Development and Comparative Analysis of a Power-over-Ethernet (PoE) DC Lighting System for Residential Buildings

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ABSTRACT

Power over Ethernet (PoE) technology optimizes lighting systems by transmitting power and data transmission over the same Ethernet cable. This technology holds the promise of significant advancements in energy efficiency, cost-effectiveness, and flexibility in lighting design. Through PoE, lighting systems can be centrally controlled and managed, allowing for dynamic adjustments in brightness, color temperature, and fixture behavior. This enhances user comfort and leads to energy savings by optimizing usage. Furthermore, PoE eliminates the need for separate electrical wiring, simplifying installation and reducing upfront costs. This makes it an attractive choice for both new construction projects and retrofitting existing spaces. This paper explores the design and implementation of a PoE based DC (Direct Current) lighting system and the power savings and versatility offered in doing so. The system uses a PoE Switch or Relay (PoES) to direct the data and the power to the DC lights. PoE Controllers (LINCS) are used to supply the power to the lights themselves. Kinetic switches are used to supply a wireless and unpowered method of turning on and off the lights. Finally, the PoE Central Control (COR-TAP) is configured to receive input from the kinetic switches and issue commands to different LINCs. This system was installed in a real-world residential building for testing. The results show that the DC lights alone are 33% more efficient than traditional AC lighting. However, when considering the entire system, the DC test bed consumed 15W compared to 10W for the AC lighting system. Scaling the system revealed that if deployed in more than two rooms, the DC lighting system becomes more efficient, reaching a maximum of 22% power savings. Through this comparative study, it is evident that the new system can improve lighting efficiency, connectivity, and flexibility compared to traditional AC lighting systems but also calls for improving the DC distribution devices to reduce power consumption.

1. INTRODUCTION

1.1 Power over Ethernet (PoE)

The integration of Power over Ethernet (PoE) technology with Direct Current (DC) distribution has emerged as a transformative approach in the realm of lighting systems. PoE facilitates the simultaneous transmission of power and data through standard Ethernet cables, offering a versatile and efficient solution for powering various devices (Minoli et al., 2017).In the context of lighting applications, PoE presents a promising avenue for enhancing energy efficiency, cost-effectiveness, and scalability (Cao et al., 2018). DC distribution plays a pivotal role in PoE lighting systems by enabling the efficient delivery of power to lighting fixtures. By leveraging DC distribution in buildings with onsite DC sources powering end uses, substantial energy savings of up to 18 percent have been demonstrated compared to traditional Alternating Current (AC) distribution methods (Vossos et al., 2022).This integration not only optimizes energy utilization but also streamlines installation processes by eliminating the need for licensed electricians (Arnold and Pennel, 2020).

Research conducted by Tesla Motors underscores the economic advantages of deploying DC systems in commercial buildings, particularly for lighting applications. Their analysis revealed a noteworthy 5% reduction in annual costs for direct-DC Light Emitting Diode (LED) lighting systems compared to conventional AC systems (Thomas andMorgan, 2012). Furthermore, the industry is witnessing a transition towards PoE-compatible DC lights, with more than 17 manufacturers offering such products. This shift signifies the increasing acceptance and adoption of PoE technology within the domain of lighting and smart buildings (Arnold and Pennel, 2020). Despite the myriad benefits associated with PoE lighting systems integrated with DC microgrids, challenges persist. Current PoE lighting systems may exhibit lower energy efficiency than traditional AC systems in certain scenarios due to power losses in CAT 5/6/7 cabling and standby power losses in PoE switches (Harper andGraeber, 2020). Efforts are underway to mitigate these issues through the development of standards, distributed architectures, and larger gauge cables aimed at minimizing losses. However, further research and market implementation are imperative to fully unlock the potential of PoE lighting systems with DC microgrid integration

1.2 Direct Current (DC) Nanogrid House

The innovative approach taken by the DC Nanogrid House in creating a fully DC-powered residential setting provides a perfect testbed for PoE centric technologies. By integrating renewable energy sources and developing a sophisticated Energy Management System (EMS) to control the Nanogrid, the DC Nanogrid House serves as a living laboratory for exploring the benefits of DC power in residential environments (Purdue University, 2022). Most importantly, it houses a DC distribution panel. The panel serves as a 380 V DC source (Ore and Groll, 2022). It receives its power from three main sources: a battery, an inverter, and solar panels. The voltage can be stepped down and used to power PoE, Internet of Things (IoT), and household devices at 48VDC. This proves useful in two ways. It could be used to validate the reduced power consumptions of DC Nanogrids and by proxy show how DC lighting can be made more efficient with a DC source instead of an AC source.

1.3 Motivation

As highlighted before, DC Lighting research has gained significant attention over the years due to the multiple benefits it provides. The research, however, has mainly been conducted in commercial environments (Choi and Lee, 2018). Furthermore, AC distribution systems have been the standard for electricity in the US since 1885 (Allerhand, 2017).Hence, DC lighting power conservation studies have been done on AC nano grids, leading to power losses in conversion. The motivation for this research stems from a desire to bridge these existing knowledge gaps in PoE DC lighting systems and contribute novel insights to the field. This study evaluates residential lighting on DC and AC power to determine energy efficiency and cost savings with DC power distribution. Comparing DC and AC power for residential lighting aims to reveal benefits of DC power systems. The goal is to analyze how DC technology enhances energy efficiency, reduces costs, and improves scalability in residential lighting. Motivated by sustainability, innovation, and technological advancements, this research emphasizes PoE DC lighting advantages and its user-friendly nature in homes. To what extent can Power over Ethernet (PoE) Lighting on DC distribution systems reduce power consumption and increase lighting system versatility in residential spaces? This question encapsulates the core focus of investigating the transformative potential of PoE technology integrated with DC distribution specifically within the context of residential buildings. To answer the above question, A PoE lighting system will be designed, tested, and installed from scratch along with a DC distribution panel. A comparative study on power consumption and versatility of AC lighting systems on AC power with DC lighting systems on DC power will be conducted.

2. DEVELOPMENT & INSTALLATION OF LIGHTING SYSTEM

2.1 Frontend Components and Connections

The PoE consists of six main physical components. The first of the components is the power source. The DC distribution system provides a nominal 380VDC voltage and a DC stepdown circuit was used to reduce it to a nominal 48VDC.The component that directs the power and information to the different parts of the system is the PoE switch. It operates using a 48 VDC power source. The PoE switch is connected directly to the network cabinet and the COR-TAP using ethernet cables. The COR-TAP is the physical hub for the controls and configuration of the entire system. A USB receiver is attached to the COR-TAP to detect 8-byte signals within a 20 m radius. Kinetic switches are motion powered switches with two buttons. They send out an 8-byte signal with its unique device identifier that can be programmed into the system to control lighting or other devices. The data in such signals are used to control the entire system, replacing the need for physical wiring between the switches and the lights. These components can be seen in Figure 1. After receiving the signals sent out by the switches, based on the control instructions on the COR-TAP, it will route the power to the respective LINCS. The LINCs are IoT enabled devices that facilitate power routing to different loads and receive data from sensors as well. These devices, although have much wider capabilities, are used to send or not send power to the DC Lights. The DC LED lights are rated at 120lm/W (Figure 2). Each of these components are wired to each other either using CAT 5/6/7 cables to enable communication or 20 AWG cables to power components. The wiring diagrams to connect all the fundamental components mentioned above can be seen in Figure 3.

Figure 1: (a) PoE Switch; (b) COR-TAP and USB Reciever;(c) Double Rocker Kinetic Switches

Figure 2: (a) LINC power router ; (b) DC LED Light

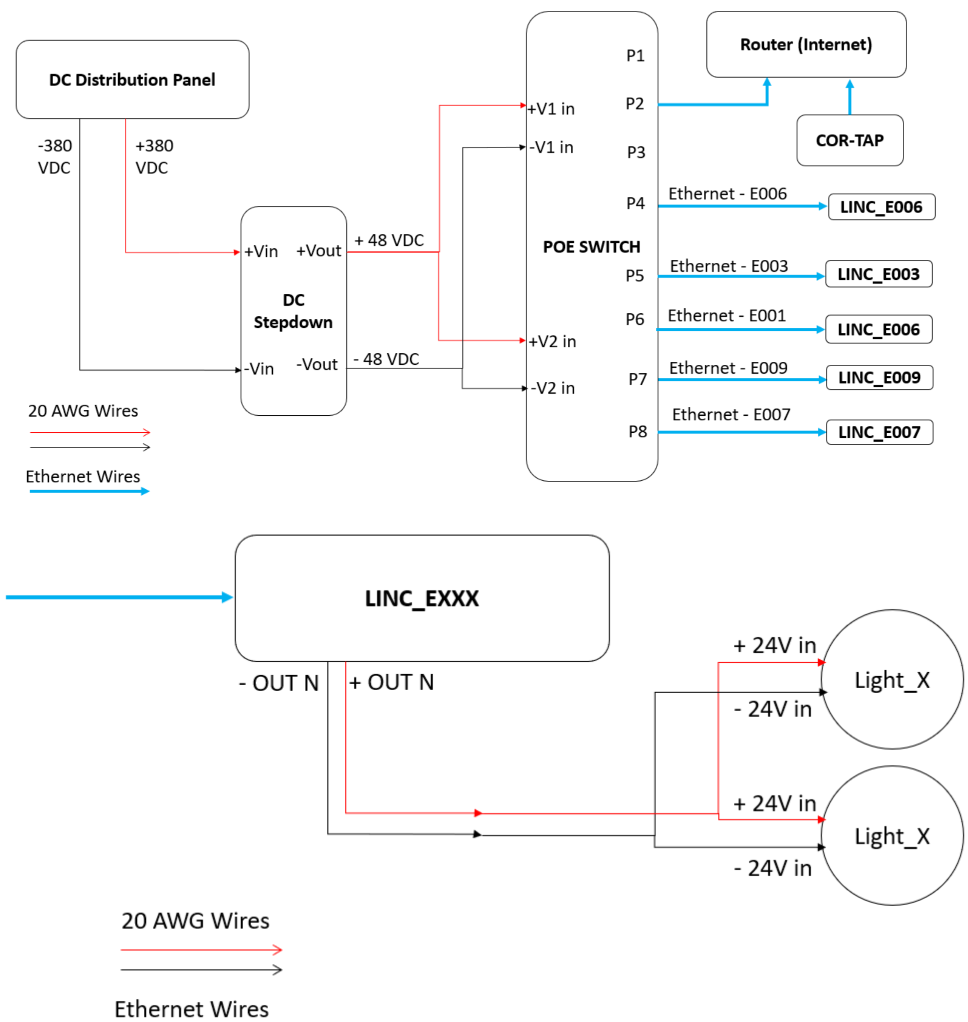

Figure 3: (a) DC distribution Panel to PoE Switch;(b) LINCs to DC lights

2.2 Backend Controls and Sensors

As the system uses a lot of the same devices, each item required a unique identification. This allowed the controls configuration to be structured and changeable if need be. The system revolved around the Component Identification table. This allowed the layout for the lighting in the test bed to also be made efficiently. This can be seen in Figure 4.

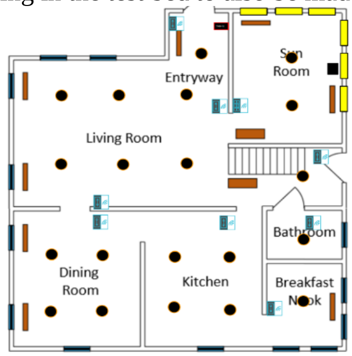

Figure 4: DC Lights and LINCs layout on the first floor

With each key network component with a unique ID, the COR-TAP controls page was used to configure each set of lights to their respective kinetic switch. The configuration page facilitates the control of the lights using conditional statements to turn on/off each respective light. This was done by determining which button on each kinetic switch was pressed/unpressed or active/inactive.

To measure the power consumption of the new lighting system, an in-house DC current sensing system was used. The sensor used was the ACS712-5A. The sensor is designed to measure currents between 0-5A and is powered by a 5V source. It measures current and transmits analog data with a sensitivity of 185mv/A. It was connected directly after the 48V step down on the DC panel in series. Hence it measures the total current draw. The system used to capture the data was a Raspberry Pi4. Additionally, since the Raspberry Pi has no analog inputs, a 16-bit analog to digital converter, ADS1115, was used. The wiring diagram can be seen in Figure 5.

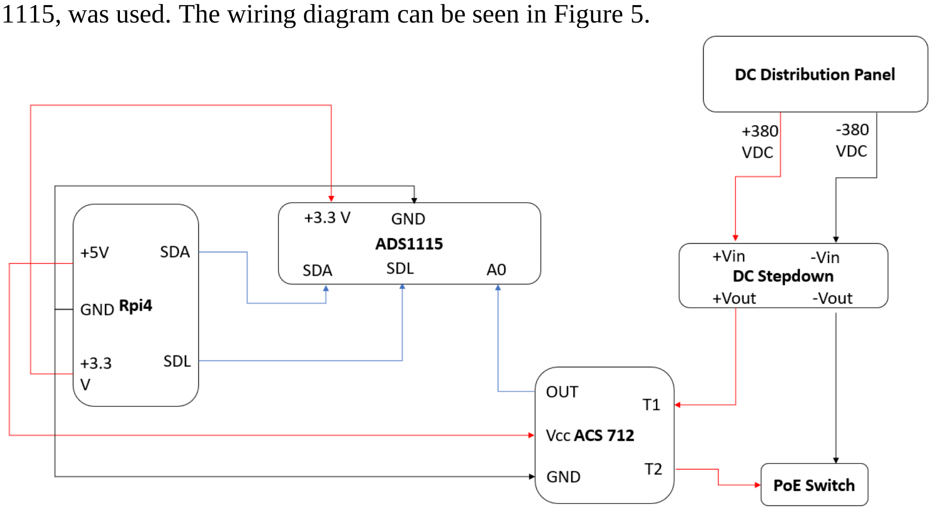

Figure 5: Wiring between Raspberry Pi4, ADS1115, and ACS712 sensor

The Raspberry Pi had a Python Script that converted the analog signal received at pin A0 sent by the ACS712 into the current measured across the terminals T1 and T2. After doing so it uses equation (1) to find the power used by the load.

$$P = U_{source} * I = 48V * I \tag{1}$$

Where U_{source} is the source voltage in volts, I is the measured current in amps, and P is the power consumed in watts. It is important to note that the source voltage is not measured and is assumed a constant 48 V as per the specifications of the DC stepdown used (VICOR, n.d.)

2.3 Testing & Installation

Bench-top testing of the PoE system was first conducted to understand each component and their operation. To ensure the power, wiring, and logic had been setup properly, the system was first tested with a 48V DC source and one DC light following the wiring diagram in Figure 4. Secondly, to optimize the wiring, one output wire from the LINC was wired to two lights. This way, we were able to control more lights with less control logic. The testing setup for this can be seen in Figure 6 below.

Figure 6: Multiple Lights on single output wire

Finally, the lights were installed in the living room and used as the test bed to validate the entire system. As can be seen in Figure 8, there is also a centrally located AC light as a point of comparison for the PoE lighting system. The AC light present in the living room, rated for an efficacy of 80 lm/W, already has a data acquisition system attached to it from previous projects at the DC House. This data acquisition system measured the AC power consumed by all devices in the living room which called for a data cleaning to determine the AC light's power. Hence, a comparative study can be done with DC lighting to determine the total power savings. The versatility provided by the DC system will be looked at from a qualitative perspective in the next section. The lights installed in the living room can be seen in Figure 7.

Figure 7: Lighting Testbed in Living Room

2. RESULTS AND DISCUSSION

3.1 Data Collection and Results

First, to obtain the power consumption of the AC lights, the lights were turned on sometime between 5-10 p.m. for three hours. This provided the data to determine the average power consumption for the AC lights. The data processing was completed using a Python script. The resulting time series plot can be seen in Figure 8 below.

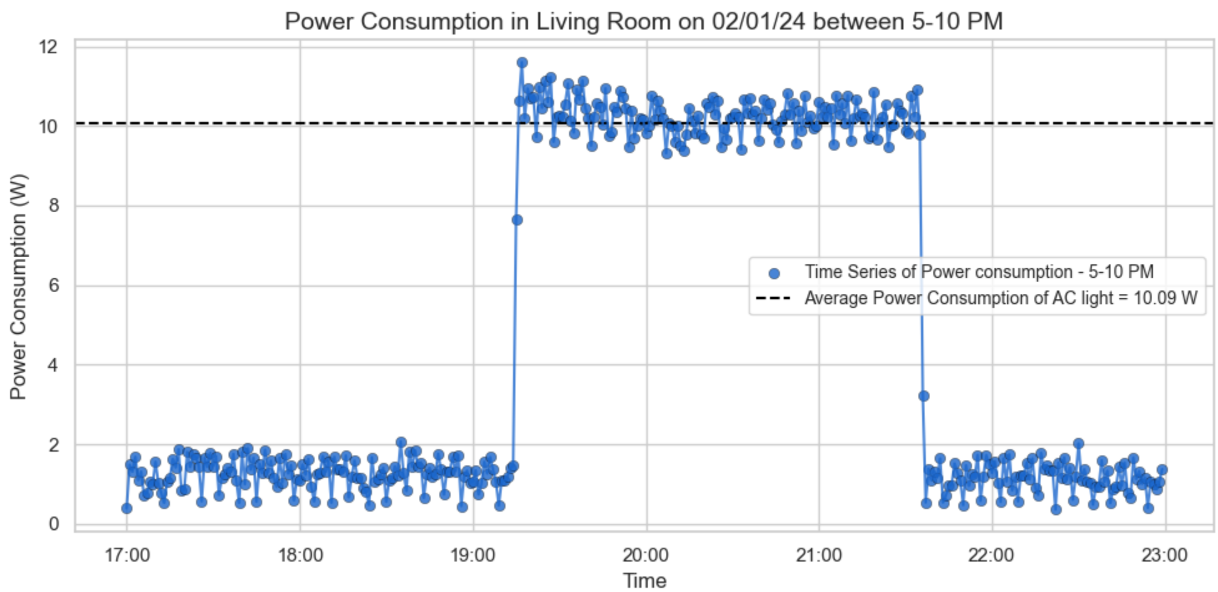

Figure 8: Power Consumption(W) time series of AC lights in living room of DC Nanogrid House

For the DC lighting system, the data collection method was slightly different. Since the current sensor was set up at the source, it measured the power consumed by the entire DC system -i.e. the Lights, LINCs, and PoE Switch all together. The base power of the LINC and the PoE switch were measured first for 30 minutes by turning the DC panel on and ensuring the lights were off. After this, the lights were turned on and the data was measured again for two hours. To determine the power consumption of the lights alone, the base power was subtracted from the total power. This was possible as the only active load on the DC panel was the DC Lighting system. The resulting time series can be seen in Figure 9.

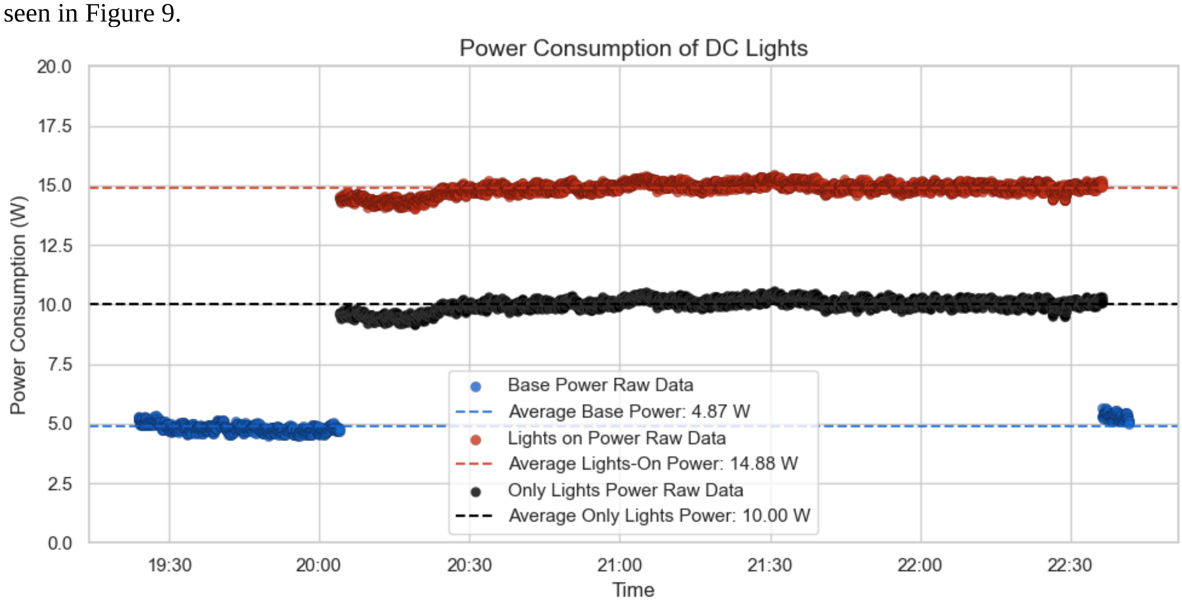

Figure 9: Power Consumption(W) time series of DC lights during testing period

3.2 Analysis & Discussion

The AC lighting system, which is the traditional approach, consumed an average power of 10.09 W during the testing period as seen in Figure 9. The DC lighting system consumed an average power of 14.88 W. The lights themselves consume approximately 10.00 W. At surface level, the DC Lights shows only about a 0.9% savings in power. However, consider the useful work that the lights do. The DC lights, rated at 120lm/W, produce 1200 lm for a 10W power consumption. The AC lights however, rated for an efficacy of 80 lm/W, produce only 800 lm for the same wattage. For this DC rating, one would only need to supply 6.67 W to produce 800 lm from the DC lights. This can be done by dimming which will be further explored in the next section. Hence, the DC lights themselves reduce the power consumption for the same useful work by approximately 33.3%. However, from an overarching system perspective, the DC lighting system consumes more power than the AC lighting system on a small scale. This again shows the negative sides of DC distribution – the distribution devices contribute to a significant section of the power consumption. This calls for improvements to critical components of the DC distribution system.

Consider scaling up the lighting system to a larger deployment size. Assume that we scale up with similar size rooms in a residential setting. In every room we would have 4 DC lights and 1 AC light. Two rooms can share one LINC and up to 14 rooms would still only require one PoE switch (as there are 7 available ports on the PoE Switch). A set of 4 lights, as seen from the test results, to produce the same lumens as the AC lights would consume 6.67 W. Each LINC consumes 2.00W and the PoE Switch consumes 3.00 W according to their rating and observed measurements (Figure 9). The total AC and DC power for this scaling process can be modeled by equations (2) and (3) and then compared using equation (4).

$$P_{AC} = P_{AC\ Lights} * n \tag{2}$$

$$P_{DC} = P_{PoES}\left(\frac{n}{14}\right)_{ceiling} + P_{LINC}\left(\frac{n}{2}\right)_{ceiling} + n * P_{DC\ Lights} \tag{3}$$

$$P_{S,\%} = \frac{P_{AC} - P_{DC}}{P_{DC}} * 100 \tag{4}$$

Where P_{AC} is the total AC power consumed, $P_{AC\ Lights}$ is the power of a single AC light, P_{DC} is the total DC power consumed in watts, P_{PoES} is the power consumed by the PoE switch, P_{LINC} is the power consumed by a LINC, $P_{DC\ Lights}$ is the power consumed by a set of 4 DC lights, $P_{S,\%}$ is the percentage of power saved by the DC lighting system , n is the number of rooms. To visualize the difference in power consumption at different scales, consider Figure (10) below.

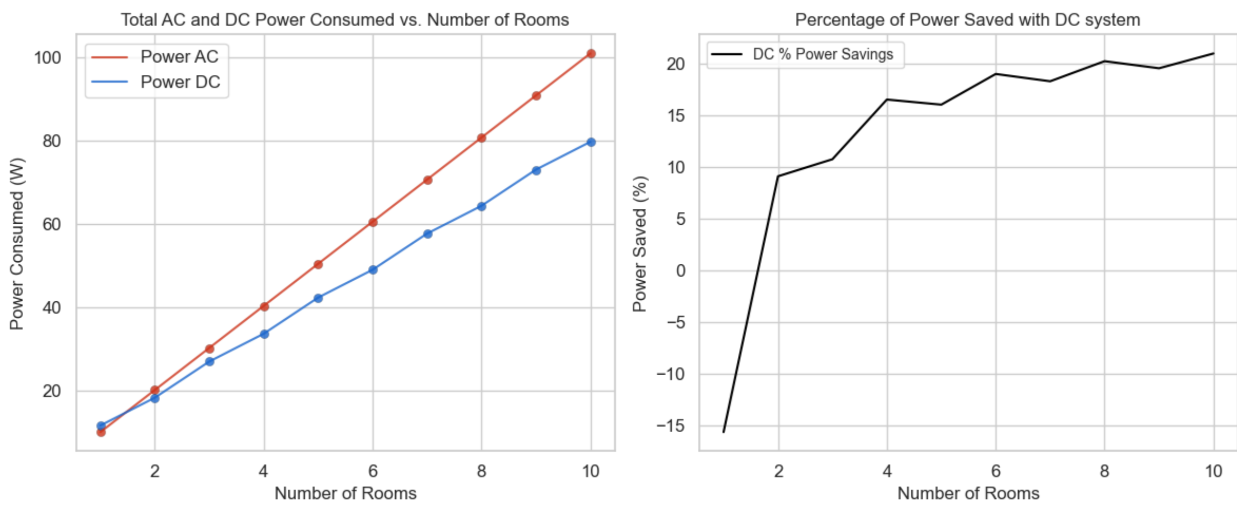

Figure 10: Residential Scale (a) AC vs DC lighting system power consumption; (b) DC Power savings (%)

Through this scaling, we see that the larger the scale, the higher the power savings of the DC lighting system. The scaling analysis was stopped at 10 rooms as residential spaces usually do not have more. Further continuing the scaling for larger numbers provides us more insight (Figure 11)

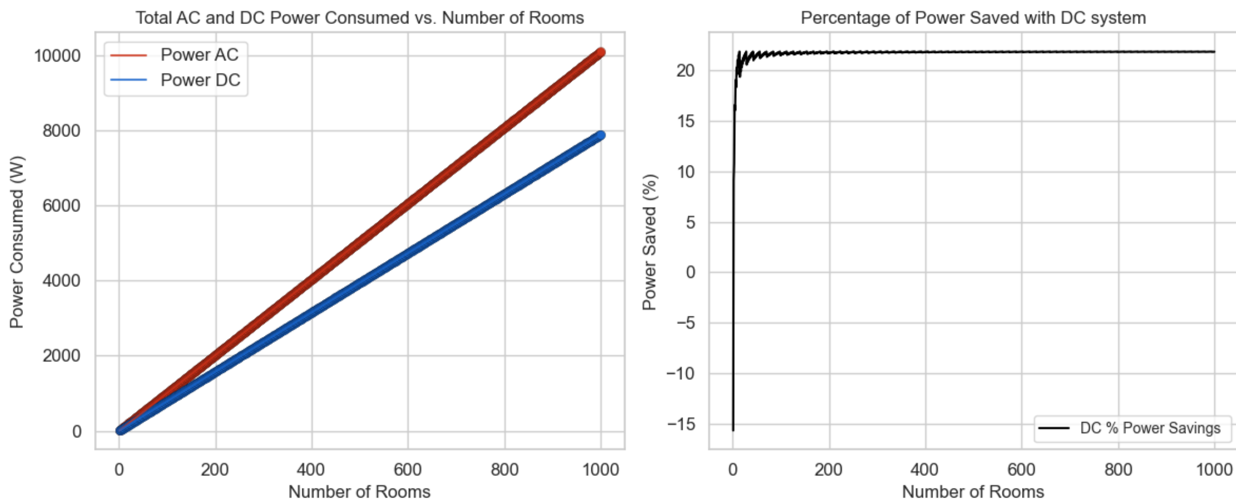

Figure 11: Commercial Scale (a) AC vs DC lighting system power consumption; (b) DC Power savings (%)

Figure 10 showcases that in residential spaces, a large-scale deployment is beneficial. Figure 11 shows that for commercial space, it is always more energy efficient to go with the DC lighting system. This significant difference in efficiency could be attributed to the inherent advantages of the DC distribution architecture. By eliminating the need for AC-to-DC conversion at the fixture level, the DC system avoids the associated power losses, leading to greater overall efficiency. Additionally, the use of high-efficiency DC-DC converters in the PoE LINC controllers further optimizes the power delivery to the LED lights.

Beyond the energy savings, the PoE DC lighting system also offers enhanced versatility and user control. The integration of kinetic switches and the COR-TAP control hub enables wireless, unpowered control of the lighting fixtures. This eliminates the need for traditional wiring between switches and lights, simplifying installation and providing greater flexibility in layout and reconfiguration. For example, changing the set of lights connected to a certain switch or adding a switch to control a set of lights is a simple drag and drop on the COR-TAP controls system. Furthermore, the centralized control offered by the PoE system allows for dynamic adjustments to lighting parameters, such as brightness and color temperature. This enables occupants to tailor the lighting to their preferences, improving user comfort and satisfaction. The potential for integrating additional smart home features, such as motion sensing and daylight harvesting, further enhances the system's capabilities and energy-saving potential.

The integration of PoE technology with DC lighting systems presents a compelling solution for enhancing the aesthetic appeal of residential spaces as well. PoE-enabled DC lights exhibit a sleek and minimalist design that harmonizes with modern interior styles, eliminating the need for bulky transformers and ballasts typical of AC lighting setups. This streamlined design contributes to a clean and unobtrusive aesthetic, enhancing the visual appeal of living spaces. The amount of visible wiring greatly reduces, resulting in a clutter-free installation and a polished look. The uniform illumination provided by DC LED lights ensure consistent and glare-free lighting across spaces, avoiding the uneven or spotty lighting associated with traditional AC installations. Collectively, these features position PoE-enabled DC lighting systems as an attractive choice for enhancing both the functionality and visual aesthetics of residential environments.

3.3 Further Improvements

While the current DC lighting system demonstrates significant advantages at larger scales, there are opportunities for further improvements. An interesting study which could further validate the DC lighting system is a study that measures the power losses associated with AC distribution. The average base power required by the DC distribution system alone is about 5.00 W. Studying an AC breaker box and the power needed to operate them and comparing them to the DC distribution system would provide valuable information on which distribution is more efficient as well. The current DC lights typically operate at 120 lm/W. However, newer models surpassing 200 lm/W present options for improved illumination levels. Despite concerns about excessive brightness, dimming functionality provides a solution for tailored lighting control. Enabling dimming capabilities across AC and DC lighting systems not only addresses brightness concerns but also contributes significantly to energy savings.

Beyond basic illumination, PoE systems introduce a realm of IoT functionality that improves lighting management. By integrating diverse sensors such as luminescence and occupancy sensors, these systems automate light control based on ambient conditions and occupancy status, eliminating the need for manual switches, and optimizing energy usage. The versatility of PoE infrastructure allows for seamless integration of such sensors, paving the way for a fully automated lighting system that adapts intelligently to its environment. Expanding on the capabilities of PoE beyond lighting applications, the current system can be utilized for a variety of purposes. PoE technology can power and connect a range of devices such as sensors for monitoring energy consumption, temperature control systems, air quality sensors, occupancy detectors, security cameras, RFID sensors for access control, video conferencing equipment in conference rooms, monitors, laptops, and even medical devices like patient entertainment systems or staff laptops. The flexibility and efficiency of PoE make it a versatile solution for powering and networking various devices in office environments.

3. CONCLUSION

In conclusion, the exploration into the integration of PoE lighting systems with DC distribution has provided valuable insights into its potential for residential use. Motivated by the need to fill gaps in existing knowledge and offer new perspectives, the study focused on assessing the benefits of this technology in reducing power consumption and increasing versatility in home lighting. Through careful development, installation, and testing of a PoE-based DC lighting system, alongside a thorough comparison with traditional AC lighting systems, the study brings to light some advantages and disadvantages of DC lighting systems for residential settings.

One notable limitation pertains to the efficiency of DC lighting systems at lower scales, such as in studios or smaller living spaces. In the test bed, the DC lighting system consumes a surplus of 2.00 W in comparison to the AC lighting system. In such environments, the DC lighting systems increases the power consumption compared to AC. This is because of the components needed to distribute the DC power such as the PoE Switch and the LINC. The inherent power losses associated with DC distribution infrastructure components, underscore the need for continued advancements in these critical elements to maximize the overall efficiency of DC lighting systems in residential applications.

The study highlights significant advantages of PoE-based DC lighting systems in residential settings, especially at larger scales. The DC lights themselves demonstrate a remarkable 33% lower wattage per lumen compared to traditional AC lights, resulting in long-term energy and cost savings. Scaling analysis reveals a notable improvement in power efficiency with increased deployment size, at a maximum of 22% power saved compared to AC lighting systems (Figure 10 and 11). Integration of kinetic switches and centralized control hubs enables wireless and unpowered control of lighting fixtures, eliminating the need for complex wiring, and enabling seamless adjustments to lighting parameters such as brightness and color temperature. This flexibility not only enhances user comfort and satisfaction but also contributes to energy savings by allowing occupants to tailor lighting conditions to their specific preferences and needs.

Looking ahead, there are several avenues for future research that could further enhance the efficacy and applicability of DC lighting systems. Comparative studies between AC and DC distribution systems could provide valuable insights into their respective efficiency and performance characteristics. Additionally, exploring advancements in DC lighting technology, such as higher luminous efficacy models and the integration of PoE systems with IoT functionality beyond lighting applications, offer promising directions for future investigation. By addressing these research gaps, we can continue to advance the development of sustainable lighting technologies and contribute to the creation of more energy-efficient and comfortable residential environments.

NOMENCLATURE

PoE	Power over Ethernet
DC	Direct Current

PoES	Power over Ethernet Switch
IoT	Internet of Things
LED	Light Emitting Diode
USB	Universal Serial Bus
EMS	Energy Management System

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