch (0.5 m) length 24 AWG with $0.04\ \Omega$ DCR (at $0.0842\ \Omega/\text{m}$) and connecting hardware adding $0.04\ \Omega$ DCR.

⁴ By comparison, $\pm(0.5\ \Omega + 1\%)$ accuracy has been proposed for next-generation DC loop resistance measurement field testers (TIA 2015c).

⁵ Assuming 7 ft (2.1 m) length 26 AWG with $0.29\ \Omega$ DCR (at $0.1339\ \Omega/\text{m}$) and connecting hardware adding $0.04\ \Omega$ DCR.

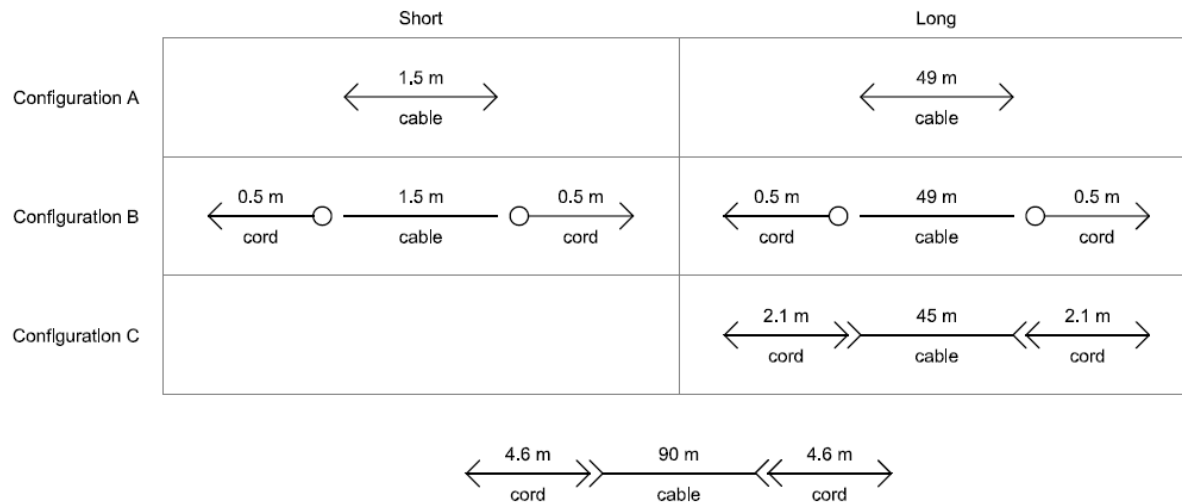


Figure 1. Cabling configurations A (plug-terminated cable), B (unterminated cable with short patch cords in lieu of plugs), and C (jack-terminated cable with plug-terminated patch cords).

3.3.1 Incorporating Patch Cord

IEEE 802.3 specifies the use of Category 5 or better (i.e., higher) cables in PoE applications, limits the overall resistance of the link section (loosely referred to as the “channel”) between PSE and PD, and limits link section length to 100 m. The standard references TIA-568-C.2 (TIA 2009) performance requirements for Category 5e or higher cabling, and references its precursor, TIA/EIA-568-A, for Category 5.⁶ TIA 568-C.2 specifies a maximum conductor DCR of 0.0938 Ω /m for solid-conductor “horizontal” cables at 20°C, versus 0.14 Ω /m for patch cords with solid or stranded conductors (Excel Networking 2013). In contrast, although TIA TSB-184-A (TIA 2017) assumes Category 5e horizontal cables are 24 AWG with DCR of 0.0938 Ω /m at 20°C, it also assumes that Category 6 horizontal cables are 23 AWG with DCR of 0.0732 Ω /m.

IEEE 802.3 limits channel pair loop DCR (equivalent to the summed DCR of multiple conductors and connectors in series from PSE to PD) to 12.5 Ω at 20°C for a Type 4 PSE; this ensures it can support a Class 4 PD with the worst-case output conditions of 50 V and 0.6 A, with headroom for operation up to 65°C. For example, this would support 90 m of 24 AWG solid-conductor cable with 10 m of 26 AWG patch cord and four plug-jack “connecting hardware” connections. Connecting hardware DCR at 20°C is limited to 0.3 Ω for Category 3 and to 0.2 Ω for Category 5e or higher,⁷ and actual connecting hardware DCR is understood to be around 0.043 Ω on average (Darshan 2014). Notably, product datasheets for plugs and jacks often only state contact DCR, which is only a component of (and is thus less than) connecting hardware DCR. In addition, a channel that includes four jacks and four plugs is generally termed a four-connector channel, even though it contains eight modular connectors (Kish 2006).

IEEE 802.3 specifies a minimum PSE output voltage of 50 V for Type 2 PSEs (capable of sourcing 30 W over two pairs), and this value is expected to be applied to Type 3 PSEs in IEEE 802.3bt (capable of sourcing 60 W over four pairs). In contrast, typical PSE voltage is expected to be at an intermediate value between this 50 V floor and the 57 V ceiling. The datasheet for the PoE switch used in the study does not state nominal output voltage for its eight PSEs; a value of 54 V is assumed for this investigation, as in Part 1 of the study.

⁶ TIA is in the process of changing the naming convention for its 568-series documents from [number]-[revision].[part] to [number].[part]-[revision] to align with its other publications; for example, whereas TIA-568-B.2 was replaced by TIA-568-C.2, TIA-568-C.2 will be replaced by TIA-568.2-D.

⁷ TSB-184-A states that for the purpose of DC power transmission, Category 5 cabling is considered equivalent to Category 5e.

ANSI C137.3 recommends limiting PD input power to 55 W for 4-pair PoE over 24 AWG cabling (including solid-conductor cable and patch cords with connectors). Figure 2 shows the expected range of cable power losses for a 55 W luminaire, as a percentage of PSE output power, illustrating sensitivity to DCR and PSE output voltage.⁸ Note that whereas only solid-conductor DCR was addressed in Part 1 (with only one uninterrupted cable between PSE and luminaire),⁹ channel DCR (with additional cabling between PSE and luminaire) is addressed for some tests in Part 2. Specifically, patch cords and jack-terminated cables were used for some Part 2 testing, as detailed in the following sections.

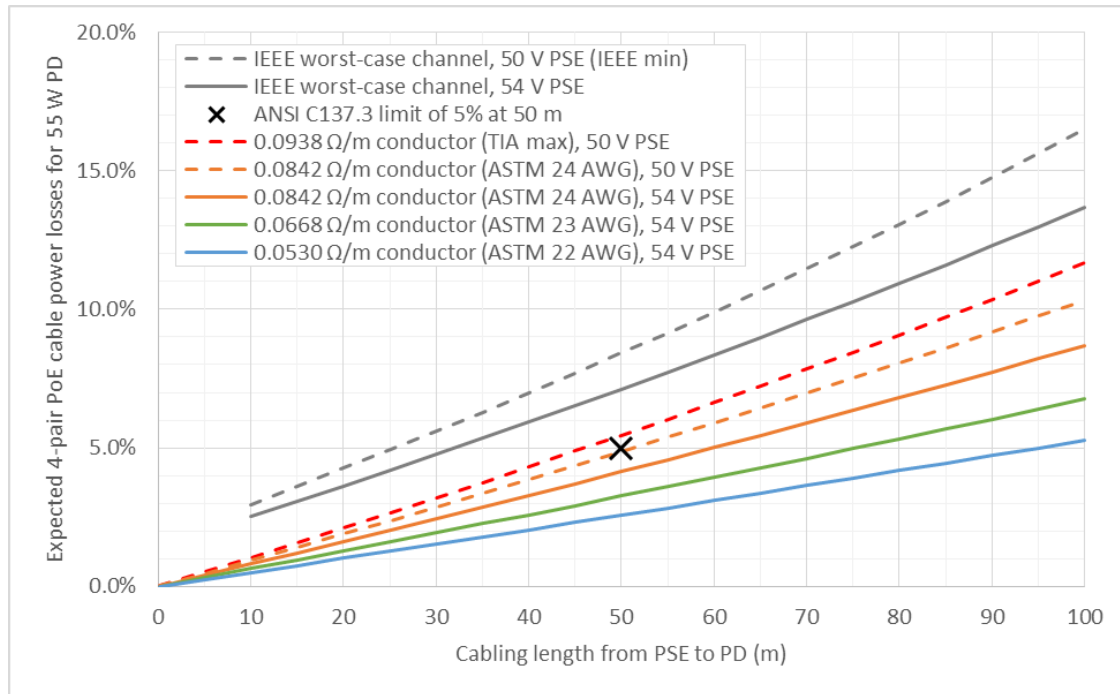


Figure 2. Range of expected 4-pair PoE cable power losses for 55 W PD. The IEEE worst-case channel includes 10 m of patch cord and four connectors (2.6 Ω at 20 °C in conditioned space), plus up to 90 m of solid-conductor cable (0.11 Ω/m at 65 °C in plenum). Conductor temperature is 20 °C for the other five curves.

3.4 Test Units

ANSI C137.3 addresses unshielded twisted pair (UTP or U/UTP) telecommunications cables as defined in TIA-568-C.2.¹⁰ This effectively excludes shielded cables,¹¹ which can take one of the following three forms:

- Four individually unscreened conductor pairs are contained by an overall shield (e.g., F/UTP)
- Four individually screened conductor pairs are contained by an overall shield (e.g., F/FTP)
- Four individually screened conductor pairs have no overall shield (e.g., U/FTP).

However, the cables selected for testing in this investigation varied by shielding in addition to AWG, Category, and manufacturer. Cable models used in Part 2 are described in Table 1. The Test ID naming

⁸ Based on standard or worst-case values (rather than measurements by PNNL), as indicated. Worst-case values reflect cable operation at temperatures up to 65 °C (Di Minico 2004).

⁹ This is termed “direct attach,” where channel has plug connectors at each end with no connecting hardware between.

¹⁰ The terms UTP and U/UTP are used interchangeably. Designations that include a forward slash (e.g., F/UTP) are defined in ISO/IEC 11801.

¹¹ Some cables marketed as UTP contain discontinuous “isolation” wrap that resembles the foil used in F/UTP cables. However, such wrap does not meet electrical continuity requirements for shielded cabling.

convention is shielding-AWG-Category-model. For example, the unshielded 24Cat5e-4 is the fourth 24 AWG Category 5e cable, acquired for testing in June 2018. An “s” prefix added in Part 2 indicates the cable is shielded.

Table 1. Cables and Test Configurations used in Part 2 to Evaluate ANSI C137.3 Guidance.

Test ID	Configuration(s)	AWG	Category	Shielding	Rated Conductor DCR
s24Cat5e-3	A	24	5e	F/UTP	$\leq 9.38 \Omega / 100 \text{ m}$
24Cat5e-4	A	24	5e	U/UTP	$\leq 8.9 \Omega / 100 \text{ m}$
s23Cat6-3	A	23	6	F/UTP	$\leq 9.38 \Omega / 100 \text{ m}$
23Cat6A-3	B and C	23	6A	U/UTP	$\leq 7.61 \Omega / 100 \text{ m}$

Unshielded cable 24Cat5e-4 was acquired primarily for the bundle testing described later in this report, but in a quantity sufficient to enable testing for comparison with Part 1. The other three cables were previously acquired for the Part 1 study, but were excluded from that testing due to compatibility issues described in the Part 1 report. Testing was conducted as follows.

- Shielded cables s24Cat5e-3 and s23Cat6-3 were included in Part 2 after verifying they were compatible with the luminaire used in this study.¹² Testing for these cables and unshielded cable 24Cat5e-4 was in configuration A, the same as in Part 1.
- According to correspondence with the manufacturer of unshielded cable 23Cat6A-3, the product is not intended for use with field-terminated plugs. Consequently, this cable was tested in configurations B (approximating configuration A using short patch cords in lieu of field-installed plugs) and C (only measurement is for 45 m length cable with two 2.1 m length patch cords).

Connectors were selected based on overall cable diameter and overall diameter of the insulated conductor, as stated in product literature or from correspondence with the manufacturers. As in Part 1, shielded cables were terminated with shielded connectors, and unshielded cables received unshielded connectors.

3.5 Test Results

Measurements from testing are presented in Table 2. The switch-reported measurements indicate an average luminaire input power of roughly 44 W for each of the four luminaires in the set. According to the product datasheet, this would indicate the PoE switch’s internal power supply was loaded to as little as 32% of its capacity (assuming no other losses internal to the PoE switch) and was operating at 88% to 91% efficiency (corresponding to 20% and 50% power supply loading, respectively). Lacking an overall efficiency rating for the PoE switch (which would account for other internal losses in addition to power supply losses), intermediate values near 89.3% were used to calculate estimated output power from measured input power.¹³ As would be expected, this yielded estimates that were somewhat higher than the total output power reported by the PoE switch. This may indicate that the actual efficiency of the PoE switch was somewhat lower than 89.3%, but much of the discrepancy could also be explained by overlapping measurement uncertainties for the two instruments (reference meter and PoE switch).

¹² As detailed in the Part 1 report, the Part 1 study revealed that luminaire B was not compatible with shielded cabling. To complete testing while ensuring that luminaire A and our spare PoE switch were not damaged, shielded cabling was simply excluded from Part 1. Only luminaire A was used in Part 2.

¹³ Efficiency values estimated by linear interpolation vary slightly because power supply loading varies slightly with cable model and length.

Table 2. Cable Power Losses.

Test ID	Length (m)		T _a (°C)	Reference Meter-Based				PoE Switch-Based		
	Cable	Cord		P _a (W)	P _{as} (W)	P _{ase} (W)	P _c	P _a (W)	P _{ae} (W)	P _c
s24Cat5e-3 (config. A)	1.5	-	27.3	210.7	188.1	187.9	3.3%	177.0	176.8	3.5%
	49	-	27.8	217.0	193.9	194.1		182.9	183.0	
24Cat5e-4 (config. A)	1.5	-	26.4	210.7	188.0	187.8	3.4%	176.9	176.7	3.7%
	49	-	26.6	217.1	194.0	194.1		183.0	183.1	
s23Cat6-3 (config. A)	1.5	-	26.8	210.7	188.0	187.9	2.8%	177.0	176.9	3.0%
	49	-	27.0	216.1	193.0	193.1		182.0	182.1	
23Cat6A-3 (config. B)	1.5	0.5	24.4	210.6	188.0	187.8	2.6%	176.9	176.7	3.0%
	49	0.5	25.1	215.6	192.6	192.7		181.9	182.0	
23Cat6A-3 (config. C)	0*	-	-	-	-	187.9	2.8%	-	176.8	3.2%
	45	4.3	25.7	216.1	193.1	193.2		182.4	182.5	

Where:

T_a is the average ambient temperature for 20 minute period

P_a is the average PSE output power for 20 minute period

P_{as} is P_a scaled by efficiency of power supply in PoE switch

P_{ase} is P_{as} extrapolated to 0 m or 50 m

P_{ae} is P_a extrapolated to 0 m or 50 m

P_c is the calculated cable power losses, assuming constant-power PD

* indicates P_{ase} and P_{ae} were simply calculated as the average of 1.5 m values in preceding rows

3.6 Analysis

The test results were analyzed primarily to explore the impact of cable selection on PoE system energy efficiency and to evaluate the effectiveness of the ANSI C137.3 guidance.

3.6.1 Impact of Cable Selection

The effect of cable selection on percent cable power losses for 50 m cables is illustrated in Figure 3, with results from Part 1 of the study also shown for reference. Shielded cables, which were not tested in Part 1, are distinguished from unshielded cables using different symbols. Configuration C was excluded from the plot because it included only one measurement, with a combination of a 45 m cable and two 2.1 m patch cords differing in AWG.

As in Part 1, cable power losses varied with AWG as expected—numerically larger AWG corresponds to smaller diameter and greater DCR per unit length, resulting in greater I²R losses. Losses in Part 2 fell within the range observed in Part 1 for each AWG. Although other cable selection factors (e.g., manufacturer, Category, shielding) may affect cable power losses, these effects were not large enough to be reliably detected in this study.

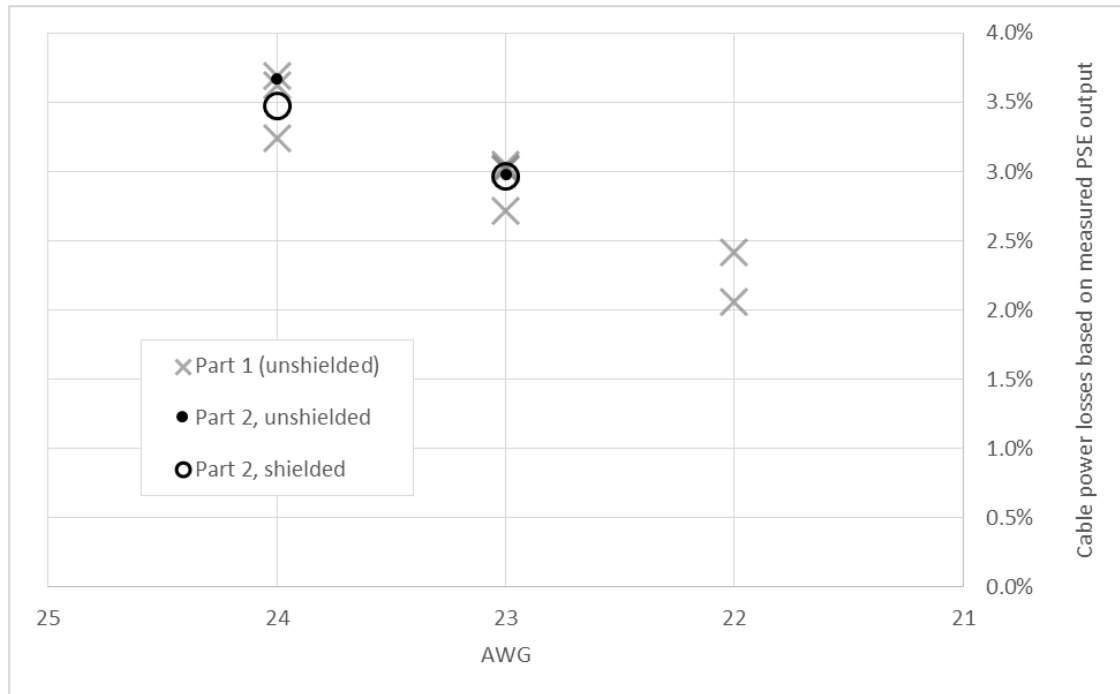


Figure 3. Impact of 50 m cable selection on cable power losses with the 44 W luminaire as PD, using configuration B (patch cord in lieu of field-terminated plug) for 23Cat6A-3 and configuration A (same as Part 1) for the other three cables.

3.6.2 Effectiveness of ANSI C137.3 Guidance

Similar to Figure 2, Figure 4 shows the expected range of cable power losses for a 44 W luminaire at 20°C, illustrating sensitivity to PSE output voltage and DCR. Percent cable power losses were found to be consistently below the 5% threshold in ANSI C137.3 for all four cable models, as in Part 1. Figure 5 shows that, based on PoE switch-reported PSE output power measurements, cable power losses with the 44 W luminaire as PD ranged from 3.0% to 3.7%. By way of comparison, expected cable power losses with this lighting load range from 2.7% to 4.0%. However, it should be noted that although predicted losses agreed closely with measurements, the luminaire was not strictly proven to hold input power constant as cable length varied.

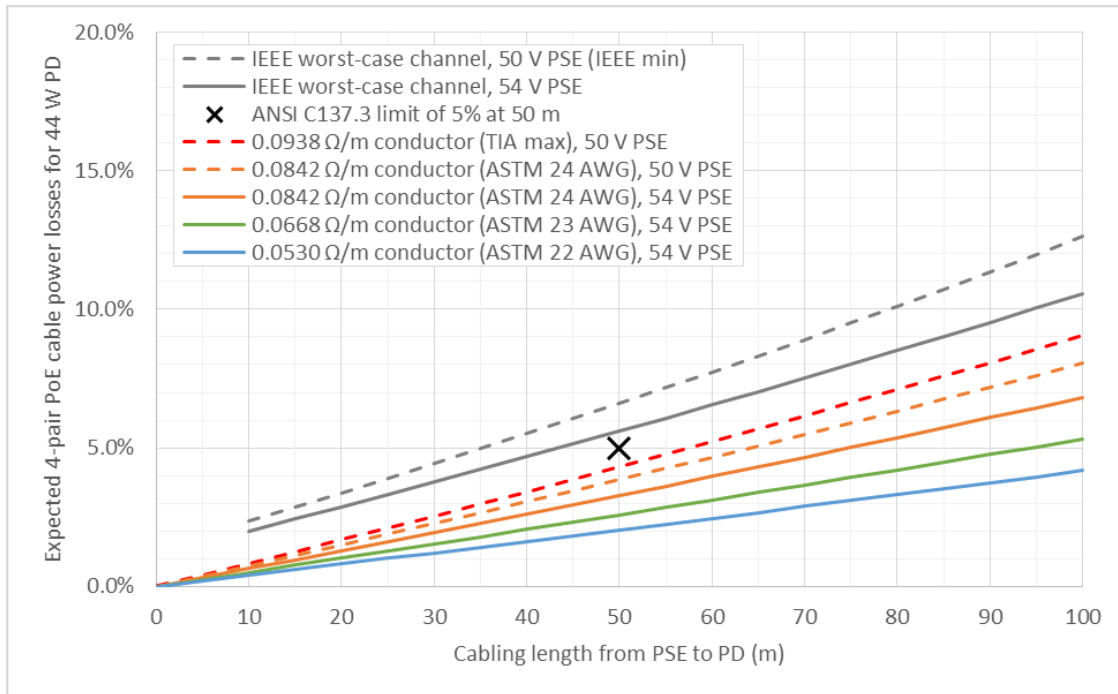


Figure 4. Range of expected 4-pair PoE cable power losses for 44 W PD. The IEEE worst-case channel includes 10 m of patch cord and four connectors (2.6 Ω at 20°C in conditioned space), plus up to 90 m of solid-conductor cable (0.11 Ω /m at 65°C in plenum). Conductor temperature is 20°C for the other five curves.

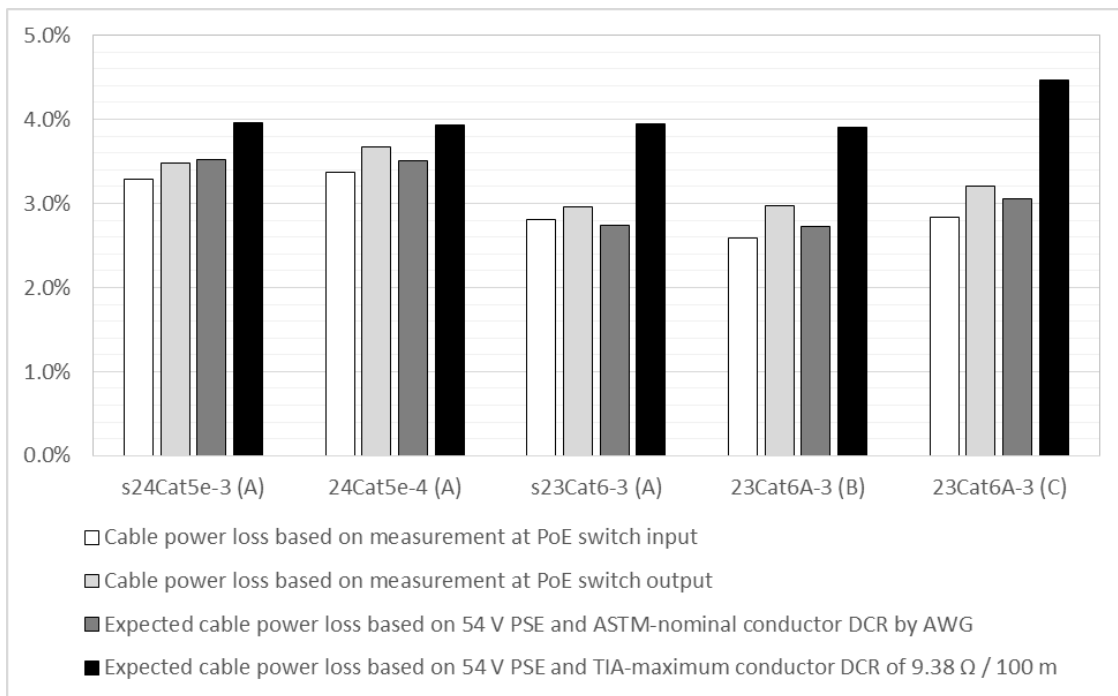


Figure 5. 50 m cable power losses with 44 W PD, based on standard or measured values as shown. X-axis labels indicate test configuration (A, B, or C) in parentheses. Configuration C includes 45 m length cables with two 2.1 m patch cords.

3.6.3 PoE Lighting System Power

The power dissipated by conventional line voltage lighting systems is traditionally evaluated primarily on the basis of luminaire input power. In low-voltage (e.g., PoE) lighting systems, losses in other elements merit additional consideration. Although PoE luminaires are expected to have higher luminous efficacy than line-voltage luminaires that are otherwise equivalent (because AC-DC power conversion does not take place in PoE luminaires), PoE switches and low-voltage Ethernet cabling are not perfectly efficient. Figure 6 shows that in this study, which followed the guidance in ANSI C137.3 to limit cable losses to 5% of PSE output power, measurements that included the PoE switch and 49 m cables were 19% higher than would have been expected considering luminaire input power alone. Notably, whereas Part 1 included 22 to 24 AWG cables, Part 2 only included 23 and 24 AWG cables. In addition, the PoE switch was loaded to less than 50% of its capacity, thereby reducing its efficiency. Values in the figure were calculated as the quotient of measured PoE switch input power (with 49 m cables) and combined luminaire input power (four 44 W units).

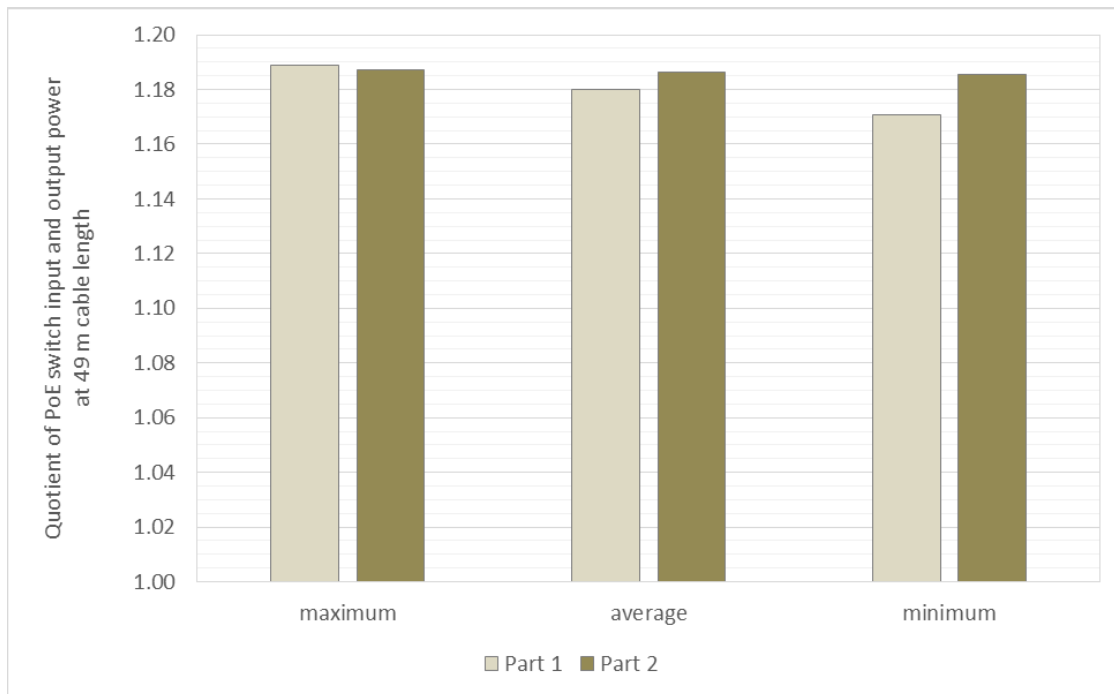


Figure 6. System power (including PoE switch and 49 m cables) relative to combined luminaire input power (4 x 44 W).

4 Cable Bundles in Conduit

As with other testing in this study, the goal of bundle testing reported herein was to better understand energy efficiency, rather than to address safety. The potential for increased cable heating in PoE applications has been widely recognized, particularly for large loads sinking power from conductors with a relatively small diameter. Heating due to I^2R losses is compounded when cables are installed in large bundles and/or in conduit, particularly in the core of a bundle, due to increased insulation and mutual heating. Multiple organizations have published test results or guidance aimed at characterizing temperature rise in such applications:

- UL conducted a study in 2015 on temperature rise at the center of large bundles of PoE cables, both in open air and inside conduit (UL 2015). Cables tested varied by AWG and cable design (e.g., cable diameter, Category, and shielding). A variety of additional variables included current, bundle size, and bundle enclosure (e.g., cable tray or conduit). Among other key findings was the determination that cable design has as much effect on the temperature rise as AWG, and that sealing the ends of conduit with

firestop material had little or no effect on the measured temperatures. The test results were used to develop Table 725.144 in the 2017 NEC, which limits current based on AWG and bundle size. The study also informed the creation of the new LP cable certification program.

- TIA used member test results to develop PoE application guidance and a test method published in TSB-184-A, which suggests limiting bundle size to 24 and temperature rise to 15°C, recommends Category 6A for new installations, and states that Category 5e (and Category 6) is acceptable for existing installations. Cables with metallic elements (e.g., screen or shield) are recommended to mitigate temperature rise. The standard includes modeled temperature rise data for many different combinations of bundle size, Category, current, and bundle enclosure (open air or in-conduit); a specific AWG is explicitly assumed for each Category (e.g., 23 AWG for Category 6), but cable diameter and metallic elements are not directly addressed.

Shielded cables are commonly reported to dissipate heat more effectively than unshielded cables, both individually and in bundles; the same is true for cables of higher Category. However, shielded and higher-Category cables typically have a larger diameter than unshielded and lower-Category cables of the same AWG, and it is often unclear to what extent cable diameter might account for any observed differences in heat dissipation.

4.1 Test Setup

The functional test setup for bundle testing in this investigation was the same as in section 3.1 of this report.

4.2 Test Setup Implementation

The test setup was implemented using the same equipment as in section 3.2 of this report.

4.3 Test Method and Calculations

For each model cable, four 90 m lengths were cut and field-terminated with RJ45 jacks. One nominal 15-foot (approximately 4.6 m) length 24 AWG patch cord with factory-terminated RJ45 plugs was used at each end of cable, resulting in a channel that approaches the 100 m limit specified by IEEE for link section length. Shielded patch cords and jacks were used for shielded cables; unshielded patch cords and jacks were used for unshielded cables. Each model cable was tested in two configurations, as shown in Table 3.

Table 3. Cable Bundling Test Configurations.

Configuration	Bundle size	Conduit fill ratio
Loose in cable tray	n/a	n/a
Bundled in conduit	128	≥ 40%

Cables were first tested loose in an open air cable tray (i.e., not bundled), as shown in Figure 7, to provide baseline measurements for comparison with measurements for cables bundled in conduit. Cables were then bundled and tested in uninsulated Schedule 40 PVC conduit that had been cut to 2.2 m length, as shown in Figure 8. This length was chosen to be similar to conduit lengths used or recommended in other studies (UL 2015), while enabling a sufficient bundle size with four 90 m cable lengths. A bundle size of 128 cables in cross-section was used, corresponding to the most restrictive ampacity bin (bundle size of 92–192 cables) in Table 725.144 of the 2017 NEC.



Figure 7. Cable loose in cable tray (not bundled), prior to connecting the field-terminated jacks to the patch cords with factory-terminated plugs.



Figure 8. Cable bundled in Schedule 40 PVC conduit, prior to connecting the field-terminated jacks to the patch cords with factory-terminated plugs.

Conduit was sized for each cable to slightly exceed the 40% fill ratio limit specified by the 2017 NEC (for common conditions per Table 1 in Chapter 9) and TIA-569-D (TIA 2015b). Conduit fill ratio was calculated as shown in Equation 1. Note that conduit internal diameter rather than trade size is used for the calculation;¹⁴ values were taken from the product datasheets, and closely agreed with corresponding values for Schedule 40 PVC from Table 4 in Chapter 9 of the NEC, but differed from values published by BICSI (BICSI 2018).

¹⁴ Conduit internal diameter can differ substantially from trade size. For example, a trade size of 1.25 inch corresponds to 1.36 inch internal diameter.

Equation 1. Conduit Fill Ratio.

$$\text{Conduit fill ratio} = 100 n_{\text{cables}} \left(\frac{\phi_{\text{cable}}^2}{\phi_{\text{conduit}}^2} \right)$$

Where:

n_{cables} = bundle size, or number of cables in bundle cross-section

ϕ_{cable} = cable outside diameter (mm)

ϕ_{conduit} = conduit inside diameter (mm)

An external thermistor probe was connected to the temperature logger with a 3 foot cable. Bundle core temperature was measured by inserting the probe along the central axis of bundle, roughly 0.5 m into the conduit, before sealing the end with fire putty.

Serial testing of each of the three cable models and two test configurations was performed over the course of six days, with each test starting in the afternoon and finishing in the morning of the next day. Luminaires were operated in full output mode and allowed to run overnight for 16 hours. PoE switch input power and output power measurements were automatically logged at 5 minute intervals. Ambient temperature and bundle core temperature were automatically logged at 1 minute intervals.

4.4 Test Units

Cables selected for bundle testing are described in Table 4. All cables were 24 AWG to maximize current draw and corresponding cable heating due to I^2R losses. The unshielded Category 5e cable (24Cat5e-4) served as a baseline, and had the smallest diameter. The shielded Category 5e (s24Cat5e-3) and unshielded Category 6 (24Cat6-1) cables were selected for their larger diameters and different designs.

Table 4. Cables Selected for Bundle Testing.

Test ID	AWG	Cable Ø (mm)	Category	Shielding	Rated Conductor DCR
24Cat5e-4	24	4.57	5e	U/UTP	$\leq 8.9 \Omega / 100 \text{ m}$
s24Cat5e-3	24	5.97	5e	F/UTP	$\leq 9.38 \Omega / 100 \text{ m}$
24Cat6-1	24	5.56	6	U/UTP	$\leq 9.38 \Omega / 100 \text{ m}$

Schedule 40 PVC conduit was sized to yield fill ratios minimally exceeding the NEC limit of 40%, as shown in Table 5.

Table 5. Baseline (cables loose in cable tray) versus In-Conduit (cables bundled) Test Configurations.

Test ID	Cable Ø (mm)	Bundle Size	Conduit Trade Size (inches)	Conduit Inside Ø (mm)	Fill Ratio (%)
24Cat5e-4	4.57	128	3	77.0	45
s24Cat5e-3	5.97	128	4	101	44
24Cat6-1	5.56	128	3.5	89.2	50

4.5 Test Results

Substantial force was required to pull the 128-cable bundles through each conduit at a greater than 40% fill ratio; this was especially true at a 50% fill ratio. TIA-568.0-D (TIA 2015a) specifies a limit of 110 Newtons (N), or 25 pounds-force (lbf), for maximum cable pulling tension (IEEE 2016). This limit is understood to apply to individual cables, rather than to the bundle as a whole (Landphair 2013). Cable pulling tension was not measured during testing, but was assuredly well below the corresponding limit of 3200 lbf for a bundle with 128 cables in cross-section. Cable jackets (i.e., outer shells) for s24Cat5e-3 and 24Cat6-1 were punctured

in spots at the leading end of the bundle (where widest) during the conduit testing, due to contact with the conduit edge during cable pulling, such that twisted pairs were visible through the small resulting holes. However, conductor insulation was not visibly damaged.

PoE switch-reported PSE output power was summed across the four PSEs, and the 20 minute trailing average was used to reduce jitter for the plots in Figure 9. Similarly, the 20 minute trailing average measured PoE switch input power is plotted in Figure 10. Plots of ambient temperature and bundle core temperature are provided in Figure 11 and Figure 12, respectively; the temperature data did not exhibit appreciable jitter and thus did not require any smoothing.

PoE switch input voltage ranged from 121.4 to 124.3 V_{rms} across the six tests. Ambient temperature in the CLTB is not controlled, and ambient temperature was observed to range from 20.4°C to 27.3°C. Bundle core temperature varied from 24.3°C to 30.0°C.

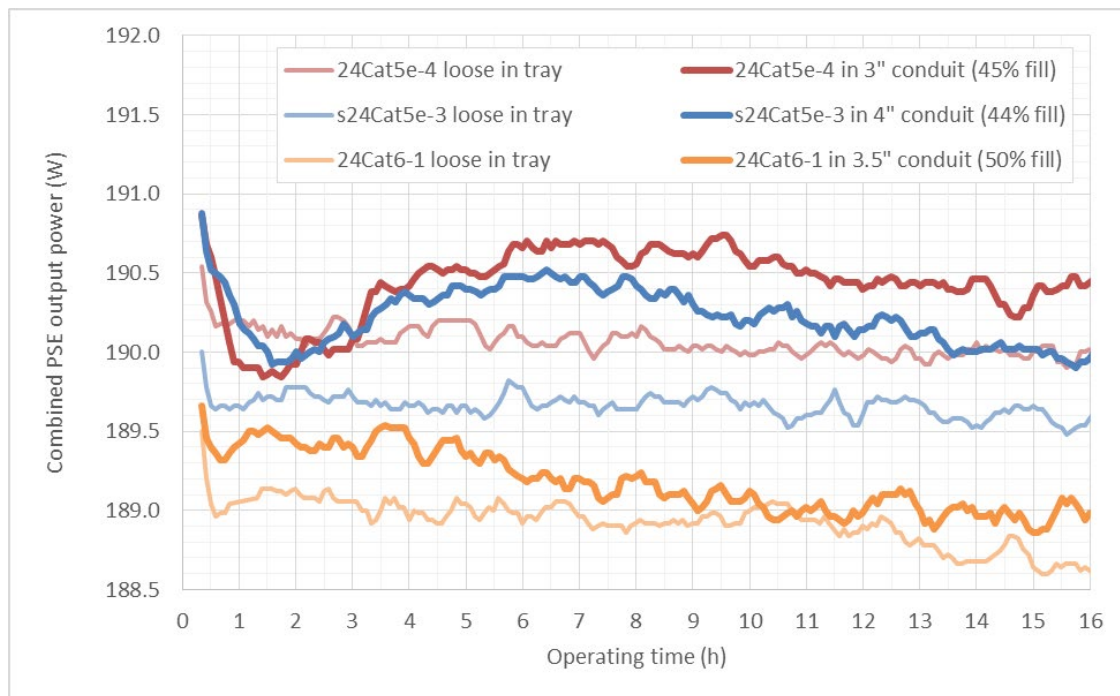


Figure 9. Overnight PoE switch-reported power measurements for cables loose in tray and bundled in conduit. Power was recorded at 5 minute intervals and plotted as a 20 minute moving average.

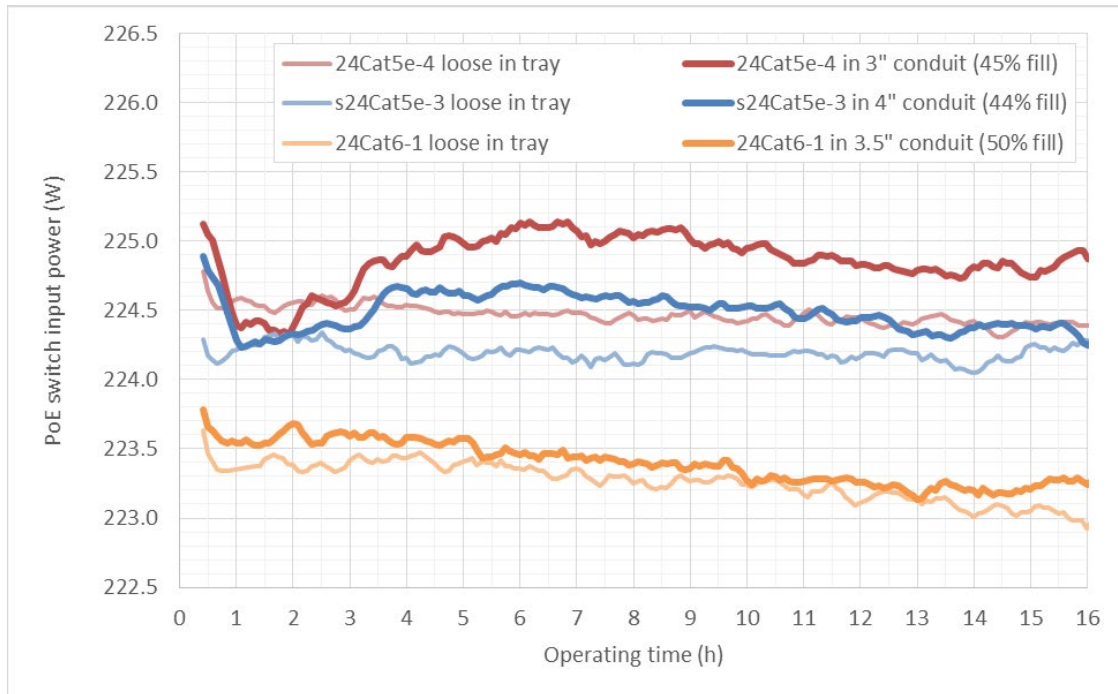


Figure 10. Overnight PoE switch input power measurements for cables loose in tray and bundled in conduit. Power was recorded at 5 minute intervals and plotted as a 20 minute moving average.

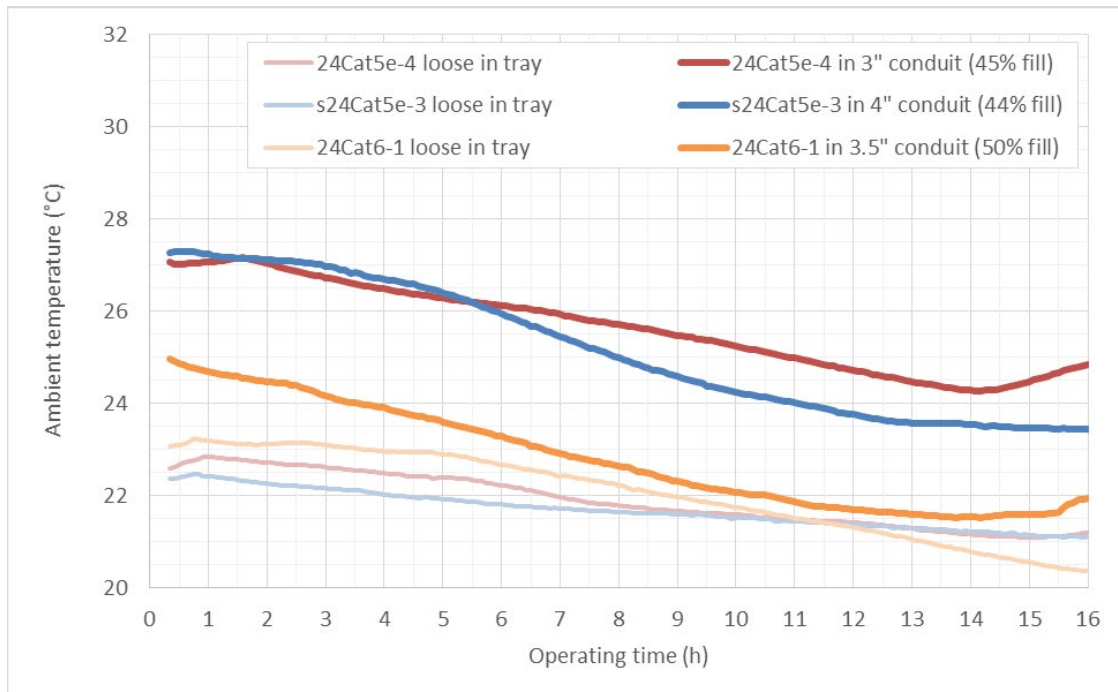


Figure 11. Overnight ambient temperature measurements for cables loose in tray and bundled in conduit. Temperature was recorded at 1 minute intervals and plotted without smoothing.

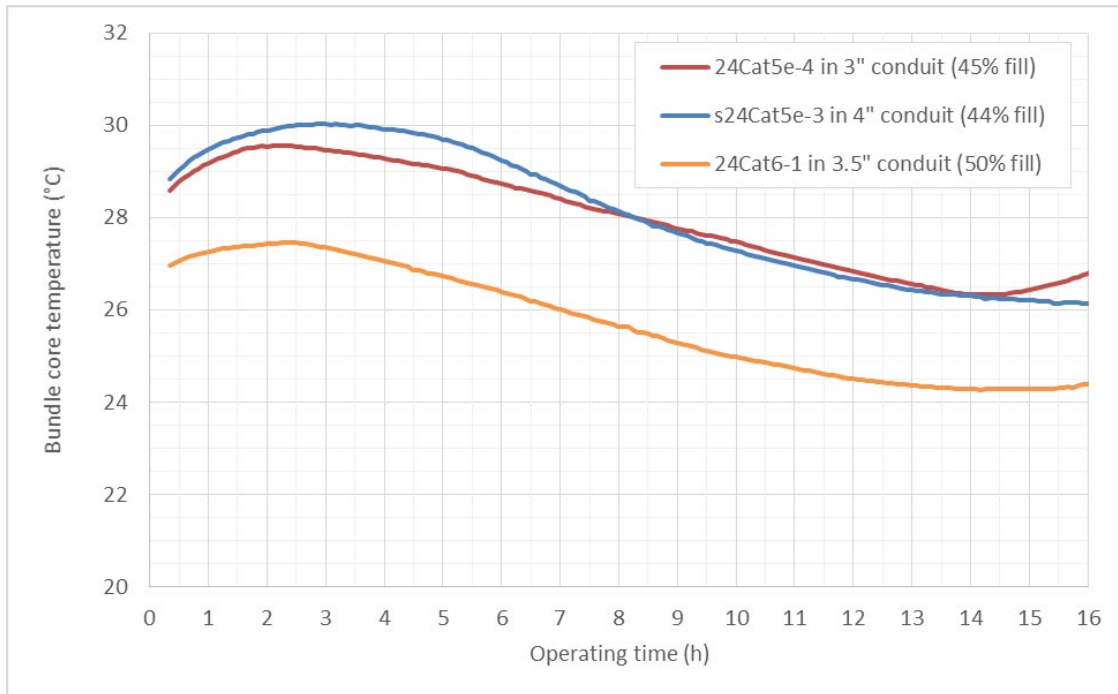


Figure 12. Overnight bundle core temperature measurements for cables loose in tray and bundled in conduit. Temperature was recorded at 1 minute intervals and plotted without smoothing.

4.6 Analysis

Median power and temperature measurements for the first 16 hours of operation are summarized in Table 6. Several observations can be made from this information.

- Bundle core temperature was generally about 3°C higher than ambient temperature. Because bundle core temperature was measured at a location between the midpoint and one end of the conduit, these values are expected to be somewhat lower than the temperature at the midpoint. Bundle core temperature would also be higher with increased current, elevated ambient temperature, and/or insulated conduit.
- Ambient temperature was fairly consistent across the three tests with cables loose in the tray (median values were within 0.5°C). In contrast, median ambient temperature for the tests in conduit was substantially lower (by 2.3°C to 3.1°C) for cable 24Cat6-1 than for cables 24Cat5e-4 and s24Cat5e-3.
- Similarly, whereas median PoE switch output power increased by 0.2 W when cable 24Cat6-1 was tested in conduit, it increased by 0.5 W for cables 24Cat5e-4 and s24Cat5e-3. However, these increases were all relatively small—less than 0.3% higher than when tested loose in the tray.¹⁵
- Power with cables loose in the cable tray was highest for 24Cat5e-4 and lowest for 24Cat6-1; this pattern held when cables were bundled in conduit. Although this might be attributable to differences in DCR between the three nominally 24 AWG cables, it could also be due to the variations in room ambient temperature, which can affect other factors such as luminaire input power.

¹⁵ Note that, by way of comparison, the accuracy of PSE output power measurement was assumed to be no better than ±1% in Part 1 of this study.

Table 6. Median Measured Values for Power and Temperature over First 16 Hours of Operation.

Test ID	Configuration	PoE Switch Output Power (W)	PoE Switch Input Power (W)	Ambient Temperature (°C)	Bundle Core Temperature (°C)
24Cat5e-4	loose in tray	190.0	224.5	21.8	-
	in 3" conduit (45% fill)	190.5	224.9	25.7	28.0
s24Cat5e-3	loose in tray	189.7	224.2	21.6	-
	in 4" conduit (44% fill)	190.2	224.5	24.9	28.1
24Cat6-1	loose in tray	188.9	223.3	22.1	-
	in 3.5" conduit (50% fill)	189.1	223.4	22.6	25.6

Whereas the shielded and unshielded Cat5e cables (with conduit fill ratio of around 45% and both starting near 27°C ambient) reached peak output power after about six hours of operation, the unshielded Cat6 (with a fill ratio of 50% in intermediate 3.5 inch conduit and starting near 25°C ambient) cable reached peak power almost immediately. However, the resolution of the y-axis in Figure 9 and Figure 10 is relatively fine compared to the 0.1 W resolution of the PoE switch-reported output power values, so these apparent trends could be at least partly attributed to chance.

PoE switch-reported PSE output power is plotted against ambient temperature in Figure 13 to show that although ambient temperature was comparable for portions of the Cat6-1 testing (both loose in cable tray and bundled in conduit), ambient temperature differed between tests for Cat5e-4 and sCat5e-3. The closer view provided in Figure 14 includes fitted regression lines that suggest the insulation provided by conduit does increase PSE load by increasing cable temperature and conductor DCR. However, the effect with a 44 W luminaire as PD appears to be relatively small—in this case, resulting in a power increase of less than 0.1% (or 0.2 W, just above the 0.1 W resolution of PoE switch-reported PSE output power measurements).

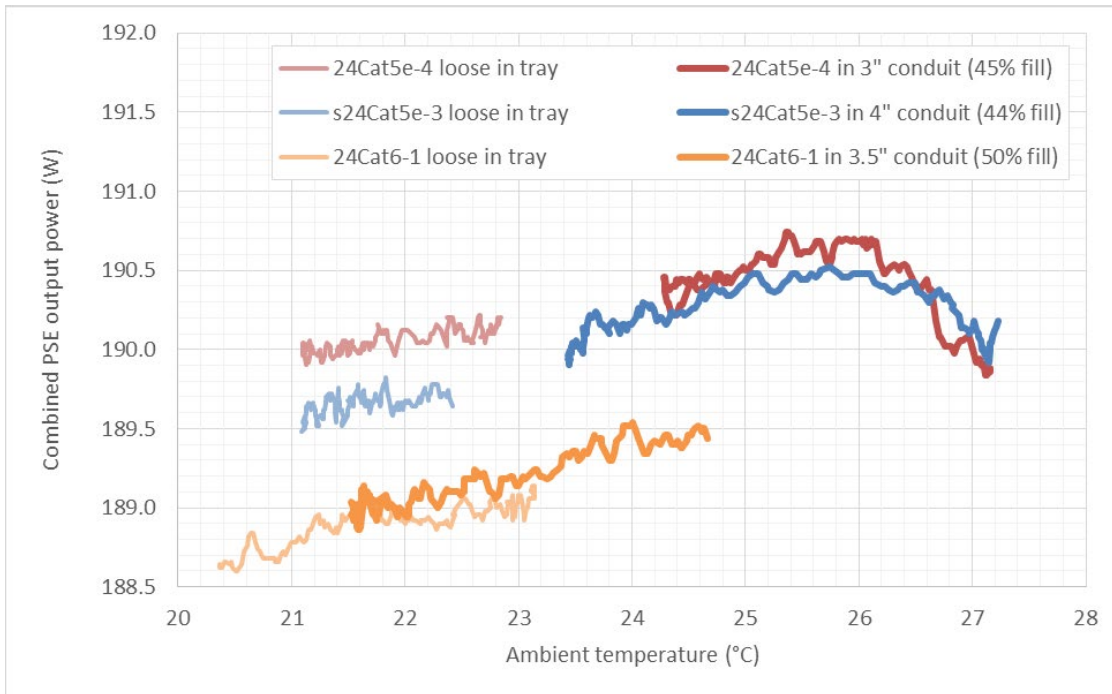


Figure 13. Combined 20 minute average PSE output power versus ambient temperature excluding the first hour of operation (loose in cable tray and bundled in conduit for all three cable models).

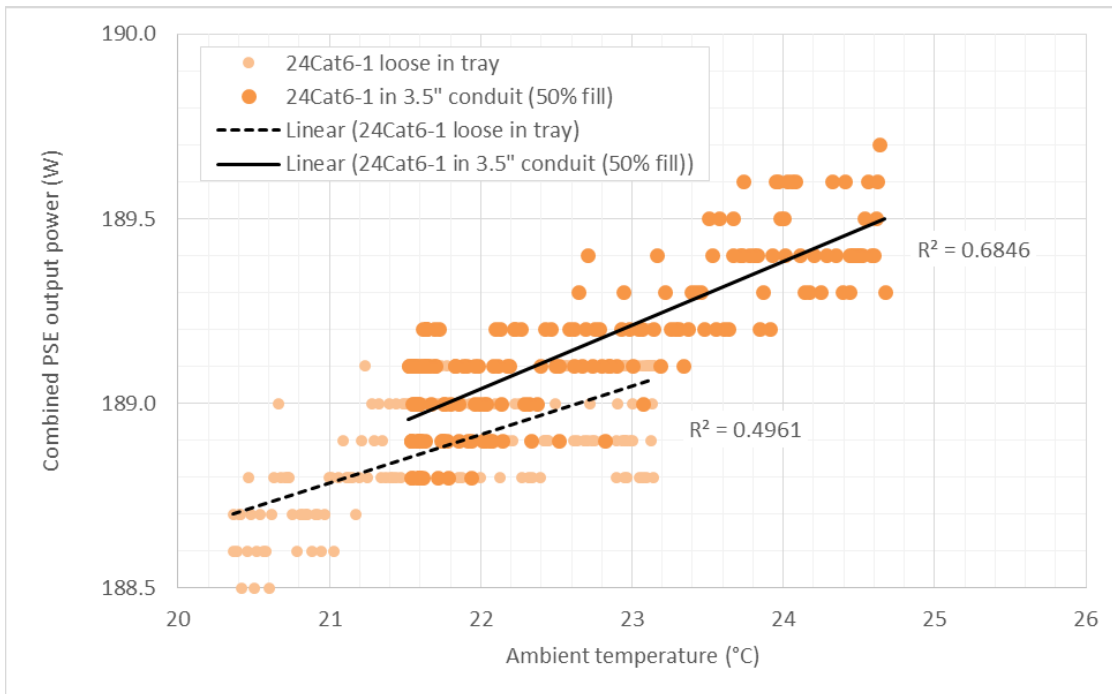


Figure 14. Combined PSE output power versus ambient temperature excluding the first hour of operation (loose in cable tray and bundled in conduit for cable Cat6-1 only).

For 47.5 W average PSE output power, and assuming 54 V PSE output voltage, conductor current in this study would be roughly 0.22 A. Table 7 summarizes temperature rise reported by others in similar applications. Please note the following:

- Whereas the UL values reflect test data, the TIA TSB-184-A values reflect modeled results.
- TIA TSB-184-A assumes Category 5e horizontal cable is solid-conductor 24 AWG with DCR of $0.0938 \Omega/\text{m}$ at 20°C (the maximum per TIA-568-C.2). Consequently, the TSB-184-A data should be viewed as an upper limit for expected temperature rise.
- TSB-184-A does not indicate type or size of conduit, and UL does not indicate size of conduit.

Table 7. Temperature Rise Data for 4-pair PoE Published by Others.

Data Source	AWG	Category	Shielding	Bundle Size	Conduit	Conductor Current (A)	Temperature Rise ($^\circ\text{C}$)
TIA TSB-184-A	24	5e	-	127	Yes	0.300	13.44
UL (UL 2015)	24	5e	UTP	91	Metal	0.175	5

According to the UL report, the use of firestop material at the ends of a 1.28 m (6 ft) conduit did not significantly affect the temperatures near the center. In this study, the temperature probe was not located at the midpoint of the conduit, so the measured bundle core temperature is expected to be somewhat understated. With four 44 W luminaires and PSEs sourcing 189 W combined, cabling losses are estimated at 3.25 W per 8.5 Ω channel. A 10°C temperature rise (between the TIA and UL values in Table 7) would yield an approximate upper limit of 0.6 W for the expected total increase in cable losses due to temperature rise. For a 3°C temperature rise (median measured for 24Cat6-1), the corresponding estimate would be 0.2 W, in close agreement with the difference between fitted trend lines in Figure 14.

5 Cable Bend Radius

TIA-568.0-D specifies a minimum internal bend radius of four times (4x) the cable diameter. Excessive cable bending can potentially damage the cable jacket or conductor insulation, compromise connectivity (e.g., via crosstalk and attenuation), affect impedance, and increase DCR unbalance (Megger 2011, Andress 2007, Fluke Networks 2016). The potential effect on DCR—which would in turn affect power and energy losses—in PoE applications is unclear.

5.1 Test Setup

The functional test setup for bundle testing in this investigation was the same as in section 3.1 of this report.

5.2 Test Setup Implementation

The test setup was implemented using the same equipment as in section 3.2 of this report, except the reference meter was not used; power measurements were solely by PSE. The measurement resolution of PoE switch-reported output power per PSE was one decimal place, same as for the combined output power of multiple PSEs (as used in Part 1).

5.3 Test Method and Calculations

Three 25 m cable lengths were cut and field-terminated with suitable plugs for each cable model. Each length was then tested in the following sequence, using the same stabilization criteria as in Part 1, except as noted.

1. Baseline PoE switch-reported PSE output power was first recorded with cable in a loose configuration (prior to bending), as shown in Figure 15.
2. PoE switch-reported PSE output power was then recorded after the cable was wrapped 24 times around a portable metal shelving unit, as shown in Figure 16 and Figure 17. The cable was formed into a 90° angle at each of the 96 bends, with an internal radius of 2.63 mm, resulting from the 5.26 mm diameter of the wire mesh frame. Cable tension was maintained by securing the bent cables in place using a wood board with bolts, washers, and nuts.



Figure 15. Example of cable prior to bending.



Figure 16. Example side view of bent cable.



Figure 17. Example top view of bent cable.

In all bending tests, a single 44 W luminaire was used, loading the PoE switch to just 9% of its capacity; the PoE switch datasheet only states rated efficiency at or above 20% loading of its power supply, and the efficiency curve may not be linear below this loading. Furthermore, some baseline tests (prior to bending) were run in parallel to save time, precluding comparison of PoE input power measurements with PSE output power measurements. Consequently, PoE switch-reported values for PSE output power were used in lieu of PoE switch input power measurements.

5.4 Test Units

A variety of cables were selected to explore potential factors including cable diameter, AWG, Category, and shielding. Cable characteristics are summarized in Table 8. Cable 24Cat5e-5 was acquired in February 2017 for use in the CLTB ceilings, with enough spare material remaining for bend testing in this study.

Table 8. Cables Used for Bend Testing.

Test ID	AWG	Cable Ø (mm)	Category	Shielding	Rated Conductor DCR
s24Cat5e-3	24	5.97	5e	F/UTP	$\leq 9.38 \Omega / 100 \text{ m}$
24Cat5e-5	24	5.33	5e	U/UTP	$\leq 9.38 \Omega / 100 \text{ m}$
23Cat6A-1	23	6.99	6A	U/UTP	$< 9.38 \Omega / 100 \text{ m}$
22Cat5e-1	22	5.84	5e	U/UTP	Not stated*

* Datasheet referenced ANSI/TIA-568-C.2 and ANSI/ICEA S-90-661-2012.

5.5 Test Results

The results from bend testing are presented in Table 9. Ambient temperature is provided for reference only.

Table 9. Results from Bend Testing.

Test ID	Unit	Scenario	T _a (°C)	P _a (W)	P _d (W)
s24Cat5e-3	1	Loose*	29.2	45.4	0.0
		Bent*	29.4	45.4	
	2	Loose	27.5	45.2	0.1
		Bent	27.9	45.3	
	3	Loose	27.5	44.9	0.0
		Bent	28.3	44.9	
24Cat5e-5	1	Loose	27.0	44.8	0.0
		Bent	27.2	44.8	
	2	Loose	27.0	45.3	0.0
		Bent	27.7	45.3	
	3	Loose	27.0	45.0	0.0
		Bent	28.0	45.0	
23Cat6A-1	1	Loose	28.0	44.5	0.0
		Bent	29.0	45.1	
	2	Loose	26.8	45.1	0.0
		Bent	26.3	45.1	
	3	Loose	26.8	44.8	0.0
		Bent	26.6	44.8	
22Cat5e-1	1	Loose*	29.2	44.6	-0.1
		Bent*	29.6	44.5	
	2	Loose	26.2	45.0	0.0
		Bent	27.6	45.0	
	3	Loose	26.2	44.7	0.0
		Bent	28.9	44.7	

Where:

T_a is the average ambient temperature for 20 minute periodP_a is the average PSE output power for 20 minute periodP_d is the difference between P_a values for loose versus bent* indicates P_a stabilized to 0.7% or better (rather than 0.3%)

5.6 Analysis

Cable bending was found to have no appreciable effect on cable power losses, regardless of cable design (AWG, cable diameter, Category, or shielding), and in spite of the 96 bend radii being less than half of the cable diameter for all models tested (more than eight times smaller than the TIA minimum). However, the matrix of potential factor interactions was not exhaustive (e.g., no 22 AWG Category 6 cable was tested) and luminaire input power was well below the power levels permitted by IEEE 802.3bt. Increased current density could potentially amplify any effects not detected with the loads and instrumentation used in this study.

Similarly, repeated cable (and conductor) flexing could compromise energy and connectivity performance in PoE applications.

6 Summary and Recommendations

Based on the limited testing conducted in Parts 1 and 2 of this study, and assuming average cable length does not exceed 50 m in practice, the guidance offered in ANSI C137.3 appears to be effective in limiting cable power losses to 5% of PSE output in PoE lighting applications. Although the standard's best-case assumptions

of ASTM-nominal DCR and operation at 20°C may tend to understate DCR values in the field, this appears to be offset by the worst-case accommodation of the minimum PSE voltage permitted by Clause 33 of IEEE 802.3.

In addition, with 44 W luminaires as PDs (sinking power from a UPOE switch) and room ambient temperatures below 30°C, cable power losses were not substantially increased by cable bending or bundling in uninsulated conduit. However, product selection and installation variables will have increased importance as PDs approaching 90 W input power—and connected by a single Ethernet cable—are introduced following publication of IEEE 802.3bt.

6.1 Research Questions, Answers, and Recommendations

PoE is still relatively new to the lighting community and, by the same token, lighting is still relatively new to the PoE community. The key research questions for this study are reviewed below, accompanied by answers based on study findings and recommendations intended to help streamline the adoption of PoE technology in lighting applications.

1.	<p>Question</p> <ul style="list-style-type: none"> Does the guidance in ANSI C137.3 ensure power losses in a 50 m Ethernet cable do not exceed 5% of PSE output? <p>Answer</p> <ul style="list-style-type: none"> Yes, the guidance was shown to effectively limit power losses to less than 5% in the cables tested (varying in AWG, Category, shielding, and manufacturer). However, these findings should not be construed as being representative of all cable models and installation practices. For example, power losses would be greater when cables are connected to patch cords, bundled in conduit, and loaded with PDs approaching 90 W input power. <p>Recommendation(s)</p> <ul style="list-style-type: none"> ANSI C137.3 should be revised or amended to clarify whether shielded cabling is included in its scope. PoE lighting system specifiers should state that minimum AWG must be per ANSI C137.3 guidance, or specify minimum AWG directly if a limit below 5% is desired or average cable length exceeds 50 m. Manufacturers of cabling (e.g., cables, patch cords, connectors) should state nominal DCR on product datasheets to further enable the design of energy-efficient PoE lighting systems. PoE lighting system specifiers/suppliers/installers should publish statistics on PoE cable lengths used for each project (e.g., minimum, maximum, mean, median), along with information on each model used (e.g., AWG, Category, shielding, fire rating). Lighting industry stakeholders should provide input to DOE on cabling configurations and installation practices that best reflect real-world PoE lighting applications, whether they are likely to perform differently from the scenarios already tested in Parts 1 and 2 of this study, and whether DOE testing results would be valuable.
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2.	<p>Question</p> <ul style="list-style-type: none"> To what extent do losses vary between models of cable differing in AWG, Category, shielding, and manufacturer? <p>Answer</p> <ul style="list-style-type: none"> Cable losses were found to decrease with increasing conductor diameter (i.e., numerically smaller AWG), as would be expected based on I^2R models. No appreciable difference was observed for the other characteristics; however, considering the study limitations (e.g., the set of cables tested), this does not mean these parameters do not affect cable losses. Notably, three cables—two of which were shielded—were previously excluded from the Part 1 study due to compatibility issues. All three cables were included in this Part 2 study. In addition, whereas no patch cords were used in Part 1, patch cords were used in some Part 2 testing. <p>Recommendation(s)</p> <ul style="list-style-type: none"> Lighting industry stakeholders should provide input to DOE on whether additional or new cable models or types are likely to perform differently from the ones already tested in Parts 1 and 2 of this study, as well as whether DOE testing results would be valuable.
3.	<p>Question</p> <ul style="list-style-type: none"> To what extent do field installation variables (e.g., bending, bundling, conduit) affect cable power losses? <p>Answer</p> <ul style="list-style-type: none"> With 44 W luminaires as PDs and room ambient temperatures below 30°C, cable power losses were not substantially increased by cable bending or bundling in uninsulated conduit. However, environments with higher ambient temperatures will have greater power losses due to increased conductor DCR. In addition, product selection and installation practices will have increased importance as PDs approaching 90 W input power—conveyed by a single Ethernet cable—are introduced following publication of IEEE 802.3bt. <p>Recommendation(s)</p> <ul style="list-style-type: none"> Lighting industry stakeholders should provide input to DOE on cabling configurations and installation practices that best reflect real-world PoE lighting applications, whether they are likely to perform differently from the scenarios already tested in this Part 2 investigation, and whether DOE testing results would be valuable.
4.	<p>Question</p> <ul style="list-style-type: none"> What knowledge gaps remain to be filled by future PoE cable energy losses research? <p>Answer</p> <ul style="list-style-type: none"> The increased PD input power limits in IEEE 802.3bt will lead to increased energy losses in PoE cables, but the typical size of the effects and the circumstances in which they will be realized remains to be determined. <p>Recommendation(s)</p> <ul style="list-style-type: none"> Lighting industry stakeholders should identify any relevant studies currently unknown to DOE, as well as identify any weaknesses or gaps in existing studies, for DOE consideration in the planning of future investigations.

6.2 Next Steps

This study is the second in a planned series of investigations into the system-level energy efficiency of PoE and other connected lighting systems. DOE plans to conduct at least one additional study of PoE cable energy losses following the publication of IEEE 802.3bt. Ideas for the next study presently under consideration include:

- Characterization of additional models of a given cable type. For example, although plenum-rated CMP cables are necessary in ceiling plenum applications and might be used more broadly to simplify inventory, riser-rated CMR cables are generally less expensive and this fire rating might suffice in other applications. Price also appears to correlate more strongly with Category than with AWG; this may be driving recent product introductions by several manufacturers of 22 AWG Category 5e cables marketed for PoE applications.
- Characterization of cable types (e.g., Category 7 or higher) and cabling configurations (e.g., including patch cords and RJ45 jacks) not yet tested.
- Improvement of the test setup, perhaps through incorporation of PSE/PD emulators with power measurement capability. Although these types of equipment are not actual PoE switches or lighting loads, they may better implement desired test setup functionality, and they offer the benefit of published measurement accuracy ratings. They can also enable exploration of the effect of different PSE output voltages within the range permitted by IEEE. It is expected that publication of IEEE 802.3bt will lead to more options for sources and sinks of PoE power that more fully stress cables to standard limits.

DOE is also planning other studies that explore the impact of device selection or varying system use on system energy performance for PoE or other connected lighting systems. The following studies are under consideration:

- Characterization of the effect of PoE switch selection on PoE system energy efficiency
- Characterization of the effect of different connected lighting system architectures (e.g., direct or indirect PoE loads from different manufacturers) on system energy efficiency
- Characterization of the effect of different connected lighting system use cases (e.g., varying in network traffic) on system energy efficiency.

DOE requests feedback on this report, and would welcome any input from lighting and PoE industry representatives and other impacted stakeholders. In particular, DOE is interested in recommendations on what next steps should be prioritized over others. Email any feedback to DOE.SSL.UPDATES@ee.doe.gov.

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