Industrials/Multi-Industry

Who Makes the Data Center 2025

Primer

A global view of the $500+bn data center market

Understanding the data center end market has grown in importance given high growth rates and scale. We estimate global data center spending will reach $506bn in 2025E, comprised of $418bn of IT equipment and $88bn of infrastructure spending. This is up 25% y/y. We forecast a 23% CAGR for the market over 2024-28, including a 19% CAGR for infrastructure spending. We provide historical context on the size, shape, and ownership of the global data center market.

The key product lines for data center infrastructure

We focus on 12 product and service categories: chillers, construction firms, cooling towers, computer room air handlers, coolant distribution units, engineering firms, generators, networking equipment, power distribution equipment, servers, switchgear, and uninterruptible power supplies. We show average content per megawatt (MW) and market shares for each of these categories. We estimate the all-in cost of building a data center at $39mn/MW. We anticipate next generation AI architectures will be significantly more capital intensive at $52mn/MW.

Implications of AI semiconductor evolution: from AC to DC

We explain the reasons why artificial intelligence (AI) semiconductor manufacturers are switching to “rack scale” architectures, with ever increasing density of chips per rack. These industry trends have already driven rapid growth in liquid cooling in thermal equipment. However, we see an emerging shift to high voltage direct current (DC) architecture for electrical equipment. We size the potential for electrical equipment content and costs to change as the industry pivots away from low voltage alternating current (AC) designs.

From air to liquid: a closer look at CDUs

Rising rack density is driving adoption of liquid cooling solutions. The industry is coalescing on single-phase, direct-to-chip solutions. Coolant distribution units (CDUs) are the key equipment needed to power these offerings. Larger format, in-row CDUs have outgrown smaller in-rack variants. We show 30 vendors and highlight the five we think currently have the most market share.

AI data centers & electricity demand

Over the last few months, there have been several announcements of gigawatt-scale data centers. Using multiple academic forecasts, we see AI electricity demand growing at a 40+% CAGR, with low- to mid-teens growth for total data center demand. We provide case studies of how these large projects have progressed and are obtaining power. We argue that the electricity demand for AI inference (i.e., running previously trained models) will overtake AI training before the end of the decade. While efficiency gains are possible, we see increased adoption more than offsetting this.

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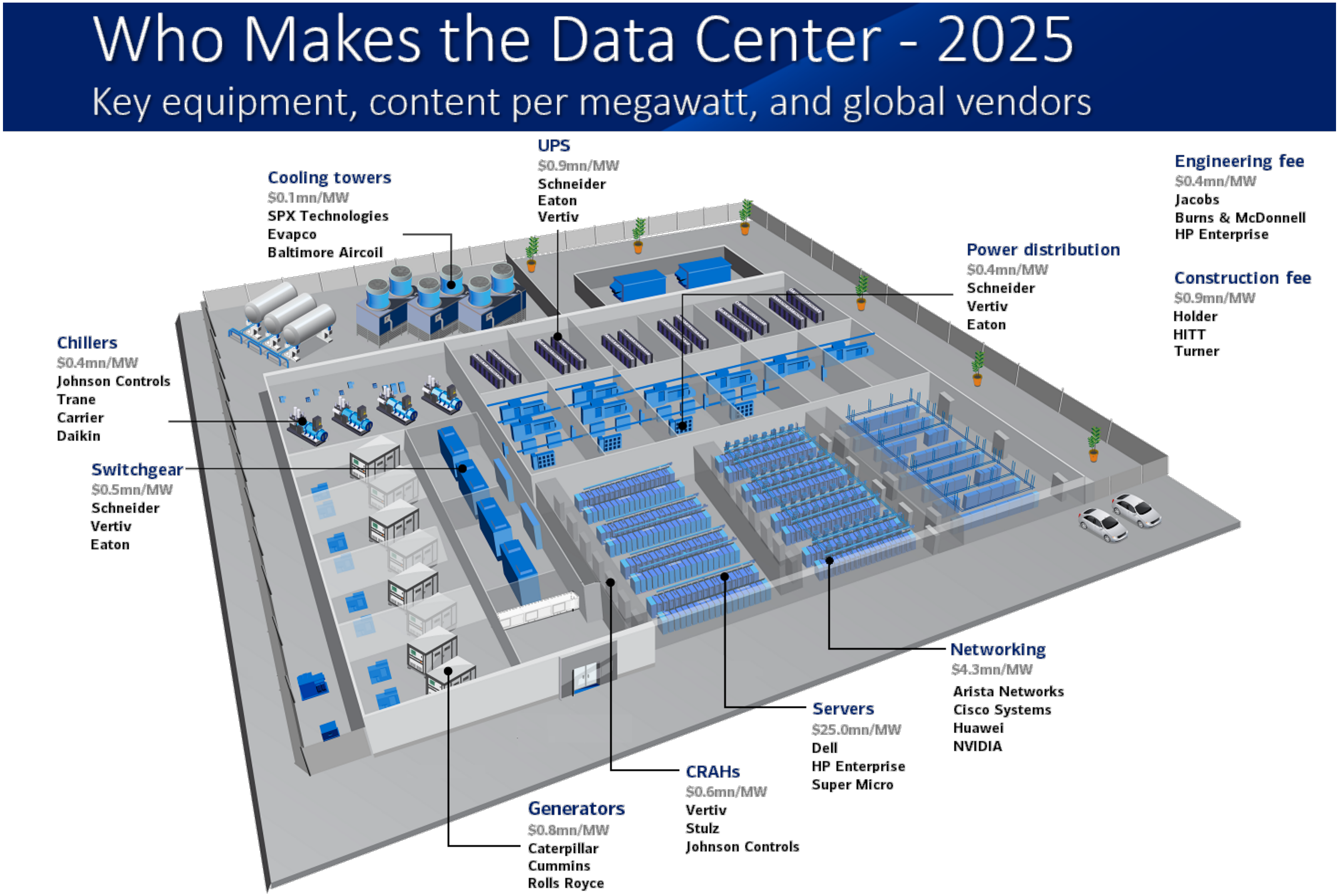
Exhibit 1: Who Makes the Data Center - 2025
Estimated capex costs of $39mn per megawatt



Source: BofA Global Research

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Data center market to hit $900+bn in '28E

We estimate data center capex was more than $400bn globally in 2024, rising to more than $500bn in 2025E. We expect AI adoption to drive a 23% market-wide CAGR over 2024-28E. We size Electrical and Thermal equipment markets at $18bn and $10bn markets, respectively, in 2024.

Exhibit 2: We forecast the global data center market to grow at a 23% CAGR over 2024-28E to reach over $900bn in 2028
AI adoption drives strong growth in infrastructure

($bn)	2022	2023	2024	2025E	2026E	2027E	2028E	'24-'28E CAGR
AI Servers	17	50	139	222	340	456	549	41%
AI Networking	3	8	15	21	29	39	50	35%
AI Storage	1	3	9	13	19	25	30	37%
AI-related IT Equipment	21	61	162	256	389	519	629	40%
Non-AI IT Equipment	206	176	171	162	160	159	163	-1%
Subtotal: IT Equipment	**227**	**238**	**334**	**418**	**548**	**678**	**792**	**24%**
Construction & installation	23	26	35	41	49	58	68	18%
Electrical	13	15	18	21	25	29	34	17%
Air-cooling	*5*	*6*	*8*	*9*	*11*	*12*	*14*	14%
Liquid-cooling	*0*	*1*	*1*	*3*	*5*	*7*	*9*	60%
Thermal	6	7	10	12	16	19	23	25%
Generators	4	5	7	9	10	12	14	18%
Engineering	2	3	4	5	6	7	8	19%
Sub-total: Infrastructure	**48**	**54**	**73**	**88**	**106**	**125**	**147**	**19%**
Total	**275**	**292**	**406**	**506**	**654**	**803**	**939**	**23%**

Source: BofA Global Research

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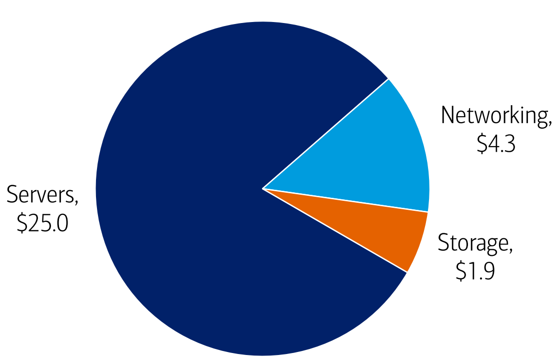
Per megawatt costs analysis

Exhibit 3: IT equipment costs ($mn per MW)
Servers are the majority of IT equipment capex



Source: BofA Global Research

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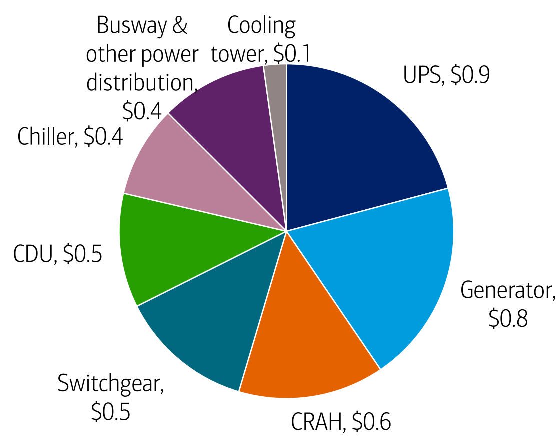
Exhibit 4: Infrastructure equipment-only costs ($mn per MW)
Electrical equipment is the largest category of infrastructure capex



Source: BofA Global Research

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The percentage mix varies from our market size as the total market includes replacement/refresh spending. We estimate the all-in cost of building a traditional data center to be $39mn per megawatt.

As discussed later in this report, there are significant infrastructure changes ahead for the next generation of AI chips (e.g., NVIDIA's proposed Rubin chip architecture). We estimate the cost of this future state data center at $52mn per megawatt.

The largest difference is higher server costs for next generation chips. Higher rack density leads to a lower number of racks and square footage per megawatt, reflected in lower building costs power distribution equipment costs. This future state data center assumes direct-to-chip liquid cooling and high voltage direct current electrical systems.

Exhibit 5: Data center costs per megawatt

Servers are the largest area of data center capex

	Traditional data center		Future state data center	
Category	**Cost/MW**	**% of total**	**Cost/MW**	**% of total**
Servers	25,000,000	64%	37,500,000	73%
Networking	4,250,000	11%	3,750,000	7%
Storage	1,900,000	5%	1,900,000	4%
Subtotal IT equipment	31,150,000	80%	43,150,000	84%
Uninterruptible Power Supplies (UPS)	850,000	2%	985,000	2%
Switchgear	530,000	1%	615,000	1%
Busway & other power distribution	420,000	1%	300,000	1%
Subtotal electrical equipment	1,800,000	5%	1,900,000	4%
Computer room air handler (CRAH)	575,000	1%	575,000	1%
Cooling distribution units (CDUs)	0	0%	450,000	1%
Chiller (285-ton capacity)	360,000	1%	360,000	1%
Cooling tower	90,000	0%	90,000	0%
Subtotal thermal equipment	1,025,000	3%	1,475,000	3%
Backup diesel generator	800,000	2%	800,000	2%
Engineering fee	400,000	1%	480,000	1%
General contractor overhead & profit	900,000	2%	900,000	2%
Building costs	1,300,000	3%	1,100,000	2%
Installation costs	1,500,000	4%	1,800,000	3%
Subtotal E&C	4,100,000	11%	4,280,000	8%
Grand total	38,875,000	100%	51,605,000	100%

Source: BofA Global Research

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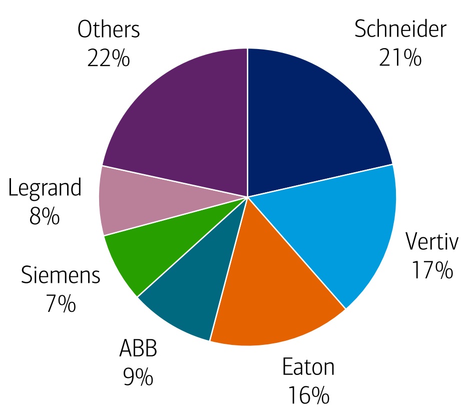
Vendor shares on broad infrastructure product categories

Across data center electrical products, we estimate Schneider is the share leader in this $18bn market. Across all thermal products, we estimate Vertiv is the share leader in this $10bn market.

Exhibit 6: Vendor shares across all electrical equipment; Schneider is the market leader (2024)

Six largest vendors have over 75% market share



Source: BofA Global Research

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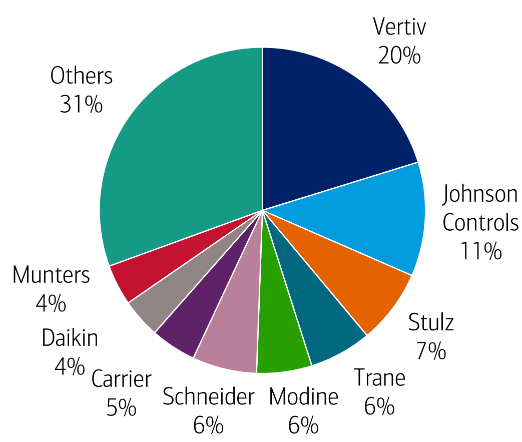
Exhibit 7: Vendor shares across all thermal equipment; Vertiv is the market leader (2024)

Eight largest vendors have ~65% market share



Source: BofA Global Research

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Types of data centers

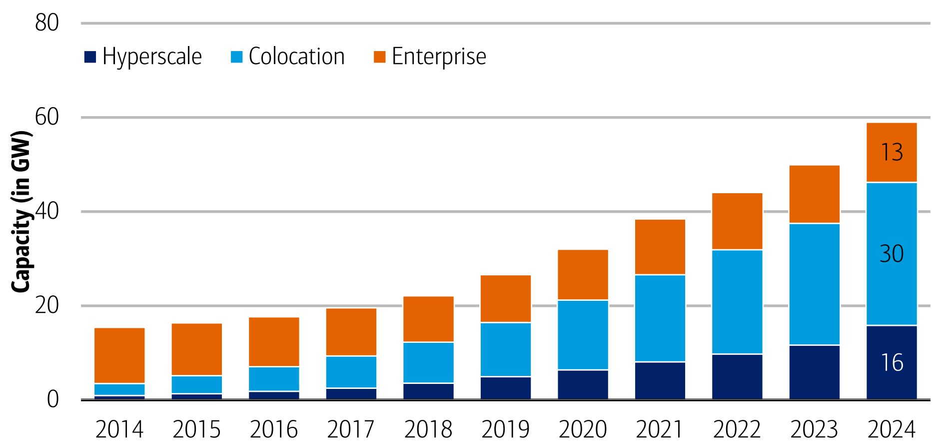
- **Enterprise:** a facility owned by a single organization housing its IT infrastructure. Typically, they are owned by large corporations, financial institutions, or government agencies. Over the past ten years, the square footage growth of these data centers has been flat. However, upgrade and modernization projects have increased the capacity.

- **Single-tenant colocation:** a facility owned and managed by a third party and leased to a single tenant. Historically, these came from sale leasebacks (i.e., enterprise-owned data center is sold to an investor and then leased back). Over the past ten years, cloud service providers have used this method to expand in new geographies. Initial lease terms are typically long with options to expense (e.g., 10-year initial lease with two additional 10-year options).

- **Multi-tenant colocation:** a facility owned and managed by a third party and leased to multiple tenants. Rents are generally based on a combination of power usage and number of racks. Tenants benefit from shared services (e.g., network connectivity, physical security). Can be subdivided into retail (smaller space commitments; less flexibility) and wholesale (requires larger commitments; more flexibility in design).

- **Hyperscale:** a very large data center engineered to provide maximum uptime (i.e., Tier 4 ranking in Uptime Institute's classification), support distributed computing (e.g., sharing workloads across servers and sites), and scalability. The definition of "large" varies, but typically greater than 20 megawatts. Distributed computing and hyperscale data centers are closely associated with cloud service providers, such as Amazon Web Services and Microsoft Azure. However, not every hyperscale data center is used for cloud services and not all cloud servers are in hyperscale data centers.

Exhibit 8: Globally, colocation is the largest data center type, but hyperscaler is fastest growing
Hyperscalers added slightly more capacity than colocation firms in 2024



Source: BofA Global Research

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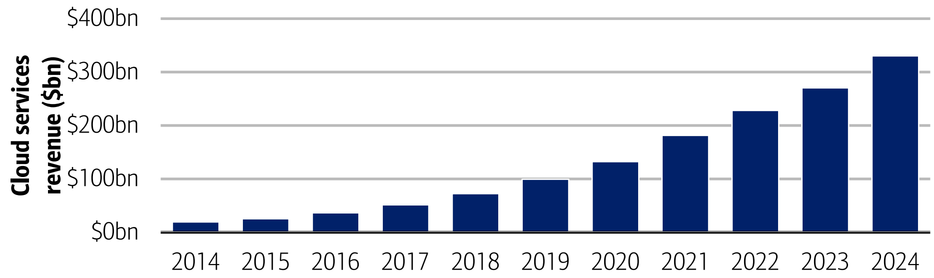
As measured by electrical capacity, we estimate global data centers grew at a 14% CAGR over 2014-24 and a 17% CAGR over 2019-24. While corporations continue to run and maintain a significant number of data centers, hyperscale and colocation firms have made nearly all the capacity additions since 2013. We note that small colocation companies (e.g., <10 data centers) collectively comprise a meaningful portion of data center space (20-25%). These firms typically own smaller sites (e.g., <20 megawatts) outside major markets.

Evolution of cloud growth

In 2005, Nicholas Carr authored an article entitled *The End of Corporate Computing* predicting enterprises would stop building their own data centers and use third-party services. Amazon Web Services launched the next year, driving a boom in cloud services. In 2017, cloud service providers and colocation companies surpassed enterprise-owned data centers (as measured by electrical capacity).

Cloud service providers are profitable. Amazon Web Services generated $40bn of GAAP operating profit on $108bn of revenue, or a 37% operating margin. For most IT workloads, colocation provides a lower total cost of ownership. However, it requires upfront capex (for services & related IT equipment), multi-year commitments (to colocation firms), and higher levels of IT management and support. In contrast, cloud services are flexible and offer higher uptime levels.

Exhibit 9: Cloud services revenue has grown from under $20bn in 2014 to $330bn in 2024
The three largest firms are Amazon Web Services, Microsoft Azure, and Google Cloud



Source: Synergy Research Group, company filings

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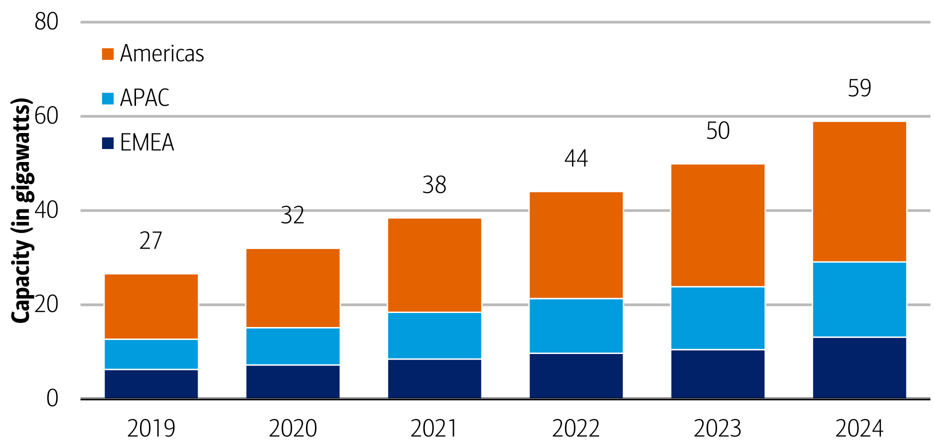
Regional breakout: Americas home to over half of capacity

We estimate data centers (measured by electrical capacity) grew at an 17% CAGR over 2019-24. We find only relatively modest differences in growth by region. EMEA has been a relative laggard (16% CAGR), Asia Pac a touch better (20%), and the Americas region right in line (17%).

Exhibit 10: Americas is largest region for data center capacity with slightly over 50% over total
Asia Pac has had the fastest % growth rate, but Americas has added the most capacity in gigawatts



Source: BofA Global Research, Schneider Electric, JLL, IEA

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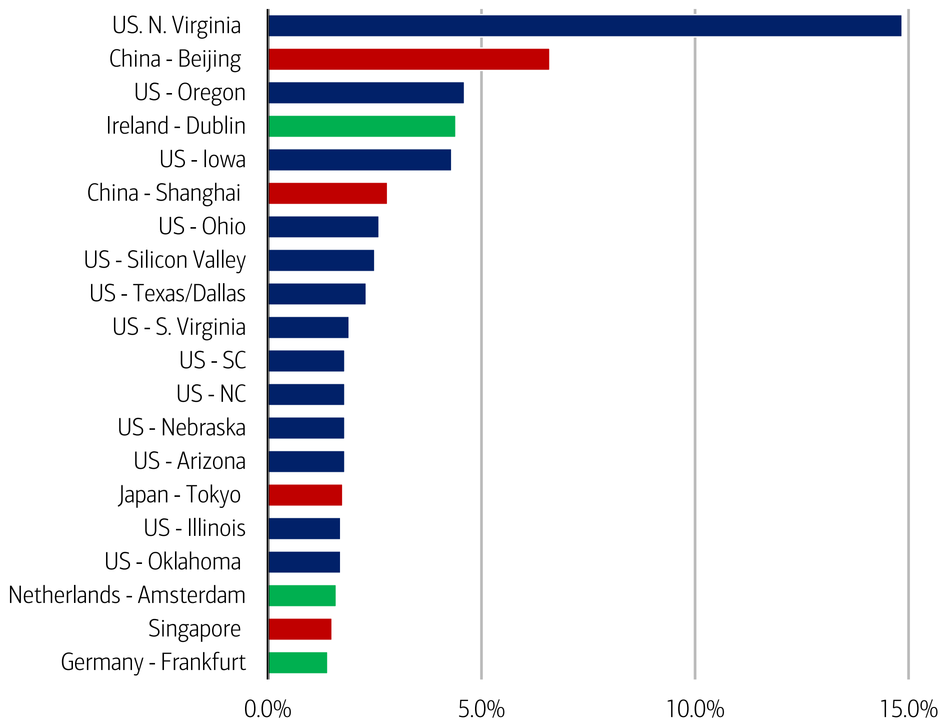
Hyperscaler capacity is largely concentrated in the same key regions globally. Below, we look at the top 20 locations for hyperscaler data center capacity globally. Navy represents North America, Red represents APAC, and Green represents EMEA. The largest single hyperscaler location globally is US Northern Virginia, which represents almost 15% of global capacity for hyperscalers. The second largest capacity is in Beijing, with ~7% capacity.

Exhibit 11: Hyperscale data center capacity by country/region, ranked by top 20 largest regions
US Northern Virginia has the largest concentration of data center capacity



Source: Synergy Research

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Colocation economics

We walk through typical per megawatt project economics for a new build wholesale colocation project (i.e., one leased to a small number of clients on long-term leases).

- **$2mn per MW.** Land costs, utility connections, and site works. This would vary by location/site.

- **$11mn per MW for the powered shell.** Turner & Townsend's Data Center Cost Index uses real construction data from 300 projects. These costs include the building shell, mechanical, electrical, thermal, equipment and installation labor costs, and general contractor margin and contingency.

Typical annual rent is $2-3mn per megawatt; we assume $2.5mn. Current occupancy rates in the US are 96-97%, we conservatively assume 90% over the 20 years. The largest operating expense is electricity ($0.08 per kilowatt hour is average US industrial cost implying $0.7mn for 100% utilization, or $0.63mn given 90% occupancy level). Staffing levels are around two full-time employees per megawatt; we assumed $0.25mn in wages. We assume property taxes of 1% on property value. Typical EBITDA margins are 40-50%; we assume 45%.

For free cash flow, we assume maintenance capex of 1.5% of original $11mn powered shell cost. We assume project financing of $7mn in equity (at 10% cost) and $6mn in 20-year amortizing mortgage debt (at 6% rate), yielding a weighted average cost of capital of 8.5%. This would be a 46% loan-to-value, in line with recent data center financings. We use a 21% corporate tax rate for cash income taxes.

After the 20-year holding period, we assume the data center is sold. Recent data center transactions have been at around 5-7% capitalization rates; we assume 7.0% for the exit at the end of year 20 (i.e., 14.3x net operating income). These assumptions yield an 11.0% internal rate of return (IRR) and a $2.8mn net present value (relative to the original $7mn equity investment).

Exhibit 12: Illustrative economics for wholesale colocation project

We assume 90% occupancy, $2.25mn of annual initial revenue, 3% inflation, and 45% EBITDA margin

$mn	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Rent/MW	2.50	2.58	2.65	2.73	2.81	2.90	2.99	3.07	3.17	3.26	3.36	3.46	3.56	3.67	3.78	3.89	4.01	4.13	4.26	4.38
Occupancy	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%
Revenue	2.25	2.32	2.39	2.46	2.53	2.61	2.69	2.77	2.85	2.94	3.02	3.11	3.21	3.30	3.40	3.51	3.61	3.72	3.83	3.95
Operating expenses	-1.24	-1.27	-1.31	-1.35	-1.39	-1.43	-1.48	-1.52	-1.57	-1.61	-1.66	-1.71	-1.76	-1.82	-1.87	-1.93	-1.99	-2.05	-2.11	-2.17
EBITDA	1.01	1.04	1.07	1.11	1.14	1.17	1.21	1.25	1.28	1.32	1.36	1.40	1.44	1.49	1.53	1.58	1.62	1.67	1.72	1.78
EBITDA margin	*45%*	*45%*	*45%*	*45%*	*45%*	*45%*	*45%*	*45%*	*45%*	*45%*	*45%*	*45%*	*45%*	*45%*	*45%*	*45%*	*45%*	*45%*	*45%*	*45%*
Maintenance capex	-0.17	-0.17	-0.18	-0.18	-0.19	-0.20	-0.20	-0.21	-0.21	-0.22	-0.23	-0.23	-0.24	-0.25	-0.26	-0.26	-0.27	-0.28	-0.29	-0.30
Interest expense	-0.36	-0.35	-0.34	-0.33	-0.32	-0.30	-0.29	-0.28	-0.26	-0.25	-0.23	-0.21	-0.19	-0.18	-0.15	-0.13	-0.11	-0.08	-0.06	-0.03
Cash income taxes	-0.14	-0.15	-0.15	-0.16	-0.17	-0.18	-0.19	-0.20	-0.21	-0.23	-0.24	-0.25	-0.26	-0.28	-0.29	-0.30	-0.32	-0.33	-0.35	-0.37
Free cash flow	0.35	0.37	0.40	0.43	0.46	0.49	0.52	0.56	0.59	0.63	0.67	0.70	0.75	0.79	0.83	0.88	0.93	0.98	1.03	1.08
Debt repayment	-0.16	-0.17	-0.18	-0.19	-0.21	-0.22	-0.23	-0.25	-0.26	-0.28	-0.29	-0.31	-0.33	-0.35	-0.37	-0.39	-0.41	-0.44	-0.47	-0.49
Depreciation	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37
Revenue	2.25	2.32	2.39	2.46	2.53	2.61	2.69	2.77	2.85	2.94	3.02	3.11	3.21	3.30	3.40	3.51	3.61	3.72	3.83	3.95
Cash operating expenses	-1.41	-1.45	-1.49	-1.54	-1.58	-1.63	-1.68	-1.73	-1.78	-1.83	-1.89	-1.95	-2.00	-2.07	-2.13	-2.19	-2.26	-2.32	-2.39	-2.47
Net operating income (NOI)	**0.84**	**0.87**	**0.90**	**0.92**	**0.95**	**0.98**	**1.01**	**1.04**	**1.07**	**1.10**	**1.13**	**1.17**	**1.20**	**1.24**	**1.28**	**1.31**	**1.35**	**1.39**	**1.44**	**1.48**
EBITDA	1.01	1.04	1.07	1.11	1.14	1.17	1.21	1.25	1.28	1.32	1.36	1.40	1.44	1.49	1.53	1.58	1.62	1.67	1.72	1.78
Maintenance capex	-0.17	-0.17	-0.18	-0.18	-0.19	-0.20	-0.20	-0.21	-0.21	-0.22	-0.23	-0.23	-0.24	-0.25	-0.26	-0.26	-0.27	-0.28	-0.29	-0.30
Interest expense	-0.36	-0.35	-0.34	-0.33	-0.32	-0.30	-0.29	-0.28	-0.26	-0.25	-0.23	-0.21	-0.19	-0.18	-0.15	-0.13	-0.11	-0.08	-0.06	-0.03
Cash income taxes	-0.14	-0.15	-0.15	-0.16	-0.17	-0.18	-0.19	-0.20	-0.21	-0.23	-0.24	-0.25	-0.26	-0.28	-0.29	-0.30	-0.32	-0.33	-0.35	-0.37
Free cash flow	**0.35**	**0.37**	**0.40**	**0.43**	**0.46**	**0.49**	**0.52**	**0.56**	**0.59**	**0.63**	**0.67**	**0.70**	**0.75**	**0.79**	**0.83**	**0.88**	**0.93**	**0.98**	**1.03**	**1.08**
Electricity	-0.63	-0.65	-0.67	-0.69	-0.71	-0.73	-0.75	-0.78	-0.80	-0.82	-0.85	-0.87	-0.90	-0.93	-0.95	-0.98	-1.01	-1.04	-1.07	-1.11
Staffing	-0.25	-0.25	-0.26	-0.27	-0.28	-0.29	-0.30	-0.30	-0.31	-0.32	-0.33	-0.34	-0.35	-0.36	-0.37	-0.39	-0.40	-0.41	-0.42	-0.43
Real estate taxes	-0.13	-0.13	-0.14	-0.14	-0.15	-0.15	-0.16	-0.16	-0.16	-0.17	-0.17	-0.18	-0.19	-0.19	-0.20	-0.20	-0.21	-0.21	-0.22	-0.23
SG&A costs	-0.23	-0.24	-0.24	-0.25	-0.26	-0.27	-0.27	-0.28	-0.29	-0.30	-0.31	-0.32	-0.33	-0.34	-0.35	-0.36	-0.37	-0.38	-0.39	-0.40
Operating expenses	**-1.24**	**-1.27**	**-1.31**	**-1.35**	**-1.39**	**-1.43**	**-1.48**	**-1.52**	**-1.57**	**-1.61**	**-1.66**	**-1.71**	**-1.76**	**-1.82**	**-1.87**	**-1.93**	**-1.99**	**-2.05**	**-2.11**	**-2.17**

Source: BofA Global Research

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AI power usage: training versus inference

A few quick definitions

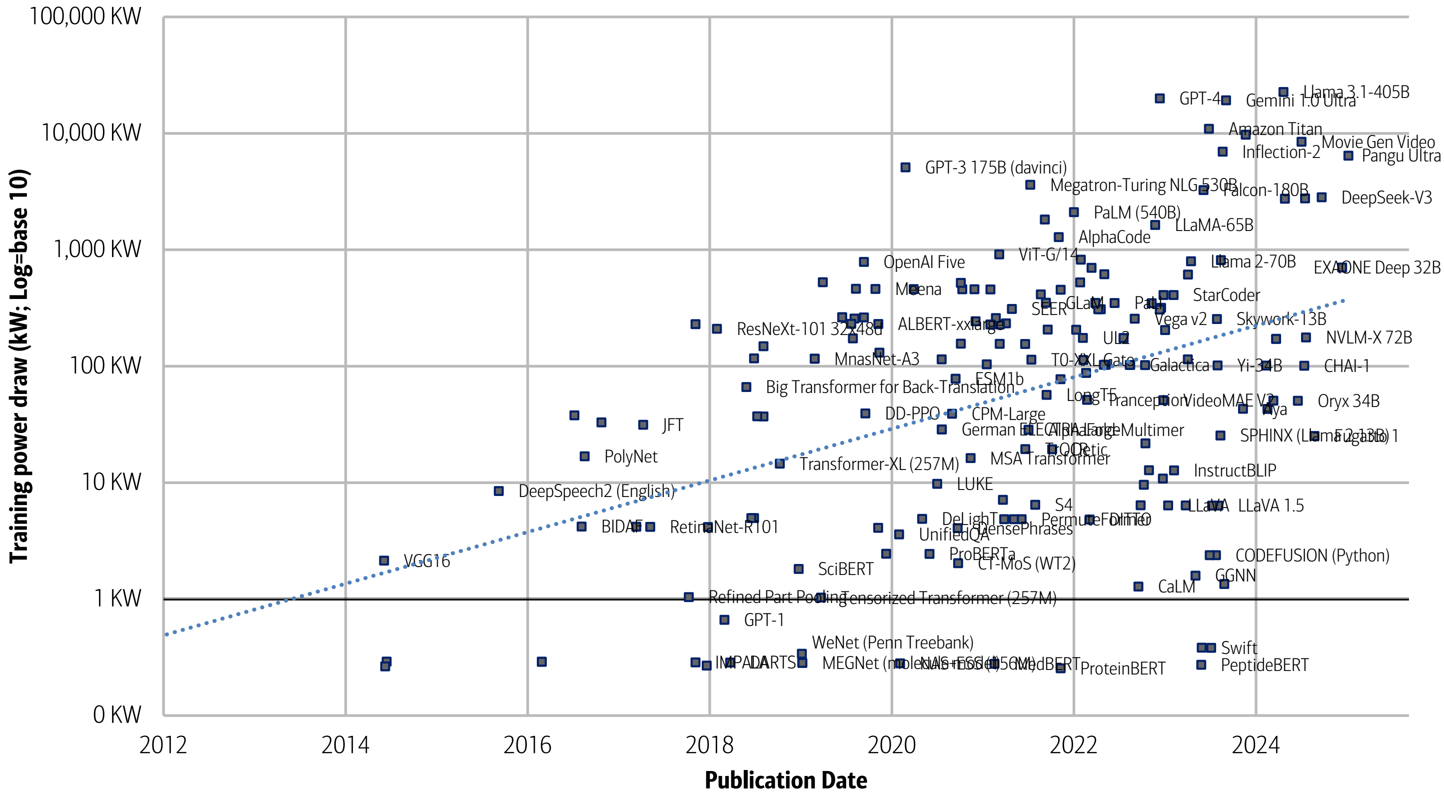
- **AI training:** an iterative process of teaching a code base to identify relationships from a data set so it can make accurate predictions. Training involves iteration over huge datasets with many GPU (graphic processing unit) nodes in parallel with a single large model training run consuming hundreds of MWh of energy. For example, OpenAI's GPT-3 (175bn parameters), reportedly used 1,287 MWh to train, while newer GPT-4 models required an estimated 50x more electricity to train. Furthermore, training often pushes hardware to peak utilization with GPUs at 90-100% utilization for days/weeks. However, once the model is trained, that particularly task is completed (though models are frequently retrained or fine-tuned), with frequency depending on R&D needs.

- **AI inference:** the use of a trained AI model to make predictions based on new data. Inference power requirements tend to be more distributed and continuous, with each inference using a relatively small amount of energy: a typical query on OpenAI's ChatGPT-4o consumes an estimated 0.3 watt hours (on par with energy usage of a Google search). However, similar to Google searches, inference serves millions (and up to billions) of queries, and the aggregate energy can rival or exceed training over time. Indeed, inference likely consumes far more energy than training over the lifetime of a mainstream model.

Training power draw continues to accelerate

Training power draw continues to rise despite advances in training techniques (e.g., reinforcement learning). Power draw is defined as the electricity used by a data center for servers simultaneously working on an individual model.

Exhibit 13: Estimated training power draw for AI models continue to increase over time
Exponential growth in peak power usage has continue despite advancements in training techniques



Source: Epoch AI (Creative Commons License); BofA Global Research

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Training has become longer and more costly. Training state-of-the-art models, such as Gemini's 1.0 Ultra (released in 2023) took around 100 days to train. In contrast, AlexNet in 2012 (which utilized GPUs) was trained in five or six days. This reflects increasingly large datasets despite increasingly advanced hardware. The training compute of notable AI models has been increasing exponentially, doubling roughly every five months and particularly in the last five years. Per Stanford AI, cutting edge AI models require colossal amounts of data, compute power, and financial resources.

Inference electricity demand to grow with usage

AI reasoning models use a "chain of thought" methodology that breaks the task into parts. This allows the model to do better on tasks related to logic, math, and pattern finding. However, it requires greater computational intensity during inference. According to an MIT Technology Review article published on Jan 31st, the DeepSeek reasoning model used 87% more energy than Meta's Llama 3, a model with the same number of parameters, for a similar inquiry, as it generates much longer responses. This is particularly relevant as compute is expected to shift more toward inference versus training over time. (O'Donnell, James. "*DeepSeek might not be such good news for energy after all.*")

Images & videos are even more energy intensive

Different inferencing tasks require different levels of computing power. An MIT Technology Review study suggests that video generation is by far the most intensive by a factor of ~1000x (versus a large text model).

MIT Technology Review measured energy used for inference for text generation using Meta's Llama models, which are open source. The smallest model in the cohort, Llama 3.1 8B, had 8 billion parameters (adjustable inputs in the model). The largest model, Llama 3.1 405B, had 405 billion parameters. Notably, DeepSeek has over 600 billion parameters. More parameters drive more energy per response. Prompts themselves also can drive higher energy needs, with more complicated requests driving more energy usage. According to Microsoft researchers in 2024, doubling the energy required by the GPUs running the model is roughly equivalent to the total operation's energy needs, including the cooling and the CPUs (central processing units) as well as other infrastructure.

Image generation models require a different architecture called diffusion, which transforms noise/words into images. The energy requirement is not dependent on the prompt, but rather by the size of the model, image resolution, and the number of steps the process takes, which can generate higher quality. Per MIT, image generation typically has fewer parameters than a large text model, which drives the lower energy usage.

MIT used a Chinese AI startup video model called CogVideoX to estimate video generation energy. This went from 109,000 joules (in the August 2024 model) for eight frames per second to 3.4mn joules in November 2024 for 16 frames per second for a five-second video. MIT notes that these are lower-quality videos with 16 frames per second are similar to silent-era (1920's) film quality, whereas closed-loop models such as OpenAI's Sora have much higher quality and therefore likely require more energy.

Exhibit 14: Inference tasks ranked by energy usage, 2025
Video Generation requires 1000x more energy than large scale text models

Inference	Joules per GPU	Total joules	W per hour
Text Model - Small	57	114	0.016
Image Generation - Small	1,141	2,282	0.317
Image Generation - Large	2,282	4,564	0.634
Text Model - Large	3,353	6,706	0.931
Video Generation	3,400,000	6,800,000	944.445

Source: MIT Technology Review, BofA Global Research

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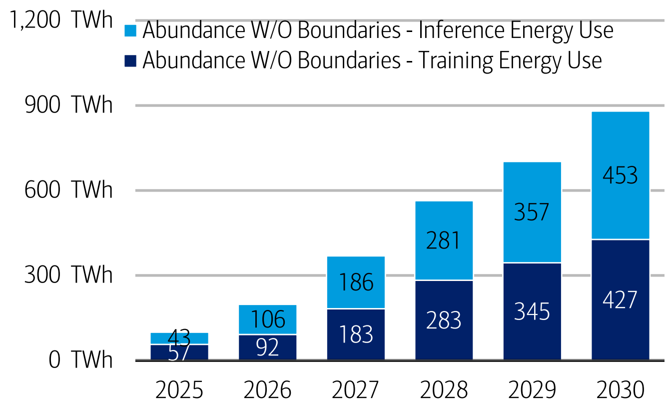
According to the Stanford 2025 AI Index report, inference energy efficiency has been improving at a 40% per annual rate and hardware costs have been declining (30)% annually. Despite this, Schneider forecasts that Generative AI inference will become the primary driver of AI electricity consumption within the AI sector by 2027-2028. This reflects increasing deployment of LLMs (Large Language Models, largely being integrated into industrial applications. As usage scales, this more than offsets any hardware efficiency gains.

Putting it together: training & inference energy needs

In Schneider Electric's Sustainable AI whitepaper from December 2024, the company outlines a series of scenarios, including Sustainable AI and "Abundance Without Boundaries." Abundance Without Boundaries assumes a "Jevons Paradox" scenario, which assumes rapid expansion of AI workloads and increased energy consumption despite some improvements in hardware efficiency and algorithmic optimization. The "Abundance Without Boundaries" scenario assumes energy demands for data centers are met and adoption increases. It assumes modest hardware efficiencies, with joules per GenAI token decreasing at a rate of 1% annually from 2025-2030, but offset by acceleration in adoption.

The Sustainable AI case study assumes slightly more modest adoptions (but still at a 20% CAGR for industry use cases and a 43% CAGR for consumer users) but with more rapid hardware efficiencies. Sustainable AI assumes that the joules per GenAI token decrease at a rate of 5% annually every year until 2030, but that acceleration in adoption more than offsets the improvement in inference. In this scenario, inference outgrows training even more given training is more likely to lend itself to efficiencies and adoption has a larger impact on the inference power demand. This blends to a total AI energy usage CAGR of 44%.

Exhibit 15: Abundance training vs. inference, TWh, 2025-2030
Schneider's abundance without boundaries scenario forecasts 54% AI CAGR



Source: Schneider Energy Whitepaper, BofA Global Research

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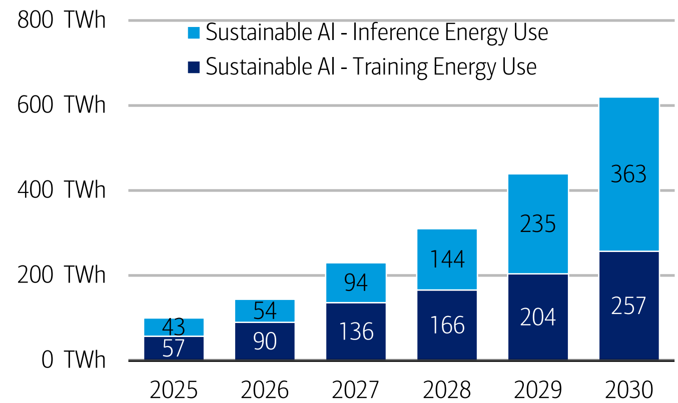
Exhibit 16: Sustainable AI training vs. inference, TWh, 2025-2030
Schneider's sustainable scenario forecasts 44% AI CAGR



Source: Schneider Energy Whitepaper, BofA Global Research

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Below we showcase key assumptions in each of the models made by Schneider for abundance without boundaries and sustainable AI.

Exhibit 17: Key input assumptions in "Abundance without borders" and Sustainable AI scenarios
Schneider assumes materially increased efficiency in the sustainable AI scenario

	2025-2030 CAGR	
	Sustainable AI	Abundance without boundaries
AI Growth	44.0%	54.5%
Training Growth	37.1%	54.0%
Inference Growth	72.1%	78.4%
Industry Users	20.1%	29.7%
Consumer Users	43.1%	49.6%
Joule per GenAI token	-4.7%	-1.0%
Tokens per GenAI Output	2.5%	4.1%
Joule per Output	-2.3%	3.0%

Source: Schneider Energy Whitepaper, BofA Global Research

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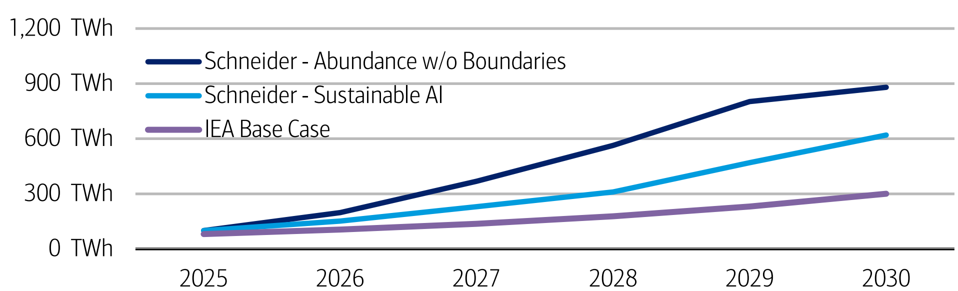
Below, we show the AI scenarios we discuss in this report. We note that Schneider's assumption for AI adoption, even in its Sustainable AI scenario, is more aggressive than the IEA (International Energy Agency) assumption.

Exhibit 18: Schneider versus IEA assumptions for energy usage, 2025-2030
Schneider vs. IEA demand, 2025-2030



Source: Schneider Energy Whitepaper, BofA Global Research

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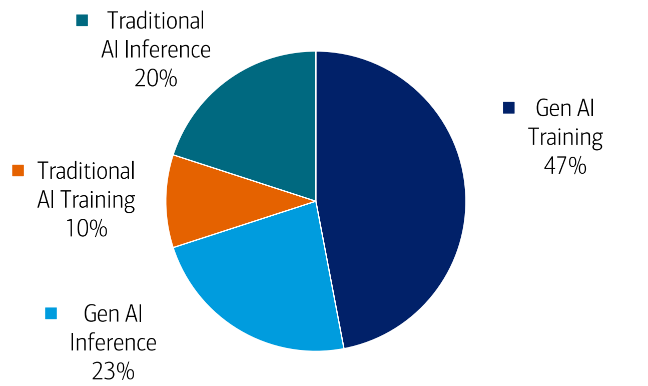
Generative AI inference is the key driver of growth

Below we show drivers of electricity usage for artificial intelligence applications in 2025 and 2030. We use Schneider's "Sustainable AI" scenario.

Exhibit 19: Split of AI energy usage, % of total TWh, 2025
Generative AI training is the largest AI data center use of energy in 2025



Source: Schneider Electric Whitepaper, BofA Global Research
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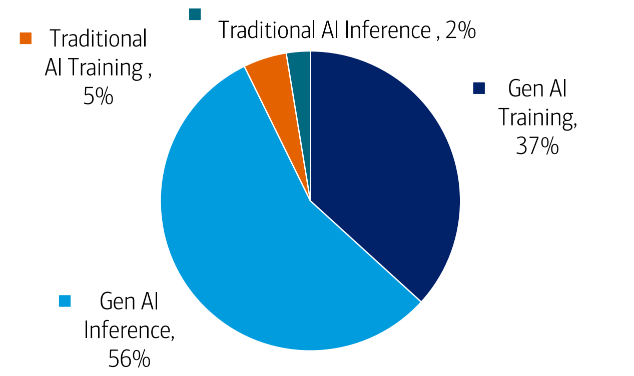
Exhibit 20: Split of AI energy usage, % of total TWh, 2030
Generative AI inference is the largest AI data center use of energy by 2030



Source: Schneider Electric Whitepaper, BofA Global Research
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What about efficiency gains in inference?

Per industry sources (e.g., April 2023 article *Trends in AI inference energy consumption: Beyond the performance-vs-parameter laws of deep learning - ScienceDirect*), efficiency for AI inference is improving. However, this largely reflects efficiency in scaled models rather than cutting edge models, which continue to increase in power usage. For cutting edge models, efficiency does not cancel out performance increases.

In Schneider's Sustainable AI scenario, which assumes rapid hardware efficiencies (e.g., a 5% CAGR for reduction in energy per GenAI output over 2025-2030), inference energy usage still grows at a 53% CAGR over this timeframe (vs. 60% in the abundance without boundaries scenario). This is a 7% reduction in the CAGR. The largest reduction in the CAGR is in training, which is forecast to go from a 50% CAGR to 35%. This reflects more hardware efficiencies reflected in training, with adoption driving more of an acceleration. Per Schneider: it's likely that a popular model (e.g., ChatGPT) requires many more times the quantity racks for inference than it did for training since their queries are now in the millions per day.

Schneider also notes that as data becomes scarce, a trade-off between data efficiency and energy efficiency may emerge, with more data-efficient models potentially requiring greater computational resources.

A selection of data center projects

Exhibit 21: We highlight the considerable AI-driven buildouts over the next several years across all regions
Multiple projects are above 1 GW

Entity	Cost	Size (sq ft)	Power (GW)	Tech Partners	Purpose	Project Notes
USA						
Meta - Richland (Louisiana)	$10bn	4 million	2 GW		Train large AI models (e.g. LLaMA)	Largest Meta data center; 9 building campus under construction through 2030. First phase expected online by 2028
OpenAI - "Stargate" (multi-site)	$500bn (planned over 4 years)	N/A	Multi-GW	Nvidia, Oracle, Arm, Microsoft	AI Infrastructure for model training	Initial $100bn deploying now in Texas. Aims to secure US AI leadership; multiple campuses planned
Google + Intersect Power		Industrial parks	GW-scale	Google custom (TPUs)	Hyperscale cloud & AI compute	Partnership to co-locate new data centers with dedicated clean energy generation. Multiple US sites with combined capacity of several GW to support Google's AI services. First phase operational by 2026
Middle East						
UAE-US AI Campus (Abu Dhabi)	Estimated 10s of $bns	10 sq mi campus	5 GW (1 GW first phase)	Various	Regional cloud & AI services hub	Joint project announced by UAE & US in 2025 to build a massive AI-focused data center campus in Abu Dhabi. Built by G42 (UAE) to host US hyperscalers. Aiming to serve roughly half the globe with low-latency AI workloads

Exhibit 21: We highlight the considerable AI-driven buildouts over the next several years across all regions
Multiple projects are above 1 GW

Entity	Cost	Size (sq ft)	Power (GW)	Tech Partners	Purpose	Project Notes
Saudi "HUMAIN" AI Factories		Multiple sites	0.5 GW	Nvidia	Sovereign AI infrastructure	PIF-backed initiative to make KSA a global AI leader. Plans to add 500 MW of AI data centers over 5 years using hundreds of thousands of NVDA GPUS
Malaysia (SE Asia)						
YTL Power - Kulai AI Campus	$4.3bn	1,640 acres	0.5 GW	Nvidia	Cloud + AI supercomputers	Malaysia's first large-scale AI data center park. First phase operational from mid-2024
AirTrunk JHB2 (Johor)	$3.5bn	N/A	0.27 GW		Hyperscale cloud + AI workloads	Second Johor campus by AirTrunk, will add additional 0.27 GW to 0.15 GW (JHB1) in Johor. Uses advanced liquid cooling for high density AI compute
STACK Johor Campus		1 million	0.22 GW		Hyperscale cloud & AI colocation	US-based STACK Infrastructure's entry to Malaysia with a 0.22 GW two facility campus targeting cloud and AI/ML customers. First 0.12 GW building slated for completion by 4Q 2026
Yondr Malaysia Campus			0.2 GW		Hyperscale cloud & AI colocation	UK-based Yondr Group announced plans in 2023 for a 0.2GW data center campus in Malaysia.
India						
Reliance Jio & Nvidia AI		Multiple DCs	2 GW	Nvidia	National AI cloud & model training	Announced Sep. 2023 to build India's own foundational models and infrastructure, aiming to serve 450 million Jio users and Indian researchers with AI capabilities
National Supercomputers	$800m	Various labs	0.01-0.02 GW each	AMD & Nvidia	Scientific HPC & AI research	India is deploying multiple petascale systems and planning an exascale system by late 2020s.
Europe						
France - UAE 1 GW AI Campus	€30-50bn	Multiple sites	1 GW		Sovereign cloud & AI R&D	Franco-Emirati venture to build a 1GW AI data center campus in France.
JUPITER (Germany)	€500m+		0.02 GW	Nvidia, SiPearl	Scientific supercomputing (exascale)	EUs first exascale computer, operational in 2025
Northern Europe AI Cloud (Norway)			0.1-0.15 GW	AMD, Nvidia	Cloud AI compute	Oracle is deploying 130,000 AMD MI300X GPUs (roughly >0.1GW) in Norway while CoreWeave is installing one of Europe's largest Nvidia GPU clusters at the same campus
EDF "Project Giga" (France)			3 GW		Power infrastructure for hyperscalers	Initiative by French utility EDF to supply low carbon power and land for three 1 GW-scale AI data centers in France.
Others (China/Global)						
Baidu "Kunlun" Cluster (China)		Beijing DCs	N/A		Train large Chinese AI models	In 2025, Baidu powered up a cluster with 30k of its 3rd gen Kunlun P800 AI chips (domestic GPU alternative), hosted across Baidu's data centers in China
"Eastern Data, Western Compute" (China)		¥79bn	>0.02 GW (by 2025), potentially up to tens of GW	Phytium, Huawei	National distributed computing network	Chinese gov't project launching large data center clusters in western provinces into process data from populous east. Targets 50 intelligent computing centers by 2025, expected to add tens of gigawatts of DC capacity by 2030
Global Cloud X (e.g. AWS, Azure)		Multi-region Campuses	0.1-0.3 GW each	AWS Trainium, Nvidia, AMD	AI-enabled cloud expansions	AWS, MSFT data center projects for new cloud zones across the globe

Source: BofA Global Research

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Case study: Stargate Texas

A Houston-based site developer (Lancium) initially acquired the 800-acre site in Taylor County in 2021. Local government was very supportive, with the city annexing the site and providing property tax incentives. Construction of power and natural gas infrastructure began in November 2022. The data center developer (Crusoe) broke ground on a 200-megawatt site in June 2024 after having signed a multi-year lease with OpenAI. Crusoe internal funds were augmented by a joint venture with Blue Owl Capital for a total of $3.4bn in project funding, suggesting an all-in cost of $17mn per megawatt.

Each building has four data halls, with each hall having up to 500 racks with 25 megawatts of load. In the initial configuration, the site would have two buildings yielding the 200-megawatts in total. The initial building was energized in 3Q25. Only in March 2025 was the expansion to the current 1.2-gigawatt size announced.

Given the size and scale, Crusoe did not select traditional diesel backup generators. Instead, Crusoe contracted for 29 units of GE Vernova's LM2500 aeroderivative gas turbines. At 35 megawatts each, Crusoe will have nearly 1 gigawatt of electric capacity. Startup time for backup power generation is critical for data centers. These turbines' design evolved from jet engines and can generate electricity in five minutes (versus ~2 hours ramp-up time for heavy-duty gas turbines operating in combined cycle format).

Key takeaways

Stargate's 1.2-gigawatt project benefited from (1) site development that started four years earlier including grid interconnections; (2) a build-to-suit project for an investment grade credit tenant with a signed lease; and (3) favorable local government support.

Case study: xAI Memphis

xAI repurposed an existing facility (a former Electrolux plant built 2013) in Memphis, which reduced the construction timeline. The contractor filed permits in April 2024. However, the local utility (Memphis Power & Light) could only provide 50 of the targeted 150 megawatts. To provide bridge power, xAI bought 35 portable gas turbines. These did not need to have permits for the first 365 days of operation. xAI used 3rd-party pre-built racks and the first phase (including 100,000 GPUs) was energized approximately three months later. xAI then contracted with a separate utility (Tennessee Valley Authority) for an additional 100 megawatts of grid interconnect.

Key takeaways

xAI was able to move so quickly due to (1) repurposing an existing site with grid interconnect; (2) using gas turbines for bridge power; and (3) a large natural gas distribution main being already connected to the site.

Case study: Stargate UAE

In May 2025, Pres. Trump announced an US-United Arab Emirates (UAE) AI Acceleration Partnership. OpenAI, in conjunction with UAE AI development firm G42, Oracle, Nvidia, Cisco, and Softbank, are building a 200-megawatt AI cluster outside of Abu Dhabi. The first phase of the project is expected to go live in 2026, with plans to expand to 1 gigawatt over time.

During the Biden administration, the UAE's access to AI chips had been restricted due to the AI Diffusion Framework.

Case study: Google demand response

Google has signed three demand response agreements with electric utilities in the US (Nebraska, Indiana, and Tennessee), Belgium, and Taiwan. Given its standardized network topology, Google has developed load-shifting software to shift compute among data centers. To be clear, these are non-urgent tasks (e.g., batch processing) and Google is not limiting or stopping compute on Google Cloud (e.g., cloud services).

Data centers use 1-2% of total electricity today…

Data centers consume approximately 1-2% of global electricity production. Estimates range from 240-340 terawatt hours (TWh) in 2022 according to the International Energy Agency to 409 TWh in 2023 according to a meta-analysis[1] of 46 forecasts and 499 TWh in 2023 per Schneider.[2]

In the US, Berkeley Lab estimated data center electricity usage at 176 TWh in 2023.[3] Using a separate methodology, McKinsey estimated it at 147 TWh in 2023.[4]

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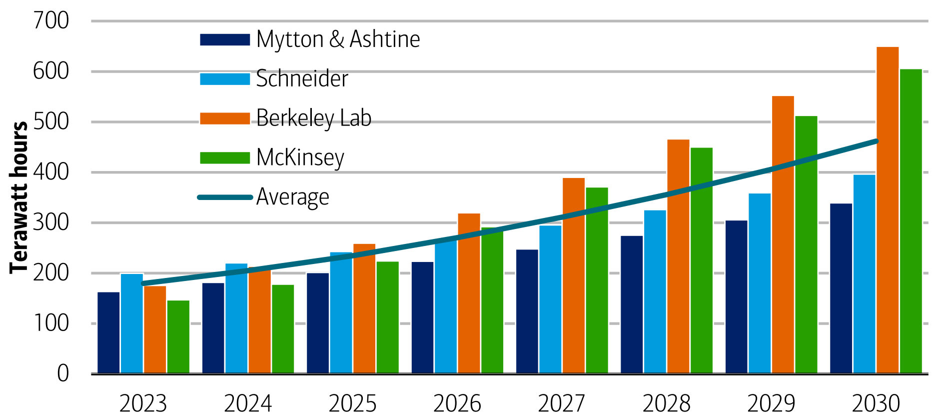
[1] Mytton, D., & Ashtine, M. (2022). *Sources of data center energy estimates: A comprehensive review*. Joule.
[2] Avelar, V., Donovan, P., Lin, P., Torell, W., Torres Arango, M. (2023). *The AI Disruption: Challenges and Guidance for Data Center Design*. White Paper 110.
[3] Shehabi, A., Smith, S.J., Hubbard, A., Newkirk, A., Lei, N., Siddik, M.A.B., Holecek, B., Koomey, J., Masanet, E., Sartor, D. 2024. *2024 United States Data Center Energy Usage Report*. Lawrence Berkeley National Laboratory, Berkeley, California.
[4] Green, A. Tai, H., Noffsinger, J., Sachdeva, P., Bhan, A., and Sharma, A. *How data centers and the energy sector can sate AI's hunger for power*.

…but likely to grow at a low- to mid-teens CAGR

Forecasting data center electricity consumption has been a prevalent topic among academics and industry research. Forecast methodologies range from bottom-up (e.g., equipment shipments), to top-down (e.g., data consumption), and extrapolation (e.g., energy intensity per chip). The median of 46 separate forecasts (Mytton & Ashtine) suggests data center energy usage will grow at an 11% CAGR through 2030 globally. We also show Schneider's Energy's global forecast.

US-specific forecasts are higher, given the bulk of AI-related deployments are occurring in the US. Berkeley Lab's forecasts US-specific data center loads to rise at a ~20% CAGR (2023-30; range: 15-23%). McKinsey's US-specific data center forecast is ~23% CAGR (2023-30).

Exhibit 22: US data center electrical demand (2023-2030)
Average of multiple forecasts suggests a low- to mid-teens CAGR



Source: Mytton & Ashtine, Schneider Energy Management Research Center, Berkeley Lab, McKinsey, BofA Global Research
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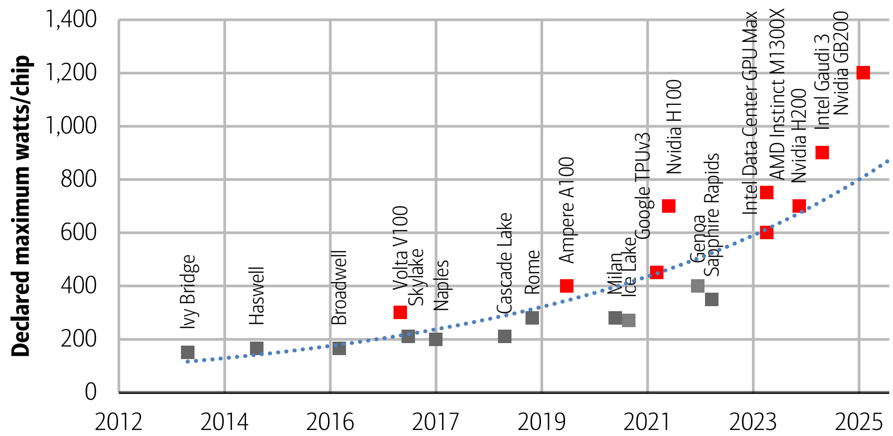
Evolution of chips and rack density

1. Rising watts per chip

The power consumption per chip has increased 4x from Nvidia's first-generation Volta architecture to the current Blackwell. Many of the ways to increase computing performance require additional power. Put simply, supply voltage cannot scale down proportionally with node sizes. Putting more transistors on each chip requires more power. In addition, power consumption rises linearly with faster clock speeds.

Exhibit 23: Watts per chip is growing with GB200 setting a new high
Nvidia's Blackwell chips draw 4x the watts versus first-generation Volta chips



Source: Dell Technologies, Uptime Institute
Note: Red dots are GPUs, Grey dots are CPUs

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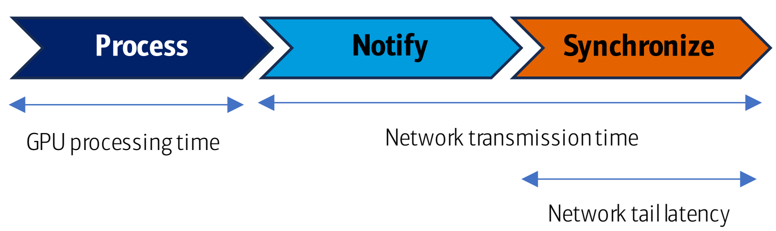
2. Massively parallel processing

GPUs perform calculations in parallel. When thousands of GPUs work together in an AI cluster, if even one GPU lacks the data it needs, all other GPUs stall. This means that network latency delays can reduce overall performance significantly. Putting more GPUs within a single rack reduces the need for networking and high-speed interconnects.

Exhibit 24: Parallel processing time for GPUs in AI model training
Network transmission time can eat up 30% of job completion time



Source: BofA Global Research

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These trends drive increased rack density…

In 2021, the average rack density was less than 10 kilowatts (kW) per rack. A reference Hopper rack (H200 chips) would draw 35kW. A reference Blackwell rack (B200 chips) would draw 120kW. Based on released statistics from Nvidia, we estimate a reference Rubin Ultra rack would reach 600kW in a single rack.

Exhibit 25: Nvidia chip release schedule and reference rack architecture
Rack-level power density is rising exponentially

Release	GPU	TDP per chip (watts)	Rack	GPUs/rack	kW per rack
		Hopper architecture			
1H22	H100	700	DGX	8	35
2H24	H200	700	DGX	8	35
		Blackwell architecture			
2H24	GB100	1,000	DGX	72	120
2H24	GB200	1,000	DGX	72	120
2H25	GB200 / NVL72	1,350	Oberon	72	162
		Rubin architecture			
2H26	Rubin	1,800	Oberon	144	300
2H27	Rubin Ultra	3,600	Kyber	144	600
		Feynman architecture			
2H28	Feynman	???	Kyber	???	???

Source: Company reports, BofA Global Research

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While we highlight Nvidia's roadmap, other chip firms are following a similar trajectory. Given the increasing importance of scale-up capabilities in AI data center, each major accelerator vendor is developing its own protocol. On 6/12, AMD (Advanced Micro Devices) announced a reference rack infrastructure for its Instinct MI350 GPUs. These racks feature up to 128 GPUs/rack, with each GPU drawing up to 1,400 watts, suggesting a 180+ kW rack density. AMD also announced its next generation Helios rack infrastructure, planned for release in 2026. This will feature 72 MI400 GPUs. In January 2025, Intel announced it was also developing a "system-level solution at rack scale" for its Gaudi data center accelerator chips.

All these firms are optimizing AI model performance across dimensions – chip-level, chip-to-chip bandwidth, and network throughput. This results in increased rack density, not as a goal, but as an outcome.

Exhibit 26: NVDA vs. AMD vs. AVGO Key Accelerator Specs and Scalability
NVDA's latest Blackwell generation scales up to 72 GPUs in a rack, AVGO's latest TPUv7 up to 256 TPUs. AMD's MI400 Series will scale up to 72 GPUs by 2H26

	NVIDIA					AMD			Broadcom	
	B200	**B300**	**R200**	**R300**	**F200**	**MI355X**	**MI400**	**MI500**	**TPUv6**	**TPUv7**
Architecture	Blackwell	Blackwell Ultra	Rubin	Rubin Ultra	Feynman	CDNA 4	CDNA Next	CDNA Next	Trillium	Ironwood
Process Node	TSMC 4NP	TSMC 4NP	TSMC N3P	TSMC N3P	2nm?	TSMC N3P	2nm?	2nm?		TSMC N3P
Scalability - Rack	72x (NVL72)	72x (NVL72)	72x (NVL144)	144x (NVL576)	TBD	8x	72x	256x	NA	256x
Scalability - Pod	128x	128x	TBD	TBD	TBD		TBD	TBD		36x
Scalability - Total	9,216x	9,216x								9,216x
Memory Interface	8S HBM3e 8H	8S HBM3e 12H	8S HBM4 12H	16S HBM4e 8H	HBM5?	8S HBM3e 12H	HBM4	HBM4e?	HBM	HBM
Memory Capacity	Up to 192 GB	Up to 288GB	Up to 288 GB	Up to 1,024 GB		Up to 288 GB	432 GB	TBD	32GB	192GB
TDP	1200W	1400W	1800W	3600W		1,400W				
Launch Time	4Q24	3Q25	2H26	2H27	2H28	3Q25	2H26	2H27	2Q24	2H25
Scale up	NVLink 5.0	NVLink 5.0	NVLink 6.0	NVLink 7.0	NVLink 8.0	IF	IF over Ethernet	UALink		ICI
Scale up switch	NVSwitch 4	NVSwitch 4	NVSwitch 6	NVSwitch 7	NVSwitch 8	PCIe	TH-6 102.4T	UASwitch		
Scale out (Ethernet)	Spec-5 51.2T	Spec-5 51.2T	Spec-6 102.4T	Spec-6 102.4T	Spec-7 204.8T		UEC	UEC	TH-5 51.2T	TH-6 102.4T
Scale out (IB)	Q-X800	Q-X800	Q-X1600	Q-X1600	Q-X3200	-	-	-	-	-
CPU (if paired)	Grace	Grace	Vera	Vera	Vera	Zen 5 (Turin)	Zen 6 (Venice)	Zen 7 (Verano)		
NIC	CX8 800G/s	CX8 800G/s	CX9 1.6T/s	CX9 1.6T/s	CX10 3.2T/s	Pollara 400	Vulcano	Vulcano		

Source: BofA Global Research

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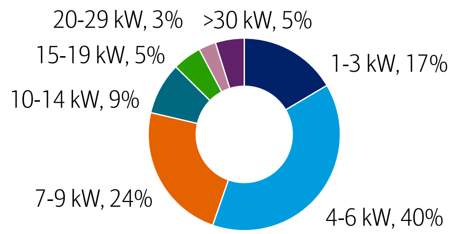
...which existing data centers are unprepared for

According to a 2024 Uptime Institute survey, only 5% of data centers have average rack densities greater than 30 kW. In other words, only 5% of data centers are designed to house even Hopper (H200) chips.

Exhibit 27: Global survey of over 700 data centers shows less than 5% are AI-ready
Only 5% of data centers have average rack density above 30 kW



Source: Uptime Institute

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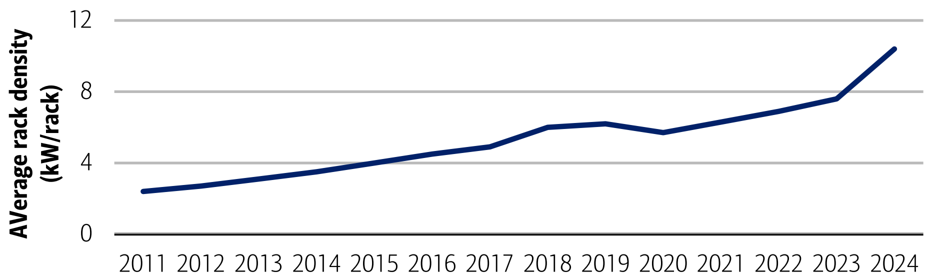
Looking at average rack density over time, there was a clear inflection upward in 2024 as AI data centers began to go live. With rack densities 5-10x higher, even a small number of AI data centers drives the overall survey average up.

Exhibit 28: Average kW per rack has risen from 2kW in 2011 to over 10kW in 2024
While rising, the rack density remains low



Source: Uptime Institute

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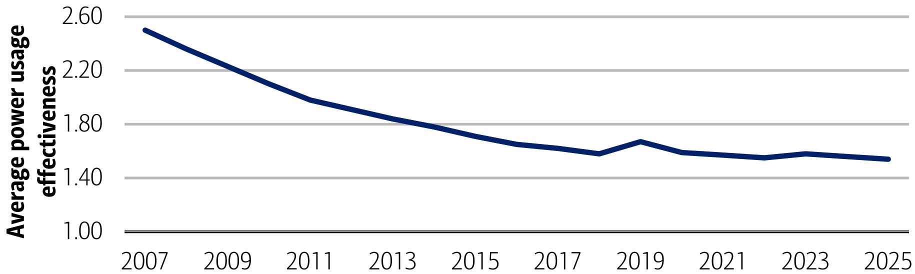
The Uptime Institute surveys data center operators annually on their facilities' average rack density. The average response has more than doubled since 2017, from less than 6kW in 2017 to ~12kW in 2023. According to JLL, the typical rack density among hyperscale facilities is ~36kW, and expected to continue to rise. Hyperscalers are contributing more to the square footage pipeline at likely above-average rack densities.

Energy efficiency curves for data centers

Power usage effectiveness (PUE) measures the total electricity used by the data center divided by the electricity used by IT equipment. 2025's average PUE of 1.54 means that cooling, electrical, lighting, and other devices used 54% of the electricity going to IT equipment. By definition, the lowest PUE is 1.00 (all electricity goes to IT equipment).

Average PUE has declined since 2007, but has remained in the 1.5-1.6 range since 2016. Among cloud providers, Google has the lowest fleet-wide PUE at 1.10 in 2024. This shows that there is considerable room for improvement.

Exhibit 29: Power usage effectiveness has fallen since 2007, but has remained 1.5-1.6 since 2016
Power usage effectiveness was 1.54 in 2025 compared to 1.65 in 2016



Source: Uptime Institute

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EU regulations: reporting is step one

In September 2023, the European Union passed the Energy Efficiency Directive. The first (mandatory) data reporting was September 15, 2024. It is due annually by May 15th thereafter. Required data includes floor area, installed power, network traffic, electricity consumption, temperature set points for cooling, and wager usage.

In June 2025, the EU's Commissioner for Energy and Housing announced plans for further data center energy regulation by March 2026. While details have yet to be announced, regulations will aim at increasing energy efficiency.

Rack architecture evolution

NVL72 increases infrastructure content per MW

The first liquid-cooled server was introduced by IBM (the IBM System/360 Mainframe) in 1964. However, advances in semiconductor design (i.e., complementary metal-oxide semiconductors) enabled a step-function reduction in the required electricity current for chips. The last widespread commercial liquid-cooled design was 1995. Since then, air-cooled server designs in open racks have dominated data centers.

Nvidia's NVL72 rack design was announced in March 2024. It consists of 36 Grace CPUs and 72 B100 GPUs, all liquid cooled. To reduce network transmission lag, engineers brought more GPUs into the rack, connecting them with Nvidia's proprietary NVLink, which offers up to 130 terabytes per second of bandwidth. Increased power density is an outcome (not a goal) of reducing latency. To compensate for the increased power density, Nvidia's engineers opted for liquid cooling.

The NVL72 also has innovation in power delivery. Rather than use rack PDUs (power distribution unit), the NVL72 uses a 1,400-amp busbar to deliver electricity to servers. Included in each rack are eight power shelves (similar to rack PDUs, but controlling the busbar).

We compare electrical and thermal content per megawatt in the NVL72 relative to Nvidia's prior DGX SuperPOD air-cooled architecture, we find four differences:

- **CDU:** Most obviously, the NVL72 requires a coolant distribution unit (CDU) to drive its liquid cooling system.

- **Lower air-cooling content:** We estimate a one-third reduction in the number of computer room air handlers (CRAHs) as a result of the heat captured by the cold plate and liquid cooling system.

- **More power shelves:** Nvidia's reference architecture for the DGX SuperPOD has three power shelves per rack, while the NVL72 has eight. Even with the lower number of racks per megawatt in the NVL72 configuration, it still requires more power selves.

- **UPS for CDUs.** Given the importance of the CDUs, they will need to have a separate back-up uninterruptible supply systems (UPS).

On balance, we estimate the NVL72 architecture increases content/MW for both the electrical (+7%) and thermal (+18%) equipment relative to the DGX "SuperPOD" configuration. The overall infrastructure content/MW rises to $3.1mn from $2.8mn.

Exhibit 30: We find the costs per megawatt of the NVL72 rack (including liquid-cooled 72 GPUs) is ~12% higher versus the HGX rack (including 32 air-cooled GPUs)
The NVL72 architecture would have fewer racks per megawatt, but increased content per rack for electrical and thermal equipment manufacturers

	HGX	**NVL72**	
# of GPUs (B200s)	32	72	
# of CPUs	8	36	
kW/rack	66	142	
Implied racks/MW	15.2	7.0	
($ per MW)	**HGX**	**NVL72**	**% ch.**
rPDUs / Power shelves	200,000	246,400	
UPS for CDUs	0	100,000	
Other electrical	1,500,000	1,500,000	
Electrical sub-total	**1,700,000**	**1,846,400**	**9%**
CDU	0	400,000	
CRAHs	600,000	400,000	
Other cooling	500,000	500,000	
Cooling sub-total	**1,100,000**	**1,300,000**	**18%**
Infrastructure total	**2,800,000**	**3,146,400**	**12%**

Source: BofA Global Research

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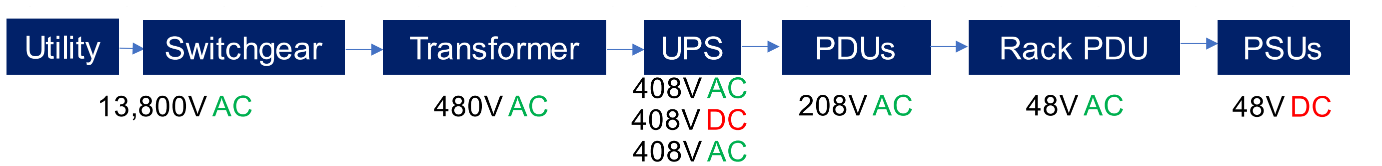
The existing power distribution architecture

Typically, data centers receive three-phase alternating current (AC) electricity at 13,800 volts or 34,500 volts. Over a series of transformer, switchgear, power distribution units, busways, and uninterruptible power supplies (UPS), this electricity is stepped down and converted to 48-volt direct current (DC) which powers IT servers and other equipment.

The example below shows a double-conversion UPS. Incoming AC power is converted to DC power to charge the batteries. Then an inverter converts the DC power back to AC for further distribution. These double-conversion UPS are considered the best solution given it is always "on" and offers power conditioning features (e.g., manage over/under voltage, decrease frequency variation).

Exhibit 31: Traditional power distribution takes AC electricity, converts to DC for UPS batteries, then back to AC for distribution to the rack
Voltage is stepped down from 13,800 volts to 48 volts over several intermediate steps



Source: BofA Global Research
UPS: Uninterruptible Power Supply. PDU: Power Distribution Units. Rack PDU: offers plugs for IT and networking equipment to plug into. PSUs: Power Supply Units which take AC power and convert it to DC for IT equipment.

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Raising the voltage to save on wiring

As GPUs for AI applications have increasingly higher computational needs and demand more electricity, existing power distribution systems will struggle to cope. Large data center operators are proposing changes to existing power distribution systems.

In October 2024, Microsoft and Meta, as part of the Open Compute Project, announced a reference rack architecture called Mt. Diablo. This uses 400-volt direct current (DC), which is significantly higher than the current 48-volt.

On 5/28, Nvidia announced that it would develop a new power infrastructure with an 800-volt direct current (DC) architecture to deliver power requirements of 1+ megawatt server racks. The company has plans to deploy it by 2027.

Exhibit 32: Nvidia's proposed 800-volt direct current architecture eliminates PDUs and replaces rack PDUs with an electrical sidecar
AC electricity is only converted to DC once through pathway to the rack

Source: BofA Global Research
UPS: Uninterruptible Power Supply.

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Electrical power (measured in watts) can be broken down into voltage (measured in volts) and current (measured in amps). The carrying capacity for wiring is determined by the current (amps). Thus, higher voltage can carry more electrical power using the same diameter wire. This reduces the amount of copper needed within the rack. Compared to a 208-volt system, a 400-volt system would reduce the copper wire weight by 52% per Schneider Electric.

The Mt. Diablo/Open Compute Project proposal would allow equipment to be installed by electricians with low voltage certifications (e.g., less than 600 volts). Nvidia's proposal would require installation by electricians with medium voltage certification, which would limit the potential workforce of installers.

How will UPS architecture change

There are four main parts of a UPS: (1) a rectifier to convert AC to DC, which powers the battery; (2) the battery; (3) inverter to convert DC electricity back to AC; and (4) the static bypass switch, which allows power to continue to flow even if the UPS itself fails. In the high voltage direct example, the UPS no longer needs an inverter to convert the DC electricity back to AC. The UPS continues to need a rectifier, battery, and static bypass switch.

This is not the first time that DC architecture has been tried in data centers. In 2011, ABB acquired a majority stake in DC power distribution firm Validus DC. They built several DC-based data centers globally. The absent of standards and equipment meant that the initial cost to deploy was much higher.

Direct current does not have a frequency (no variation) and therefore no harmonics. However, they can still have variation in output power and current. In theory, a DC UPS system should cost 10-20% less than an AC UPS. However, the higher voltage requires more expensive safety equipment versus lower voltage. Net-net, we do not expect high voltage DC UPS pricing to be lower than current AC UPS, particularly in the early years with limited capacity.

From an operators' perspective, the main benefit of an 800-volt direct current (800V DC) UPS versus the 208-volt alternating current (208V AC) UPS is a slight uptick in power efficiency. According to Schneider, by removing the AC-to-DC conversion and DC-to-AC reconversion and increasing the voltage can reduce to total electricity consumption of a data center by ~1%. This would be an annual savings of ~$7,000 per megawatt (assuming 100% utilization an $0.08 per kilowatt cost).

Moving power equipment outside the rack to save space

Power supply units (PSUs), which convert AC to DC, take up valuable space within the rack. At higher voltage, these will take up even more space. This is why Nvidia and the Open Compute Project are proposing moving electrical equipment to a "side car" next to the rack containing servers.

Exhibit 33: Oberon rack
Servers placed horizontally; power equipment located within the rack

Source: Company presentations

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Exhibit 34: Kyber rack
Servers placed vertically, power equipment located in a side car next to the rack

Source: Company presentations

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Exhibit 35: Mt. Diablo rack
Power equipment located in a side car next to the rack

Source: Open Compute Project

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Details on the increase in Rubin Ultra infrastructure

Nvidia's Rubin Ultra GPU and its NVL576 Kyber racks were initially unveiled as a mockup in March 2025. Rubin Ultra will follow Rubin and Blackwell chips. The Rubin Ultra is intended to ship in 2H27. The current Blackwell B200 server racks can use up to ~120kW per rack. The first Vera Rubin rack, to launch in the 2H26 (the name for the combination of the Vera CPU and Rubin GPU) will use the same infrastructure as Grace Blackwell (the Grace CPU and Blackwell GPU combination).

However, the next iteration of Rubin – Rubin Ultra – will have 2x the number of GPUs per rack. The single rack solution, dubbed Kyber, will be able to handle 600kW. Each rack will consist of four "pods" with 18 blades in each pod.

Early thoughts on Kyber rack

The Kyber rack (and 800V direct current architecture) will require several changes. First, the power shelves would come out of the rack and go into a power side car. The floor power distribution units (PDUs) would be eliminated. We assume that direct current UPS pricing would be similar to current alternating current pricing.

Nvidia's mockup included one power sidecar, one CDU, and one networking/storage rack for each server rack. This likely increases the CDU costs per MW, as a dedicated CDU is needed for each rack. However, according to press articles with Nvidia executives, the Kyber rack is intended to be "100% liquid cooled." This implies custom cold plates than could cover the entire server blade (not just GPUs/CPUs), reducing the amount of air-cooling content. Net-net, we expect electrical and thermal content/MW to be above the current DGX SuperPOD configuration, but similar to the NVL72.

Exhibit 36: We expect roughly similar content per megawatt for Kyber rack as current NVL72 rack
The Kyber rack architecture remains uncertain

	DGX	NVL72		Kyber	
# of GPUs (B200s)	32	72		144	
# of CPUs	8	36		36	
kW/rack	66	142		600	
Implied racks/MW	15.2	7.0		1.7	
($ per MW)	**DGX**	**NVL72**	**% vs. DGX**	**Kyber**	**% vs. DGX**
Power shelves	200,000	246,400		492,800	
UPS for CDUs	0	100,000		100,000	
Floor PDUs	200,000	200,000		0	
Other electrical	1,300,000	1,300,000		1,300,000	
Electrical sub-total	**1,700,000**	**1,846,400**	**9%**	**1,892,800**	**11%**
CDUs	0	400,000		600,000	
CRAHs	600,000	400,000		200,000	
Other cooling	500,000	500,000		500,000	
Cooling sub-total	**1,100,000**	**1,300,000**	**18%**	**1,300,000**	**18%**
Infrastructure total	**2,800,000**	**3,146,400**	**12%**	**3,192,800**	**14%**

Source: BofA Global Research

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ASICs chips following similar infrastructure evolution

Application-Specific Integrated Circuit (ASIC) semiconductors are customized for a particular use. ASIC chips can be designed to lower electricity requirements for certain tasks relative to more general-purpose chips, such as CPUs. However, we see strong evidence that ASICs chips are following a similar infrastructure development path as GPUs.

The largest buyers of ASICs for data centers are cloud services firms, including Amazon Web Services, Microsoft Azure, and Google Cloud. All three of these firms have introduced liquid-cooling architectures (in chronological order):

- **Google Cloud** is now on its sixth generation Tensor Processing Unit (TPU), which is an ASIC chip for AI applications. Despite the potential for lower electricity draw, Google Cloud has been using liquid cooling for TPUs since 2019, according to press reports.

- In 2024, **Microsoft Azure** announced its AI-specific ASICs chip (Maia 100) would use a liquid-cooled system.

- **Amazon Web Services** is introducing its third generation Trainium chips in 2026. These are ASICs chips for AI applications. Amazon Web Services VP of Infrastructure Prasad Kalyanaraman has stated that Trainium3 chips would require liquid cooling. Here again, despite the potential for lower electricity usage, these ASICs chips are moving to a liquid cooled architecture.

Implications for incumbent equipment vendors

Given Eaton, Vertiv, nVent, and other IT infrastructure companies specifically manufacture on/around the rack, this has raised investor questions on whether this will disrupt market share. We argue the data center industry prioritizes uptime/reliability, which historically has benefited incumbents. Service capabilities are another barrier to entry, particularly for operators adopting new equipment.

When NVIDIA announced its 800-volt direct current architecture, it listed three of the largest incumbents as partners for the development of the power system. Vertiv (May 2025) and Eaton (July 2025) have both announced plans to release compatible products.

Exhibit 37: List of NVIDIA partners in development of 800-volt direct current architecture
Eaton, Schneider, and Vertiv are listed as the only partners for data center power systems

Silicon providers			
Analog Devices	MPS	Renesas	Texas Instruments
Infineon	Navitas	ROHM	
Innoscience	OnSemi	STMicroelectronics	
Power system components			
Delta	Lead Wealth	LiteOn	Megmeet
Flex Power			
Data center power systems			
Eaton	Schneider Electric	Vertiv	

Source: NVIDIA

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However, the proposed direct current architecture would result in simplified uninterruptible power supplies (UPS). The hypothetical cost of a direct current UPS is 10-20% lower than an alternating current UPS. However, we see this being largely offset by additional costs for higher-voltage switchgear and rectifiers (AC to DC convertors). Net-net, industry participants expect content per megawatt for electrical equipment to remain relatively similar.

Overview of data center thermal systems

Key components

- **Computer room air conditioners (CRACs):** used in small data centers, these are full air conditioning units located inside the data hall. They are tied to a condenser located outside of the building. CRACs have small cooling capacities.

- **Computer room air handlers (CRAHs):** used in larger data centers. These blow air over a coil with chilled facility water to lower the temperature inside the data hall. They are connected to a chiller. Often used in data centers with raised floors, where cold air is blown under the IT equipment and hot air rises to the top of the data hall.

- **Fan walls:** A type of high-capacity CRAH. Large fans blow air over chilled water in coils. Designed to lower air temperatures by 15-25 degrees (with water temperatures rising 15-25 degrees). Often used in data centers without raised floors.

- **Chillers.** A high-capacity refrigeration unit that removes heat from facility water for distribution inside the building. Heat is absorbed from the facility water into the chilled coolant through the evaporator heat exchanger. The coolant is then run through a compressor, increasing the pressure and temperature. The condenser heat exchanger transfers the heat to either outside air or water. Finally, the refrigerant runs through an expansion value, lowering the pressure and temperature before going into the evaporator heat exchanger. There are two varieties:

    - **Air-cooled chillers** are typically located outside the building. The condenser transfers heat to the outside air.

    - **Water-cooled chillers** are typically located inside the building (mechanical space). It uses a liquid-to-liquid heat exchanger to transfer heat to a dedicated cooling loop. That loop is connected to a cooling tower outside the building.

- **Cooling towers.** Heat rejection equipment that dissipates heat into the outside air. Cooling towers are giant heat exchangers used to reject heat created by IT equipment inside the data hall. Cooling towers take condenser water (hot) water and cool it using outside air. They come in two varieties.

  - **Wet cooling towers** use water evaporation to create additional cooling capacity. However, this consumes a large amount of water (e.g., “open circuit”). Wet cooling towers are efficient in hot and dry regions; however, the costs are higher for the equipment and installation and the water consumption.

  - **Dry cooling towers** are closed-circuit (e.g., no water loss) towers were there is no direct contact between the ambient air and the fluid being cooled. Facility water transfers to the air through radiators. Dry towers have lower initial maintenance costs and can work in most climate conditions; however, there is a lower capacity and can’t cool below a certain temperature.

- **Compressors:** equipment that increases refrigerant pressure by reducing the volume. Compressors are the most critical part of the chiller and largely determine its capacity, efficiency, and power usage. There are many different types of compressors, but the largest chillers tend to use centrifugal compressors. These compressors pull refrigerant using centrifugal force and compress it using an impeller. They are more energy efficient, particularly in large capacity applications.

- **Coolant Distribution Units (CDUs):** circulates and pumps coolant in a closed-loop system to row manifolds, rack manifolds, and through either cold plates or rear door heat exchangers. The coolant (typically a water-glycol mix) returns to the CDU where it runs through a heat exchanger. The heat is there transferred either to air (“liquid-to-air CDU”), or facility water/dedicated cooling loop (“liquid-to-liquid CDU”) for heat rejection. CDUs will typically come with two pumps, offering redundancy around mechanical failure. CDUs will also have sensors to monitor and control temperature, pressure, and flow rate. CDUs come in two forms:

  - **In-rack CDUs:** small scale CDUs that fit within a single rack and pump coolant through rack manifolds. By design, they have limited capacity.

  - **In-row CDUs:** larger format CDUs that sit outside of the rack and typically serve multiple racks.

- **Liquid cold plate:** a metal block specifically designed to sit on top of a chip with microchannels for coolant to flow through the chip. The liquid cold plate facilitates heat exchange from the semiconductor into the cooling fluid.

- **Quick disconnectors:** couplings with zero leaking of coolant. Used to connect the liquid cold plates to the rack manifold and to connect the rack with the row manifold. Quick disconnectors in data center applications typically have a latch to secure the connection.

Chillers

Exhibit 38: Example of water-cooled centrifugal chiller
Chills facility water to circulate to computer room air handlers

Source: Company website

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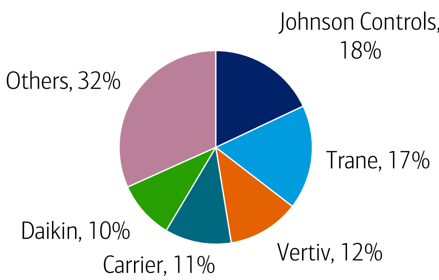
Every one megawatt of power supplied to a data center requires approximately 285 tons of cooling, similar to the requirements for a 115,000 square foot commercial building. A 285-ton chiller is roughly $300-400,000. Based on the 9 GW of data center capacity added in 2024, we estimate a $3.1-3.5bn market size.

Exhibit 39: Estimated data center chiller market share
We estimate JCI is the market leader



Source: BofA Global Research, company filings

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Cooling towers

We estimate cooling towers costs ~$300,000 on average, but these costs vary with size. A single cooling tower can provide heat rejection for 3-4 MW of supplied electrical power (e.g., 1,000 tons of cooling). We estimate that the cooling tower market for data centers was $0.7-0.9bn in 2024.

Exhibit 40: Example of cooling tower
This tower is 32 feet high with a cooling capacity of 2,400 tons

Source: Company website

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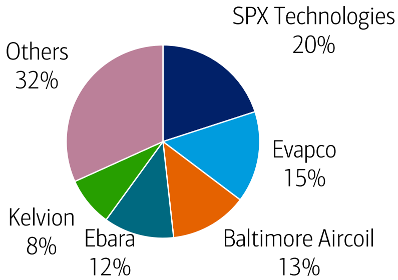
Wet vs dry cooling towers is something to be considered for data centers. Wet cooling towers are open-circuit cooling towers where water comes in contact with the ambient air. Dry cooling towers are closed circuit cooling towers were there is no direct contact between the ambient air and the fluid being cooled. Wet cooling towers are reliable in hot ambient temperatures and have high cooling capacity; however, the costs are higher for the equipment and installation and the water consumption. Dry towers have lower initial maintenance costs and can work in most climate conditions; however, there is a lower capacity and can't cool below a certain temperature.

Exhibit 41: Estimated data center cooling tower market share
We estimate SPX is the market leader



Source: BofA Global Research, company filings

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Computer room air handling units & other

Computer room air handling units (CRAHs) use chilled facility water and blow air over a radiator. CRAHs are a major part of the thermal equipment located in the "white space" of a data center (i.e., where IT equipment is located). Other equipment includes aisle containment systems, in-rack cooling fans, and related sensors & controls.

Exhibit 42: Computer room air handling unit
CRAHs are typically located around the walls of the data hall

Source: Company filing

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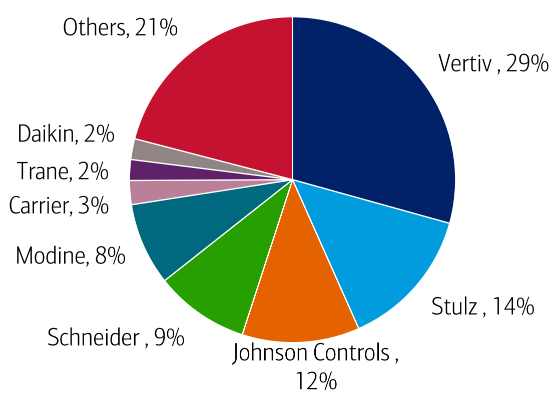
We estimate the CRAHs and related equipment is a $5-6bn market. A portion of this total market is driven by replacement demand. The market for new construction is likely $4-5bn.

In 2021 Johnson Controls acquired Silent-Aire, a manufacturer of CRAHs and other equipment with $0.7bn in revenue. Other large HVAC manufacturers, such as Carrier, Trane, and Daikin also make CRAHs.

Exhibit 43: Estimated data center CRAH & related equipment market share
We estimate Vertiv is the market leader



Source: BofA Global Research, company filings

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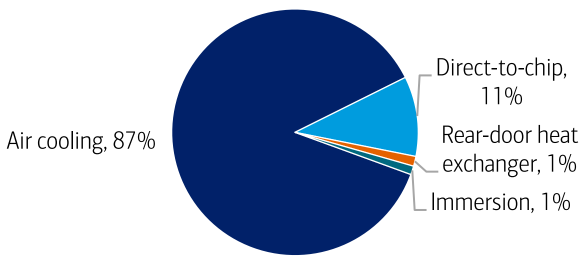
A deeper dive into CDUs

Breaking down the cooling market

Traditionally, racks are cooled with air. Liquid cooling includes direct-to-chip applications (~11% of the market), immersion cooling (~1%), and rear-door heat exchangers (1%).

Importantly, liquid cooling is additive to existing air-cooling equipment. While liquid cooling is transferring heat from the chip itself, other IT equipment and power equipment still needs to be air cooled.

Exhibit 44: Thermal management by method, 2024
Air cooling remains dominant part of broader $10bn data center thermal market



Source: BofA Global Research

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Direct-to-chip emerging as preferred choice for industry

Historically, liquid cooling was used largely for high-performance computing applications. Rising rack density is driving increased interest in adoption of liquid cooling. Under the absolute right containment and right cooling, air-cooling would reach its maximum cooling limit at 60-70kW per rack. We note this would be the maximum, not the average.

Direct-to-chip cooling has been the leading alternative cooling method. Liquid cooling solutions can be retrofit into the existing infrastructure with relatively little disruption.

We think liquid cooling demand among colocation companies is more likely to accelerate versus decelerate, as AI chip availability broadens out. Absent a "pause" by cloud service providers on AI build outs, we think demand for CDUs will remain strong.

Exhibit 45: In-row or floor-mounted CDUs
Positioned at the end of a row and serving multiple racks

Source: Company presentation

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Exhibit 46: In-rack CDU
Mounted inside the rack and serving one rack

Source: Company presses release

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Existing racks can be retrofit for liquid cooling by adding cold plates and connecting to the plates with couplings and tubing. Heat is transferred from the chip to the cold plate and into the fluid, which is then circulated back to a cooling distribution unit (CDU). Most liquid cooling systems use two cooling loops: a primary cooling loop (also known as an external loop) and secondary cooling loop (also known as an internal loop). A CDU is used to thermally couple the external and internal loops. Heat is transferred from the internal loop to the external loop within the CDU. The CDU external loop connects to the data center infrastructure. The CDU internal loop connects to the piping and manifolds

Exhibit 47: Different cooling mechanisms and max capacity
D2C cooling can handle >110kW per rack, according to Data Center Dynamics sources

	Air Cooling	D2C		Immersion	
		Single Phase	Two Phase	Single Phase	Two Phase
Max per rack	60-70kW	110+kW	> single phase	150-170kW	> single phase
Method	Air, fans	Cold plate, propylene-glycol, refrigerant		Freezer chest, dielectric fluid	Dielectric fluid (PFAS)

Source: Data Center Dynamics, BofA Global Research

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Rear-door heat exchangers

Rear-door heat exchangers help manage densities from 20kW to ~75kW. The technologies do not bring liquid directly to the server, but the infrastructure is similar to direct liquid cooling. Passive or active heat exchangers replace the rear door of the IT equipment rack with a liquid heat exchanger. Passive heat exchangers use server fans that remove heated air through a liquid-filled coil in the rear door of the rack. The coil then absorbs the heat before the air goes into the data center. Active heat exchangers also have fans that pull air through the coils.

Exhibit 48: Active rear-door heat exchanger
Positioned at the back of a rack with chilled water and fans

Source: Company presentation

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Exhibit 49: Immersion cooling tank
Servers are placed inside and surrounded by cooling fluid

Source: Company presentation

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What's in liquid cooling?

A liquid cooling system includes:

- A CDU, which isolates a fluid loop from the rest of the cooling system. This is typically a single enclosure with all parts integrated within it. A CDU provides temperature control, flow control, pressure control, fluid treatment, and heat exchange and isolation. The CDU takes the heat from the fluid loop and exchanges it out of the system. It also must isolate the fluid in the loop from the rest of the cooling system.
- A redundant pump system (e.g., one more pump than needed) with filtration for the cooling fluid.
- A heat exchanger, responsible for passing the heat to a secondary cooling loop.
- A controller, with autonomically and autonomously will control the pump system and gather information from different sensors.

Immersion cooling

Single-phase cooling immersion cooling uses a pump to circulate coolant around immersed server racks. In two-phase cooling, server heat turns the coolant into vapor, which then rises, condenses through coils, and returns. Both methods result in better power usage effectiveness (PUE) ratios.

Technically, there is ~2 GW of capacity using immersion cooling, but the majority relates to crypto mining versus cloud, colocation, or enterprise data centers. One major barrier to adoption is that immersion cooling voids the chip OEM (original equipment manufacturer) warranty. Another barrier is the immersion fluid itself. Immersion cooling involves chemistry with Per- and polyfluoroalkyl substances (PFAS). 3M (MMM) announced it would exit production of its ~$1.6bn in sales PFAS manufacturing back in December 2022, with official phaseout by the end of 2025. While Illinois Tool Works (ITW) and others offers alternatives to Novec fluid, we still see some reluctance from data center operators to adopt immersion.

Pros and Cons Part I: Liquid-to-air or liquid-to-liquid?

There are three main ways to reject heat from a server. Below we show the differences between existing heat rejection systems and dedicated heat rejection systems. The reject heat-to-air in IT space (closed loop heat rejection) utilizes a liquid-to-air CDU. The other two formats of heat rejection utilize liquid-to-liquid CDUs. The most energy efficient heat rejection system would be rejecting heat to an independent water system, which makes the most sense for large-scale AI server deployments. The closed loop heat rejection is costly for large scale deployments, but the investment is much smaller and the time to deployment is shorter.

Exhibit 50: Existing heat rejection systems vs. dedicated heat rejection systems

Below we overview the different kinds of cooling

	Existing heat rejection system		Dedicated heat rejection system
What is it:	**Reject heat to air in IT space**	**Reject heat to facility water systems**	**Reject heat to independent water systems**
Description:	The liquid loop is a self-contained system within the IT space. The heat in the IT room is eventually rejected to the outdoors by the existing air-cooling infrastructure.	The IT fluid loop is an isolated loop fed off a chilled or condenser water loop. The server heat is transferred from the IT fluid loop to the facility loop via the CDU heat exchanger. The heat is then rejected outdoors or reused for other purposes.	Liquid-to-liquid CDU optimizes temperature and flow of the IT fluid loop and heat rejection loops without constraints imposed by shared air-cooled heat rejection system. A dry cooler provides water for liquid-cooling, while a free-cooling chiller provides low-chilled water temperature for air cooling.
CDU type:	Liquid-to-air	Liquid-to-liquid	Liquid-to-liquid
Cost:	Costly for large-scale deployments	Better for mid to large-sized deployments for data centers with chiller plants	More efficient for significant liquid-cooled server deployments
Time to deployment:	No chilled or condenser water necessary, uses existing heat rejection system	Uses existing heat rejection system , but needs site installation work (CDU connection to facility water systems, TCS piping to racks)	Requires additional facility-level piping system with longest deployment time. But implementation does not disrupt the existing cooling system
Energy efficiency:	Less	More	High (very rarely requires mechanical cooling)

Source: BofA Global Research, Schneider Energy Whitepaper

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Pros and Cons Part II: Rack mounted or floor mounted?

Below, we show the advantages and disadvantages of a rack-mounted solution as opposed to a floor-mounted solution. An in-rack solution has the CDU within the IT rack space, typically mounted at the bottom of the rack. The CDU includes a pumping unit, filtration, and controls. Heat is transferred to the data center air via a fan-assisted rear-door heat exchanger (liquid to air) or to a facility loop via a liquid-to-liquid heat exchanger.

A floor-mounted CDU is dedicated to a row or multiple rows of racks, sharing an IT fluid loop. This can be placed at the end of the row or further away from the cluster. Similar to the in-rack unit, heat is transferred to the data center either via a fan-assisted rear-door heat exchanger (liquid to air) or to a facility loop via a liquid-to-liquid heat exchanger.

Exhibit 51: In-the-rack vs. outside-the-rack solution
Pros and cons for rack-mounted vs. floor-mounted solutions

	Rack Mounted	Floor Mounted
Rack Capacity:	1 CDU per rack	CDU cools rows or multiple rows of racks
Loops:	1 IT fluid loop per rack	Rows or multiple rows of racks share 1 IT fluid loop
Usage:	<10 liquid-cooled racks	>10 liquid-cooled racks
Space:	Occupies IT rack space	Does not occupy IT rack space
Time to deployment:	Faster to implement (no redesign)	Slower to implement
Cost:	Higher cost per kW IT load for large deployments	Lower cost per kW IT load for large deployments
Densities for liquid-to-air:	20-40kW	60kW
Densities for liquid-to-liquid:	40-60kW	>300kW
Risk of failure	Potential failure modes are limited to 1 rack	All racks on a single loop can become susceptible to failure

Source: BofA Global Research, Schneider Energy Whitepaper

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Pros and Cons Part III: Single-phase or two-phase?

Two-phase direct-to-chip liquid cooling involves the coolant going from a liquid to a gas. This phase transition can absorb more heat, but requires the use of specific coolants that boil in the required temperature ranges of safe operation of the semiconductor. The vapor then returns to the condenser for recirculation.

Two-phase direct-to-chip cooling remains a nascent approach (see more details in the

COOLERCHIPS: research beyond D2C section below). Third-party research firms suggest a market size of less than $50mn in 2024. Vertiv has tested a prototype two-phase system (see *Maturation of Pumped Two-Phase Liquid Cooling to Commercial Scale-Up Deployment,* Nov. 2024*)*.

It is important to note that both single-phase and two-phase approaches will net CDUs, cold plates, access to facility water supply, and heat rejection (e.g., cooling tower). The key difference is that two-phase systems use specialized coolants/refrigerants, while single-phase systems tend to use a water-glycol mix.

Practical difficulties with a two-phase approach include:

- Managing the difference in density (and hence pressure) as the coolant/refrigerant enters the cold plate as a liquid versus exiting the cold plate as a gas. The variation in pressure in a single-phase approach is far less.

- Water-glycol mix is cheap; the customized refrigerants needed for two-phase systems adds to the overall cost. Manufacturers of cold plates and quick disconnects have optimized their products for single-phase systems. Customized accessories for a two-phase system would add to the cost.

- Variations in the level of vaporization can result in a wider disparity of heat transfer versus single-phase systems. Vaporization (e.g., the creation of bubbles) can vary based on minor differences within the microchannels of cold plates. This can be overcome through system-wide simulation and testing, but adds an additional level of complexity.

CDU competitive landscape

Given the high-growth prospects, it is not surprising that the liquid cooling market has seen many new entrants. By our count, there are 30 vendors offering more than 100 CDU variants in the market today.

Given the conservative nature of data center operators, we argue that reputation and service capability will play a major factor in decision making. We think this bodes well for Vertiv, which has more than 440 service centers globally offering same-day service in most locations.

Exhibit 52: CDU competitive landscape – 30 vendors offering 100+ variants across in-rack and in-row offerings

The high-growth prospects of direct-to-chip liquid cooling have attracted new entrants

	In-rack		In-row	
-	Liquid-to-air	Liquid-to-liquid	Liquid-to-air	Liquid-to-liquid
Accelsius		■		■
Auras	■	■	■	■
Boyd	■	■		■
Carrier				■
Chilldyne				■
Cool IT	■	■	■	■
Coolcentric		■		■
Cooler Master		■	■	
DCX		■		■
Delta Electronics		■	■	■
Envicool	■	■	■	■
Excool				■
FlaktGroup				■
Flex / JetCool	■	■		■
Hon Hai (Foxxconn/Ingrasys)	■	■		■
Kaori	■	■		■
LiquidStack (Trane)				■
LiteOn		■		■
Modine / Airedale				■
Munters				■
Nautilus				■
Nidec		■		■
Nortek Air Solutions				■
nVent	■	■		■
Rittal		■		■
Schneider / Motivair		■		■
Stulz				■
Trane				■
Vertiv	■	■	■	■
Zutacore (Carrier)	■			

Source: BofA Global Research

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Given the nascent nature of the CDU market (~$1.2bn in revenue in 2024), we do not have the same level of confidence in market shares relative to larger, more established product categories. The table below groups the vendors into three tiers (with vendors listed alphabetically in each tier). Tier 1 vendors have at least $100mn in CDU-related revenue and offer multiple variants. Tier 2 vendors have strong products and existing thermal offerings, but we do not believe have more than $100mn in CDU-related revenue.

For reference, the ten CDU manufacturers listed as Nvidia partners at the 2025 Computex conference were: Auras, Boyd, Cooler Master, CoolIT Systems, Delta, Flex/JetCool, LiteOn, Motivair/Schnedier, Nidec, and Vertiv.

New entrants, such as Carrier, JetCool, Munters, Nautilus, Nortek, and Trane, may have garnered more revenue in 2025, but our focus is on 2024 given data availability.

Exhibit 53: Tiering CDU manufacturers by 2024 revenue

Exact market share calculation is difficult given the early stage of the CDU market

Tier 1	Tier 2	Tier 3
Delta Electronics	Auras	Envicool
nVent	Boyd	Hon Hai (Foxxconn/Ingrasys)
Schneider / Motivair	Cooler Master	Kaori
Vertiv	CoolIT	Nidec
	DCX	Stulz

Source: BofA Global Research

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We provide a brief view of the Tier 1 CDU vendors below (in alphabetical order):

Delta Electronics

Delta Electronics (ticker: 2308 TT; covered by our colleague Robert Cheng) is a manufacturer of power supplies and video display products. Delta offers liquid-to-liquid in-rack and in-row CDUs and liquid-to-air in-row CDUs.

nVent

nVent (ticker: NVT) is a US-based manufacturer of electrical products. nVent manufactures both in-rack and in-row solutions. nVent introduced its first standardized liquid cooling unit, RackChiller CDU800, in November 2020. The company also offers smaller, in-rack coolant distribution units. nVent has been building up CDU service capabilities as well.

Schneider Electric / Motivair

Schneider (ticker: SU FP, covered by our colleague Ben Heelan) is a manufacturer of electrical and automation products. Within the data center business, the company offers a full range of electrical and thermal products. Within thermal, Schneider offers traditional air-cooling products, as well as in-row, in-rack, and floor-mounted liquid cooling solutions. Schneider closed on the acquisition of US-based Motivair in February 2025. We estimate combined pro forma CDU sales in excess of $100mn.

Vertiv

Vertiv (ticker: VRT) has a large portfolio of liquid cooling products. This includes coolant distribution units (CDUs), active and passive rear-door heat exchangers, and heat rejection systems. The company acquired CoolTera in 2023, which added to its CDU manufacturing capabilities and intellectual property position.

COOLERCHIPS: research beyond D2C

What is the COOLERCHIPS program?

The US Department of Energy’s Advanced Research Projects Agency-Energy (ARPA-E) launched the COOLERCHIPS program in September 2022. COOLERCHIPS, which is an acronym for Cooling Operations Optimized for Leaps in Energy, Reliability, and Carbon Hyper-Efficiency for Information Processing Systems, provides federal funding to research with the explicit goal of reducing total cooling energy expenditure to less than 5% of a typical data center’s IT load at any time and any location in the US for high-density compute systems (e.g., artificial intelligence workloads).

ARPA-E has granted more than $83mn across 19 projects since its launch in 2022. We focus on an Nvidia-led consortium’s project, which is likely to be used in conjunction with the Feynman chip architecture in 2028-29.

Vertiv, Nvidia partnership exploring combo of D2C and immersion cooling

Vertiv is part of a consortium led by Nvidia that received a $5mn grant from the US in 2023 for COOLERCHIPS initiative. The consortium is exploring hybrid designs including partial immersion cooling. This program is working to develop a modular data center with a cooling system combining direct-to-chip, pumped two-phase and single-phase immersion in a rack manifold with built-in pumps and a liquid-vapor separator. According to program files, the design would cool chips with a two-phase cold plate with the rest of the server components submerged in an immersion sled. The cooling design would incorporate green refrigerants for two-phase cooling and dielectric fluid for immersion.

Immersion cooling is not the preferred technology by industry participants

Immersion cooling poses several challenges to data center operators. Before changing components in an immersion cooling tank, all IT components must be powered down. The tanks add considerable weight, which makes retrofit more difficult. The most used dielectric fluids for immersion cooling are fluorocarbons, such as perfluoroalkyl substances (PFAS). These introduce potential environmental and human health concerns. For these reasons, industry participants we spoke with would prefer cooling architectures that avoid immersion sleds.

Modest success on cooling, but still in early stages

As of March 2025, some of the projects that COOLERCHIPS has invested in are showing successful first prototypes on real servers. This includes teams achieving less than 5% energy used for cooling for a rack >120kW, meaning 95% or more of the energy is available for power and compute and a 90% reduction in cooling energy compared to today's energy usage (which is ~40% energy usage for cooling). Industry participants are still debating potential winners and losers for next-generation chip cooling between single-phase cooling, two-phase cooling, immersion cooling, and direct-to-chip cooling.

Reducing thermal resistance for a 1kW chip

Currently, in high-density data centers, the room is 40 degrees lower than the chip's heat (e.g., 70 degrees Celsius for the chip; 30 degrees Celsius for the room). This is in order to transfer the heat effectively from the chip. If COOLERCHIPS program designs are successful, for a 1KW chip (in line with Blackwell Ultra density), the temperature difference could be reduced to 10 degrees Celsius. An operator would then be able to run chips at 40 degrees Celsius, which would yield more efficient chips. Running the building at 60 degrees Celsius would clearly not be possible, in our view, unless the infrastructure was redesigned to not need human presence in the data center.

Potential shifts to cooling infrastructure

According to De Bock, shifts to cooling technology for servers with >3kW density could include better flow manipulation of cold plates to transfer heat more efficiently, shifting the materials in the cold plate (e.g., silicon to replace copper/aluminum), and increasing the length of replacement cycle for immersion cooling fluids (which currently need to be replaced every ~6 months).

Overview of data center electrical systems

Tracing electricity from the utility to the server

The utility provides either high-voltage or medium-voltage electricity. For larger data centers taking high-voltage lines, there would be a step-down power transformer located near the site. Alternating current (AC) electricity enters the data center at medium voltage. This will pass through switchgear before being stepped down to low voltage AC by a transformer.

Electricity then goes to the uninterruptible power supply (UPS). The UPS converts the electricity to DC to charge the batteries, then converts it back to AC to send on. Traditionally, electricity was then distributed through power distribution units (PDUs). In more modern data centers, electricity goes through a higher-capacity busway. The electricity then goes to the rack, where it flows into rack power distribution units (typically along the side of the rack). Individual servers are plugged into these rack PDUs. Finally, the electricity is converted to DC by power supply units (PSUs) located within the rack.

Uninterruptible power supply (UPS)

Uninterruptible power supply (UPS) provides automated backup electrical power for a data center. UPS systems can also perform power conditioning, including voltage fluctuations, under- or over-voltage conditions, and frequency variations. We focus on the large-scale UPS market, which is most applicable to data centers.

Exhibit 54: Example of uninterruptible power supply (UPS)
The UPS contains both batteries and power conditioning equipment

Source: Company website

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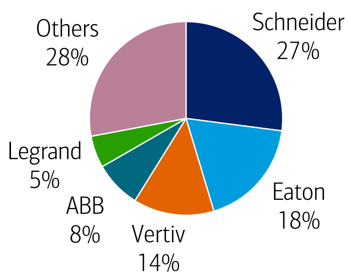
UPS provide short-term backup power (typically 15-30 minutes) in the event of a power failure until the backup generators are up and running. The size of the UPS battery array is therefore proportional to the supported data center electrical load.

We estimate a $8.5-9.5bn market size, which includes a significant amount of replacement revenue. Data center operators typically replace UPS every 10 years, given increased risk of failure after this period. Based on the 9 GW of data center capacity added in 2024, we estimate the new install market size at closer to $7bn.

Exhibit 55: Estimated data center UPS market share
We estimate Schneider is the market leader



Source: BofA Global Research, company filings

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Switchgear

Switchgear is equipment that controls, protects, and isolates electrical equipment. Common components include switches, fuses, isolators, relays, and circuit breakers. Data centers typically have two kinds of switchgear. A set of medium-voltage switchgear for the incoming electrical supply from the utility before it goes to the step-down transformer. Then a set of low-voltage switchgear before the electrical supply reaches the UPS backup batteries.

Exhibit 56: Example of low-voltage switchgear
Provides power distribution to data center racks

Source: Company website

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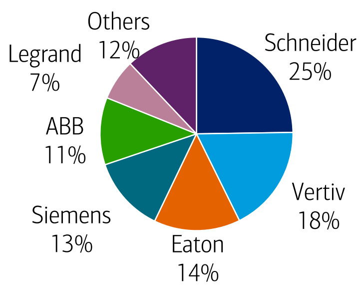
Based on the 9 GW of data center capacity added in 2024, we estimate a $5.0-5.5bn market size. Switchgear is ubiquitous throughout electricity distribution and the broader market is more than $100bn. The broader market is dominated by ABB, Eaton, Legrand, Schneider, and Siemens.

Exhibit 57: Estimated data center medium- and low-voltage switchgear market share
We estimate Schneider is the market leader



Source: BofA Global Research, company filings

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Power distribution equipment

Traditionally, electrical power went from the UPS system to power distribution units (PDUs). PDU components typically include circuit breakers, power monitoring panels, power metering, and cabling to each rack. PDUs have drawbacks, including taking up floor space in the data hall and generating waste heat.

In high-density data centers, busway is an alternative approach to PDUs. Busway is typically mounted overhead, providing power to each rack through plug-in units with breakers. The busway draws power directly from low-voltage switchgear. While busway takes up less floor space, it is typically more expensive to install and less flexible to changes in rack location.

Exhibit 58: Example of rack power distribution unit
Provides plugs for servers, storage, and networking equipment inside the rack

Source: Company website

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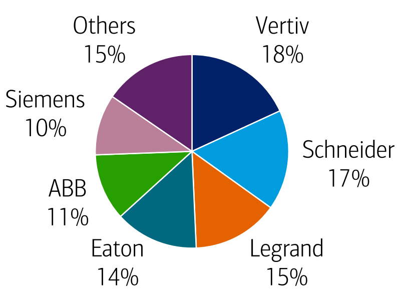
Finally, rack power distribution units (rPDUs) are mounted on the rack itself. rPDUs provide outlets to plug in servers, storage, and networking equipment. These are the last step in power distribution to IT equipment. In tier 3 and tier 4 data centers, there are two rack PDUs for each rack, providing redundancy.

Based on the 9 GW of data center capacity added in 2024, we estimate a $4.2-4.7bn market size. Similar to UPS, data center operators typically replace rack PDUs every 10 years, given increased risk of failure after this period, so this includes a portion of replacement revenue.

Exhibit 59: Estimated data center power distribution equipment market share
We estimate Vertiv is the market leader



Source: BofA Global Research, company filings

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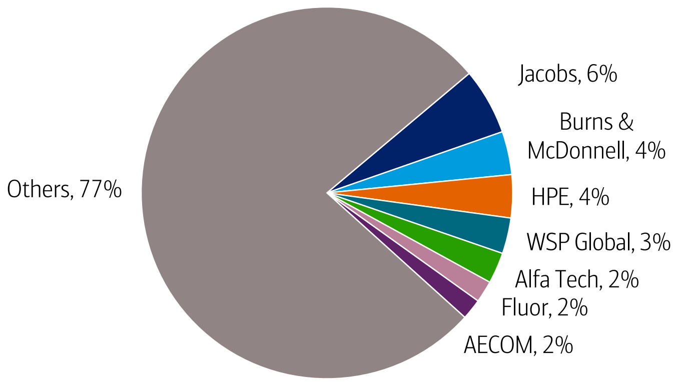
Engineering

Design & engineering services generally cost 4.5-6.5% of the infrastructure costs of a data center (e.g., excluding IT equipment). Publicly traded US firms covered by our colleague Michael Feniger include Jacobs Solutions (J), Fluor (FLR), and AECOM (ACM). These firms are highly diversified among end markets, with data centers representing a small percentage of total revenue.

These engineers plan the electrical, mechanical, cooling, fire protection, and physical security systems of the data center. Importantly, they must understand the IT infrastructure (e.g., network, routing, storage), which has implications for the physical infrastructure requirements.

Based on the 9 GW of data center capacity added in 2024, we estimate a $4bn market size.

Exhibit 60: Engineering firms estimated market share within data centers
We estimate Jacobs is the market leader in a fragmented market



Source: BofA Global Research

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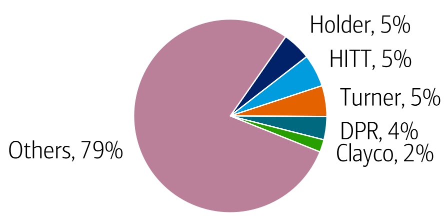
Construction

Construction firms oversee all aspects of the construction project including project management, specialty contractors, material purchasing, and equipment rental. These firms report modest operating margins, given the large amount of pass-through costs. The average operating margin is approximately 4% among publicly traded contractors with data center exposure.

Publicly traded firms include Balfour Beatty and Skanska. There are also smaller, private construction firms that specialize in data centers, such as US-based T5 Construction Services and Ireland-based Mercury Engineering.

Based on the 9 GW of data center capacity added in 2024, we estimate a $65-80bn market size. However, this would include material & equipment pass-through costs. Using an average margin of 4%, this would imply $2.6-3.2bn of operating profit.

Exhibit 61: Construction firms market share within data centers
We estimate no firm has greater than 10% market share



Source: BofA Global Research

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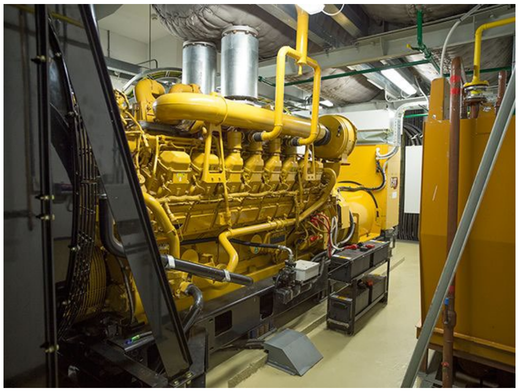
Generators

Typical diesel backup generators cost $400-550,000/MW. Total system costs would include fuel tank, fuel pump, and installation costs, which collectively add an additional $350-500,000/MW. Generators are typically sized to fully supply the electrical consumption of the data center. For example, a 10MW datacenter will typically have 10MW worth of generator power on site to ensure 99.999% uptime for clients.

Exhibit 62: Example of a diesel generator
This generator creates 1.25MW of electricity and consumes 86 gallons of diesel per hour



Source: Company website

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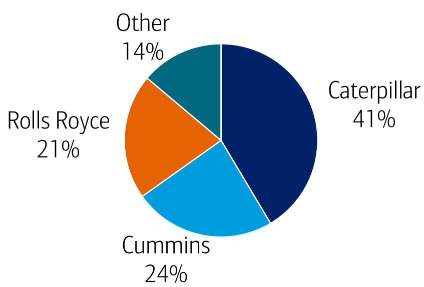
Based on the 9 GW of data center capacity added in 2024, we estimate a $7.2bn market size for generator equipment only (excluding ancillary products and installation costs). In 2023, Cummins gave a $6bn market size, but this has likely expanded significantly in 2024.

Exhibit 63: Estimated data center generator market share
We estimate Caterpillar is the market leader



Source: BofA Global Research, company filings

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Servers

Servers are the largest single product category of data center capex. In 2024, data centers bought 13.5mn servers spending approximately $280bn. On a dollar basis, AI servers comprised approximately half of this spending, but traditional servers represented the vast majority on a unit basis.

Exhibit 64: Example of a data center server
This server contains eight Nvidia H200 GPUs and two Intel CPUs and draws 3,200 watts

Source: Company website

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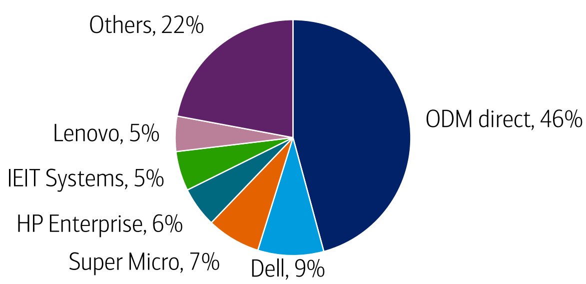
Original design manufacturers (ODMs) are companies that produce servers to their own design. For example, Google's Tensor Processing Units (TPUs) are custom semiconductors and these are put into servers at Google Cloud data centers. Similarly, Amazon Web Services has its own custom semiconductors (Graviton) and servers. Original equipment manufacturers (OEMs) are companies building servers to clients' specifications.

The largest OEM is Dell Technologies, with an estimated 9% market share.

Exhibit 65: Estimated data center server market share
Dell is the largest OEM



Source: BofA Global Research

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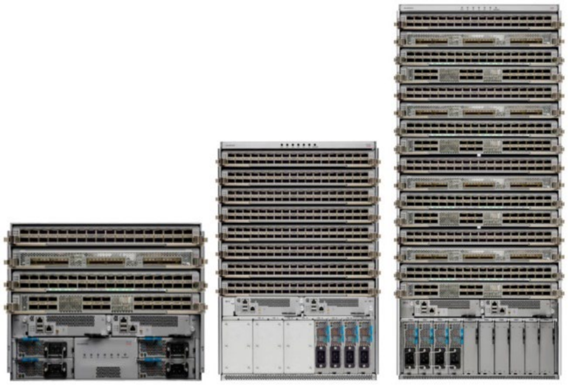
Networking equipment

Networking equipment includes several different pieces of equipment. Switches communicate within the data center or local area network. Typically, each rack would have a networking switch. Routers handle traffic between buildings, typically using internet protocol (IP). Some cloud service providers use "white box" networking switches (e.g., manufactured by third parties to their specifications).

Exhibit 66: Example of routers
Routers can handle terabytes of data throughput per second



Source: Company website

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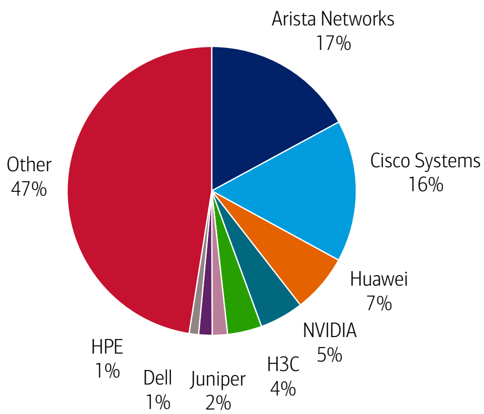
AI workloads are bandwidth-intensive, connecting hundreds of processors with gigabits of throughput. As these AI models grow, the number of GPUs required to process them grows, meaning bigger networks are required to interconnect the GPUs.

We estimate a $36bn market size for networking equipment. Arista and Cisco Systems are the two largest vendors.

Exhibit 67: Estimated data center networking equipment market share
Arista and Cisco Systems are the two largest vendors



Source: BofA Global Research

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