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A Simulation Based Comparison of AC and DC Power Distribution Networks in Buildings

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***Abstract*—Direct current (DC) power distribution has recently gained traction in buildings research due to the proliferation of on-site electricity generation and battery storage and an increasing prevalence of end uses operating internally on DC. The research discussed in this paper uses Modelica-based simulation to compare the efficiency of DC building power distribution with an equivalent alternating current (AC) distribution. A variety of parametric simulations determine how and when DC distribution proves advantageous. This work shows that using DC distribution can be considerably more efficient than AC: a medium office building using DC distribution has an expected baseline of 11% savings, but may save up to 17%. In these results, the baseline simulation parameters are for a zero net energy (ZNE) building with enough battery storage to act as an islanding microgrid. DC is generally most advantageous in buildings with large solar capacity, large battery capacity, and high voltage DC distribution. In addition, based on the efficiency modeling results, a comparison of the economic performance of DC vs. AC distribution systems in commercial buildings is conducted. The results for the baseline scenario show that DC distribution systems in buildings can be cost effective when PV generation and battery storage are included in the building.**

Keywords—commercial buildings, efficiency, direct current, simulation, Modelica

I. INTRODUCTION

Recent interest in direct current (DC) power distribution systems in buildings has been spurred by a number of factors, including a rapid growth in photovoltaic (PV) system installations [1], the emergence of batteries in the building sector [2], and the increasing market of end-use loads operating internally on DC such as electronics, motors with variable frequency drives (VFDs), and light emitting diode (LED) lighting [3]. Direct power distribution of DC from PV systems and batteries to DC appliances can reduce power conversion losses from DC to alternating current (AC) and back, leading to electricity savings within the building power distribution system [4]. DC distribution systems have been proposed and implemented successfully in data centers, where electricity savings of between 7% and 28% have been estimated between a 380 V DC and a 208 V AC distribution system [5]. Commercial buildings in the United States, which currently consume 61% of their energy in electricity [6], have been early adoption use cases for DC distribution systems, primarily in lighting applications, due to the high coincidence of solar generation and commercial end-use loads.

A number of studies have addressed the potential electricity savings from DC distribution systems in commercial buildings. The reported savings differ widely, from 2% [7] to as much as 19% [8]. Higher savings were reported in systems that were connected to a DC source such as PV and batteries. In general, the reported savings were highly dependent on the converter efficiencies for the AC and DC distribution systems, the DC distributions system topology and voltage levels, and the coincidence of loads with PV generation. For example, Denkenberger, et al. [9] estimated 2% electricity savings for a typical code- compliant office building and 8% savings for a zero net energy (ZNE) office building with on-site PV generation.

Several existing studies have employed simple analytical models that calculate annual electricity savings by using average, static values for power conversion efficiencies [7]–[11]. Other research efforts estimate savings based on experimental test setups. Most of these studies are of narrow scope, focusing on distributing DC to a limited set of end-use loads. Weiss et al [12] estimated electricity savings in a DC office test bed operating at 380 V DC, which included PV generation, electric vehicle (EV) charging, lighting, and electronic loads. That study, although experimental, also used average converter efficiency values to calculate DC distribution system savings of up to 5.5% compared to an equivalent AC system. Boeke and Wendt [13] reported 2% measured and 5% potential electricity savings from a 380 V DC distribution system with PV generation implemented in an office LED lighting test bed at the Philips High Tech Campus, in Eindhoven, Netherlands.

Few studies have used detailed, validated simulation models to estimate energy savings. Fregosi, et al. [14] employed energy analysis simulation tools to assess the performance of a high bay LED DC distribution system. The simulation software developed by the National Renewable Energy Laboratory (NREL) considered various commercial building types, operating schedules, system configurations, and climate zones to project 6%-8% electricity savings by using DC distribution. That study, although based on validated simulation models, was limited in scope and did not account for realistic converter efficiencies at part-load conditions.

This study addresses a pressing need for more detailed simulation-based studies of comparable AC and DC building networks. The simulation models use realistic load and generation profiles, as well as realistic power conversion efficiency curves that account for part-load energy consumption. In addition, the modeled buildings account for wiring loss at the AC and DC distribution voltages.

This study also evaluates the economic performance of the analyzed DC and AC building networks, taking into account their capital costs and lifetime operating costs. Few studies have addressed the cost-effectiveness of DC distribution systems vs. AC distribution systems, primarily due to a lack of DC case studies and commercially available end-use loads operating on DC. Planas et al [15] estimated that metering costs, converters, and line distribution costs can be lower for DC systems. However, system protection costs can be higher for DC systems due to generally lower voltage distribution and technology maturity in AC systems. Glasgo et al. [16] performed an economic evaluation of DC distribution systems using Monte Carlo simulation for residential buildings. This study follows a similar approach for the analyzed commercial AC and DC networks, and compares the lifecycle cost (LCC) and payback period (PBP) of the DC vs. AC networks for the baseline simulation scenario.

Section II discusses the modeled building distribution network topologies and voltage rails. In Section III, the paper explains the efficiency modeling assumptions for each type of component within the building model. Section IV describes how the parametric simulations are performed. In Section V, the simulation results are presented and discussed, and finally, Section VI presents the economic evaluation for the baseline simulation networks.

II. Building Distribution Network Topologies

The building network topologies are categorized by their distribution and coupling. Distribution refers to how the building's electrical power is delivered to the loads, and designates whether the network should be considered AC or DC. Coupling refers to how the PV array is connected to the battery. Network topologies are denoted by their distribution type, along with a subscript of their coupling setup. This study examines and compares two network topologies:

- AC_{AC}: AC electrical distribution and AC PV to battery coupling
- DC_{DC}: DC electrical distribution and DC PV to battery coupling

Simulations are performed on models of a medium office building using the EnergyPlus reference buildings for building dimensions and load profiles [17]–[19]. The diagrams of each network topology are shown in Figs. 1 and 2. The simulated models utilize one or more of the following power distribution voltages:

- AC Low Voltage: 120 V_{RMS} single phase (208 $V_{RMS,L\text{-}L}$ for three phase)
- DC Low Voltage: 48 V
- DC High Voltage: 380 V

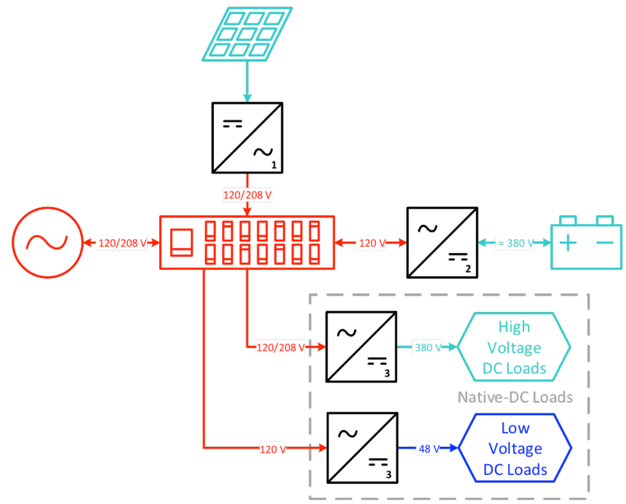

Fig. 1. Medium office building network AC_{AC}: AC distribution AC coupled. Converters: 1. string inverter (MPPT), 2. battery inverter (BiD, CC), 3. load-packaged rectifier.

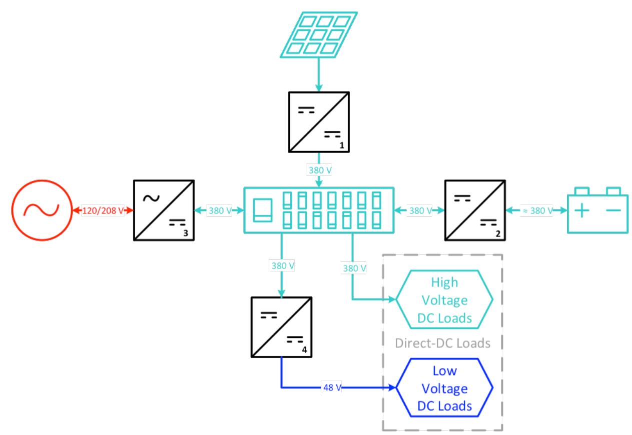

Fig. 2. Medium office building network DC_{DC}: DC distribution DC coupled. Converters: 1. MPPT module (MPPT), 2. battery charge controller (BiD, CC), 3. grid tie inverter (BiD), 4. DC-DC step-down. Certain loads such as LEDs require an additional DC-DC converter (not shown)

The 48 V DC rail represents a power over Ethernet (PoE) style power distribution [20]–[22]. The 380 V DC rail follows the EMerge Alliance 380 V DC standard for power distribution to data centers [23]–[25].

Each building topology has several types of essential power converters, shown in Figs. 1 and 2. Converters can have one or more of the following special functions:

- Bidirectional (BiD): Power can flow into either port.
- Maximum Power Point Tracking (MPPT): Capable of performing the MPPT algorithm on a DC port. Can interface with a solar array.
- Charge Controller (CC): Capable of controlling charge flow on a DC port via a battery charging algorithm. Can interface with a battery bank.

III. Components of the Building Electrical Network

The electrical sources and sinks in the modeled building are the loads, solar generation, battery, and a grid connection. The electrical losses in the modeled building are attributed to converters, building distribution wiring, and chemical loses in the battery. This section describes the modeling setup and assumptions for the sources, sinks, and loss components in the building network model.

A. Load Center

The load center is a panelboard through which all of the building's loads are connected. Similar to the modeling done by Backhaus, et al. [7], all of the modeled loads in this research are assumed to be operating internally on DC. DC loads are considered to be either native-DC (i.e. DC-internal) or direct-DC, depending on whether the building's electrical distribution network is AC or DC, respectively. Direct-DC loads may either connect directly to the DC building distribution or utilize a DC-DC converter to step the input voltage to an appropriate level. Native-DC loads always require a rectifier to interface with the AC building network.

The hourly load data in this model are sourced from a DOE reference building data set, which provides electrical loads for the following end-uses: heating, cooling, fans, interior lighting, exterior lighting, and interior equipment [17]–[19].

B. Solar Generation

The PV array is modeled as a power source with a time variant output power that is determined by the amount and angle of solar irradiation (from PVWatts) [26], [27]. The PV panels are always operating at a constant MPPT voltage, which is a reasonable approximation for most panels [28], [29].

C. Converters

Converters contribute the most to overall building network electricity loss, and the DC building network is designed to reduce the number of conversions. In general, the efficiency of converter products increases with power capacity and operating voltage. Each converter in Figs. 1 and 2 has a representative efficiency curve (i.e., efficiency as a function of its output power relative to its maximum output power capacity) based on data from converters currently available on the market. Efficiency data can be obtained as visual curves from datasheets, or as select data points from online sources [30].

In order for a converter's efficiency curve to be simulated, its rated power capacity must be known. At every conversion stage, the modeled building is assumed to contain enough parallel converters to meet the peak power requirements. The conversion stage power is equally distributed over all converters at all times. Rated power capacity and operating voltage are the main factors in choosing converter product data to provide a consistent and accurate comparison between AC and DC distribution.

Converters often have negative impact on power quality. Line current harmonics generated at the input of rectifiers can contribute to wiring loss in the grid; however, harmonic distortion isn't very significant to the scope of this study since the AC and DC distribution networks both require an eventual rectification stage. In addition, many converters have power factor correction front-end circuits that greatly reduce input current harmonics. Switching rectifiers and inverters often have a displacement power factor greater than 0.99 and total harmonic distortion less than 5% [7]. As such, power quality is considered to have a second-order impact on building efficiency and is not modeled. It is important to note that many AC loads currently on the market do not use switching rectifiers and have a considerably lower power quality (for example, induction motors or low power wall adapters). Because power quality can be important for other reasons, in-depth power quality simulations are encouraged in future work.

D. Battery

The battery operates as a source or sink, when discharging or charging, respectively. There are many types of batteries, each of which is well suited for certain climates and techno-economic conditions. Since the type of battery is a second-order effect in comparing DC and AC building distribution, a representative generic battery is used for the model in this research.

To ensure safety and longevity, batteries require a charge controller. The controller prevents battery damage and degradation by enforcing a maximum charge or discharge current and limiting the depth of discharge. The modeled battery controller in this work uses a simple charging algorithm, similar to the work done by Hittinger, et al. 2015 [31]. The controller charges the battery when the PV output power exceeds the load demand. Likewise, it discharges the battery when the load demand exceeds PV generation. As such, grid export or import is only allowed when the battery is fully charged or discharged, respectively.

E. Building Wiring

Wiring loss can be substantial in larger buildings with low distribution voltage. As such, it is common for larger buildings to be designed with a high voltage backbone and a low voltage local distribution. Since the wiring loss is due entirely to resistive I^2R losses (skin effect and inductive losses are ignored), the building's wires are modeled as resistors. The resistance of a wire is calculated from its length and resistance per length. The length is determined and modeled via geometric methods. The resistance per length is based on the ampacity of the modeled loads.

IV. Modelica Simulation Procedure

The main purpose of the simulation is to compare the efficiency of equivalent AC and DC building distribution networks. It is also desirable to determine the most suitable conditions for a DC network. Parametric simulations with a year-long duration are necessary to accomplish these goals. This section describes the procedure for selecting parameters and performing simulations.

The AC and DC building networks are modeled in Modelica and simulated in Dymola. The use of Modelica has become prevalent in buildings research because it allows for precise customized transient simulations, and provides the option of simulating combined electrical and mechanical systems. The parametric simulations are managed by a Python script, which sets the parameters, initiates the Modelica runs, and plots the results.

The parametric simulations are organized into experiments. In each experiment, several inputs are parametrically varied in order to test for a specific result. For each parameter, a baseline value is established as an experimental control. The following parameters can be selected as parametric inputs:

- Solar capacity: The maximum output of the solar array in the best conditions. The baseline value is the solar capacity required for a ZNE building.
- Battery capacity: The storage capacity of the battery. The baseline value is 50% of the battery capacity required for a ZNE building to store all excess solar on the sunniest day.
- Converter oversize ratio: The sizing of converters relative to their peak power. The baseline value is 150%, which is a typical case.
- Converter efficiency curve: Specifies whether converters should use the median or maximum of efficiency curve sets. The baseline is the median efficiency curve, which is a typical case.

The baseline value for the solar capacity is found by determining the required solar capacity such that the annual solar generation energy matches the annual load energy. As mentioned in Section III, the annual hourly solar and load profiles are obtained from PVWatts and the DOE reference buildings respectively.

Many published works detail theoretical methods for sizing the battery for either stand-alone or grid-connected systems [32]–[36]. Most of these methods solve an intricate convex optimization problem. Economically sizing the battery for grid-connected networks also requires knowledge of the hourly electricity tariff. In this work, the battery controller described in Section III.D is designed to minimize grid intake, and thus ignores electricity rates. In addition, the availability of hourly PV and load data allows for most of the equations in [32]–[36] to be simplified or ignored.

The baseline value for the battery capacity is found by measuring the daily excess solar energy. The daily excess solar energy E_{ex} can be determined as:

$$E_{ex} = \int_{day} P_{ex} \mid P_{ex} > 0 \tag{1}$$

where the hourly excess solar power P_{ex} is the difference between the total solar generation and total load demand. The largest the battery should ever be sized, C_{max}, is the maximum value of E_{ex} over a full year. Sizing $C > C_{max}$ adds unutilized additional capacity. Batteries are expensive, and smaller batteries are often desirable in grid-connected buildings. As such, the baseline battery capacity is established as 50% of C_{max}. Battery capacities at or above the baseline value may be relevant for islanding microgrid buildings.

V. Results and Discussion

A. Overview of Experiments

Simulations are performed on the modeled small and medium office buildings. In each case, the efficiencies of the two primary topologies AC_{AC} and DC_{DC} are compared. Efficiency is calculated as:

$$\text{Efficiency} = 100\left(1 - \frac{E_{Loss}}{E_{Load}}\right), \tag{2}$$

where E_{Loss} is the total annual loss energy, and E_{Load} is the total annual load demand energy.

For each modeled building, three parametric experiments are performed in order to determine when DC is most advantageous. The solar and battery experiments observe the effect of varying the solar capacity and battery capacity, respectively. The converter experiment observes the effect of varying the quality and size of the converters used in the building.

It is important to note that the parameter values are selected to simulate a wide range of scenarios. Many of these scenarios are not necessary or practical at present, but could easily be considered in the future as renewables become prevalent. For example, the ZNE baseline is an important scenario because the California Public Utilities Commission has plans to achieve ZNE in residential buildings by 2020 and commercial buildings by 2030 [37]–[40].

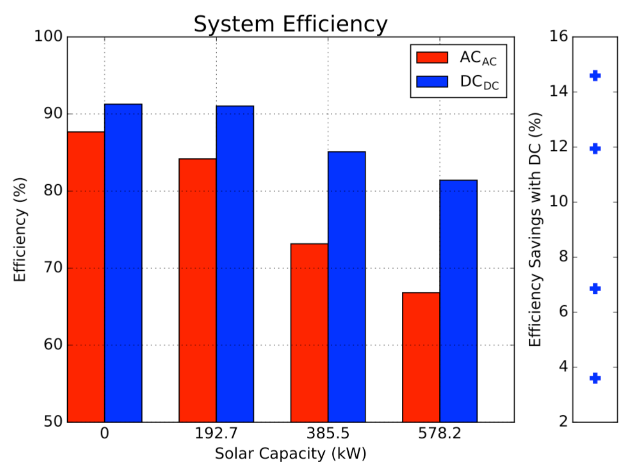

Fig. 3. The solar experiment observes the effect of setting the solar capacity parameter to 0%, 50%, 100%, and 150% of the baseline value. The baseline is the solar capacity required for a ZNE building. 150% of the baseline represents a building that is designed as a power producer. As a control, the battery is also scaled by the same percentages relative to its baseline. For reference, the roof area can hold up to 266.4 kW (not including parking canopies, etc).

B. *Solar Experiment*

The results of the solar experiments are shown in Fig. 3. An immediate observation is that the DC_{DC} topology performs better when there is ample solar generation. Without solar generation or storage, all the power is supplied from the grid. In DC_{DC}, the grid power is converted to DC at the grid tie inverter. In AC_{AC}, the grid power is converted at the load-packaged rectifiers. Grid tie inverters are optimized for high power, and usually have a higher efficiency than load-packaged rectifiers. However, the grid tie inverter in DC_{DC} is often operating at a low region of its efficiency curve. In addition, power to the LEDs in DC_{DC} must also pass through an LED driver, thus presenting two conversion stages in the power flow.

While a large solar capacity is necessary for DC_{DC} to be more efficient than AC_{AC}, its benefits diminish after a certain size. DC distribution is optimal when use of the grid tie inverter is minimized. Whenever the building must engage in grid import or export, the grid tie inverter incurs a substantial loss. Frequent grid export can happen because of an oversized solar capacity or an undersized battery.

C. *Battery Experiment*

The results of the battery experiments are shown in Fig. 4. Similar to the solar experiment, the DC_{DC} topology performs better when there is plenty of storage. As previously mentioned, a large battery capacity allows for minimizing the use of the grid tie inverter. DC distribution systems without storage would likely be designed with a smaller solar capacity that is matched to the peak demand. Alternatively, batteryless DC systems may contain an MPPT inverter that exports the excess solar directly to the grid.

It is important to note that the grid tie inverter will always have some use even if the battery is drastically oversized. Seasonal effects make it impossible to size the solar capacity to perfectly match the load demand. In these experiments, the baseline solar capacity is sized for a ZNE building. Nonetheless, there is still some amount of grid import during the winter and grid export during the summer.

D. *Converter Experiment*

The results of the converter experiments are shown in Fig. 5. The efficiency curve parameter reveals that there is a much smaller variance in the quality of DC products than for AC products. The efficiency curves of the product data indicate that the smaller spread in DC product quality is because the efficiency is already nearly 100%. In some sense, the maximum efficiency curves represent the average quality of products in the future. As such, AC products have much more room for improvement than DC products.

The converter experiments also reveal how the relative efficiencies of AC and DC products change with their oversize ratio. The converter oversize ratio translates to the converter's operating region on its efficiency curve. The results in Fig. 5 show that AC products perform substantially worse when operating at low power. In practice, designers will never oversize converters by 400%. However, the 400% oversize ratio can be somewhat representative of a building operating at half its population capacity.

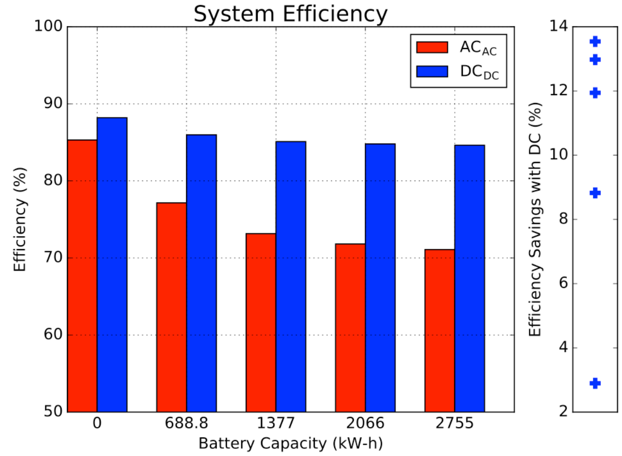

Fig. 4. The battery experiment observes the effect of setting the battery capacity parameter to 0%, 50%, 100%, 150%, and 200% of the baseline value. The baseline is 50% of the smallest size required to store the excess solar on the sunniest day.

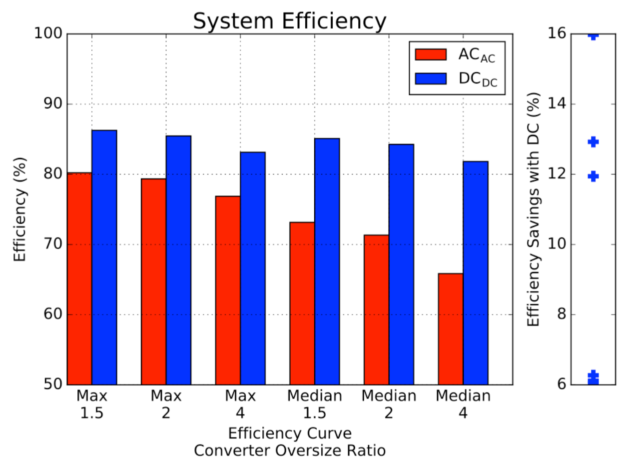

Fig. 5. The converter experiment observes the effect of varying the quality and size of the converters used in the building. In this experiment, the converters all use either the median or maximum efficiency curves, and have oversize ratios of 150%, 200%, and 400%.

E. *Baseline and Summary*

DC_{DC} outperforms AC_{AC} in every experiment. The efficiency savings with DC is 11.0% with baseline parameter values, and can be up to 17.3%. The upper bound on efficiency savings is a scenerio in which all of the parametric values are unrealistically advantageous for DC. Specifically, this means that the solar capacity is 150% of baseline, the battery capacity is 200% baseline, and the converter oversize ratio is 400%.

F. *Loss Analysis*

The loss breakdown for the small and medium buildings is shown in Fig. 6. The percent loss of component N is:

$$\text{Percent Loss} = 100\left(1 - \frac{E_{Loss,N}}{E_{Load}}\right), \quad (3)$$

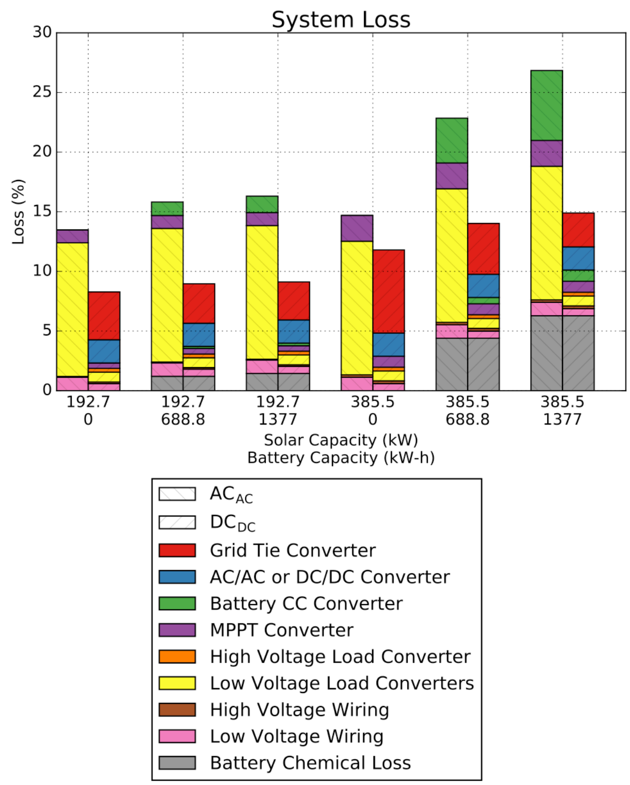

Fig. 6. Loss breakdown and analysis. Solar capacity is 50% and 100% of the baseline. Battery capacity is 0%, 50%, and 100% of the baseline. Converters are categorized by function. Battery CC converters include battery inverters and DC-DC charge controllers. MPPT converters include string inverters and MPPT DC-DC modules. Load converters include any of the load-packaged rectifiers and DC-DC LED drivers. In all buildings, the solar panel wiring is categorized as high voltage.

where $E_{Loss,N}$ is the annual loss energy of a specified component, and $E_{Load,N}$ is the total annual load demand.

In this analysis, the solar capacity and battery size are parametrically varied. The results lead to several immediately apparent observations. First, load-packaged rectifiers cause the most loss in the AC_{AC} topology. Load-packaged rectifiers are not optimized for high power and are relatively inefficient. Second, the grid tie converter loss is very high in batteryless DC_{DC} buildings with a large solar capacity. The fourth pair of bars in Fig. 6 shows that a batteryless ZNE building barely benefits from DC distribution. Finally, the use of a battery introduces a considerable amount of loss in both grids, particularly for the ZNE baseline solar capacity. The practicality of storage in a grid-connected system is debatable and generally varies by region. However, if a battery is to be introduced, it is important to note that DC-DC battery charge controllers greatly outperform AC battery inverters.

VI. Economic Evaluation

To evaluate the cost effectiveness of DC distribution systems in commercial buildings, the economic performance of the baseline AC and DC networks is compared. The metrics used for this economic evaluation are the LCC and PBP, which are calculated according to the following equations:

$$\boldsymbol{LCC = Total\ Installed\ Cost + Lifetime\ Operating\ Cost} \quad (4)$$

$$\boldsymbol{PBP = \frac{Installed\ Cost_{DC\ System} - Installed\ Cost_{AC\ System}}{Operating\ Cost_{AC\ System} - Operating\ Cost_{DC\ System}}} \quad (5)$$

In equation (4), the total installed cost includes the capital installed cost of the power system components for each network, and the lifetime operating cost is the present value of the system's operating cost, over its lifetime. In equation (5) the operating cost corresponds to the first year's operating cost.

The economic analysis considers the incremental cost differences between the two networks, which are assumed to be identical except for their power distribution systems and their DC-internal end-use loads. Therefore, the estimated installed cost difference between the AC and DC network is due to their respective converters (inverters, rectifiers, DC-DC converters, appliance power supplies, etc.). The annual operating costs are estimated based on the systems' annual electricity consumption, which is derived from the efficiency modeling and electricity prices. Inputs for the lifetime operating costs include consumer discount rates, electricity price trends for future years, and building and components lifetimes. It should be noted that the following parameters are not included in this economic evaluation:

- Installation costs, system design, and other 'soft costs', primarily due to lack of sufficient data. Such costs are expected to be higher for the DC system, because of the nascent stage of the technology.
- Potential non-energy benefits associated with the DC network, including higher reliability (due to fewer components at the appliance level), increased resiliency (due to their ability to be islanded from the grid), and better power quality (due to less converters compared to the AC network and greater isolation from the frequency and voltage disturbances on the AC grid).
- The cost of end-use loads in the DC network vs. the AC network. Because all loads are assumed to be DC-internal in both networks, the difference between the end-uses in the DC vs. the AC network is an appliance rectifier that converts DC to AC within the loads. At scale, this difference is expected to favor the economics of the DC system.
- Maintenance and repair costs for both networks. The need for fewer power system components, and simpler power electronics for appliances in the DC network would presumably lead to lower maintenance and repair costs, compared to the AC system.

To account for variability and uncertainty in several of the inputs, the LCC and PBP are calculated using Monte Carlo simulation. For example, for converter data (power system components), average market costs were used, with a ±10% variability. Table 1 summarizes the assumptions used for each input in the LCC and PBP calculations, along with their variabilities, and sources.

The annual electricity consumption for each grid is the annual net power imported from the grid. Also, the total

TABLE I. LCC AND PBP INPUTS

Cost Input	Description	Value/ Units	Source
Annual electricity use	Net annual grid-imported electricity consumption for each system	Depends on Simulated System	Energy efficiency analysis
Power system component cost[a]	Rectifiers, inverters, DC-DC Converters, etc.	Average values ±10%	Online retailers
Electricity Prices	Average commercial sector electricity Prices	0.114 $/kWh ($2015)	Energy Information Administration (EIA 2014)
Electricity Price Trends	Projected commercial electricity prices	Average annual growth rate - 0.12%	Annual Energy Outlook 2016 (AEO2016)
Systems Lifetime	Average lifetime for power system components	10 years (±5 years uniform distribution)	Based on power system component average lifetimes
Discount Rate	Consumer discount rate for office buildings	6.04% (1.05% standard deviation normal distribution)	Damodaran online http://pages.stern.nyu.edu/~adamodar/

[a] Note: There are no market price data for the DC systems' Grid-Tie Bidirectional Inverter. It was assumed that its price was 2X the price of a typical string inverter (used in the AC system), consistent with pricing for the battery inverter, which performs similar functions.

installed cost for each grid is estimated by scaling a typical cost/kW for each power system component (based on market surveys) with the peak power through the component, based on the efficiency modeling. Table 2 shows the total installed cost and annual electricity consumption for each network, average LCC savings of DC vs. AC network, % of cases with positive LCC savings (from Monte Carlo simulation), and average PBP for the baseline scenario analyzed in the efficiency modeling.

VII. CONCLUSION

Parametric simulations are performed in Modelica on modeled AC and DC building distribution networks. The baseline parameter values coorespond to a ZNE building with a generous battery capacity and properly sized converters. This research found that the baseline efficiency savings of a medium office building with DC distribution is 11.0%. The best case scenarios yield savings of 17.3%. This study also confirms that DC distribution is best suited for buildings with a large solar capacity, a large battery bank, and a high voltage distribution backbone.

The experimental results contain many scenarios that are not necessarily practical or representative of current designs, but are interesting and important from a visionary perspective. The solar capacity baseline is important because ZNE buildings will likely become prevalent in the next two decades [17]–[19]. The battery experiments are harder to justify since the introduction of storage incurs a great cost in both economics and efficiency. Nonetheless, as on-site renewable generation becomes prevalent, the grid export tariff may become significantly lower than that of grid import [41]. Eventually, on-site storage may be of great value to grid-connected buildings everywhere. In addition, large battery capacity is crucial for islanding microgrid buildings.

TABLE II. LCC AND PBP RESULTS FOR BASELINE SCENARIO

Description	Network	Value
Total Installed Cost ($)	AC_{AC}	252,098
	DC_{DC}	301,155
Net Annual Electricity Consumption (kWh/yr)	AC_{AC}	176,775
	DC_{DC}	100,656
Average LCC Savings ($)	AC_{DC} vs. DC_{AC}	61,487
% Cases with Net Benefit - DC Network	AC_{DC} vs. DC_{AC}	>90%
Average PBP - DC Network (Years)	AC_{DC} vs. DC_{AC}	0.7

Regarding the economic evaluation, the results show that based on the approach followed here, DC distribution networks in commercial buildings can be cost-effective when PV generation and battery storage are included in the building. DC distribution is not economically justified in a building without storage. This is due to both the lower electricity savings and the relatively higher incremental cost for the DC network compared to AC. Further, the economic evaluation does not consider retrofit systems, which at current market conditions should incur high installation costs, especially if new wiring is wiring is required in the building.

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