AXIS 6: Power & Cooling (Comparative Analysis)

Presentation Format: 30-45 min presentation (through Google Meet)

- **Mission**:
  - Explain the power and thermal challenges of modern AI infrastructure
  - Compare cooling technologies and analyze datacenter design tradeoffs
  - YOU CAN USE CHATGPT but always add source to every statements you say
    - If unsure of statements (because no sources found), put in italic in a different colors
  - Some data in tables below were not checked. If you decide to use them, feel free but it needs sources OR a formula that explains how to get the value

Part A: The Power Trajectory of AI Systems

GPU Power Evolution

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

GPU	Year	TDP (W)	FP16 TFLOPs	W/TFLOP	Process Node
V100	2017	?	?	?	?
A100	2020	?	?	?	?
H100 SXM	2022	?	?	?	?
H200 SXM	2024	?	?	?	?
B200 SXM	2024	?	?	?	?
B300	2025	?	?	?	?
R100 (Rubin)	2026	?	?	?	?

- System-level power (full node):

System	GPUs	GPU Power	Total System Power	Year
DGX-1	8× V100	?	?	2017
DGX A100	8× A100	?	?	2020
DGX H100	8× H100	?	?	2022
DGX B200	8× B200	?	?	2024
GB200 NVL72	72× B200	?	?	2024

- Rack power density evolution:

Era	Typical Rack Power	kW/rack	Cooling Method
Traditional IT (2010)	?	?	Air
GPU compute (2018)	?	?	Air
AI training (2022)	?	?	Air/DLC
AI training (2024)	?	?	DLC required
AI training (2026)	?	?	DLC/Immersion

- What drives power increases?

Part B: GPU Power Delivery

How does GPU power delivery work?

- Power delivery hierarchy
  - From grid to chip: what are the conversion stages?
  - Where are the efficiency losses?
  - How is power distributed within a GPU?

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Grid (AC) → Transformer → UPS → PDU → PSU → VRM → GPU Die
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Stage	Input	Output	Typical Efficiency	Loss
Utility transformer	?	?	?	?
UPS	?	?	?	?
PDU	?	?	?	?
PSU (AC-DC)	?	?	?	?
VRM (DC-DC)	?	?	?	?

- Voltage Regulator Modules (VRMs)
  - What is a VRM and why is it critical?
  - What are the phases and how do they work?
  - Why is VRM efficiency important?
  - What are the thermal challenges?

VRM Aspect	Description	Typical Value
Input voltage	?	?
Output voltage	?	?
Phase count	?	?
Efficiency	?	?

VRM Aspect	Description	Typical Value
Power loss (1kW GPU)	?	?

- 12V vs 48V power distribution
  - Why is 48V better for high-power systems?
  - What is the current reduction benefit?
  - Who is pushing 48V adoption?
  - What are the challenges?

Aspect	12V Distribution	48V Distribution
Current for 1kW	?	?
Cable thickness	?	?
I^2R losses	?	?
Connector size	?	?
Industry adoption	?	?

- 12VHPWR connector issues
  - What is the 12VHPWR connector?
  - What problems occurred?
  - What is 12V-2x6 (the replacement)?
  - How much power can these connectors handle?

Connector	Max Power	Pins	Issues
8-pin PCIe	?	?	?
12VHPWR	?	?	?
12V-2x6	600a?W	?	?

- 800V DC for AI factories
  - 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

- How does air cooling work?
  - Heat sink design principles

- Airflow management (hot aisle/cold aisle)
- Fan power consumption
- What are the limits?

Air Cooling Aspect	Typical Value	Limit
Max heat dissipation per GPU	?	?
Max rack density	?	?
Airflow per rack	?	?
Fan power overhead	?	?

- When does air cooling fail?
  - At what TDP does air become impractical?
  - What are the acoustic limits?
  - How does altitude affect air cooling?

Direct Liquid Cooling (DLC)

- How does DLC work?
  - Cold plate design and attachment
  - Manifold and distribution systems
  - Coolant types and flow rates
  - Heat rejection (CDU, dry coolers, cooling towers)

DLC Component	Function	Key Specifications
Cold plate	?	?
Manifold	?	?
Quick disconnects	?	?
CDU (Coolant Distribution Unit)	?	?
Facility water loop	?	?

- DLC performance characteristics:

Aspect	Air Cooling	Direct Liquid Cooling
Max GPU TDP supported	?	?
Max rack density	?	?
PUE impact	?	?
Maintenance complexity	?	?
Capital cost	?	?
Operating cost	?	?

- Coolant types:

Coolant	Thermal Properties	Cost	Safety	Use Case
Water/glycol	?	?	?	?
Propylene glycol	?	?	?	?
Dielectric fluids	?	?	?	?

Immersion Cooling

- How does immersion cooling work?
  - Single-phase vs two-phase
  - Tank design and fluid management
  - Heat rejection methods
  - Maintenance considerations

Aspect	Single-Phase Immersion	Two-Phase Immersion
Fluid type	?	?
Operating principle	?	?
Max heat flux	?	?
Fluid cost	?	?
Complexity	?	?
Maturity	?	?

- Immersion cooling advantages and challenges:

Advantage	Challenge
Highest heat density	?
No fans required	?
Reduced PUE	?
Component longevity	?

Rear-Door Heat Exchangers (RDHx)

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

RDHx Type	Cooling Capacity	Best For
Passive RDHx	?	?
Active RDHx	?	?

Part D: Power Usage Effectiveness (PUE)

Understanding PUE

- What is PUE?
  - Definition: Total Facility Power / IT Equipment Power
  - What does PUE measure and not measure?
  - What are the components of overhead?

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PUE = (IT Load + Cooling + Power Distribution + Lighting + Other) / IT Load
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PUE Component	Typical % of Overhead	Reduction Strategies
Cooling	?	?
Power distribution losses	?	?
Lighting and other	?	?

- PUE benchmarks:

Datacenter Type	Typical PUE	Best-in-Class PUE
Legacy enterprise	?	?
Modern enterprise	?	?
Hyperscale (air)	?	?
Hyperscale (DLC)	?	?
AI-optimized	?	?

- How does cooling choice affect PUE?

Cooling Method	Typical PUE	Why
Traditional air (CRAC)	?	?
Hot/cold aisle containment	?	?
Free air cooling	?	?
Direct liquid cooling	?	?

Cooling Method	Typical PUE	Why
Immersion cooling	?	?

- Best-in-class examples:

Company	Facility	PUE	How Achieved
Google	?	?	?
Meta	?	?	?
Microsoft	?	?	?
NVIDIA DGX Cloud	?	?	?

- Beyond PUE: other efficiency metrics
    - What is WUE (Water Usage Effectiveness)?
    - What is CUE (Carbon Usage Effectiveness)?
    - Why do these matter for AI datacenters?

Metric	Definition	Typical Values	Best-in-Class
PUE	?	?	?
WUE	?	?	?
CUE	?	?	?

Part E: Infrastructure Requirements

Power Density Planning

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

Density Tier	kW/Rack	Infrastructure Requirements
Low density	?	?
Medium density	?	?
High density	?	?
Ultra-high density	?	?

- Power distribution architecture:

Component	Function	Sizing Consideration
Utility feed	?	?
Main switchgear	?	?
UPS systems	?	?
PDUs	?	?
RPPs (Remote Power Panels)	?	?

Cooling Capacity Planning

- Cooling load calculations
  - How do you size cooling for AI racks?
  - What is N+1 redundancy?
  - How much water is needed for DLC?

Cooling Capacity Unit	Conversion	Context
1 ton of cooling	? BTU/hr	? kW
1 kW IT load (air)	? tons	Includes overhead
1 kW IT load (DLC)	? tons	Direct rejection

- Water requirements for liquid cooling:

Cooling Method	Water Usage	GPM per MW
Evaporative (cooling tower)	?	?
Dry cooler	?	?
DLC (closed loop)	?	?

Backup Power Systems

- UPS sizing and architecture
  - What UPS topologies exist?
  - How long does UPS need to last?
  - What is rotary vs battery UPS?

UPS Type	Efficiency	Runtime	Best For
Double conversion	?	?	?
Line interactive	?	?	?
Rotary UPS	?	?	?
Battery + flywheel	?	?	?

- Generator requirements:

Facility Size	Generator Capacity	Fuel Storage	Startup Time
10 MW	?	?	?
100 MW	?	?	?
500 MW	?	?	?
1 GW	?	?	?

Grid Connection for GW-Scale Facilities

- What does a GW-scale AI datacenter need?
  - Substation requirements
  - Transmission line upgrades
  - Grid stability considerations
  - Timeline for new connections

Scale	Grid Requirements	Typical Lead Time
50 MW	?	?
200 MW	?	?
500 MW	?	?
1 GW+	?	?

- Power sourcing strategies:

Strategy	Description	Pros	Cons
Grid connection	?	?	?
On-site generation	?	?	?
PPA (Power Purchase Agreement)	?	?	?
Behind-the-meter solar/wind	?	?	?
Nuclear (SMR)	?	?	?

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?

- How do GPUs implement DVFS?

Power State	Voltage	Frequency	Power	Use Case
Max boost	?	?	?	Peak compute
Base clock	?	?	?	Sustained
Idle	?	?	?	Low utilization
Sleep	?	?	?	Inactive

- Power gating
  - What is power gating?
  - What can be gated (cores, memory, I/O)?
  - What are the wake-up latencies?

Thermal Throttling Behavior

- How do GPUs throttle under thermal stress?
  - Temperature thresholds
  - Throttling mechanisms
  - Performance impact

Threshold	Temperature	Action
Target	~83°C	?
Throttle start	~85°C	?
Max operating	~90°C	?
Shutdown	~95°C	?

Heat Sink and Cold Plate Design

- Heat sink design principles:

Parameter	Impact	Tradeoff
Fin density	?	?
Base thickness	?	?
Heat pipe count	?	?
Material (Cu vs Al)	?	?

- Cold plate design for GPUs:

Design Aspect	Consideration	Best Practice
Contact area	?	?

Design Aspect	Consideration	Best Practice
Channel design	?	?
Flow rate	?	?
Pressure drop	?	?

Stranded Power in Datacenters

- 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	?
Dell	PowerEdge XE	?	?
HPE	Cray EX	?	?
Supermicro	GPU servers	?	?
Lenovo	ThinkSystem	?	?

Cooling Infrastructure Vendors

Company	Products	Technology Focus
Vertiv	Liebert, CDUs	Full stack cooling
Schneider Electric	APC, cooling	Power + thermal
Asetek	Cold plates, CDUs	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: Summary Comparison

Cooling Technology Comparison

Aspect	Air Cooling	Rear-Door HX	Direct Liquid	Single-Phase Immersion	Two-Phase Immersion
Max kW/rack	?	?	?	?	?
PUE achievable	?	?	?	?	?
Capital cost	?	?	?	?	?
Operating cost	?	?	?	?	?
Maintenance	?	?	?	?	?
Maturity	?	?	?	?	?
GPU compatibility	?	?	?	?	?

AI System Power Summary

System	GPUs	Total Power	Cooling Method	Rack Density
DGX A100	8× A100	~6.5 kW	Air	?
DGX H100	8× H100	~10.2 kW	Air/DLC	?
DGX B200	8× B200	~14.3 kW	DLC	?
GB200 NVL72	72× B200	~120 kW	DLC	?
AMD MI300X (8-way)	8× MI300X	?	?	?
Google TPU v5p pod	?	?	?	?

Datacenter Efficiency Comparison

Operator	Facility Type	PUE	WUE	Cooling Method
Google	Hyperscale	?	?	?

Operator	Facility Type	PUE	WUE	Cooling Method
Meta	Hyperscale	?	?	?
Microsoft	Azure	?	?	?
AWS	Cloud	?	?	?
CoreWeave	AI-focused	?	?	?
Lambda Labs	AI-focused	?	?	?

TCO Impact of Cooling Choice

Cost Component	Air Cooling	DLC	Immersion
Capital ($/kW IT)	?	?	?
Power cost ($/kW-yr)	?	?	?
Maintenance ($/kW-yr)	?	?	?
Floor space ($/kW-yr)	?	?	?
5-year TCO ($/kW)	?	?	?