Title

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Techno-Economic Analysis of DC Power Distribution in Commercial Buildings

ABSTRACT

Improvements in building end-use efficiency have significantly reduced the energy intensity of new buildings, but diminishing returns make it a challenge to build very-low energy buildings cost-effectively. A largely untapped efficiency strategy is to improve the efficiency of power distribution within buildings. Direct current (DC) distribution with modern power electronics has the potential to eliminate much of the power conversion loss in alternating current (AC) building distribution networks that include photovoltaics and DC end uses. Previous literature suggests up to 15 percent energy savings from DC power distribution in very energy efficient buildings with onsite generation and battery storage. This paper extends prior energy modeling of DC versus AC distribution in buildings, to consider the cost of implementing DC systems on a life-cycle basis. We present a techno-economic analysis framework that evaluates the cost-effectiveness of DC systems in U.S. commercial buildings, based on commercially available products for various PV and battery storage capacities. We use Monte Carlo simulation to account for uncertainty and variability in the cost inputs, and compute the payback period (PBP) and lifecycle cost (LCC) savings of DC versus AC distribution systems. We also conduct a sensitivity analysis to evaluate how future efficiency improvements in power converters and changes in electricity tariffs may affect LCC savings. This analysis shows that DC systems can be cost-effective in all scenarios that include large capacities of battery storage and onsite solar, whereas for systems without storage, DC distribution is generally not cost-effective due to lower energy bill savings.

Keywords:
Direct current; DC distribution; Techno-economic analysis; Commercial building;

1. Introduction

Alternating current (AC) has been the near-universal form of power distribution within buildings for over 100 years, primarily due to the relative ease and lower cost of voltage conversions with AC power, compared to direct current (DC) power. Despite this long history and dominant position, some power engineers in the building industry are reconsidering whether DC may be a preferred choice for distributing power in buildings, due to a variety of technology and market changes. First, the development of modern power electronics has made DC power conversion much easier and less costly without the use of AC transformers. Second, a variety of new, distributed power sources that “natively” generate DC power, such as photovoltaics (PV) have become much more affordable and widespread [1], thus making DC power commonly available in buildings. Third, chemical batteries for energy storage, which operate on DC power, are increasingly being used in buildings for power reliability, energy bill savings, and to provide services to the grid. Fourth, the growth of electric vehicles (EVs) – another form of battery storage – is leading to significant new native-DC load in buildings for EV charging. Fifth, the drive to reduce the energy use of buildings has led to widespread adoption of very efficient, and native DC, end-use technologies such as light-emitting diodes (LEDs), variable-speed driven motors, and electronic controls [2]. All of these market and technology trends are being accelerated by a variety of policies at both the national, state, and local level to promote energy efficient buildings and adoption of solar, energy storage, EVs, and other native-DC technologies. There are also a variety of non-energy benefits that are causing people to reconsider DC power, such as ease of communications and controls[3], resilience during power outages, interoperability, and other factors [4]–[7].

A significant advantage of DC distribution in buildings with onsite DC sources (e.g., PV) and native-DC electric end uses is that it can avoid wasted energy due to DC-AC-DC power conversions. Several studies have computed or measured the energy savings from DC distribution, with savings ranging from a few percent to about 15 percent [8]–[23]. Several factors influence these energy savings, including the configuration of the building distribution system, the presence of battery storage, the coincidence of electricity consumption and PV generation, and the relative efficiency of power converters in the DC versus AC distribution system [24]. Especially, in very efficient new buildings, which have realized much of the savings potential in traditional end-uses, these savings from DC power distribution could be one of the largest remaining sources of energy savings, if the technology proves to be cost-effective.

DC distribution has had successful commercial application in data centers [25] and is beginning to gain traction in commercial buildings for lighting applications, with several companies offering DC-powered luminaires and DC lighting systems [26]–[28]. Despite these developments, the market for DC in buildings faces significant barriers, such as the lack of available DC-ready appliances and distribution system components (e.g., converters, plugs, circuit breakers), the relative immaturity of technology standards, and lack of awareness among building owners, designers, and operators.

Another fundamental market driver for DC distribution in buildings is cost. DC is cost-effective in high voltage electricity transmission applications [29] and is estimated to result in capital cost reductions and lifecycle cost savings in data centers operating at 380 volts (V) DC [30], [31]. However, the cost of DC distribution in the building sector has sometimes been touted as an opportunity but more often presented as a barrier—an opportunity because it can lead to power systems with fewer converters, appliances with simpler power electronics, and power and communications shared by the same wiring; and a barrier because of limited component selections in the market (which are often more expensive than the equivalent AC solution) as well as higher soft costs (e.g., design and permitting costs) [24].

A relatively small but growing number of studies have addressed the cost-effectiveness of DC distribution in buildings, compared to the standard AC. Glasgo et al. [16] assessed the technical and economic feasibility of DC distribution to efficient DC appliances in residential applications compared to AC distribution to baseline appliances, using end-use electricity consumption data from 120 homes in Austin, Texas, for various distribution configurations. The authors used a Monte Carlo simulation to account for the uncertainty of efficiencies and costs of power system components, electric end uses, and other factors, such as discount rates. They found that direct-DC distribution to a variable speed brushless DC (BLDC) air conditioner, compared to a baseline AC-supplied air conditioner, was a cost-effective measure; whereas, all other scenarios, including a whole-house direct-DC system, were not. Similar to Glasgo et al., Thomas et al. [32] used a Monte Carlo simulation to analyze a DC lighting system in a commercial office building and estimated a 5 percent reduction in levelized annual costs for direct-DC LED lighting systems, compared to equivalent systems with AC distribution.[1] Other studies, when conducting economic analyses of DC distribution systems, compared the relative cost difference of power system components and appliance converters in AC versus DC building distribution systems [23], [33], [34]. Notably, in [34], the analysis focused on office buildings, and was primarily dependent on the use of regressions between price and power ratings of DC-DC, AC-DC, and DC-AC converters.

DC distribution eliminates the need for AC-DC power converters at the appliance level for native DC loads, but may require the use of DC-DC converters, depending on the input DC voltage of the load. According to Wunder et al. [35], 50 percent of power conversion losses and 70 percent of

[1] Note that this research assumed that DC distribution eliminated the need for LED drivers.

weight and volume in internal switch mode power supplies could be eliminated with DC distribution. Rodriguez-Diaz et al. [36] argue that direct-DC distribution to appliances (e.g., laptops) that utilize external power supplies can lead to a 55 percent cost reduction on the power supply cost, due to the use of fewer power electronic components (e.g., rectifier, radio frequency interference suppression, and power factor correction) in the DC power supply. In practice, although the cost of DC converters should be less than their AC counterparts, this is not always the case because existing component topologies and configurations may require redesign, and the lack of demand for DC products does not create the necessary economies of scale to reduce manufacturing costs. [37]

From a qualitative perspective, according to a 2016 online survey of 39 individuals, including researchers, DC equipment suppliers, and other stakeholders familiar with DC distribution systems, the cost of DC distribution systems is one of the main barriers against their development. Follow-up interviews to a subset of survey respondents underscored the need for additional data and research on DC systems cost. [24] A similar survey in 2017 requested estimates from industry experts for the capital cost of a DC distribution system compared to an equivalent AC system in a standard office building. Respondents stated that today's DC systems would generally be more expensive than AC systems, while in 10 years, they estimated that DC systems costs would be comparable or slightly lower than those of AC systems. [38] This assessment is consistent with findings from Foster Porter et al. [39] and Denkenberger et al. [10], who claim that DC distribution can be cost-effective in zero net energy (ZNE) buildings, assuming the cost of DC products is significantly reduced through production volumes and market maturity. Furthermore, Fregosi et al. [14] anticipate that at scale, DC systems in commercial buildings can reach a 15 to 20 percent capital cost reduction, and the total cost of ownership can be 30 percent lower than comparable AC systems. In general, previous research has found that from a strictly technical standpoint, DC systems can cost the same or less than the equivalent AC systems. The current price premium is primarily a function of market conditions, such as production volumes, product availability, and lack of experience in the building industry.

We note that all previously mentioned analyses assume new construction scenarios, rather than retrofits of existing buildings, which are typically more costly. For example, Glasgo et al. [16] did not consider retrofits because the associated costs would not be recovered even by the largest energy cost savings of DC distribution and more efficient end uses. Similarly, Mackay et al. [40] estimate that retrofit costs are likely to outweigh the benefits of DC distribution in existing infrastructures, while King and Brodrick [41] claim that residential electric installations may cost up to twice as much for renovations, compared to new construction. None of these prior studies considered the value of non-energy benefits to building owners and occupants, which are expected to be an important motivation for adoption of DC power in buildings.

Based on the review of the literature on energy savings and cost, building DC systems currently may have higher capital costs than AC systems, but their electricity savings could outweigh those costs and yield desirable paybacks for certain use cases. One such use case is high-efficiency commercial buildings with onsite PV, due to the high fraction (over 60 percent) of their energy consumed as electricity [42], and the high coincidence of solar generation and commercial end-use loads. This helps explain why much of the early adoption of DC distribution systems has been in commercial buildings, primarily for lighting applications. This paper extends previous work conducted by Gerber et al. (2018) to model three medium-sized commercial buildings in Los Angeles, while parametrically varying the solar generation and battery storage capacity to find economically optimal values. We use Monte Carlo simulation to account for uncertainty and variability in the cost inputs, and compute the payback period (PBP) and lifecycle cost (LCC) savings of DC versus AC distribution systems. We also assess how future efficiency improvements in power converters and changes in electricity tariffs may affect LCC savings.

This work makes the following key contributions to the literature:

- It addresses the electric loads of different types of commercial buildings, and includes a parametric analysis to determine the energy and economic conditions in which DC distribution is favorable from an LCC and PBP perspective.
- It includes a technical analysis on the building distribution systems and end-use topologies: earlier research suggests that the distribution system configuration has a large impact on its efficiency, and therefore, its cost. Based on this analysis, this work utilizes detailed market price data on the cost differences between AC and DC distribution system components, including end-use appliances.
- It uses actual electricity tariffs, rather than average electricity price values used in previous research.

The following sections of this paper are organized as follows: Section 2 discusses the methodology and model inputs, including details on the distribution system design. Section 3 presents the results of the efficiency and techno-economic (TEA) analysis, and Section 4 includes conclusions, policy implications, and recommendations for future work.

2. Methodology and Model Inputs

2.1. Modeled Buildings

We analyzed three small- to medium-size commercial buildings, in Los Angeles, California, drawing building dimensions and load profiles from the EnergyPlus reference buildings [43], [44]. These buildings are a medium-size office building, a full-service restaurant, and a stand-alone retail space. They were selected to capture a variety of load types and load profiles. Hourly electrical load data were estimated using EnergyPlus for the following electrical end uses: heating, cooling, fans, pumps, interior lighting, exterior lighting, interior equipment, and refrigeration—the latter for the restaurant only. All buildings are low-rise, which makes them ideal for onsite PV systems. Table 1 shows a summary of the reference buildings' physical characteristics.

Table 1. Reference Buildings' Physical Characteristics

Building Type	**Floor Area (m^2)**	Number of Floors	Length (m)	Width (m)	Building Height per Floor (m)
Medium Office	4,982	3	49.9	33.3	4.0
Stand-alone Retail	2,294	1	54.3	42.4	6.1
Full Service Restaurant	511	1	22.6	22.6	3.1

2.2. Selection of DC Distribution Network Topology

The distribution topology of a DC distribution network can have a large impact on both its efficiency and cost. The primary design choices in distribution topology are in the wiring network and the distribution voltages. DC buildings can be wired as a bus network or a star network. In a bus network, the end-use loads are all electrically connected in parallel, as shown in (a). This type of network is common in traditional AC building distribution wiring, and can be configured in a radial, ring, or mesh pattern [45], [46]. The main advantages of a bus network are in its cost and flexibility. However, bus networks can suffer from voltage regulation stability issues. Star networks, shown in (b), utilize point-to-point connections between the various power sources and sinks. This type of network is only possible with DC, and is currently present in various DC standards such as Power over Ethernet (PoE) [47], [48] and universal serial bus (USB) [49]. Star networks can be fairly expensive since every hub requires a power server (i.e., an intelligent power distribution manager) and every load requires a dedicated wire. Nonetheless, DC power servers with solid-state breakers can current-limit individual ports, allowing them to effectively replace panelboards. Power servers also provide a straightforward means for controls, data transfer, and microgrid security.

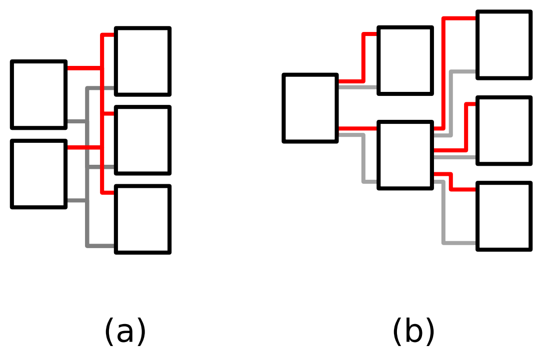


Figure 1. Conceptual diagrams of a generic (a) bus network, and (b) star network.

In this work, the modeled DC building employs a combined bus/star topology. As shown in (a)   (b) (a) and (b), the wiring for the DC bus/star topology closely resembles that of the AC building. The AC building is bus-connected from an electrical standpoint. However, circuits in commercial buildings are commonly wired through subpanels, and the wiring scheme actually resembles a star topology. Besides the bus/star, other DC wiring topologies may well prove to increase efficiency or reduce cost, depending on future trends in circuit protection and load distribution.

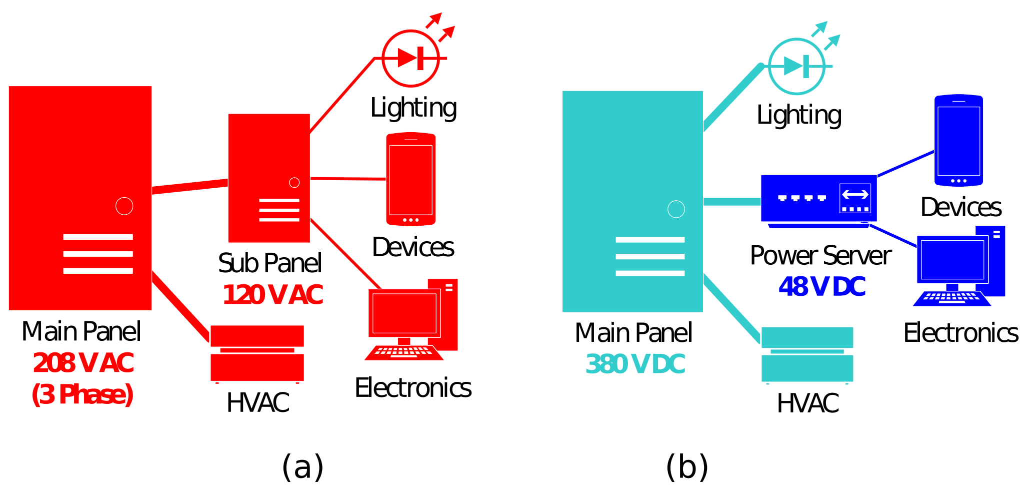


Figure 2. Star topology for the (a) AC and (b) DC building distribution systems in this study. The 48V power server in the DC building effectively replaces the subpanels in the AC building.

Although no universal standard exists for DC building distribution voltage, many candidates have emerged in literature and industry. These voltage levels can be classified as being either an infrastructure level or a plug level. Common DC infrastructure-level voltages range from 326 V to 400 V, with the Emerge 380 V standard being the most prevalent in the United States [50]. Since wire loss is less significant at higher voltages, infrastructure voltage levels are intended for high-power loads and/or long wiring runs. In contrast, plug-load voltage levels are intended for safe operation of low-power devices. Common DC plug-load voltage levels include the 48 V telecommunications and PoE standard, the 24 V Emerge standard [50], and the 5-20 V USB-PD standard [49]. DC plug load voltages are all less than 50 V, which qualifies them as safe to touch [51]. Because wire loss is inversely proportional to the square of the distribution voltage, plug-level voltages are only suitable for localized low-power loads [52], [53]. Although 24 V distribution is practical in many applications, it requires many power servers to offset the quadrupled wire loss compared to 48V. Even at 48V, 5 to 15 percent wiring loss can be present in a 50 meter (m) PoE wiring run [52], and so 48 V power servers should be localized to serve several rooms at most. Overall, 48 V is an optimum that minimizes wire loss while still being safe to touch.

In this work, the modeled DC building distributes power with infrastructure and plug voltage levels at 380 V and 48 V, respectively. To reduce wire losses, 380 V distribution is assumed for connecting PV generation, battery storage, and high-power loads such as heating, cooling and air conditioning (HVAC) and refrigeration. The lighting is also powered at 380 V due to long wire runs and the expectation that most lighting systems are hardwired (and therefore not occupant-replaceable) in commercial buildings. For electronics and other plug loads, 48 V distribution is assumed through localized 380-48 V DC-DC converters.

2.3. Optimized Load Design for DC Input

As discussed in [2], the most efficient electricity end uses are internally DC. Therefore, similar to the analysis in [17] and [54], and to minimize losses for the DC distribution system, the building model assumes that all electric loads can be supplied directly with DC power. In this sense, the loads are optimally designed such that their internal DC voltage is matched to the distribution.

Motor loads (e.g., HVAC, fans, pumps, and refrigeration) are all modeled with variable frequency drive (VFD) BLDC permanent magnet motors. BLDC motors with an AC input require an input rectification stage, as shown in Figure 3. The output of the rectifier is stored on a DC capacitor bus, which powers a set of inverters that supply the stator coils with variable frequency AC. In optimally designed direct-DC VFDs, the DC capacitor bus operates at the same voltage as the DC distribution. A direct-wired connection between the two would bypass the rectification stage, thus allowing for savings in efficiency and cost [55].

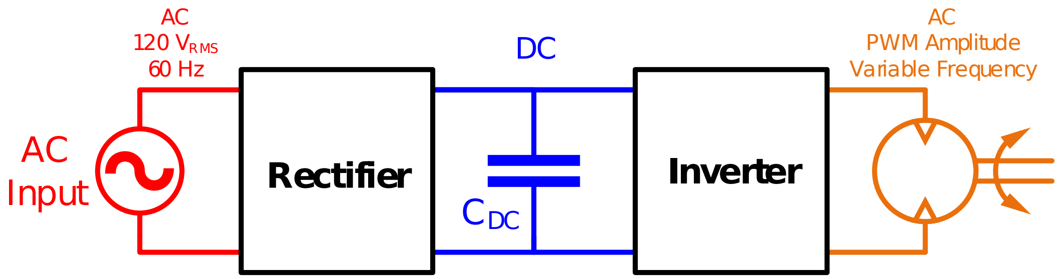


Figure 3. Block schematic of a BLDC motor with VFD. The inverter is powered from an internal DC stage (blue), and outputs AC at a variable frequency (orange). For AC distribution, a rectifier is required to convert 60 Hz AC (red) for the internal DC stage. For DC distribution, the internal stage of a carefully designed VFD can be connected directly to the building distribution system.

LEDs are a current-controlled load because their luminosity is nearly proportional to their current. As such, the LED driver conversion stage is required, even with DC distribution. However, the efficiencies of DC LED drivers can often be found in the 95 to 98 percent range; whereas, AC LED drivers often exhibit 86 to 93 percent efficiency [17]. In addition, DC LED drivers are typically less expensive because they do not have to rectify the AC input or cancel the 120 Hz AC power ripple [56].

Electronic devices such as computers often have several internal voltage rails, each of which requires a DC-DC converter. The DC input rail is the regulated output of the AC wall adapter. If the DC input rail voltage is designed at 48 V, it can be connected directly to the 48 V distribution, thus obviating the need for a wall adapter.

2.4. Building Distribution Systems and Loads

Diagrams for the AC and DC electrical systems are shown in Figure 4 and Figure 5, respectively. The building models utilize one or more of the following power distribution voltages:

- AC Building: 120 V AC (plug) and 208 V AC three-phase (infrastructure)
- DC Building: 48 V DC (plug) and 380 V DC (infrastructure)

In the building model, the electrical sources and sinks are PV generation, a battery, a grid connection, and end-use equipment. Electrical losses are attributed to converters, building distribution wiring, and chemical losses in the battery. The building model assumes that the electrical end uses in the AC and DC building are identical (all are internally DC), and they have the same layout and usage profiles. PV generation data for each building are derived from PVWatts [57]. The simulation models, inputs, and assumptions for each component are discussed in detail in [17].

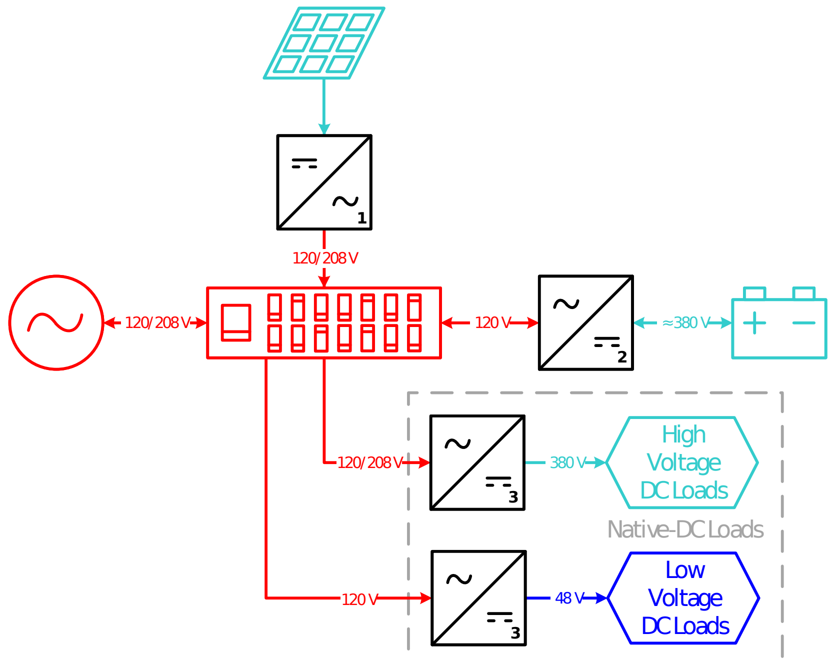


Figure 4. Building network with AC distribution. Converters: 1. string inverter (performs maximum power point tracking), 2. battery inverter (performs bidirectional charge control), and 3. load-packaged rectifier or wall adapter.

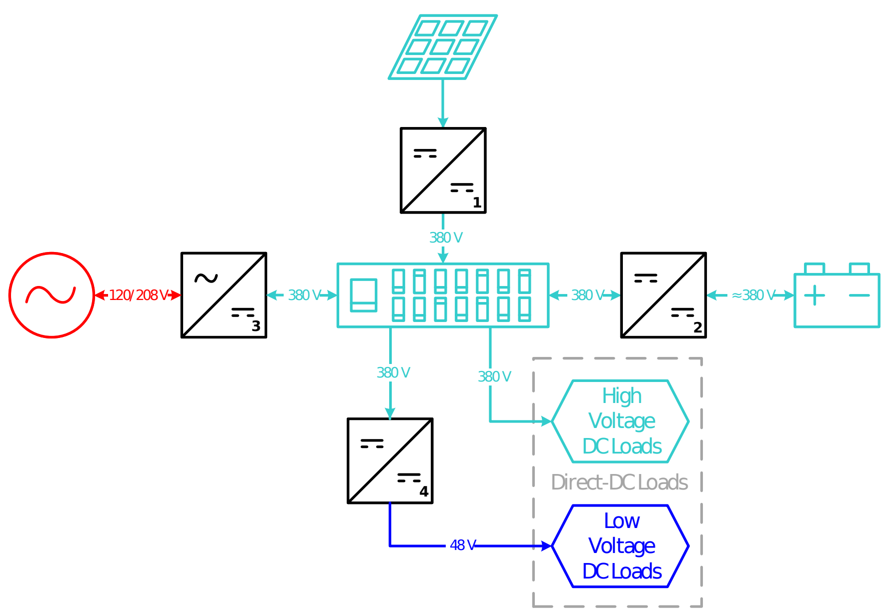


Figure 5. Building network with DC distribution. Converters: 1. MPPT module (performs maximum power point tracking), 2. battery charge controller (performs bidirectional charge control), 3. grid tie inverter (bidirectional), and

4. DC-DC step-down, which could be a 48 V power server. Certain loads such as LEDs require an additional DC-DC converter (not shown).

2.5. Techno-economic Analysis Methodology

To evaluate the cost-effectiveness of the DC distribution, we compare its economic performance to a corresponding AC distribution system. This comparison considers the incremental cost difference between these two systems, under the assumption that the AC and DC buildings are the same other than their distribution systems. Thus the TEA is limited to capital and operating cost differences due to different system components in the AC and DC distribution systems. The methodology and metrics (LCC and PBP) used in this TEA are consistent with those used by the United States Department of Energy (DOE) to determine consumer economic impacts of energy conservation standards to appliances [58].

The LCC is calculated according to Equation 1:

$$LCC = Total\,Installed\,Cost + Lifetime\,Operating\,Cost \quad \textbf{(1)}$$

The total installed cost includes the cost of the building distribution system and costs of electrical end-use equipment. Installation costs and other soft costs, such as permitting and design costs, are ignored in this analysis due to lack of data. The lifetime operating cost represents the present value of the system’s operating cost, which includes any maintenance and repair costs, over its lifetime.

The lifetime operating cost is calculated according to Equation 2:

$$Lifetime\,Operating\,Cost = \sum_{y=1}^{Lifetime} \frac{Operating\,Cost(y)}{(1+r)^y} \quad (2)$$

The PBP, is calculated according to Equation 3:

$$PBP = \frac{Total\,Installed\,cost_{DC} - Total\,Installed\,cost_{AC}}{Annual\,Operating\,cost_{AC} - Annual\,Operating\,cost_{DC}} \quad (3)$$

Figure 6 shows a flow diagram of inputs and outputs for the LCC and PBP calculations.

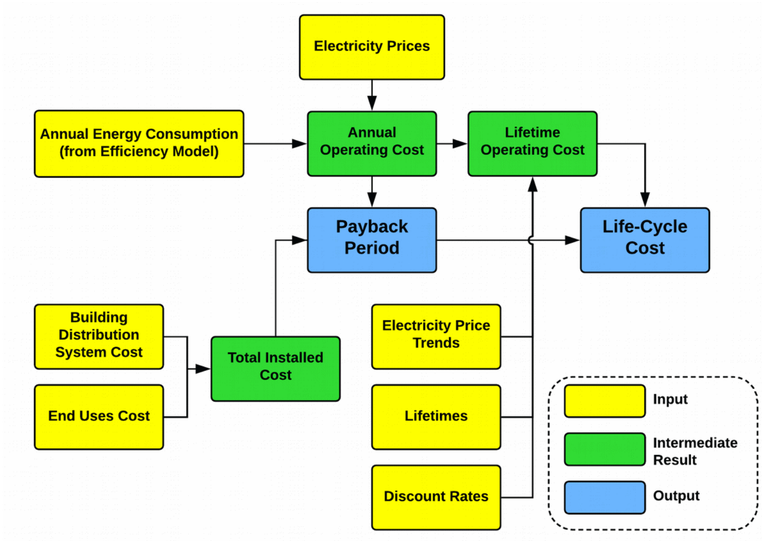


Figure 6. LCC and PBP flow diagram

The TEA was performed by running 1,000 Monte Carlo simulations for each scenario, to account for input uncertainty and variability. The simulations were conducted using Microsoft Excel and Crystal Ball, a commercially available Excel add-in software.

2.6. Techno-economic Analysis Inputs

To determine the total installed cost of each system, we first estimated the cost of a building's major electrical infrastructure, including circuit breakers and all the components shown in Figure 4 and Figure 5. Infrastructure component costs (in $/kilowatt) were derived from online retailers, distributors, and manufacturer estimates. Then, these costs were scaled by the peak annual power through each component, oversized by 150%, which is a typical oversize factor for power converters.

Building wiring losses were incorporated in the efficiency analysis as described in [17]. The AC and DC buildings were assumed to utilize the same infrastructure-level wiring at 208 V and 380 V, respectively, and thus have an identical infrastructure-level wiring cost. However, these buildings use different wiring schemes for electronics: the AC building distributes at 120 V through 12-gauge solid copper wire and standard duplex receptacles, and the DC building distributes at 48 V through category 5 Ethernet cable and Ethernet jacks. Based on wiring cost data for underfloor wiring systems [59], the cost differences between the AC versus DC electronics wiring schemes were negligible, and thus ignored in this analysis.

For end-use equipment, the cost difference between DC and AC was attributed to specific electrical components that differ between the two distribution types: AC and DC LED drivers for lighting, wall adapters for electronics, and bridge rectifiers for high-power loads, such as HVAC and refrigeration. We developed cost versus power functions based on online cost data from digikey.com, as shown in Figure 7.

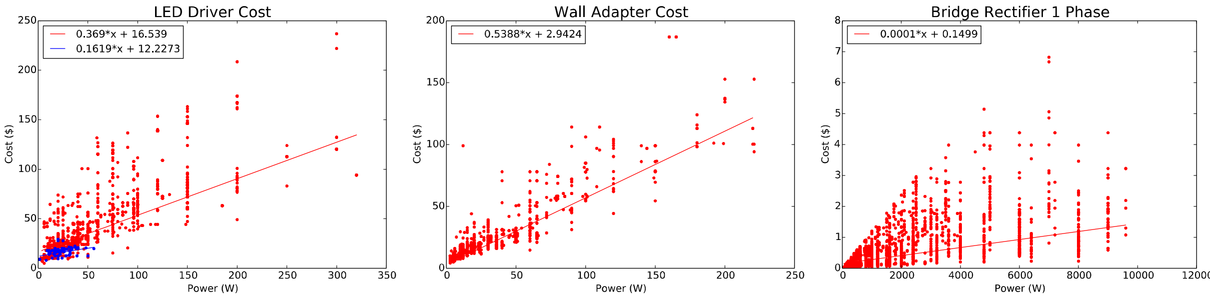


Figure 7. Cost data and linear regressions for LED drivers (left), wall adapters (middle), and bridge rectifiers (right). The regressions were determined after subjecting the cost data to several analytic filters: After removing obvious outliers that were unrealistically overpriced, the data were sorted and grouped into power bins. Within each bin, only the lowest 25th percentile of the data (in cost) was used for determining the regressions. Each bin's quartile was weighted according to the number of points in the bin, and from this, a linear least-squares regression was computed. Note that due to the very low price of bridge rectifiers (~$0.2/kilowatt) they were eventually excluded from the TEA.

The distribution of wattages for the AC and DC LED drivers (and therefore, their costs) was determined by utilizing the distribution of LED luminaire types and their corresponding wattages for each of the analyzed buildings, as presented in Table 2. Further, to determine the total number of LED drivers in each building, we utilized the average number of lamps per 1,000 ft. for each building, according to the same study and scaled it by each building's floor area (shown in Table 1).

Table 2. Wattage Rating and Distribution of Lighting Technologies by Building Type

LED Lighting Type	LED Wattage Rating by Building			Distribution of LED Lighting by Building		
	Restaurant (watts)	Office (watts)	Retail (watts)	Restaurant (%)	Office (%)	Retail (%)
General Purpose	6	9	7	42	15	22
Integrated Fixture/Luminaire	13	28	28	10	53	35
Linear	18	24	4	4	15	9
Reflector	12	11	14	18	4	19
Reflector Low Voltage	13	8	7	12	4	8
Miscellaneous	13	17	15	14	9	8

Note: LED wattage rating by building and distribution of LED lighting by building were obtained from Table D4 and D3 of the 2015 U.S. Lighting Market Characterization [60].

To determine the distribution of load types for electronics, we identified such end uses for the office and retail building (the restaurant was assumed not to include electronic loads) in the 2012 Commercial Buildings Energy Consumption Survey (CBECS) [42] and estimated wattage ranges for these loads based on various sources [61], [62]. Note that the restaurant was assumed to not include electronic loads. Table 3 summarizes electronic end uses identified in the 2012 CBECS and corresponding power draw ranges. A 50 percent oversizing factor was applied on these power draws to derive wall adapter wattage ratings.

Table 3. Electronics Power Draw Estimates and Weighted Distributions by Building Type

CBECS Electronic Load	Power Draws		Building Type	
	Min	Max	Office (%)	Retail (%)
Computers	70	93	30	22
Laptops	19	30	8	2
Printers	5	15	8	13
Copiers	8.2	30	3	5
Cash Registers	5	10	1	12
Servers	100	200	2	2
TV/Video Displays	81	197	2	11
Monitors	14	85	46	32

To determine lifetime operating costs, we first utilized the results of the efficiency analysis, which derives the annual electricity use of each building, and the Pacific Gas & Electric A-1 electric rate schedule[2] for small general commercial service [63] to compute annual electricity bills. We then estimated future electricity prices by applying electricity price trends based on EIA's Annual Energy Outlook 2018 (AEO 2018) and derived the present value of future costs by applying discount rates specific to each building type. Note that building electrical equipment lifetimes were assumed to be 10 years on average. Table 4 lists cost ranges[3] and sources for each of the power system components included in the TEA.

[2] The A-1 rate does not include a demand charge.
[3] Cost ranges in the Monte Carlo simulation are all assumed to be uniform distributions, with equal probabilities between the min and max values.

Table 4. Summary of Techno-economic Analysis Inputs

Parameter	Min/Nominal Value	Max Value	Unit	Source
First Cost Parameters				
AC inverter cost	190	290	$/kW	Civicsolar.com, altestore.com
AC battery inverter cost	370	660	$/kW	Civicsolar.com, stratensolar.com
DC optimizer cost	100	220	$/kW	stratensolar.com, distr. quotes
DC grid-tie inverter*	370	660	$/kW	Civicsolar.com,stratensolar.com
DC 380-48 V converter	250	450	$/kW	Distributor quotes
AC circuit breaker (20A)	16	18	$/unit	mouser.com
DC circuit breaker (20A)	30	36	$/unit	mouser.com
AC LED driver	Cost-power regression, ±10%		$/unit	digikey.com
DC LED driver	Cost-power regression, ±10%		$/unit	digikey.com
AC wall adapter cost	Cost-power regression, ±10%		$/kW	digikey.com
Sales tax	8.5%		%	thestc.com
Operating Cost Parameters				
Distr. Syst. Efficiency	Varies		%	Efficiency analysis
System lifetime	8	12	years	Typical equip. lifetimes
Office build. disc. rate	5.05% with 1.05 std deviation		%	Damodaran online
Restaurant disc. rate	6.07% with 0.92% std deviation		%	Damodaran online
Retail disc. rate	5.63% with 1.05% std deviation		%	Damodaran online
Electricity prices	Varies by time-of-use rate		$/kWh	PG&E, Hawaiian Electric
Electricity price trends	94%–114% of base year price		%	AEO 2018
Monte Carlo Simulation Parameters				
Number of simulations	1,000 runs			

* The cost of the DC grid-tie inverter (bidirectional) was assumed to be similar to the cost of the battery inverter, because both components have similar functions. The bidirectional inverter was also assumed to include battery charge control.

2.7. Sensitivity Analyses

This study uses parametric analysis to determine the energy and economic conditions in which DC distribution is favorable. We examined six parametric runs for each building, in which the solar and battery capacity are varied relative to their baseline values. The baseline solar capacity is the amount that will generate enough energy on an annual basis to equal the building's annual energy consumption, thus qualifying the building as zero net electricity (ZNe). Note that the reference buildings in this study used natural gas for some end uses that were not covered by the solar generation. The baseline battery capacity is half the capacity required to store all the excess PV (the difference between the daily generation and the load) on the sunniest day of the year. For example, in Los Angeles, this capacity can actually store all of the excess PV on nearly 80 percent of the days. The battery capacity is set to either zero, half-baseline, or baseline, while the solar capacity is set to either its half-baseline or baseline value.

We also examined a near-future scenario, in which the efficiencies of power system components for both building distribution systems have improved. Specifically, for this scenario we used maximum converter efficiency curves, whereas for the baseline scenario, we used median converter efficiency curves. For details on the converter efficiency curves, see Appendix E in [17]. This scenario also assumed an electricity tariff that encourages self-consumption, to account for increased penetrations of solar generation and includes a time-of-use rate, which is minimized during peak solar hours (9am -5pm). This time-of-use program is currently used in residential systems in Hawaii [64].

3. Results

3.1. Efficiency Results

In each parametric run, the DC building has lower electrical losses than the AC building, as shown in Figure 8 for the medium-size office building. The analysis shows that energy savings can range from approximately 8 percent in an office with PV and no battery to approximately 15 percent in a building with a large PV array and battery. Appendix A reports the loss analyses for other buildings in modern and future scenarios.

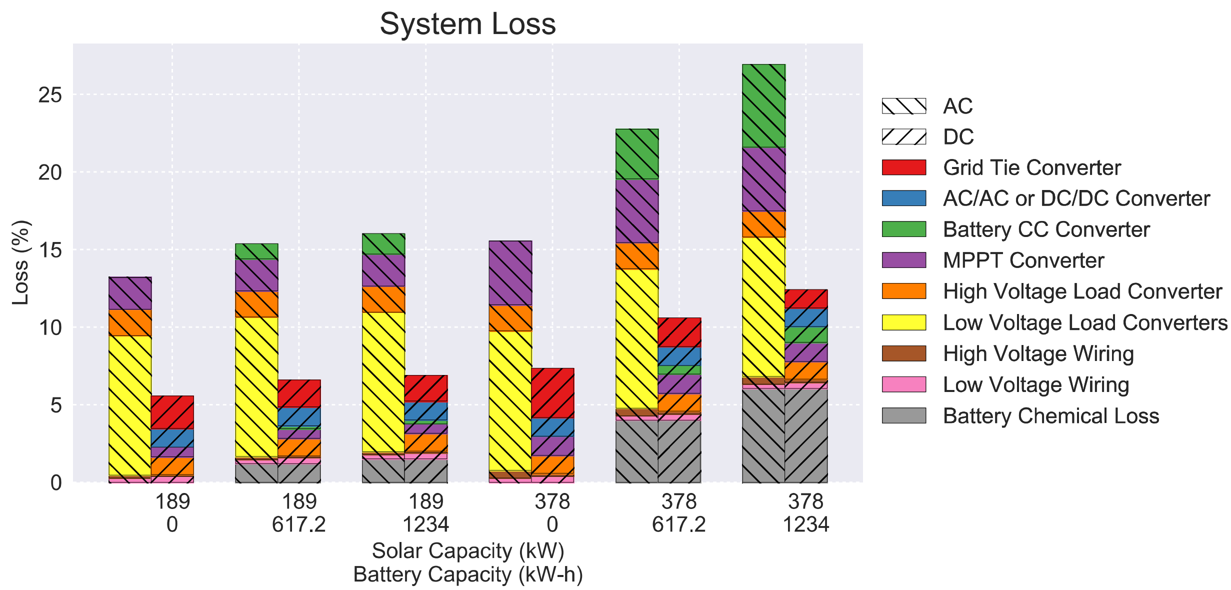


Figure 8. Energy simulation loss analysis results for the medium-size office building. The savings from DC distribution increase for buildings with larger solar and battery capacity, shown as the scenarios progress to the right. The most significant loss in each building is from low-voltage AC load converters, which include internal power supply rectifiers and wall adapters.

3.2. Techno-economic analysis results

Results for all PV and battery capacities for the current and future scenario are presented in Table 5 and Table 6, respectively.

For the current scenario, the DC systems of the medium office building and restaurant have positive LCC savings and payback periods of four years or less in all simulations that include battery storage. The same buildings, at the maximum capacity of PV and battery storage, have DC systems with lower first cost than their corresponding AC systems, leading to instant payback periods. This is due primarily to the relative cost of the DC versus AC system power system components, e.g., the cost of the DC optimizer ($100–$220 per kilowatt-hour [kWh]) versus the cost of the inverter ($190–$290 per kWh), and their high capacity, which dominates the cost of the system. However, for systems without battery storage, DC distribution has negative LCC savings in most cases, and payback periods ranging between 5 and 20 years.
The retail building has slightly lower efficiency savings compared to the office building and restaurant (see Appendix A), thus making it difficult to recoup the electricity bill savings over the lifetime of the equipment (assumed 10 years on average). Also, as discussed earlier, the DC

distribution system of the restaurant does not include a secondary 48 V DC bus, which requires a 380-48 V DC-DC converter, thus incurring fewer power losses as well as lower overall first cost.

For the future scenario, improvements in converter efficiencies for both the AC and DC distribution systems lead to lower efficiency savings, while the applied electricity tariff reduces the incremental electricity bill savings of the DC versus the AC distribution system. A comparison of the LCC savings under the current versus the future scenario is presented in Figure 9.

Table 5. Techno-Economic Analysis Results for the Current Scenario

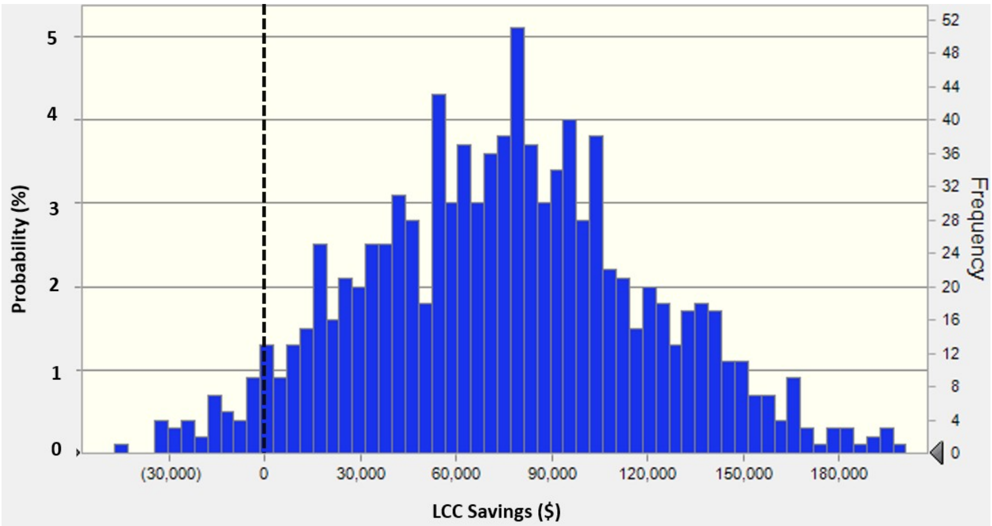
Medium Office Building						
Parameter/PV & Battery Scenario	50% PV, No Batt.	50% PV, 50% Batt.	50% PV, 100% Batt.	100% PV, No Batt.	100% PV, 50% Batt.	100% PV, 100% Batt.
AC First Cost ($)	89,000	174,000	203,000	144,000	247,000	307,000
DC First Cost ($)	196,000	196,000	196,000	346,000	315,000	299,000
AC LCC ($)	822,000	934,000	973,000	299,000	494,000	619,000
DC LCC ($)	835,000	849,000	856,000	405,000	420,000	442,000
Mean LCC Savings ($)	-16,000	82,000	115,000	-106,000	74,000	177,000
% Simulations with Positive LCC Savings	26.1%	99.8%	100.0%	0.4%	95.3%	100.0%
Mean PBP (years)	9.5	1.7	0	17.1	3.9	0
Retail						
Parameter/PV & Battery Scenario	50% PV, No Batt.	50% PV, 50% Batt.	50% PV, 100% Batt.	100% PV, No Batt.	100% PV, 50% Batt.	100% PV, 100% Batt.
AC First Cost ($)	43,000	73,000	77,000	71,000	112,000	144,000
DC First Cost ($)	148,000	148,000	148,000	167,000	167,000	167,000
AC LCC ($)	387,000	427,000	430,000	136,000	211,000	273,000
DC LCC ($)	451,000	456,000	455,000	186,000	204,000	222,000
Mean LCC Savings ($)	-65,000	-30,000	-26,000	-51,000	6,000	51,000
% Simulations with Positive LCC Savings	0.0%	7.4%	11.5%	0.9%	60.7%	96.4%
Mean PBP (years)	19.9	12.6	11.9	16.2	6.8	2.4
Restaurant						
Parameter/PV & Battery Scenario	50% PV, No Batt.	50% PV, 50% Batt.	50% PV, 100% Batt.	100% PV, No Batt.	100% PV, 50% Batt.	100% PV, 100% Batt.
AC First Cost ($)	30,000	60,000	65,000	56,000	95,000	129,000
DC First Cost ($)	59,000	58,000	59,000	126,000	115,000	101,000
AC LCC ($)	335,000	385,000	391,000	107,000	177,000	245,000
DC LCC ($)	319,000	329,000	330,000	132,000	138,000	143,000
Mean LCC Savings ($)	13,000	53,000	58,000	-26,000	39,000	101,000
% Simulations with Positive LCC Savings	90.8%	100.0%	100.0%	7.8%	98.5%	100.0%
Mean PBP (years)	5.1	0	0	11.8	2.5	0

Note: Costs reported are rounded to the nearest thousand.

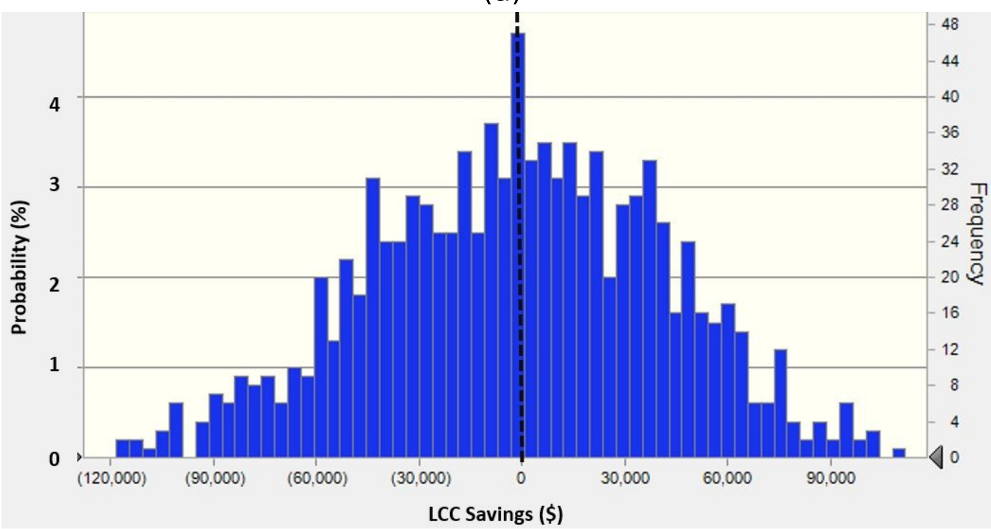
Table 6. Techno-Economic Analysis Results for the Future Scenario

Medium Office Building						
Parameter/PV & Battery Scenario	50% PV, No Batt.	50% PV, 50% Batt.	50% PV, 100% Batt.	100% PV, No Batt.	100% PV, 50% Batt.	100% PV, 100% Batt.
AC First Cost ($)	89,000	173,000	201,000	144,000	246,000	305,000
DC First Cost ($)	200,000	196,000	196,000	355,000	324,000	308,000
AC LCC ($)	659,000	763,000	797,000	239,000	400,000	496,000
DC LCC ($)	717,000	726,000	731,000	404,000	409,000	416,000
Mean LCC Savings ($)	-64,000	31,000	60,000	-166,000	-8,000	80,000
% Simulations with Positive LCC Savings	0.1%	86.8%	98.5%	0.0%	46.1%	95.5%
Mean PBP (years)	19.2	3.4	0	37.9	9.0	0.2
Retail						
Parameter/PV & Battery Scenario	50% PV, No Batt.	50% PV, 50% Batt.	50% PV, 100% Batt.	100% PV, No Batt.	100% PV, 50% Batt.	100% PV, 100% Batt.
AC First Cost ($)	43,000	73,000	77,000	71,000	112,000	142,000
DC First Cost ($)	149,000	149,000	149,000	168,000	168,000	168,000
AC LCC ($)	319,000	356,000	359,000	115,000	179,000	227,000
DC LCC ($)	402,000	405,000	405,000	189,000	202,000	213,000
Mean LCC Savings ($)	-85,000	-52,000	-48,000	-73,000	-24,000	13,000
% Simulations with Positive LCC Savings	0.0%	0.1%	0.2%	0.0%	14.7%	70.3%
Mean PBP (years)	36.7	23.5	22.1	31.4	13.3	5.0
Restaurant						
Parameter/PV & Battery Scenario	50% PV, No Batt.	50% PV, 50% Batt.	50% PV, 100% Batt.	100% PV, No Batt.	100% PV, 50% Batt.	100% PV, 100% Batt.
AC First Cost ($)	30,000	60,000	65,000	57,000	95,000	128,000
DC First Cost ($)	71,000	71,000	71,000	141,000	131,000	117,000
AC LCC ($)	277,000	321,000	326,000	92,000	151,000	203,000
DC LCC ($)	300,000	308,000	309,000	160,000	161,000	158,000
Mean LCC Savings ($)	-23,000	12,000	17,000	-67,000	-10,000	45,000
% Simulations with Positive LCC Savings	0.0%	89.9%	95.7%	0.0%	28.4%	99.7%
Mean PBP (years)	17.1	3.5	2.0	36.9	10.4	0

Note: Costs reported are rounded to the nearest thousand.



(a)



(b)

Figure 9. Distribution of LCC savings for the medium-size office building, in the 100% PV, 50% battery scenario for the current (a) and future (b) scenario. In the current scenario, about 95 percent of simulation runs yield positive LCC savings, while in the future scenario, this percentage falls to about 46 percent.

Conclusions and Discussion

This paper presented a techno-economic evaluation of DC distribution in commercial buildings. This work was based on (a) a technical analysis of the building distribution systems and end-use topologies, (b) a detailed efficiency model [17], and (c) an LCC and PBP analysis framework that utilized price data from commercially available products. We found that DC distribution systems are cost-effective in most scenarios that included large capacities of

PV and battery storage; whereas, in those scenarios that did not, DC systems were generally not cost-effective.

Although this work clearly shows that DC distribution can make sense economically in commercial buildings with large battery storage systems and onsite PV arrays, it does not address whether commercial buildings with battery storage are cost-effective compared to those without. It is rather focused on the AC versus DC distribution comparison. We should also note that the current market for DC systems is at its nascent stage, therefore costs not considered in this analysis, such as installations costs, permitting costs, and other soft costs are expected to be higher for DC systems in the short run. However, as the market for DC distribution reaches maturity, we expect such costs to become comparable to those for AC systems, while other potential benefits of DC (e.g., ease of communications and controls, increased reliability from simpler appliances) could translate to additional cost savings for DC distribution.

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Appendix A. Loss Analysis Results

This section presents a loss breakdown for the medium-size office, retail, and restaurant buildings in Los Angeles. It includes the simulated losses for the current (Figures A-1 to A3) and future (figures A-4 to A-6) scenarios for these buildings.

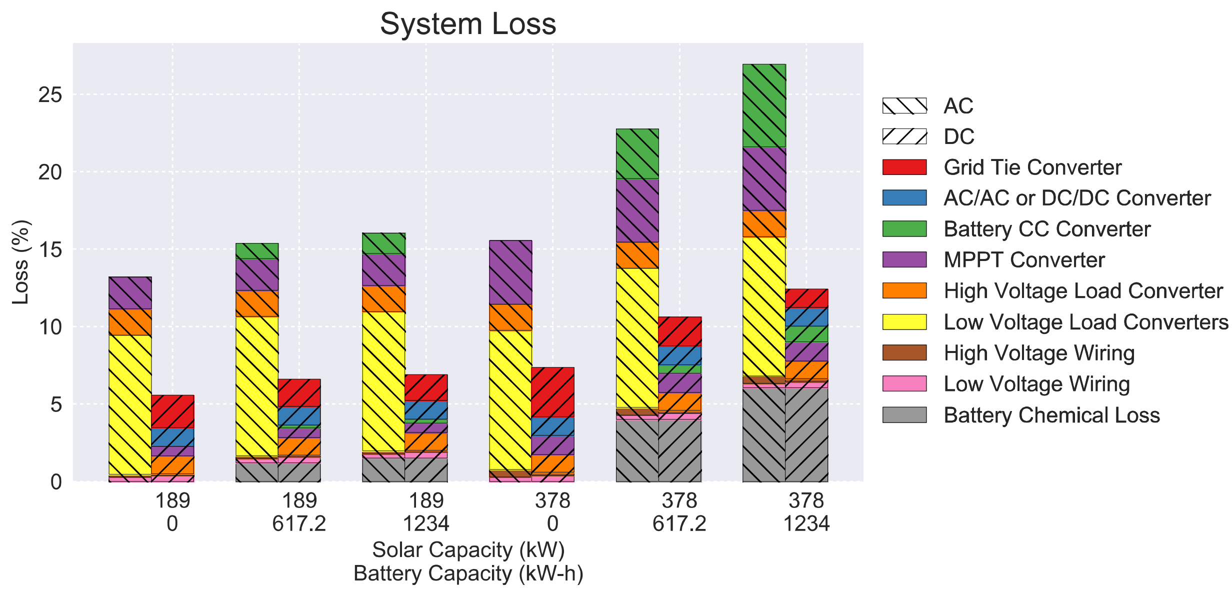

Figure A-1. System losses for the medium office building – current scenario.

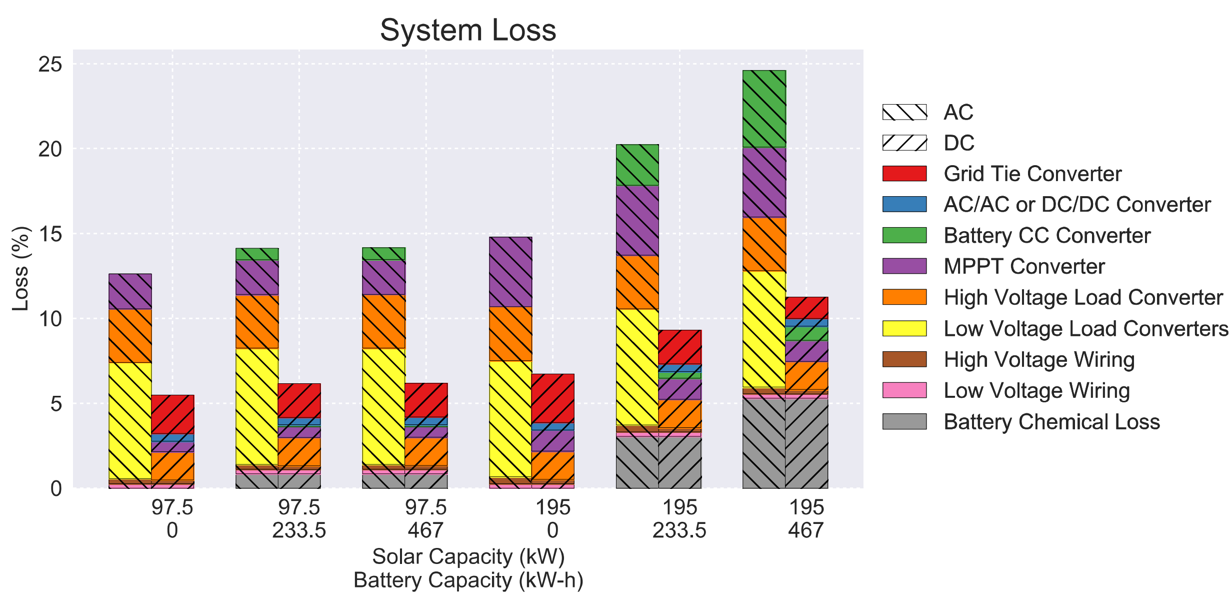

Figure A-2. System losses for the retail building – current scenario.

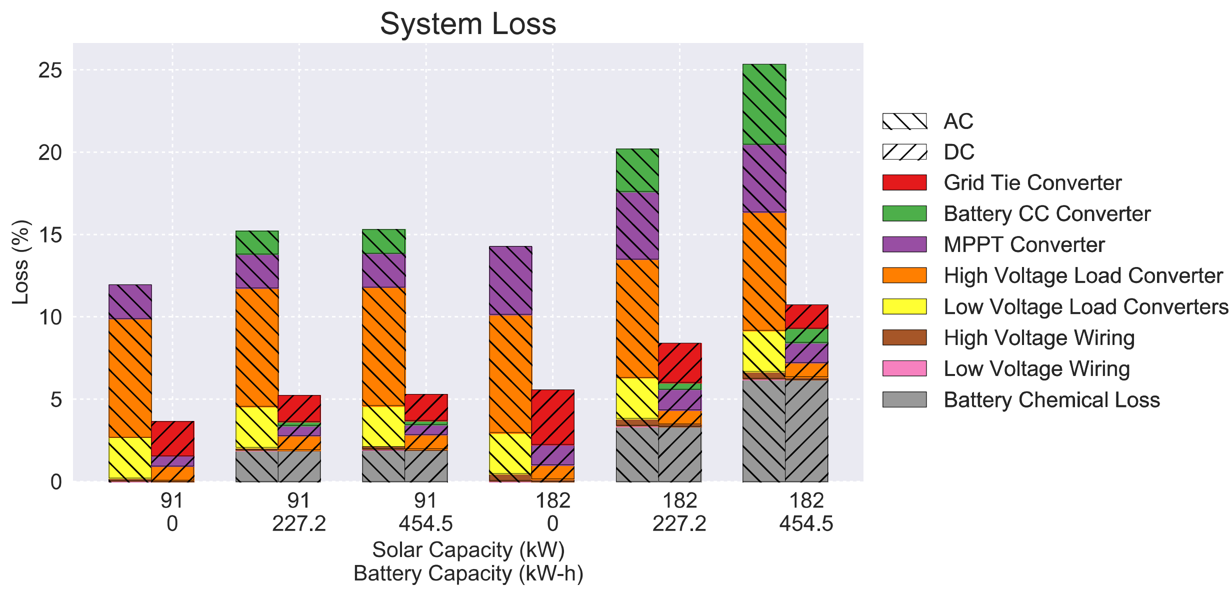

Figure A-3. System losses for the restaurant – current scenario.

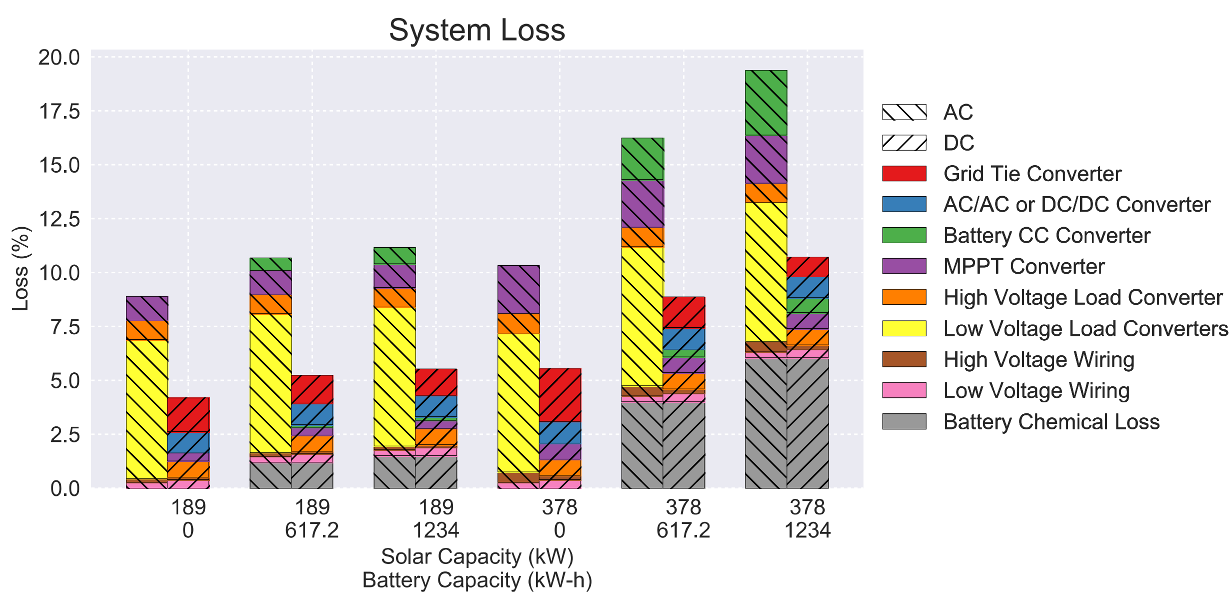

Figure A-4. System losses for the medium office building – future scenario.

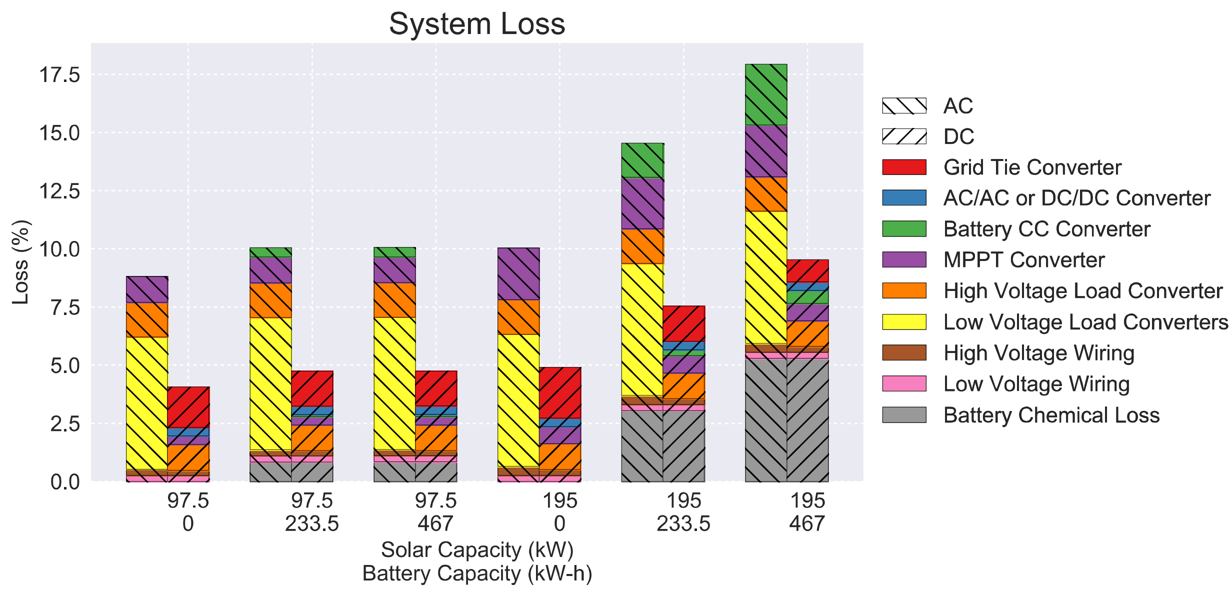

Figure A-5. System losses for the retail building – future scenario.

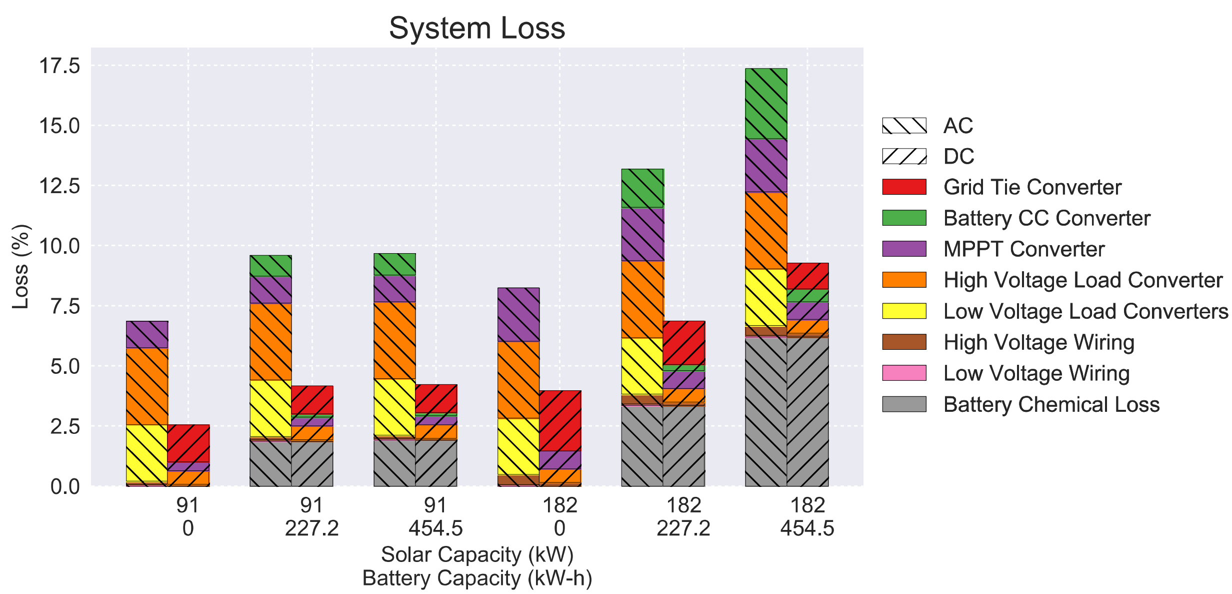

Figure A-6. System losses for the restaurant – future scenario.

Bibliography

[1] A. Perea *et al.*, "Solar Market Insight: 2017 Year in Review," Solar Energy Industries Association, Mar. 2018.

[2] K. Garbesi, V. Vossos, and H. Shen, "Catalog of DC Appliances and Power Systems," Lawrence Berkeley National Laboratory, Berkeley, CA, LBNL-5364E, 2011.

[3] B. Nordman and K. Christensen, "The need for communications to enable DC power to be successful," in *2015 IEEE First International Conference on DC Microgrids (ICDCM)*, 2015, pp. 108–112.

[4] S. Pantano, P. May-Ostendorp, and K. Dayem, "Demand DC. Accelerating the Introduction of DC Power in the Home," CLASP, May 2016.

[5] Strategen Consulting and ARUP Group, “Direct-Current Scoping Study: Opportunities for direct current power in the built environment.,” US Department of Energy, Building Technologies Office, Technical Report, 2014.

[6] B. T. Patterson, “DC, Come Home: DC Microgrids and the Birth of the ‘Enernet,’” *IEEE Power Energy Mag.*, vol. 10, no. 6, pp. 60–69, Nov. 2012.

[7] K. George, “DC Power Production, Delivery and Utilization: An EPRI White Paper,” 2006.

[8] S. Backhaus *et al.*, “DC Microgrids Scoping Study—Estimate of Technical and Economic Benefits,” Los Alamos National Laboratory, LA-UR-15-22097, Mar. 2015.

[9] P. Savage, R. R. Nordhaus, and S. P. Jamieson, “From Silos to Systems: Issues in Clean Energy and Climate Change: DC microgrids: benefits and barriers,” Yale School of Forestry & Environmental Sciences, 2010.

[10] D. Denkenberger, D. Driscoll, E. Lighthiser, P. May-Ostendorp, B. Trimboli, and P. Walters, “DC Distribution Market, Benefits, and Opportunities in Residential and Commercial Buildings,” Pacific Gas & Electric Company, Oct. 2012.

[11] V. Vossos, K. Garbesi, and H. Shen, “Energy savings from direct-DC in U.S. residential buildings,” *Energy Build.*, vol. 68, Part A, pp. 223–231, Jan. 2014.

[12] R. Weiss, L. Ott, and U. Boeke, “Energy efficient low-voltage DC-grids for commercial buildings,” in *2015 IEEE First International Conference on DC Microgrids (ICDCM)*, 2015, pp. 154–158.

[13] U. Boeke and M. Wendt, “DC power grids for buildings,” in *2015 IEEE First International Conference on DC Microgrids (ICDCM)*, 2015, pp. 210–214.

[14] D. Fregosi *et al.*, “A comparative study of DC and AC microgrids in commercial buildings across different climates and operating profiles,” in *2015 IEEE First International Conference on DC Microgrids (ICDCM)*, 2015, pp. 159–164.

[15] K. Engelen *et al.*, “The Feasibility of Small-Scale Residential DC Distribution Systems,” in *IECON 2006 - 32nd Annual Conference on IEEE Industrial Electronics*, 2006, pp. 2618–2623.

[16] B. Glasgo, I. L. Azevedo, and C. Hendrickson, “How much electricity can we save by using direct current circuits in homes? Understanding the potential for electricity savings and assessing feasibility of a transition towards DC powered buildings,” *Appl. Energy*, vol. 180, pp. 66–75, Oct. 2016.

[17] D. L. Gerber, V. Vossos, W. Feng, C. Marnay, B. Nordman, and R. Brown, “A simulation-based efficiency comparison of AC and DC power distribution networks in commercial buildings,” *Appl. Energy*, Jan. 2018.

[18] D. J. Hammerstrom, “AC Versus DC Distribution Systems. Did We Get it Right?,” in *IEEE Power Engineering Society General Meeting, 2007*, 2007, pp. 1–5.

[19] Z. Liu and M. Li, “Research on Energy Efficiency of DC Distribution System,” *AASRI Procedia*, vol. 7, pp. 68–74, 2014.

[20] M. Noritake, K. Yuasa, T. Takeda, H. Hoshi, and K. Hirose, “Demonstrative research on DC microgrids for office buildings,” in *Telecommunications Energy Conference (INTELEC), 2014 IEEE 36th International*, 2014, pp. 1–5.

[21] P. Paajanen, T. Kaipia, and J. Partanen, “DC supply of low-voltage electricity appliances in residential buildings,” in *CIRED 2009 - 20th International Conference and Exhibition on Electricity Distribution - Part 1*, 2009, pp. 1–4.

[22] M. R. Starke, L. M. Tolbert, and B. Ozpineci, “AC vs. DC distribution: A loss comparison,” in *Transmission and Distribution Conference and Exposition, 2008. T #x00026;D. IEEE/PES*, 2008, pp. 1–7.

[23] S. Willems and W. Aerts, “Study and Simulation Of A DC Micro Grid With Focus on Efficiency, Use of Materials and Economic Constraints,” University of Leuven, Leuven, Belgium, 2014.
[24] V. Vossos, R. Brown, M. Kloss, K. Johnson, M. Khattar, and D. Gerber, “Review of DC Power Distribution in Buildings: A Technology and Market Assessment,” Lawrence Berkeley National Laboratory, Berkeley, CA, LBNL-2001006, May 2017.
[25] B. Petschke, “Is DC Power the Future of Data Center Design?,” 11-Jun-2015. [Online]. Available: http://blog.stulz-ats.com/dc-power-data-center. [Accessed: 19-Jun-2017].
[26] “Nextek,” *Nextek Power Systems*, 2018. [Online]. Available: https://www.nextekpower.com/. [Accessed: 10-Apr-2018].
[27] Lumencache, “Lumencache,” 2018. .
[28] IGOR, “Power Over Ethernet Lighting | POE Lighting Control,” *IGOR*, 2018. [Online]. Available: http://www.igor-tech.com/. [Accessed: 28-Feb-2016].
[29] M. P. Bahrman, “HVDC transmission overview,” in *2008 IEEE/PES Transmission and Distribution Conference and Exposition*, 2008, pp. 1–7.
[30] G. AlLee and W. Tschudi, “Edison Redux: 380 Vdc Brings Reliability and Efficiency to Sustainable Data Centers,” *IEEE Power Energy Mag.*, vol. 10, no. 6, pp. 50–59, Nov. 2012.
[31] D. E. Geary, “Phasing out AC - Directly,” in *2012 IEEE Energytech*, 2012, pp. 1–6.
[32] B. A. Thomas, I. L. Azevedo, and G. Morgan, “Edison Revisited: Should we use DC circuits for lighting in commercial buildings?,” *Energy Policy*, vol. 45, pp. 399–411, Jun. 2012.
[33] A. Sannino, G. Postiglione, and M. H. J. Bollen, “Feasibility of a DC network for commercial facilities,” *IEEE Trans. Ind. Appl.*, vol. 39, no. 5, pp. 1499–1507, Sep. 2003.
[34] G. Laudani and P. Mitcheson, “Comparison of cost and efficiency of DC versus AC in office buildings,” Imperial College, London, U.K.
[35] B. Wunder, L. Ott, M. Szpek, U. Boeke, and R. Weis, “Energy efficient DC-grids for commercial buildings,” in *Telecommunications Energy Conference (INTELEC), 2014 IEEE 36th International*, 2014, pp. 1–8.
[36] E. Rodriguez-Diaz, J. C. Vasquez, and J. M. Guerrero, “Potential energy savings by using direct current for residential applications: A Danish household study case,” in *2017 IEEE Second International Conference on DC Microgrids (ICDCM)*, 2017, pp. 547–552.
[37] “Personal Communication. John Wang, ABB.,” 12-Oct-2016.
[38] B. Glasgo, “Device-Level Data Analytics to Guide Policy,” Carnegie Mellon University, Dissertation, 2017.
[39] S. Foster Porter, D. Denkenberger, C. Mercier, P. May-Ostendorp, and P. Turnbull, “Reviving the War of Currents: Opportunities to Save Energy with DC Distribution in Commercial Buildings,” ECOVA, 2014.
[40] L. Mackay, T. Hailu, L. Ramirez-Elizondo, and P. Bauer, “Towards a DC distribution system - opportunities and challenges,” in *2015 IEEE First International Conference on DC Microgrids (ICDCM)*, 2015, pp. 215–220.
[41] D. King and J. Brodrick, “Residential DC Power Bus. Opportunities for Savings?,” *ASHRAE Journal*, pp. 73–77, Sep-2010.

[42] EIA, “2012 Commercial Buildings Energy Consumption Survey: 2012 CBECS Survey Data,” 2017. [Online]. Available: https://www.eia.gov/consumption/commercial/data/2012/.
[43] M. Deru *et al.*, “US Department of Energy commercial reference building models of the national building stock,” National Renewable Energy Laboratory, Golden, CO, NREL/TP-5500-46861, 2011.
[44] DOE, “Commercial Reference Buildings,” 2017. [Online]. Available: https://energy.gov/eere/buildings/commercial-reference-buildings.
[45] T. Liu, G. Li, B. Han, D. Zhang, and S. Youssouf, “Research on the topology of DC distribution network and the influence of distributed generations access to the network,” in *2015 5th International Conference on Electric Utility Deregulation and Restructuring and Power Technologies (DRPT)*, 2015, pp. 512–517.
[46] Y. Yi, Z. Yuan, and Y. Ji, “Research on Topology of DC Distribution Network Based on Power Flow Optimization,” in *2017 IEEE International Conference on Energy Internet (ICEI)*, 2017, pp. 344–348.
[47] F. G. Osorio, M. Xinran, Y. Liu, P. Lusina, and E. Cretu, “Sensor network using power-over-ethernet,” in *Computing and Communication (IEMCON), 2015 International Conference and Workshop on*, 2015, pp. 1–7.
[48] J. Johnston, J. Counsell, G. Banks, and M. J. Stewart, “Beyond power over Ethernet: The development of digital energy networks for buildings,” in *CIBSE Technical Symposium 2012-Buildings Systems and Services for the 21st Century*, 2012, p. Session–5.
[49] USB 3.0 Promoter Group, “Universal Serial Bus 3.2 Specification.” USB 3.0 Promoter Group.
[50] EMerge Alliance, “Our Standards.” [Online]. Available: http://www.emergealliance.org/Standards/OurStandards.aspx. [Accessed: 22-Mar-2018].
[51] Occupational Safety and Health Administration, *Code of Federal Regulations*, vol. 1910.303(g)(2)(i). .
[52] J. Tuenge, K. Kelly, and M. Poplawski, “Connected Lighting Systems Efficiency Study—PoE Cable Energy Losses, Part 1,” Pacific Northwest National Lab. (PNNL), Richland, WA (United States), 2017.
[53] Vicor, *Why Today’s Applications are Moving to 48V*. 2018.
[54] D. L. Gerber, V. Vossos, W. Feng, A. Khandekar, C. Marnay, and B. Nordman, “A simulation based comparison of AC and DC power distribution networks in buildings,” in *2017 IEEE Second International Conference on DC Microgrids (ICDCM)*, 2017, pp. 588–595.
[55] U. Boeke and L. Ott, “Impact of a 380V DC Power Grid Infrastracture on Commercial Building Energy Profiles,” DCC+G & eniac, White Paper, Apr. 2014.
[56] E. Waffenschmidt, “Direct Current (DC) Supply Grids for LED Lighting,” *LED Professional*.
[57] NREL, *PVWatts Calculator*. 2017.
[58] G. Rosenquist, K. Coughlin, L. Dale, J. McMahon, and S. Meyers, “Life-cycle cost and payback period analysis for commercial unitary air conditioners,” Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, CA (US), Berkeley, CA, LBNL-54244, Mar. 2004.
[59] RSMeans, *Electrical Costs with RSMeans Data 2018*, 41st ed. Gordian, 2017.
[60] Navigant Consulting, Inc., “2015 U.S. Lighting Market Characterization,” U.S. Department of Energy, Nov. 2017.

[61] B. Urban, K. Roth, M. Singh, and D. Howes, “fraunhofer energy consumption of consumer electronics 2017 - Google Search,” Fraunhofer USA, Dec. 2017.
[62] FEMP, “Energy-and Cost-Savings Calculators for Energy-Efficient Products,” 2018. [Online]. Available: https://www.energy.gov/eere/femp/energy-and-cost-savings-calculators-energy-efficient-products. [Accessed: 28-Mar-2018].
[63] PG&E, “Tariffs,” 2018. [Online]. Available: https://www.pge.com/tariffs/index.page. [Accessed: 26-Mar-2018].
[64] Hawaiian Electric, “Time of Use Program.” [Online]. Available: https://www.hawaiianelectric.com/save-energy-and-money/time-of-use-program. [Accessed: 26-Mar-2018].

List of Acronyms:

AC	alternating current
BLDC	brushless direct current
DC	direct current
HVAC	heating, ventilation, and air conditioning
LED	light-emitting diode
LCC	lifecycle cost
MPPT	maximum power point tracker
PBP	payback period
PoE	power over Ethernet
PV	photovoltaic
TEA	techno-economic analysis
VFD	variable frequency drive
ZNE	zero net energy
ZNe	zero net electricity