AXIS 6: Power & Cooling

Charly Saugey
Paul Haardt
Corentin Colmel

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Mission

- Explain the power and cooling challenges of modern AI infrastructures
- Compare cooling technologies and analyze datacenter design trade-offs

Part A: Evolution of AI System Power

GPU Power Evolution

Key questions

- How has GPU power consumption evolved?
- What is driving the increase in power?
- Is there a maximum ceiling to GPU power?
- How does power scale with performance?

Part A: Evolution of AI System Power

GPU	Year	TDP (W)	FP16 TFLOPs	W/TFLOP	Process Node
V100	2017	300 🔗	125 🔗	2.40 🔗	TSMC 12nm FFN 🔗
A100	2020	400 🔗	624 🔗	0.64 🔗	TSMC 7nm 🔗
H100 SXM	2022	700 🔗	1979 🔗	0.35 🔗	TSMC 4N 🔗
H200 SXM	2024	700 🔗	1979 🔗	0.35 🔗	TSMC 4N 🔗
B200 SXM	2024	1000 🔗	4500 🔗	0.22 🔗	TSMC 4NP 🔗
B300	2025	1100 🔗	4500 🔗	0.24 🔗	TSMC 4NP 🔗
R100 (Rubin)	2026	*~2300* 🔗	*~4000* 🔗	*~0.58* 🔗	*TSMC N3* 🔗

System-level power (full node)

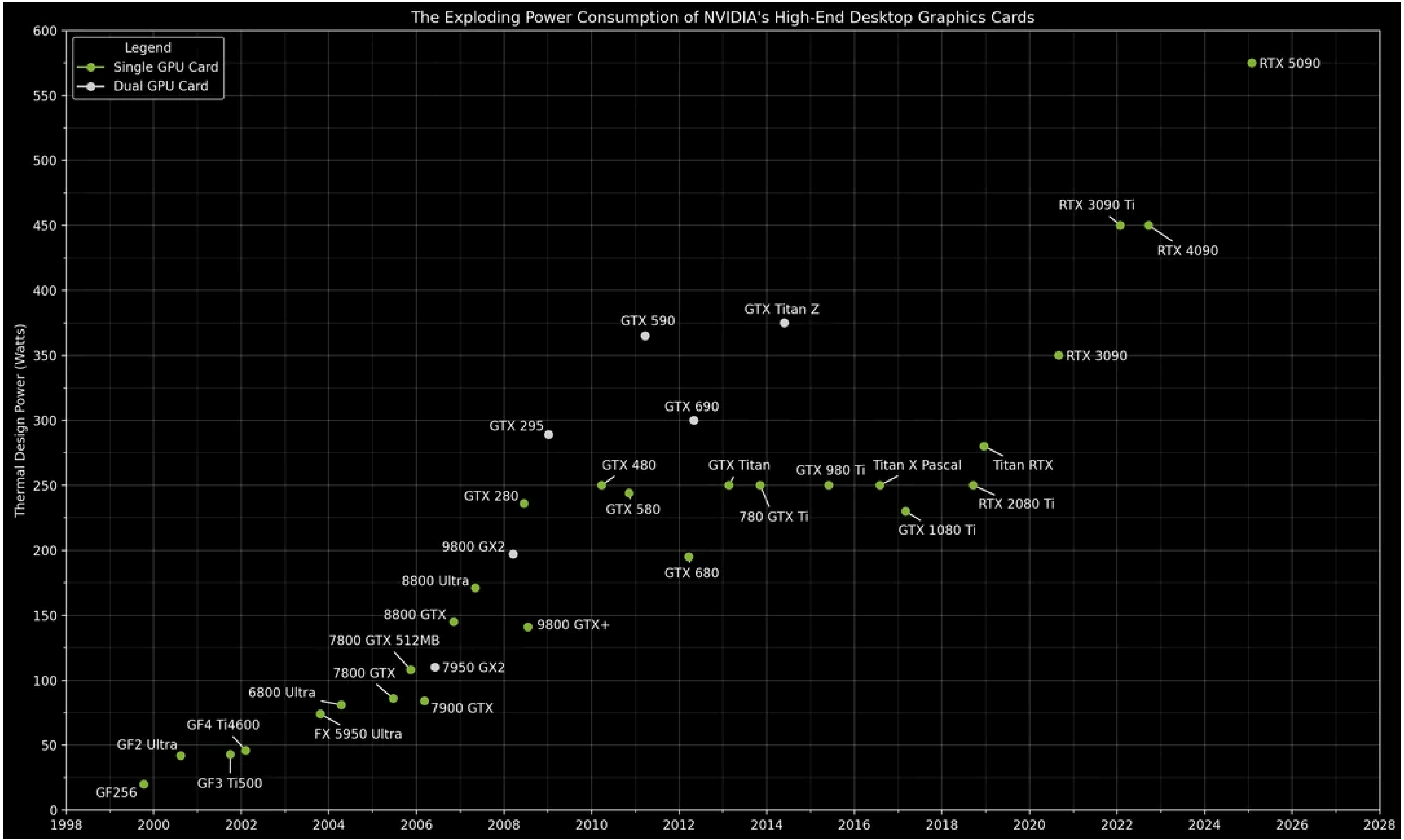
System	GPUs	GPU Power	Total System Power	Year
DGX-1	8× V100	2.4 kW 🔗	~3.5 kW 🔗	2017 🔗
DGX A100	8× A100	3.2 kW 🔗	~6.5 kW 🔗	2020 🔗
DGX H100	8× H100 SXM	5.6 kW 🔗	~10.2 kW 🔗	2022 🔗
DGX B200	8× B200 SXM	8.0 kW 🔗	~14.3 kW 🔗	2024 🔗
GB200 NVL72	72× B200	72.0 kW 🔗	~120 kW 🔗	2024 🔗

Part A: Evolution of AI System Power

Evolution of rack power density

Era	Typical Rack Power	kW/rack	Cooling Method
Traditional IT (2010)	5–10 kW/rack 🔗	~8 🔗	Air
GPU compute (2018)	15–25 kW/rack 🔗	~20 🔗	Air
AI training (2022)	30–50 kW/rack 🔗	~40 🔗	Air / DLC
AI training (2024)	60–120 kW/rack 🔗	~80 🔗	DLC required
AI training (2026)	150–300 kW/rack 🔗	~200 🔗	DLC / Immersion

Part A: Evolution of AI System Power

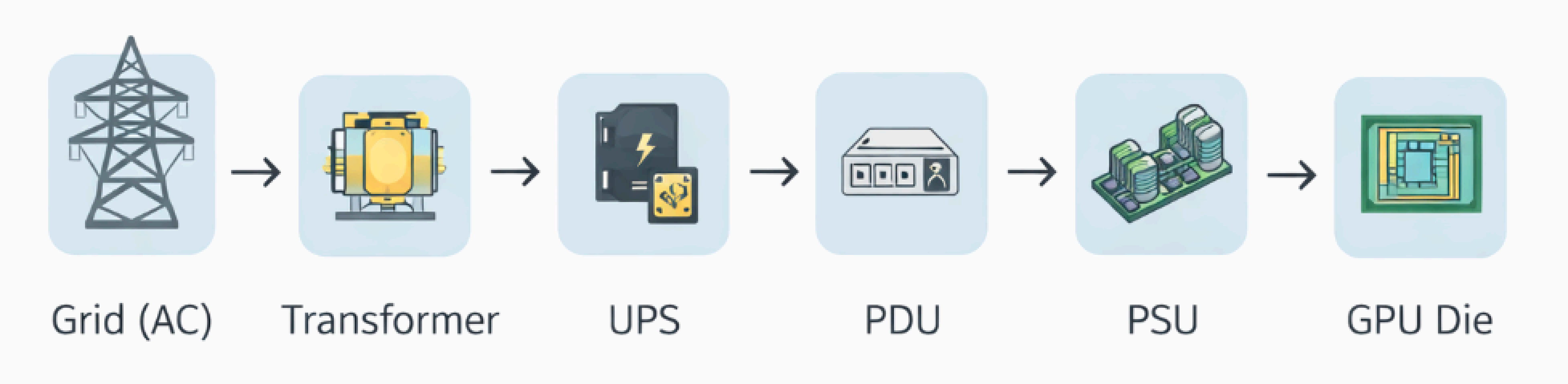


Part B: GPU Power Delivery

How does GPU power delivery work?

Key questions

- From grid to chip: what are the conversion stages?
- Where do efficiency losses occur?
- How is power distributed inside a GPU?



Part B: GPU Power Delivery

Stage	Input	Output	Typical Efficiency	Loss
Utility transformer	HV AC (10–30 kV)	LV AC (400–480 V)	98–99%	1–2%
UPS	AC	AC (conditioned)	94–97%	3–6%
PDU	AC	AC	98–99%	1–2%
PSU (AC-DC)	AC (200–240 V)	DC (12 V / 48 V)	92–96%	4–8%
VRM (DC-DC)	DC (12 V / 48 V)	DC (~0.7–1.1 V)	85–95%	5–15%

Voltage Regulator Modules (VRMs)

VRM Aspect	Description	Typical Value
Input voltage	Voltage supplied to VRM	12 V or 48 V 🔗 🔗
Output voltage	Core supply voltage (Vcore)	0.7–1.1 V 🔗
Phase count	Parallel VRM phases	10–20 phases 🔗
Efficiency	DC-DC conversion efficiency	85–95% 🔗

12V vs 48V Power Distribution

Aspect	12V Distribution	48V Distribution
Current for 1kW	~83 A	~21 A
Cable thickness	Thick (high current)	Thinner
I^2R losses	High (×16 vs 48V)	Much lower
Connector size	Large / many pins	Smaller / fewer pins
Industry adoption	Legacy servers	AI & hyperscale

Connector considerations

Connector	Max Power	Pins	Issues
8-pin PCIe	150 W	8	Limited power, multiple cables needed
12VHPWR	600 W	16 (12+4 sense)	Overheating, insertion sensitivity
12V-2x6	600 W	16 (12+4 sense)	Improved safety, still high current

800V DC for AI factories

Questions

- Why is NVIDIA pushing 800V DC?
- What efficiency gains are possible?
- How does this change datacenter design?
- What are the safety considerations?

Part C: Cooling Technologies

Air Cooling

Questions

- How does air cooling work?
- What are the design principles of a heat sink?
- What are the limits?
- When does air cooling fail?
- At what TDP does air become impractical?
- What are the acoustic limits?
- How does altitude affect air cooling?

Part C: Cooling Technologies

Air Cooling Aspect	Typical Value	Limit
Max heat dissipation per GPU	300–600 W	~800 W
Max rack density	20–40 kW	~50 kW
Airflow per rack	~160 CFM/kW	>160 CFM/kW
Fan power overhead	2–10%	10–20%

Direct Liquid Cooling (DLC)

How does DLC work?

- Cold plate design and attachment
- Manifolds and distribution systems
- Coolant types and flow rates
- Heat rejection (CDU, dry coolers, cooling towers)

Part C: Cooling Technologies

DLC Component	Function	Key Specifications
Cold plate	Heat transfer from GPU to liquid	Metal base plate (typically copper), microchannels 🔗
Manifold	Distribute fluid to cold plates	Row/rack manifolds for supply/return distribution 🔗
Quick disconnects	Serviceable maintenance connections	Serviceable quick disconnect fittings between loop and cold plates 🔗
CDU (Coolant Distribution Unit)	Pump + heat exchanger + filtration	60–100 L/min (example CDU spec) 🔗
Facility water loop	Reject heat to building	Heat exchanger to facility water / external heat rejection loop 🔗

Part C: Cooling Technologies

Aspect	Air Cooling	Direct Liquid Cooling
Max GPU TDP supported	~800 W 🔗	1,000 W+ 🔗
Max rack density	~40–50 kW 🔗	~100–200+ kW 🔗
PUE impact	Higher overhead 🔗	Lower overhead 🔗
Maintenance complexity	Low 🔗	Medium/High 🔗
Capital cost	Lower 🔗	Higher 🔗
Operating cost	Higher fan energy 🔗	Lower pumping energy (typically) 🔗

Part C: Cooling Technologies

Coolant	Thermal Properties	Cost	Safety	Use Case
Water/glycol	Common liquid-cooling working fluid (e.g., PG-25)	Low	Conductive, leak risk	Cold plates, DLC loops
Propylene glycol	Used as glycol mix / antifreeze variant	Low–Medium	Less toxic than ethylene glycol	Cold climates, DLC
Dielectric fluids	Electrically insulating immersion fluids	High	Non-conductive (safer for electronics)	Immersion cooling

Immersion Cooling

Topics

- Single-phase vs two-phase
- Tank design and fluid management
- Heat rejection methods
- Maintenance considerations

Part C: Cooling Technologies

Aspect	Single-Phase Immersion	Two-Phase Immersion
Fluid type	Dielectric fluid (no phase change)	Low-boiling dielectric fluid
Operating principle	Liquid absorbs heat, remains liquid	Liquid boils, vapor condenses
Max heat flux	High	Very high
Fluid cost	Medium	High
Complexity	Medium	High
Maturity	Commercially mature	Emerging / niche

Part C: Cooling Technologies

Advantage	Challenge
Highest heat density	Specialized fluids
No fans required	Hardware compatibility
Reduced PUE	Higher CAPEX
Component longevity	Maintenance procedures

Rear-Door Heat Exchangers (RDHx)

Questions

- What is RDHx?
- How does it supplement air cooling?
- What power densities can it support?
- When is it the right choice?

Part C: Cooling Technologies

RDHx Type	Cooling Capacity	Best For
Passive RDHx	~20–35 kW per rack	Medium-density racks, retrofit
Active RDHx	~30–80 kW per rack	High-density GPU racks

Part D: Power Usage Effectiveness (PUE)

Understanding PUE

Definition

- PUE = Power Usage Effectiveness
- PUE = Total Facility Power / IT Equipment Power
- 1 PUE = (IT Load + Cooling + Power Distribution + Lighting + Other) / IT Load

Questions

- What does PUE measure and not measure?
- How does cooling choice affect PUE?
- What are the components of overhead?

Part D: Power Usage Effectiveness (PUE)

PUE Component	Typical % of Overhead	Reduction Strategies
Cooling	~40%	DLC, free cooling, containment
Power distribution losses	~10–12%	High-efficiency UPS/PSU
Lighting and other	~3–5%	LED, automation

PUE benchmarks

Datacenter Type	Typical PUE	Best-in-Class PUE
Legacy enterprise	1.8–2.5	~1.6
Modern enterprise	1.4–1.6	~1.3
Hyperscale (air)	1.2–1.4	~1.09
Hyperscale (liquid)	1.1–1.2	~1.02–1.03
AI-optimized	1.1–1.3	~1.05–1.1

Part D: Power Usage Effectiveness (PUE)

Cooling Method	Typical PUE	Why
Traditional air (CRAC)	~1.6	Energy-intensive compressors
Hot/cold aisle containment	~1.4	Optimized airflow
Free air cooling	~1.2	Minimal active cooling
Direct liquid cooling	~1.1	Direct heat transfer
Immersion cooling	~1.02–1.03	Near elimination of HVAC

Best-in-class examples

Company	Facility	PUE	How Achieved
Google	Hyperscale DC	1.09 (2024)	Free cooling + control/optimization
Meta	Hyperscale DC	1.09 (reported)	Efficiency improvements (site-dependent)
Microsoft	Hyperscale DC (example)	1.12 (expected)	Efficiency-focused design (example site)

Beyond PUE: other efficiency metrics

Metric	Definition	Typical Values	Best-in-Class
PUE	Total / IT ratio	~1.1–1.6	~1.02–1.09
WUE	Liters water / kWh IT	~0.2–1.8	≤0.2
CUE	$kgCO_2$ / kWh IT	Variable	Near zero (low-carbon energy)

Part E: Infrastructure Requirements

Power Density Planning

Questions

- How do you plan for increasing density?
- What infrastructure upgrades are needed?
- How do you handle mixed densities?

Part E: Infrastructure Requirements

Density Tier	kW/Rack	Infrastructure Requirements
Low density	5–10 kW	Air cooling, standard power
Medium density	10–30 kW	Hot/cold aisle, high airflow
High density	30–80 kW	RDHx or DLC
Ultra-high density	>80 kW	DLC or immersion

Power distribution architecture

Component	Function	Sizing Consideration
Utility feed	Power from grid	Peak MW + redundancy
Main switchgear	Distribution & protection	Fault current rating
UPS systems	Backup & conditioning	MW load, minutes runtime
PDUs	Rack-level distribution	kW per rack
RPPs	Branch circuits	Density zones

Cooling capacity planning

Cooling capacity Unit	Conversion	Context
1 ton of cooling	12,000 BTU/h 🔗	3.52 kW 🔗
1 kW IT load (heat)	~0.284 ton 🔗	Rule of thumb (1 kW power ≈ 1 kW heat)
1 MW IT load (heat)	~284 ton 🔗	Useful for plant-level sizing

Water requirements for liquid cooling

Cooling Method	Water Usage	m^3/h per MW
Evaporative (cooling tower)	High	1.5–2
Dry cooler	Low	0.1–0.3
DLC (closed loop)	Very low	~0.05

Backup power systems

UPS Type	Efficiency	Runtime	Best For
Double conversion	94–97%	5–15 min	Critical loads
Line interactive	96–98%	5–10 min	Edge DC
Rotary UPS	96–98%	Seconds	Large DC
Battery + flywheel	95–98%	Seconds–minutes	High power

Generator requirements

Facility Size	Generator Capacity	Fuel Storage	Startup Time
10 MW	10–12 MW	Hours	<10 s
100 MW	120 MW	Hours	<10 s
500 MW	600 MW	Hours	<15 s
1 GW	1.2 GW	Hours	<15 s

Grid connection for gigawatt-scale sites

Scale	Grid Requirements	Typical Lead Time
50 MW	Substation tie-in	1–2 years
200 MW	Dedicated substation	2–3 years
500 MW	Transmission upgrade	3–5 years
1 GW+	New transmission lines	5+ years

Power sourcing strategies

Strategy	Description	Pros	Cons
Grid connection	Utility power	Simple	Carbon intensity
On-site generation	Gas/diesel	Fast backup	Emissions
PPA	Long-term renewable contract	Green energy	Price lock
Behind-the-meter solar/wind	Local generation	Low carbon	Intermittent
Nuclear (SMR)	Small modular reactors	Stable low-carbon	Regulatory

Part F: Deep Dive Topics

Chip-Level Power Management

Dynamic Voltage and Frequency Scaling (DVFS)

- How does DVFS work?
- What is the power/frequency relationship?

Part F: Deep Dive Topics

Power State	Voltage	Frequency	Power	Use Case
Max boost	High	High	Very high	Peak compute
Base clock	Nominal	Nominal	High	Sustained
Idle	Low	Low	Low	Low utilization
Sleep	Very low	~0	Very low	Inactive

Thermal throttling behavior

Threshold	Temperature	Action
Target	83 °C	Nominal cooling control
Max operating	88 °C	Increased cooling / management
Slowdown	92 °C	Clock throttling begins
Shutdown	95 °C	Hardware shutdown

Heat sink and cold plate design

Parameter	Impact	Tradeoff
Fin density	Heat transfer surface	Airflow restriction
Base thickness	Heat spreading	Mass
Heat pipe count	Heat transport	Cost
Material (Cu vs Al)	Thermal conductivity	Weight / price

Design Aspect	Consideration	Best Practice
Contact area	Thermal resistance 🔗	Maximum coverage 🔗
Channel design	Turbulence / heat transfer 🔗	Microchannels 🔗
Flow rate	Liquid ΔT / thermal performance 🔗	Sufficient, not excessive 🔗
Pressure drop	Pump load 🔗	Minimize 🔗

Stranded Power in Datacenters

Questions

- What is stranded power?
- Why does it occur?
- How much power is typically stranded?
- How do you minimize stranded capacity?

Part G: Companies & Industry Landscape

System Vendors

Company	Products	Cooling Approach	Market Position
NVIDIA	DGX, MGX, HGX	Air + DLC ready	AI platform leader
Dell	PowerEdge XE	Air + DLC	Enterprise AI servers
HPE	Cray EX	DLC	HPC & AI leader
Supermicro	GPU servers	Air + DLC	Broad OEM supplier
Lenovo	ThinkSystem	Air + DLC	Enterprise / HPC

Cooling Infrastructure Vendors

Company	Products	Technology Focus
Vertiv	Liebert (cooling), thermal chain	Full-stack cooling
Schneider Electric	APC + cooling	Power + thermal
Asetek	Cold plates / CDU	DLC pioneer
CoolIT	DLC systems	Rack-level DLC
GRC	ICEraQ	Single-phase immersion
LiquidCool	Immersion tanks	Two-phase immersion
Submer	SmartPod	Immersion systems

Power Infrastructure Vendors

Company	Products	Specialty
Schneider Electric 🔗	UPS, PDUs, switchgear 🔗	End-to-end power 🔗
Vertiv 🔗	UPS, PDUs 🔗	Critical power 🔗
Eaton 🔗	UPS 🔗, PDUs 🔗	Power distribution 🔗
ABB 🔗	Transformers 🔗, switchgear 🔗	Utility-scale 🔗
Caterpillar 🔗	Generators 🔗	Backup power 🔗

Part H: Final Comparison

Cooling Technology Comparison

Aspect	Air Cooling	Rear-Door HX	Direct Liquid	Single-Phase Immersion	Two-Phase Immersion
Max kW/rack	~20–50 kW	~20–80 kW	~50–200+ kW	~80–250+ kW	~100–300+ kW
PUE achievable	~1.2–1.6	~1.15–1.4	~1.05–1.2	~1.03	~1.02
Capital cost	Low	Medium	High	High	Very high
Operating cost	Medium/High	Medium	Low/Medium	Low	Low
Maintenance	Simple	Moderate	Moderate/Complex	Complex	Very complex
Maturity	Very mature	Mature	Mature	Mature (commercial)	More niche
GPU compatibility	Universal	Universal	Cold plate required	Immersion-compatible hardware	Immersion-compatible hardware

AI System Power Summary

System	GPUs	Total Power	Cooling Method	Rack Density
DGX A100	8× A100	~6.5 kW	Air	Variable (depends on servers per rack)
DGX H100	8× H100	~10.2 kW	Air / DLC	Variable
DGX B200	8× B200	~14.3 kW	DLC	Variable
GB200 NVL72	72× B200	~120 kW	DLC	~120 kW/rack
AMD MI300X (8-way)	8× MI300X	~6.0 kW (GPUs only)	Air	Variable
Google TPU v5p pod	8,960 TPU v5p chips	Not disclosed	DLC	Not disclosed

Datacenter Efficiency Comparison

Operator	Facility Type	PUE	WUE	Cooling Method
Google	Hyperscale	1.09 (TTM)	Not publicly disclosed (global)	Mix (free cooling + liquid depending on site)
Meta	Hyperscale	1.08 (2023 avg)	WUE reported (see sustainability report)	Mix (air optimizations + water systems)
Microsoft	Azure	Not publicly disclosed (global)	WUE improvement reported	Mix (air + "zero-water" innovations on new sites)
AWS	Cloud	1.15 (global)	Not publicly disclosed (global)	Mix (air + optimizations)
CoreWeave	AI-focused	1.15 (Barcelona site announced)	"Zero water" announced (Barcelona site)	Free air + optimized design
Lambda Labs	AI-focused	Not disclosed	Not disclosed	Not disclosed

TCO Impact of Cooling Choice

Cost Component	Air Cooling	DLC	Immersion
Capital ($/kW IT)	Low	High	High / Very high
Power cost ($/kW-yr)	High (fans/HVAC)	Lower	Lower
Maintenance ($/kW-yr)	Low	Medium	High
Floor space ($/kW-yr)	High (limited density)	Lower	Lower
5-year TCO ($/kW)	Variable (often higher at high density)	Often lower at high density	Often lower if extreme density