A Comparative Study of DC and AC Microgrids in Commercial Buildings Across Different Climates and Operating Profiles

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***Abstract*—Bosch has developed and demonstrated a novel direct current (DC) microgrid system that maximizes the efficiency of locally generated photovoltaic energy while offering high reliability, safety, redundancy, and reduced cost compared to equivalent alternating current (AC) systems. Several demonstration projects validating the system feasibility and expected efficiency gains have been completed and additional ones are in progress. This paper gives an overview of the Bosch DC microgrid system and presents key results from a large simulation study done to estimate the energy savings of the Bosch DC microgrid over conventional AC systems. The study examined the system performance in locations across the United States for several commercial building types and operating profiles. It found that the Bosch DC microgrid uses generated PV energy 6%–8% more efficiently than traditional AC systems.**

Keywords—DC microgrid; energy efficiency; PV; LED

I. INTRODUCTION

Zero net energy policy goals for buildings in the United States and across the world imply a high penetration of distributed renewable energy resources and a substantial increase in energy efficiency. According to the National Science and Technology Council, aggressive adoption of energy efficiency technologies will reduce building energy consumption by 60%–70% [1]. The remaining 30%–40% of energy must come from onsite generation to achieve zero net site energy. Distributed renewable energy will be deployed on a large scale only when its assets provide attractive returns to owners and enable utilities and grid operators to safely and reliably mitigate the impact of renewables' intermittency on the electricity distribution infrastructure.

The direct current (DC) microgrid presented in this paper offers significant energy efficiency, cost, reliability, and safety benefits compared to conventional alternating current (AC) systems. In the Bosch DC microgrid (DCMG) architecture, onsite DC distributed generation such as solar PV is directly connected to energy-efficient DC lighting, DC ventilation, and other DC loads via a 380 V nominal DC bus. A central AC/DC gateway converter provides supplemental grid power whenever local generation cannot fully supply the load. Thus, the DCMG eliminates the use of AC/DC rectifiers at the loads and reduces the need for DC/AC inverters that are currently required to interconnect solar photovoltaics (PV) to the electric utility.

The reduction in conversion equipment makes the overall system more efficient and reliable and reduces maintenance costs. The use of a separate DC bus provides a built-in mechanism for operating critical DC loads during grid outages (to the extent that energy is available from local DC generation or storage) without requiring a mechanical transfer switch. From the utility perspective, the DC architecture reduces the size of inverters required to export excess PV energy, thereby mitigating the potential impact of PV variability on the grid. Furthermore, DC-based battery storage can be much more efficiently connected to a DCMG, enabling a more cost-effective way to smooth solar power intermittency.

By transitioning most of the major hard-wired loads in a building to the DC distribution system, customers can expect up to 30% lower total cost of ownership over the life of the system, higher reliability, and optimized use of renewable generation compared to a conventional AC microgrid. At scale, the capital cost is anticipated at 15%–20% lower than a comparable AC system; the operating costs will also be significantly lower over the 25-year life of the system. The DC system architecture is applicable to a wide variety of commercial buildings, including big-box retail stores, warehouses, distribution centers, and manufacturing facilities.

In addition to several systems installed at Bosch facilities, two high-profile DCMG projects are currently underway at external sites. The U.S. Department of Defense has awarded Bosch a demonstration project to be completed in 2015 that involves the retrofit of a building at Fort Bragg in Fayetteville, North Carolina. In addition, the California Energy Commission has awarded Bosch and its partners a demonstration project in southern California that will include 300 kW of installed PV.

Section II of this paper provides an overview of the Bosch DCMG system and its components. Sections III and IV summarize the methodology and key results, respectively, for a DCMG simulation study and system energy analysis conducted by the National Renewable Energy Laboratory (NREL). The study estimated the performance of the DCMG for several key metrics, including annual grid energy, system energy efficiency, and PV utilization fraction, for several commercial building types under a variety of operating schedules.

II. System Overview

Bosch has installed the DCMG at several pilot sites. The purposes of the demonstrations are to validate the expected efficiency gains and to confirm safe and reliable operation of the DCMG. Fig. 1 shows an installation in Charlotte, North Carolina, that has been operating since August 2014. An equivalent AC system was installed next to the DC system for efficiency comparison, and the cumulative data to date show that the DC system uses PV energy about 8% more efficiently than the AC system. This early demonstration is done with DC induction fixtures, whereas current and future installations will have DC LED fixtures. The expected efficiency gain for the DC version of each lighting technology is approximately 4% when compared to equivalent AC technology.

A. Configuration

The patented system configuration and control enable powering of DC loads (such as lighting and ventilation) directly from PV arrays with only a single conversion stage between the source and load, so that the PV energy is delivered with minimal losses. In contrast, a conventional AC system requires two conversions. Fig. 2 shows the basic DCMG configuration alongside a conventional AC system. In the DC system, only the DC light-emitting diode (LED) driver appears in the PV-to-load path. In the basic configuration, the AC/DC gateway is a rectifier. The PV is sized such that it does not normally exceed the load, so an inverter is not needed.

In the Bosch DCMG, maximum power point tracking (MPPT) is performed by the voltage regulation of the AC/DC gateway converter, which is not directly in the PV-to-load path but rather supplies the balance of power required to operate the load. This patented configuration enables higher efficiency and greater reliability than other DC systems which use a dedicated MPPT converter through which all the PV power passes.

More advanced configurations include ventilation fans, forklift chargers, flow batteries, ultracapacitors, and bidirectional AC/DC gateways. A bidirectional converter enables the PV system to be sized larger than the load power for more flexibility. Lighting and ventilation are the preferred load types because their profiles are predictable and align well with PV generation profiles.

B. Components

1) AC/DC Gateway: In the DC system, the AC/DC gateway replaces a traditional PV inverter. The AC/DC gateway's primary function is to provide power to the load whenever the PV array does not provide sufficient power. The AC/DC gateway is composed of parallel connected rectifiers, inverters, and/or bidirectional AC/DC converters, depending on the size of the PV and loads in a particular installation. Having separate inverter and rectifier stages allows for custom sizing for either direction for highest efficiency and lowest cost. Having multiple parallel stages also increases the redundancy of the system. When drawing energy from the grid or exporting energy to the grid, the efficiency of the DCMG is approximately equal to that of a conventional AC system. For

Fig. 1. DC microgrid demonstration in Charlotte, North Carolina. Credit: Dusan Brhlik, Bosch

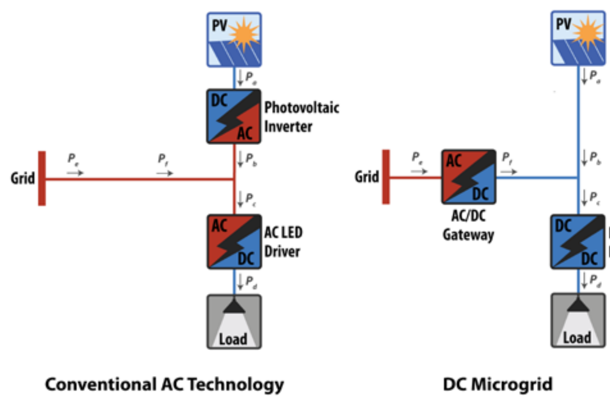

Fig. 2. Configurations of conventional AC and Bosch DC microgrid systems.

this reason, the systems are sized such that most PV energy is either used immediately or stored on the DC side, without passing through the AC/DC gateway.

Although the AC/DC gateway provides convenience for operating the DC loads when solar power is not available, it is not necessary for running the DCMG in islanded mode. When a grid outage occurs, the system seamlessly reverts to islanded operation where the light output and fan speed adjust to match available generation and/or energy storage.

2) DC LED Driver: In the DCMG, a custom DC-input LED driver replaces the AC-input LED driver. The DC driver does not require a rectifier and is optimized to achieve maximum efficiency within the DC input voltage range. Therefore, the DC LED driver efficiency is approximately 97%–98%, compared to 93%–94% for the highest efficiency 277 V AC drivers.

Compared to an AC driver, the DC LED driver also has a smaller component count and greater reliability because a rectification stage is not present. The expected driver lifetime increases because internal heat generation is significantly reduced and because electrolytic capacitors, which are required for the rectification stage of an AC driver, can be eliminated. Given the extremely long expected lifetime of LEDs, LED drivers are the least reliable component in an LED fixture. Without an electrolytic capacitor, the DC LED driver is potentially much more reliable than an AC one, with early studies indicating that the DC driver electronics will outlast the LEDs themselves in typical building applications.

III. Energy Analysis Model

Using best-in-class modeling tools, NREL performed a simulation study to analyze the energy performance of both unidirectional (basic) and bidirectional (advanced) versions of the Bosch DCMG in high bay LED lighting applications for several typical scenarios in various locations throughout the United States. The full study is available in [2].

In the analysis, NREL assumed a simple lighting system containing only a PV array, an LED load, a DC LED driver, and an AC/DC gateway (Fig. 2). NREL simulated the performance of this basic system in a variety of scenarios resulting from the combination of:

- *Four building types:* retail, supermarket, refrigerated warehouse, and nonrefrigerated warehouse.
- *Five operating schedules:* 6 a.m.–10 p.m. 5 days/week, 6 a.m.–10 p.m. 7 days/week, 8 a.m.–8 p.m. 7 days/ week, 24 hours/day 5 days/week, and 24 hours/day 7 days/week.
- *Two DCMG types:* unidirectional and bidirectional.
- *Five PV array sizes:* 100%, 125%, 150%, 200%, and 250% of installed high bay lighting load capacity.
- *Five hundred fifty-four geographic locations:* 544 in the contiguous United States and 10 in Hawaii.

The set of analysis cases (scenarios) examined was not an exhaustive combination of all these categories but rather a selective subset representing likely design cases (see [2] for details). For each case, NREL developed a baseline system model that represents conventional AC technology and an equivalent DCMG system model with identically sized PV generation and lighting load. NREL simulated the AC baseline and DCMG models for each geographic location and compared the systems' performance.

A. Evaluation Framework

An unbiased comparison of energy performance between conventional AC technology and an equivalent DCMG system requires that the definitions of energy inputs and outputs are consistent between the two system types. Fig. 3 presents a generic conceptual representation of a building electric power distribution network that contains a PV source, a DC load, and a grid interconnection. This conceptual model is useful for structured comparison of AC and DC distribution systems.

Three possible converter locations are identified in Fig. 3: at the PV source, at the load, and at the grid interconnection. The wiring between these converters may be either AC or DC depending on the system configuration. The figure also identifies six power measurement points, P_a–P_f, one on each side of each of the three converters.

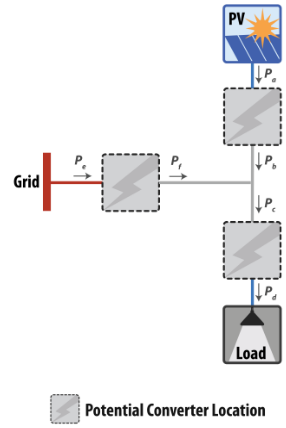

Fig. 3. Conceptual representation of a building electric power distribution network with local PV generation, DC load, and grid interconnection.

Depending on how converters are selected and configured, the generic network of Fig. 3 may represent either a conventional AC system or the Bosch DCMG. In the AC case, there is no central AC/DC converter and $P_e = P_f$. The PV system uses a conventional PV inverter and the load uses an AC driver. In the DC case, there is instead no converter at the PV source and therefore $P_a = P_b$ (except in cases of curtailment; see below). A DC driver matches voltage between the PV source and the lighting load and a central, or gateway, AC/DC converter provides the balance of power. If the available generation exceeds the combined load demand and export capacity of the gateway inverter, then PV curtailment occurs. The model represents the curtailed energy conceptually as a system loss between points a and b, such that $P_b < P_a$.

B. Definition of Performance Metrics

To characterize the performance of the DCMG compared to an AC system, NREL developed seven energy performance metrics. Four metrics—grid energy intensity, energy efficiency, PV utilization fraction, and grid utilization fraction—describe the performance of the high bay lighting electric power distribution system. The remaining three are site metrics that describe the changes in site energy for a building employing a DCMG compared to a building with an AC baseline system. (Source energy and cost metrics were outside the scope of the study, but are recommended for future work.)

To define these annual metrics, let t represent an arbitrary time period in a set of time periods $\boldsymbol{T} = \{1,2,\ldots,T\}$ that span an entire year, each with duration Δt. Within each time period t the system is assumed to operate at steady-state (powers P_{at}–P_{ft} are constant) such that $E_{at} = P_{at}\Delta t$, $E_{bt} = P_{bt}\Delta t$, and so forth. The notation $t \in \boldsymbol{T}$ indicates an operation that occurs over all time periods in set $\boldsymbol{T}$.

Given these definitions, the grid energy intensity is the annual grid electricity consumption of the high bay lighting system normalized by the floor area (A_{Floor}).

$$\text{Grid Energy Intensity} = \frac{\sum_{t\in\boldsymbol{T}} E_{et}}{A_{\text{Floor}}} \quad (1)$$

This metric varies significantly with PV system size and is therefore most useful for comparing analysis scenarios with identically sized PV arrays. Because it measures total energy consumption, this metric provides the fairest point of comparison from a cost perspective.

The system energy efficiency is the ratio of total output (load) energy to total input (source) energy, including energy from both the electric grid and the PV array.

$$\text{Energy Efficiency} = \eta_E = \frac{\sum_{t\in\boldsymbol{T}} E_{dt}}{\sum_{t\in\boldsymbol{T}}(E_{et} + E_{at})} \tag{2}$$

Energy efficiency differs from instantaneous (power) efficiency, which depends on the power flows at a particular instant in time. Energy efficiency is equivalent to weighted average power efficiency with weights proportional to system load at each time step.

The PV utilization fraction is a PV-specific energy efficiency metric defined as the fraction of PV energy that serves a useful purpose; that is, the fraction that is either delivered to the load or exported to the electric grid.

$$\text{PV Utilization Fraction} = \frac{\sum_{t\in\boldsymbol{T}|E_{ft}\le 0}(E_{dt} - E_{et}) + \sum_{t\in\boldsymbol{T}|E_{ft}>0}\left(\frac{E_{dt}}{E_{ct}}\right)E_{bt}}{\sum_{t\in\boldsymbol{T}} E_{at}} \tag{3}$$

The numerator of (3) sums all useful PV energy: energy delivered to the load (E_d) and exported to the grid ($-E_e$) whenever PV generation exceeds load, plus the PV array's portion of energy delivered to the load whenever load exceeds PV generation. The denominator sums all PV generation.

The grid utilization fraction is the counterpart to the PV utilization fraction—it provides a measure of the efficiency of grid-to-load energy transfer.

$$\text{Grid Utilization Fraction} = \frac{\sum_{t\in\boldsymbol{T}|E_{ft}>0}\left(\frac{E_{dt}}{E_{ct}}\right)E_{ft}}{\sum_{t\in\boldsymbol{T}|E_{ft}>0} E_{et}} \tag{4}$$

The metric applies during grid import operation only; the numerator sums the grid's part of energy delivered to the load whenever load exceeds PV generation.

To assess the whole-building (site) impact of the distribution system type, NREL simulated the performance of the entire building using the internal heat gains associated with each system type: the AC baseline and the DCMG (see Section III-C). This process yielded net annual site electricity, natural gas, and total energy consumption for each system type ($E_{\text{SiteElectric}}$, $E_{\text{SiteNaturalGas}}$, and $E_{\text{SiteEnergy}}$, respectively). The three site performance metrics summarize the site impacts normalized by floor area, with the general formula:

$$\text{Site Change in [Energy Type] Intensity} = \frac{E_{\text{[EnergyType],DC}} - E_{\text{[EnergyType],AC}}}{A_{\text{Floor}}} \tag{5}$$

The site change in electricity intensity includes the change in grid energy intensity of the high bay lighting subsystem rather than being in addition to it. The site change in total energy intensity combines the direct and indirect effects on electricity and gas consumption into a single metric.

C. Modeling Approach

At present, no single simulation environment is well equipped to model building energy performance and DCMG behavior simultaneously. Therefore, NREL developed a multistep simulation approach that combines three energy modeling tools: EnergyPlus [3] for whole-building energy simulation, System Advisor Model (SAM) [4] for PV array simulation, and tailored MATLAB [5] functions for electric power distribution system efficiency analysis.

Calculating the system power flows requires three inputs:

1. High bay lighting load pre- or post-converter (P_c or P_d) at each simulation time step
2. PV array power generation pre- or post-converter (P_a or P_b) at each simulation time step
3. An electric power distribution system model, including converter models for the LED driver, PV inverter, and/or gateway converter, as appropriate.

The EnergyPlus models provide the high bay lighting load and the SAM models provide the PV array generation data. The MATLAB functions combine these data and compute the power flows for each distribution system type: AC and DC. To ensure a fair comparison, the building model, DC PV generation, and DC lighting load in each analysis case were identical for the AC baseline and DCMG systems.

Simulation and energy analysis proceeded in four steps:

1. *Developed template models:* NREL created building and PV array template models for each combination of building type, operating schedule, and PV array size.
2. *Simulated the baseline:* NREL applied site-specific adjustments and simulated each template model at each of the 554 geographical locations.
3. *Compared the performance of distribution systems:* NREL used the results from the baseline simulations to develop and simulate site-specific models for both system types for each analysis case.
4. *Evaluated the whole-building impacts:* NREL used the results of the distribution system energy analysis to evaluate the whole-building energy impacts of the high bay lighting system for both system types.

NREL then computed each energy performance metric for each analysis case using the simulation results.

NREL selected a subset of the U.S. Department of Energy Commercial Reference Building Models [6] to provide prototypes for each of the four building types. NREL increased the retail building model size to 98,769 ft² to better represent large, or big-box, retail stores; added refrigerated cases to the warehouse model to create a refrigerated warehouse model; modified model schedules to match the five operating schedules used in the analysis; modified the lighting load to represent a typical high bay LED system; and performed various site-specific adjustments (see [2] for details).

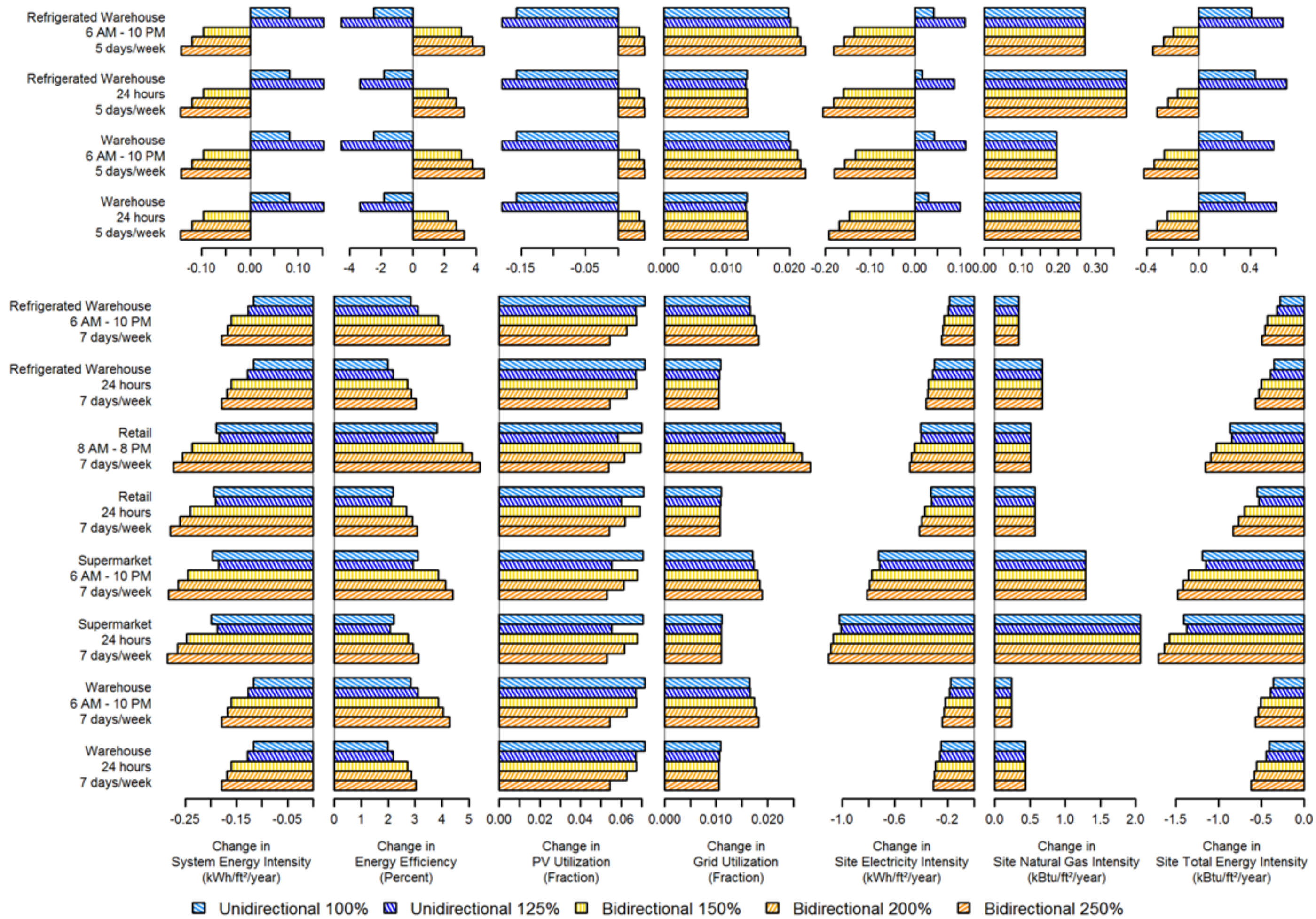

Fig. 4. Average changes in energy performance metrics: DC microgrid compared to AC baseline. Note differences in scale between buildings with 5 days/week operation and buildings with 7 days/week operation.

NREL developed PV array models in SAM for each combination of building type and PV array scaling factor. For each array model, NREL sized the PV array such that the derated array wattage approximately equals the total installed high bay lighting load multiplied by the array scaling factor (see [2] for details). NREL then simulated each PV array model at each of the 554 geographic locations.

For all analysis cases, the PV array sizes and configurations are identical for the baseline AC and DC systems; the systems differ only in the presence or absence of the PV inverter. Therefore, a single SAM model provides DC production data for both systems. For the baseline system, the SAM model output provides both the DC and AC array power (P_a and P_b, respectively, in Fig. 3) at each time step. For the DC system, only the DC array power P_a is used as input to the electricity distribution efficiency model. SAM's MPPT algorithm also provides the optimal PV array operating voltage at each time step; this voltage is then assigned to the DC bus in the DCMG system model.

Because dedicated tools for the efficiency analysis of mixed AC-DC distribution systems are not readily available, NREL developed tailored models in MATLAB. To model the converters, NREL adapted the Sandia PV inverter model [7] to represent generic power electronics converters. The resulting model has the form:

$$P_{\text{in}} = P_{\text{out}} + \alpha_1 + \alpha_2 P_{\text{out}} + \alpha_3 P_{\text{out}}^2 \\ +\alpha_4 (V - V_0) + \alpha_5 P_{\text{out}}(V - V_0) + \alpha_6 P_{\text{out}}^2 (V - V_0) \quad (6)$$

In (6), P_{in} is the converter input power, P_{out} is the converter output power, V is the converter terminal voltage at the variable voltage terminal, V_0 is the nominal voltage at the converter variable voltage terminal, and α_1–α_6 are empirically derived converter loss coefficients fit using linear least squares. The distribution system models omit wiring losses, which are generally negligible compared to power electronics conversion losses, such that in all cases $P_c = P_b + P_f$.

Given measured performance data and simulation data supplied by Bosch and from public sources, NREL generated best-fit empirical models for each system converter (Table 1 on following page). NREL scaled the converters to correspond to PV generation and connected load for each analysis case (see [2] for details).

Given the scaled converter models for each analysis case, NREL computed the energy performance for the AC baseline and DCMG system types using the simulation data from the baseline building and PV models as inputs. This procedure yielded powers P_a–P_f for every hour of the year.

TABLE I. SYSTEM CONVERTER MODELS AND NOMINAL EFFICIENCIES

System Type	Converter	Full Load Efficiency
AC baseline	PV inverter	96.9%
AC baseline	AC LED driver	93.7%
DC microgrid	Gateway rectifier (AC/DC)	97.0%
DC microgrid	Gateway inverter (DC/AC)	96.9%
DC microgrid	DC LED driver	97.7%

IV. ANALYSIS RESULTS

For buildings that operate 7 days/week, the Bosch unidirectional DCMG improved annual PV energy utilization by approximately 6%–8% and reduced high bay lighting grid electricity consumption by approximately 0.1–0.3 kWh/ft^2/year (Fig. 4). The DCMG performed well in all climates compared to the AC baseline. The improvement in PV utilization was slightly higher in cloudy climates because the DCMG reduces—or, in the unidirectional case, eliminates—inverter operation at inefficient part-load ratios. The DCMG performed best when the PV array size was well matched to the load. Unidirectional systems in which the PV array was oversized (nominally 125% of the load) had lower PV utilization due to occasional curtailment of surplus PV energy.

For buildings that operate 5 days/week, however, PV curtailment during low load conditions (weekends) reduced DCMG performance significantly, particularly in sunny climates. For such buildings, the unidirectional DCMG decreases PV energy utilization by up to 20% compared to the AC case (Fig. 4). The bidirectional DCMG still performs better than the AC baseline because it can export energy; however, the PV energy utilization improvement over baseline is reduced to 2%–5% because gateway inverter losses increase. Thus, without the addition of energy storage, the DCMG is not as well suited to buildings without continuous (7 days/week) operation. (Analysis of the impact of energy storage was outside the scope of the NREL study.)

Because the lighting load interacts with heating, ventilation, and air-conditioning systems, whole-building energy impacts varied widely by climate zone and building type. For all building types, the DCMG used grid electricity slightly more efficiently than the baseline AC case. As a result, the DCMG reduced internal heat gains to the conditioned space, reducing cooling load (primarily electricity) but increasing heating load (primarily natural gas). In slightly fewer than half the analysis cases, the reduction in cooling energy exceeded the increase in heating energy, resulting in greater site energy savings than achieved by the DCMG alone. Since electricity is typically more expensive than natural gas, the DCMG can save money even in locations where net site energy savings are negligible.

Site energy reductions were greatest in hot-humid climates (Fig. 5). The supermarket building type had the greatest site electricity savings because the reduction in internal heat gains significantly reduced refrigeration load in addition to reducing cooling load; the open refrigerated cases in the supermarket model are highly sensitive to changes in space internal gains.

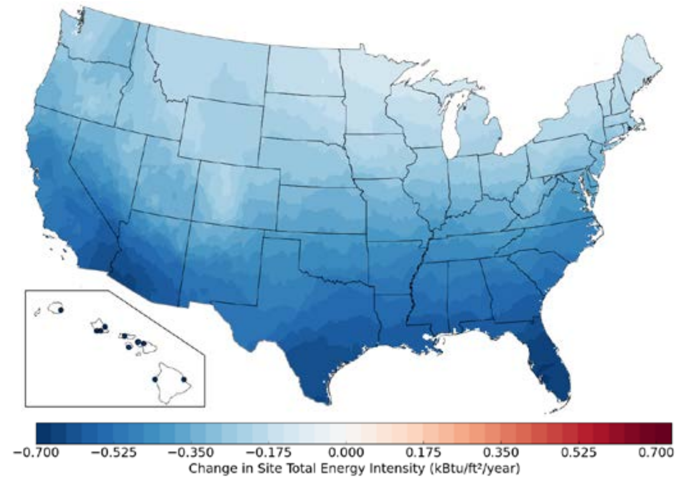

Fig. 5. Performance comparison map of site energy intensity (DC microgrid compared to AC baseline): warehouse, 6 a.m.–10 p.m. operation, 7 days/week, unidirectional DC microgrid, 100% array scaling factor.

V. CONCLUSION

Bosch has developed a novel DC microgrid design that connects PV generation to DC loads with a minimal number of energy conversions, significantly increasing energy efficiency compared to a traditional AC system. NREL's simulation study of the DC microgrid concluded that it improves the percentage of PV energy that performs useful work to approximately 97% from a baseline value of 90%, with small variations in response to design parameters, operating conditions, and location.

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