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Techno-economic analysis of DC power distribution in commercial buildings

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HIGHLIGHTS

- Analysis on the cost-effectiveness of DC distribution in commercial buildings.
- Lifecycle cost and payback period analysis using Monte Carlo simulation.
- Evaluation for various solar and battery storage capacities.
- Sensitivity analysis for future conditions.
- DC can be viable in commercial buildings with DC loads, PV and storage.

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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% 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.

A techno-economic analysis framework based on commercially available products that evaluates the cost-effectiveness of DC systems is presented. The analysis is conducted for three commercial building types in two California climate zones and for various PV and battery storage capacities. Monte Carlo simulation is used to compute the payback period and lifecycle cost savings of DC versus AC distribution systems. A future-market scenario is also examined, which evaluates how future efficiency improvements in power converters and changes in electricity tariffs may affect cost 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.

1. Introduction

Although the earliest building power systems used direct current (DC) power, alternating current (AC) has been the near-universal form of power delivered to building devices for over 100 years, primarily due to the relative ease and lower cost of voltage conversions. Despite this long history and dominant position, building power engineers are reconsidering whether DC may actually be the preferred choice, due to a variety of technology and market changes. First, modern power electronics have made DC power conversion much easier, more reliable, 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], making DC power commonly available in buildings. Third, batteries, which operate on DC power, are increasingly being deployed for power reliability, energy bill savings, and to provide grid services. Fourth, the emergence of electric vehicles (EVs) – a mobile form of battery storage – creates a significant new native-DC load and opportunities for cost savings when powered directly with DC [2]. Fifth, the drive to reduce energy use in buildings has led to widespread adoption of efficient, and native-DC end-use technologies such as light-emitting diodes (LEDs), variable-speed driven motors, electronic controls and other native-DC technologies [3]. These market and technology trends are being accelerated by a variety of policies at national, state, and local

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Nomenclature

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

levels to promote energy efficient buildings. Similarly, policies are stimulating adoption of PV, energy storage, and EVs. There are also a variety of non-energy benefits that are causing people to reconsider DC power, such as ease of communications and controls [4], reliability and resilience, power quality, interoperability, and other factors [5–8].

An obvious and 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 [9–21] or measured [22–24] the energy savings from DC distribution, with savings ranging from a few percent to about 15%. Numerous 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 [25]. 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 [26] and is beginning to gain traction in commercial buildings for lighting applications, with several companies offering DC-powered luminaires and DC lighting systems [27–29]. 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 [30] and is estimated to result in capital cost reductions and lifecycle cost savings in data centers operating at 380 V DC [31,32]. 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) [25]. A relatively small but growing number of studies have addressed the cost-effectiveness of DC distribution in buildings, compared to the standard AC and are summarized in the following sections.

Glasgo et al. [14] 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 1000 Monte Carlo simulations to account for the uncertainty of efficiencies and costs of power system components, electric end uses, and other factors, such as discount rates. The Monte Carlo simulations used uniform distributions for system component costs and converter efficiencies, primarily due to the lack of data to better define distributions. The analysis considered converter peak efficiencies, since converter efficiencies were assumed to have similar degradation under part-load conditions between the AC and DC distribution system. It was 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.

Thomas et al. [33] analyzed a DC lighting system in a simulated commercial office building and estimated a 5% reduction in levelized annual costs for direct-DC LED lighting systems, compared to equivalent systems with AC distribution.[1] Similar to Glasgo et al., this study used Monte Carlo simulations with uniform distributions for converter efficiencies and equipment costs, and did not account for part-load converter efficiencies. Note that this research assumed that DC distribution eliminated the need for LED drivers.

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 [20,34,35]. These studies were limited in scope, and did not account for system components shared between the AC and DC distribution system, nor did they account for the economic impact of the systems over their lifetimes. Notably, in [35], the analysis focused on office buildings, and was primarily dependent on the use of power functions between price and power ratings of DC-DC, AC-DC, and DC-AC converters. In [36], a cost comparison was conducted between a DC and an AC distribution system in a modeled house with battery storage. It was assumed that all loads can operate on DC or AC, so the cost difference was mainly due to power converters in the distribution systems (inverter for the AC system versus charge controller and DC-DC converter for the AC system). It was found that the cost of the DC system was slightly higher compared to that of the AC system. In [37], an economic assessment of DC and AC microgrids in off-grid communities (powering AC loads) was performed, in which the total system cost was expressed as the sum of the components that comprised it based on market-available equipment. Finally, Backhaus et al. [9] performed a scoping study on the potential benefits of DC microgrids, which also included a preliminary assessment of their associated capital as well as operating costs. One of their key assumptions was that the cost of bidirectional converters in DC architectures is equal to the cost of their respective unidirectional components.

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. [38], 50% of power conversion losses and 70% of weight and volume in internal switch mode power supplies could be eliminated with DC distribution. Rodriguez-Diaz et al. [39] argue that direct-DC distribution to appliances (e.g., laptops) that utilize external power supplies can lead to a 55% volume reduction (and therefore 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. They also point out the benefits of eliminating certain

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

components from power supplies with a high likelihood of failure, such as the electrolytic capacitor. Stippich et al. [40] modified several low power appliances (a computer monitor and power supply, a blender, an AC-DC wall adapter and USB charger, and LED lighting) with an internal DC stage to be directly fed with DC. They measured efficiency savings and identified a potential for cost savings due to the elimination of rectifiers and power factor correction components. 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 [41]. The study presented here is following a data-based approach to estimate the costs of DC-system components, using actual price data, including web-scraped data where possible, and by applying an uncertainty analysis with Monte Carlo simulations.

Planas et al. [42] performed an economic qualitative analysis on the development costs of AC versus DC microgrids. They note that installation costs, which largely depend on the number of installed components, can be lower in DC microgrids with many DC end uses, such as offices and data centers, compared to those of AC microgrids. According to the same authors, despite the higher cost of DC technologies currently available, DC system design can be simpler and therefore cheaper due to a higher number of variables monitored in the AC system. However, they argue that protection costs are generally higher for DC systems due to their immaturity. Several DC system manufacturers claim reduced installation costs, in particular for Power over Ethernet (PoE) lighting systems, ranging between 25 and 40% compared to traditional AC systems [43,44]. However, these claims remain unsubstantiated and may actually be offset in the short term by other soft costs, such as permitting and design costs, due to the immaturity of the technology and the lack of experience among practitioners, e.g., electricians and architects.

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 adoption. Follow-up interviews to a subset of survey respondents underscored the need for additional data and research on DC systems cost [25]. 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 [45]. This assessment is consistent with findings from Foster Porter et al. [46] 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. [12] anticipate that at scale, DC systems in commercial buildings can reach a 15–20% capital cost reduction, and the total cost of ownership can be 30% 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.

All previously mentioned analyses assume new construction scenarios, rather than retrofits of existing buildings, which are typically more costly. For example, Glasgo et al. [14] 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. [47] estimate that retrofit costs are likely to outweigh the benefits of DC distribution in existing infrastructures, while King and Brodrick [48] claim that residential electric installations may cost up to twice as much for renovations, compared to new construction.

Based on the review of the literature on energy savings and costs, 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%) of their energy consumed as electricity [49], and the high coincidence of solar generation and commercial end-use loads. Such buildings are becoming more commonplace as climate change goals are requiring a huge increase in building and end-use system efficiency. For example, California has set a goal for zero net energy commercial buildings by 2030. As discussed in [3], the most efficient appliances are native-DC, therefore DC distribution in highly-efficient buildings with DC end uses and onsite PV may be the ideal path for achieving building efficiency goals.

Despite the interest and potential need for DC distribution in commercial buildings, its cost-effectiveness has not been thoroughly analyzed in the literature. This paper extends previous work conducted by Gerber et al. (2018) to model three medium-sized commercial buildings with PV in two California climate zones (Los Angeles and San Francisco), while parametrically varying the solar generation and battery storage capacity to find economically optimal values. Monte Carlo simulation is used 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. A *future-market* scenario that addresses how future efficiency improvements in power converters and changes in electricity tariffs may affect results is also assessed.

This work makes the following key contributions:

- It calculates operating costs based on a detailed power loss model that incorporates converter efficiency curves from actual market data. Other studies estimated operating costs by considering only peak converter efficiencies.
- 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.
- It follows a data-based approach for cost inputs using detailed market data, where available, and incorporates well-defined distributions for the Monte Carlo analysis.
- 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 uses actual electricity tariffs rather than average electricity prices 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

Three small- to medium-size commercial buildings are analyzed, drawing building dimensions and load profiles from the EnergyPlus Reference Buildings [50,51]. 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 profiles. Hourly electricity 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

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	4982	3	49.9	33.3	4.0
Stand-alone Retail	2294	1	54.3	42.4	6.1
Full Service Restaurant	511	1	22.6	22.6	3.1

for onsite PV systems. Table 1 shows a summary of the Reference Buildings' physical characteristics.

2.2. Selection of DC distribution network topology

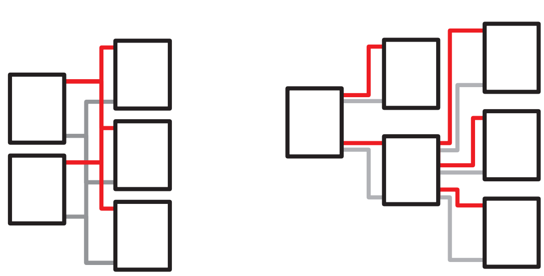
The distribution topology of a DC distribution network can have a large impact on both its efficiency and cost. The primary design choices in distribution topology are in the wiring network and the distribution voltages. DC buildings can be wired as a bus network or a star network. In a bus network, the end-use loads are all electrically connected in parallel, as shown in

Fig. 1(a). This type of network is common in traditional AC building distribution wiring, and can be configured in a radial, ring, or mesh pattern [52,53]. 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

Fig. 1(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 PoE [54,55] and universal serial bus (USB) [56]. 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.

In this work, the modeled DC building employs a combined bus/star topology. As shown in Fig. 2(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.

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*



(a) (b)

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

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 [57]. 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 [57], and the 5–20 V USB-PD standard [56]. DC plug load voltages are all less than 50 V, which qualifies them as safe to touch [58]. Because wire loss is inversely proportional to the square of the distribution voltage, plug-level voltages are only suitable for localized low-power loads [59,60]. Although 24 V distribution is practical in many applications, it requires many power servers to offset the quadrupled wire loss compared to 48 V. Even at 48 V, 5–15% wiring loss can be present in a 50 m PoE wiring run [59], 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

Similar to the analysis in [17] and [75], and to minimize losses for the DC distribution system, the building model assumes that all 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 building distribution voltage. The following section describes how the major load types in the buildings (i.e., motor loads, lighting, and electronics) are technically configured to be supplied directly by DC.

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 Fig. 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 [61].

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 95–98% range. AC LED drivers, on the other hand, often exhibit 86–93% efficiency [15]. 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 [62]. 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 Figs. 4 and 5, respectively. The building models utilize one or more of the following power distribution voltages:

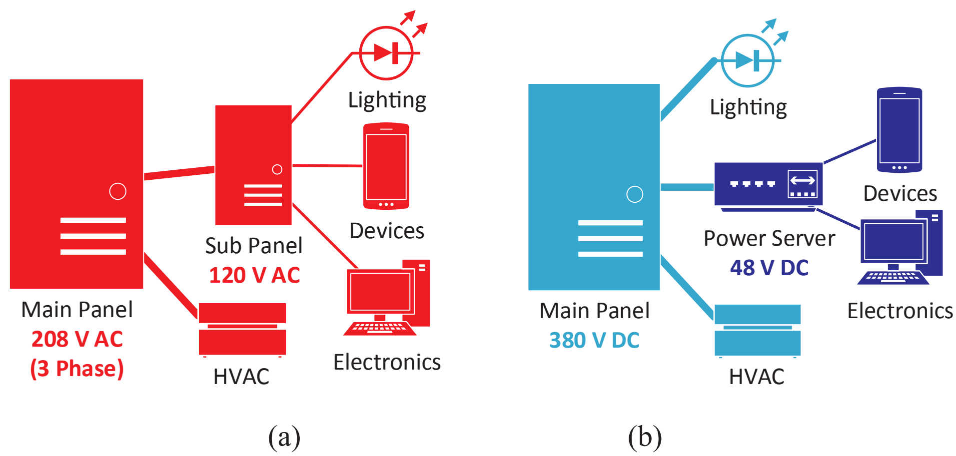


Fig. 2. Star topology for the (a) AC and (b) DC building distribution systems in this study. The 48 V power server in the DC building effectively replaces the subpanels in the AC building.

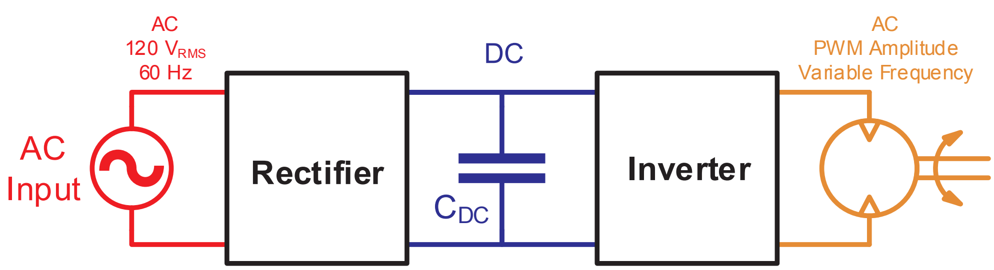


Fig. 3. Block schematic of a BLDC motor with VFD. The inverter is powered from an internal DC stage (blue), and outputs AC at a variable frequency (orange). For AC distribution, a rectifier is required to convert 60 Hz AC (red) for the internal DC stage. For DC distribution, the internal stage of a carefully designed VFD can be connected directly to the building distribution system. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

- AC Building: 120 V AC (plug) and 208 V AC three-phase (infrastructure).[2]
- 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 in each climate zone (San Francisco and Los Angeles) are derived from PVWatts [63]. The simulation models, inputs, and assumptions for each component are discussed in detail in [15].

2.5. Techno-economic analysis methodology

To evaluate the cost-effectiveness of the DC distribution, its economic performance is compared 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 [64]. The DOE uses the LCC and PBP as part of a series of metrics and criteria used to determine the regulatory requirements of the standards program for new or amended appliance standards [65].

The LCC is calculated according to Eq. (1):

$$\text{LCC} = \text{Total Installed Cost} + \text{Lifetime Operating Cost} \tag{1}$$

The total installed cost includes the cost of the building distribution system and costs of electrical end-use equipment. As discussed in the introduction, although DC distribution may lead to lower installation costs (especially in PoE systems), it may also lead to increased soft costs, such as permitting and design costs. However, such cost differences between AC and DC systems have not been thoroughly documented, and therefore are not considered in the analysis.

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 Eq. (2):

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

where r is the discount rate.

The PBP, is calculated according to Eq. (3)[3]:

$$\text{PBP} = \frac{\text{Total Installed Cost}_{DC} - \text{Total Installed Cost}_{AC}}{\text{Annual Operating Cost}_{AC} - \text{Annual Operating Cost}_{DC}} \tag{3}$$

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

The TEA was performed using Monte Carlo simulation and probability distributions for each scenario, to account for input uncertainty

[2] The selected AC building distribution voltages correspond to relatively small buildings that do not include internal AC transformers. For larger buildings with transformers, the AC building losses and costs may be higher.

[3] Note that Eq. (3) assumes that the DC system's total installed cost (Total Installed Cost$_{DC}$) is higher than the AC system's total installed cost (Total Installed Cost$_{AC}$). In cases where this is not true, the PBP yields a negative result, which in practice represents an instant payback.

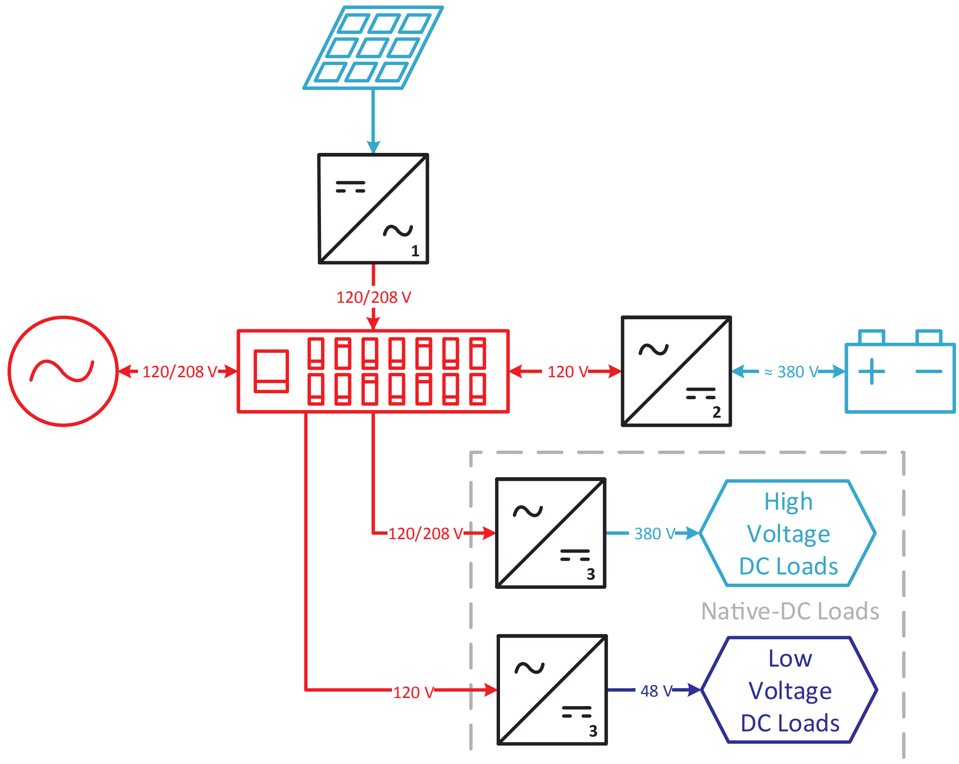


Fig. 4. Building network with AC distribution. Converters: 1. String inverter (performs maximum power point tracking), 2. Battery inverter (performs bidirectional charge control), and 3. Load-packaged rectifier or wall adapter.

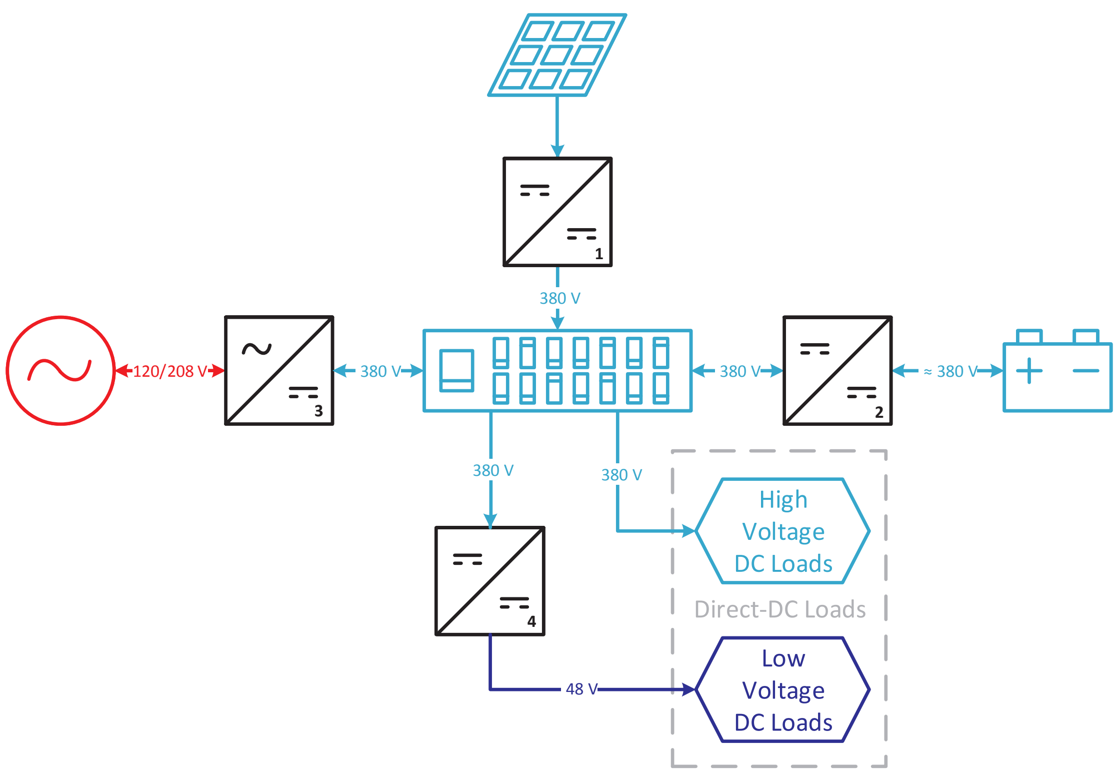


Fig. 5. Building network with DC distribution. Converters: 1. MPPT module (performs maximum power point tracking), 2. Battery charge controller (performs bidirectional charge control), 3. Grid tie inverter (bidirectional), and 4. DC-DC step-down, which could be a 48 V power server. Certain loads such as LEDs require an additional DC-DC converter (not shown).

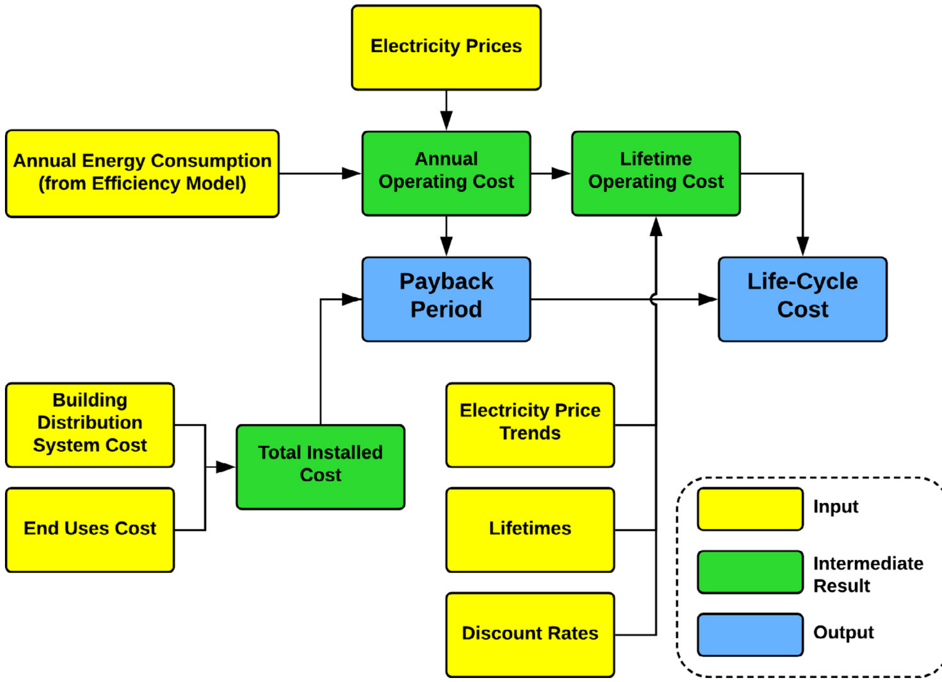


Fig. 6. LCC and PBP flow diagram.

and variability. The simulations were conducted using Microsoft Excel and Crystal Ball, a commercially available Excel add-in software.[4] The LCC and PBP results are based on 10,000 samples per Monte Carlo simulation run for each scenario and are generated as a distribution of values from which summary statistics are calculated, such as average LCC and PBP, and the percent of runs with positive LCC savings. Each calculation uses input values sampled from a probability distribution or defined as single point values. For example, probability distributions are used to characterize equipment lifetimes, discount rates, and equipment prices, and single point values characterize other inputs, such as sales tax. The following section provides more information on the variability applied to the TEA model inputs.

2.6. Techno-economic analysis inputs

To determine the total installed cost of each system, first, the cost of a building's major electrical infrastructure was estimated, including circuit breakers and all the components shown in Figs. 4 and 5. Infrastructure component costs (in $/kW) were derived from online retailers, distributors, and manufacturer estimates. These costs were then scaled by the peak annual power through each component, oversized by 125%, which is a typical oversize factor for power converters. All costs are reported in 2018 current U.S. dollars.

Building wiring losses were incorporated in the efficiency analysis as described in [15]. The AC and DC buildings were assumed to utilize the same infrastructure-level wiring at 208 V and 380 V, respectively, and have identical infrastructure-level wiring costs. 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 [66], 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. Cost versus power functions were developed based on online cost data from digikey.com, as shown in Fig. 7.

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, the average number of lamps per m^2 for each building was utilized, according to the same study and scaled it by each building's floor area (shown in Table 1).

To determine the distribution of load types for electronics, such end uses were identified for the office and retail building (the restaurant was assumed not to include electronic loads) in the 2012 Commercial Buildings Energy Consumption Survey (CBECS) [49] and estimated wattage ranges for these loads based on various sources [67,68]. 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 125% oversizing factor was applied on these power draws to derive wall adapter wattage ratings.

To determine lifetime operating costs, the results of the efficiency analysis were first utilized, which derived the annual net electricity consumption (in 8760 hourly values) for each distribution system, and then multiplied by the corresponding time-of-use hourly electricity rates for each building type and scenario, to compute annual electricity bills. Electricity prices for future years over the lifetime of the equipment were estimated by applying electricity price trends to the annual electricity bills based on the U.S. Energy Information Administration's (EIA's) Annual Energy Outlook 2018 (AEO 2018) [69]. For the current-market scenario, California's Pacific Gas & Electric A-1 electric rate schedule[5] for small general commercial service [70] was used. For the

[4] During a simulation, multiple scenarios of a model are calculated by repeatedly sampling values from the probability distributions for the uncertain variables. During a single simulation run, Crystal Ball randomly selects a value from the defined possibilities (the range and shape of the probability distribution) for each uncertain variable and then recalculates the desired outcome.

[5] The A-1 rate does not include a demand charge.

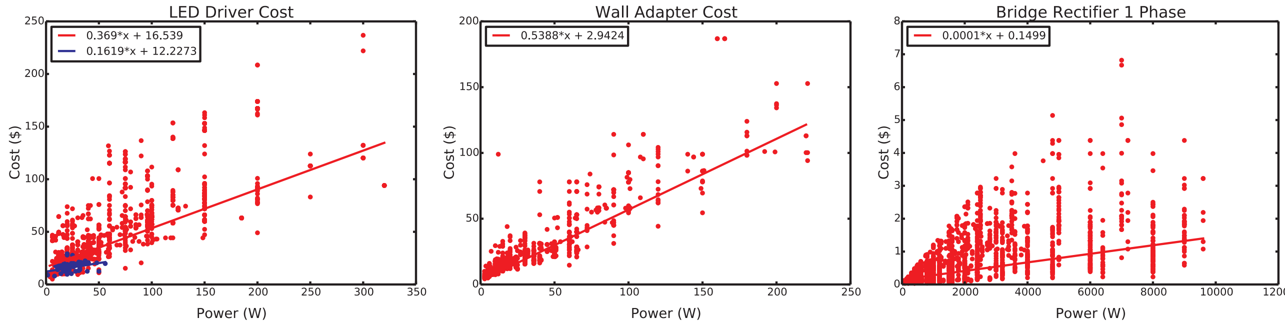


Fig. 7. Cost data and linear regressions for LED drivers (left), wall adapters (middle), and bridge rectifiers (right). The regressions were determined after subjecting the cost data to several analytic filters: After removing obvious outliers that were unrealistically overpriced, the data were sorted 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/kW) they were eventually excluded from the TEA.

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 (W)	Office (W)	Retail (W)	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 [74].

Table 3
Electronics power draw estimates and weighted distributions by building type.

CBECS Electronic Load	Power Draws (W)		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

future-market scenario (discussed more in Section 2.7), an electricity tariff that is currently used in residential systems in Hawaii [71] was implemented.

The present value of future operating costs was estimated by applying discount rates specific to each building type, according to the analysis discussed in [72]. The sampled discount rates used in the Monte Carlo simulation for the office building, restaurant, and retail building are derived from normal distributions with parameters corresponding to those listed in Table 2.2 of [72], for the 'Office', 'Food Service', and 'Retail Other' sectors, respectively. See Table 4 for the discount rate input values.

For system lifetimes, similar to [14,33], a 10-year average lifetime for power distribution equipment was assumed for the reference scenario. Equipment lifetime is better represented as a survival function than a single-point value [73]. Consistent with appliance efficiency standards methodology, a survival function was used to derive lifetime distributions. The parameters of this survival function were determined following the average lifetime constraint and the assumption that 90% of the equipment fails at twice the average lifetime. For example, for a 10-year average lifetime, 90% of the equipment was assumed to fail by year 20. It was also assumed that no equipment fails before the first year to account for a typical 1-year warranty for power converters. The survival function has the form of a cumulative Weibull distribution, as discussed in [73], and shown in Eq. (4):

$$P(x) = e^{-\left(\frac{x-\theta}{\alpha}\right)^{\beta}} \; for \; x > \theta \; and$$
$$P(x) = 1 \; for \; x \leqslant \theta \tag{4}$$

Where:

$P(x)$ is the probability that the equipment is in use at age x
α = scale parameter,
β = shape parameter, which determines the way the failure rate changes over time, and,
θ = delay parameter, which corresponds to the delay before any failure occurs (set to 1)

The shape and scale parameters were derived using a least squares fitting[6], and specifically for the 10-year average lifetime scenario their values were 1.310 and 9.756, respectively. Note that a shape value greater than 1 typically indicates an increasing failure rate as equipment ages.

Table 4 summarizes the TEA input parameters for determining the first (installed) cost and the operating cost, and lists information on the variability and uncertainty applied to those parameters. During the Monte-Carlo simulation, the costs for the power system components are set by drawing from uniform distributions defined by the ranges indicated in Table 4 (with equal probabilities between the min and max values). These ranges were determined by analyzing webscraped price

[6] Specifically, a downhill simplex algorithm was utilized through *scipy.optimize.fmin* https://docs.scipy.org/doc/scipy/reference/generated/scipy.optimize.fmin.html

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	Weibull distribution (Avg = 10)		years	Typical equip. lifetimes
Office build. disc. rate	6.04% with 1.05 std deviation		%	[72]
Restaurant disc. rate	5.73% with 0.92 std deviation		%	[72]
Retail disc. rate	5.89% with 1.05 std deviation		%	[72]
Electricity prices	Varies by time-of-use rate		$/kWh	PG&E, Hawaiian Electric
Electricity price trends	94–114% of base year price		%	[69]
Monte Carlo Simulation Parameters				
Number of simulations	10,000 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, similar to [9]. The bidirectional inverter was also assumed to include battery charge control.

data (e.g., for circuit breakers), collecting online retail prices, and reviewing distributor quotes for certain less ubiquitous DC system components. As discussed earlier, system lifetimes are sampled from Weibull distributions, while discount rates are sampled from normal distributions, the parameters of which are listed in Table 4. Using a Monte-Carlo simulation allows for results of a probabilistic nature and for sensitivity analyses to be performed. Those are discussed in the following section.

2.7. Scenarios and sensitivity analyses

As discussed earlier, this study uses parametric analysis to determine the energy and economic conditions in which DC distribution is favorable. Six parametric runs for each building, and each city were examined, 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 electricity 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% of the days. The battery capacity is set to either zero, half-baseline (50% battery), or baseline (100% battery), while the solar capacity is set to either its half-baseline (50% PV) or baseline value (100% PV).

The future-market scenario was also examined, in which the efficiencies of power system components for both building distribution systems have improved. Specifically, for this scenario, maximum converter efficiency curves are used, whereas for the current-market scenario, median converter efficiency curves are used. For details on the converter efficiency curves, see Appendix E in [15]. Furthermore, the future-market scenario utilizes a time-of-use electricity tariff currently implemented in Hawaii. The Hawaii tariff was selected to account for future increased penetrations of solar generation (which are already occurring in Hawaii), since during peak solar hours (9 am–5 pm) this electricity rate is minimized to encourage self-consumption. Overall, the comparison of DC versus AC distribution is examined for a combination of 2 climate regions in California, 3 types of commercial buildings, 2 market conditions, and 6 distribution system configurations, for a total of 72 scenarios, as shown in Fig. 8.

In addition to the aforementioned scenarios, and to examine the effect of system lifetime on the TEA results, a sensitivity analysis was conducted by assuming a 5 year, and a 15 year average system lifetime, using the methodology for determining the Weibull distribution parameters. The shape and scale values were derived to be 1.057 and 4.088 for the 5-year lifetime, and 1.279 and 15.107 for the 15-year lifetime, respectively. This sensitivity analysis was conducted for the current-market San Francisco restaurant under all system configurations.

3. Results

3.1. Efficiency results

In each parametric run, the DC building has lower electrical losses than the AC building, as shown in Fig. 9 for the office building in Los Angeles. The analysis shows that energy savings can range from approximately 8% in an office with PV and no battery to approximately 15% in a building with a large PV array and battery for both climate zones. Appendix A reports the loss analysis results for other building types in the current-market and future-market scenarios in Los Angeles.

3.2. Techno-economic analysis results

Results for all PV and battery capacities for the current-market and future-market scenario in Los Angeles are presented in Tables 5 and 6, respectively.

For the current-market scenario (Table 5), the DC systems of the medium office building and restaurant have positive LCC savings and payback periods of four years or less in simulations that include battery storage. The same buildings, at the maximum capacity of 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 $/kWh) versus the cost of

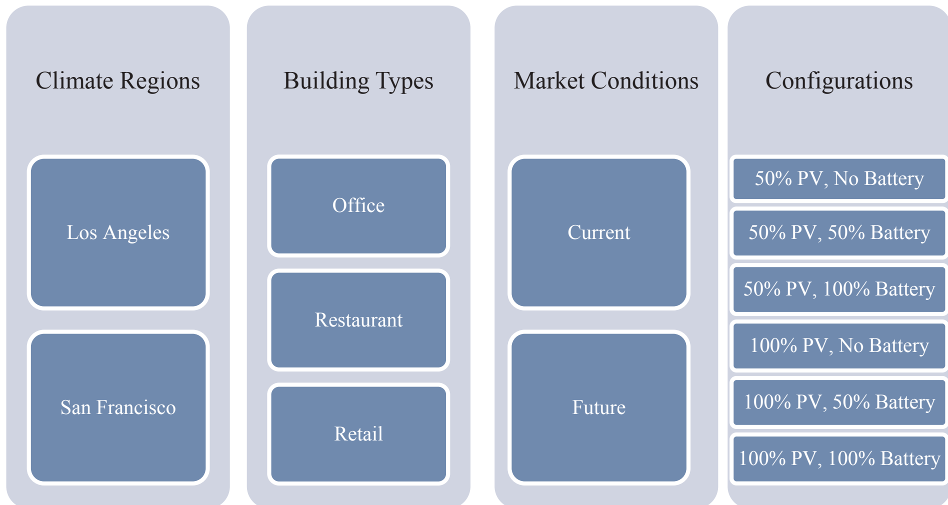


Fig. 8. Graphic representation of scenarios considered in the analysis.

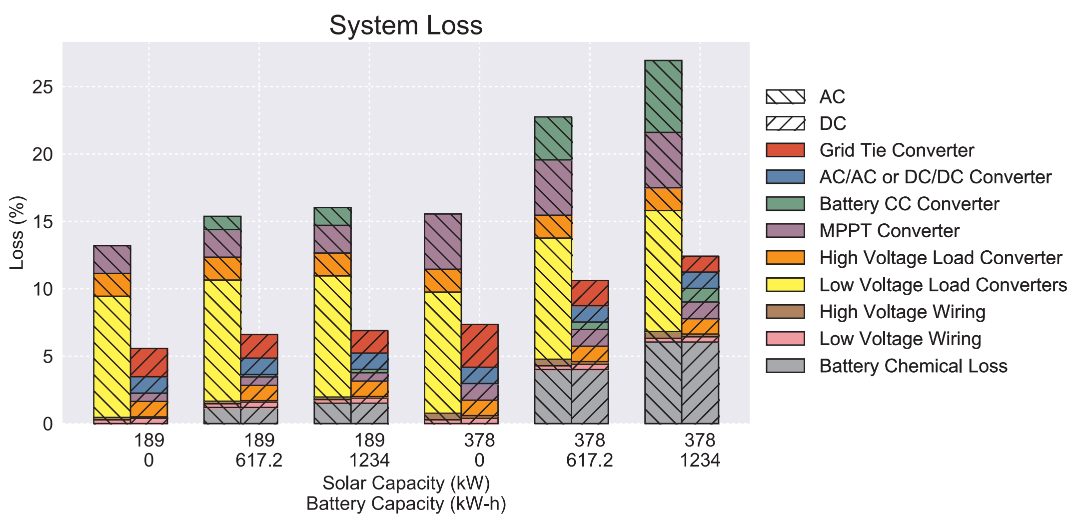


Fig. 9. Energy simulation loss analysis results for the medium-size office building. The savings from DC distribution increase for buildings with larger solar and battery capacity, shown as the scenarios progress to the right. The most significant loss in each building is from low-voltage AC load converters, which include internal power supply rectifiers and wall adapters.

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), making it difficult to recoup the electricity bill savings over the lifetime of the equipment (assumed 10 years on average). In addition, 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. Also, the office building has better coincidence of loads and PV generation compared to other buildings, thus drawing less energy from the grid when PV or battery power is not available.

For the future-market scenario (Table 6), improvements in converter efficiencies for both the AC and DC distribution systems lead to lower efficiency savings for the DC system, while the applied electricity tariff reduces the incremental electricity bill savings of the DC versus the AC distribution system. The TEA results for the future-market scenario follow a similar trend as those of the current-market; however, they are less favorable for the DC system.

Fig. 10 shows the distribution of LCC savings for the medium-office building in Los Angeles at the future-market scenario for all PV and battery size configurations, resulting from 10,000 Monte Carlo simulation runs for each configuration.

The TEA results in San Francisco are slightly more favorable compared to their respective Los Angeles results (Fig. 11a). This somewhat counterintuitive result can be explained as follows: San Francisco receives lower insolation on an annual basis [63], therefore the buildings' PV capacity is scaled to be slightly higher than the PV capacity in the Los Angeles buildings so that generation will match the buildings' annual electricity consumption. Also, the total amount of electricity to and from the grid for the San Francisco versus the Los Angeles buildings is lower. This shows a better coincidence of PV and loads in San Francisco, which clearly favors DC, since it does not need to be converted to AC when fed back to the grid, or to DC when imported from the grid. In addition, the TEA results are strongly sensitive to the system lifetime, as shown in Fig. 11b. A longer lifetime increases lifetime operating costs as well as savings for the DC system over the systems' lifetime. Evidently, the effect is one of diminishing returns because of discounting future cost savings. This can be seen by comparing TEA savings between 5 and 10 years lifetime, versus 10 and 15 years lifetime in Fig. 11b.

Table 5
Techno-economic analysis results for the current-market scenario in Los Angeles.

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.
Medium Office Building						
AC First Cost ($)	89,000	175,000	204,000	145,000	248,000	308,000
DC First Cost ($)	193,000	193,000	193,000	343,000	312,000	296,000
AC LCC ($)	680,000	787,000	825,000	269,000	448,000	560,000
DC LCC ($)	679,000	690,000	694,000	391,000	394,000	406,000
Mean LCC Savings ($)	−30,000	66,000	98,000	−122,000	50,000	149,000
% Simulations with Positive LCC Savings	25.2%	90.2%	97.8%	2.4%	72.9%	97.3%
Mean PBP (years)	9.2	1.4	0	16.8	3.7	0
Retail						
AC First Cost ($)	43,000	73,000	77,000	71,000	112,000	143,000
DC First Cost ($)	145,000	145,000	145,000	164,000	164,000	164,000
AC LCC ($)	342,000	381,000	384,000	128,000	198,000	256,000
DC LCC ($)	393,000	397,000	396,000	180,000	195,000	209,000
Mean LCC Savings ($)	−67,000	−32,000	−28,000	−53,000	2,000	45,000
% Simulations with Positive LCC Savings	1.0%	14.9%	18.2%	5.2%	49.4%	83.7%
Mean PBP (years)	19.2	12.0	11.3	15.5	6.4	2.1
Restaurant						
AC First Cost ($)	30,000	61,000	66,000	57,000	96,000	130,000
DC First Cost ($)	58,000	58,000	58,000	127,000	117,000	103,000
AC LCC ($)	307,000	355,000	361,000	102,000	170,000	235,000
DC LCC ($)	280,000	289,000	290,000	133,000	137,000	139,000
Mean LCC Savings ($)	10,000	49,000	54,000	−31,000	33,000	94,000
% Simulations with Positive LCC Savings	62.1%	98.9%	99.4%	13.9%	81.9%	99.8%
Mean PBP (years)	5.0	0	0	12.1	2.6	0

Note: Costs reported are rounded to the nearest thousand.

Table 6
Techno-economic analysis results for the future-market scenario in Los Angeles.

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.
Medium Office Building						
AC First Cost ($)	89,000	174,000	201,000	145,000	247,000	306,000
DC First Cost ($)	195,000	192,000	192,000	350,000	319,000	303,000
AC LCC ($)	552,000	652,000	685,000	222,000	372,000	460,000
DC LCC ($)	589,000	595,000	599,000	390,000	386,000	387,000
Mean LCC Savings ($)	−68,000	25,000	54,000	−169,000	−15,000	70,000
% Simulations with Positive LCC Savings	1.1%	76.0%	93.0%	0.0%	38.6%	88.4%
Mean PBP (years)	18.5	2.7	0	36.9	8.3	0
Retail						
AC First Cost ($)	43,000	73,000	77,000	71,000	112,000	142,000
DC First Cost ($)	144,000	144,000	144,000	163,000	163,000	163,000
AC LCC ($)	279,000	315,000	318,000	109,000	169,000	215,000
DC LCC ($)	344,000	347,000	347,000	180,000	192,000	201,000
Mean LCC Savings ($)	−82,000	−50,000	−46,000	−71,000	−23,000	13,000
% Simulations with Positive LCC Savings	0.0%	1.1%	2.0%	0.1%	20.0%	65.7%
Mean PBP (years)	34.7	21.7	20.4	29.6	12.0	4.0
Restaurant						
AC First Cost ($)	30,000	60,000	65,000	57,000	95,000	128,000
DC First Cost ($)	58,000	57,000	58,000	128,000	117,000	104,000
AC LCC ($)	249,000	291,000	297,000	88,000	144,000	194,000
DC LCC ($)	248,000	254,000	255,000	143,000	143,000	138,000
Mean LCC Savings ($)	−12,000	23,000	28,000	−56,000	1,000	55,000
% Simulations with Positive LCC Savings	16.7%	94.8%	97.3%	0.1%	50.7%	99.0%
Mean PBP (years)	11.5	0	0	31.0	6.5	0

4. Conclusions and discussion

This paper presented a techno-economic evaluation of DC distribution in highly efficient commercial buildings with DC loads. TEA results were generated for three commercial building types in two California cities with several PV and battery capacities, for current and future market conditions. This work was based on (1) a technical analysis of the building distribution systems and end-use topologies, (2) a detailed efficiency model that incorporates real converter efficiency curves [15], and (3) an LCC and PBP analysis framework that utilizes Monte Carlo simulation and price data from commercially available products.

Results show that DC distribution systems are cost-effective in most scenarios that include large capacities of PV and battery storage; whereas, in those scenarios that do not, DC systems are generally not cost-effective. The sensitivity analyses reveal that coincidence of load and PV generation increases efficiency savings and economic benefits. Perhaps one of the most important factors affecting energy and cost savings is the DC system configuration. Simpler systems, with less power conversion steps have fewer components and incur lower power losses. For example, the restaurant, which is assumed not to have a secondary 48 V DC bus yields the most desirable installed cost ratio (of DC versus AC system cost) compared to the other buildings.

Although this work clearly shows that DC distribution can make

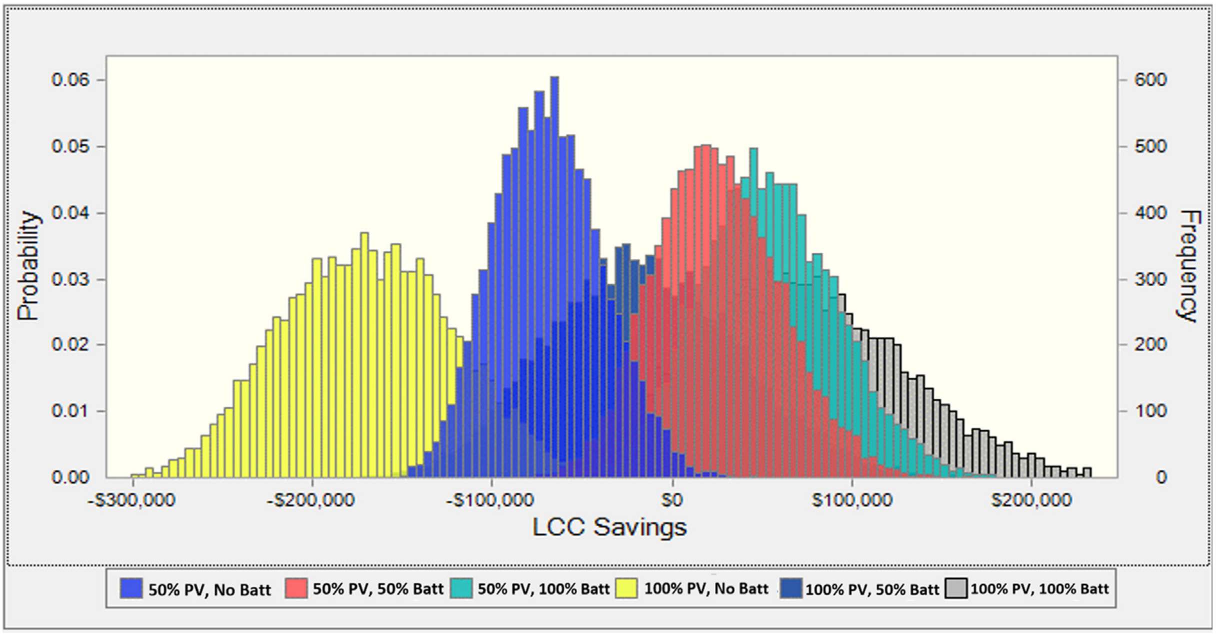


Fig. 10. Overlay histograms of LCC savings for the future-market office building in Los Angeles.

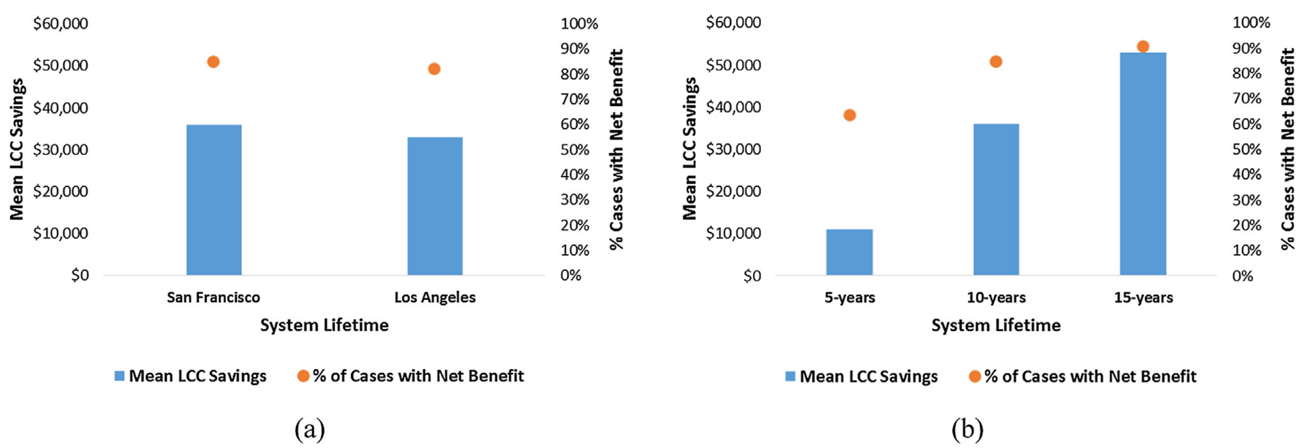


Fig. 11. Effect of system location (a) and system lifetime (b) to TEA results. This sensitivity analysis is presented for the restaurant at the current-market scenario.

sense economically in efficient commercial buildings with DC loads, 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. Rather, it focuses on the AC versus DC distribution comparison. Note that the current market for DC systems is at its nascent stage, therefore costs not considered in this analysis, such as installation costs and soft costs are expected to be higher for DC systems in the short run. However, as the market for DC distribution continues to edge towards maturity, such costs are expected to become comparable to those of AC systems (on a per installed unit basis), while other potential benefits of DC could translate to additional cost savings for DC distribution. Indeed, resiliency, ease of communications and controls, and increased reliability from simpler appliances (without internal AC/DC conversions) may actually be more important motivation factors for adoption of DC power in buildings than just energy savings. Therefore, more research related to quantifying the benefits of the non-energy attributes of DC distribution is warranted. An important limitation of this study is that its first cost inputs are reflective of the current market and the scarcity of available DC products. To evaluate the cost-effectiveness of DC distribution on an ongoing basis, a tool that can be easily updated with new inputs for different system configurations and implementation scenarios is recommended.

Acknowledgements

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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 (Figs. A1–A3) and future (Figs. A4–A6) scenarios for these buildings.

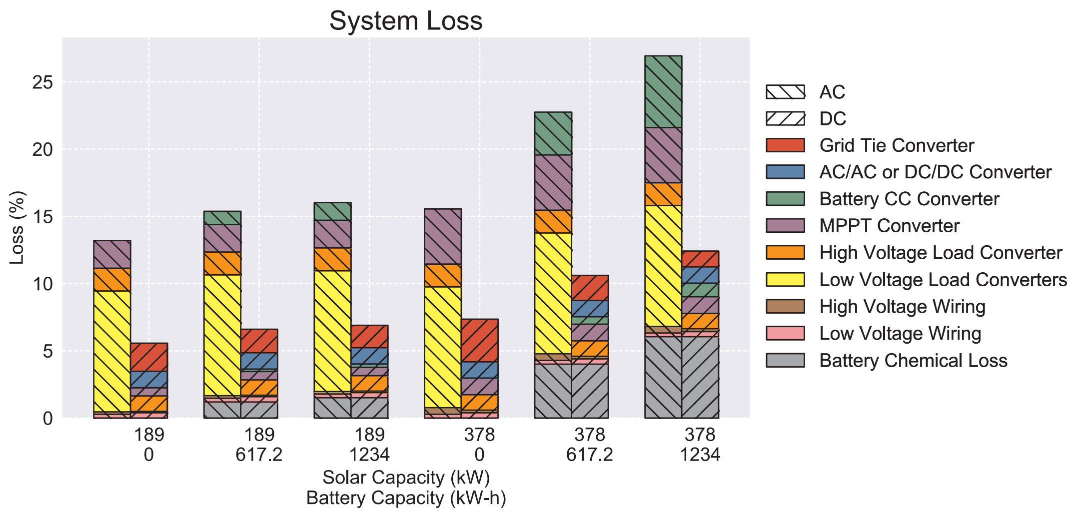

Fig. A1. System losses for the medium office building – current scenario.

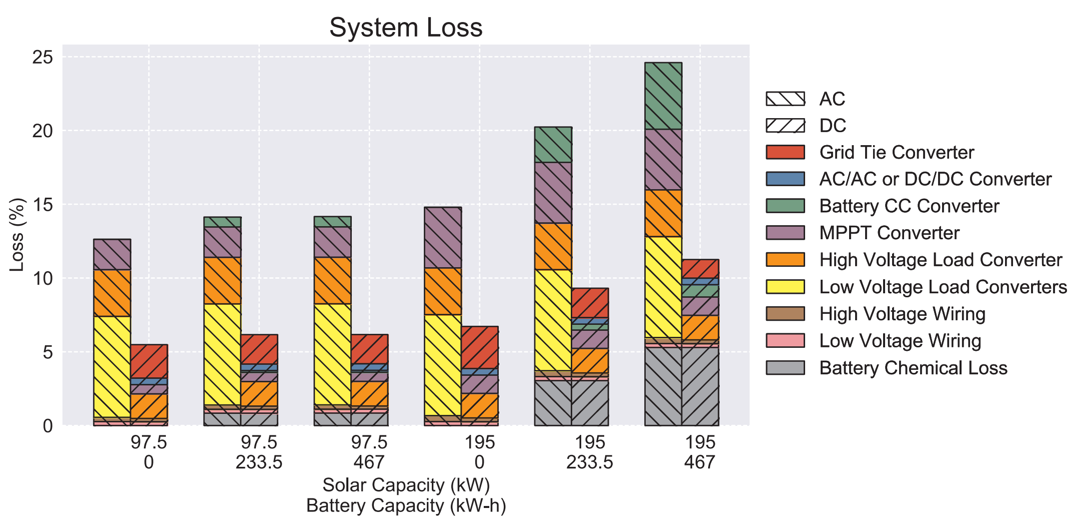

Fig. A2. System losses for the retail building – current scenario.

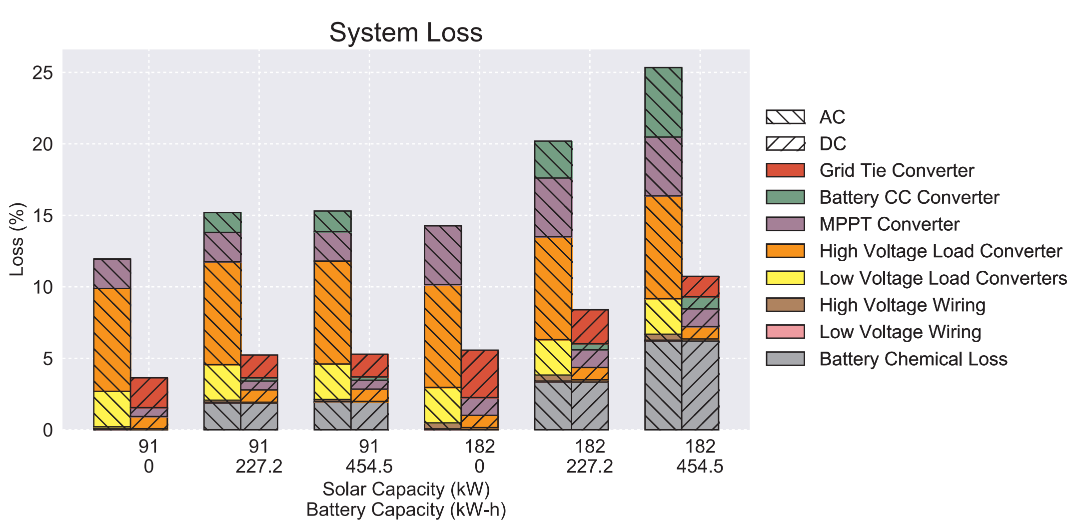

Fig. A3. System losses for the restaurant – current scenario.

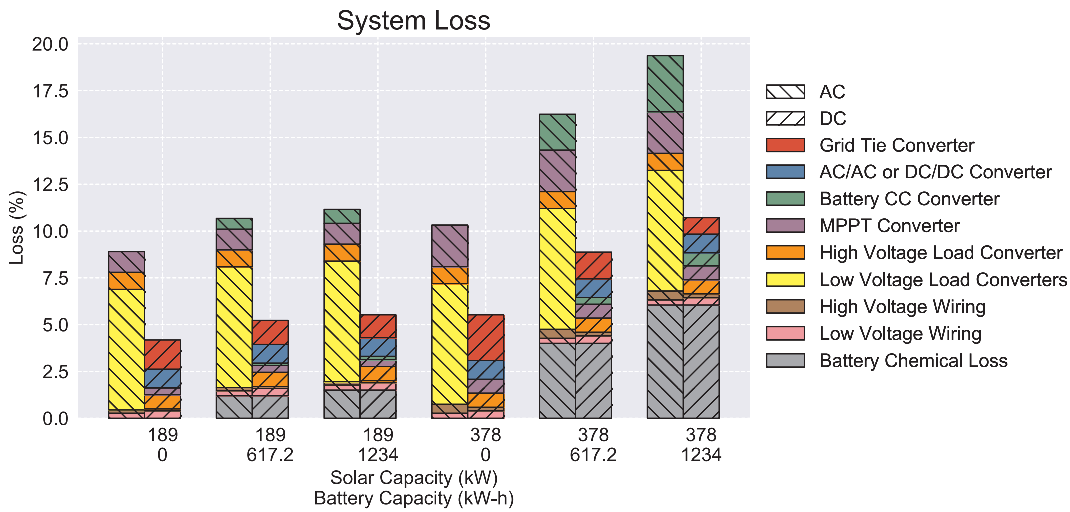

Fig. A4. System losses for the medium office building – future scenario.

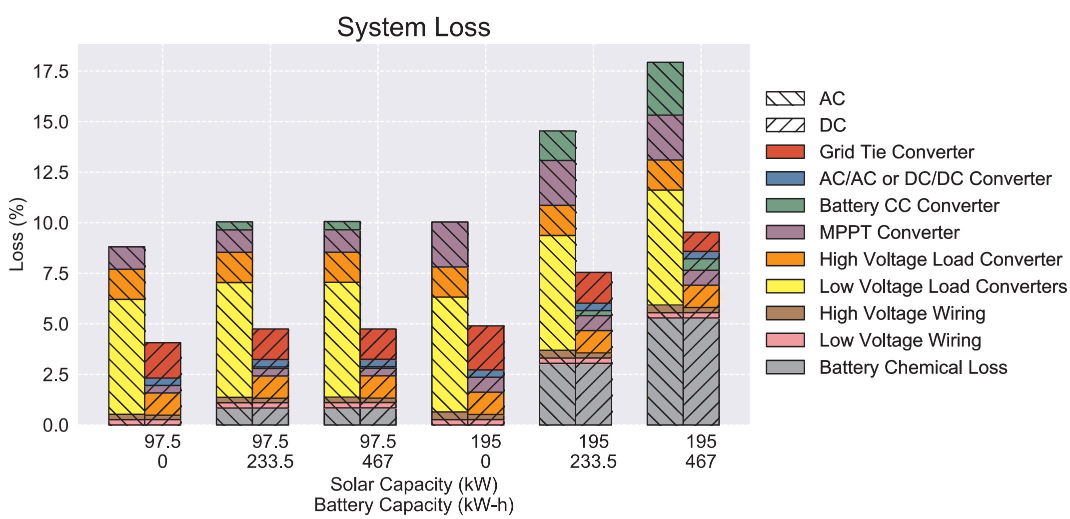

Fig. A5. System losses for the retail building – future scenario.

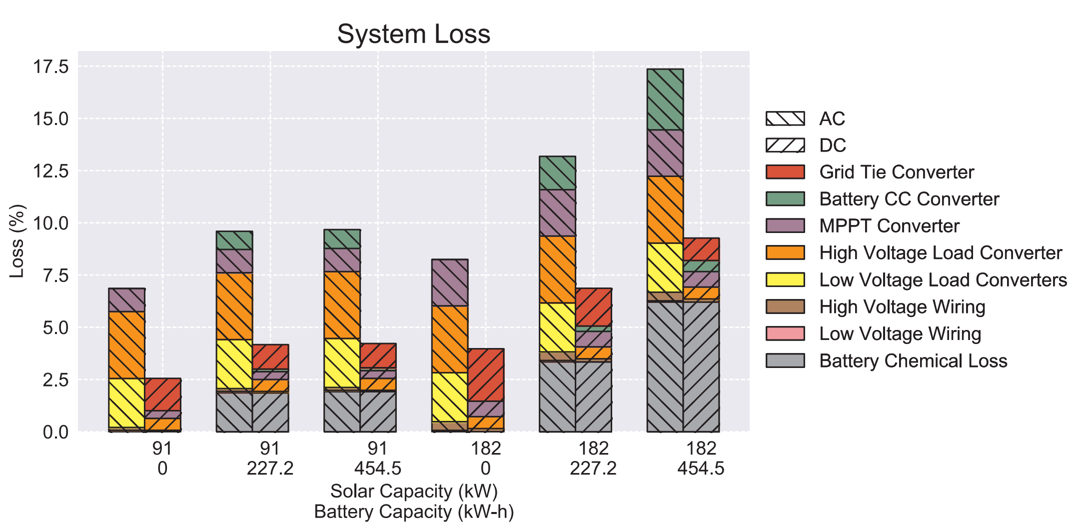

Fig. A6. System losses for the restaurant – future scenario.

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