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DATA CENTRES AND INDIA'S POWER GRID

Technical Review of Grid Integration Challenges and Research Agenda

WHITE PAPER

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2026

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This report reflects inputs and review from stakeholders across the Indian power ecosystem, including utilities, system operators, market institutions, regulators, and technology providers. Any remaining errors or omissions are the responsibility of the authors.

FOREWORD

AI training workloads introduce rapid power fluctuations of 20–40% at sub-minute timescales, creating "instant fluctuations" that can strain even the most robust systems.

Visakhapatnam is currently at the heart of a historic transformation within the digital economy and energy sector. The landmark **$15 billion** investment announcement of the **"Google AI Hub"**—which brings a **1 GW** data center investment into the Visakhapatnam Economic Region—has effectively turned our city into a magnet for major global players. With a total of **6 GW** in data center commitments now on the horizon, alongside new sea landing cable stations, we are witnessing a complete reshaping of our regional economic landscape

As the Chairman and Managing Director of **APEPDCL** and Vice Chairman of the **Center of Excellence for Energy Transition (CoEET)**, I am pleased to introduce this white paper, **"Data Centers and India's Power Grid,"** developed in collaboration with **FSR Global**.

This unprecedented scale of computational infrastructure—where individual AI clusters are reaching the gigawatt scale—presents a fundamental **"Grid Challenge"**. Unlike traditional industrial loads, modern data centers maintain exceptionally high load factors. Furthermore, AI training workloads introduce rapid power fluctuations of **20–40%** at sub-minute timescales, creating "instant fluctuations" that can strain even the most robust systems. To manage this, we must transition from reactive oversight to a model of proactive and intelligent grid management.

This white paper provides a strategic framework to navigate these complexities through three critical pillars:

- **Grid Readiness Certification:** Establishing world-class power quality standards (IEEE 519/1159) to meet the 99.995% uptime required by hyperscalers.
- **Behind-the-Meter Renewable Integration:** Developing frameworks to absorb excess captive RE generation while managing the "Duck Curve" dynamics through advanced battery storage.
- **Data Centers as Grid Assets:** Regulatory enablement to provide critical primary and secondary frequency response to the grid.

At APEPDCL, our commitment is to ensure Andhra Pradesh remains the premier destination for high-tech investment by building a power grid that is as intelligent as the AI hubs it supports.

Prudhvi Tej Immadi (IAS)
Managing Director, APEPDCL
Vice Chairman, Center of Excellence for Energy Transition (CoEET)

Contents

Abstract

India's data center capacity is projected to grow significantly by 2030, with estimates ranging from 4–5 GW (conservative) to 12–17 GW (aggressive). This paper uses an 8–10 GW scenario representing AI-accelerated growth for analytical purposes. This expansion is part of a global surge that will see data center electricity consumption double from 415 TWh to 945 TWh by 2030 [1], introducing significant challenges for a grid already managing ambitious 500 GW non-fossil energy targets.

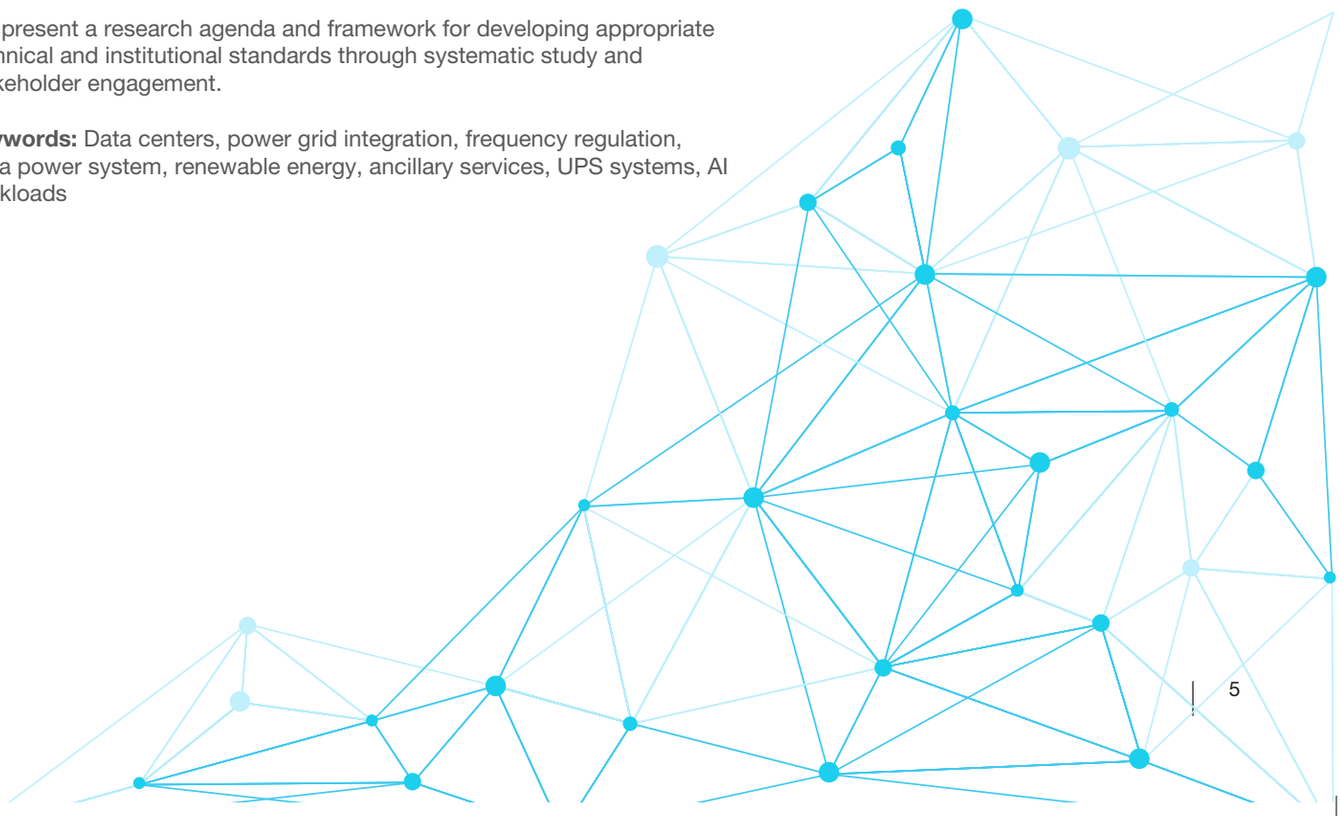
This white paper reviews technical literature on data center-grid interactions, examining steady-state loading patterns, dynamic stability implications of UPS fault-ride-through behavior, and AI workload variability. Drawing on international case studies from Ireland (22% of electricity from data centers), Texas (226 GW interconnection queue), Singapore (efficiency mandates), and France (DCFlex pilot), we identify key areas requiring India-specific study.

The analysis suggests that without proactive grid integration planning, concentrated data center growth could contribute to localized voltage and frequency challenges during grid disturbances—as illustrated by the August 2024 high-frequency events reaching 50.39 Hz during solar surplus periods.

Beyond the technical dimensions—which are tractable through established power engineering methods once validated load models are developed—the paper identifies institutional challenges that are less well understood and potentially more consequential. At projected scale, data centers are positioned to reshape procurement through open access and captive generation, creating cross-subsidy erosion and stranded infrastructure risk for distribution utilities. RE procurement claims risk certificate trading without atmospheric benefit unless additionality criteria are enforced.

We present a research agenda and framework for developing appropriate technical and institutional standards through systematic study and stakeholder engagement.

Keywords: Data centers, power grid integration, frequency regulation, India power system, renewable energy, ancillary services, UPS systems, AI workloads



1 INTRODUCTION

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1.1 The Regulatory Window

India's data center capacity is projected to reach 8–10 GW by 2030, backed by investment commitments exceeding $50 billion. The facilities being designed and contracted in 2025–2026 will operate for 15–20 years, locking in design choices—UPS ride-through capability, grid interface specifications, procurement structures—that will prove costly to retrofit.

This paper argues that the data center buildout is not primarily a load growth problem but a market structure challenge. At projected scale, data centers acquire sufficient commercial leverage to reshape electricity procurement through open access and captive generation, eroding DISCOM cross-subsidy revenue by an estimated Rs. 15,000–25,000 crore annually and creating stranded infrastructure risk for utilities that invest in dedicated connection assets. The technical dimensions—dynamic load modeling, ride-through standards, power quality—are tractable in principle but require validated models and India-specific standards that do not yet exist. The institutional dimensions—tariff design, interconnection cost allocation, RE procurement additionality—are less well understood and, in our assessment, more consequential.

This paper synthesizes primary regulatory sources (CEA, CERC, state commission orders), GRID-INDIA operational data, applicable IEEE/IEC standards, and international case studies to frame the research agenda for both.

1.2 Scale of the Challenge

Global data center electricity consumption will double from approximately 415 TWh (2024) to 945 TWh by 2030 [1], with AI's share rising from an estimated 5–15% to 35–50%. India is outpacing global trends—historical capacity CAGR of ~24% versus ~15% globally [1]—positioning it to increase its share of global data center energy from 3.1% to 6.0% by 2030.

The IndiaAI Mission (Rs. 10,371 crore government allocation), combined with major private-sector commitments—Reliance + Nvidia's AI campus partnership, with Bloomberg reporting a potential $20–30 billion, 3 GW facility in Jamnagar (January 2025), Amazon AWS's $8.3 billion Maharashtra investment [2], and over $30 billion in combined announcements from Microsoft and Google—signals unprecedented growth [3].

Current installed capacity stands at approximately 1.0–1.4 GW, concentrated in Mumbai ~53% of installed capacity [4]), Chennai, Hyderabad, Bengaluru, NCR, and increasingly Visakhapatnam. Industry projections for 2030 vary significantly (Table 1) [3, 5, 6]. This paper uses the 8–10 GW AI-accelerated scenario for analytical purposes.

1.3 The Grid Context

This capacity expansion enters a grid navigating declining system inertia, afternoon generation surplus from solar, and transmission evacuation constraints [7, 8]—challenges that the August 2024 frequency excursions (50.39 Hz peak) brought into sharp focus [9, 10].

Data centers add a qualitatively different problem: constant-power electronic loads whose behaviour during grid disturbances bears no resemblance to the agricultural, industrial, and residential loads that India's grid codes and planning tools were built for. The IEGC operating band of 49.90–50.05 Hz for normal operation [11] leaves minimal headroom.

Table 1: India Data Center Capacity Projections for 2030

Scenario	Capacity	Sources
Conservative	4–5 GW	Savills India, CRN
Base case	5–7 GW	IEEFA, JLL
AI-accelerated	8–10 GW	S&P Global, Jefferies
Aggressive	12–17 GW	Various industry reports

Capacity Growth Scenarios (2024-2030)

Four Scenarios based on different growth drivers and policy outcomes

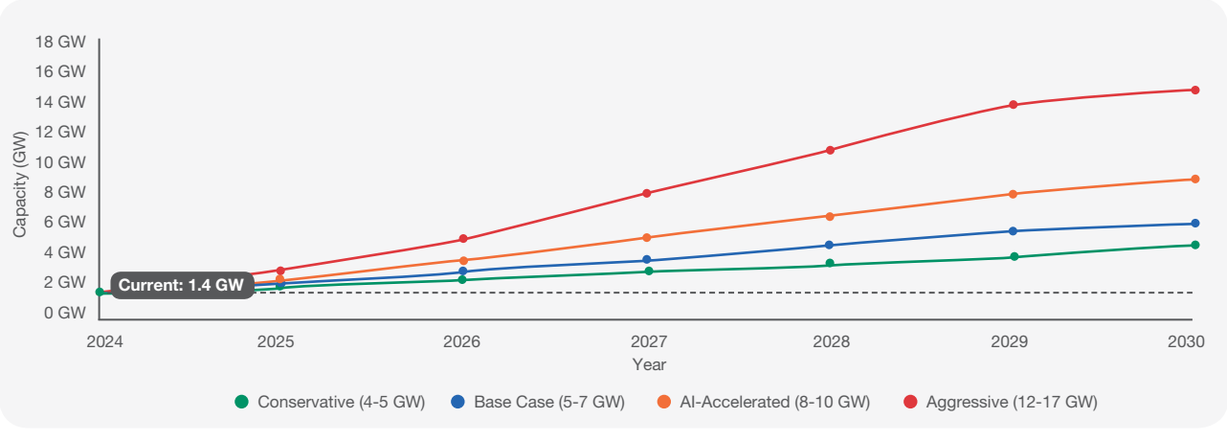

Figure 1: India Data Center Capacity Growth Scenarios (2024–2030). The shaded regions represent different growth trajectories ranging from conservative (4–5 GW) to aggressive (12– 17 GW), with the AI-accelerated scenario (8–10 GW) used for analytical purposes in this paper.

Regional Distribution

Current and projected data center concentration by region

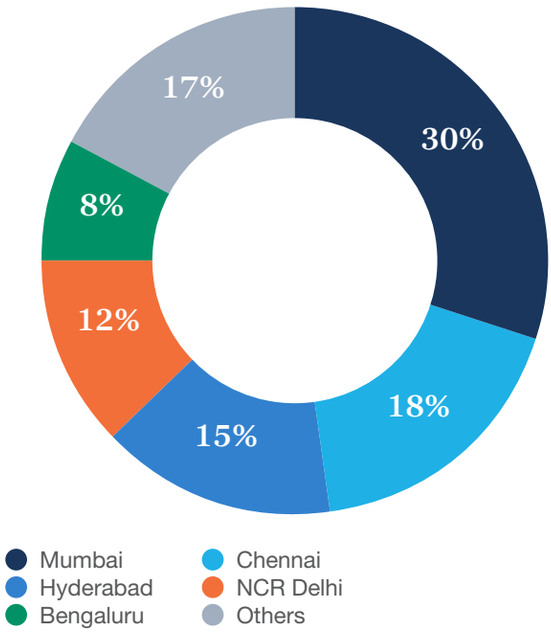

Figure 2: Projected Regional Distribution of Data Center Capacity in India (2030). Current capacity is concentrated in Mumbai (~53% of installed base [4]); by 2030, growth in Chennai, Hyderabad, and NCR is expected to diversify the distribution while Mumbai retains the largest share.

- **Declining System Inertia:** Replacement of synchronous generators with inverter-based resources reduces the grid's natural resistance to frequency deviations
- **Increased Variability:** Solar and wind generation introduce uncertainty at timescales from seconds to hours
- **Duck Curve Emergence:** GRID-INDIA's August 2024 reports document significant afternoon generation surplus periods, with frequency excursions reaching 50.39 Hz [5, 6]
- **Transmission Constraints:** Green Energy Corridors from Rajasthan face severe evacuation bottlenecks, with 4.3 GW of RE curtailed during peak hours [7]

The tight frequency regulation band mandated by the Indian Electricity Grid Code (IEGC)—49.90 to 50.05 Hz for normal operation—leaves minimal headroom for large load variations [8].

1.4 Research Questions

This paper addresses the following research questions:

1. How do modern data center loads, particularly those supporting AI/ML workloads, differ from traditional industrial loads in their electrical behavior?
2. What are the steady-state and dynamic impacts of large-scale data center deployment on the Indian power grid?
3. What can data center demand flexibility realistically offer grid operations—and what is beyond its capability?
4. What are the implications for electricity market structure, distribution utility viability, and resource governance when a concentrated consumer category acquires leverage to reshape procurement?
5. What governance frameworks are needed where data center water demand intersects with agricultural and municipal allocations in water-stressed regions?


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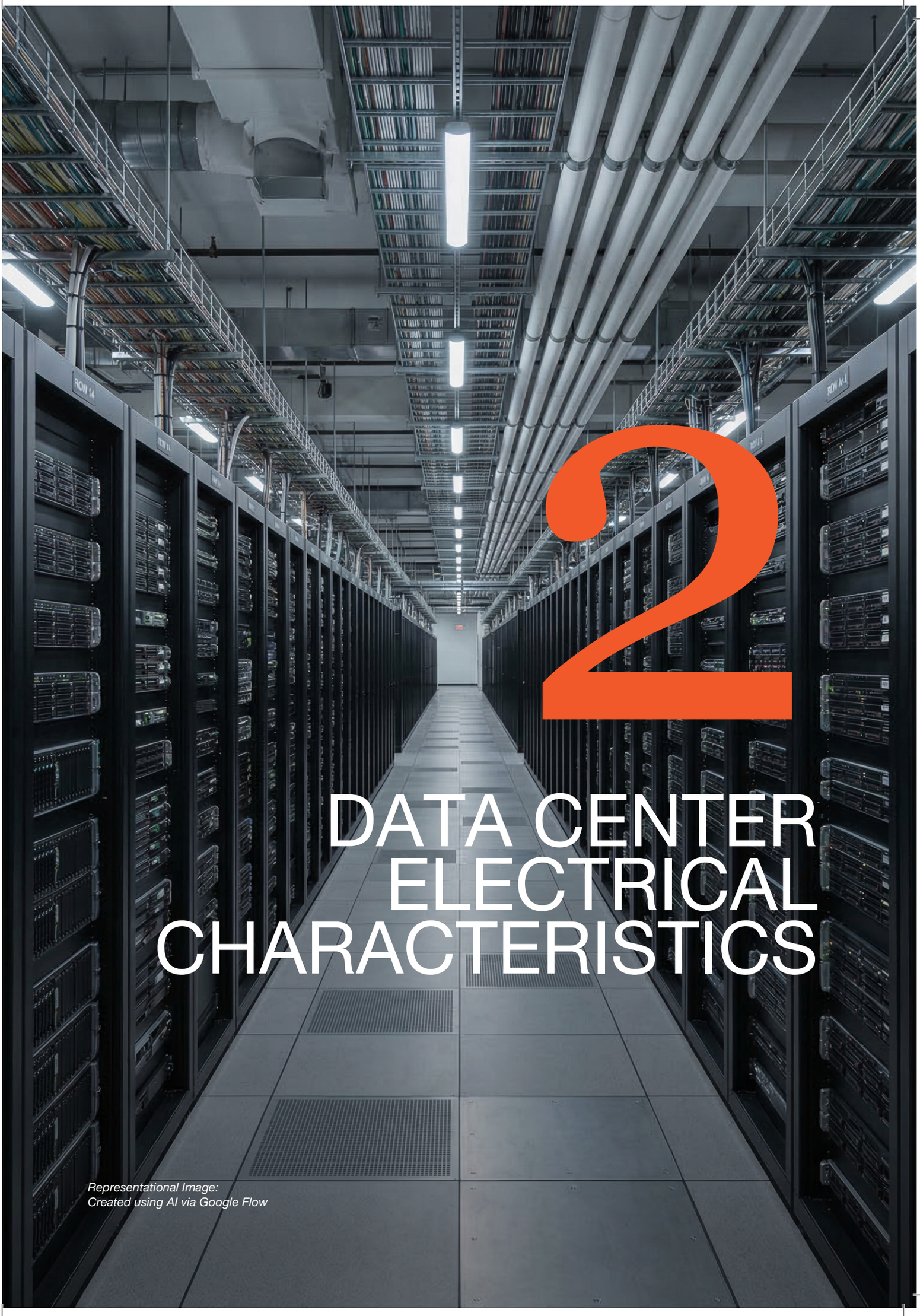


2

DATA CENTER ELECTRICAL CHARACTERISTICS

Representational Image:
Created using AI via Google Flow

2.1 Load Profile and Power Quality

Data centers maintain load factors above 0.85 (versus 0.5–0.6 for typical industrial loads), with power factors of 0.95–0.99 at the IT load level due to active power factor correction. Overall facility power factor ranges from 0.90–0.95 (air-cooled, due to induction motor cooling loads) to 0.95–0.98 (liquid-cooled). Switch-mode power supplies generate characteristic harmonics at the 5th, 7th, 11th, and 13th orders; aggregated THD of 5–15% at the point of common coupling without mitigation can exceed IEEE 519 limits [12].

2.2 AI/GPU Workload Dynamics

AI training workloads present a qualitatively different load profile. Large language model training involves synchronized computational phases—forward pass, gradient synchronization, optimizer step—that complete in seconds, creating power oscillations of 20–40% of cluster rated capacity [13]. For a 100 MW AI training cluster, this means 20–40 MW fluctuations at sub-minute timescales.

Industry analysis suggests AI datacenters may exhibit power fluctuations an order of magnitude larger than traditional cloud facilities—15 MW versus 1.5 MW [13]. Meta's LLaMA 3 training on 24,576 H100 GPUs [14] involved scenarios where GPU clusters increased or decreased power consumption simultaneously, with industry estimates of fluctuations on the order of tens of megawatts.[1]

2.3 UPS Topology and Grid Interface

The dominant double-conversion (online) UPS rectifies incoming AC to DC, maintains a battery bus, and inverts back to AC for IT loads, providing complete isolation from grid disturbances. Grid interface characteristics include input power factor of 0.99 with active front-end rectifiers and THD below 5% with 12-pulse or active front-end designs. During voltage sags, the battery supplies the deficit with no output disturbance—until input protection trips, at which point the entire facility load vanishes instantaneously.

2.4 Dynamic Load Modeling Gap

Every grid impact assessment in this paper—and every stability study that GRID-INDIA or the SLDCs will undertake for data center interconnection—depends on having an accurate dynamic load model. Without validated models, the downstream analysis is unreliable. This gap is more fundamental than any individual grid code requirement.

Indian power system studies rely on composite load models combining static polynomial (ZIP) representations with induction motor equivalents [15]. These were developed for agricultural pumps, industrial drives, and residential air conditioning [16]. A data center with active power electronics front-ends, UPS battery systems, and rapid GPU-driven power cycling bears no resemblance to this load mix.

The distinction matters. During a voltage disturbance, a conventional industrial load draws increased or reduced current in broadly predictable ways. A double-conversion UPS maintains constant power to the IT load by drawing from its battery bus—presenting near-zero load change to the grid until its input protection trips, at which point the entire facility load vanishes instantaneously [17]. This binary behaviour—full load or no load, with minimal intermediate states—is qualitatively different from anything in standard load model libraries.

For AI-heavy facilities, the problem compounds. The sub-minute power oscillations described in Section 2 occur at timescales faster than most load models are designed to capture [13]. Whether these oscillations aggregate into grid-visible effects or cancel out across thousands of servers within a facility is an empirical question that cannot be resolved through assumption.

Four parallel efforts would address this gap: 1. Field measurement campaigns at existing Indian data centers to characterize real power, reactive power, and harmonic behaviour across operating conditions—particularly during grid voltage and frequency excursions. 2. Validated component models for double-conversion UPS systems, including battery charge/discharge dynamics and protection trip logic, suitable for PSS/E or PowerFactory [18]. 3. Aggregate facility models that represent the collective behaviour of hundreds of UPS modules, cooling systems, and power distribution units at a single site. 4. Sensitivity testing of existing SLDC stability study conclusions to data center load model assumptions—particularly for the Western Region, where Mumbai's concentration warrants immediate attention.

Until these models exist, grid impact assessments for large data center interconnections are better treated as indicative rather than definitive, and planning margins would benefit from reflecting this uncertainty.

[1] SemiAnalysis is an industry newsletter; the specific oscillation magnitudes have not been independently verified in peer-reviewed literature. Meta's infrastructure report confirms the training cluster scale but does not quantify power fluctuations.

Traditional vs AI Data Center Load Profiles

Comparison of power demand patterns over a 24-hours period

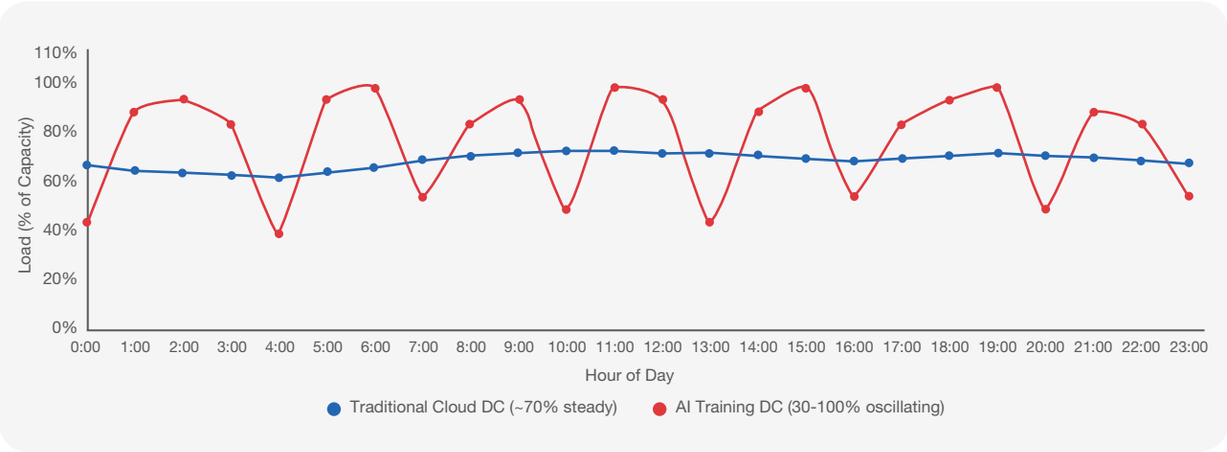


Figure 3: Comparison of Traditional vs. AI Data Center Load Profiles. Traditional cloud workloads maintain steady utilization around 70%, while AI training workloads exhibit rapid oscillations between 30–100% as GPUs cycle through forward pass, gradient calculation, and synchronization phases.

Table 2: Industry Examples of AI Cluster Scale

Facility	IT Capacity	Notes
OpenAI cluster	~300 MW IT	Large-scale training
Meta LLaMA-3	30 MW IT	24,000 H100 GPUs
xAI Colossus	150 MW	Demand response enabled

AI Cluster Scale Comparison

Power requirements of major AI training deployments

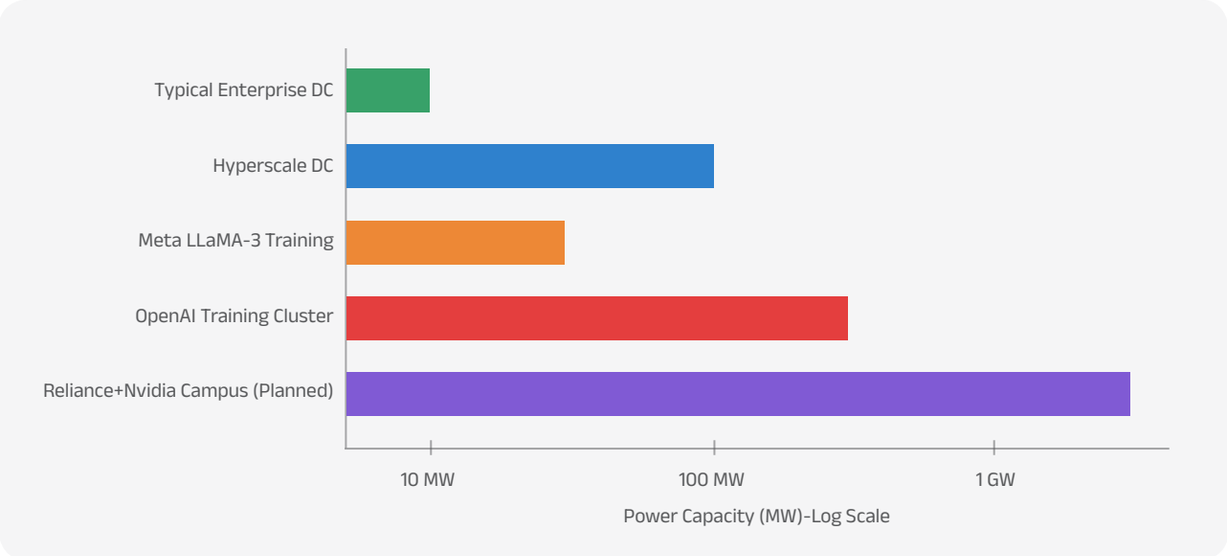


Figure 4: AI Cluster Scale Comparison (logarithmic scale). Modern AI training facilities operate at scales orders of magnitude larger than traditional data centers, with announcements like Reliance's 3 GW AI campus representing a new frontier in facility size.

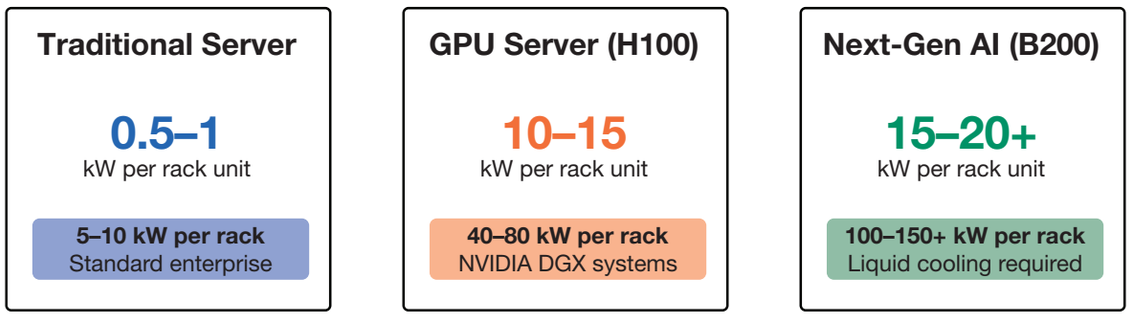
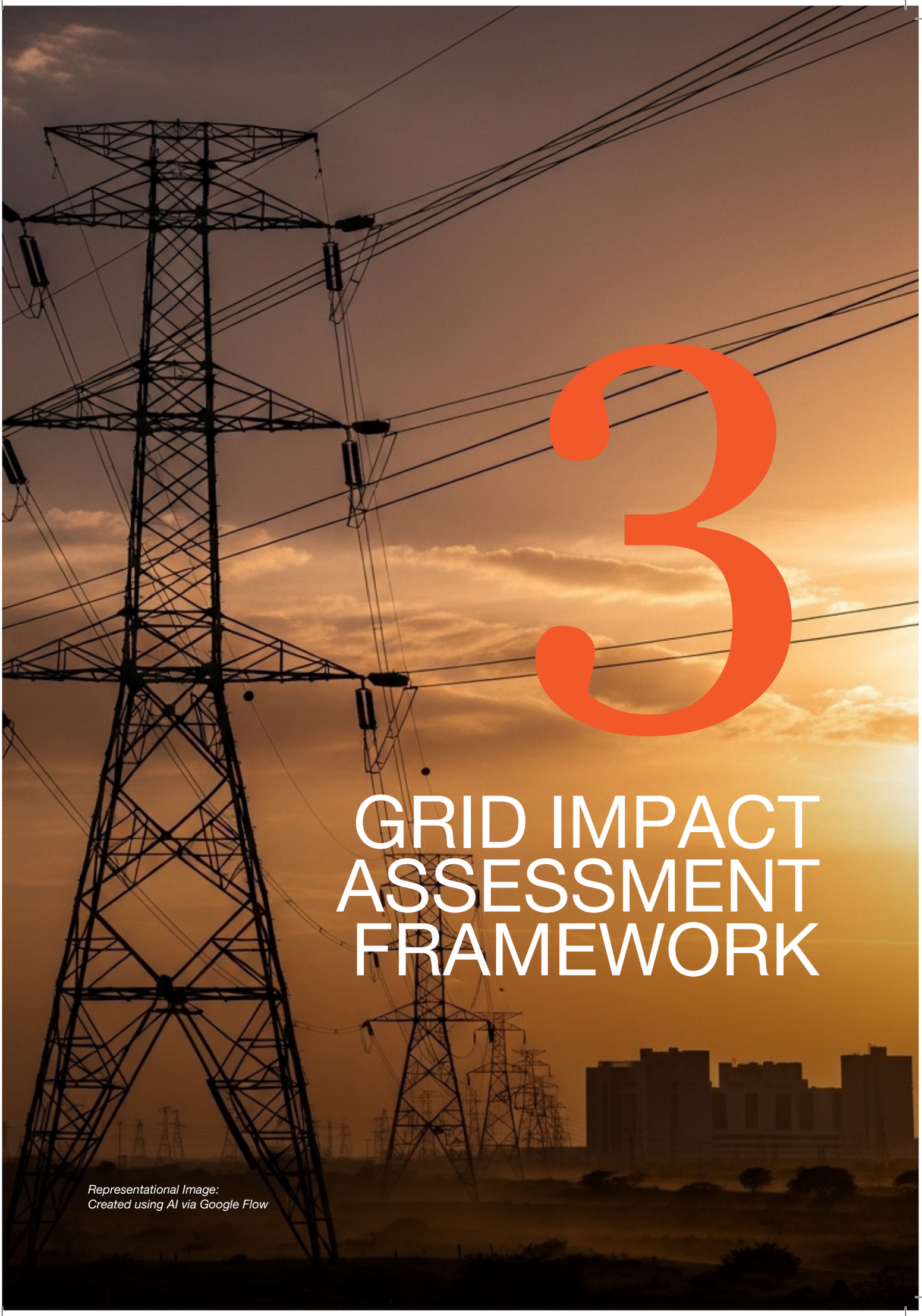


Figure 5: Evolution of Rack Power Density. AI workloads are driving rack densities from traditional 5–10 kW to 40–100 kW per rack, requiring advanced cooling solutions and higher- capacity electrical infrastructure.

1. Rectify incoming AC to DC
2. Charge battery bank and supply DC bus
3. Invert DC back to AC for IT loads
4. Provide complete isolation from grid disturbances

Grid interface characteristics include input power factor of 0.99 with active front-end rec- tifiers, THD <5% with 12-pulse or active front-end designs, and no output disturbance during voltage sags (battery supplies deficit).



3

GRID IMPACT ASSESSMENT FRAMEWORK

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3.1 Steady-State Analysis

At projected 2030 penetration levels (8–10 GW), data centers would represent approximately 2.6–3.3% of India's total electricity consumption.[2]

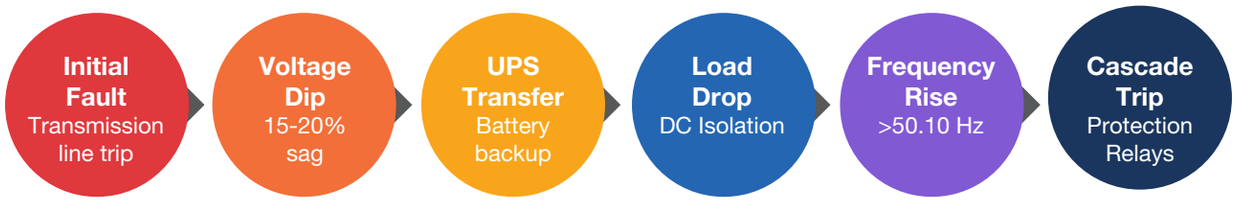
Regional concentration creates localized impacts: Western Region (Mumbai): 2–3 GW concentrated load on Kalwa/Padghe corridor. Southern Region: Chennai-Hyderabad-Visakhapatnam: 2–3 GW distributed across states, with Visakhapatnam emerging as a major new corridor (~1.75 GW committed). Northern Region (NCR): 1–1.5 GW with air quality restrictions on backup generation.

3.2 Dynamic Stability Considerations

During the July 2024 Virginia incident, 1.5 GW of data center load disconnected across 60 facilities during voltage depressions of 0.25–0.40 per unit over an 82-second auto-reclosing sequence [17]. UPS protection settings were not coordinated with grid requirements, demonstrating the potential for cascading disconnections at regional scale.

Cascading Disconnection Scenario

Potential cascade sequence following a major grid disturbance



Virginia July 2024 Incident

A similar cascade resulted in 1.5 GW of data center load disconnecting from the PJM grid, demonstrating the systemic risks of concentrated DC loads.

Figure 6: Cascading Disconnection Scenario. A grid fault can trigger a chain reaction: initial voltage dip causes UPS systems to transfer to battery, simultaneous load reduction creates frequency deviation, which can trigger additional disconnections at other facilities, potentially destabilizing the grid further.

3.3 Ride-Through and Power Quality

Current Indian grid codes focus ride-through requirements on generators, not large loads. Data centers' UPS behaviour during voltage and frequency disturbances creates a load-equivalent concern [18]. International frameworks—the ENTSO-E Demand Connection Code [20], Ireland's CRU Large Energy User Policy [21]—provide reference points, and decentralized control has demonstrated voltage deviation reduction from 0.383 pu to 0.087 pu (84% improvement) using 5 ms intervals [18].

On power quality: per IEC 61000-3-3 [22], a 100 MW load step at a 220 kV bus with 10 GVA short-circuit capacity produces $\Delta V/V = 1\%$, with Pst of 0.3–0.5 (below the 1.0 limit). Large AI clusters (500+ MW) at weaker grid points require site-specific flicker assessment.

3.4 Distribution-Level Impacts

A substantial share of India's data centers connect at 33 kV or 11 kV distribution voltages. A 20 MW data center draws roughly 24 MVA continuously; many 33/11 kV substations in Indian urban areas operate with transformers already loaded to 60–70% during summer peaks [23]. Adding a data center can push loading into contingency-risk territory.

Rapid AI workload transients at distribution voltages, where short-circuit ratios are lower, produce proportionally larger voltage swings than the flicker assessment above (which assumed a 220 kV bus with 10 GVA fault level) would suggest [22]. UPS solid-state transfer switches disconnect within half a cycle [18], and sudden load reduction on a distribution feeder can cause relay miscoordination at the substation.

CEA's technical standards address generators and transmission-connected loads [24], but distribution-level connection of 10–50 MW constant-power electronic loads falls into a procedural gap.

[2] Calculation: At 9 GW capacity with ~85% load factor, annual consumption would be approximately 67 TWh (9 GW × 0.85 × 8,760 hours). Against projected 2030 national consumption of ~2,300 TWh [19], this represents approximately 3% of demand.

4

INTERNATIONAL EXPERIENCE

Representational Image:
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4.1 Ancillary Services: What Data Centers Can and Cannot Provide

Much of the optimism around data center grid participation conflates what co-located equipment can do with what the data center load itself can do [25]. A clear-eyed assessment requires separating these.

What data center loads cannot provide. PRAS under CERC's framework requires fully automated, instantaneous response to frequency deviations [25, 26]. Server workloads are not designed to be modulated by grid frequency signals, and no operator will accept a control architecture where external grid conditions interrupt computation. SRAS requires response within 30 seconds sustained for 30 minutes [25]. Abruptly reducing 30% of a training cluster's power for 30 minutes is a service outage, not demand response.

What co-located batteries can provide. A BESS at the same point of coupling can provide both PRAS and SRAS—but this is a standalone storage investment that happens to share a site, not "data center participation" in any operationally meaningful sense. BESS installed for UPS backup is sized and financed for reliability, not grid services. Every cycle used for frequency response degrades cells intended for a different purpose. At CERC's current compensation levels—Rs. 8–10 lakh/MW-year for PRAS, Rs. 6–8 lakh/MW-year for SRAS [25, 26]—the revenue may not justify the cost or the risk.

What AI-heavy facilities can genuinely offer: scheduled demand flexibility. AI training workloads can tolerate planned interruptions [13]. Checkpoint-restart architectures allow training jobs to be paused and resumed with some efficiency overhead [27]. The constraints are specific: advance notice of hours, not seconds; training workloads only, not inference or cloud services with SLA commitments. The analogy is interruptible industrial tariffs, not spinning reserve.

For India's grid, where the primary emerging challenge is absorbing midday solar surplus [9, 10], this has genuine value. A large AI campus that increases training workload during the 10:00–14:00 solar surplus window and reduces it during the 18:00–22:00 evening peak provides real load shaping—by reducing the ramping burden on thermal generators, not through real-time frequency response.

Regulatory implication. CERC's Ancillary Services Regulations 2022 include provisions for "entity capable of providing demand response" [25], creating a legal pathway. But the framework was designed for dispatchable generation and storage, not for schedulable-but-not-dispatchable loads. A new product category—"scheduled demand modulation," with its own notification periods, minimum duration, verification protocols, and compensation—would better capture what data centers can actually provide. Fitting data center flexibility into existing PRAS/SRAS categories risks producing either non-compliance or non-participation.

4.2 Ireland: Crisis and Response

Ireland's data centers consume 22% of total metered electricity 2024 data) [28–30], up from 5% in 2015. EirGrid imposed an effective moratorium on new connections in the Dublin area from 2021. The CRU's December 2025 Large Energy User Policy replaced the moratorium with dispatchability requirements for facilities above 5 MW, an 80% renewable mandate through long-term PPAs, and required participation in demand response programs [21].

Representational Image:
Created using AI via Google Flow

Data Center Electricity Share by Region

Percentage of national/regional electricity consumed by data centers

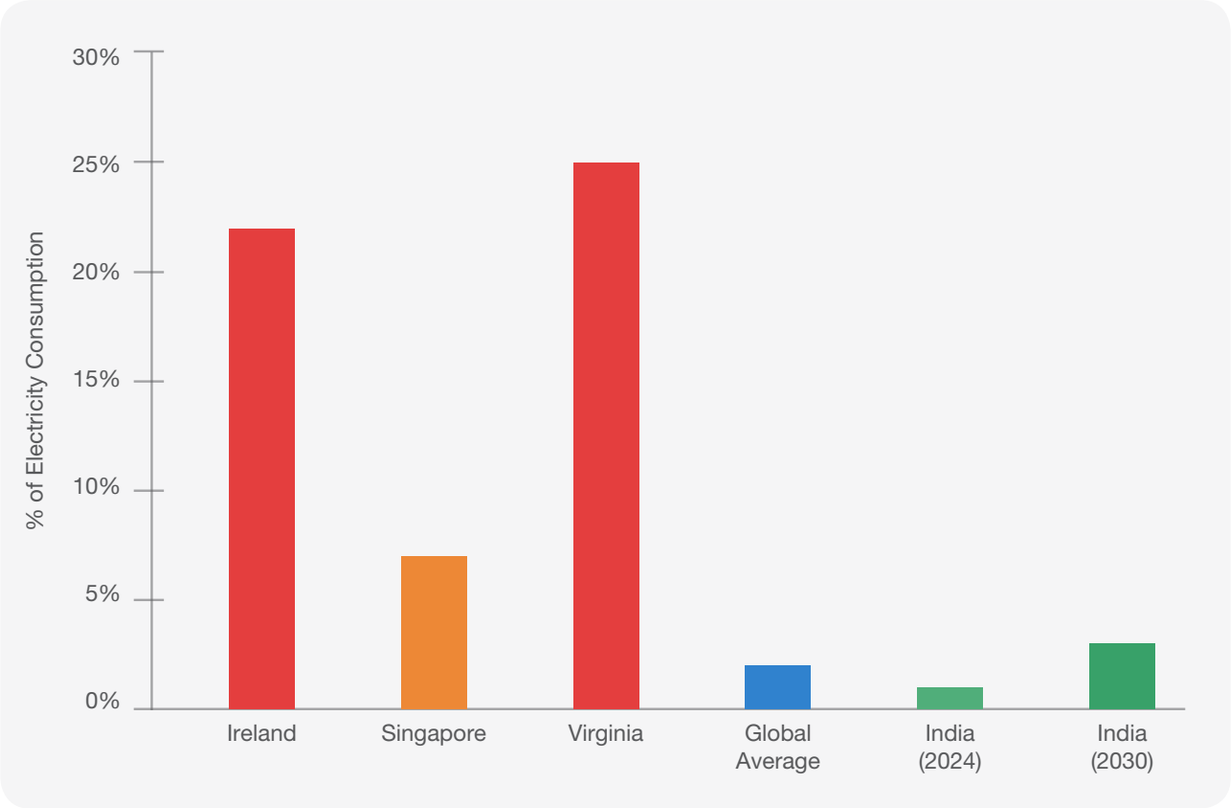


Figure 7: Data Center Share of National Electricity Consumption. Ireland leads globally at 22%, while India's projected 2030 share of 2.6–3.3% remains manageable at the national level but creates significant regional concentrations.

4.3 Texas (ERCOT): Queue Explosion

ERCOT's large load interconnection queue reached 226 GW by November 2025—up 259% in a single year—with data centers comprising over 70% of requests [31, 32]. Texas RE warned that "disorganized integration of large loads constitutes the largest increased risk to the grid" [33]. Senate Bill 6 introduced mandatory curtailment protocols and more rigorous interconnection criteria for large electronic loads [34].

4.4 Singapore: Efficiency-First Approach

Singapore imposed a complete moratorium on new data centers from 2019–2022, then introduced competitive allocation with efficiency mandates: PUE ≤1.30 (CFA1, 2022) and PUE ≤1.25 (CFA2, December 2025), plus a 10-year roadmap for existing facilities to upgrade [35, 36]. India's diverse climate zones may warrant differentiated regional efficiency standards rather than uniform national mandates.

Regulatory Response Matrix

Comparison of policy approaches across jurisdictions

Jurisdiction	Moratorium	Efficiency Mandates	Grid Services	RE Requirements	Key Policy
Ireland	✓ 2021-22	—	✓	80% RE by 2025	Strict connection criteria
Singapore	✓ 2019-22	PUE ≤ 1.25	—	BCA Green Mark	Efficiency-first approach
Texas (ERCOT)	—	—	✓ SB6	—	Market-based curtailment
Virginia (PJM)	—	—	✓	State RE mandates	Transmission upgrades
India (Potential)	—	Under discussion	Potential	RPO obligations	Framework emerging

Figure 8: International Regulatory Response Matrix. Different jurisdictions have adopted varied approaches to data center grid integration, from moratoria (Ireland 2021–25, Singapore 2019–22) to efficiency mandates (Singapore) to grid service requirements (Texas SB6). Note: Ireland's moratorium was replaced by the CRU's Large Energy User connection policy in December 2025.

4.5 France: DCFlex Pilot

The DCFlex initiative tests data center grid service feasibility [37–39]: a three-year program with RTE, EPRI, Schneider Electric, and major hyperscalers, testing frequency response, demand management, and renewable integration. A France demonstration began in early 2025; results are expected 2025–2027. This pilot provides a model for validating grid services participation before regulatory mandates.

5

INDIA-SPECIFIC GRID INTEGRATION CHALLENGES

Representational Image:
Created using AI via Google Flow

5.1 Frequency Regulation Context

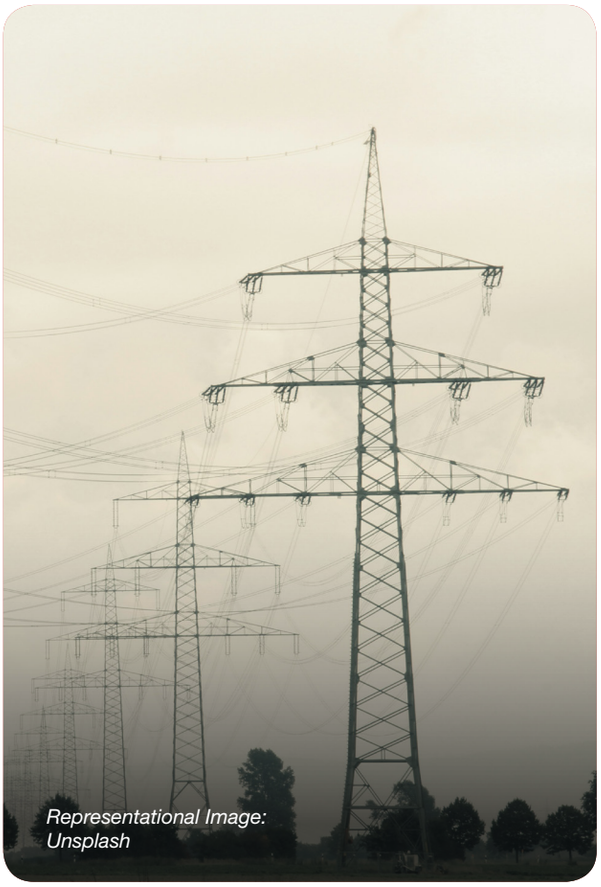
August 2024 High-Frequency Events [9, 10]: August 4: Peak 50.39 Hz 26% of time above 50.05 Hz ceiling; 226 minutes). August 11: Peak 50.329 Hz (33% of time above ceiling; 120 minutes). August 25: Peak 50.377 Hz (38% of time above ceiling; 258 minutes). Root causes included solar generation ~40 GW exceeding demand and inflexible thermal generation at minimum levels.

Table 3: India Frequency Operating Bands

Frequency	Status	Action
50.00 Hz	Ideal	No action
49.95–50.05 Hz	Normal	No action
49.90–49.95 Hz	Alert	Monitor closely
<49.90 Hz	Emergency	Load shedding
>50.05 Hz	Over-frequency	RE curtailment

- August 18: Peak 50.26 Hz (26% time above ceiling)

Root causes included solar generation ~40 GW exceeding demand and inflexible thermal generation at minimum levels.



Representational Image: Unsplash

Frequency Operating Bands

IEGC frequency bands and recent excursion events

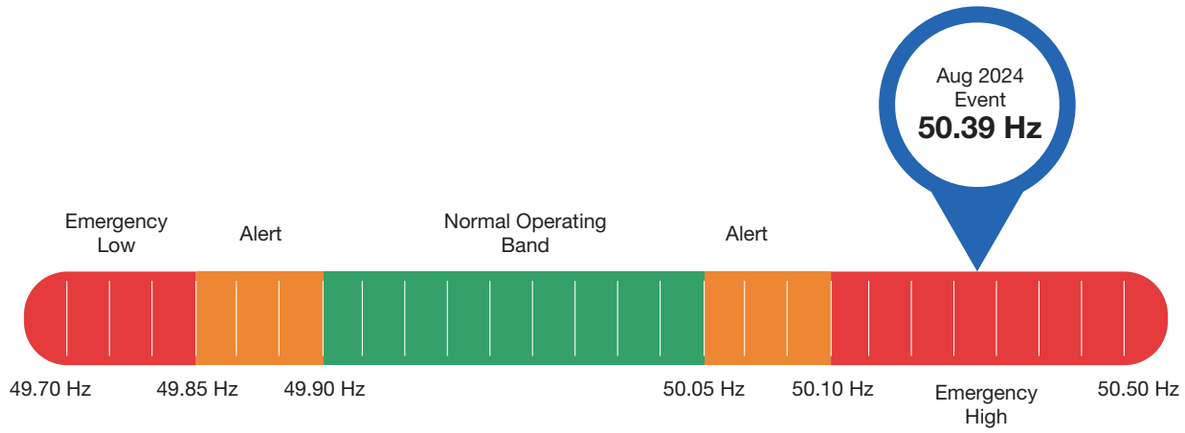


Figure 9: India Frequency Operating Bands per IEGC. The tight normal operating band (49.90– 50.05 Hz) leaves minimal headroom for large load variations. The August 2024 high-frequency events (peak 50.39 Hz) highlight challenges from solar generation surplus.

5.2 Declining System Inertia

The POSOCO-IIT Bombay study (2022) established comprehensive inertia monitoring [16, 40]. Key findings: Current system inertia constant (H): approximately 8–9 seconds under normal conditions. COVID-19 lockdown (2020): drop to H = 7.22 seconds. Projected decline with increasing RE penetration.

System Inertia Decline (H Values)

Declaring synchronous inertia as renewable penetration increases

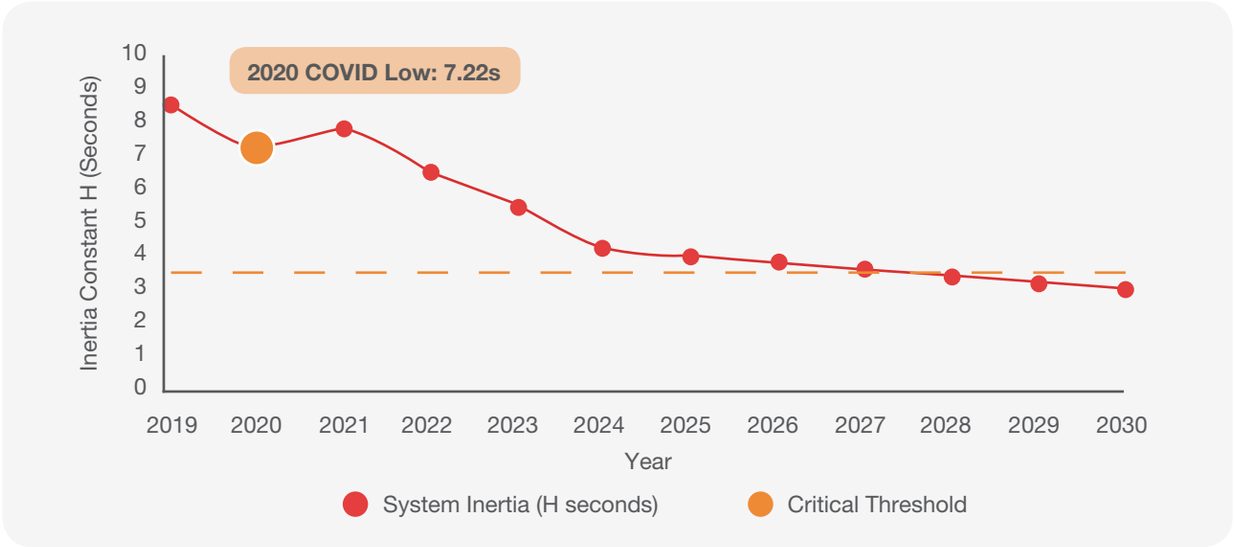


Figure 10: System Inertia Decline Projection. As synchronous generators are displaced by inverter-based renewable resources, system inertia (H) is projected to decline from current levels of 8–9 seconds toward critical thresholds, increasing the grid's sensitivity to disturbances.

5.3 Ancillary Services Framework

The CERC Ancillary Services Regulations 2022 expanded the framework [25, 26]: PRAS: Fully automated, instantaneous response. Estimated compensation: Rs. 8–10 lakh/MW-year. SRAS: Response time <30 seconds; minimum duration 30 minutes. Compensation: Rs. 6–8 lakh/MW-year + Rs. 0.10–0.50/kWh incentive. Current Status: Only 51 of 82 eligible inter-state coal/gas plants (72 GW capacity) are AGC-equipped.

The regulations include provisions for "entity capable of providing demand response" to participate, potentially enabling data center participation—though the realistic scope of that participation is narrower than often assumed (see Section 4.1).

5.4 Transmission Constraints

PGCIL's Green Energy Corridors face challenges [7, 30, 31]:
GEC Phase-I: 9,700 ckm target, 9,161 ckm achieved (94%)
Rajasthan Evacuation Issues:

- Commissioned RE capacity: ~23 GW
- Usable evacuation capacity: ~18.9 GW
- Peak-hour curtailment: ~4.3 GW
- Rs. 20,000 crore (~$2.4 billion) investments at risk

5.5 Backup Generation and Air Quality Constraints

In the National Capital Region, data center backup diesel generation conflicts directly with CAQM air quality restrictions [42].

Standard data center design calls for N+1 diesel generator redundancy [43]. A 200 MW facility implies 200–250 MW of installed diesel capacity. In normal operation, these generators run only during grid outages or scheduled maintenance. But CAQM imposes restrictions on diesel generator operation during severe air quality episodes—periods that can extend for weeks during the November–January winter season.

The operational conflict: if a grid disturbance occurs during a CAQM-restricted period and diesel backup cannot start, the data center's only fallback is UPS battery reserve—typically 5–15 minutes for double-conversion systems [43]. Adequate for brief faults, insufficient for extended outages. The facility chooses between violating air quality restrictions and losing IT operations.

This makes grid ride-through capability far more important for NCR-based data centers. If backup generation is unavailable during certain periods, the UPS and grid interface must ride through a wider range of disturbances. This regional variation is relevant to grid code design—a uniform national LVRT standard may prove insufficient for NCR [11].

The constraint is spreading. State pollution control boards in several states have imposed or proposed seasonal diesel generator restrictions in urban areas [42]. As data centers expand to tier-2 cities with their own air quality challenges, the backup generation constraint will widen.

Gas-based backup, fuel cells, and extended-duration battery systems offer partial mitigation, but none currently matches diesel's combination of cost, energy density, and operational simplicity at data center scale.

6

MARKET STRUCTURE IMPLICATIONS

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At the scale projected for 2030 [3, 6], data centers are not merely large loads. They are economic actors with sufficient commercial leverage to reshape procurement patterns, stress tariff architectures, and alter the financial viability of distribution utilities. Technically sound grid code recommendations will fail on implementation if the institutional ground has shifted. This section addresses what existing data center grid integration literature largely overlooks.

6.1 Distribution Utility Revenue and Cross-Subsidy Erosion

India's cross-subsidy tariff structure—where HT commercial and industrial rates fund below-cost agricultural and domestic supply [23, 44]—means data centers represent among the highest-value customers a DISCOM can serve. They consume large volumes at high load factor, pay commercial tariff rates, and impose modest peak demand charges because their load profile is flat. A 100 MW data center paying Rs. 8–9/kWh (typical HT industrial/IT rate in Maharashtra [45])[3] generates Rs. 600–670 crore annually for the DISCOM.

The risk is migration. Data centers are ideal open access candidates: large, creditworthy, technically sophisticated, and motivated by both cost savings and RE commitments. Even after cross-subsidy surcharge and additional surcharge, open access tariffs offer 15–25% savings over DISCOM commercial rates in several states [46, 47]. The captive generation route, particularly group captive structures with equity participation, allows data centers to avoid cross-subsidy surcharge entirely [46]—several large operators already use group captive solar arrangements.

If even half of the projected 8–10 GW capacity migrates to some combination of open access, captive, and behind-the-meter supply, the revenue loss to DISCOMs could reach Rs. 15,000–25,000 crore annually[4] —concentrated in the states that can least afford it [23].

The pace matters: a hyperscale data center can move from announcement to full open access operation in 18–24 months, giving the DISCOM far less time to adjust tariffs or find replacement revenue than traditional industrial migration in steel or cement, which unfolds over a decade.

This is not a problem that grid codes can solve. It is a tariff design question, and the data center buildout makes the timeline for addressing it more pressing.

6.2 Renewable Energy Procurement and the Additionality Question

India's RPO framework applies to all open access consumers and captive generators, with targets reaching 43.33% by FY2030 [48]. Compliance is straightforward: purchase RECs or sign PPAs with RE generators [49]. But compliance and decarbonization are not the same thing.

The additionality question: does data center RE procurement cause new clean generation to be built, or does it simply reallocate existing generation between buyers? If a data center signs a 25-year PPA with a solar farm that would have been built anyway to meet other consumers' RPO obligations, no additional carbon reduction occurs [50]. The data center claims renewable supply; the displaced buyer purchases from the dirtier residual mix. The atmospheric outcome is unchanged.

Genuine additionality requires new-build PPAs with projects not already contracted to SECI or state distribution companies, or direct investment beyond RPO mandates. If India were to mandate high renewable supply percentages for data centers (following Ireland's 80% model [21]), additionality criteria would be important. Without them, such a mandate risks generating certificate trading activity without atmospheric benefit. The current REC framework does not distinguish additional from non-additional procurement [49].

[3] Classification varies by state: some classify data centers under IT/ITeS (industrial tariff), others under HT commercial. The rate used here reflects the lower industrial/IT classification.

[4] Estimate based on blended HT commercial tariff rates across Maharashtra, Tamil Nadu, Telangana, and Karnataka, applied to 4–5 GW of migrated capacity at 0.85 load factor.

6.3 Interconnection Cost Allocation

Interconnection planning for data centers benefits from accounting for full lifecycle commercial behaviour. A facility that connects at 200 MW and draws 200 MW for 25 years is a straightforward planning problem. A facility that connects at 200 MW, draws 200 MW for three years, then progressively shifts to 120 MW grid offtake with the balance from captive and open access sources is a fundamentally different one—and it is the more likely scenario.

ERCOT's experience with cryptocurrency mining facilities—which requested large connections, operated briefly, then reduced load—prompted Texas to introduce minimum commitment requirements under SB6 [34]. The UK uses "use of system" charges designed to recover network costs regardless of actual consumption [51]. India lacks an equivalent framework. CEA connectivity standards [24] and CERC sharing regulations [52] do not contemplate a large consumer that systematically reduces grid dependence after connection infrastructure is built.

When a 200 MW data center requests grid connection, the utility invests in substation bays, transformer capacity, transmission reinforcement, and protection upgrades [24]—Rs. 200–400 crore in dedicated assets with 25–30 year economic lives [7]. If the data center then progressively reduces grid offtake, the utility is left with stranded or under-recovered assets.

Elements of a commitment framework include: minimum offtake guarantees (e.g., 60–70% of contracted demand for 10 years), upfront capital contribution toward dedicated infrastructure, mandatory 12–18 month advance notice before significant load reduction, and exit charges for residual network cost recovery [51]. These mechanisms exist internationally and in Indian industrial tariff structures.

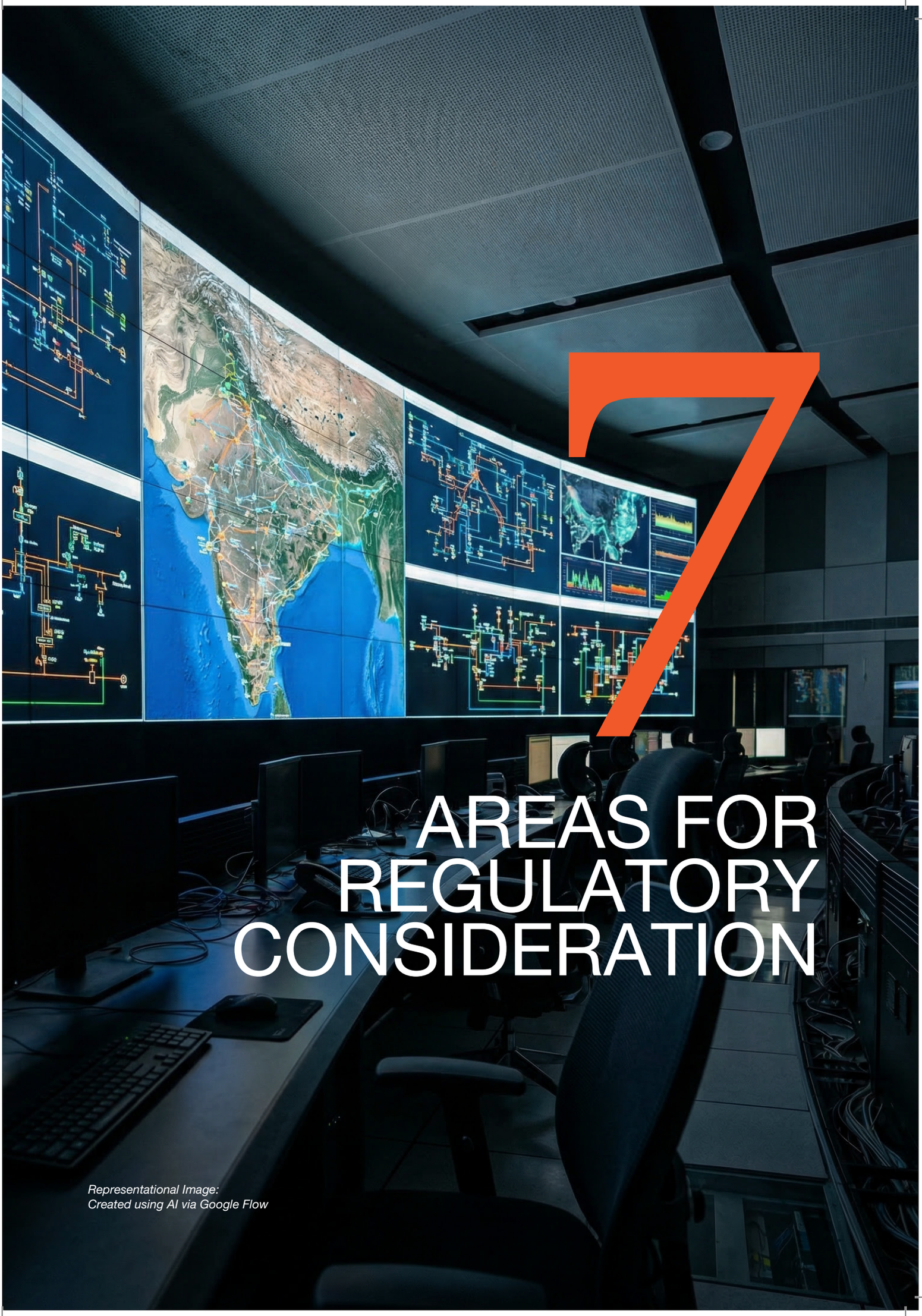
6.4 State-Level Variation

Andhra Pradesh (APEPDCL/APERC): Visakhapatnam is emerging as India's fastest-growing data center corridor, with committed capacity approaching 1.75 GW. AP's Data Center Policy 4.0 (2024–2029) offers aggressive incentives including electricity tariff discounts and duty exemptions, capped at Rs. 4,800 crore.

Maharashtra (MSEDCL/MERC): The largest absolute exposure. Mumbai hosts ~53% of current capacity, and the Western Region could see 4–5 GW by 2030. If 2.5–3 GW of Mumbai-region data centers migrate partially to open access and captive supply, MSEDCL could lose Rs. 5,000–8,000 crore annually in HT commercial revenue.

Tamil Nadu (TANGEDCO/TNERC): Chennai is the second major hub. TNERC's restrictive open access framework has historically slowed migration, but data center operators are using group captive structures to circumvent these barriers [46]. TANGEDCO's financial position is among the weakest nationally [23].

Telangana and Karnataka: Hyderabad and Bengaluru are growing hubs with different regulatory postures. Both states illustrate a common tension: restricting open access discourages investment; permitting unrestricted migration erodes the tariff structure that subsidizes over 30 million agricultural connections nationally [23].



7

AREAS FOR REGULATORY CONSIDERATION

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Implementation of any national framework falls within SERC jurisdiction for connectivity conditions and tariff structures [46]. State-level adaptation—informed by the variation described in Section 6—is essential.

7.1 Technical Standards and Grid Codes

India's IEGC does not currently include provisions for large electronic loads [11]. International frameworks—the ENTSO-E Demand Connection Code [20], Ireland's CRU policy [21], Singapore EMA efficiency mandates—provide reference points, though each reflects jurisdiction-specific conditions. Key areas warranting India-specific analysis:

Low Voltage Ride-Through (LVRT), Frequency Ride-Through (FRT), Rate of Change of Frequency (RoCoF), Harmonic Limits — plus Dynamic Load Modeling: A coordinated measurement program at existing data centers across the Western and Southern regions would address the prerequisite gap identified in Section 2.4 [15].

7.2 Market Mechanisms

Scheduled Demand Flexibility: A new market product—distinct from PRAS and SRAS [25]—for compensated load modulation with advance notification [27]. Illustrative parameters include 2–4 hour advance notification to the SLDC, minimum 2-hour commitment duration, seasonal availability declaration by the operator, and verification through 15-minute interval metering at the PCC. Compensation could be benchmarked to avoided thermal ramping costs, with specific levels determined through cost-of-service analysis.

Representational Image:
Created using AI via Google Flow

Connectivity Conditions: Interconnection agreements for large data centers could incorporate minimum offtake guarantees—illustratively, 60–70% of contracted demand over a 10-year horizon, calibrated through stakeholder consultation—commensurate with dedicated infrastructure investment [24]. Disclosure of planned captive generation, open access procurement, or significant behind-the-meter capacity at the interconnection planning stage would allow infrastructure sizing to reflect realistic long-term offtake [46]. Additional provisions worth examining include upfront capital contribution toward dedicated infrastructure, advance notice before significant load reduction, and exit charge mechanisms for residual network cost recovery, as practiced in UK use-of-system frameworks [51]. Texas SB6 introduced analogous requirements after cryptocurrency mining facilities requested large connections then reduced load [34].

RE Additionality: If renewable energy mandates are introduced for data centers, the analysis in Section 6 suggests additionality criteria would be important [50]—ensuring a defined share comes from new-build projects not already contracted to SECI, state utilities, or other obligated entities [48]. Certificate-only compliance risks generating trading without incremental clean generation.

Water Governance: Interconnection applications for facilities in high or extremely high water stress districts could include WUE disclosure and region-specific thresholds informed by CWMI water stress classifications, along with clearance from the state groundwater authority where borewell extraction is planned [53].

7.3 Grid Services and Behind-the-Meter

Data centers can incorporate behind-the-meter microgrid capabilities—solar PV, battery storage, backup generation, and energy management systems. The realistic scope of data center grid service participation is examined in Section 4.1: the genuine opportunity lies in scheduled demand modulation of deferrable AI training workloads, with advance notification of hours rather than seconds, analogous to interruptible industrial tariffs rather than spinning reserve.

7.4 Implementation Pathway

Phase 1 (Foundation): Advisory issuance, stakeholder consultation, voluntary pilots. International experience suggests this phase benefits from a formal discussion paper setting out anticipated compliance requirements—ride-through capability, harmonic limits, dynamic load modeling obligations—with indicative timelines. Facilities entering construction during Phase 1 would benefit from incorporating anticipated requirements from the outset, rather than designing to current (minimal) standards. The experience with retrospective enforcement of tightened DSM penalties on RE generators—where facilities designed to earlier standards resisted compliance [54]—illustrates the cost of regulatory ambiguity during transition.

Interconnection agreements could include a clause acknowledging anticipated grid code requirements, providing regulatory certainty for both parties.

Phase 2 (Development): Evaluation of pilots, scheduled demand flexibility market participation, development of binding guidelines. Connection agreements could incorporate the minimum commitment and exit charge provisions described in Section 6.

Phase 3 (Maturation): Expansion based on learnings, integration of carbon pricing with additionality-linked RE procurement [50], monitoring of progress against load modeling validation milestones.

Implementation Pathway Timeline

Recommended phased approach for policy development

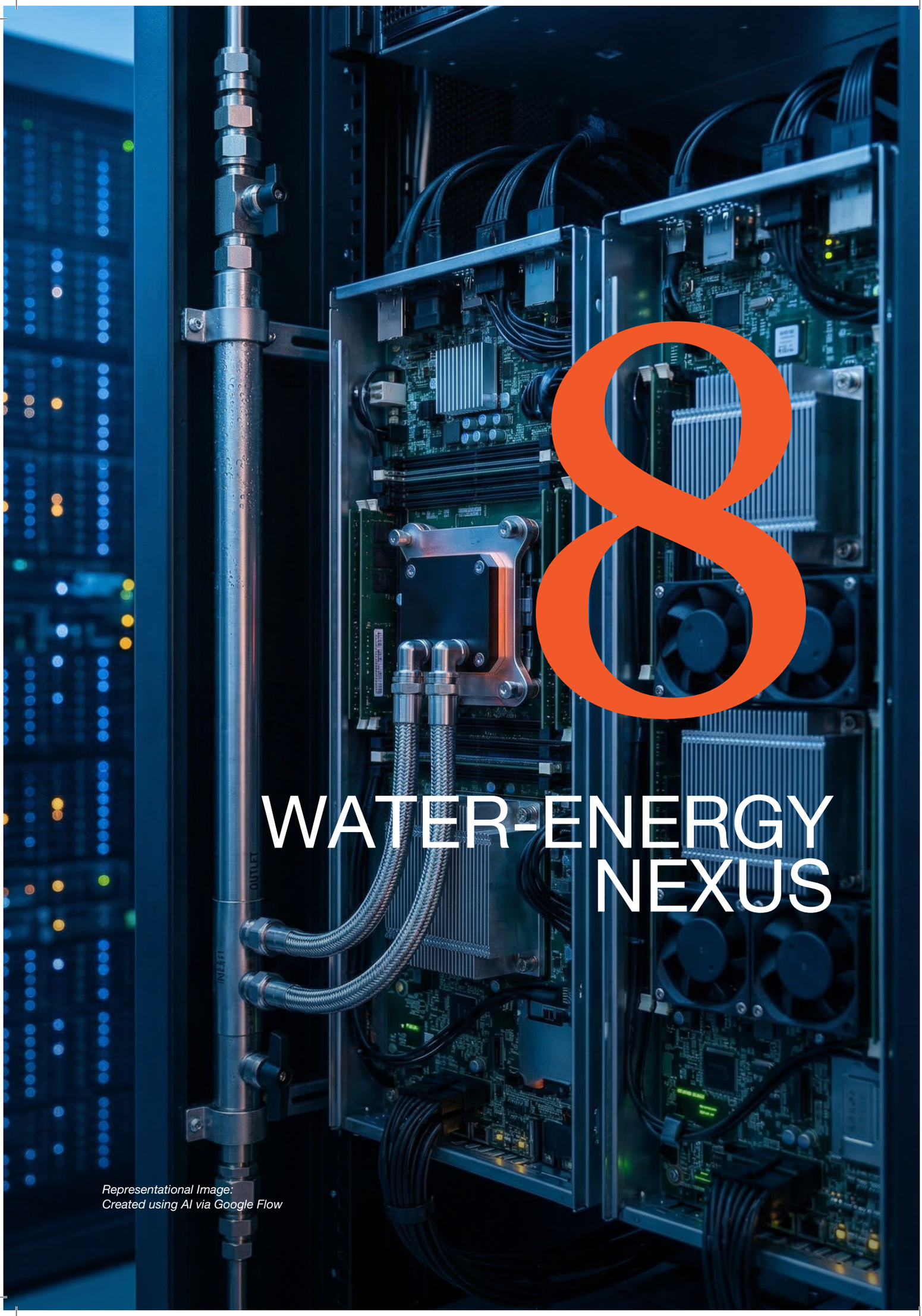
	Phase 1: Foundation (Year 1-2)	Phase 2: Development (Year 2-4)	Phase 3: Maturation (Year 4-6)
Regulatory	**Advisory Framework** Voluntary reporting, best practices	**Guidelines Issued** Grid code amendments, efficiency standards	**Mandatory Compliance** Enforceable standards, penalties
Market	**Pilot Programs** DR pilots in select states	**Enable Participation** AS market access for DCs	**Full Integration** Capacity market, carbon pricing
Infrastructure	**Assessment** Grid impact studies, capacity planning	**Targeted Upgrades** Substation reinforcement, RE corridors	**Dedicated Infrastructure** DC zones with integrated RE/storage
Monitoring	**Baseline Metrics** Establish KPIs, data collection	**Real-time Tracking** Grid operator visibility	**Predictive Analytics** AI-driven grid management

Figure 13: Proposed Implementation Pathway for Data Center Grid Integration. A phased approach allows for learning from pilots before mandating requirements, with stakeholder en- gagement throughout the process.

Ancillary Services Revenue Model

Annual revenue potential for a 100 MW data center

Figure 14: Potential Ancillary Services Revenue Model for a 100 MW Data Center. Grid services participation could generate Rs. 5–5.5 crore annually, providing economic incentive for data centers to transition from passive loads to active grid assets.



8

WATER-ENERGY NEXUS

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8.1 Current Water Consumption

Data center water consumption varies significantly based on cooling technology and climate con- ditions. Industry benchmarks suggest approximately 25.5 million liters annually per 1 MW IT load for evaporative-cooled facilities operating at high utilization [2]. However, actual consump- tion can range from near-zero (for fully air-cooled or direct liquid-cooled facilities) to higher values in hot-arid climates. India's diverse climate zones—from hot-arid Rajasthan to tropical Chennai to more temperate Bangalore—make uniform national estimates problematic; regional assessments are warranted.

8.2 Water Usage Effectiveness

WUE measures liters of water per kWh of IT energy. Industry standard benchmarks from Lawrence Berkeley National Laboratory and EESI [32, 33]:

The choice of cooling technology has direct grid implications beyond water consumption. Facilities using evaporative cooling maintain significant mechanical cooling loads—chillers, cooling towers—that contribute induction motor content to the overall load profile, reducing power factor and introducing sub-cycle transients during compressor cycling. Facilities adopting direct liquid cooling eliminate most mechanical cooling load, producing a flatter, more purely electronic load profile with higher power factor but also higher sensitivity to voltage disturbances, since the remaining load is almost entirely UPS-backed IT equipment with the binary disconnection behaviour described in Section 2.4.

Table 4: WUE by Cooling Technology

Cooling Technology	WUE (L/kWh)
Evaporative cooling	1.8–2.5
Hybrid (evap + dry)	0.8–1.5
Air-cooled (dry)	0.1–0.3
Liquid cooling (direct)	0.0–0.1

8.3 Geographic Mismatch

Major data center hubs correlate with water-stressed regions [34]:

- Chennai: Extremely high water stress
- Hyderabad: High stress
- Bengaluru: Extremely high stress

Community concerns have been reported including farmer protests in Maharashtra and community opposition in Karnataka citing groundwater depletion.

Regional Water Stress Map

Data center concentration vs. water stress levels across major hubs

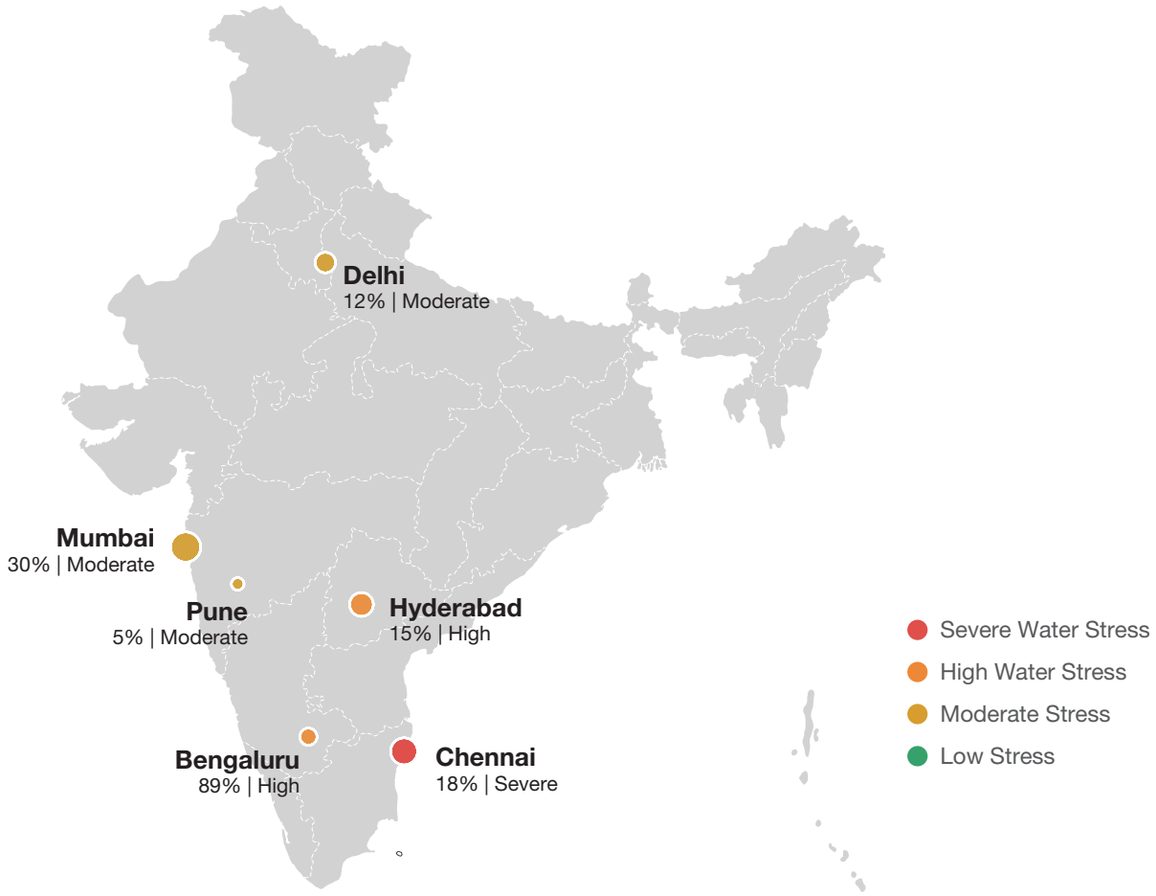

Figure 11: Data Center Locations and Regional Water Stress in India. Major data center hubs (Mumbai, Chennai, Hyderabad, Bengaluru) are concentrated in regions experiencing moderate to severe water stress, creating potential conflicts with agricultural and municipal water needs.

Cooling Technology Comparison

Characteristics of different data center cooling approaches

Evaporative Cooling

1.8-2.5 L/kWh

PUE: 1.1-1.3
Cost: Low
Best for: Humid climates

Hybrid Cooling

0.8-1.5 L/kWh

PUE: 1.2-1.4
Cost: Medium
Best for: Variable climates

Air-Cooled

0.1-0.3 L/kWh

PUE: 1.4-1.6
Cost: Medium-High
Best for: Cool climates

Liquid Cooling

0.0-0.1 L/kWh

PUE: 1.05-1.2
Cost: High
Best for: AI/HPC

Figure 12: Water Usage Effectiveness (WUE) by Cooling Technology. Direct liquid cooling and air-cooled systems offer significant water savings compared to traditional evaporative cooling, an important consideration for deployment in water-stressed regions.

9

CONCLUSIONS

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India's data center expansion from 1.4 GW to a projected 10 GW by 2030 is not primarily a load growth problem—it is a market structure problem that happens to have load growth consequences.

Key Findings:

1. Modern data centers exhibit unique electrical behaviors including high load factors and rapid transients that differ from traditional industrial loads
2. Concentration creates potential for simultaneous disconnection during grid faults, as the July 2024 Virginia incident demonstrated [17]. This risk is amplified where air quality restrictions remove the diesel backup fallback (see Section 5.5)
3. International experience demonstrates importance of proactive planning
4. Data centers can potentially transition from passive loads to active grid assets, though the realistic opportunity lies in scheduled demand flexibility rather than real-time frequency response (see Section 4.1)
5. At projected scale, data centers acquire sufficient commercial leverage to reshape electricity procurement through open access and captive generation, with potential revenue implications for DISCOMs of Rs. 15,000–25,000 crore annually [23]. Parallel attention to tariff design, interconnection cost allocation, and RE procurement additionality is needed alongside technical grid code development (see Section 7).

The Opportunity: Beyond challenges, data centers represent flexible loads that can absorb excess renewable generation, grid assets that can provide frequency response, and renewable energy drivers creating economic demand for large-scale RE projects.

With appropriate planning and regulation developed through systematic study and stake- holder engagement, India can achieve its ambitious data center growth targets while maintaining grid reliability and advancing renewable energy integration.

Realizing this potential requires acting before the investment cycle locks in suboptimal outcomes. The facilities being designed in 2025–2026 will operate for 15–20 years. If they are built without ride-through capability, without grid service enablement, and without interconnection commitments that protect utility solvency, retrofitting later will be expensive, contested, and slow. India can accommodate its data center ambitions without compromising grid reliability or the financial architecture that sustains universal electricity access—but only if regulatory engagement begins now, before the construction cycle forecloses the option.

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