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# Final Report

FY2015 DOE SBIR Phase II Release 2: Topic 3a

DOE-VOLT-11860

LOW-COST, HIGH EFFICIENCY INTEGRATION OF SOLID-STATE LIGHTING AND BUILDING CONTROLS USING A PET POWER DISTRIBUTION SYSTEM

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**Figure 1: PCX500 Digital Electricity Transmitter**

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## 1. Executive Summary

This SBIR program, across Phase I and Phase II, investigated an electrical power distribution system using a protocol called Packet Energy Transfer (PET). PET distributes electricity in discrete pulses, each combined with a verification signature. The pulse and signature combination are referred to as an energy packet. The packet is sent from a transmitter unit to a receiver unit. If the transmitter detects that a packet was not properly transferred to the receiver, packet transfer is terminated until the fault is removed.

Since each packet contains only a small amount of energy, the power transmission lines between the transmitter and receiver lines are touch and fire safe; even when transmitting thousands of Watts of electrical power. This results in the ability to use the same rapid wiring practices as Ethernet cabling, thus significantly increasing speed of installation and reducing installation costs. The protocol also offers embedded data inside the energy packet to monitor or control a remote device under power.

A PET system offers the possibility of significantly reducing the cost and complexity of lighting power distribution and was proposed as a method to incentivize more rapid transition to solid state lighting in US buildings. Additionally, the PET architecture greatly reduces the required driver circuitry in SSL fixtures, thereby addressing the most unreliable component in the fixture while simultaneously increasing system efficiency.

Phase I of this SBIR provided a proof point that a suitable PET system could be constructed and applied to SSL applications. With support from the DoE, VoltServer created a 300W scaled model of a PET transmitter and demonstrated the device powering A19 bulbs. Additionally, a comparison of installation costs was conducted to verify the potential installation savings. Phase I was completed in March 2015.

Based on the results of Phase I, VoltServer in conjunction with its partner, Fraunhofer USA, were awarded a Phase II program with the following summarized objectives:

- Significantly increase the power capabilities of the transmitter unit for commercial applications.
- Show a side by side comparison of a PET installation to a standard electrical installation.
- Verify that the transmitter can be safety approved by a Nationally Recognized Test Laboratory (NRTL)
- Verify that the technology can be approved by an authority having jurisdiction (AHJ) for installation in a commercial building.

The Phase II program has been segmented into two pilots. The first pilot was completed in August 2016. The pilot entailed the installation of LED lighting in the Rhode Island Quonset Airport main hanger. VoltServer was successful in scaling the transmitter unit from 300W in Phase I to 12kW in Phase II. In addition, the state electrical inspector approved the digital electricity installation as meeting National Electric Code requirements. The 20,000 sq. ft. installation included a side by side comparison of conventional and PET electrical distribution. The comparison of installation methods and system efficiency was performed by our partner, the Fraunhofer Center for Sustainable Energy (CSE) who acted as an independent organization for evaluating program objectives. Fraunhofer's analysis concluded that the VoltServer equipment cost and installation was less expensive than conventional methods if the size of the installation was at a scale large enough to amortize the cost of the 12kW transmitter equipment and installation as is explained further in this report.

**Pilot #1: Quonset Airport Hangar with new PET powered Solid State Lighting**

As Phase I and Phase II has progressed, VoltServer has substantially grown in the market for powering digitally connected systems. At the time of the Phase I proposal the company was just completing its first installation for powering communications in Washington State University stadium. At the time of this report the company has installed PET in over 400 large venues that include conference centers, high rises and the 2018 Super Bowl Stadium. A common tool for digital connectivity in these applications is Power over Ethernet (PoE) switches. Initially the PoE switches were used for WiFi access points and security cameras. However, during early 2017 PET was applied to higher power PoE switches that could support LED lighting. Cisco has been a leader in this area with its development of the 480W plenum rated “CDB” digital building switch.

Recognizing how LED lighting fits into the greater ecosystem of the connected systems, VoltServer, in communication with the DoE, modified the goal for Pilot #2 to focus on connected systems incorporating PoE lighting.

The location for Pilot #2 is the Sangar building in Ft. Worth Texas. The building is joined with the 15 floor Sinclair building. The Sinclair building will also incorporate future PoE lighting powered by PET as a Marriott Autograph hotel complex. This is part of a commercial follow-on project with VoltServer. The project incorporating the two adjoining buildings is referred to as the “Sinclair Project”. The Pilot became operational in January 2017. The project is a full rehabilitation of a 15 floor, 1940s “art deco” era building into a new Marriott Autograph Collection hotel combined with an adjacent 9 floor building containing a CVS, Data Center and commercial space. The project incorporates the latest intelligent building infrastructure including high efficiency VRF heating and cooling and PoE throughout the complex. PoE powers and controls LED lighting, motorized blinds, HVAC components, access controls, security and a host of other Internet of Things (IoT) devices. Pilot #2 used PET to power the PoE switches for a 9-floor portion of the complex. The PoE switches in turn power the connected devices.


**Pilot #2: The Sinclair Marriott Autograph Hotel Complex**

The value of PET to the Sinclair project is that it allows the rapid installation of Cisco CDB PoE switches throughout the complex without the traditional “hard conduit” wiring needed in commercial electrical systems, and fully integrates monitoring and control of end point devices. The VoltServer transmitters are located on the sixth floor of the complex and power dozens of CDBs. It should be noted that the energy tradeoffs in a connected building environment are more holistic than purely the electrical plug-efficiency of the LED lighting. Energy use is reduced by coordination of a host of IoT devices such as room by room adjustment of HVAC controls, the automated opening and closing of blinds based on occupancy sensors and time of day, and integration of room controls and lighting with the hotel reservation system and room access controls. It is this holistic approach to energy management using connected infrastructure that greatly compensates for the fact that powering LED lights with PoE switches is marginally less efficient and more expensive than traditional methods. This report details these finding along with other key metrics such as installation time and cost and feedback from the building owner.

This DoE program, concluding with the Sinclair project, resulted in numerous ongoing opportunities for VoltServer to promote solid state lighting within intelligent infrastructure. Besides an anticipated commercial contract for the remainder of the Marriott complex, we have executed on multiple opportunities directly or indirectly related to the program. The program had a significant hand in our more than 4X increase in employees and revenue since the Phase I SBIR. We would like to acknowledge the Department of Energy for sponsoring this important work.

Farukh Aslam of Sinclair Holdings hosted dozens of walk throughs and demos to other developers, design firms and real estate investment trusts. Mr. Aslam directly promoted PET as an enabler for intelligent, connected buildings at industry conferences such as BICSI international, Cisco Live and Marriott Innovation Days. Mr. Aslam has been instrumental in our progress.

Finally, we would like to acknowledge Fraunhofer CSE for their professional and even-handed project management, testing and analysis throughout the program.

## 2. Phase II, Goals and Results

For this midterm report, the goals established in the SBIR Phase II proposal are presented along with the status at the time of the report. In certain cases, the team elected to diverge from the stated goals due to specific business drivers that would better be served through a modification of the proposal goals or because there where technical constraints that drove a change. In either case the divergence is noted in the particular section.

**Task 1: Product-Ready PET-Integrated SSL System Development (Months 1-17)**

Based on our Phase I effort, VoltServer has identified several promising entry points into the SSL market – notably commercial troffers, high bay, and horticultural troffer lighting fixtures. We will focus the hardware development effort on developing product-ready PET SSL systems targeted for these markets, which, at the conclusion of this project, will be offered as a commercially available option. The specific goals of the hardware development are to develop a PET system that: (1) is tightly integrated with a commercial lighting fixture for a targeted application; (2) achieves an efficiency of 93%; (3) is listed by a Nationally Recognized Test Laboratory (NRTL) to all applicable standards; (4) incorporates inline communications to a central receiver; and (5) incorporates advanced sensors. The objective is that the systems provided for demonstration during Year 2 of this project will be "production ready" units that could be scaled up and distributed either directly by VoltServer, or through a channel partnership. VoltServer will conduct this work in their R&D laboratories in East Greenwich, RI.

**Table 1:Phase II Status**

| | Phase II Target | Status |
|---|---|---|
| **Transmitter Rating (W)** | 14,000 | 12,000 (purposely reduced in power and size of unit to accommodate commercially available components) |
| **Transmitter Efficiency** | 96% | 95.5% |
| **System Efficiency** | 93% | 92.5% (direct drive, See Tbl 4.2 Fraunhofer report) |
| **Communications** | Inline PET Data Transfer, tie in to commercial lighting system | In-line communication demonstrated |
| **Listings** | IEC/UL-62368-1, UL1598 | IEC/UL 62368-1 and UL 1598 certified |
| **Receiver Form Factor** | TBD, 40W | 4"L x 2.0"Wx 1.6"H, 600W |
| **Control System Feature Set** | On/Off, Dimming, Temperature/Ambient Light Sensor, Wi-Fi or other access pt | On/Off & Dimming demonstrated |

***Task 1.1: Lighting System Specification:*** VoltServer will down-select to 1-2 specific lighting fixtures to target the design, and finalize specifications for integrating PET into these fixtures. This selection process will be driven by input from Cree, pilot/demonstration partners, and other potential first customers to balance fit for the market and technical/programmatic feasibility. VoltServer will consult with Cree and other manufacturers as needed to identify all applicable standards, and then identify any requirements necessary to achieve these listings.

**Status:** With assistance of Cree, the team selected the Cree CXB LED High-bay for the first Pilot of Phase II. This is a 240W, 24,000 lumen fixture with an efficacy of 113 Lumen/W (Figure 2). Cree managed the NRTL listing of the CXB product to UL 1598. The fixture was listed for a dual power input allowing it to accept either conventional AC power or the DC power from a VoltServer receiver unit mounted next to the fixture. This will allow Cree to apply one product to both conventional and digital electricity applications, but it does not fully present the efficiency and cost benefits of a direct DC drive fixture. A direct drive version of the fixture was prototyped and was evaluated for efficiency by Fraunhofer CSE as is detailed in their appended report. The dual listed and direct drive versions of the Cree fixture are shown in Figure 3.

**Figu** **ture**


**Figure 3: Cree Dual AC/DC High-bay (left) and Direct DC Drive (right)**

As part of Pilot # 2, VoltServer verified operation with the Cisco CDB PoE swtich. The CDB product was designed by Cisco to be plenum rated and fanless for use in ceiling installations. It is an 8-port switch with 480W of total power available at 60W per port.

**Figure 6: VoltServer RX520 receiver with Cisco CDB PoE switch**

The location for Pilot #2 is the Sangar building in Ft. Worth Texas. The project is a full rehabilitation of a 15 floor, 1940s era building into a new Marriott Autograph Collection hotel combined with an adjacent 9 floor building containing a CVS, Data Center and commercial space. The project incorporates the latest intelligent building infrastructure, including high efficiency HVAC systems and PoE throughout the complex. The PoE powers and controls LED lighting, motorized blinds, HVAC, access controls, security and a host of other Internet of Things (IoT) devices. Pilot #2 provided PET powering for the PoE switches in the 9 floor portion of the complex. The VoltServer transmitters were placed on floor 6 of the complex. The transmitters power 36 of the Cicso PoE switches. More detail is provided in section 3.3 of the accompanying Fraunhofer final report.

***Task 1.2: PET Hardware Development:*** Based on the product specification defined in Task 1.1, VoltServer will reengineer the PET receiver / transmitter systems to meet the new requirements. In the case of the receiver, this will entail increasing power ratings to 40W, modifying form factor (as necessary) for fixture integration, and incorporating firmware and hardware modifications to: (a) improve performance and expand the feature set of the inline communications; and (b) comply with all listing requirements. For the transmitter, this entails increasing power rating to 14kW, incorporating modifications to enable the expanded advanced control feature set, and increasing the efficiency to 96%.

**Status:** To accommodate the high-bay fixture, which can range up to 300W in power consumption, we elected to design a higher power receiver rated at 600W (Figure 4) versus the target of 40W. This power rating accommodates a very large industrial luminaire or groups of multiple, smaller units. The receivers are fully developed and NRTL listed to IEC/UL 62368-1. In the case of the direct DC drive fixture, a dimming feature using in-line communications has been demonstrated. Thermal testing was performed on the RX520 to determine its power rating versus ambient temperature it is depicted in Figure 5.

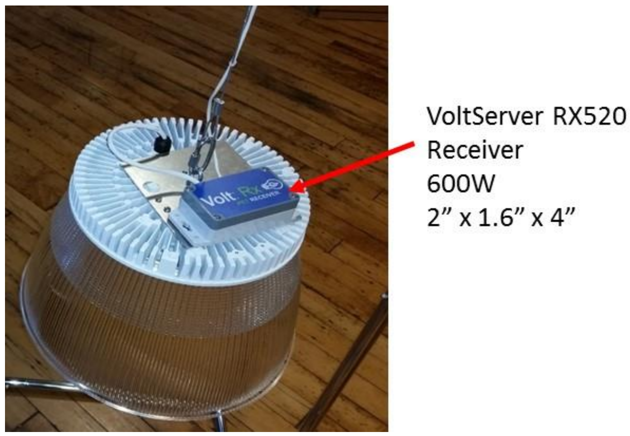


**Figure 4 - RX520 Receiver mounted on Cree High-bay**

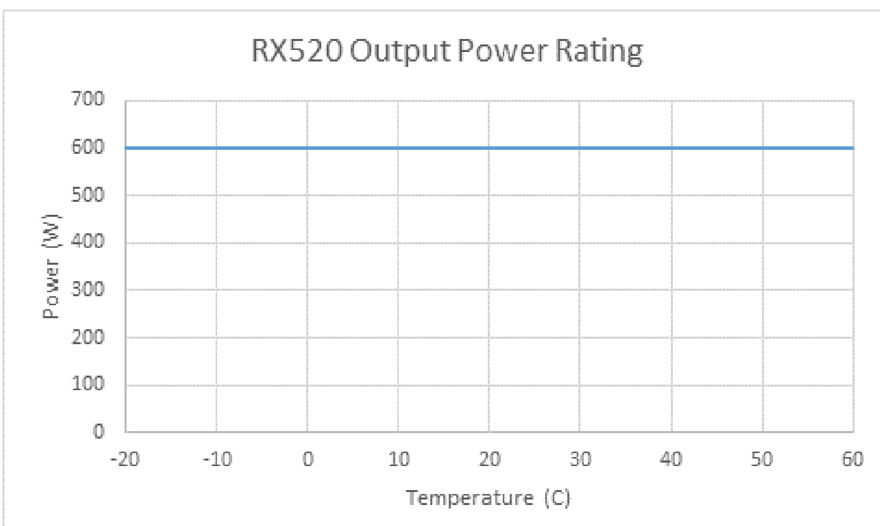


**Figure 5- RX520 Power Rating vs. Ambient Temperature**

In the Phase II proposal, 14kW was targeted for the power rating of the transmitter unit. Due to available power converter modules, we elected to reduce the power per transmitter to 12kW using four 3kW modules (lower half of Figure 6) but were able to keep the size of the transmitter to 3.5"H x 17.5"W x 24"D, 39 pounds. The completed transmitter is shown in Figure 6.


**Figure 6: Completed VTX500 12kW Transmitter Unit**

The transmitter power capabilities were tested at ambient and elevated temperatures inside an environmental chamber. A plot depicting test results of power versus ambient temperature is shown in Figure 8.

**Figure 7: VTX500 Instrumented for Thermal Testing**

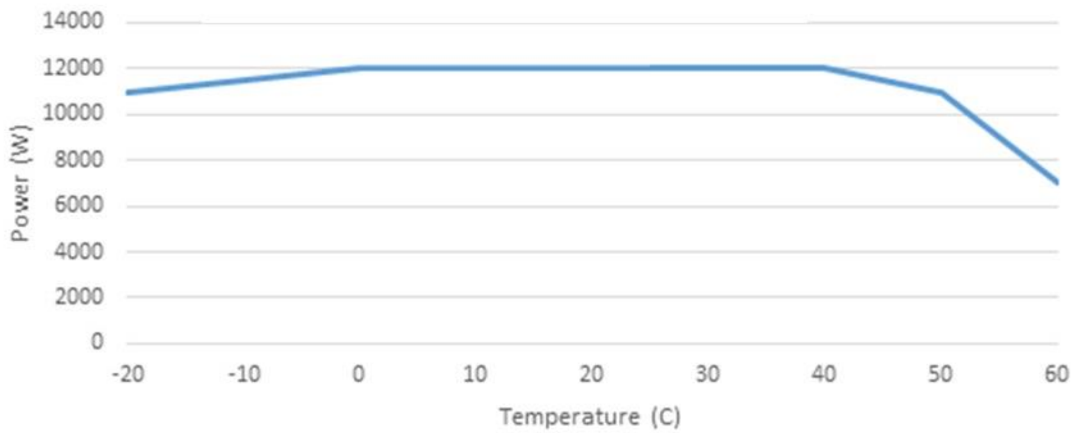


**Figure 8: VTX500 Output Power vs. Temperature**

The transmitter efficiency was measured by Fraunhofer to be 95.5% as is detailed in section 4.2 of the accompanying final report from Fraunhofer.

The VTX500 transmitter is NRTL listed for installation in North America and internationally listed for installations worldwide. The lab certification is shown in Figure 9.

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CERTIFICATE OF COMPLIANCE

The product(s) listed below are authorized to be labeled with the Curtis-Straus mark as shown in the following box when made in accordance with the Description and under the conditions set forth in the Certification Listing Agreement and Test Report(s) listed below.

C US
TSAA

| | | | |
|---|---|---|---|
| File Number: | TSAA | Work Order: | Q3690 |
| Date: | March 24, 2017 | | |
| Participant Company: | Voltserver, Inc. | | |
| Participant Address: | 42 Ladd Street, Suite 227, East Greenwich, RI 02818 | | |
| Manufacturing Facility Code: | XIA | | |
| CANADA Standard: | CSA C22.2# 60950-1-07 + Am1 (2011) + Am2 (2014), CSA C22.2# 60950-21-03 & CSA C22.2# 62368-1-12 | | |
| USA Standard: | UL 60950-1 2nd Ed + Am1 (2011) + Am2 (2014), UL 60950-21 & UL 62368-1 | | |
| Product(s) Listed: | Digital Remote Line Power Transmitter, Voltserver Models: VTX500, PTX350-XXX; JMA Models: FDET2-TR1, FDET-1800-24 | | |

Authorized by: Michael Buchholz, Certifier

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**Figure 9: VTX500 Transmitter Certification**

***Task 1.3: Lighting Fixture Integration for Year 1 Pilot:*** VoltServer will integrate PET into the selected lighting fixture. Multiple fixture configurations will be developed to incorporate different combinations of LED drivers (driverless LEDs and LEDs with a conventional driver), building controls, sensor integration, and connectivity. VoltServer will build sufficient fixtures to execute a Year 1 pilot demonstration, as outlined in Task 2.

**Status:** VoltServer prototyped a direct drive version of the Cree CXB. This resulted in a significant decrease in part count, weight and volume of the fixture. The converted fixture is shown in Figure 10. As discussed above, Cree opted to qualify a dual AC/DC version of the CXB so that it can be used in both conventional AC and VoltServer DC applications. In this case, the conventional driver remains in the fixture and takes a DC input from the output of the VoltServer receiver. Although this is not the most efficient approach from the point of view of cost or energy, the business approach allows a single product to serve both AC and DC power sources. As part of the program a direct drive prototype that applied DC power directly to the LED engine without an intermediate LED driver was evaluated for light performance, efficiency and cost. The results are listed in section 4.2 of the accompanying Fraunhofer final report.

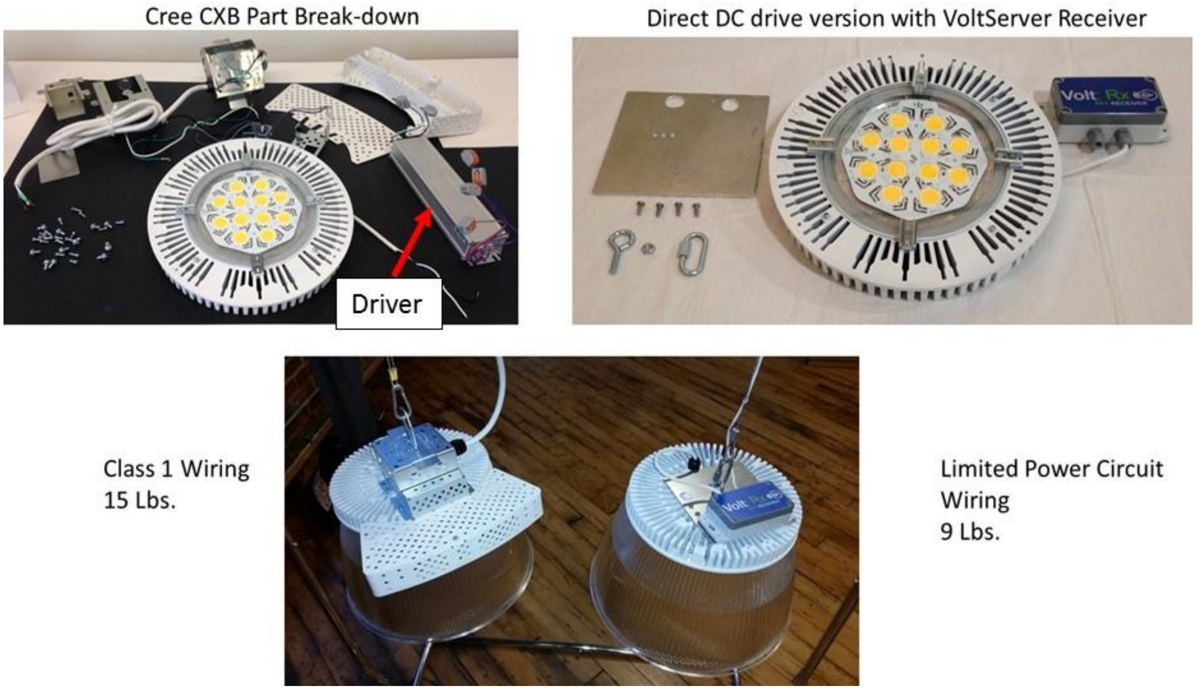


**Figure 11: Direct Drive versus Driver Version of Cree Fixture**

***Task 1.4: NRTL Listing:*** With engineering support from Cree, VoltServer will contract with an NRTL to obtain the listings that will mark PET fixtures as Class 2 limited power sources suitable for commercial SSL applications (i.e., IEC/UL-62368-1 and UL1598).

**Status:** As discussed in Task 1.1 Cree supervised the NRTL listing of a DC version of the Cree CXB fixture under UL 1598. The fixtures were listed labeled for dual AC/DC input and are compatibility with VoltServer receiver units.

***Task 1.5: Lighting Fixture Integration for Year 2 Pilot:*** VoltServer will integrate PET technology into the selected lighting fixture for the Year 2 pilot demonstration, incorporating design modifications based on the Year 1 pilot testing and continued development. Cost reduction efforts will be undertaken on the receiver, direct drive troffer, and transmitter, and VoltServer will establish a manufacturing methodology with lighting manufacturer. In addition, VoltServer will improve electronics controls and software to allow more refined control over lighting grid to optimize energy use (e.g., On/Off, Dimming, Temperature/Ambient Light Sensor, Wi-Fi or other access pt). As with the Year 1 pilot, multiple fixture configurations will be developed. VoltServer will build sufficient fixtures to execute a Year 2 pilot demonstration, as outlined in Task 3.

**Status:** The Year 2 program goals were redirected with DoE approval. The new goals focused on PoE lighting. In the Pilot, thirty-six RX520 PET receivers power thirty-six PoE switches. The PoE switches then power and control LED lighting, motorized blinds, HVAC, access controls, security and a host of other Internet of Things (IoT) devices. Pilot #2 provided PET powering of the PoE switches for the 9 floor section of a Marriott hotel complex in Ft. Worth Texas. The building is shown in Figure 12 below. The transmitters and LED lights as installed are shown in Figure 13 and Figure 14. The Sangar building installation is described in more detail in section 3.3 of the Fraunhofer report.


**Figure 12: The Sinclair/Sangar Buildings (The 9 floor section is the Sangar Building), Future Marriott Hotel Complex**

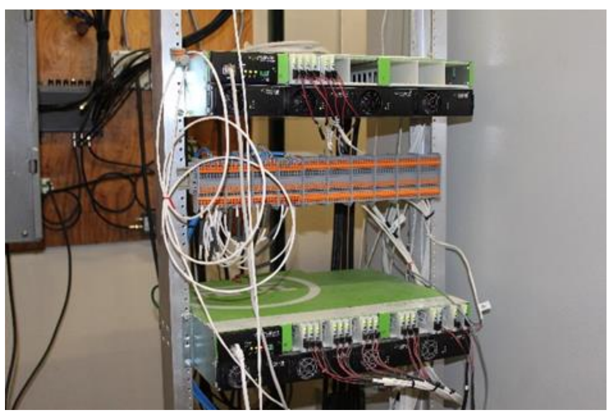

**Figure 13: VoltServer Transmitters in the Sinclair Building**

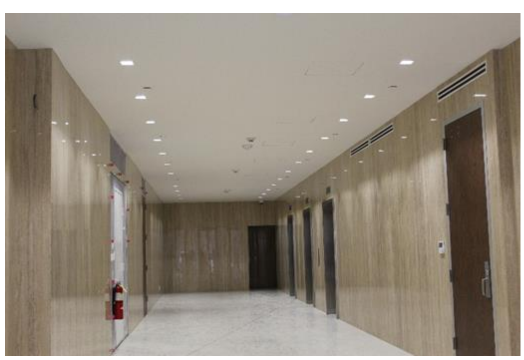

**Figure 14: PoE powered LED lights in Lobby, PoE switches throughout building are PET powered**

**Task 2: Pilot-Scale Technology Validation (Months 6-14)**

During the second half of Year 1, VoltServer will collaborate with the Fraunhofer Center for Sustainable Energy Systems (CSE) to install PET SSL fixtures at Fraunhofer CSE's Boston R&D center for an extended period of validation testing. As outlined in the Facilities/Equipment and Consultants and Subcontractor sections, the combination of ongoing R&D in sustainable energy technologies, in-use office space, technology showcase, as well as Fraunhofer CSE's ongoing collaboration with VoltServer, makes this an ideal location for a pilot demonstration of PET technology. We propose to utilize approximately 3,000 sq ft office space at the Fraunhofer building to install, commission, and operate conventional technology and PET technology in a controlled, side-by-side comparison for a period of at least 6 months. The demonstration will compare the performance of (1) driverless PET SSL commercial troffers; (2) PET SSL commercial troffers with standard drivers; and (3) conventional (non-PET) SSL troffers across a range of metrics. The goal of this pilot demonstration is to assess the performance of PET across multiple dimensions in a real-world application, using a controlled test protocol with independent third party validation of the results, and provide real-world experience with the technology. VoltServer will conduct their portion of the work in their R&D laboratories in East Greenwich, RI. Fraunhofer will conduct their portion of the work, including the Pilot-scale demonstration in their R&D center in Boston, MA. Both parties will travel as necessary.

**Status:** The program team was able to secure a pilot test site at the Rhode Island Quonset Airport main hangar. It is a 20,000 square foot facility which was underserved by its existing HID highbay lighting. The Rhode Island Airport Corporation executed a beta test agreement with VoltServer and the initial installation phases occurred in May-July 2016. Due to the commercial advantages and scale of the airport location, it was selected as the pilot location instead of the Fraunhofer pilot location (Figure 15, Figure 16).

As discussed above, the Year 1 pilot used dual-rated high bay lights that accept conventional AC power or the DC power from the VoltServer receiver. The high bays contained a dual listed AC/DC on-board driver. Separately, performance testing of a direct drive version of the light was performed at the VoltServer and Fraunhofer laboratories. The Quonset installation is described in detail in section 3.2 of the Fraunhofer report.

Figure 15: Rhode Island Quonset Airport Hangar

Figure 16: Existing HID Lighting (hangar doors open to sunlight)

***Task 2.1: Field Test Plan Development:*** VoltServer and Fraunhofer will collaborate to develop an experimental design that accurately and robustly characterizes the performance of conventional and PET systems. Note that the specifics, including layout and total number of fixtures, are illustrative. The actual test will be designed to reflect with the actual constraints of the selected space at the CSE facility: one option will be to retrofit PET lighting into Fraunhofer's 3$^{rd}$ floor office side by side with conventional SSL fixtures; a second option is to install PET lighting alongside conventional lighting in a planned build out of 4$^{th}$ or 5$^{th}$ floor office space.

**Status:** As discussed above, due to commercial advantages and scale, the Rhode Island Quonset Airport hangar was chosen as the pilot location for Year 1. In the first phase of the installation, conventional Cree LED high bays were installed using standard Class 1 electrical installation practices as depicted in **Error! Reference source not found.**. In Phase II of the installation, the dual rated Cree high-bays were installed using the digital electricity system and NEC Article 725 limited power wiring practices as depicted in **Error! Reference source not found.**.

During the entire installation, a licensed and insured electrician firm was employed and all installed equipment was NRTL listed and approved by the state electrical inspector. A beta test agreement was executed with the Rhode Island Airport Corporation (RIAC). Multiple site walk-throughs and meetings occurred with the airport management. The results are described in more detail in section 3.2 of the Fraunhofer report.

***Task 2.2: Pilot SSL System Installation:*** Fraunhofer will contract with an independent design and construction vendor to install the pilot system. Following installation, Fraunhofer will instrument the new equipment with data acquisition equipment as specified in the field test plan and tie in to the BMS as feasible. VoltServer and Fraunhofer will jointly qualify the installed system to verify that the system is functioning and that the data acquisition equipment is providing accurate data.

**Status:** A licensed and insured electrical firm was selected to complete the installation. The installation was recorded by Fruanhofer to analyze the installation time and methods in each step of installation. The beta test agreement executed with the airport specifies the airport's agreement to allow performance measurement during and after the installation. Details are included in section 3.2 of the Fraunhofer report.

***Task 2.3: Field Test Plan Execution:*** Fraunhofer will execute the field test plan. As needed, the test plan will be revised in consultation with VoltServer. Although VoltServer will be involved in developing the experimental design and managing the overall project task, Fraunhofer will ultimately execute the testing and validate the results to preserve independence.

**Status:** Fraunhofer performed field testing prior to the first installation to obtain light measurements and power consumption of the existing HID lighting. Additional light and power measurements occurred in each subsequent phase of installation. Details in section 3.2 of the Fraunhofer report.

***Task 2.4: Assessment and Reporting:*** Fraunhofer will review data with VoltServer on an ongoing basis. Fraunhofer will then conduct independent analysis to assess performance, and extend the results as needed. This assessment will extend the quantitative and qualitative results from the pilot to develop a refined financial analysis spreadsheet tool to independently quantify value proposition for different use cases, such as: (a) driverless / new construction / controls; (b) driverless / retrofit; and (c) standard drive / new construction, and accounting for differences in equipment cost, installation cost, energy use, and reliability. It will also extrapolate reliability test data into MBTF estimates, and help assess the value of inline controls integration.

**Status:** Fraunhofer accumulated data from the Airport Hanger installation. Details in section 3.2 of the Fraunhofer report.

**Task 3: Commercial-Scale Demonstration and Technology Validation (Months 1-23)**

In Year 2, VoltServer will continue to collaborate with Fraunhofer CSE to install PET SSL fixtures at a beta customer's site for an extended period of validation testing. We propose to utilize at least 5,000 sq ft of commercial building space to install, commission, and operate conventional technology and PET technology in a controlled, side-by-side comparison for a period of at least 6 months. VoltServer will conduct their portion of the work in their R&D laboratories in East Greenwich, RI. Fraunhofer will conduct their portion of the work in their R&D center in Boston, MA. The Pilot-scale demonstration site location will be identified and selected in Year 1. Both VoltServer and Fraunhofer will travel as necessary.

**Status:** The Sinclair project in Fort Worth, Texas was selected for this project component. It was not possible to conduct side by side testing with legacy electricity fixtures because the building owner opted to fully convert the building to PET and PoE powering. The system was first installed in January 2017 and has been operating continuously without incident.

Please see section 3.3 of the Fraunhofer report for more detail.

***Task 3.1 Year 2 Pilot Demonstration Site Selection:*** During the first year of the program, using the Fraunhofer pilot installation as a sales tool, VoltServer will identify a commercial partner that represents a volume opportunity for demonstrating the technology with a beta customer. The ideal beta customer is a construction firm, building owner, and/or building operator that has significant holdings or customers. VoltServer has been in discussions with Tishman Construction, Beacon Properties, and Positive Energies LLC, who are all are prime examples of these ideal customers. Positive Energies LLC is a major building owner/operator who is already working with VoltServer on a PET microgrid pilot. Positive Energies have written a letter of support for this Phase II project expressing their strong interest in additional PET pilots for SSL applications. During this task, VoltServer will select a beta customer and site based on their ability to successfully demonstrate the objectives of the Phase II project. The planned installation would be 5,000 sq. ft. or greater.

**Status:** The Sinclair project in Fort Worth, Texas was selected for this project component. Since the system was installed in January 2017 the building owner has hosted dozens of walk throughs and demos to other building owners, design firms, real estate investment trusts. A two-floor CVS store is one of the tenants that willingly adopted the DC infrastructure.

Large OEMs have also toured the facility including LG, Samsung, Delta Controls and many others. The Sinclair owner is now preparing to install PET in the remainder of the Sinclair complex, including the adjoining 15-floor Marriott Autograph hotel. The Marriott project is a commercial contract for VoltServer outside of the DoE program. VoltServer is now involved in a number of resulting commercial opportunities directly resulting from the DoE program at Sinclair.

Please see section 3.3 of the Fraunhofer report for more detail on the Sinclair installation.

***Task 3.2 Field Test Plan Development***: VoltServer and Fraunhofer will collaborate to revise the experimental design from the Year 1 pilot. As in the Year 1 pilot, Fraunhofer will conduct side-by-side performance assessment of PET technology compared to conventional technology. In addition, the installation process itself will be audited to quantify differences in installation time, labor cost, and materials. To accomplish this, the systems will be installed using an “equivalent” installation setup – i.e., the same number of fixtures, with same spatial configuration. Fraunhofer will audit the full installation process, including: (1) materials; (2) design time; (3) install time; and (4) labor cost. During the actual installation, Fraunhofer will conduct detailed analysis of installation tasks, divided into buckets with a “Time & Motion” analysis. This will, for example, distinguish between time spent laying conduit vs. wiring vs. controls integration.

**Status:** The Sinclair project in Fort Worth, Texas was selected for this project component. It was not possible to conduct a full side by side testing with legacy electricity fixtures because the building owner opted to fully convert the building to PET and PoE powering. Fraunhofer did, however, apply lessons learned from Pilot #1, data provided by the building owner, and vendor data to estimate installed cost of the “as built” system to other power distribution technologies. The results of this analysis indicate significant reduction in the installed cost of a PET+PoE power distribution system relative to conventional wiring methods. These results were also consistent with the anecdotal experience of the building owner. The system was first installed in January 2017 and has been operating continuously without incident.

Please see section 3.3 of the Fraunhofer report for more detail.

***Task 3.3 Pilot SSL System Installation:*** VoltServer will contract with an independent design and construction vendor to install the pilot system, including the installation audit. Fraunhofer will install data acquisition instrumentation. VoltServer and Fraunhofer will jointly qualify the installed system to verify that the system is functional.

**Status:** The Sinclair project in Fort Worth, Texas was selected for this project component. The building owner opted to use their own internal employees and contractors for the installation.

Please see section 5.3 of the Fraunhofer report for more detail on power consumption and operation.

***Task 3.4 Field Test Plan Execution:*** Fraunhofer will execute the field test plan, revising as necessary based on consultation with VoltServer. As in Year 1, VoltServer will be involved in developing the experimental design and managing the overall project task, but Fraunhofer will ultimately execute the testing and validate the results to preserve independence.

**Status:** The Sinclair project in Fort Worth, Texas was selected for this project component.

Please see section 3.3 of the Fraunhofer report for more detail on the installation execution.

***Task 3.5 Assessment and Reporting:*** Fraunhofer will review data with VoltServer on an ongoing basis, and then revise the Year 1 analysis to incorporate results from the Year 2 pilot, including the installation audit. The results of this analysis will be a validated lifecycle cost model and accompanying white paper that assesses the performance of PET-integrated SSL technology.

**Status:** Completed. Please see the Fraunhofer report for more detail.

**Task 4: Project Management and Reporting (Months 1-24)**

VoltServer will manage the project according to best practices, including budgeting, forecasting, resource allocation, subcontractor management, and technical communications (reports, presentations, etc.). The results of the Phase II effort will be consolidated into a comprehensive final report. VoltServer will conduct this work in their R&D laboratories in East Greenwich, RI.

**Status:** Completed. Please see the Fraunhofer report for more detail.

**Task 5: Commercialization (Months 1-24)**

In Phase I, at no cost to the Government, VoltServer will work with Fraunhofer and other project partners and industry stakeholders to develop a path to market. Cree, VoltServer and Fraunhofer will jointly contribute insight during the program to identify market opportunities that have the most attractive value proposition and sharpen the program objectives accordingly. This will include identifying potential partners such as building owners, building operators, lighting designers, controls and integration companies. These efforts are outlined in detail in the commercialization plan. The results of this effort will be presented in the Phase II final report. VoltServer will conduct their portion of the work in their R&D laboratories in East Greenwich, RI. Fraunhofer will conduct their portion of the work in their R&D center in Boston, MA. Both parties will travel as necessary.

**Status:** The pilot #2 installation resulted in a stream of ongoing opportunities. Much of this was due to a building owner that is a fervent proponent of intelligent DC infrastructure. The owner, Farukh Aslam of Sinclair Holdings hosted dozens of walk throughs and demos to other building owners, design firms, real estate investment trusts. Mr. Aslam spoke and directly promoted PET at industry conferences including BICSI international and Cisco Live. The work of the DoE program resulted in numerous commercial opportunities that promote intelligent, connected infrastructure with a primary focus on solid state lighting.

END OF REPORT

Fraunhofer USA Center for Sustainable Energy Systems

# Low-Cost, High Efficiency Integration of Solid State Lighting and Power Over Ethernet using a DE Power Distribution System

Final Report to VoltServer

by Matthew Kromer, Sidharth Choudhary, and Tsz Yip

April 2018

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# Technical Report

| | |
|---|---|
| **Project Title:** | Low-Cost, High Efficiency Integration of Power-Over-Ethernet Lighting using a DE Power Distribution System |
| **Reporting Period:** | July 2017 – January 2018 |
| **Submission Date:** | April 28, 2018 |
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# Table of Contents

# Executive Summary

Fraunhofer CSE conducted a pilot deployment and technical evaluation of DE-integrated solid-state lighting (SSL) for two different applications. The Phase I pilot evaluated the use of digital electricity (DE)-integrated lighting in a high-bay lighting application. The Phase II pilot evaluated the deployment of DE power distribution to power Power-over-Ethernet (PoE) switches in a mixed-use commercial application at the Sanger Building in Fort Worth, Texas.

The scope of this assessment consisted of: (1) deploying DE power distribution in an operational setting to gain operational experience with the technology; (2) evaluating the labor to install a DE-integrated LED lighting system relative to conventional LED lighting; (3) characterization of the power conversion efficiency of DE power distribution to conventional power distribution topologies; and (4) conducting bottom-up analysis of the installed cost of commercial projects using DE power distribution relative to conventional power distribution methods.

Key findings and recommendations are summarized below:

- DE systems were successfully installed, inspected, and are in continuous operation at two different pilot locations: In Phase I, the 20,000 Providence Jet Center hangar, part of the Quonset State Airport in Rhode Island, was retrofitted with energy efficient solid state lighting by replacing the high intensity discharge (HID) fixtures onsite. The retrofit resulted in a ~200% increase in illumination and 75% increase in the lighting efficiency. In Phase II, DE power distribution was installed at the Sanger Building in Ft Worth, Texas to drive PoE switches in a connected buildings application. The Sanger Building installation has been operating continuously since commissioning in Jan 2017.
- Time and motion analysis of the lighting installation process indicate that, at scale, a DE installation reduces labor installation time by 15% (smaller projects) to 30% (larger projects). This is due to a ~50% decrease in wiring time. In addition, the time and motion analysis highlighted potential for further streamlining the DE installation process by utilizing a simpler connector for fixture interconnections.
- The power conversion efficiency of DE direct-drive, DE bridge-mode, and conventional AC-driven LED systems was characterized over multiple product iterations, as was a DE+PoE system. The direct-drive system shows an AC-to-LED input power conversion efficiency of approximately 93%, comparable to the performance of a conventional AC-drive LED systems. Losses are primarily due to the DE chassis power supply, measured at ~96%. The power conversion efficiency of the optimized bridge mode system was approximately 87%. Losses are primarily due to the chassis (~96% efficiency) and the LED driver (~94% efficiency). Power conversion efficiency of the conventional LED system was measured at approximately 93%. The DE+PoE system show full-load power conversion efficiency of ~86%.
- Installed cost was evaluated over a range of deployment scenarios that evaluate the impact of technology, installation size, labor classification, and labor estimation methodology. The resulting analysis indicates a reduction in labor cost for lighting projects ranging from 60% for non-electrician scenarios, approximately 30% if electrician labor rates are applied. For the DE+ PoE case, the results indicate reduction in the total installed cost on the order of 30% relative to both

a conventional AC case and an AC+PoE case. Because the commercial lighting application uses a large number of relatively low power end loads, the installation cost savings dominate, so these results appear to be robust across a range of deployment scenarios. The DE high bay lighting application is characterized by fewer, larger user loads. As such, materials costs comprise a larger portion of the installation cost, so the additional cost of the DE hardware makes the overall value proposition context-specific. For direct-drive applications, savings range from 15-30%. The additional hardware cost for bridge-mode configuration, which is not offset by a reduction in fixture cost ranges from approximate cost-parity with conventional systems to a 20% increase in installed cost.

- DE technology shows the most potential for installations in which (1) installation labor comprises a significant fraction of the total project; (2) non-electrician labor can be utilized; (3) hardware costs are minimized (e.g., through direct-drive or other topology); and (4) other benefits, such as controls/monitoring integration, offer a significant value to the end user.

In summary, DE technology shows a great deal of potential to significantly reduce the complexity of LED installs and control integration and offers a strong value proposition for projects that entail complex wiring and installations that can benefit from tightly integrated monitoring and control of device end points.

# 1 Introduction

This report summarizes the results of a pilot deployment and technical evaluation of DE-integrated solid-state lighting (SSL) in two different applications. This work was performed under DOE Award No. DE-SC0011860.

Phase I evaluated the use of digital electricity (DE)-integrated lighting in a high-bay lighting application. High-bay lights using a DE power distribution system were installed at the Quonset Airport in Rhode Island. Fraunhofer CSE conducted a time and motion study of the installation process to quantify differences between installation of conventional SSLs and DE-integrated SSL for new construction and monitored operation of the technology at the Quonset site. A separate benchtop characterization of DE technology was conducted to assess the comparative power conversion efficiency of conventional SSLs, and two different DE-integrated SSL configurations – "bridge mode" and "direct drive". Results of this analysis were used as inputs to an installation cost model of DE-integrated SSLs that can be used to extrapolate results of this evaluation to a broader array of deployment scenarios for DE-integrated high-bay lighting.

Phase II evaluated the deployment of DE power distribution to power Power-over-Ethernet (PoE) switches in a mixed-use commercial application at the Sanger Building in Fort Worth, Texas. The pilot deployment offers a case study in the use of DE to enable to enable "connected buildings" that combines rapid and flexible installation with ubiquitous sensing and control of user loads. Additional benchtop testing and analysis extended the results of the Phase I testing to quantify the comparative efficiency of a PoE+DE application. Results from the Sanger Building install were then used as inputs to the installation cost model to develop the value proposition for DE+PoE lighting.

This report is organized as follow: Section 2 provides a brief overview of DE technology. Section 3 summarizes the results of the two DE pilot deployments, which were used to characterize the installation and operation of a DE power distribution system. Section 4 summarizes the results of efficiency testing. Section 5 summarizes the methodology and results of our analysis of installation costs. Section 6 summarizes overall results and lessons learned from this study.

# 2 Technology Overview

Digital Electricity (DE) technology enables distribution of high voltage (~336V) DC power in buildings. By embedding a validation signature directly in the power distribution signal, a DE power distribution system has the ability to rapidly detect and arrest power flow in the event of a fault, thereby limiting system exposure to dangerous fault currents. This inherent and unique safety feature qualifies a HVDC DE system as a limited power circuit under NEC Article 725, which therefore eliminates the need for conduit and has the potential to limit the need for electrician labor in commercial lighting applications.

Fraunhofer CSE evaluated several different DE configurations within the scope of this project:

- Bridge-Mode High Bay fixtures: Standard Cree high bay fixtures outfitted with a DE receiver allowing it to operate on Digital Electricity. The receiver converts DE-to-DC which is then fed to the LED driver. This system adds an additional layer of power conversion which has a bearing on the overall system efficiency.

- Direct-Drive High Bay fixtures: Purpose-built fixtures which work directly on DC power, allowing for centralization of AC-to-DC conversion and elimination of distributed LED driver circuitry.
- DE-powered Power-over-Ethernet switches, capable of powering a range of end-user loads

# 3 Pilot Deployment of DE Power Distribution

## 3.1 Overview

The project team conducted two different pilot deployments of a DE power distribution for two different potential applications.

In Phase I, DE- and conventional high-bay SSLs were installed at the Quonset State Airport (KOQU) in North Kingstown, Rhode Island. The goals of this pilot were to: (1) provide a case study of LED lighting in a commercial application; (2) provide a side-by-side comparison of the labor required to install DE-integrated LED lighting relative to conventional LED lighting; and (3) provide an operational case-study of DE-integrated LED lighting in a commercial application. Fraunhofer CSE managed the installation and conducted a field evaluation of the installation process and operational performance of DE lighting, with VoltServer providing technical support.

In Phase II, DE-integrated Power-over-Ethernet lighting was installed at the Sinclair Complex in Ft Worth, Texas. The Sinclair project is a full rehabilitation of a 15 floor, 1940s era building into a new Marriott Autograph Collection hotel combined with an adjacent 9 floor building containing a CVS, Data Center and commercial space. The project incorporates the latest intelligent building infrastructure including high efficiency VRF heating and cooling and PoE throughout the complex. The PoE powers and controls LED lighting, motorized blinds, HVAC, access controls, security and a portfolio of Internet of Things (IoT) devices. The scope of Pilot #2 entailed using DE to power PoE switches for the Sanger Building, a 9-floor building at the Sinclair project. The Phase II pilot installation was managed by the customer and supported by VoltServer. Fraunhofer CSE conducted an onsite review of the Phase II installation, which provided data to support refinement of the installation cost model to model a PoE + DE application.

## 3.2 Case Study #1: LED Lighting Retrofit at the Quonset State Airport in North Kingstown, Rhode Island

A lighting retrofit was performed at the 20,000 square foot aircraft hangar part of the Providence Jet Center. The hangar is actively used on a daily basis for the berthing and maintenance of aircraft. Consequently, the entire construction and commissioning process had to be accomplished with minimal disruption.

### 3.2.1 Pre-Retrofit Lighting Configuration

The existing lighting consisted of 18 Hubbell 400W High Intensity Discharge (HID) hi-bay luminaires installed on 3 different branch circuits. Illumination was inadequate due to a combination of factors:

- Not enough fixtures to cover the entire space, leading to dark spots around the entire space

- Decay in light output of HID luminaires on account of age leading to reduced illumination and flickering. Moreover, some fixtures would cycle on and off without human intervention.
- Protective Lens on the bottom of the fixture was accumulating debris leading to even more reduced illumination from each fixture
- Slow start-up, with fixtures requiring up to 15 minutes to output at maximum light level. This meant that these fixtures could not be adapted for any smart controls such as daylighting or occupancy.

*Figure 3-1: HID fixture*

### 3.2.2 Post-Retrofit Lighting Configuration

The existing 18 HID lights were replaced with 35 250W Cree LED high bay fixtures. Initially, we installed 10 DE-integrated (Gen 1 bridge mode) LED fixtures and 25 conventional fixtures; we later upgraded a single string of conventional LEDS to DE-integrated LEDs for a total of 15 DE-integrated fixtures, and 20 conventional. Due to the lower power consumption of the LED fixtures as compared to the HID fixtures (~40% lower), the additional conventional fixtures (25 fixtures in total) were able to tap into existing branch circuits, eliminating the need to run new conduit and wiring to the mains distribution panel. However, the 15 new DE fixtures did require wiring to a DE distribution cabinet co-located with the mains distribution panel. Because the DE fixtures did not require conduit, the incremental effort for this portion of the wiring was quite straightforward.

By installing a combination of both conventional and DE-integrated SSLs, we were able to compare the two technologies in an operational environment and get valuable operational experience with DE lighting while mitigating the risk of installing DE technology by ensuring improved lighting performance from conventional SSLs alone.

### 3.2.3 Lighting Improvement

An important part of the retrofit project was to increase the illumination level in the hangar space. To demonstrate the increase in lighting levels throughout the hangar, the project team marked out a grid of

19 points throughout the space to measure lighting levels pre and post the retrofit. The lighting measurement was done with the Asensetek Lighting Passport spectrometer device, which is a "smart" spectrometer, controlled by a smartphone. It is a highly capable device, with a measuring range of 50-50,000 lux at +/- 3% accuracy (@1000lux standard light source).

There was a significant improvement in lighting in the space, with a post-retrofit average of almost 4 times more light than before the retrofit. Occupants further indicated improved user experience with the new fixtures, in particular due to the fact that (1) the new fixtures turn on instantly, increasing operational efficiency; and (2) the new fixtures did not flicker or suffer from the end-of-life degradation indicated by the pre-retrofit HID fixtures.

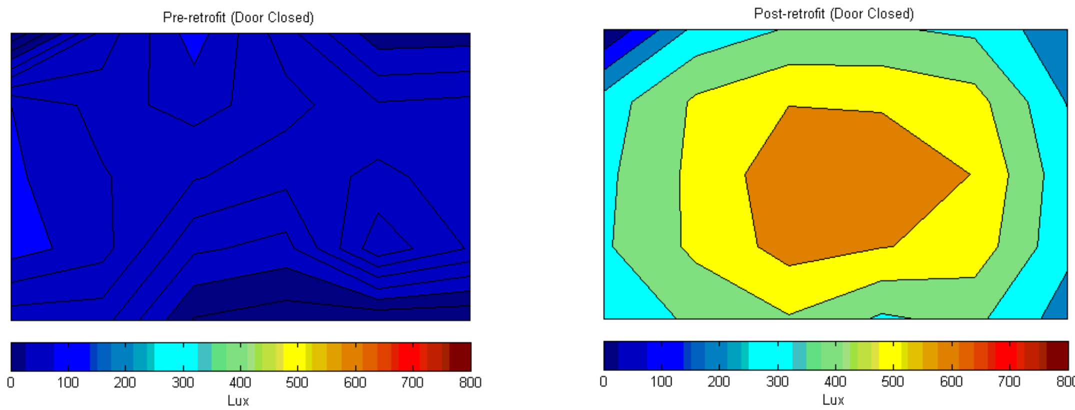


*Figure 3-2: Lighting profile hangar space (top view)*

*Figure 3-3: Hangar lighting, before (left) and after (right) retrofit*

 

### 3.2.4 Equivalent HID Install

The average illumination achieved in the hangar post the retrofit is more than 40 foot candle (430 Lux). To estimate the number of HID fixtures required to maintain the same level of illumination in the space, we utilized photometric data available for the fixtures. Apart from the standard/ non-recoverable losses due to the ballast and luminaire temperature, we factored in “recoverable” light loss factors such as Luminaire Dirt Depreciation (LDD) and Lamp Burnout (LBF) factors to model the lighting using HID fixtures. The LDD factor for the existing scenario in the hangar is lower than normal due to the accumulation of debris on the bottom lens. While this can be mitigated by regularly cleaning out the fixtures, it adds to the maintenance cost and is not done, in practice. In the case of the SSL fixtures, the absence of the bottom lens results in a much improved LDD, leading to less avoidable lumen depreciation.

*Table 3-1: Equivalent HID Lighting*

| System | Scenario | Lifetime | Fixtures | Lumens | Light Loss Factor (LLF) | Watts/ Fixture | Total Watts | W/ sq ft | Initial Illumination (Lux) | Mean Lifetime Illumination (Lux) | Lighting Oversizing % |
|---|---|---|---|---|---|---|---|---|---|---|---|
| SSL | As installed | 50,000 | 35 | 24,000 | 0.93 | 240 | 8,400 | 0.42 | 430 | 430 | 0% |
| HID | Clean fixtures, minimal loss due to dirt/debris | 15,000 | 39 | 36,000 | 0.7 | 400 | 15,600 | 0.78 | 430 | 538 | 25% |
| HID | Regular Cleaning, higher loss due to debris accumulation between cleanings | 15,000 | 45 | 36,000 | 0.61 | 400 | 18,000 | 0.90 | 430 | 624 | 45% |
| HID | No cleaning, as observed on site | 15,000 | 51 | 36,000 | 0.54 | 400 | 20,400 | 1.02 | 430 | 710 | 65% |

To account for lifetime degradation and dirt depreciation, an HID system will be required to be oversized. For the scenario observed at the airport, the system would require 16 more fixtures to provide the same illumination as the SSL system over its usable lifetime. However, with regular cleaning, this number can be reduced to only an additional 10 fixtures.

Moreover, the usable lifetime of the HID system is about 15,000 hours with up to 30% lumen loss after 8,000 hours of operation. On the other hand, SSL fixtures are designed to last much longer up to 100,000 hours but suffer light depreciation of 30% by 50,000 hours, necessitating replacement. In the lifetime of an HID luminaire, the SSL loses <4% light output.

Further, oversizing has a direct impact on the O&M costs of the lighting system as each HID fixture has a rated power of 400 W, which is 1.6x of the LED fixtures rated at 240 W. Thus, oversizing will result in a power draw of more than 2 times that of the LED fixtures for 45 HID light fixtures and >2.4 times in the worst case scenario of 51 HID fixtures.

### 3.2.5 Installation Labor Study

#### *3.2.5.1 Methodology*

The purpose of this study was to evaluate the differences in the installation of DE-integrated SSLs vis-à-vis conventional SSLs, in a controlled environment, with an aim to quantify the differences in installation time from installing DE lighting.

To gather this data, we undertook a "time and motion" (T-M) study, in which we observed the activities of the electrical contractor during the installation. In this way, we were able to generate a side-by-side comparison of the two installation methods to capture the processes involved in a typical high bay lighting construction project. Moreover, such a T-M study allows for a granular analysis of the specific tasks involved in the two installations, which can help to identify specific areas of improvement.

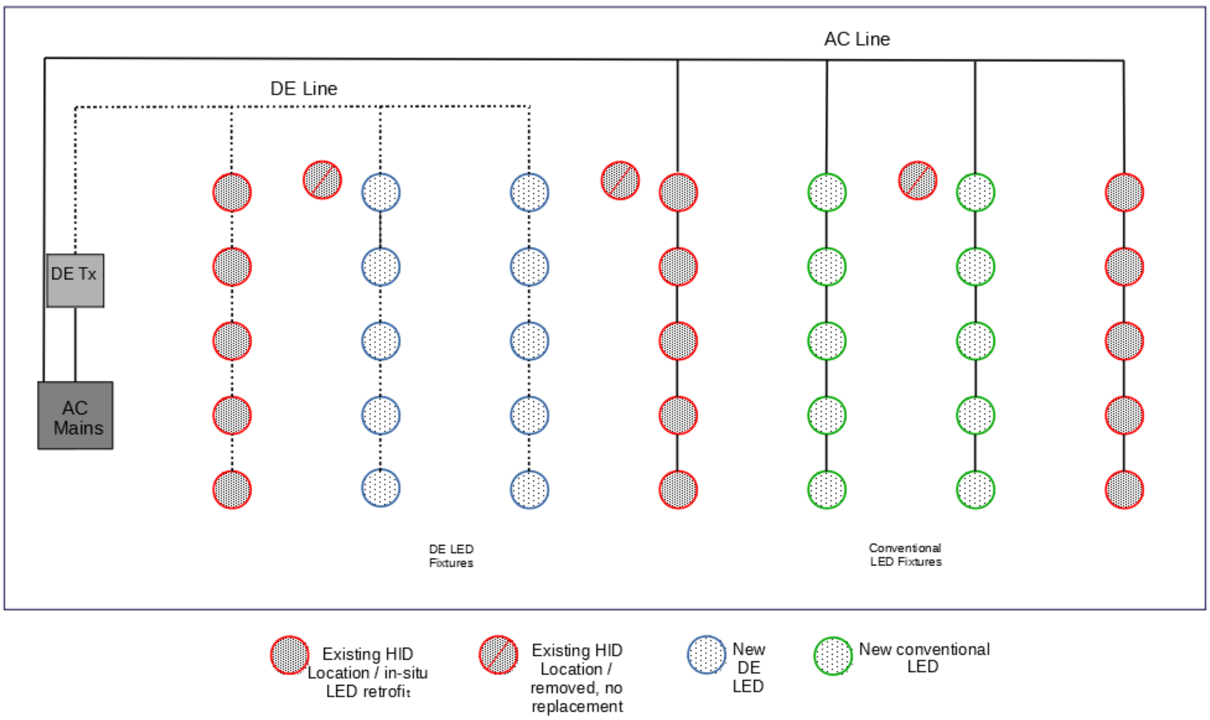


*Figure 3-4: Planned Lighting Layout*

As shown in Figure 3-4, the spatial configuration of the lights in the hangar was such that a side-by-side comparison of the conventional versus DE-integrated SSL installation would be straightforward. The side-by-side installations were essentially "equivalent", each with 2 rows of 5 luminaires, with similar spacing and similar obstructions present in each row. However, one difference was that the DE fixtures needed to be wired back to a DE power distribution hub co-located with the main distribution panel. In the case of the conventional fixtures, existing wiring was tapped to provide power to the 10 new fixtures. It is to be noted that in the case of a new installation, any fixture, be it conventional or DE, would have to be wired back to the mains.

The work for the installation was contracted to a 3rd party electrical contractor, based in Rhode Island (See Appendix for complete work order and contractor quote).

To avoid influencing the results, the protocol for the T&M study was designed to be non-intrusive. The researchers met the electrician on the install day and took about 15 minutes to review the project and familiarize the contractor with DE technology. Apart from explaining the need to wire the DE-integrated fixtures back to the mains panel, the researchers did not specify any other tasks or provide any instructions on how to proceed with the installation. Most of the work was performed by a single electrician independently, with only a few tasks requiring support from another person. The entire installation, including addition of extra conventional LED fixtures in the space, was performed across two different periods, May 26th-28th, 2016 and July 18th-25th, 2016.

A team of 3 Fraunhofer researchers observed the entire installation process, noting down time taken for various activities as captured in the table presented below. Labor was divided into "Installation Categories" and "Tasks", some of which are not differentiated between the two technologies, with the times being noted anyway (Table 3-2). Two time-lapse cameras recorded the entire installation to permit researchers to review and analyze in greater detail, if necessary.

The procedure for recording the install time was as follows:

1. Start stopwatch upon start of a new task. Note clock time to nearest minute
2. Select appropriate "Installation Category" and "Task". Provide detailed description including number of people, any obstructions, errors or any other exceptional occurrence during the task.
3. On completion of task, hit "lap time" and note down stopwatch time. Note down clock time to nearest minute

The detailed recording procedure accorded great fidelity to the installation times noted. Moreover, the extensive notes and video allowed for accurate post processing of the data to correct for variances and inefficiencies during the entire process. Further, the data was supplemented and corroborated against similar construction time and cost data from the RS Means Electrical Cost Data handbook (39th edition 2016).

*Table 3-2: Installation Categories*

| S.No | Installation Categories | Associated Activities | DE/ Conventional / Both | Notes |
|---|---|---|---|---|
| **1** | Fixture Install | Lift Move | Both | Time spent on maneuvering scissor lift to fixture location |
| | | Mark Locations | | Marking fixture mounting spots |
| | | Fixture Install | | Mounting of I hooks and hanging SSL fixture, connecting either to juncton box ot "T" connector |
| **2** | Wire Install | Lift Move | Both | Time spent on lift movement along wire path |
| | | Mark Locations | Conventional | Marking of junction box and conduit clamp locations |
| | | Prepare Conduit | | Bending and cutting of conduit |
| | | Mount Conduit | | Mounting and securing of conduit to the ceiling beam |
| | | Mount Junction Box | | Mounting of junction box above fixture locations |
| | | Pull wire | | Pulling 10AWG cable in the conduit |
| | | Make electrical connections | | Wire junction box, attach NEMA L7 "Phe" twist lock receptacle |
| | | Class 2 cable preparation | DE | Stripping conductors to feed into "T" junction connector |
| | | Mount T-splice connectors | | Securing "T" connector to ceiling beam |
| | | Mount cable | | Securing class 2 cabling to ceiling using wire ties and clamps |
| **3** | DE Cabinet Install | Mount Cabinet | DE | Hang wall mount enclosure |
| | | Install DE electronics | | Mount DE transmitter chassis |
| | | Make electrical connections | | Wire DE chassis |
| | | Distribution Panel Upgrades | | Installation of circuit breakers and running feeds to DE chassis |
| **4** | DE Homerun | Lift move | DE | Moving lift along homerun path |
| | | Class 2 cable preparation | | Stripping conductors to feed into "T" junction connector |
| | | Mount T-splice connectors | | Securing "T" connector to ceiling beam |
| | | Mount cable | | Securing class 2 cabling to ceiling using wire ties and clamps |
| **5** | Ancillary Time | Staging | Both | Staging of materials before beginning of specific tasks |
| | | Planning | | Time spent on learning and planning execution of task |
| | | Logistics | | Waiting time for equipment from shop |
| | | Clean up | | Cleaning up at the end of day |
| | | Off time | | Lunch and other off time |

#### 3.2.5.2 *Results*

A breakdown of installation time from the T&M study is shown in Figure 3-5.

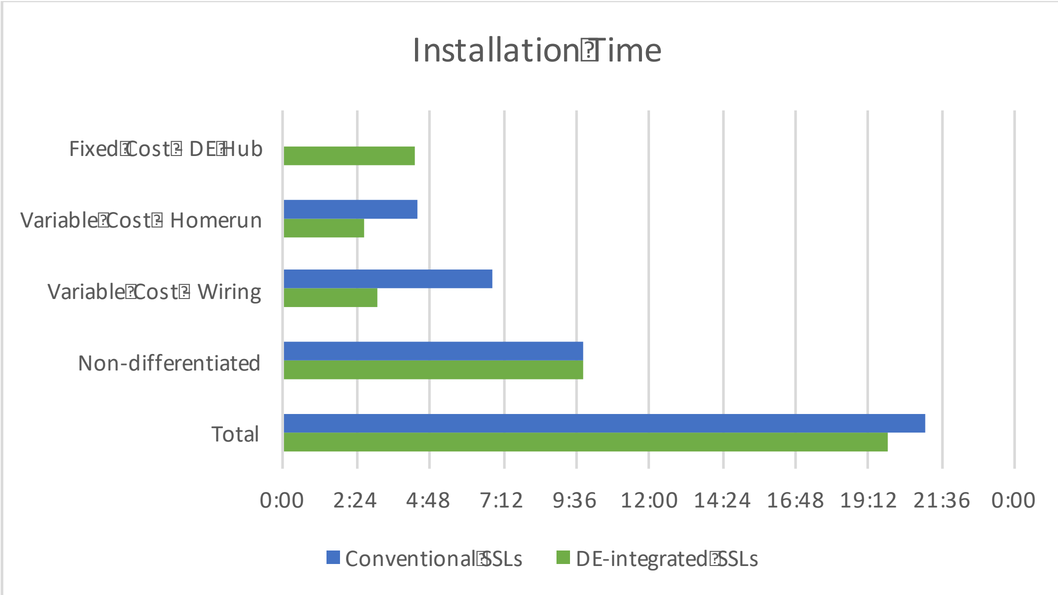


*Figure 3-5: Installation Time Comparison*

To help interpret this data, it is useful to segment installation time into several different components:

**"Fixed Installation Cost":** The "fixed cost component" corresponds to the installation labor required to install the DE hub, comprising a standard wall mount enclosure and DE chassis, which is responsible for converting AC power to DE power. This hub is an intermediate between the mains distribution panel and the DE SSL fixtures. This component exists only for the DE-integrated case as it involves the installation. This is viewed as a "fixed cost" insofar as a single DE hub is sufficient to service more than 10X the number of fixtures captured within this study.

**"Variable Installation Cost":** The "Variable Installation Cost" components consist of the time taken to lay wiring and connect fixtures within a row of lights, and the time it takes to run branch circuit wiring back to the main distribution panel ("homerun"). As noted above, the conventional fixtures were tied to pre-existing circuits and did not have a homerun installed to the mains panel. To correct for this difference, we extrapolated intra-row wiring data for the conventional lights to estimate the time required to run a conduit homerun as would be required for conventional SSL fixtures in the absence of pre-existing circuits.

**Non-Differentiated Activities:** The "Non-differentiated" category captures all the tasks that are independent of the lighting technology being installed including hanging of luminaires, staging and cleanup operations, as well as non-productive time. The time shown for "non-differentiated" activities reflects the mean of the observed between the two installs, as these do not reflect a meaningful differentiator.

As shown:

- Wiring time for the DE system is approximately 45% less than the conventional system due to the use of class 2 wiring.

- The need for a DE hub imposes an approximately 4 hour “fixed cost” on installation of a DE system. As the number of fixtures serviced increases, this component becomes a less and less relevant component of the overall labor budget.
- For the Quonset airport installation, the labor savings equates to approximately 5% of the total. However, this result is somewhat skewed by the fact that the scope of the DE install extended to only 10 fixtures. Extrapolating the results to an installation that fully populates the DE hub, the installation time difference is on the order of 30%.

In addition, it is worth noting that nearly 33% of the time spent wiring the DE system within a row entailed preparing the “T-type” connectors used on the DE fixtures. Based on a post-install evaluation of an alternate push-wire type connector, we believe that the non-homerun wiring time could be reduced by a further 15% (i.e., the “Variable Cost-Wiring” component installation task could be 15% faster than meaured).

#### 3.2.6 Operational Data from Quonset Installation

The Quonset airport installation was commissioned on July 25, 2016 and was inspected by the local wires inspector on Oct 24, 2016 (see appendix for letter of completion). This included DE-integrated fixtures in strings #1 and #2. Both commissioning and inspection proceeded as a conventional lighting project. An initial failure of a DE fixture on String #2 caused the fixture to be removed for testing. It was not replaced to avoid disruption to the airport. Due to the tight packing arrangement in the hangar, all aircraft must be removed to allow access to the ceiling for repairs.

On September 8, the contractor converted one string of conventional LEDs to DE LEDS, bringing the total to 20 conventional and 14 DE-integrated fixtures.

The installation has been in service since July 25, 2016. During the initial burn-in period, we experienced a failure of one more DE fixture, and an unexpected shut down of one DE string. The fixture was restored by swapping in a new receiver, the string was restored by cycling firmware from the ground. In December 2016, String #1 of DE lights failed. As the airport expressed satisfaction with the improved lighting even without the operational string, and repair would require moving the aircraft out of the hanger and exposure to the winter weather, the string was not restored until August 28, 2017 after the busy summer season concluded. A receiver failure had caused the string to become non-operational. These types of initial failures are to be expected when deploying a new technology for the first time. We recommend additional root cause analysis to ascertain the source of these failures such that corrective action can be taken.

Both the conventional and DE strings were instrumented throughout the period of the pilot to measure relative power consumption. The average power draw for a conventional fixture was approximately 236W, while the average power draw for the DE fixtures was approximately 245W – approximately 4% higher. The difference in power consumption between the conventional and DE system is significantly lower than that measured during benchtop testing (which was approximately 10% for the bridge mode system). It should be noted that the in-field measurements were not rigorously controlled (e.g., variability in fixtures and wiring loss could introduce measurement error). Other factors that could cause this discrepancy include (1) higher LED driver efficiency in the bridge mode system due to its higher input voltage (336V vs 277V); (2) a material difference in the receivers used in the field relative to that used for benchtop testing; (3) more optimal loading of the chassis, thereby reducing losses. A more systematic field assessment would be needed to better understand this issue.

After these initial repairs the installation ran continuously without issue. Presently, there are 34 SSL fixtures including 14 DE-integrated fixtures operational at the airport. A summary of uptime for each of the DE strings and the conventional fixtures is shown in Table 3-3.

*Table 3-3: Summary of Operational Performance*

| | Fixtures | Operational Days | Total Days | Uptime % | Comments |
|---|---|---|---|---|---|
| **DE String 1** | 5 | 240 | 240 | 100% | After repair of initial string failure. Repaired August 28, 2017 |
| **DE String 2** | 4 | 639 | 639 | 100% | Commissioned July 25, 2016<br>5th fixture was removed for testing but not replaced. |
| **DE String 3** | 5 | 594 | 594 | 100% | Conventional String was converted to DE on September 8, 2016 |
| **Conventional** | 20 | 639 | 639 | 100% | |

## 3.3 Case Study #2: Pilot Deployment of PoE DE Lighting at the Sinclair Building Project

DE-integrated Power-over-Ethernet lighting was installed in the Sanger Building at the Sinclair Complex in Ft Worth, Texas. The Sanger building is a 9-floor building including a mezzanine, basement and sub-basement. Each floor is 9,000 square feet. Presently, the 1$^{st}$ floor is being redesigned to accommodate a CVS pharmacy, floors 2 & 3 are datacenters, floors 4 to 8 are renovated office spaces (Figure 3-6).

*Figure 3-6: Sanger Building (foreground) with Sinclair Building in the back (Image provided by Sinclair Holdings, LLC)*

A block diagram of the Sanger Building installation is shown in Figure 3-7. Ceiling mounted, plenum rated, 8 port POE switches (CDB series) were installed throughout the Sanger building close to clusters of loads (on the order of 25 ft from the switch). The switches are used to power and control a range of POE loads such as SSL lighting, motorized blinds, HVAC, access controls, and security. In total, the installation included approximately a 100 LED fixtures in each data center and 290 fixtures on each of the office floors. These lights replaced traditional AC lighting systems that existed in the building till July 2016. Each POE switch is coupled with a DE receiver, which in turn receives power from a centrally located DE transmitter over a single 2-conductor limited power circuit cable. VoltServer transmitters were installed in a server room on the sixth floor of the complex. The pilot deployment of DE technology at the Sanger Building was managed by the building owner, with technical support provided by VoltServer. Fraunhofer CSE conducted a site visit to Fort Worth, Texas, to survey the project and interview the installation team (Figure 3-8Figure 3-9). The Sanger hotel DE installation was commissioned in January 2017, and has been in continuous service since that time, with no noted failures in the DE or POE systems through March 2018.

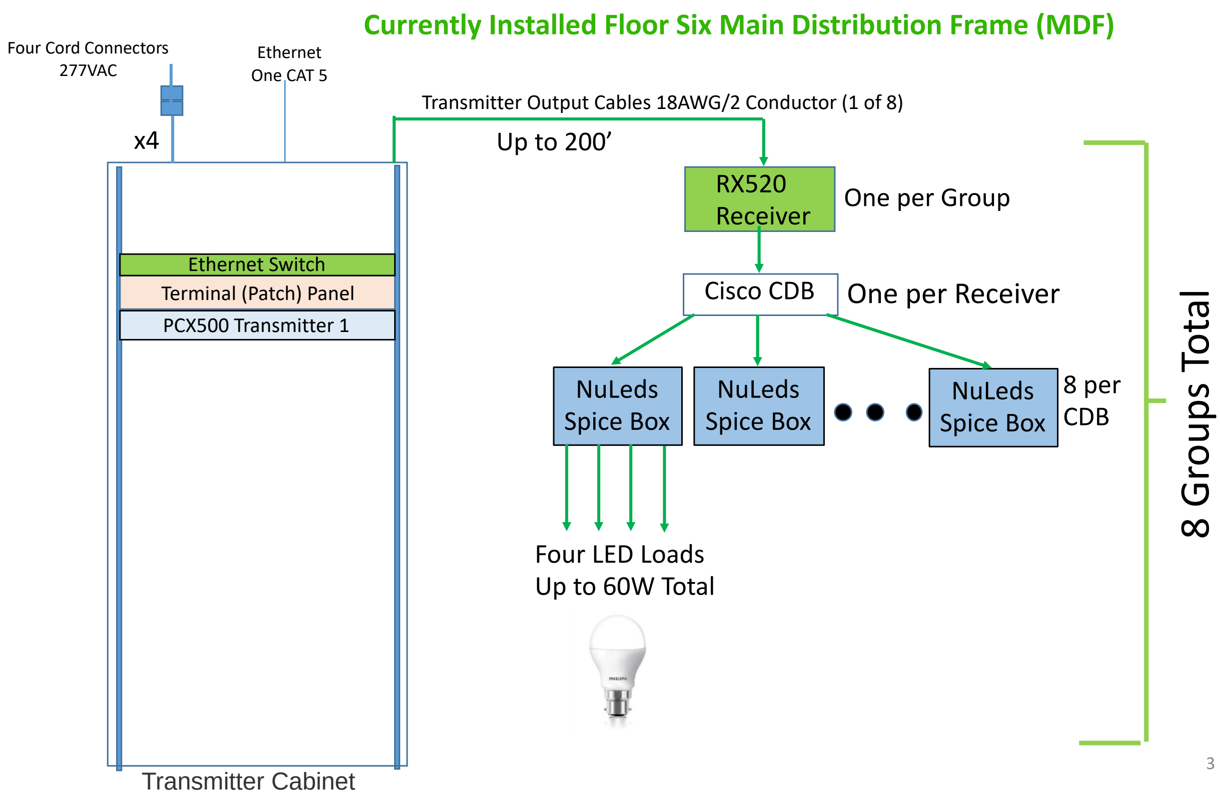


*Figure 3-7: Block Diagram of DE + PoE network installed in Sanger Building*

The value presented by DE for the Sinclair project customer was threefold. First, the hybrid DE/POE solution simplified the installation process. First, Cisco CDB PoE switches were installed throughout the complex without the need for “hard conduit” wiring needed in conventional commercial electrical systems. In addition, due to the use of limited power circuit wiring enabled by DE, the majority of the wiring was done by in-house IT networking staff. Sinclair’s project team estimates that the combination of simplified installation and the use of in-house non-electrician staff saved approximately 60% on labor and material for wiring. Although this estimate was not independently reviewed in the context of the

Sanger install, this estimate is roughly consistent with results generated by the installation cost model described in Section 5.

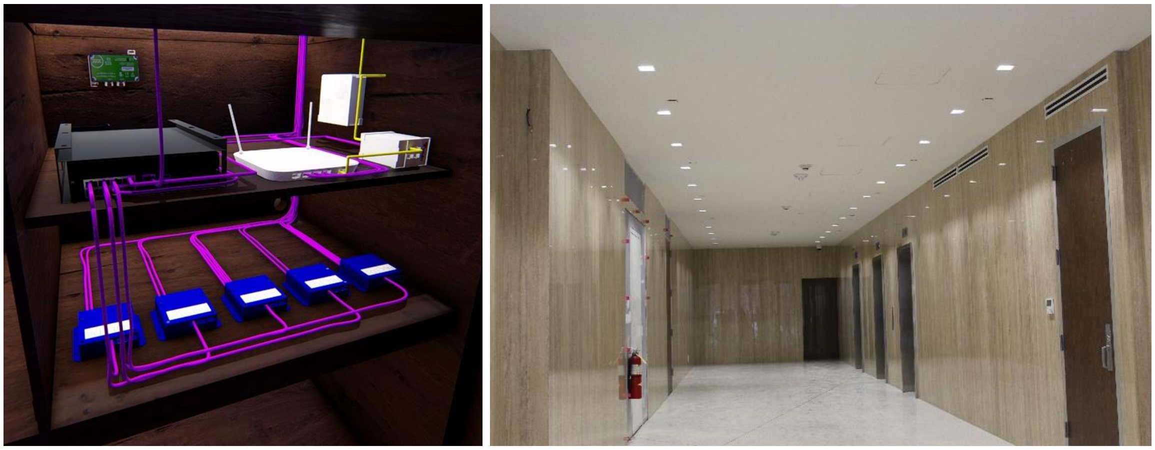

*Figure 3-8: Rendering of Cisco Switch with VoltServer Receiver and ethernet cabling to loads (Left). POE lighting powered by DE in the Sanger building (Right)*

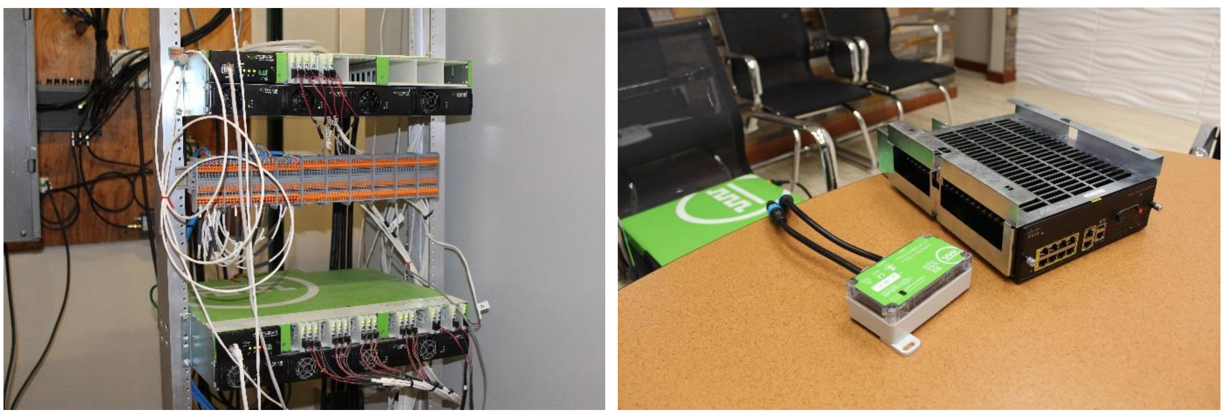

*Figure 3-9: VoltServer Server Rack (left) VoltServer Rx520 and Cisco CDB-8U (right)*

Second, using limited power circuit wiring in lieu of a traditional hard-conduit solution allows for simplified configuration and re-configuration of the floor space, which is of particular value for the mixed-use space in the Sanger building. Third, the combination of DE+POE provides near-universal monitoring and control of end-user loads and environmental sensors throughout the building (see Figure 3-10Figure 3-11). This ubiquitous sensing and control provides increased insight into the building energy usage and has allowed the system to be optimized for regular operations as well as implement advanced functionalities such as power conservation and prioritization in case of emergencies. We were not able to rigorously quantify the cause of any change in power consumption due to the deployment of DE+PoE due to the lack of well-defined baseline.[1]

[1] Sanger staff showed a 20% decrease in energy bill year over year that coincides with installation of DE technology, but this may conflate multiple contributing factors, such as differences in weather, occupancy, loads, and application, that extend beyond the differences in technology.

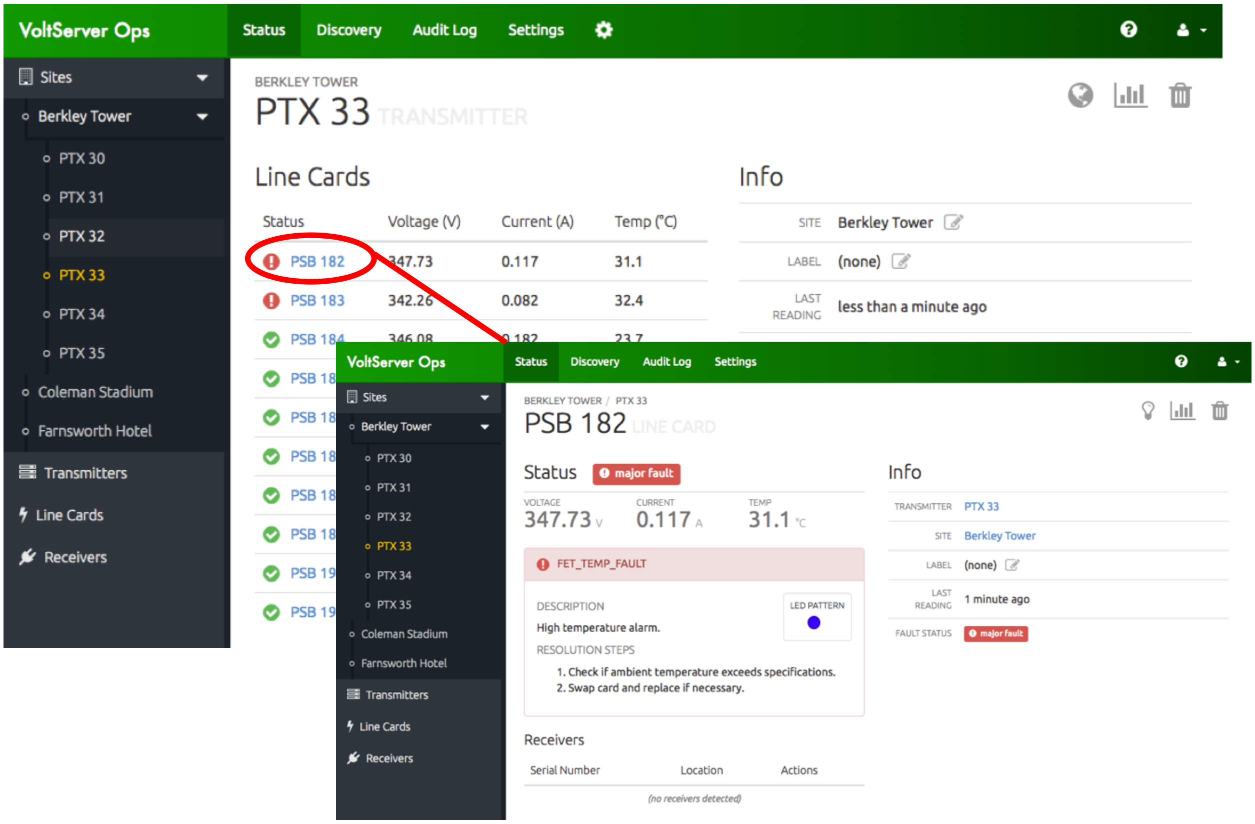


*Figure 3-10: Fault detection and isolation using the VolltServer API*

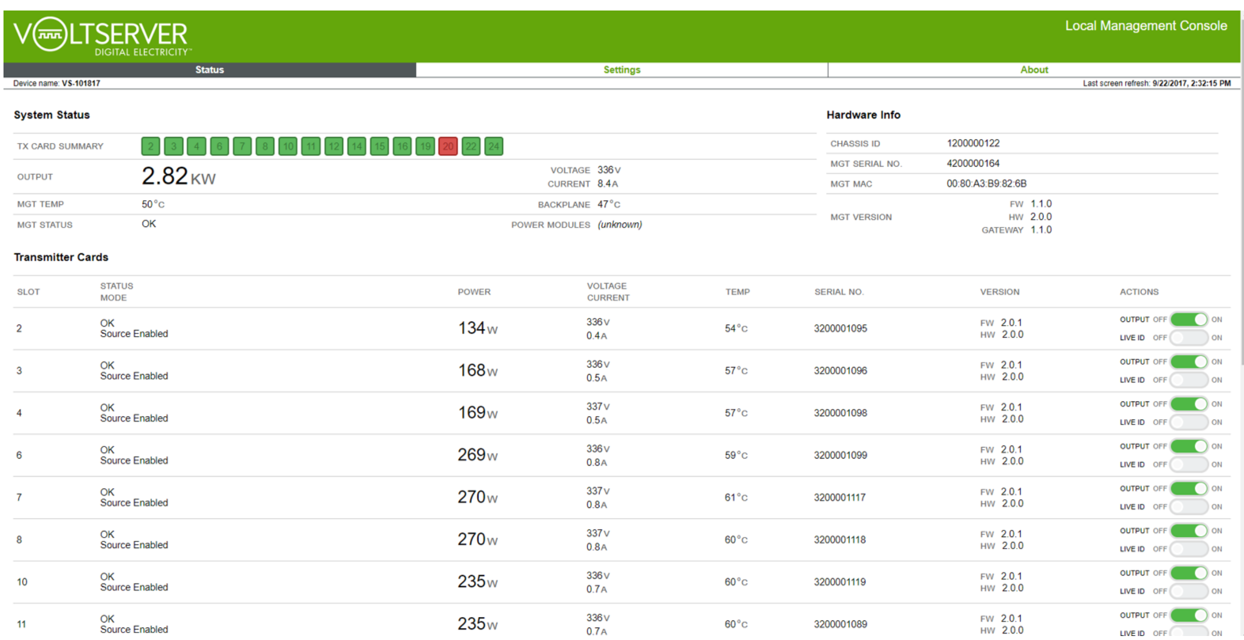


*Figure 3-11: Real-time monitoring of user loads*

# 4 Characterization of Power Conversion Efficiency

## 4.1 Overview

Fraunhofer CSE conducted benchtop testing of a DE power distribution system to characterize the power conversion efficiency of DE as applied to the user applications evaluated during Phase I and Phase II.

During Phase I, the system efficiency of direct-drive and bridge-mode DE-integrated SSL fixtures were compared to a conventional AC SSL fixture. During Phase II, the end-to-end system efficiency of a DE+PoE power distribution system were compared to a conventional AC power distribution system. Testing was performed at Fraunhofer CSE and at VoltServer by Fraunhofer technical staff, and supported by VoltServer engineers.

Efficiency was calculated by measuring the input and output power of the system under test. For these tests, the system input was defined as the connection to AC mains, and the output was defined as the input to the end-user load.

$$\eta = \frac{output\ power}{input\ power}$$

*Figure 4-1: Benchtop testing in progress*

## 4.2 DE-Integrated High Bay Lighting Test Results

A block diagram of the system configuration is shown in Figure 4-2 (bridge mode) and Figure 4-3 (direct-drive). As shown, power was measured at 3 locations: the AC input, the DE transmitter input, and the LED fixture input. Because different cabling systems were used for the AC and DE configurations, measurements of the DE system efficiency and the AC efficiency were adjusted to account for these differences in the wiring loss. This enabled us to separately capture the efficiency of the DE chassis and the combined efficiency of the DE transmitter, receiver and wiring. The direct drive and bridge mode configurations differ insofar as the direct-drive system does not include an LED driver. We measured power at the DE driver output as well to characterize performance and corroborate with losses estimated based on data from the spec sheet.

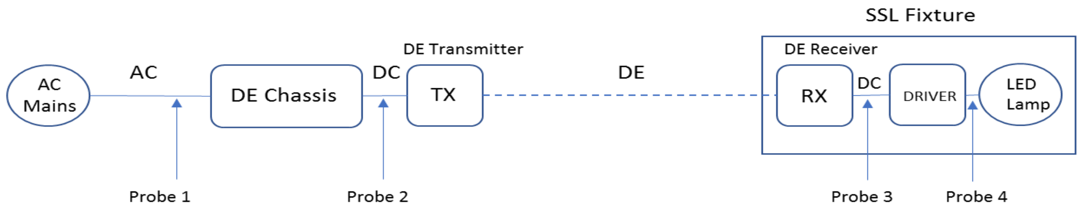


*Figure 4-2: Schematic of DE bridge mode fixture under test*

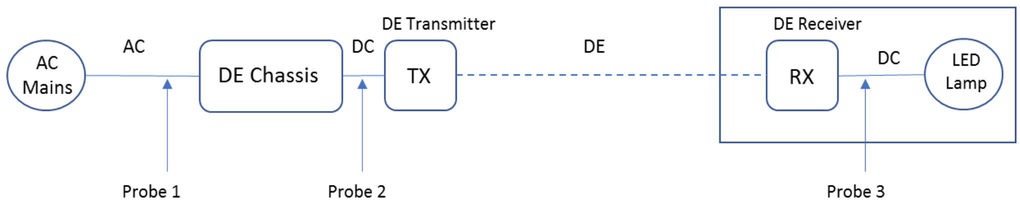


*Figure 4-3: Schematic of DE direct drive fixture under test*

Two different versions of the DE bridge mode system were evaluated. The "Gen 1" configuration replicates the hardware and Cree LED fixture that was installed at the Quonset airport. The "Gen 2" configuration is an improved production version of the DE transmitter and receiver. In addition, the "Gen 2" and "Direct Drive" were tested using an HP Winner fixture. The reason for using an alternate fixture was that the direct drive configuration did not appear to be compatible with the Cree fixture.

A summary of the measured efficiency for each of the four system configurations (Gen 1 bridge mode, Gen 2 bridge mode, direct-drive, and conventional) is shown in Table 4-1 and Table 4-2.

*Table 4-1: DE System efficiency with Cree fixture*

| System | Cable | DE Chassis | DE Sys (Tx-Rx) | Fixture | Overall Efficiency |
|---|---|---|---|---|---|
| **DE bridge mode - Gen 1** | 99.0% | 95.5% | 96.2% | 93.0% | 84.6% |
| **DE bridge mode - Gen 2** | 99.0% | 95.5% | 98.0% | 93.0% | 86.2% |
| **AC** | 99.3% | na | na | 93.0% | 92.4% |

*Table 4-2: DE system efficiency with HP Winner fixture*

| System | Cable | DE Chassis | DE Sys (Tx-Rx) | Fixture | Overall Efficiency |
|---|---|---|---|---|---|
| **DE bridge mode - Gen 2** | 99.0% | 95.5% | 98.0% | 93.8% | 87.0% |
| **DE direct drive** | 99.0% | 95.5% | 97.8% | na | 92.5% |
| **AC** | 99.3% | na | na | 93.8% | 93.2% |

As shown, the DE bridge mode configuration shows higher power conversion losses than the conventional configuration, with the direct-drive configuration showing lower loss than the bridge mode system due to elimination of the LED driver.

In general, the DE performed as expected – particularly in the direct drive case. During evaluation, it was noted that the primary driver for the DE system losses was the DE chassis power supply. We recommend exploring higher efficiency supplies to mitigate this issue as well as devising an optimum power sharing algorithm between multiple supplies to ensure suitable loading for highest efficiency operation all the chassis power supplies.

### 4.3 DE + PoE Power Distribution System Results

A similar methodology was used to characterize power conversion efficiency of the DE+PoE application as deployed at the Sanger Building in Fort Worth. The Sanger Building configuration consists of an AC mains connection to a VoltServer DE transmitter, which connects to a DE receiver, a Cisco CDB switch, a NuLEDs POE lighting controller (SPICEBox) and multiple POE LED light loads as shown in Figure 3-7. However, the end-loads and lighting controller were not available for test, which necessitated a modified test configuration in which POE splitters[2] were used to convert the POE to DC power in lieu of the NuLED controller and used DC power to drive a programmable load bank that replicates user loads. Due to multiple issues encountered with the Cisco switch, we were unable to test the PoE switch across its full operating range.[3] As such, we took measurements to the extent possible, and extrapolated a load curve over the full operating range of the DE system (12 kW).

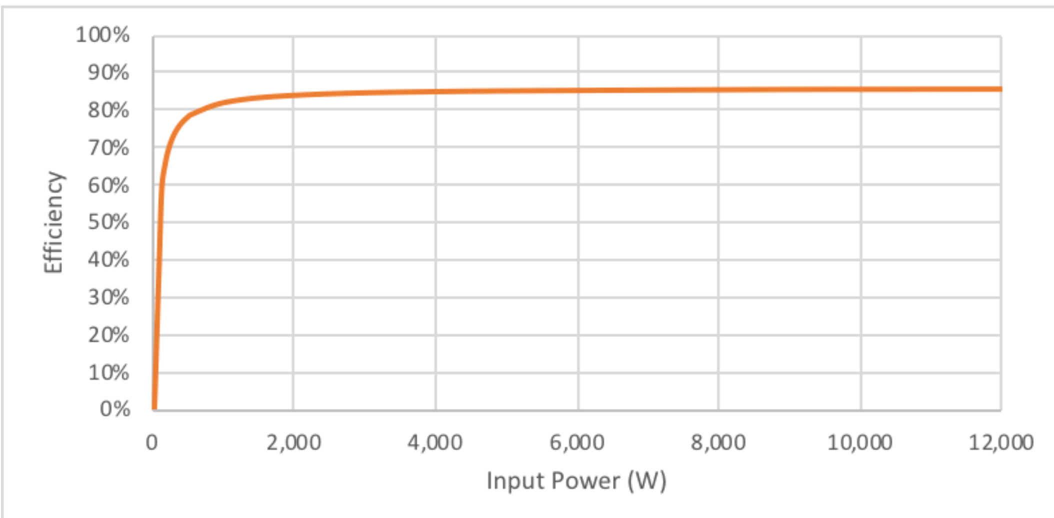


*Figure 4-4: DE+PoE System Efficiency*

An estimated load curve of the full DE-PoE system is shown in Table 4-3 Figure 4-4. It is to be noted that an individual Cisco CDB switch outputs a maximum of 480 W. Hence, 'End Load Power' shown below assumes multiple switches for load exceeding 480 W. As shown, system efficiency is lower than the conventional LED lighting baseline, at approximately 86% throughout the transmitter's operating range.

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[2] Planet 172s: UPOE splitter

[3] We were able to load only three ports to 50% loading. We replicated the same issues with both a DE and AC front-end, indicating that issues were with the downstream PoE equipment, not an unforeseen interaction with the DE equipment.

*Table 4-3: DE + PoE Power Measurements*

| Input Power (W) | DE Standby Power (W) | POE Standby Power (W) | DE Power Conversion (W) | POE Power Conversion (W) | End Load Power (W) |
|---|---|---|---|---|---|
| 47.10 | 23.60 | 23.49 | 0.00 | 0.00 | 0.00 |
| 114.17 | 23.60 | 23.49 | 13.05 | 9.33 | 44.70 |
| 150.99 | 23.60 | 23.49 | 8.63 | 5.86 | 89.40 |
| 202.93 | 23.60 | 23.49 | 12.94 | 8.79 | 134.10 |
| 254.88 | 23.60 | 23.49 | 17.26 | 11.72 | 178.80 |
| 306.82 | 23.60 | 23.49 | 21.57 | 14.65 | 223.50 |
| 358.77 | 23.60 | 23.49 | 25.88 | 17.58 | 268.20 |
| 410.71 | 23.60 | 23.49 | 30.20 | 20.51 | 312.90 |
| 462.66 | 23.60 | 23.49 | 34.51 | 23.44 | 357.60 |
| 514.60 | 23.60 | 23.49 | 38.83 | 26.37 | 402.30 |
| 566.54 | 23.60 | 23.49 | 43.14 | 29.31 | 447.00 |
| 1,085.99 | 23.60 | 23.49 | 86.28 | 58.61 | 894.00 |
| 2,124.89 | 23.60 | 23.49 | 172.57 | 117.22 | 1,788.00 |
| 4,202.67 | 23.60 | 23.49 | 345.13 | 234.44 | 3,576.00 |
| 8,358.25 | 23.60 | 23.49 | 690.26 | 468.89 | 7,152.00 |
| 10,436.04 | 23.60 | 23.49 | 862.83 | 586.11 | 8,940.00 |
| 12,513.83 | 23.60 | 23.49 | 1,035.40 | 703.33 | 10,728.00 |
| 13,812.44 | 23.60 | 23.49 | 1,143.25 | 776.59 | 11,845.50 |

# 5 Installation Cost Model

## 5.1 Overview

A bottom-up installation cost model was developed and used to conduct a parametric study of the installed costs (i.e., the labor and materials cost) of a lighting project as a function of factors such as lighting technology, installation size, labor rate, and labor estimation methodology. The cost model was initially developed to extrapolate the results of Phase I high-bay application and was extended in Phase II to model a commercial lighting application. The basic framework for the installation cost model is as follows:

1. **Model Installation space:** # of floors, Area per floor, flighting requirements. The output is a lighting fixture and wiring layout (# of fixtures, approximate location, and length of wiring runs)
2. **Estimate bill-of-materials for the lighting technology under evaluation:** A technology-specific bill-of-materials is generated. Major categories include lighting fixtures (constant across all technologies), non-lighting hardware (e.g., VoltServer DE transmitters/receivers), and wiring/conduit requirements. Based on the specific technology in question, the length and type of wiring needed (e.g., with conduit / not conduit), and the location/quantity of non-lighting equipment are estimated.
3. **Estimate technology-specific installation labor requirements:** An estimate of installation labor for the specific technology is developed. This entails defining the types of tasks required (e.g., install conduit, install riser, install service panel, etc); the scope of each task (e.g., length of conduit install, length of riser install, number of electrical service panels, etc); and the type of labor required for each task (e.g., electrician vs non-electrician).
4. **Estimate unit labor and material costs based on a combination of vendor quotes and RS Means estimates.** Results were further calibrated / validated model based on "as built" data from pilot deployments at Quonset Airport and the Sanger building.

Hence the primary inputs to the cost model consist of a model of the installation space, unit hardware costs, unit labor rates, and the technology being modeled (e.g., DE high bay lighting, conventional high bay lighting, etc). The primary output is a total installation cost, broken down into a materials and labor cost.

## 5.2 Application of Installation Cost Model to DE High-Bay Application

### 5.2.1 Input Assumptions

Based on the installation time data and bill of materials for the Quonset installation, we constructed a bottom-up cost model to conduct a parametric study of installed costs (i.e., the labor and materials cost) as a function of factors such as lighting technology, installation size, labor rate, and labor estimation methodology. The parameters explored within this parametric study are summarized in Table 5-1.

*Table 5-1: Summary - Installation Cost Model Parameters for DE-integrated high bay application*

| Parameter | Scenarios Analyzed |
|---|---|
| **Lighting Technology** | Conventional LED /<br>Bridge-Mode DE /<br>Direct-DE |
| **Labor Category** | Electrician (DE & Conventional) /<br>Maintenance Personnel (DE Only) |
| **Installation Size** | 0-120 fixtures[4] |
| **Labor Estimation Methodology** | Unadjusted ("Actual" Effort 1X Bottom-up) /<br>Adjusted ("Priced" level of effort, 2.5X Bottom up) |

**Lighting Technology:** 3 different lighting technologies were evaluated – conventional, Bridge Mode and Direct Drive DE-integrated installations. The technologies vary in terms of both installation labor and the equipment cost for an installation. The system cost for both the Gen 1 and Gen 2 DE bridge mode systems is identical.

**Labor Category:** For a typical DE installation, only the DE transmitter hub installation requires the services of a trained electrician. Wiring can be completed by a less-skilled labor category. As such, for the two DE technology configurations, we modeled a case that assumes electrician labor rates for the entire installation, and a case that assumes wiring is completed by buildings facilities personnel or general services handyman. For the conventional LED technology, we assume that all labor is conducted by an electrician.

**Installation Size:** Costs were extrapolated as a function of installation size by scaling labor and material costs from the Quonset Airport installation according to defined labor and material categories. Results were extrapolated for a fully populated, 9kW DE transmission hub, which would support 120 luminaires.

**Labor Estimation Methodology:** Two different methodologies were used to extrapolate labor costs from our bottom-up estimate of installation labor time. The first method simply assumes that a project is priced based on the *actual* installation time. However, it is quite likely that this approach significantly under-estimates the labor cost component of actual project prices quoted by contractors. For example, using the bottom-up methodology, we find that the imputed labor cost for a large installation using conventional LED technology is approximately 15% of the total installation cost (i.e., the materials cost dominates). In reality, for the actual Quonset Install, the labor cost comprised $16K out of $30K (about 55% of the total). Based on the actual time for install – approximately 80 hours – the imputed labor rate was approximately $200/hr, about 2.5X the RS Means estimates. This pricing strategy is fairly typical within the trades. To account for this discrepancy, we evaluated one case ("Unadjusted") in which bottom up cost estimates are applied as is, and a second case ("Adjusted") in which a 2.5X multiplier is applied to the bottom-up labor costs.

The cost data for DE and lighting hardware was obtained from VoltServer. The DE hardware includes 2 price points, one for the prototype systems and the other value for at-scale production. For the

[4] 120 fixtures corresponds to approximately 30kW LED lighting load, approximately 70K square feet.

comparison study, we have considered the production cost values for the 2 DE systems. The cost numbers for the balance of materials such as conduit and cabling was taken from the RS Means Electrical Cost Data handbook.

*Table 5-2: DE hardware costs*

| ITEM | Price Each, Prototype | Price Each, Production | Comment |
|---|---|---|---|
| **VoltServer Transmitter Unit, PCX500** | $ 5,340.00 | $ 4,110.00 | 5 Chan, 9kW, Includes Wall Cabinet |
| **VoltServer Receivers, RX520-LED** | $ 243.20 | $ 108.40 | DE Bridge Mode Receiver; same pricing for both Gen 1 & Gen 2 |
| **VoltServer Receivers, Direct Drive** | | $ 20.00 | DE Direct Drive Receiver |

*Table 5-3: Fixture costs*

| ITEM | w/Driver | No Driver | Comment |
|---|---|---|---|
| **CREE High-bays, 240W, 24k Lumen** | $ 379.97 | $ 250.78 | 33% reduction in production price from removed Cree driver |

### 5.2.2 Results

A comparison of the total estimated installed cost for a 120-fixture install is shown in Figure 5-1 and Figure 5-2. Figure 9 shows the installed cost estimated using the "unadjusted" bottom up cost estimate for each of the three technologies evaluated, for both electrician and non-electrician labor rates. As shown, the materials cost dominates these installs, so despite significant reduction in labor cost, the conventional system is lower cost than the DE bridge mode configuration. However, the direct-drive system due to its reduced cost owing to elimination of driver and optimized receiver design, is more cost effective in comparison to the conventional system. Figure 10 shows the same data, but applies the 2.5X unit labor adjustment factor to bring the installed cost breakdown more in line with our real-world pricing experience. In this case, the direct-drive / non-electrician labor rate scenario is approximately 32% lower cost than the conventional system while the direct-drive / electrician system is approximately 15% less. The bridge mode / non-electrician scenario is at approximately cost parity with the conventional system, while the bridge mode / electrician system is approximately 15% more expensive.

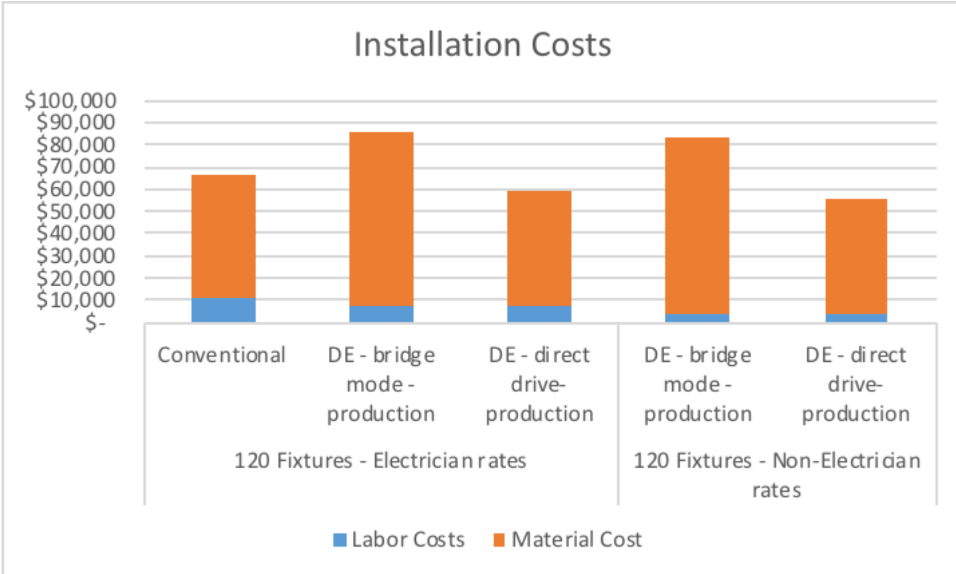



*Figure 5-1: Installation Cost Comparison at scale for all 3 systems, unadjusted labor*

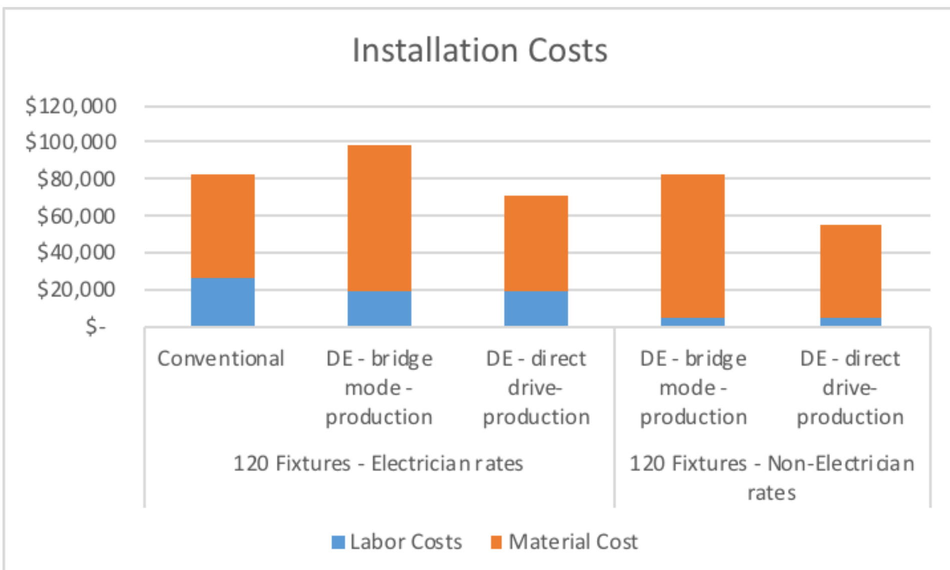



*Figure 5-2: Installation Cost Comparison at scale for all 3 systems, adjusted labor*

Figure 5-3 (unadjusted) and Figure 5-4 (adjusted) show the trend in installed cost, relative to the conventional system, for installation sizes ranging from 10 to 120 fixtures. As shown, the installed cost for DE systems rise periodically due to the need to add another DE transmitter unit to support more fixtures. A single transmitter can support 30 fixtures at observed efficiency for DE systems. Additional units can be mounted to the already installed wall cabinet.

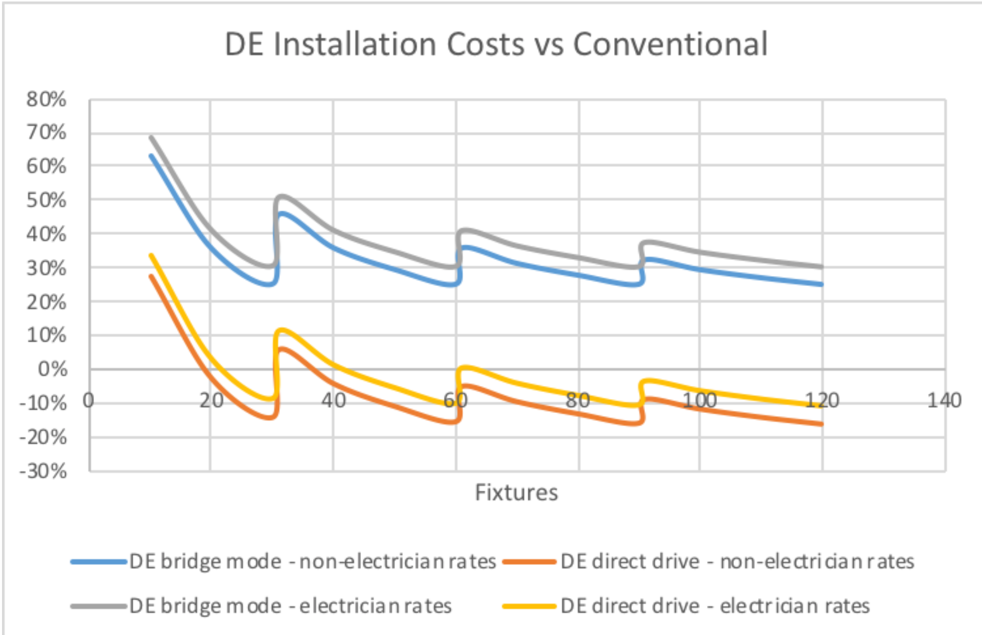


*Figure 5-3: DE system costs relative to a conventional system install, unadjusted labor*

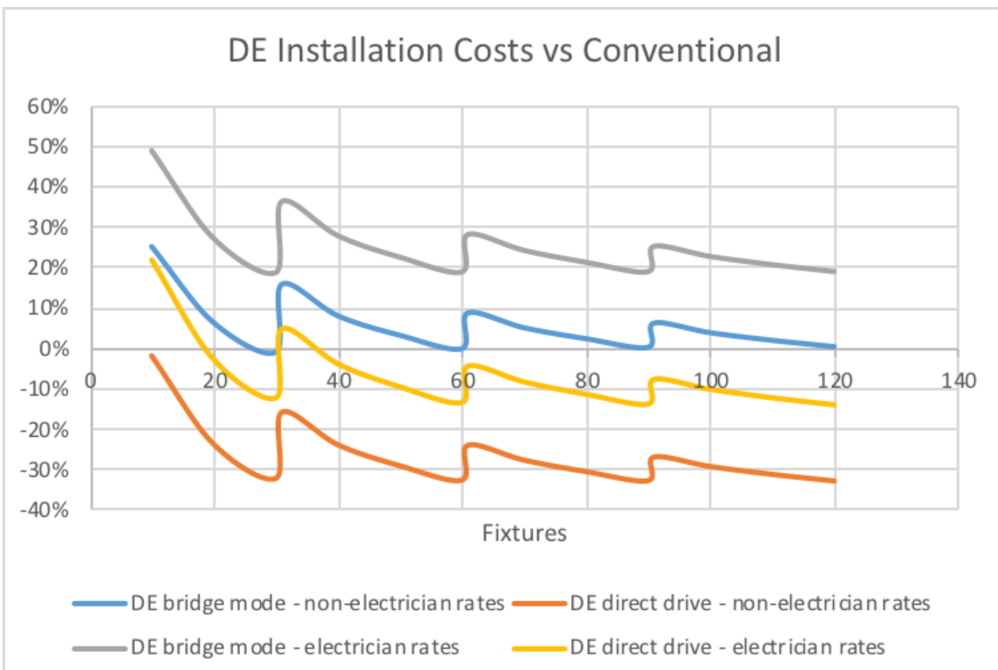


*Figure 5-4: DE system costs relative to a conventional system install, adjusted labor*

In summary, the analysis indicates that DE technology offers significant reduction in labor cost for lighting projects – approximately 60% for non-electrician scenarios, approximately 30% if electrician labor rates are applied – but the additional cost of the DE hardware makes the overall value proposition context-specific. The additional hardware cost for bridge-mode configuration, which is not offset by a reduction in fixture cost, is particularly challenging. In general, DE technology offers the most promise for applications in which:

- Installation size is larger (i.e., economics become more favorable as the scope of project increases).
- Installation labor comprises a significant fraction of the total project cost. For example, particularly complex wiring projects.
- Non-electrician labor can be utilized
- Direct-drive fixtures, or alternate system topologies that minimize the incremental material cost relative to conventional systems, can be deployed.
- Tertiary benefits, such as integration of inline controls or monitoring, offer significant user value.

## 5.3 Application of Installation Cost Model to DE Power-Over-Ethernet Application

For Phase II, the installation cost model was used to conduct a parametric study of installed costs for DE-enabled PoE applications in a commercial office building similar to the Fort Worth pilot. Three installation scenarios were analyzed as shown in Table 5-4.

*Table 5-4: Summary of Installation Cost Model Scenarios for Commercial Office Building*

| Scenario | Description | Labor Requirements | Equipment Requirements |
|---|---|---|---|
| **DE + POE** | Power Over Ethernet (POE) powered by a DE distribution system | Electrician for installing the DE transmitter hub<br><br>Balance of work performed by IT/ Maintenance staff | Electrical equipment and DE transmitter hub installed on only one floor<br><br>Each DE transmitter hub supports 3 floors, servicing 8 CDB switches and up to, for example, 256 15W lighting fixtures per floor<br><br>Conduit required from service panel to DE transmitter hub |
| **AC + POE** | POE powered by traditional AC wiring | Electrician Only for wiring to PoE Switches<br>IT/Maintenance staff install PoE wiring and fixtures | AC service panel required on each floor<br><br>Conduit required from service panel to switch |
| **AC Only** | Traditional AC wiring | Electrician Only | AC service panel required on each floor<br><br>Conduit required from service panel to fixture |

Each scenario varies in terms of both installation labor and the equipment cost of labor. Further, for a typical DE installation, only the DE transmitter hub installation requires the electrician labor. Wiring can be completed by a less-skilled labor category. In the DE scenario, it is assumed that the wiring and installation of POE switches is performed by buildings facilities personnel, as was the case in the Sanger building installation.

The installation tasks can be divided into 3 main categories:

**Electrical Service** installation which includes the main AC distribution panel, sub-panels on individual floors, safety equipment and even the DE transmitter hub. This bucket of tasks can only be accomplished by a trained electrician.

**Conduit & Cabling** installation covers all activities related to feeding AC or DE power to POE switches spread across the building. Tasks include preparation and mounting of conduit, riser install between floors, pulling wire and installation of wall switches and receptacles. Based on the nature of wiring, the task should be performed either by an electrician or a handyman. Class 2 wiring for DE and ethernet doesn't require conduit and can be accomplished by a handyman or maintenance staff.

**Fixture Install** activities include mounting the PoE switch, end user loads, and making electrical connections. In the case of an AC installation, electrician labor is required to mount and connect the POE switches but in the case of a DE installation, this task can be performed by non-electrician labor. Connecting POE loads to the switch is done using ethernet cabling which can be pulled by either category of labor. The ethernet run to loads is less than ~25 feet and is a minor task relative to other wiring tasks.

Costs were extrapolated as a function of installation size by scaling labor and material costs from a typical office floor installation. Results were extrapolated for a 9-floor office building, incorporating multiple fully populated, 12kW DE transmission hubs, supporting up to 256 15W lighting fixtures on each floor.


*Figure 5-5: POE access control (left) and assortment of POE safety/ communication devices (right)*

**Material Costs:** The cost data for DE and lighting hardware was obtained from VoltServer. The cost numbers for the balance of materials such as conduit and cabling was taken from the RS Means Electrical Cost Data handbook.

*Table 5-5: DE hardware costs*

| ITEM | Price Each, Production |
|---|---|
| **VoltServer Transmitter Unit, PCX500** | $ 4,110.00 |
| **VoltServer Transmitter Card, TX550** | $ 220.0 |
| **VoltServer Receivers, RX520-LED** | $ 108.40 |

*Table 5-6: PoE hardware costs*

| ITEM | Price ea |
|---|---|
| **Cisco CDB-8U** | $ 799.60 |

| | |
|---|---|
| **PoE driver** | $100.00 |
| **PoE light** | $30.00 |

### 5.3.1 Results

A comparison of the total installed cost as a function of building size is shown in Figure 5-6 and Figure 5-7. As shown, the DE case is approximately 30% less expensive than either the conventional AC case or the AC+PoE case. This is primarily due to significant reductions in both the labor unit cost and labor quantity relative to the other two cases examined (Figure 5-7). The difference in labor cost is split roughly 50% between process simplification (fewer hours) and between reduced unit cost (no electrician required). Relative to the conventional AC case, the DE case shows an increase in materials cost due to the additional cost of DE transmitters and receivers. However, the cost of this equipment is slightly offset by reductions in the cost of service panels (AC & AC+PoE installs both require service panels on each floor), and reduced cost of wiring (elimination of conduit).

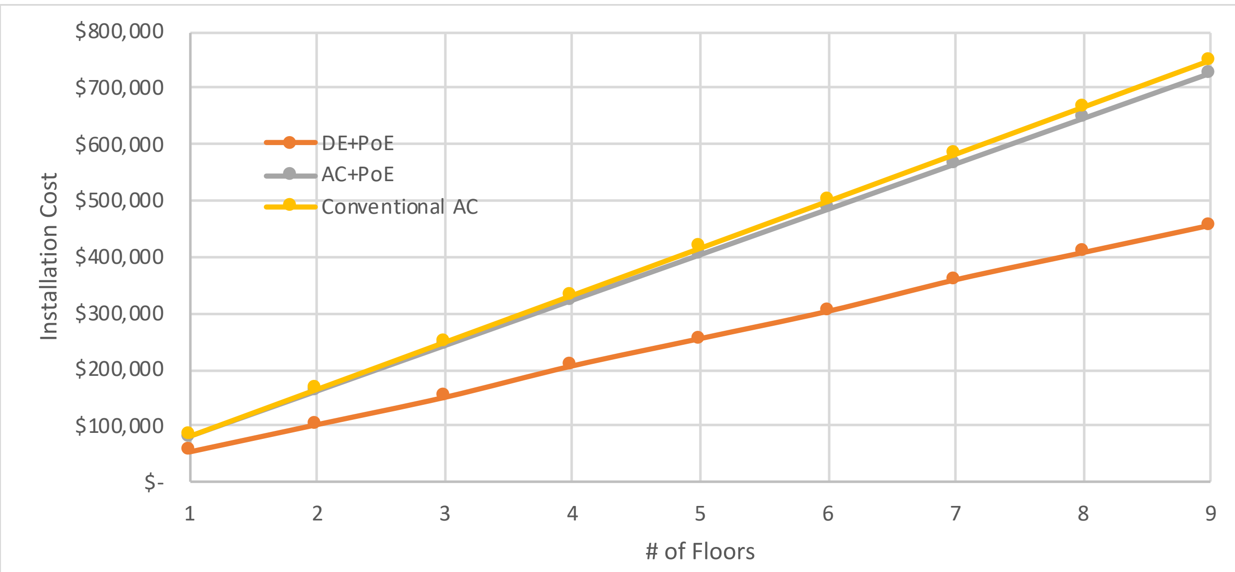



*Figure 5-6: Installation Cost for three different distribution topologies*

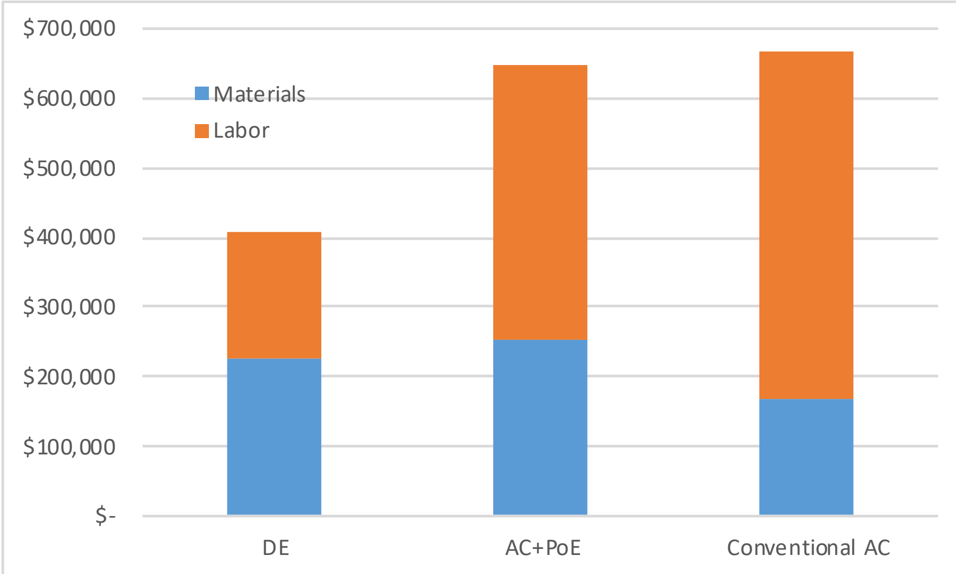


*Figure 5-7: Installation costs as a function of system topology*

## 5.4 Summary of Installation Cost Model Results

In summary, the analysis indicates that DE technology offers significant reduction in labor cost for lighting projects – approximately 60% for non-electrician scenarios, approximately 30% if electrician labor rates are applied.

For the DE+ PoE case, the results indicate a reduction in installed cost on the order of 30% relative to both a conventional AC case and an AC+PoE case. Because the commercial lighting application uses a large number of relatively low power end loads, the installation cost savings dominate, so these results appear to be robust across a range of deployment scenarios.

The DE highbay lighting application is characterized by fewer, larger user loads. As such, materials costs comprise a larger portion of the installation cost, so the additional cost of the DE hardware makes the overall value proposition context-specific. For direct-drive applications, cost savings range from 15-30% (electrician vs non-electrician labor). The additional hardware cost for bridge-mode configuration, which is not offset by a reduction in fixture cost, is particularly challenging.

The DE technology offers the highest value proposition for applications in which:

- Installation size is larger (i.e., economics become more favorable as the scope of project increases).
- Installation labor comprises a significant fraction of the total project cost. For example, particularly complex wiring projects or smaller, more varied end loads.
- Non-electrician labor can be utilized
- Direct-drive fixtures, or alternate system topologies that minimize the incremental material cost relative to conventional systems, can be deployed.
- Tertiary benefits, such as integration of inline controls or monitoring, offer significant user value.

# 6 Conclusions and Recommendations

Fraunhofer CSE conducted a pilot deployment and technical evaluation of DE-integrated solid-state lighting (SSL) for two different applications: in Phase I, we evaluated the use of digital electricity (DE)-integrated lighting in a high-bay lighting application; in Phase II, we evaluated the deployment of DE power distribution to power Power-over-Ethernet (PoE) switches in a mixed-use commercial application at the Sanger Building in Fort Worth, Texas.

The scope of this assessment consisted of: (1) deploying DE power distribution in an operational setting to gain operational experience with the technology; (2) evaluating the labor to install a DE-integrated LED lighting system relative to conventional LED lighting; (3) characterization of the power conversion efficiency of DE power distribution to conventional power distribution topologies; and (4) conducting bottom-up analysis of the installed cost of commercial projects using DE power distribution relative to conventional power distribution methods.

Key findings and recommendations are summarized below:

- DE systems were successfully installed, inspected, and are in continuous operation at two different pilot locations: DE-integrated lighting was used in a high-bay application at the Quonset State Airport. Three strings of five DE lights were installed, as well as four strings of conventional LEDs. Two of the DE strings have been in near continuous operation, an initial failure on string #1 was delayed in repair until August 2017 and has been in continuous operation since that time. DE power distribution was also installed at the Sanger Building in Ft Worth, Texas to drive PoE switches in a connected buildings application. The Sanger Building install has been operating continuously since commissioning in Jan 2017.
- Results of time and motion analysis of the lighting installation process at the Quonset pilot location indicate that, at scale, a DE installation reduces labor installation time by 15% (smaller projects) to 30% (larger projects). In addition, the time and motion analysis highlighted potential for further streamlining the DE installation process by utilizing a simpler connector for fixture interconnections.
- The power conversion efficiency of DE direct-drive, DE bridge-mode, and conventional AC-driven LED systems was characterized over multiple product iterations, as was a DE+PoE system. The direct-drive system shows an AC-to-LED input power conversion efficiency of approximately 93%, comparable to the performance of a conventional AC-drive LED systems. Losses are primarily due to the DE chassis power supply, measured at ~96%. The power conversion efficiency of the optimized bridge mode system was approximately 87%. Losses are primarily due to the chassis (~96% efficiency) and the LED driver (~94% efficiency). Power conversion efficiency of the conventional LED system was measured at approximately 93%. The DE+PoE system show full-load power conversion efficiency of ~86%. However, it should be noted that the lower overall efficiency of the DE+PoE system has the potential of being compensated by the resulting digitally connected building system with advanced building controls, such as lighting based on occupancy and ambient light, or more advanced control of HVAC systems with added features such as automatic control over window blinds.

- Installed cost was evaluated over a range of deployment scenarios that evaluate the impact of technology, installation size, labor classification, and labor estimation methodology. The resulting analysis indicates a reduction in labor cost for lighting projects ranging from 60% for non-electrician scenarios, approximately 30% if electrician labor rates are applied. For the DE+ PoE case, the results indicate reduction in the total installed cost on the order of 30% relative to both a conventional AC case and an AC+PoE case. Because the commercial lighting application uses a large number of relatively low power end loads, the installation cost savings dominate, so these results appear to be robust across a range of deployment scenarios. The DE high bay lighting application is characterized by fewer, larger user loads. As such, materials costs comprise a larger portion of the installation cost, so the additional cost of the DE hardware makes the overall value proposition context-specific. For direct-drive applications, savings range from 15-30%. The additional hardware cost for bridge-mode configuration, which is not offset by a reduction in fixture cost ranges from approximately cost parity with conventional systems to a 20% increase in installed cost.
- DE technology shows the most potential for installations in which (1) installation labor comprises a significant fraction of the total project; (2) non-electrician labor can be utilized; (3) hardware costs are minimized (e.g., through direct-drive or other topology); and (4) other benefits, such as controls/monitoring integration, offer a significant value to the end user.

In summary, DE technology shows a great deal of potential to significantly reduce the complexity of LED installs and control integration, and offers a strong value proposition for projects that entail complex wiring and installations that can benefit from tightly integrated monitoring and control of device end points.

# Appendix

## 7.1 Contractor Work Order

| | Work Package | Description | Item | Work Description | Notes |
|---|---|---|---|---|---|
| | **Electrical work order list - Quonset Airport** | | | | |
| Phase 1 | 1 | Row A & B - Conventional LED Install | 1 | Install 10 conventional LED fixtures, conduit, recceptacles, safety chains, in Rows A & B, as marked (page 2). Row A taps into existing 20A Row 3 circuit; Row B taps into existing 20A Row 2 circuit. | Conventional LED Fixtures provided by Customer |
| | | | 2 | Remove 2 existing HID fixtures (marked as 'Ex' on page 2) | |
| | 1A | Row A & B - Conventional LED (Alternate Install) | 1 | Install 10 conventional LED fixtures, conduit, recceptacles, safety chains, in Rows A & B, as marked (page 3). Individual home run wire runs from Rows A,B to two 20A breakers in breaker panel. Two home runs share one conduit run back to distribution panel (identified on page 3). | Same as item 1 but home conduit run to breakers in panel |
| | | | 2 | Remove 2 existing HID fixtures (marked as 'Ex' on page 3) | |
| Phase 2 | 2 | Install DE Transmitter Panel | 1 | Install DE transmitter panel enclosure at indicated location (page 5) | Transmitter panel provided by Customer |
| | | | 2 | Install 4 x 20A breakers in 277V distribution panel | |
| | | | 3 | Install Conduit and Feeders 4 x 20A from 277V distribution panel to DE transmitter panel enclosure (Page 7) | 8 foot conduit stub from top of transmitter, then Art 725 cable runs with hangers |
| | 3 | DE LED Install - Row C & D | 1 | Install 10 DE LED fixtures using Article 725 cable, no conduit in Rows C & D as marked (Page 5) | DE LED Fixtures provided by Customer, 1 cable for every 5 fixtures. 7 cables total. |
| | 4 | DE LED Install - Row 1, 2, 3, A, & B | 1 | Remove 3 existing HID fixtures as marked (marked as 'Ex', Page 3) | |
| | | | 2 | Replace 15 existing HID fixtures (Row 1, 2, & 3) with DE LED fixtures using Article 725 cable, no conduit (Page 6) | DE LED Fixtures provided by Customer |
| | | | 3 | Replace Conventional LED fixtures (Rows A & B) with DE LED fixtures using Article 725 cable, no conduit (Page 6) | DE LED Fixtures provided by Customer |

| **Additional Notes** |
|---|
| Work order references attached drawings of installation plan to mark install locations |
| Contractor responsible for permitting and inspections |
| Contractor to provide installation and electrical wiring plan for customer review |
| Phase 1 to occur late May |
| Phase 2 to occur late June |
| Contractor to provide suitable lift for accessing highbay ceiling |
| Customer to provide specifications for NEMA receptacles for conventional LED fixtures. Customer to provide Art. 725 Cable |
| Customer to provide all LED fixtures (conventional and DE) and DE fixture adaptor cables, contractor to provide all other materials |
| Customer responsible for disposal of HID fixtures |
| Contractor to quote each work package separately |
| Customer will provide installation instructions for DE fixtures |

## 7.2 C&K Electric Company Quote

C & K ELECTRIC COMPANY, INC.
ESTABLISHED 1923

166 DOYLE AVENUE
PROVIDENCE, RI 02906
TEL: (401) 331-3909
WWW.CKELECTRICRI.COM

April 12, 2016

Sidharth Choudhary

Fraunhofer Center for Sustainable Energy Systems CSE

RE: Quonset Airport Hanger Lighting

Dear Sir:

We have reviewed the proposed lighting upgrades at the Quonset Airport Hanger and submit the following pricing based on the Electrical Work Order List (see attached):

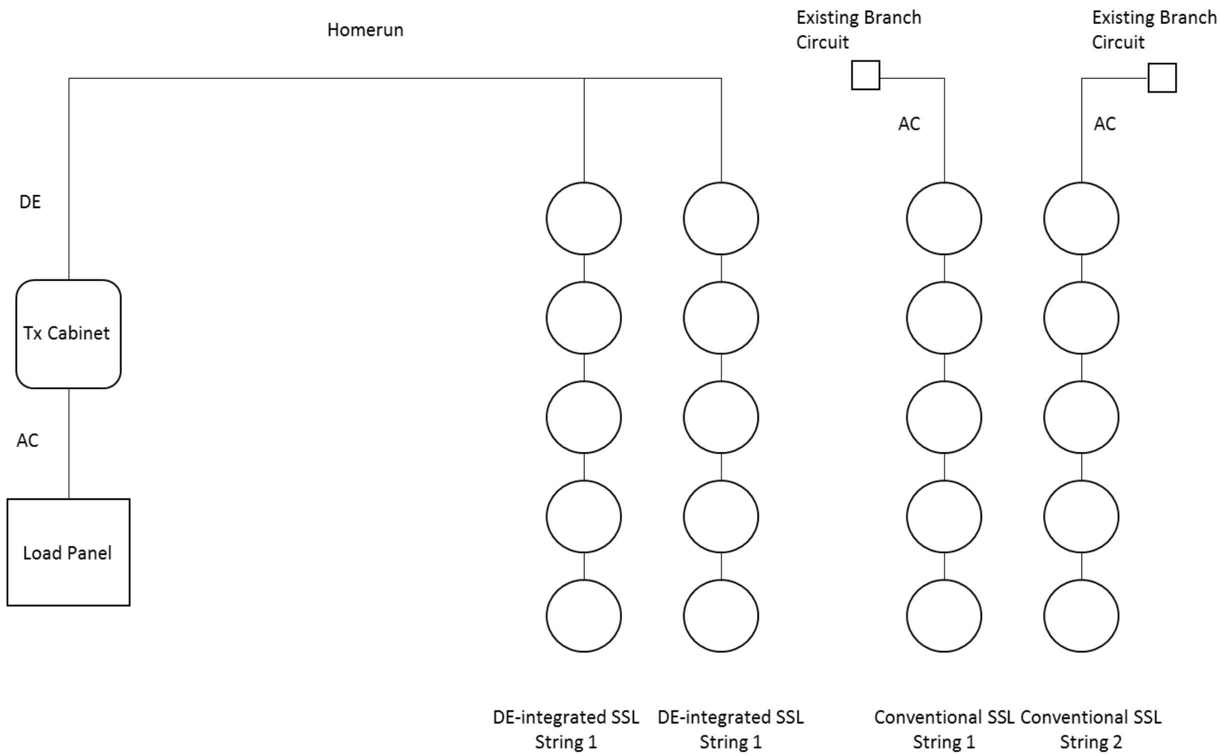
| | | |
|---|---|---|
| Work Package 1- | $6,285.00 | Add Alternate 1A- $2,790.00 |
| Work Package 2- | $1,345.00 | |
| Work Package 3- | $2,800.00 | |
| Work Package 4- | $5,300.00 | |

Very truly yours,

Robert Kelman

C & K Electric Company, Inc.
Robert Kelman

## 7.3 Side-by-Side Study Layout



## 7.4 Electrical Permit

THE STATE OF RHODE ISLAND AND PROVIDENCE PLANTATIONS
Department of Admiistration
DEPARTMENT OF CAPITAL ASSETS MANAGEMENT AND MAINTENANCE
BUILDING CODE COMMISSION
One Capitol Hill Providence Rhode Island 02908-5859

### LETTER OF COMPLETION

Project Number 16-11.03-23
Site Adress 150 Airport Road
North Kingstown

Owner RIAC
2000 Post Road
Warwick RI

Scope of Project **Install & wire 10 high bay LED lights wired from existing circuit. Install 3 - 277V 20A ckts for digital energy transmitter. Install & wire 10 digital energy LED high bay lighting fixtures using article 725 wiring method**

The work authorized by the following permits has been completed in accordance with the approved construction documents

Building Inspector
PERMIT B-0000
Signature Date:

Electrical Inspector
PERMIT E-7126 G-0000
Signature Date: 10-24-16

Mechanical Inspector
PERMIT M-0000
Signature Date:

Plumbing Inspector
PERMIT P-0000
Signature Date:

State Fire Marshal
Signature Date:

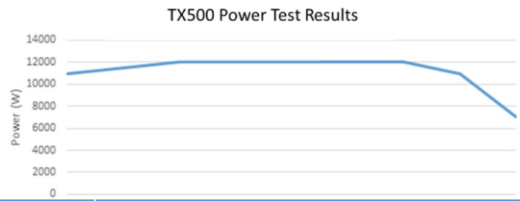
Fire Alarm Superintendant
Signature Date:

Building Commissioner
Date: 10/24/16

16-11.03-23

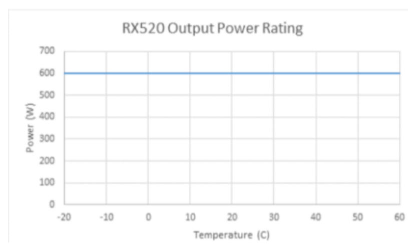
## 7.4 DE Equipment Specifications

# PCX500 Transmitter


| Item | Value | Notes |
|---|---|---|
| Input Voltage | 208-277VAC, 50-60Hz | 4 independent, 15A feeds |
| Output | 12kW 0-40°C | Up to 24 channels total <= 12kW |
| Dimensions | 16”D, 17.63”W, 3.5”H | 2U, 19” rack format |
| Weight | 20lbs | |
| Redundancy | Yes | Four hot-swappable modules, 3kW/Module |
| Efficiency | 96% | |
| Communications | Ethernet | Monitor/Control individual channels |
| Approvals | IEC/UL 60950-1, IEC/UL 60950-21, IEC/UL 62368-1, CE | |

# RX520 Receiver


| Item | Value | Notes |
|---|---|---|
| Input Voltage | DE, 320-345Vdc | DE = Digital Electricity (Packet Energy Transfer) |
| Output Power | 600W | -20 to 60°C Ambient |
| Output Voltage | 320-345VDC | |
| Dimensions | 4.72L x 2.56W x 1.59H (120L x 65W x 40.5H) | Inches (mm) |
| Weight | 0.49 lbs | |
| Environmental | IP65 | |
| Efficiency | 99.4% | |
| Communications | In-line Com. | Com. and Power on Same Conductors |
| Approvals | IEC 60950-1, CE | |