NEED FOR INNOVATIVE ENERGY, WATER AND THERMAL SOLUTIONS TO RUN NEXT GENERATION DATA CENTERS

(DEBRIEFING FROM NSF-SPONSORED COMPUTE-ENERGY NEXUS WORKSHOP IN DECEMBER 2025)

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OUTLINE

- **Workshop Organization**
  - Goals and Agenda
  - Attendees
- **Challenges** at the Intersection of Datacenter Computing and Grid-scale Energy Systems
- **Findings**
- **Implications** of Challenges and Findings
- **Next Steps**
- If time permits – insights/comments from attendees (based on break-out sessions)

WORKSHOP ORGANIZATION

- **NSF-sponsored Compute-Energy-Nexus Workshop on December 8-9, 2025, in Chicago**
- **Co-chairs: Philip Krein (EE/UIUC), Rakesh Kumar (CE/UIUC), Klara Nahrstedt (CS/UIUC)**
- **~74 invited attendees**
  - Power-Grid Industry/Utilities
  - Computing Industry
  - Federal Agencies
  - Academia
- **Goal**
  - Discuss current and future challenges and opportunities at the intersection of power grid/energy systems and data centers/computing.
  - Nucleate team to create a national strategic roadmap for integrated solutions.

AGENDA

- **Day 1**
- Keynotes
- Stakeholders & Team Interactions
- Thermal Management and Thermal Energy Integration and Recovery
- Chip and System Architecture with Energy as Peer Requirement

- **Day 2**
- Power Distribution within Data Centers
- Datasets, Modeling, Algorithms
- Ultra-scale Projects and Resources
- Summary
- Roadmap Initiation Discussion and Action Plan

CHALLENGES (1)

- **Scale in Number of Racks and Data Centers**
  - Scale is increasing at the rack level and data center campus level which causes a major challenge of power delivery to racks and data centers.
  - Many data center implementers envision near-term increase to 1MW power delivery to individual racks and 5000 MW to data centers/AI computation campuses
    - Typical large power plant delivers 1000-2000 MW
    - Largest (nuclear) power plant delivers less than 5000 MW
- **Time Scale Difference**
  - Power-grid/energy systems are massive in scale and take years to decades in making, building, and upgrading power plants, transmission, distribution lines, and systems.
  - Computing system projects are driven by Moore's Law which is synonymous with "urgency," and which compresses time scale into months.

CHALLENGES (2)

- **Rapid Growth of Dynamic AI Workloads**
  - Dynamic AI workloads cause major concerns and interaction issues with the power grid.
  - Power-grid is built for statistically predictable smoothly-varying power usage from their customers.
- **Transparency and Data Interoperability**
  - SW engineers are rarely asked to include energy optimization and energy-related telemetry into their design processes.
  - Technical information about power ramp rates, ride-through settings, and load model data are often hidden inside infrastructure specifications, behind non-disclosure agreements and/or in archives (not even digitized).
- **Other Technical Challenges**
  - Different terminology between power grid/energy systems and data center/computing systems engineers.
  - Different engineering considerations, planning, optimization, reliability issues.

CHALLENGES (3)

- **Team Building**
  - Need to build fully integrated teams and pursue combined energy and computing growth from a systems engineering perspective.
  - Need teams that will represent a comprehensive view of essential collective actions and build near-term tactical programs.
  - Need teams to develop national road maps.
- **Flexibility, Renewable Resources and Storage for AI Workloads**
  - AI computing can offer great flexibility for future power-grid operations.
  - Retiring coal plants offer interconnect points for distributed energy resources, new loads and storage.
  - Integrated effort can pursue and deliver best strategies to integrate flexibility, renewable resources, storage technologies and AI processes for cost-effective growth.
  - Fundamental challenges are different from "get more energy and quickly," or "build a different grid" perspectives.

CHALLENGES (4)

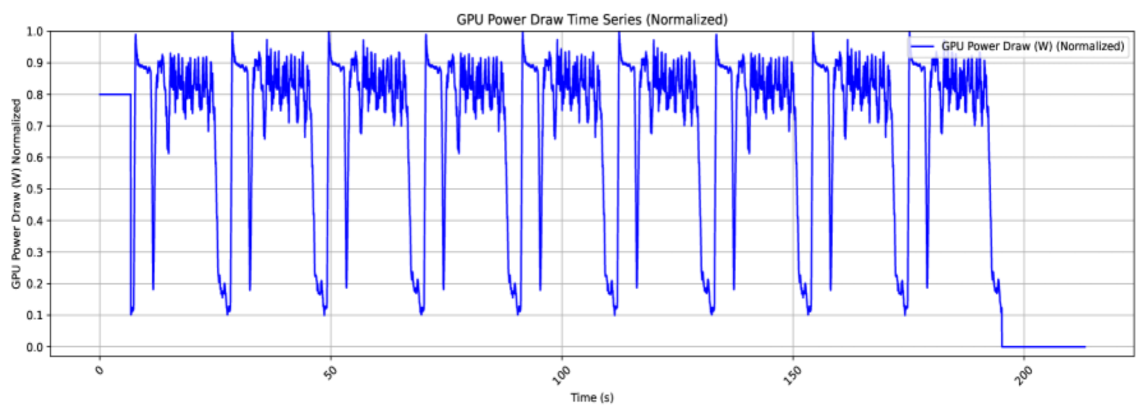
- **Funding Disparities**
  - Grid operators have been accused of underinvesting in equipment modernization and reliability improvements, but they are tightly constrained by regulators, and they must justify any investment in concrete ratepayer cost-benefit terms.
  - Computing/AI industries are experiencing massive growth in capitalization and have access to orders of magnitude more funding than grid operators.
- **Regulatory and Societal Challenges**
  - Combined with tightly regulatory regimes for utilities, it constrains utilities to respond to rapid growth needs.
  - Concerns:
    - Grid operators are concerned about adding additional supply with the risk that data centers do not materialize, leaving them supporting infrastructure without an end user,
    - Many state regulators will not approve of large supply investments without customer surety.
    - Very large computing companies are viewed as overwhelming potential small host communities, and communications are often sparse.

FINDINGS (1)

- **"Bring Your Own Power" Concept**
  - This concept is gaining traction among computing companies building hyper-scale data centers.
  - Example:
    - One computing company proposed 3000 MW natural gas turbine installation fully integrated into their data center campus.
  - This approach requires highly integrated teams since the line between computing and power-grid providers is blurring.
  - Important Issue:
    - Local power provisioning is governed by different regulatory regimes than public utilities.
    - Public utilities are under the guidelines of power deregulation efforts from 1980s/1990s, where grid was separated into generation, transmission, and distribution companies.
    - Public utilities are therefore handicapped by these guidelines and structure of future integrated expansion of the power grid.
- **Disparities in Objectives, Constraints, Priorities and Mutual Understanding**
  - <u>Grid-Operators:</u> long term horizons for electricity grids; limited funding and investment sources; regulations.
  - <u>Computing</u>: large capital investments.
  - However: "just purchase your grid company" does not avoid regulatory regimes and it is too simplistic.

FINDINGS (2)

- **Need for Detailed Operational Models of Computation for Grids**
  - Grid experts ask for detailed operational models and time predictions related to computing loads (analogous to conventional planning work for residential and industrial customers).
  - Compute experts explained that computational load details are proprietary, often unavailable, but offered that 100% equipment utilization is the objective (see figure, test traces produced by Microsoft, obviously not 100% continuous utilization).



Note 1: Grid experts commented that loads like these (in figure) can excite sub-synchronous resonances and cause physical failure of rotating generators.
Note 2: We need combinations of SW/HW activity smoothing, and rack-based batteries to mitigate this behavior.
Note 3: Power electronics experts suggested task interleaving. to smooth pulsating power flows.

Power readings from an at-scale training job on DGX-H100 racks. Reprinted from E. Choukse, et al., "Power Stabilization for AI Training Datacenters," Aug. 2025, arXiv:2508.14318v1., Licensed under CC BY-NC-SA 4.0.

FINDINGS (3)

- **Global Competition for AI Development and Understanding of Future AI Loads**
  - Today, AI development is perceived as a global competition and race for fastest possible results across corporate and national stakeholders.
  - Investments in trillions of dollars. The need for revenues and ROI pushes for fast turnaround.
  - AI loads are dominated by training processes, but future loads will be driven by AI inference processes which will change behavior and might lead to distributed computation.
  - Shift from AI training to AI inference will alter energy consumption patterns in unknown ways.
- **Understanding of Electricity as an Instantaneous Exchange Resource**
  - Electricity is not a commodity that can be shipped and stored.
  - Electricity is an exchange medium that needs instant matching; it is moment by moment balanced.

FINDINGS (4)

- **Understanding of Thermal Management**
  - All energy supplied into computing facility and processing generates heat that must be managed and dissipated.
  - Thermal engineering challenges of data centers:
    - Intense heat flux from individual devices (approaching 1kW/cm^2).
    - Diffusion of GW-level heat generated across a complete data center campus.
- **Understanding of Heterogeneity in Equipment, Energy Consumption, Policies**
  - Computing equipment is heterogeneous and difficult to model in terms of energy consumption.
  - Heterogeneity of policy aspects that constrain grid development.
  - Diverse community considerations.
  - Heterogeneity in batteries, supply, and their cost.
  - Heterogeneous reliability expectations for energy supply.

IMPLICATIONS (1)

- **Different Perspectives of Grid and Computing Providers**
  - From grid side, rapid load variations must be made up with variable sources (solar, wind), local battery storage, controlled fossil plants, or combinations.
    - Such behavior at 1000 MW scale is far outside of prior experience or available technology.
  - From compute side, resources need to be fully available and installed in time scale of months rather than years.
  - From thermal side, heat dissipation from a 5000 MW data center is on the scale of nuclear plant, but operating temperatures are intended to be quite low (order of 70° C), making heat removal very challenging.

IMPLICATIONS (2)

- **Funding Diversity**
  - Grid and data center cash flow and investments ultimately come from families and individual consumers.
    - Value of data centers is not being conveyed effectively to these end customers.
  - Investments are driven by computing industry, and they reach into energy, thermal and other contexts, hence there is a need for comprehensive system considerations and corresponding funding of energy systems.
- **Electrification of Other Sectors**
  - Other sectors are undergoing electrification changes – cement manufacturing, steel manufacturing, and other industrial process-oriented industries (robotics), electric vehicles and their charging infrastructure, ...and contribute to load growth and to flexible load demands.
  - How can data centers and potential flexibility enhance the value of distributed and renewable resources to serve other sectors?

NEXT STEPS

- **Building interfaces among technical and other stakeholder communities**
  - Grid operators, facility designers, cloud SW engineers, power system engineers, power electronics engineers, thermal system engineers, computing-networking-hardware engineers, policy experts, regulators, …
- **Need for**
  - Fine-grained data collection and development of standards for relevant data.
  - Regulatory changes to drive effective reporting about energy and water consumption.
  - Development of accurate dynamic models for grid-data center operations.
  - Comprehensive planning in conjunction with community engagement.
  - Comprehensive collaborative teams.

ADDITIONAL INSIGHTS/COMMENTS FROM ATTENDEES

INTERESTING INSIGHTS/COMMENTS FROM ATTENDEES (1) – GRID PERSPECTIVE

- **Jevons Paradox**: Efficiency improvements do not tend to reduce energy demands and may drive them up as systems get larger.
- There are a few emerging **grid load rescheduling and load throttling methods** but not at the dynamic rates associated with shifts in computing processes.
- There is an urgent need to better define **switchover and dropout behavior** to reduce unanticipated large scale grid disturbances.
- **Interesting numbers**:
  - 100 MW of electrical base load must be linked to about 3 mi^2 of land (about 750 hectares) if it is to be covered with photovoltaics and batteries.
  - 1000 MW load is typical of a large city (e.g., Philadelphia).

INTERESTING INSIGHTS/COMMENTS FROM ATTENDEES (2) – GRID PERSPECTIVE

- Anticipated spending for data centers will **reach $3 trillion by 2028 with 10%** going to electrical energy.
- Multiple project **reduce energy needs per unit of computation by 10x**, but the pace of growth exceeds the rate of improvement – Jevons paradox (training requirements are growing about 10x every 18 months).
- **Renewable energy and workload migration** are central to future development of datacenters.
- Issue of "**Who should pay for power variability?**" was raised. Cost for power variability is not fully quantified yet.

INTERESTING INSIGHTS/COMMENTS FROM ATTENDEES (3) – GRID PERSPECTIVE

- In a massive data center, even components with million-hour mean time between failures (MTBF) will experience almost daily failures based on huge numbers of devices.
  - Failure identification, management, isolation, repair must be planned into design.
- Dc distribution at 400 V and at +/- 400 V (and equivalent 800 V) are near deployment.
  - However, there are not enough qualified manufacturers/vendors to support dc distribution above 400 V dc.
  - It is important to make distinction between unipolar and bipolar dc (there were misconceptions about this distinction).

INTERESTING INSIGHTS/COMMENTS FROM ATTENDEES (4) – THERMAL PERSPECTIVE

- Data centers generate large amounts of low grade heat (rarely more than 70° C) . **Liquid cooling can help concentrate the heat** that can be used for home heating, hothouse agriculture, etc.
- Water consumption is a concern and so some data center developers go towards **closed-loop liquid cooling systems** that push heat to the atmosphere to reduce pressure on water consumption.
  - Advanced cooling methods typically require high water quality.
- **Cooling systems** sizing and reliability are critical issues.
  - Racks at 1 MW need liquid cooling and must be extremely robust (two-phase and immersive cooling are being investigated).
- Few data center integrators use **ground-source** as effective thermal storage, but ground source heat pumps have scale limitations. It is hard to envision scaling up to a factor of 1000 MW data center.

INTERESTING INSIGHTS/COMMENTS FROM ATTENDEES (5) – COMPUTING PERSPECTIVE

- LLMs impose **high cost and latency**
  - Example of tradeoffs: adding a bit of latency and slowing response by about 10% can provide 5x reduction in compute energy per token.
- Pathways to 10x and 20x improvements need **new algorithms and more flexible HW**.
- We need comprehensive **energy state management** so that idle hardware draws no power.
- **Sustainability**, including embodied carbon content, operational energy consumption, water and other factors should be highlighted at the intersections of design, operation, grid awareness, and models for hardware components, generation mix, etc.

WEBSITE OF THE WORKSHOP

- NSF Compute-Energy Nexus in Chicago | Coordinated Science Laboratory | Illinois
  - December 8-9, 2025, DPI, Chicago, IL
  - The website includes
    - Agenda, speakers, slides of presentations.
    - NSF report will be advertised on this website as well.
- **Other related workshops and reports:**
- NSF-WSCS 2024 (NSF Workshop on Sustainable Computing for Sustainability)
  - April 2024, Washington DC
- CSL Compute-Energy-Nexus Workshop | Coordinated Science Laboratory | Illinois
  - November 2024, CSL, UIUC, Urbana, IL.