

**Carbon Free Data Centers Through Solar Photovoltaic Generation, Battery Energy  
Storage, and Medium Voltage DC Power Distribution**

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## Executive Summary

Utilities, grid operators, corporations, and other stakeholders are tasked with meeting carbon emission reduction mandates at a time of rising electricity demand. Driving this trend, data centers are expected to triple their share of U.S. electricity consumption to 7.5% by 2030<sup>1</sup> and account for up to 3.2% of global emissions by 2025.<sup>2</sup> Advances in direct current (DC) distribution technology can reduce data center energy consumption and emissions through medium voltage direct current (MVDC) data center design, especially when co-located with solar-photovoltaic (PV) generation, battery storage, and other DC electricity supply sources.

Recent scrutiny toward data center load growth and the semantics of 100% renewable energy operations have spurred leading technology firms to consider the time and location of their energy consumption and generation. By 2030, Microsoft and Google intend to consume no more electricity than the instantaneous same-grid renewable power that they have procured at each location.<sup>3</sup> Google has already achieved 64% this time and location specific carbon free energy (CFE) goal by coupling 22 TWh of renewable energy purchases with scheduling that pairs data center loads to locations with available local carbon free energy.<sup>4</sup>

Our study compares an MVDC distribution architecture to the conventional low voltage alternating current (LVAC) distribution architecture serving data centers today. While MVDC has technical advantages over LVAC, its deployment remains limited. However, the proliferation of wide-bandgap (WBG) semiconductors will unlock performance improvements for critical MVDC components such as DC-DC converters and DC circuit breakers, potentially catalyzing the realization of studied MVDC benefits. Several of the potential benefits of MVDC distribution for carbon free data centers include:<sup>5</sup>

- Reduced conversion losses from DC sources (PV) to DC load due to fewer conversion stages
- Increased power capacity per unit of cable, reducing capex and losses
- Higher power quality due to fewer conversion stages
- Controllability enabled by solid state transformers
- Interoperability between disjointed alternating current grids with different properties

To value the benefits of an MVDC data center with on-site renewable generation, this study evaluates the capex savings of (1) *supply* - smaller photovoltaic and battery systems resulting from increased efficiency; and (2) *distribution* - lower cost electrical distribution equipment from the supply to the data

center's IT load. The benefits are valued against a baseline scenario of LVAC electrical distribution in an otherwise identical scenario. By quantifying these system benefits, this study highlights a cost-efficient path to meet growing data center load, particularly for data centers attempting to demonstrate 24x7 clean energy use.

This study is modeled at Google's Storey County, Nevada data center location and designed to reflect the operations of a typical hyperscale data center within a global network of the same variety. Our study assumes a dynamic load profile, designed to increase processing load alongside the co-located renewable energy plant's production. MVDC and LVAC designs are each studied across seven minimum CFE scenarios: 50%, 75%, 80%, 85%, 90%, 95%, and 100%, ensuring hourly demand and generation matching for every hour over one year.

MVDC distribution will deliver savings at each supply and demand center: the co-located PV plant, battery, and data center. Efficiency gains from MVDC result in smaller PV and battery systems to meet the same minimum CFE threshold. Savings are also achieved through lower cost DC power distribution equipment. Power distribution drives the cost and MVDC benefits at lower CFE, but above 75% CFE, capex is increasingly driven by battery economics. Notably, a disproportionate jump in battery and PV size drives a near tripling of energy supply capex from 95%-100% CFE. Together, capex investment on distribution and generation can be reduced by about 10% in each scenario.

This study narrowly focuses on valuing the capex benefits of using MVDC technology to deliver on-site CFE. It highlights one outstanding energy efficiency opportunity in an energy intense industry with few conventional efficiency measures remaining. MVDC power distribution has been shown to offer economic, resiliency, and reliability benefits in many applications, however, the technology is far from mature, ubiquitous, and derisked. We hope the following analysis catalyzes a path toward MVDC adoption.

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# 1 Introduction

The IEA estimates that data centers, cryptocurrencies, and AI accounted for almost 2% of global electricity demand in 2022, consuming 460 TWh of electricity.<sup>6</sup> In the U.S., data centers are expected to triple their share of U.S. electricity consumption from 2.5% today to 7.5% by 2030,<sup>7</sup> accounting for one-third of additional electricity demand through 2026.<sup>8</sup> By association, data center emissions are also growing, with forecasts attributing 3% of global carbon emissions to data centers by 2025.<sup>9</sup> The market for carbon free data centers is expected to increase at a 22% compound annual growth rate from \$6.1B in 2022 to \$30B by 2030.<sup>10</sup>

Grid operators and their stakeholders are met with the challenges of carbon emission reduction mandates at a time when load is increasing and expected to increase further. In January 2024, Duke Energy revised its August 2023 North Carolina carbon plan and integrated resources plan to accommodate a 25% higher demand forecast, citing data centers as a key driver for the increased demand.<sup>11,12</sup> The January revision addresses the increased demand with fossil generation, including plans for 3,125 MW of new gas generation and only 2,860 MW of new renewable generation.<sup>13</sup> Emerging technologies, enabled by local North Carolina businesses, can diminish the impact of data center load growth and halt the need for additional gas plants.

Data centers designed with medium voltage direct current (MVDC) architecture, on-site solar-photovoltaic (PV) generation, and battery energy storage may be able to reduce the carbon and financial impact of this revised load forecast, while supporting local North Carolina companies leading in the MVDC space.

One of the key enablers of MVDC deployment has been the application of silicon carbide (SiC) and gallium nitride (GaN) to solid state circuit breakers and DC-DC converters.<sup>14</sup> These wide-bandgap (WBG) semiconductors are produced by Wolfspeed, headquartered in Durham, North Carolina.<sup>15</sup> In fact, Wolfspeed supplies sixty percent of the world's silicon carbide materials today, and will expand their SiC production by 10x through a new \$5 billion facility in Chatham County, NC.<sup>16</sup> In addition, ABB, Siemens, and Hitachi, while all headquartered abroad, have significant operations in the Triangle. Each possesses rare manufacturing capabilities for key MVDC data center distribution components.

## 1.1 Key Questions

This study is focused on three key questions.

1. How can data center power systems be optimized to reliably and cost effectively meet decarbonization targets?
2. What are the cost implications across a range of minimum carbon free energy scenarios?
3. Can MVDC technologies enable decarbonization by reducing data center load and investment cost?

## 1.2 Research Objectives

The goal of this analysis is to quantify the economic benefit of co-locating solar-PV, battery storage, and MVDC distribution across a range of minimum carbon free energy (CFE) scenarios. It aims to quantify the benefits relative to the standard low voltage alternating current (LVAC) distribution architecture serving data centers today.

Additionally, this analysis seeks to quantify the distribution capex savings of implementing MVDC distribution instead of LVAC distribution.

The ultimate goal of this research is to demonstrate that MVDC distribution provides a more cost-efficient pathway to data center decarbonization. While MVDC distribution is nascent, advances in WBG semiconductors offer the potential for broad adoption as economies of scale are reached and component costs become competitive.

# 2 Background

## 2.1 24/7 Carbon Free Energy Data Centers

Operating on 100% renewable energy is an overly simplified and misinterpreted claim. Often, 100% renewable refers to an annual match of global energy consumption with global renewable energy power purchase agreements (PPAs) and/or renewable energy credits (RECs). Over the course of the year, the entity claiming 100% renewable energy operations undoubtedly used energy at times when the power plants generating their PPAs and RECs were not actually generating electricity. Their carbon footprint is more accurately described by the emissions intensity of the energy at the time of consumption, reduced by the company's same-grid, same-time renewable energy procurement.

As an example, Google matches 100% of its global energy consumption to renewable energy purchases on an annual basis, but only 64% of that renewable energy qualifies as local and time matched.<sup>17</sup> The remaining 36% can be understood through Google’s Nevada data center operations. In 2022, any Google workloads processed overnight in Nevada would occur with the same emissions intensity as the Nevada Energy grid, since Google did not have any PPAs interconnected to the Nevada Energy grid or any on-site carbon free energy generation.<sup>18</sup> Even if Google had a local solar PPA that generated energy beyond that of Google’s Nevada operations, Google would not have achieved 24/7 CFE so long as Google operated at night or under cloud cover.

Data centers offer a particularly promising opportunity to demonstrate this higher quality form of 100% clean energy operations through local, 24/7 CFE. Tech companies with global data center networks are able to direct computing workloads to where and when emissions are lowest through “load-shifting.”<sup>19</sup> Google set a goal of 100% local (on-site or same grid), time-matched CFE by 2030 and is developing carbon-aware computing capabilities to achieve that goal.<sup>20</sup> Notably, Google sources 99.96% of all energy from the grid, matching it with offsite PPAs. Since 2018, Google’s on-site generation has only grown from 9400 MWh to 9600 MWh, which is nearly a 50% decline when normalized for energy consumption.<sup>21</sup>

Google’s 24/7 CFE goal and its Nevada operations serve as inspiration and a basis for this study.

## 2.2 Overview of Enabling Technologies

Our study incorporates a series of technologies of varying maturity. When combined, these technologies may be a model for efficient, carbon free, data center operations. These technologies include:

- Solar-PV as a generation source
- Battery Energy Storage Systems (BESS) as an energy storage mechanism to serve data center load overnight and at times of limited PV generation
- Medium Voltage Direct Current (MVDC) as the system distribution technology

Solar-PV and BESS are mature technologies, deployed in segments spanning utility, industrial, residential, and beyond. MVDC technology, on the other hand, is nascent as a technology and especially so in combination with PV and BESS. Our study incorporates MVDC distribution in lieu of the conventional LVAC architecture serving data centers today.

Medium voltage (MV) lines have a voltage range between 1 kV and 35 kV, while low voltage systems have voltages below 1 kV.<sup>22</sup> Higher voltage power lines can serve a fixed load at lower current, reducing

thermal losses, providing efficiency gains, and generating material cost benefits through thinner cables. MVDC also operates using direct current (DC) as opposed to the standard alternating current (AC) on which grids operate. While there are a limited number of MVDC projects currently in operation, the existing literature suggests it can outperform conventional LVAC distribution architecture in certain applications.

Relative to LVAC, several of the potential benefits of MVDC distribution for carbon free data centers include:<sup>23</sup>

- Reduced conversion losses from DC sources (PV, Battery) to DC load, specifically due to fewer conversion stages
- Higher power quality due to fewer conversion stages
- Increased power capacity per unit of cable, reducing capex and losses
- Controllability enabled by solid state transformers
- Interoperability with multiple AC grids with different properties

The efficiency gains of MVDC distribution enable a reduction in capacity of the on-site PV array and the battery relative to LVAC distribution.<sup>24</sup> These benefits and MVDC system design are described in more depth below.

While the conventional data center architecture relies on AC distribution at all voltage levels, integrating DC power supply in equivalent AC systems can unlock significant efficiency and controllability benefits.<sup>25</sup> Since PV arrays and batteries supply DC power, the number of AC/DC power conversions are minimized, unlocking efficiency gains. In the AC design, power conversion relies on a transformer to change voltage levels and an inverter to switch current type from DC, the solar output current type, to AC. Meanwhile a DC system uses a DC-DC converter. By using WBG devices to replace Si-based DC-DC converters, the power conversion efficiencies can be maximized.<sup>26</sup> The MV solid state transformer is particularly important for integrating solar-PV and battery-based Uninterruptable Power Supply (UPS) systems.<sup>27</sup>

Figure 1 and Figure 2 illustrate a conventional LVAC system architecture and the proposed MVDC system architecture. These system diagrams assume a 16 MW IT load data center. The IT loads of the data center are allocated across four server rooms, each with a load of 4 MW, comprised of 400 server racks with a rating of 10kW each. These system architectures were designed by a research team at Georgia Tech's School of Electrical and Computer Engineering, as part of their research through ARPA-E's BREAKERS program.<sup>28,29</sup>

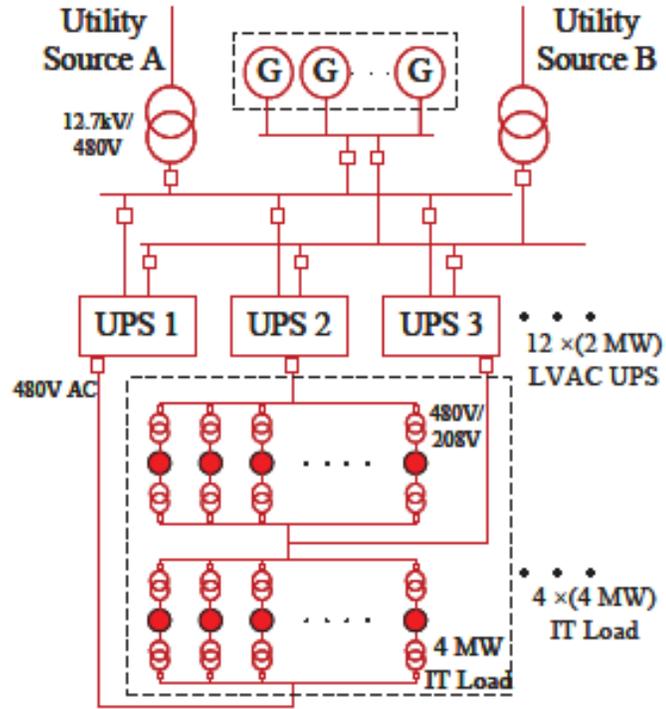


Figure 1 Conventional LVAC system architecture, grid-connected (Chen et al. 2022)

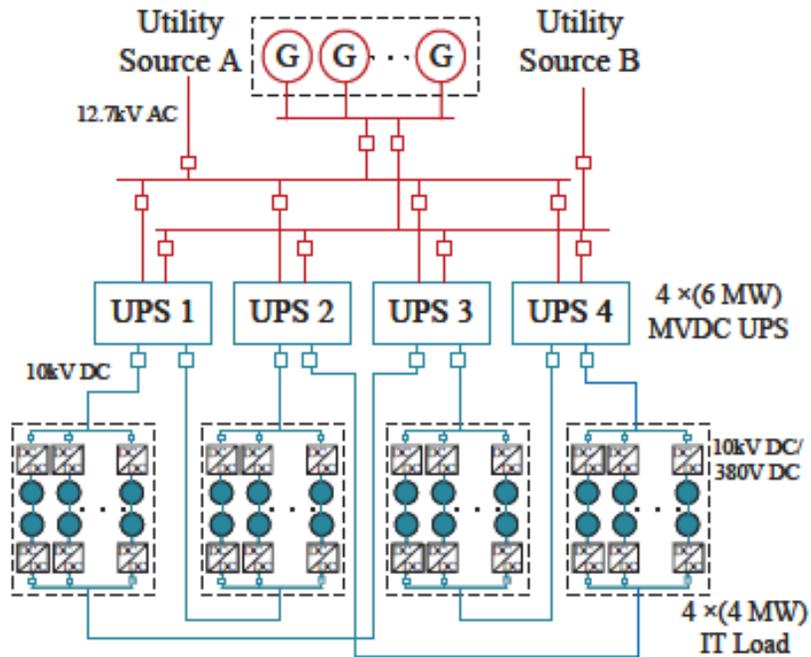


Figure 2 Conventional MVDC system architecture, grid-connected (Chen et al. 2022)

While both configurations model grid-connected generation, their broad designs can be applied to various generation scenarios, including behind-the-meter (or distributed) solar-PV generation.

Another key consideration for MVDC has been the limited reliability of DC circuit breakers, which has been a barrier for MVDC adoption. Unlike AC circuit breakers, DC circuit breakers cannot use a natural zero-crossing point to cut off large current.<sup>30</sup> In addition, DC systems faults result in a rapid rise in the fault current, a large fault range, and difficulty in locating the fault point.<sup>31</sup> Given that proper management of short circuit faults is essential to data center operability, the development of reliable and proven DC circuit breakers could drive more interest in MVDC distribution systems. Various technical solutions are commercializing, including mechanical circuit breakers, solid-state circuit breakers, and hybrid circuit breakers.<sup>32</sup> Once this critical bottleneck is solved, DC distribution networks can proliferate.

Additionally, the WBG semiconductors will enable critical MVDC components such as DC-DC converters and DC circuit breakers to operate at higher voltages, switching frequencies, and temperatures. These performance improvements will help spur WBG semiconductor adoption, leading to scale in the WBG supply chain and a step toward cost parity between DC and AC components.<sup>33</sup>

## 3 Methods and Materials

### 3.1 Research Approach

This study values the benefits of an MVDC data center with on-site renewable generation in the form of capex savings through (1) *supply* - smaller photovoltaic and battery systems resulting from increased efficiency; and (2) *distribution* - lower cost electrical distribution equipment between CFE energy supply and the data center's IT Load. The benefits are valued against a baseline scenario of conventional LVAC electrical distribution.

### 3.2 Energy Supply Capex Savings Methodology

#### 3.2.1 Location

In 2022, Google's Nevada data centers did not have any local renewable energy generation or storage PPAs, resulting in an electricity emissions intensity that matched Nevada Power's grid. At 26% CFE, Nevada was Google's second worst performing location in the Americas (see appendix 7.1).<sup>34</sup>

The following study is modeled at the site of Google's Storey County, Nevada data center. All PV generation is based on PVWatts modeled solar output at that location assuming no land constraints.<sup>35</sup> Appendix 7.2 provides a full list of PVWatts input parameters and the basis for their value.

### 3.2.2 Load Profile

The data center's energy demand is modeled under the assumption that all demand can be attributed to IT load and mechanical cooling loads, and that other power consumption is negligible in comparison. Mechanical loads require AC power supply and are assumed to be 50% of IT load at any given time, in line with prior research.<sup>36</sup> Similar to other large hyperscale data centers, the data center has an IT load capacity of 96 MW, and an overall maximum power demand of 144MW.<sup>37</sup> To put this immense load in perspective, 144 MW could meet the average demand of 108,000 American homes, or nearly all of Durham, North Carolina's 126,044 housing units.<sup>38</sup>

In a 100% CFE scenario, load-shifting and renewable energy must be sufficient to handle all global data center computing workloads with on-site or time-matched, same grid, renewable energy. While this study focuses on a single data center, it assumed that the data center is one of a network of hyperscale data centers able to employ geographic load-shifting optimized for carbon reduction. The objective data center, therefore, assumes a dynamic load profile, designed to loosely align processing load with the co-located PV plant's production.

Figure 3 shows how the processing load is adjusted to match highly variable renewable energy output at hourly intervals. The sample data, from February 19<sup>th</sup> to 23<sup>rd</sup>, shows significant intraday and interday variability, with peak daily production varying from 149 MW to 252 MW, as well as even greater magnitude hourly variations. The data center is scaled up to operate at 80% of its processing capacity when PV output can meet at least that demand. When PV output is less than 80% of processing capacity, the data center is scaled down to 40% of capacity, under the assumption that half of the workloads can undergo geographic or temporal load-shifting to a data center or time with ample CFE. Other studies have allowed up to 20% of the entire data center load to be shifted every 5 minutes,<sup>39</sup> while more conservative studies have designated only 20% of load as eligible for load-shifting.<sup>40</sup> Our study models a data center with less flexibility than the former and more than the latter, aligning closest to Lindberg, Lesieutre, & Roald (2021), which allows up to 5% of load to shift at 5-minute intervals, equivalent to about half of datacenter load every hour.<sup>41</sup> The 40% - 80% load range results in annual data center utilization rates of 41% - 57%, in line with the typical operations of enterprise data centers.<sup>42</sup>

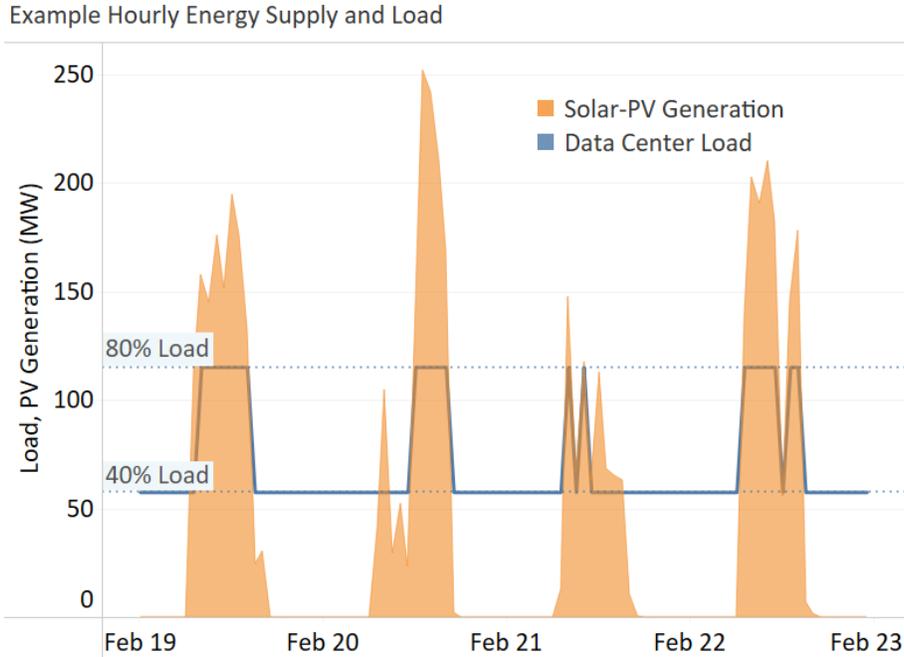


Figure 3 Sample generation and load profile from February 19<sup>th</sup>-February 23<sup>rd</sup>

Optimizing for carbon emissions within a single grid, data center load-shifting has been modeled to reduce CO<sub>2</sub> emissions by up to 33%, but doing so increases generation cost (31%) in proportion to CO<sub>2</sub> reduction.<sup>43</sup> Processing and power demand are cut in half to 40% of capacity when renewable energy is not sufficient to meet 80% of data center power/processing capacity. This allows a much smaller battery to meet data center demand during times without solar-PV availability.

Appendix 7.2 - 7.6 provides the model inputs, parameters, and decision variables across load, generation, and cost.

### 3.2.3 Generation Profile

Three forms of generation are employed to meet data center power demand: PV, battery, and grid (see Figure 4). When available, PV powers the data center and any excess is used to charge the battery, limited by the battery's power rating and usable capacity (see Appendix 7.6 for battery operations). Hourly PV generation is curtailed if it exceeds demand and battery constraints. Load in excess of PV supply is powered by the battery, and any remaining demand is served by the local grid. The battery is only charged by excess PV generation and is only discharged to the data center. That is, the battery is not grid connected and does not benefit from grid arbitrage opportunities.

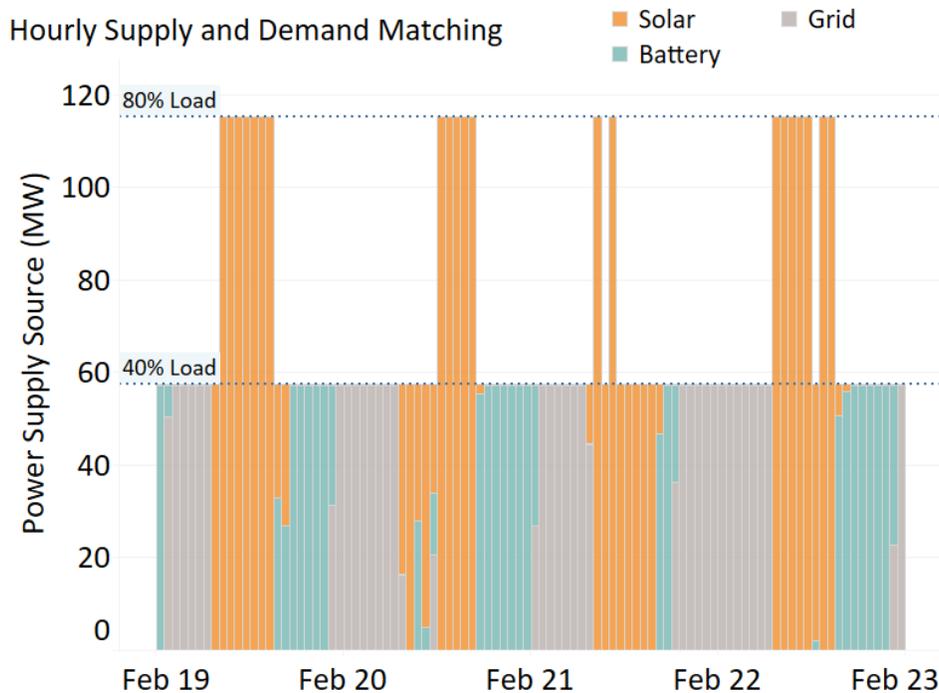


Figure 4 Sample hourly energy supply source generation from February 19<sup>th</sup> - February 23<sup>rd</sup>

The PV plant uses a two-axis tracking array of bifacial panels. Two-axis tracking systems require significantly higher investment and maintenance costs that aren't cost effective under most circumstances.<sup>44</sup> However, single axis tracking produces seasonable variable generation that is smoothed by two-axis tracking (see appendix 7.4). To maximize utilization of CFE at the data center, as well as to achieve consistent year-round operations, this study relies on a dual-axis PV array.

### 3.2.4 Energy Supply Capex Model Definition

All forms of power supply, solar-PV, battery, and grid are delivered to IT loads with lower losses. LVAC shows superior efficiency only when mechanical loads are powered by grid energy, which is a form of energy that this study aims to minimize. Otherwise, MVDC delivers power more efficiently. Appendix 7.3 shows the different power distribution steps for LVAC and MVDC architecture and the associated losses of each step.

Direct capex costs of the PV array, structural balance-of-system, and energy storage system are sourced from U.S. Solar Photovoltaic System and Energy Storage Cost Benchmarks, Q1 2023 (PVSCM).<sup>45</sup> Since PVSCM estimates are based on a single-axis tracking system, capex figures are increased by 58.5% to account for the higher investment costs of two-axis tracking systems.<sup>46</sup> The PVSCM capex figures are

unaffected by the decision variables and outputs of the energy supply capex model. All cost estimates are shown in Appendix 7.5.

The energy supply capex model achieves the minimum CFE % for each scenario, while minimizing the sum of capex across energy storage, solar-PV modules, and structural balance of system, as well as operating expenses in the form of 10 years of grid procured electricity. The model varies battery capacity, battery duration, and PV array size to achieve a cost optimal solution. This study considers an MVDC and LVAC design across seven CFE scenarios: 50%, 75%, 80%, 85%, 90%, 95%, and 100%. Demand and generation are resolved hourly. Differences in efficiency are adjusted for each energy source and power distribution design.

The energy supply capex model only addresses savings as a result of reduced battery and solar-PV plant size required to meet each CFE goal. The cost of LVAC and MVDC electrical distribution components are considered separately and explained in the next section.

### 3.3 Electrical Distribution Component Benefits

The primary differences between the AC and DC architectures are related to the number of power conversions and the type of equipment required. Compared to conventional LVAC, MVDC does not require a conversion from a main transformer to step down the voltage from the utility level to the low voltage system level. Additionally, when co-located with a solar-PV generation source, there is no need for an inverter. If the MVDC system is grid connected, a rectifier will be needed to convert the utility's AC power to DC. However, a rectifier is also part of the conventional LVAC system design. The different number of conversion stages for each system architecture is highlighted in Figure 5 below.

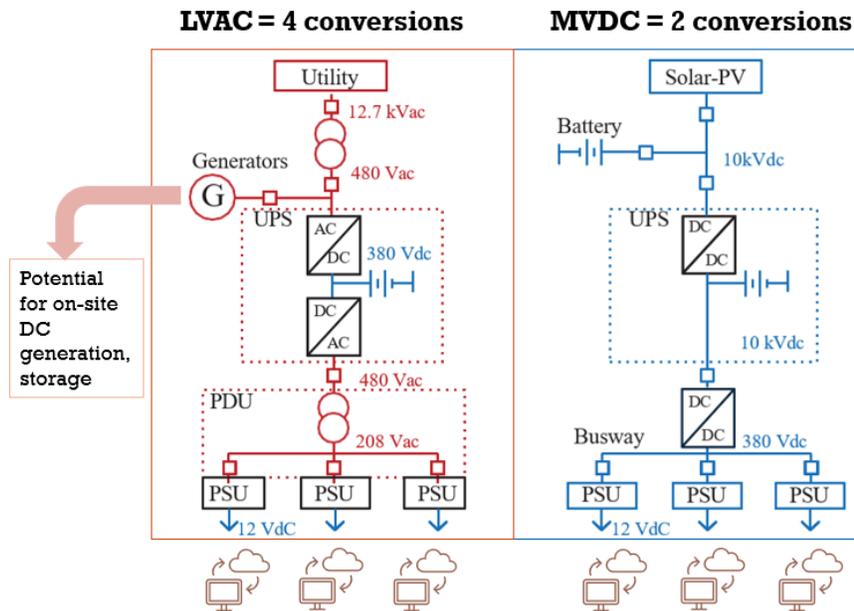


Figure 5 Comparison of conversion stages in standard LVAC distribution vs. MVDC distribution with on-site solar-PV generation and battery storage (Chen et al. 2022)

In both systems, there is an assumed 3N/2 redundancy topology, where the UPS is rated at 150% of the IT load, resulting in a 144 MW UPS in our case study.<sup>47</sup>

From a capex perspective, MVDC system architectures benefit from using higher voltage cable to transmit power throughout the system. In our model, a 10 kV DC cable is used to deliver power from the UPS to the data center IT load. This is then stepped down to 380 V, supplying the load directly via a 380 V DC Busway. In the conventional LVAC system architecture, the power supply is stepped down to 480 V at the UPS, and again to 208 V to supply the IT Load. By relying on higher voltage levels at all stages of system distribution, there is a reduction in current used to deliver the same level of power, resulting in smaller cables and reduced materials costs.<sup>48</sup>

Another critical difference in MVDC systems is the power conversion technology. By implementing DC-DC converters with a WBG semiconductor, efficiencies can be increased and the cost of power conversion per unit power can be reduced by 33% compared to standard DC-DC converters (see Table 1).<sup>49</sup> WBG semiconductors can also be implemented to improve the performance and reliability of solid-state circuit breakers.

The MVDC system experiences a relatively high cost of DC circuit breakers compared to AC circuit breakers.<sup>50,51</sup> Based on the equipment cost data (Chen et al. 2022), DC circuit breakers cost twice as much as AC circuit breakers, with the AC and DC circuit breakers averaging \$5,000/MW and \$10,000/MW, respectively.<sup>52</sup>

Equipment Cost Estimates (\$/MW)			
AC Generation	180,000	Battery (0.5 hour)	150,000
AC Transformer	50,000	AC/DC Rectifier	80,000
DC/AC Inverter	80,000	DC-DC Converter	120,000
12.7kV AC Cable	600	10kV DC Cable	400
480V AC Cable	16,000	380V DC Cable	11,000
208V AC Cable	36,000	12.7kV AC Busbar	1,000
10kV DC Busbar	800	208V AC Busway	56,000
380V DC Busway	40,000	AC Circuit Breaker	5,000
DC Circuit Breaker	10,000	GaN-based Converter	80,000

*Table 1 Electrical distribution equipment cost estimates*

The reduction in distribution system capital costs, in addition to the previously described energy supply benefits, make MVDC a promising technology to consider for carbon free data centers.

## 4 Results

### 4.1 Energy Supply Capex Savings

Figure 6 summarizes the energy supply capex model results. In every scenario, MVDC design reduces the required PV and battery capacity to meet minimum CFE thresholds. Every scenario also converged on the minimum battery duration of two hours, maximizing charge and discharge rating, while eliminating power rating related curtailment.

As CFE threshold increases from 50%-100% CFE, the share of capex attributed to the battery rises. Battery size increases by 25-26x, while PV size only increases 4.6x. Ignoring the 100% CFE outlier, the battery capacity still increases at double the rate of PV capacity, with a 6x and 3x increase, respectively. Efficiency gains from MVDC technology are most apparent through power supplied by the battery (see 7.3) and energy supplied by the battery consumes a greater share of total energy supply at higher CFE

percentages. Accordingly, the savings from MVDC rise with each CFE increase, ranging from 7.7% to 9.9%.

The last 5% of CFE comes with the greatest savings from MVDC. However, both 100% CFE MVDC and LVAC scenarios require battery capacity to increase to a value greater than any lithium-ion battery operating today, and therefore leave any savings unlikely to be realized.<sup>53</sup> It's technologically and economically impractical to achieve Google's 24/7 CFE goal through only the measures defined in this study. Moving from 95% to 100% CFE may better be accomplished by other measures, such as shutting the data center down, offsite PPAs, non-PV based CFE, or carbon removal offsets.

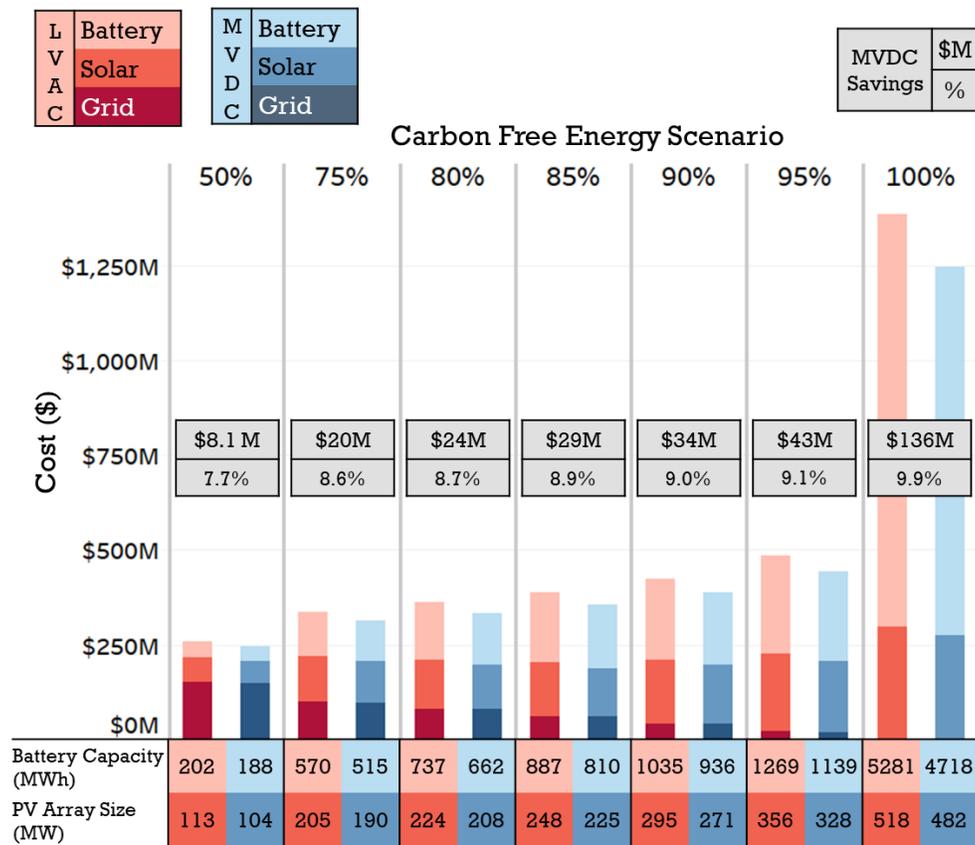


Figure 6 Energy supply size, cost, and savings outputs for each design and CFE scenario. Savings refers to the difference in PV and Battery capex needed to achieve the same CFE for each design scenario. MVDC savings does not consider grid energy costs.

#### 4.1.1 Energy Supply Capex Model Benchmark

NREL’s REopt model is designed to evaluate the technical and economic feasibility of renewable projects early in the project development process, including an output that answers the question, “How much will it cost to achieve a sustainability goal?”<sup>54</sup> PV and battery size outputs from REopt at each CFE scenario serve to benchmark the energy supply capex model’s results. REopt was run using the LVAC and CFE scenario specific efficiencies, hourly demand, and hourly PV generation. The discount rate and fixed capex cost parameters were updated to match the energy supply capex model. Other user-defined fields were kept at their default value.

Table 2 shows a summary of the differences in LVAC size and total cost between REopt and this study’s supply model (see Appendix 7.7 for full details). Aside from the 100% CFE scenario, the energy supply capex model converged on PV and battery sizes close to those of REopt. REopt generally resulted in a smaller battery and larger PV array for each scenario. However, the associated cost of the components partially offset each other, reducing the range of PV and battery cost discrepancies from 30% [-16%,14%] to 9% [-9%,0%] when evaluated over 50-95% CFE. The 100% CFE scenario result varied most from the supply capex model but did validate the dramatic rise in cost from 95-100% CFE. In fact, REopt produced an even more dramatic cost increase than the 3x increase observed in the supply capex model, indicating that the immense cost of achieving 100% CFE through only solar-PV and battery electricity may not be a model error.

CFE Scenario	PV Size	Battery	REopt Total Cost (\$M)	Supply Model	Total Cost
	Difference (Δ%)	Difference (Δ%)		Total Cost (\$M)	Difference from REopt (Δ%)
50%	-10%	-8%	\$117	\$106	-9%
75%	-14%	0%	\$253	\$235	-7%
80%	-14%	4%	\$294	\$280	-5%
85%	-11%	4%	\$336	\$325	-3%
90%	-8%	6%	\$384	\$382	0%
95%	-16%	14%	\$470	\$465	-1%
100%	-67%	30%	\$1,739	\$1,383	-20%

*Table 2 Variation in size and cost outputs between REopt and the energy supply model*

## 4.2 Distribution Capex Savings

Figure 7 compares the estimated capital cost for both distribution architectures. Based on estimated equipment cost data, total electrical component costs can be compared between the baseline LVAC and the proposed MVDC system configurations. This component of the analysis solely focuses on distribution capex savings and does not include any in-plant distribution costs, which are captured in the energy supply capex model. Therefore, no matter the CFE scenario, the calculated capital costs of the distribution architecture are based on serving a maximum IT load of 96 MW.

For a 96 MW IT load data center, the estimated electrical component cost is \$79.5M for LVAC and \$68.6M for MVDC. Savings by switching to MVDC distribution equate to \$11M, a nearly 14% decrease in capex. For a more detailed overview of the distribution capex, reference Appendix 7.8 and 7.9.

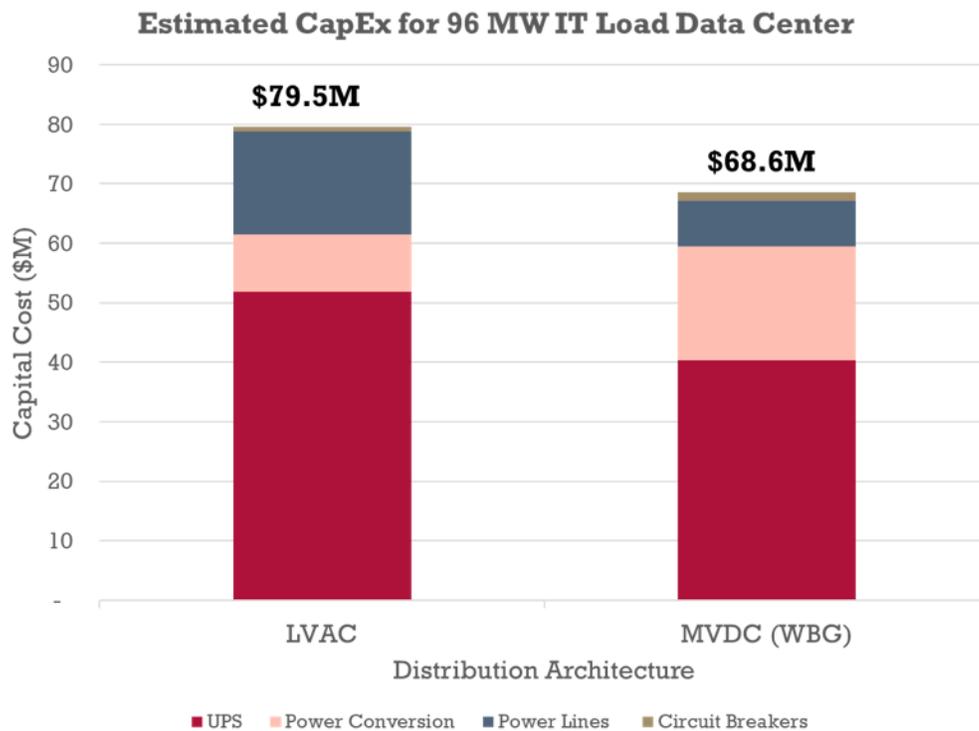


Figure 7 Estimated capex for Electrical Distribution Components

UPS savings are from the absence of a DC/AC inverter in the MVDC architecture, resulting in \$11.5M in inverter savings. Capex reduction is also driven by reduced line costs and smaller cables, as higher voltage levels throughout the system allow for reduced current to meet the system load.

A significant portion of MVDC systems cost is attributable to power conversion, which comprises 28% of total costs compared to just 12% for that of LVAC systems. This is driven by the relatively high cost of DC-DC converters. Our analysis considers the high cost attributable to constrained WBG semiconductor supply chains for DC-DC converter manufacturing, offering additional room for cost improvements as DC-DC converters become more widely available. Given the relative maturity of AC transformer technology, one can speculate that WBG DC-DC converters will decrease at a much more rapid pace than AC power conversion equipment.

### 4.3 Total Capex Savings

Figure 8 shows the results from 5.1 and 5.2, stacked to indicate total savings. MVDC distribution with on-site CFE generation and storage can reduce the capex investment cost by \$19M to \$147M, compared to traditional LVAC architectures. As a percentage reduction from LVAC, aggregate savings were similar across all CFE scenarios, ranging from 9.8% to 10.2%.

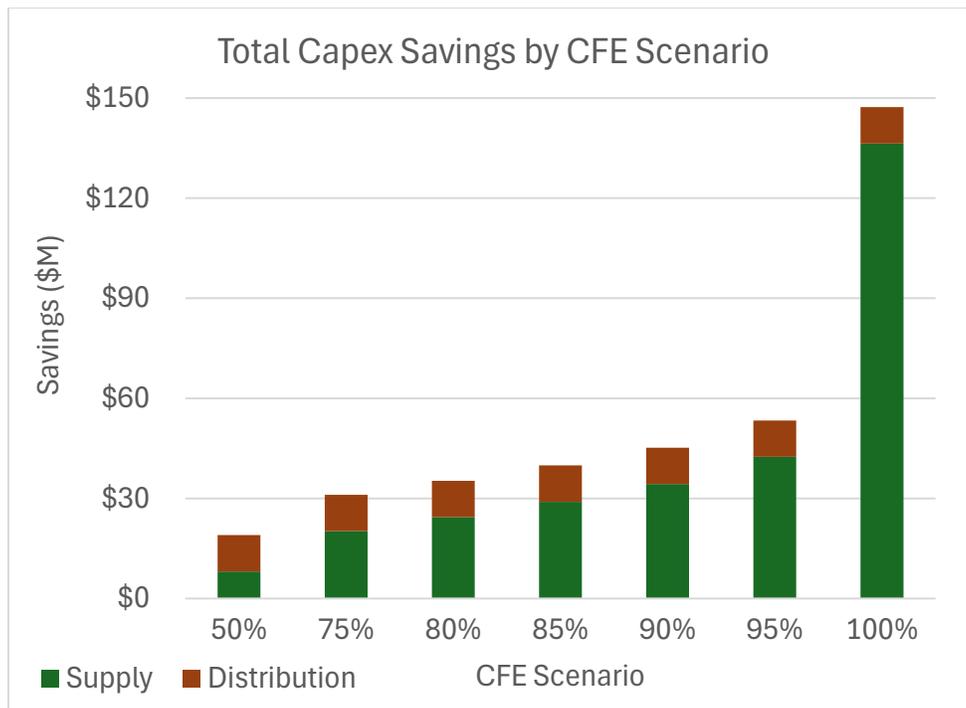


Figure 8 Combined power distribution and supply capex savings across each CFE scenario

## 4.4 Results Beyond Capex

### 4.4.1 Social Cost of Carbon Savings

Figure 9 shows the PV and battery capex savings from 5.1 and the distribution capex savings from 5.2, alongside an additional benefit from the social cost of carbon (SC-CO<sub>2</sub>). All are shown as a percent reduction from the baseline LVAC investment cost, with the total savings represented as labels above the chart. Factoring in the social cost of carbon raises the overall benefit of MVDC design from approximately 10% across all scenarios to as much as 13.1% in the 50% CFE scenario. In magnitude, including SC-CO<sub>2</sub> increases MVDC savings at 50% CFE from \$19M to over \$24M. The SC-CO<sub>2</sub> benefit reduces as the energy supply mix favors CFE over grid energy. Since the 100% CFE scenario lacks grid emissions, there are no additional savings from SC-CO<sub>2</sub>.

The present value of carbon savings is calculated from a \$185/tCO<sub>2</sub> SC-CO<sub>2</sub>, a 0.457 tCO<sub>2</sub>/MWh average grid emissions factor, and a 6.38% discount rate.<sup>55,56</sup> Grid energy is only supplied to the data center when CFE is unavailable on-site, which is likely to coincide with times of limited CFE on the broader Nevada Power grid. Accordingly, in the near-term, time-matched emissions would result in a greater grid emissions factor and greater savings from MVDC. However, CFE will make up a greater share of the local grid as renewables displace fossil fuel generation, thus limiting the additional upside potential.

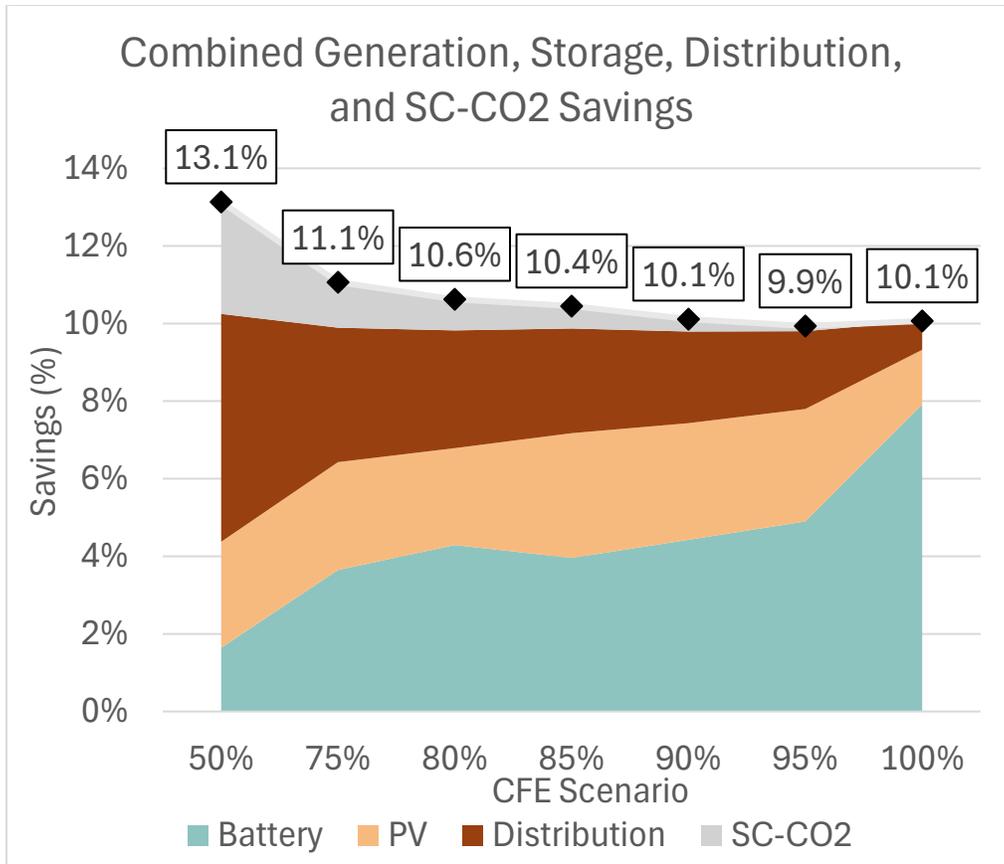


Figure 9 Combined savings from generation, storage, distribution, and social cost of carbon (SC-CO2) as a percent of LVAC capex cost

#### 4.4.2 Utilization

Figure 10 shows increasing data center utilization with higher CFE thresholds. As the CFE threshold increases, the PV array increases in size. The larger PV system provides sufficient output to completely power the data center at 80% of the data center’s processing capacity more frequently, and thus, on an annual basis, the data center achieves higher utilization. Future work should consider the benefit of higher utilization against the higher cost of generation and curtailment.

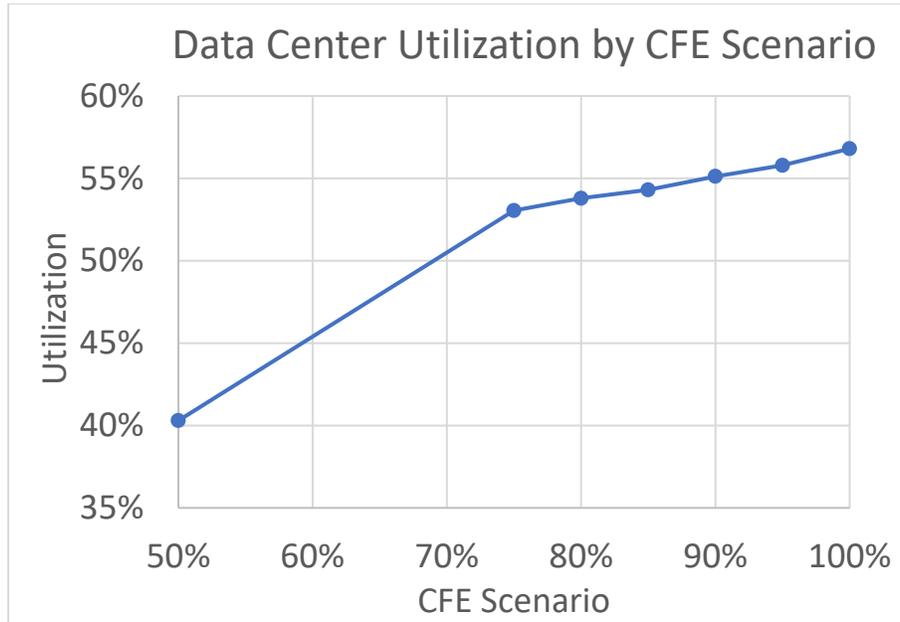


Figure 10 Data center utilization rate by CFE scenario

#### 4.4.3 Curtailment

Total annual curtailment is shown in Figure 11. Curtailment partially results from this study’s limited scope, which assumes excess energy is curtailed rather than fed to the grid. Without the grid as a demand source for excess electricity, battery storage capacity limitations result in curtailment. That is, the energy supply capex model converged on a battery power charge/discharge limit that exceeded PV output for every hour of the year. In the most extreme scenario, 100% CFE, 52.3% of all PV generation is curtailed when using MVDC distribution. An additional 3.3% is curtailed when using LVAC distribution, resulting in curtailment of 55.6% of LVAC PV generation. Higher curtailment at 50% CFE relative to 75% - 85% CFE results from the comparatively smaller ratio of battery:PV nameplate capacity needed to achieve the lower CFE threshold. The higher curtailment also results from the dynamic load profile. At 50% CFE, the model converges on a solution that has much lower utilization than the 75% CFE solution (40% vs. 53%). Many afternoons when the 75% CFE PV array supplies sufficient power to increase the IT load, the 50% CFE PV array cannot meet the same generation threshold, leaving data center operation at its lower 40% of IT load capacity. Otherwise, from 75-100% CFE, curtailment increases and MVDC produces less curtailment than LVAC.

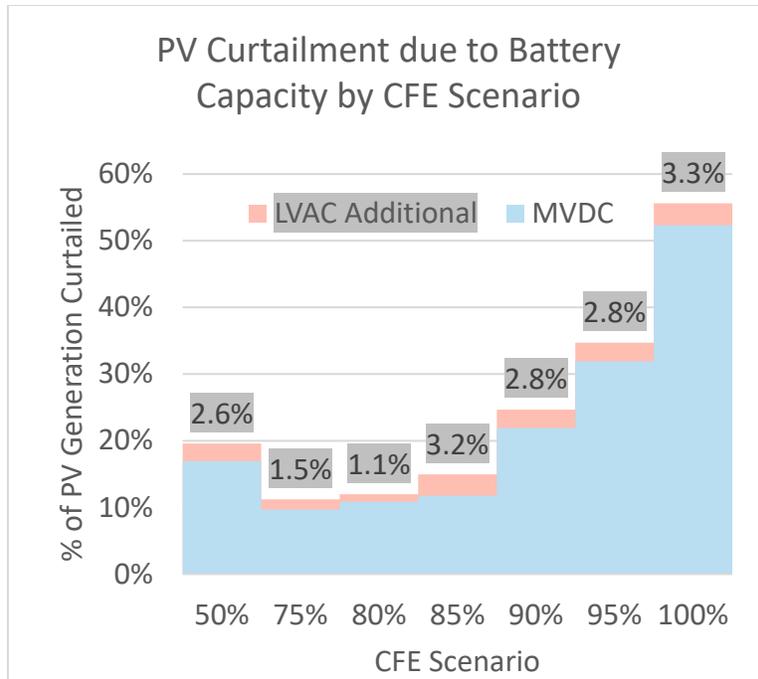


Figure 11 PV curtailment as a share of total PV generation for each CFE scenario. The gray labels show the additional curtailment with LVAC design.

## 5 Discussion

### 5.1 Relevance of Major Findings

The results of this study demonstrate the value of MVDC distribution from on-site PV generation and battery storage. Implementing MVDC distribution at Google’s Storey County, Nevada data center can reduce the aggregate capex investment of CFE generation, CFE storage, and power distribution for every minimum CFE percentage studied. As a result, the impact of MVDC can be directly understood and acted upon.

Ultimately, each study highlighting these benefits can contribute to de-risking these projects, further unlocking capital to prove these results through a First-of-a-Kind (FOAK) demonstration of such a data center. Aggregating the distribution benefits contributes to an expanded portfolio of economic benefits. The study intentionally focuses on a single real location that is in jeopardy of not meeting that company’s emission reduction goal. Ultimately, we hope the findings from this study garner serious consideration from data center developers to explore a FOAK project incorporating on-site solar-PV generation, battery storage, and MVDC distribution.

## 5.2 Energy Efficiency

Commercial data centers have made extraordinary improvements in energy efficiency, dropping from PUE values of over 2, to a global average PUE of around 1.2.<sup>57</sup> Google had already implemented these energy efficiency measures by 2013, when it achieved a global average PUE of 1.12. Over the following decade, Google's PUE dropped to 1.10 and has remained between 1.10 and 1.12 ever since.<sup>58</sup> The broader data center industry is observing the same PUE plateau. Few energy efficiency options remain if less than 20% of delivered power is lost to dissipation, cooling, and other non-IT loads.

PUE doesn't consider losses in generation, transmission, and distribution of electricity to the data center, leaving upstream losses as one of the few addressable energy efficiency opportunities remaining. Transmission losses are eliminated through on-site generation and storage, while generation and distribution losses are reduced with MVDC distribution. This study notes the advantage of MVDC distribution against LVAC distribution with on-site energy supply, but the gains from MVDC distribution are even greater if compared to offsite CFE distributed by the broader grid to an LVAC data center. This alternate baseline scenario has transmission losses beyond those noted in the LVAC analysis due to additional travel distance and voltage conversion steps. Google, or another leading tech firm, has the opportunity to develop an improved PUE-like metric that considers losses upstream from the data center. Energy system designs that reduce energy generation and investment costs will be critical as data center load growth soars. This holds especially true for firms looking to achieve corporate decarbonization goals, while addressing the computing demands of generative AI and blockchain.

## 5.3 Research Limitations and Recommendations

While this study quantifies certain benefits of powering carbon free data centers with on-site solar-PV, batteries, and MVDC, it faces limitations resulting from the finite scope of analysis and nascency of DC distribution. Further research, noted below, can address these limitations.

### 5.3.1 Electrical Distribution Component Costs and Reliability

The costs of MVDC distribution equipment, such as DC circuit breakers and DC-DC converters, will evolve at the pace of high and medium voltage DC circuit deployment. Technical research relating to circuit breakers and other protection devices such as fuses and quick disconnect switches could generate more confidence from industry. In particular, understanding the failure mechanism of multi-voltage level DC power distribution and developing methods to rapidly identify fault location will be essential to accelerating adoption of DC systems.<sup>59</sup> If demonstration projects adequately derisk DC architecture,

commercial demand for WBG semiconductors and the DC technology on which it relies, could shift toward economies of scale.

It will be important to update this study to reflect real-time developments related to component availability, capability, and cost. In-depth market analysis of WBG semiconductors and MVDC-related supply chain trends will be essential to de-risking this technology for potential deployers.

### 5.3.2 Value of Lost Load

This study does not account for the Value of Lost Load (VOLL), and other potential system reliability benefits of incorporating MVDC. With MVDC architecture, fewer power conversion stages reduce the potential for load loss, which was found to save \$180,000 in the study of a 16 MW IT load data center.<sup>60</sup> Linear extrapolation to the 96 MW data center results in a potential additional \$1M in savings.

### 5.3.3 Supplementary Revenue Streams

While this study emphasizes the potential for a data center to serve its load via on-site generation, storage, and MVDC distribution, it does not account for the value of supplying excess generation back to the grid. Due to battery capacity constraints, 10-56% of PV generation was curtailed across the modeled CFE scenarios. This energy is a valuable supply to the local electricity market, likely covering any additional costs of interconnection and improving overall project economics. If modeled with utility-network data, additional benefits such as resource adequacy, reliability, and resilience can be incorporated. Altogether, the value of excess generation may influence optimal generation, storage, and data center size, site, and cost.

### 5.3.4 Additional Limitations and Research

There are several other limitations to this study that provide opportunities for future research, listed below.

- Future studies should incorporate more sophisticated battery operations and their impact on battery degradation. They can also explore alternative technologies for generating and storing CFE, in addition to modeling multiple data centers with load-shifting across them.
- Applying this study's methodology to a client developing a data center for a genuine cost-benefit analysis comparing multiple system architectures under consideration.
- Developing an economic analysis that in addition to supplementary revenue streams values potential tax incentives and total component lifecycle costs. It is important to note that our distribution capex analysis only accounts for investment costs. It does not account for total

lifecycle costs of the distribution components. An interesting extension of the analysis would be incorporating total lifecycle costs and comparing the benefits of eliminating inverter maintenance vs. the drawbacks of maintaining novel components such as DC-DC converters and DC circuit breakers.

- Although it is beyond the scope of our paper, it would be worthwhile to analyze a variety of potential MVDC applications, such as:<sup>61,62</sup>
  - Grid distribution networks
    - Angle-DC is an operational project in the United Kingdom that is a bi-directional DC link to reinforce two sections of Scottish Power Energy Network's distribution grid<sup>63</sup>
  - Microgrids
  - Utility-scale solar
  - Offshore wind collection
  - Serving island loads
  - Connecting multiple solar farms
  - Connecting asynchronous grids
  - Large EV charging depots
  - Rail systems

## 6 Conclusion

This study demonstrated economic benefits of behind-the-meter DC electricity generation and storage when connected directly to a hyperscale data center through MVDC power distribution. Google's 24/7 carbon free energy goal, minimal use of on-site CFE, and low CFE matching in Nevada provided a basis for the parameters of the study. MVDC design is shown to improve efficiency by eliminating AC/DC conversion steps throughout the circuit, with the greatest gain occurring through battery supplied power. Efficiency benefits were valued by the difference in the necessary size of battery and PV systems to meet minimum CFE thresholds spanning from 50-100%. Higher minimum CFE thresholds required disproportionately larger batteries and showed greater overall savings from efficiency. In addition, MVDC design reduced the capex of power distribution by eliminating AC/DC conversion equipment and reducing the cost of wires through higher power DC distribution. From 95% to 100% CFE, capex costs nearly tripled as a result of the model converging on a battery with greater capacity than any in operation today. On-site PV and battery alone are a cost and technologically impractical solution to

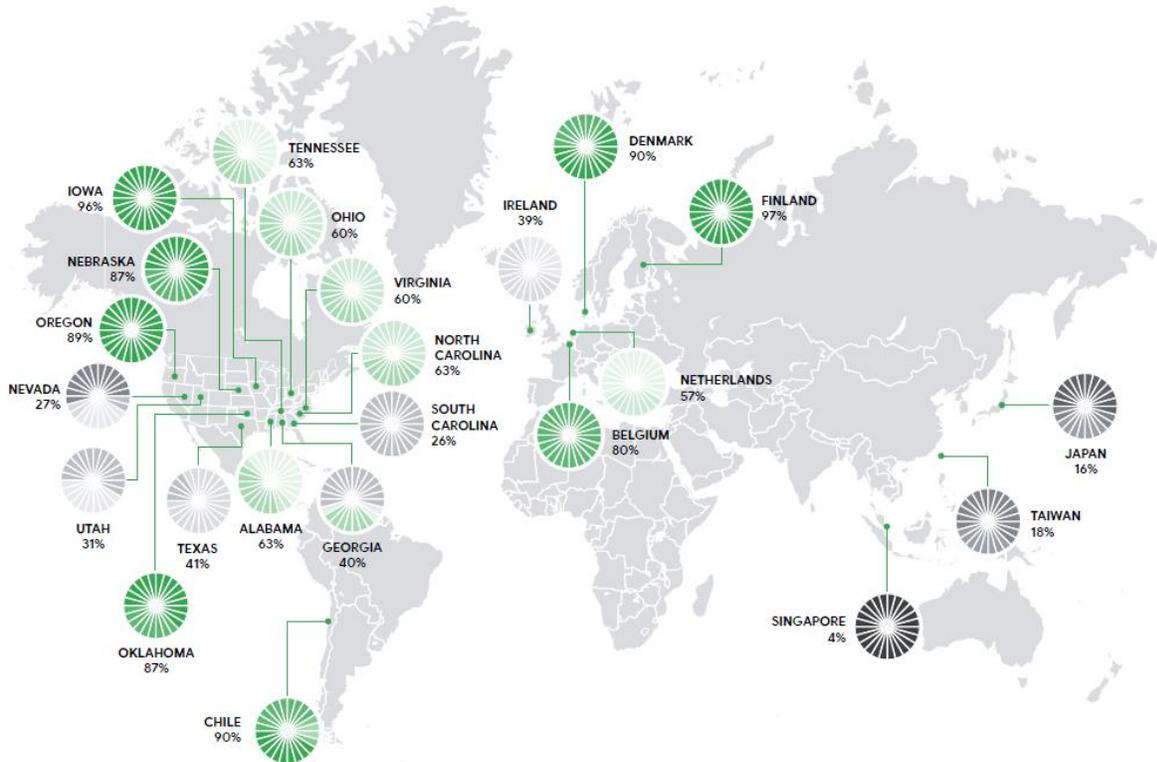
Google's 24/7 CFE goal, no matter the chosen distribution architecture, without more aggressive load-shifting to cover times of limited PV generation.

The recent advent of WBG semiconductors in DC circuit breakers and DC-DC converters has enabled a wider range of feasible DC technology applications. Most attention to DC technology is directed to high voltage DC transmission, but with reduced fixed costs, siting challenges, and permitting timelines, MVDC green data centers may offer a quicker path to demonstrating the benefits of DC grids, catalyzing the DC power distribution equipment supply chain. Further, Google's 2030 24/7 CFE energy commitment has already driven billion-dollar investments in massive solar and battery developments, as well as first-of-a-kind climate infrastructure.<sup>64</sup> Restructuring their approach to CFE procurement from offsite same-grid PPAs to on-site behind-the-meter generation may reduce Google's overall investment cost of achieving 100% local, time-matched carbon free energy.

## 7 Appendix

### 7.1 Hourly Carbon Free Energy at Google's Data Centers

In 2022, Google reached 64% CFE on an hourly and location basis.<sup>65</sup>



## 7.2 PV Watts Model Inputs

### PVWatts Hourly PV Performance Data

Requested Location	Storey county, NV	Google data center location
Location	Lat, Lng: 39.45, -119.54	Google data center location
Elevation (m)	1691	Google data center location
DC System Size (kW)	100000	Scaled linearly to match energy supply model result
Module Type	Premium (21% Efficiency)	To match PVSCM cost figures
Array Type	2-Axis Tracking	Maximize generation and smooth monthly variability
Bifacial	Yes	To match PVSCM cost figures
Array Tilt (deg)	0	Default
Array Azimuth (deg)	180	Default
System Losses (%)	0	0% to isolate losses to LVAC/MVDC differences
DC to AC Size Ratio	1	Only referencing DC output
Inverter Efficiency (%)	100	Only referencing DC output
Ground Coverage Ratio	NA	Default
Albedo	From weather file	Default

### 7.3 Efficiency Parameters

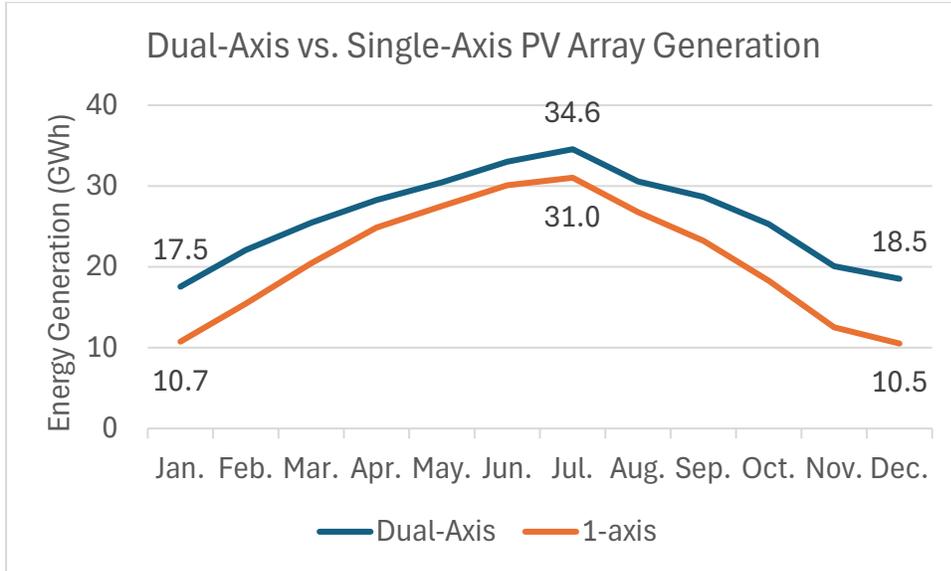
Efficiency MVDC and LVAC Design across each electricity supply source and load type. Battery efficiencies are sourced from NREL’s REopt model,<sup>66</sup> the weighted average load split is derived from Chen et al,<sup>67</sup> and the efficiency figures are derived from Siemaszko, Heinig, and Mogorovic 2023.<sup>68</sup>

Stage	MVDC; Solar-PV or Battery			MVDC, Grid		
		IT Load	Mech Load		IT Load	Mech Load
Distribution	SST DC to +/-10kVDC	0.987	0.987	HV-MV transformer	0.995	0.995
Distribution	DC Cables	0.99	0.99	MV DC cables	0.99	0.99
V Stepdown (LV Distribution)				Power Converter	0.99	0.99
UPS	DCUPS Efficiency	0.999		DCUPS	0.999	
V Stepdown (MV Distribution)	SST +/-10kV-380VDC	0.987	0.987	SST ±10 kVDC-380 VDC	0.987	0.987
PDU				PDU		
PSU (IT)	Drive inverter (DC-AC)		0.98	Drive inverter (DC-AC)		0.98
Drive (Mech)	PSU-DC	0.956		PSU-DC	0.956	
	<b>Efficiency, non-battery</b>	<b>0.921</b>	<b>0.945</b>	<b>Efficiency, non-battery</b>	<b>0.919</b>	<b>0.944</b>
<b>WEIGHTED AVERAGE</b> (1/3 Cooling, 2/3 IT load)		0.9288			0.9272	
Battery discharge, AC (Inverter)						
Battery Internal Efficiency		0.975	0.975			
	<b>From Battery</b>	<b>0.898</b>	<b>0.922</b>			

Stage	LVAC, Solar-PV or Battery			LVAC, Grid		
		IT Load	Mech Load		IT Load	Mech Load
Distribution	Transformer and Inverter	0.968	0.968	HV-MV transformer	0.995	0.995
Distribution	AC Cables	0.99	0.99	MV AC cables	0.99	0.99
V Stepdown (LV Distribution)	MV-LV Transformer	0.995	0.995	MV-LV Transformer	0.995	0.995
UPS	ACUPS Efficiency	0.963		ACUPS	0.963	
V Stepdown (MV Distribution)						
PDU	500kVA PDU	0.991		PDU	0.991	
PSU (IT)	VFD		0.973	VFD		0.973
Drive (Mech)	PSU-AC	0.932		PSU-AC	0.932	
	<b>Efficiency, non-battery</b>	<b>0.849</b>	<b>0.928</b>	<b>Efficiency, non-battery</b>	<b>0.873</b>	<b>0.954</b>
<b>WEIGHTED AVERAGE</b> (1/3 Cooling, 2/3 IT load)		0.8755			0.8998	
Battery discharge, AC (Inverter)		0.973	0.973			
Battery Internal Efficiency		0.975	0.975			
	<b>From Battery</b>	<b>0.806</b>	<b>0.881</b>			

### 7.4 Dual-Axis vs. Single-Axis PV Array Generation

Chart showing lower variability and greater generation from a dual-axis PV array than the single-axis alternative at the Storey County, Nevada location.<sup>69</sup>



## 7.5 Energy Supply Capex Model Cost Parameters

The energy supply capex parameters were selected from PVSCM and include only direct capex costs.<sup>70</sup>

Grid energy costs were sourced from and NREL's REopt model.<sup>71,72</sup>

<b>Grid Energy</b>	<b>Value</b>	<b>Unit</b>	<b>Source, note</b>
Energy cost	\$75	\$/MWh	\$.075/kWh
Discount Rate	6.38%		Sourced reOPT APIv3
Grid Power Years	10	Years	Similar to battery life and 2035 Duke energy CPIRP
<b>Battery</b>			
Li-Ion Cells	\$116.53	\$/kWh-CAP	PVSCM
Racks with BMS	\$48.55	\$/kWh-CAP	PVSCM
Rest of Container	\$40.78	\$/kWh-CAP	PVSCM
<b>ESS Total</b>	<b>\$205,866</b>	<b>\$/MWh-CAP</b>	
<b>Solar-PV Panels</b>			
	Cost	Unit	
Two-axis Premium	1.585		Adjustment, dual axis investment cost / single axis <sup>1</sup>
SBOS	\$113.79	\$/kWdc	Single-axis PVSCM
Cells	\$176.07	\$/kWdc	Single-axis PVSCM
Frame	\$20.72	\$/kWdc	Single-axis PVSCM
Junction Box	\$6.46	\$/kWdc	Single-axis PVSCM
Other Material	\$44.15	\$/kWdc	Single-axis PVSCM
<b>Solar-PV Total</b>	<b>\$572,598</b>	<b>\$/MWdc</b>	

<b>Battery Not Included</b>	<b>Reason</b>
Bi-Inverter	A/C Only, considered in Distribution Savings Model
Labor	Not CapEx
Electricity	Indirect Cost
Depreciation	Indirect Cost
Maintenance	Indirect Cost
Profit	Indirect Cost
Shipping	Indirect Cost

<b>Solar Not Included</b>	<b>Reason</b>
Labor	Not CapEx
Electricity	Indirect Cost
Depreciation	Indirect Cost
Maintenance	Indirect Cost
Profit	Indirect Cost
Shipping	Indirect Cost

## 7.6 Energy Supply Capex Model Definition

Battery is allowed to charge and discharge at 1C, based on battery storage time output.

Key
Scenario Dependant
Fixed Parameter
Decision Variable
Decision Variable Contingent Parameter
Output

### Scenarios

Distribution Architecture	{LVAC, MVDC}
Minimum CFE	{50%, 75%, 80%, 85%, 90%, 95%, 100%}

Load	Value	Unit
IT Load, Max	96	MW
Cooling Coefficient (% of IT Load)	0.5	
Cooling Load, Max	48	MW
Datacenter Load, Max	144	MW
High Demand Utilization	80%	
Low Demand Utilization	40%	
Min PV supply, high demand	80%	

Supply/Generation	MVDC Value	LVAC Value	Unit
PV System Size	Decision Variable		MW
Battery Cap, Nameplate	Decision Variable		MWh
Battery Storage Time	Decision Variable		Hours
PV Delivered Efficiency	0.93	0.88	
Grid Source, Efficiency	0.93	0.90	
Battery Inverter Efficiency	1.00	0.97	
Battery Depth of discharge	0.8		
Battery Internal Efficiency	0.975		
Battery Output Efficiency	0.91	0.83	
Battery Capacity, usable	Output		MWh
Discharge Rate	Output, Battery Constraint		MW

Constraint	Value/Source
% Carbon Free >=	{50-100%}
Battery Storage Time >=	2 Hours
Battery Storage Time <=	8 Hours
Battery Discharge Rate <=	Charge Rate
Battery Storage <=	Battery Capacity

Output, Analysis	Unit
Demand (Load)	MWh
Load served by PV	MWh
Load served by Battery	MWh
Load served by Grid	MWh
PV Produced Energy (No Losses)	MWh
PV Potential Supply (incl. Losses)	MWh
Grid Procured Energy	MWh
PV Curtailment	MWh
% Data Center Utilization	%

Cost Outputs	Unit
Battery Capex Cost	\$
Solar Capex Cost	\$
10-year Grid Energy Cost	\$
<b>Total Cost</b>	<b>\$ Objective, minimize</b>
<b>Total Capex</b>	<b>\$</b>

## 7.7 REopt vs. Energy Supply Capex Model System Size and Cost Outputs

CFE %	PV System Size			Battery		
	REopt (MWdc)	Supply Model (MWdc)	Supply Model Difference (Δ%)	REopt (MWh)	Supply Model (MWh)	Supply Model Difference (Δ%)
50%	124	113	-10%	221	202	-8%
75%	238	205	-14%	568	570	0%
80%	259	224	-14%	709	737	4%
85%	280	248	-11%	853	887	4%
90%	320	295	-8%	976	1035	6%
95%	422	356	-16%	1111	1269	14%
100%	1,581	518	-67%	4052	5281	30%

CFE %	PV Cost		Battery Cost		Total Cost		
	REopt (\$M)	Supply Model (\$M)	REopt (\$M)	Supply Model (\$M)	REopt (\$M)	Supply Model (\$M)	Difference from REopt (Δ%)
50%	\$71	\$64	\$45	\$42	\$117	\$106	-9%
75%	\$136	\$117	\$117	\$117	\$253	\$235	-7%
80%	\$148	\$128	\$146	\$152	\$294	\$280	-5%
85%	\$160	\$142	\$176	\$183	\$336	\$325	-3%
90%	\$183	\$169	\$201	\$213	\$384	\$382	0%
95%	\$241	\$204	\$229	\$261	\$470	\$465	-1%
100%	\$905	\$296	\$834	\$1,087	\$1,739	\$1,383	-20%

## 7.8 Distribution Capex Details, by Category

Equipment cost sourced from Chen et al.<sup>73</sup>

	<b>UPS (\$)</b>	<b>Power Conversion (\$)</b>	<b>Power Lines (\$)</b>	<b>Circuit Breakers (\$)</b>	<b>Total (\$)</b>
<b>LVAC</b>	51,840,000	9,600,000	17,366,400	720,000	79,526,400
<b>MVDC (WBG)</b>	40,320,000	19,200,000	7,603,200	1,440,000	68,563,200
<b>MVDC Savings %</b>	22.2%	-100.0%	56.2%	-100.0%	13.8%

## 7.9 Distribution Capex Details, by Component

Equipment cost sourced from Chen et al.<sup>74</sup>

Category	Component	\$/MW at point of use	LVAC (MW)	MVDC (WBG) (MW)	LVAC Cost (\$)	MVDC (WBG) Cost (\$)
Backup Gen.**	AC Generation	180,000	80	80	14,400,000	14,400,000
Conversion	AC Transformer	50,000	192	0	9,600,000	-
Conversion	DC-DC Converter	120,000	0	0	-	-
Conversion	GaN-based Converter	80,000	0	240	-	19,200,000
UPS	Battery (0.5 hour)	150,000	192	192	28,800,000	28,800,000
UPS	AC/DC Rectifier	80,000	144	144	11,520,000	11,520,000
UPS	DC/AC Inverter	80,000	144	0	11,520,000	-
Lines	12.7kV AC Cable	600	144	144	86,400	86,400
Lines	480V AC Cable	16,000	144	0	2,304,000	-
Lines	208V AC Cable	36,000	144	0	5,184,000	-
Lines	12.7kV AC Busbar	1,000	144	0	144,000	-
Lines	208V AC Busway	56,000	144	0	8,064,000	-
CB	AC Circuit Breaker	5,000	144	0	720,000	-
CB	DC Circuit Breaker	10,000	0	144	-	1,440,000
Lines	10kV DC Cable	400	0	144	-	57,600
Lines	380V DC Cable	11,000	144	144	1,584,000	1,584,000
Lines	10kV DC Busbar	800	0	144	-	115,200
Lines	380V DC Busway	40,000	0	144	-	5,760,000

\*\*Backup generation not included in distribution capex analysis

## 8 References

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- <sup>1</sup> Vivan Lee, “The Impact of GenAI on Electricity: How GenAI Is Fueling the Data Center Boom in the U.S.,” September 13, 2023, <https://www.linkedin.com/pulse/impact-genai-electricity-how-fueling-data-center-boom-vivian-lee>.
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