Government of India

Study on Promoting **Sustainable Cooling Technologies in Data Centres**

OZONE CELL

Ministry of Environment, Forest and Climate Change (MoEF&CC)

Study on Promoting Sustainable Cooling Technologies in Data Centres

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ENVIRONMENT, FOREST AND CLIMATE CHANGE
GOVERNMENT OF INDIA

भूपेन्द्र यादव
BHUPENDER YADAV

MESSAGE

India is in the midst of a historic digital transformation, with data centres emerging as the critical infrastructure underpinning our nation's economic growth and technological sovereignty. The expansion of the data centre sector creates an opportunity to ensure that the infrastructure powering our digital future is efficient, resilient and aligned with our environmental goals.

Cooling is an integral part of data centre operations, as continuous heat generation from IT equipment requires reliable and efficient cooling systems. As the data centre sector expands, adopting energy-efficient cooling technologies and transitioning to non-ODS and low-GWP refrigerants can improve energy efficiency, reduce environmental impacts and support the sustainable growth of India's data centre infrastructure. This transition also supports India's commitments under the Montreal Protocol and its Kigali Amendment to phase down the use of high-GWP refrigerants.

The study, "**Promoting Sustainable Cooling in Data Centres in India**" provides an overview of cooling technologies, refrigerant use, and energy consumption patterns in the Indian data centre sector. It serves as a valuable knowledge product for promoting sustainable and energy-efficient cooling practices in data centres.

(Bhupender Yadav)

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MESSAGE

The expansion of India's data centre infrastructure is a direct reflection of our dynamic and digitally empowered economic growth. As these facilities grow in number and capacity, so does the need for cooling, making it important to find ways to meet this demand while using energy more efficiently.

The findings of report on **"Study on Promoting Sustainable Cooling in Data Centres in India"** support the objectives of the India Cooling Action Plan (ICAP) and India's commitments under the Kigali Amendment. As data centres operate around the clock, adopting energy-efficient cooling systems and low-GWP refrigerants can help improve energy efficiency, reduce environmental impacts and lower power demand. This will support the sustainable growth of India's digital infrastructure while reducing pressure on the power system.

This study serves as a useful guide for stakeholders. It provides the necessary technical insights to promote the widespread adoption of sustainable cooling solutions throughout the data centre industry. It should be widely disseminated to empower operators, manufacturers, and policymakers to make informed decisions that support sustainable cooling in data centre sector.

I commend the work of the team associated in preparing this report.

(Kirti Vardhan Singh)

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AND CLIMATE CHANGE

MESSAGE

Data centres are a critical component of India's digital infrastructure, and their continued growth is driving increasing demand for efficient and reliable cooling. As cooling accounts for a significant share of data centre energy consumption, improving cooling efficiency and adopting climate-friendly technologies and refrigerants are essential for making data centre more energy efficient and environmentally sustainable.

The study, *"Promoting Sustainable Cooling in Data Centres in India,"* provides an overview of cooling technologies, refrigerant use, energy consumption, and operational practices in the sector. It highlights opportunities to enhance cooling efficiency and sustainability while supporting the transition towards non-ODS and low-GWP alternatives.

The India Cooling Action Plan (ICAP) provides the overarching policy framework for our endeavours. This study builds upon the ICAP by serving as a knowledge resource to guide the development of sector-specific standards, codes, and best practices. It will further strengthen ongoing efforts towards institutional capacity building and targeted skill-development programmes for the service sector, while promoting more efficient and sustainable cooling practices.

I congratulate all those associated with the preparation of this informative report.

(Tanmay Kumar)

Place: New Delhi
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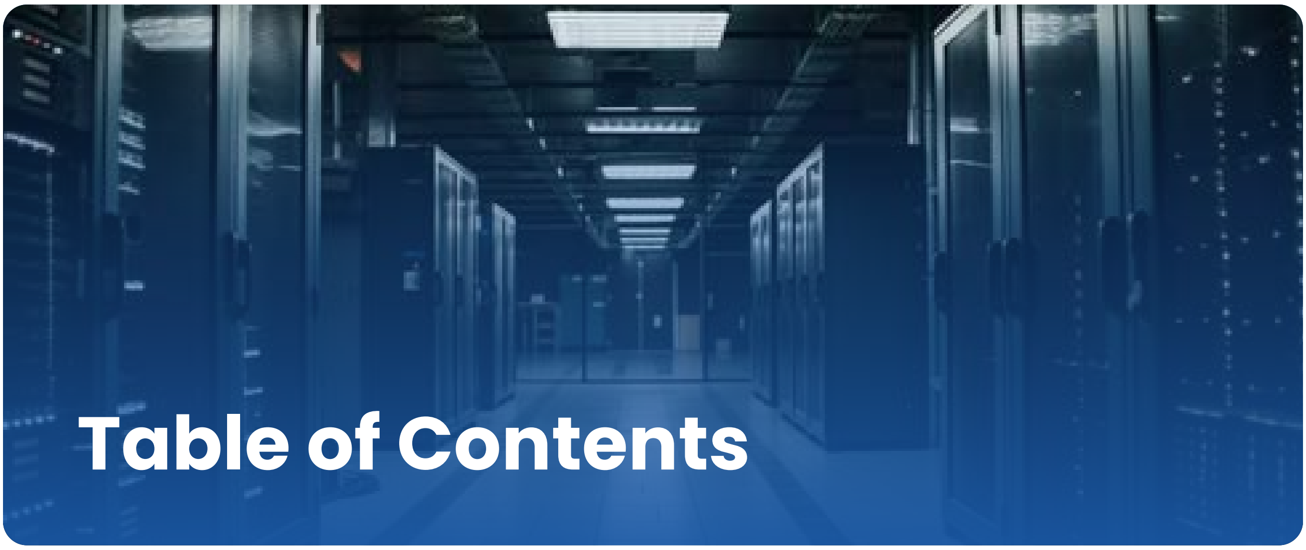

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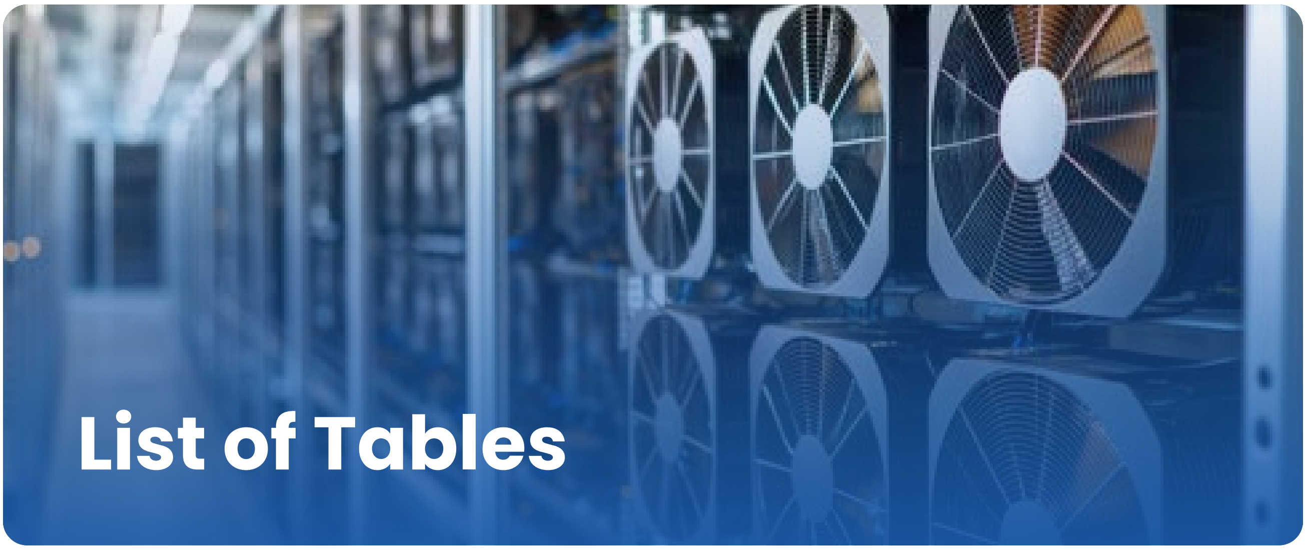

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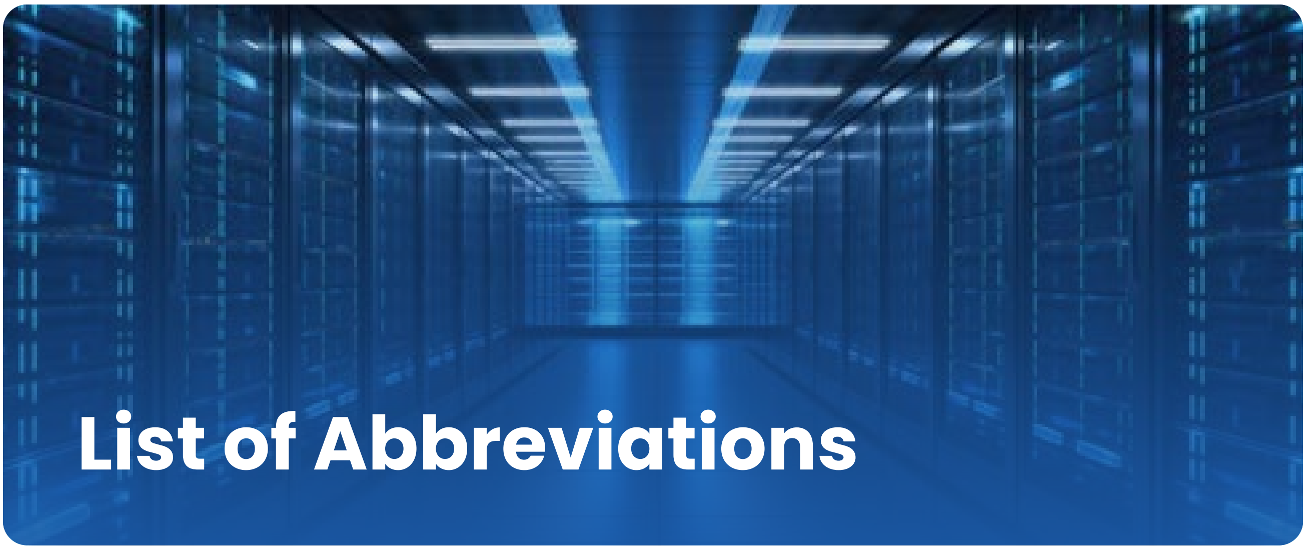


List of Abbreviations

AC	Air Conditioning
AEEE	Alliance for an Energy Efficient Economy
AEMC	Australian Energy Market Commission
AHRI	Air-Conditioning, Heating, and Refrigeration Institute
AHU	Air Handling Unit
AI	Artificial Intelligence
AIGZ	AI Growth Zone
AMER	The Americas
APAC	Asia-Pacific
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BEE	Bureau of Energy Efficiency
BESS	Battery Energy Storage System
BMS	Building Management System
BTM	Behind-the-Meter
BYOP	Bring Your Own Power
CAC	Cold-Aisle Containment
CAGR	Compound Annual Growth Rate
CAPEX	Capital Expenditure
CDU	Coolant Distribution Unit
CEA	Central Electricity Authority
CEPA	Comprehensive Economic Partnership Agreement
CFC	Chlorofluorocarbon
CGWB	Central Ground Water Board
CHP	Combined Heat and Power
CLCT	Closed Loop Cooling Tower
COP	Coefficient of Performance

CRAC	Computer Room Air Conditioner
CRAH	Computer Room Air Handler
CUE	Carbon Usage Effectiveness
DC	Data Centre
DCEZ	Data Centre Economic Zone
DCIE	Data Centre Infrastructure Efficiency
DCIM	Data Centre Infrastructure Management
DG	Diesel Generator
DH	District Heating
DISCOM	Distribution Company
DLC	Direct Liquid Cooling
DX	Direct Expansion
ECBC	Energy Conservation Building Code
EOL	End-of-Life
EPA	Environmental Protection Agency
EPC	Engineering, Procurement and Construction
EPRI	Electric Power Research Institute
ERE	Energy Reuse Effectiveness
ERP	Enterprise Resource Planning
ESSCI	Electronics Sector Skills Council of India
EU	European Union
GHG	Greenhouse Gas
GPU	Graphics Processing Unit
GW	Gigawatt
GWP	Global Warming Potential
HCFC	Hydrochlorofluorocarbon
HFC	Hydrofluorocarbon
HFO	Hydrofluoroolefin
HPC	High-Performance Computing
HPMP	HCFC Phase-out Management Plan
HVAC	Heating, Ventilation and Air Conditioning
ICAP	India Cooling Action Plan
IEA	International Energy Agency
ITI	Industrial Training Institute
LRM	Lifecycle Refrigerant Management
MW	Megawatt
MWh	Megawatt-hour
NCR	National Capital Region
ODP	Ozone Depletion Potential
ODS	Ozone-Depleting Substance

OEM	Original Equipment Manufacturer
PAC	Precision Air Conditioner
PCM	Phase Change Material
PDU	Power Distribution Unit
PPA	Power Purchase Agreement
PSU	Power Supply Unit
PUE	Power Usage Effectiveness
PV	Photovoltaic
RAC	Room/Refrigeration Air Conditioner
RDHE / RDHx	Rear-Door Heat Exchanger
RE	Renewable Energy
REC	Renewable Energy Certificate
REF	Renewable Energy Factor
RHL	Refrigerant Handling Licence
SGST	State Goods and Services Tax
STP	Sewage/Effluent Treatment Plant
TES	Thermal Energy Storage
TFA	Trifluoroacetic Acid
TR	Tons of Refrigeration
TRAI	Telecom Regulatory Authority of India
TWh	Terawatt-hour
UPS	Uninterruptible Power Supply
VFD	Variable Frequency Drive
WUE	Water Usage Effectiveness
WRE	Water Reuse Effectiveness

Executive Summary

India's data centre (DC) sector is entering a phase of rapid expansion. From approximately 1.5 GW installed IT capacity across 302 DCs in 2025, is estimated to exceed 17 GW across around 350 facilities by 2032, supported by a growing investment pipeline. Upcoming facilities are expected to be significantly larger, with individual projects reaching GW-scale capacities, several orders of magnitude above the current average facility size of around 10 megawatt (MW). Driven by artificial intelligence (AI), cloud computing, digitalisation, and data localisation, DCs are becoming critical infrastructure underpinning India's digital economy. This expansion will have significant implications for electricity, water, and greenhouse-gas emissions, with cooling playing a central role in resource efficiency and environmental performance. Cooling can account for approximately 30–50% of total data centre energy consumption, with the share tending to be higher in older or less efficient facilities. Given the 15–20-year lifecycle of cooling systems, equipment and refrigerants selected during the current build-out will remain in operation through the steepest phase of India's HFC phase-down under the Kigali Amendment to the Montreal Protocol, beginning in 2028. Cooling decisions made today are therefore long-term commitments with implications for energy efficiency, refrigerant transition, and resource sustainability.

Commissioned by the Ozone Cell, Ministry of Environment, Forest and Climate Change, under HPMP Stage III, this study assesses cooling technologies, refrigerant practices, and resource-efficiency opportunities in Indian DCs and proposes measures to support their sustainable growth. It draws on field assessments, stakeholder consultations, and national and international literature and policy review, adopting a technology-neutral, performance-based approach with emphasis on Power Usage Effectiveness (PUE) and Water Usage Effectiveness (WUE).

The study finds that rising rack power densities are driving a transition from conventional air cooling towards liquid cooling, including direct-to-rack and direct-to-chip solutions. It assesses resource-efficient approaches including high-efficiency equipment and system design, climate-appropriate cooling, low-GWP refrigerants, water optimisation and reuse, waste-heat recovery, and renewable energy integration. Indian and international case studies reported demonstrate the potential benefits and applicability of these approaches under different operating and climatic conditions.

Field assessments of seven DCs across Mumbai, Pune, and Delhi NCR, including hyperscale and enterprise facilities commissioned between 2015 and 2024, provided insights into current cooling practices and operational performance. The assessed facilities predominantly use air- and hybrid-cooling systems and showed relatively low IT capacity utilisation, indicating opportunities to improve system efficiency and cooling performance. Server inlet temperatures also indicate scope to evaluate higher operating setpoints, where compatible with IT equipment requirements.

The report indicates that improving PUE from an industry-typical 1.60 to 1.25 could save approximately 37 TWh of electricity by 2032, equivalent to nearly Delhi's current annual electricity consumption. Combined with higher renewable energy use, these efficiency gains could reduce the sector's carbon footprint by around 60%, from an estimated 126 million tonnes CO_2e under the 2032 business-as-usual scenario. However, these gains need to be considered alongside the water requirements of different cooling systems. By 2032, annual water consumption could range from near-negligible levels for air-cooled systems to as much as 331 billion litres for water-cooled systems, equivalent to around one-fifth of Delhi's current annual water supply. This highlights the need to pursue energy and carbon efficiency while also considering water availability and resource constraints when selecting cooling systems.

Building on India's institutional and policy foundation, the study recommends a phased sequencing of opportunities across near-, medium- and long-term horizons. Near-term measures centre on common indicators and a standardised national format for voluntary PUE and WUE disclosure, technical guidance on low-GWP refrigerant handling and liquid cooling, and a national water-stress advisory drawing on CGWB and CWC data. Over the medium term, wider benchmarking, harmonisation of relevant BIS codes and standards, technician skilling scaled through NSDC and Skill India, and dedicated financing for cooling upgrades and refrigerant transitions can consolidate these practices. Complementary areas include liquid and hybrid cooling selected on local energy and water availability rather than PUE alone, accelerated consideration of low-GWP and non-ODS refrigerants ahead of the HFC phase-down from 2028, grid-aware siting in Tier-2 and Tier-3 locations with available power and land, treated-wastewater reuse, waste-heat recovery, and improved operational practices that can deliver efficiency gains at limited capital cost. Consistent with the emphasis on building on existing frameworks rather than creating parallel mechanisms, coordinated action from various stakeholders can strengthen resource efficiency and resilience while supporting India's continued digital and AI-led growth.

01 Introduction

India is undergoing a rapid digital transformation, accompanied by a sharp increase in the demand for computing, data storage, digital services and data localisation requirements. The expansion of internet and mobile connectivity, digital public infrastructure, cloud-based services, e-commerce, financial technologies, and emerging applications such as artificial intelligence is driving continued growth in the country's digital infrastructure. Data centres (DCs) are at the heart of this transformation, providing the physical infrastructure required to process, store, and manage the growing volumes of data generated by the digital economy. A DC is a physical room, building, or facility that houses IT infrastructure for building, running, and delivering applications and services, while also storing and managing the data associated with those applications and services[1].

Globally, data generation is expanding at an unprecedented pace, with total data volumes projected to reach approximately 400 zettabytes by 2028, nearly 2.7 times the levels recorded in 2024[2]. According to the State of India's Digital Economy Report 2024, India is the third-largest digitalised country globally in terms of economy-wide digitalisation and ranks 12th among G20 countries in the level of digitalisation of individual users. India's digital economy contributed nearly 11.74% of the national GDP in 2022–23, equivalent to approximately INR 31.64 lakh crore (USD 402 billion), and is projected to contribute nearly one-fifth of the national income by 2029–30[3]. Despite this strong growth, India's DC market remains relatively underpenetrated, with approximately 1 megawatt (MW) of DC capacity per million internet users, compared to around 4 MW in China and 51 MW in the United States, indicating substantial potential for future capacity expansion[4]. Over the past decade, digital-enabling industries have grown significantly faster than the overall economy, highlighting the growing importance of digital infrastructure in India's economic growth.

The rapid expansion of India's DC infrastructure is accompanied by a corresponding increase in demand for electricity, cooling, water, and other resources. As DC capacity grows and computing densities continue to rise, particularly with the increasing adoption of high-performance and AI workloads, managing these resource requirements is becoming increasingly important. Cooling is a critical component of this resource demand, influencing both the energy and water performance of DCs, as well as their operational reliability and resilience. Ensuring that India's DC growth is supported by energy- and water-efficient cooling systems will therefore be essential to achieving sustainable and resource-efficient digital infrastructure.

1.1 Overview

A comprehensive understanding of the DC sector is essential for identifying opportunities to promote sustainable cooling technologies. This chapter presents the global and Indian DC landscape, covering classifications, market size and investment flows, energy consumption patterns, environmental footprint, and India's evolving DC ecosystem, including key geographic hubs, and growth drivers.

1.1.1 Classification of Data Centres

DCs are classified based on their ownership, scale, deployment model, and operational purpose. From single-organisation enterprise DCs to distributed edge DCs designed for low latency, each type is built to handle specific IT loads and architectural scales.

Table 1 provides a comprehensive comparison of these global DC types, detailing their typical size, and primary industry use cases.

Table 1: Classification of Data Centre Types by Function and Scale

	Edge DC	Enterprise DC	Colocation DC	Hyperscale DC
Purpose	Bring computing closer to users and devices for low latency.	Support internal IT operations and critical workloads.	Provide shared IT infrastructure for multiple customers.	Deliver massive compute power for cloud and large-scale services.
Ownership	Distributed providers or organisations	Individual organization	Third-party providers	Large cloud providers or hyperscalers
Typical Size	100 – 10,000 sq. ft	100 - 2000+ sq. ft[5]	500 – 10,000+ sq. ft[6]	10,000 sq. ft or larger[7].
Common Use Cases	IoT, 5G, Streaming, Real-time analytics, Edge AI	ERP, Databases, Internal apps, Business-critical systems	Hosting, Connectivity, DR, Cloud on-ramp, Enterprises	Cloud services, AI/ML, Big data, Software as a Service (SaaS), Global applications
Expected growth rate by 2030 (global)	25- 27% CAGR[8]	17- 31% CAGR	8- 16% CAGR	14-26% CAGR

India currently has around 302 DCs[9], but most are small in capacity and serve distributed enterprise needs. The upcoming pipeline is shifting toward fewer but much larger hyperscale facilities, driven by AI workloads and GPU-intensive computing that significantly increase rack densities and cooling requirements. This is leading the sector toward high-density, power-intensive campuses designed to support large-scale digital and AI infrastructure.

The DC tier classification system is a globally recognised framework used to evaluate the reliability, availability, redundancy, and fault tolerance of DC infrastructure. The framework categorises facilities into four progressive levels, Tier I through Tier IV, based on the architectural resilience of critical systems like power supplies, cooling infrastructure, and backup systems. As facilities progress from Tier I to Tier IV, the level of redundancy and cooling requirements increases significantly. Consequently, improving cooling efficiency and adopting sustainable cooling technologies have become increasingly important for higher-tier DCs[10].Table 2 outlines the key parameters and operational differences between each tier.

Table 2: Data Centre Tier Classification and Reliability Requirements

Parameter	Tier I	Tier II	Tier III	Tier IV
Power and cooling path	Single	Single	Multiple active and passive	Multiple independent, isolated
Redundancy[11]	None	Partial power and cooling redundancy	N+1 fault tolerance	2N or 2N+1
Uptime[12]	99.671%	99.741%	99.982%	99.995%
Maintainability	Full site shutdown for any planned maintenance/ repair	Still requires a full site shutdown for planned maintenance.	Allows for planned maintenance or equipment replacement without impacting operations	Allows for planned maintenance or equipment replacement without impacting operations
Fault tolerance	No fault tolerance; susceptible to disruptions from human error or equipment failure	Limited fault tolerance. Still vulnerable to unexpected shutdowns	Not completely fault tolerant; susceptible to unscheduled outages	Completely fault tolerant. An equipment failure or interruption will not affect IT operations

Note: N represents the minimum baseline capacity required to support full IT operations. N+1 adds one extra backup component to handle single-unit failures or maintenance; N+2 adds two. 2N provides two fully independent, duplicated systems, while 2N+1 adds an additional spare component to that dual-system setup for maximum fault tolerance.

DCs comprise integrated IT, power, cooling, networking, and monitoring systems designed to ensure reliable digital operations. Traditionally, rack power densities ranged from 5–8 kW and relied on air-based cooling. However, AI and high-performance computing have increased rack densities to 30–50 kW, with future deployments expected to reach 150 kW per rack, driving the adoption of advanced cooling technologies such as direct-to-chip liquid cooling, rear-door heat exchangers, and immersion cooling. Intelligent monitoring through BMS and DCIM platforms further enhances operational efficiency, reliability, and security. A summarised figure of DC components is given in Figure 1.

Connectivity and external system

- Routers (Internet service provider (ISP), Gateway protocol, peering)
- Fiber uplinks
- Load balancers
- Wide area network gateways Cloud interconnects
- Cross connects
- Network time protocol (NTP) servers
- GPS Antennas

Facility management and safety

- Biometric Access Systems
- Surveillance cameras
- Smoke detection system
- Fire alarm control panels
- Gas-based fire suppression systems
- Emergency lighting and exit signage
- Emergency power-off switch

Cooling system

- Chillers
- Cooling towers
- Evaporators, condensers, and water pumps
- Hot/cold aisle containment
- Coolant distribution units (CDUs)

Monitoring and control system

- Data centre infrastructure management(DCIM)
- Building management system (BMS)/Supervisory control and data acquisition(SCADA)
- Sensors
- Smart Power distribution unit (PDUs)
- UPS management system Leak detectors
- Cooling system
- actuators/controllers

Electrical and power supply

- High/low tension panel
- Transformers
- Uninterruptible power supply (UPS)
- Diesel generator sets
- Battery banks
- Automatic/static transfer switch
- Power distribution unit (PDU)
- Busbars
- Cabling

IT Infrastructure

- Servers (Rack, blade, GPU, CPU)
- Network-attached storage, Storage area network
- Solid state/hard disk drive storage
- Core and access switches
- Routers
- Firewalls
- Load balancers
- Network interface cards

Figure 1: Components of a typical data centre

Figure 2 also includes selected photographs illustrating the cooling infrastructure and interior views of representative DC facilities.

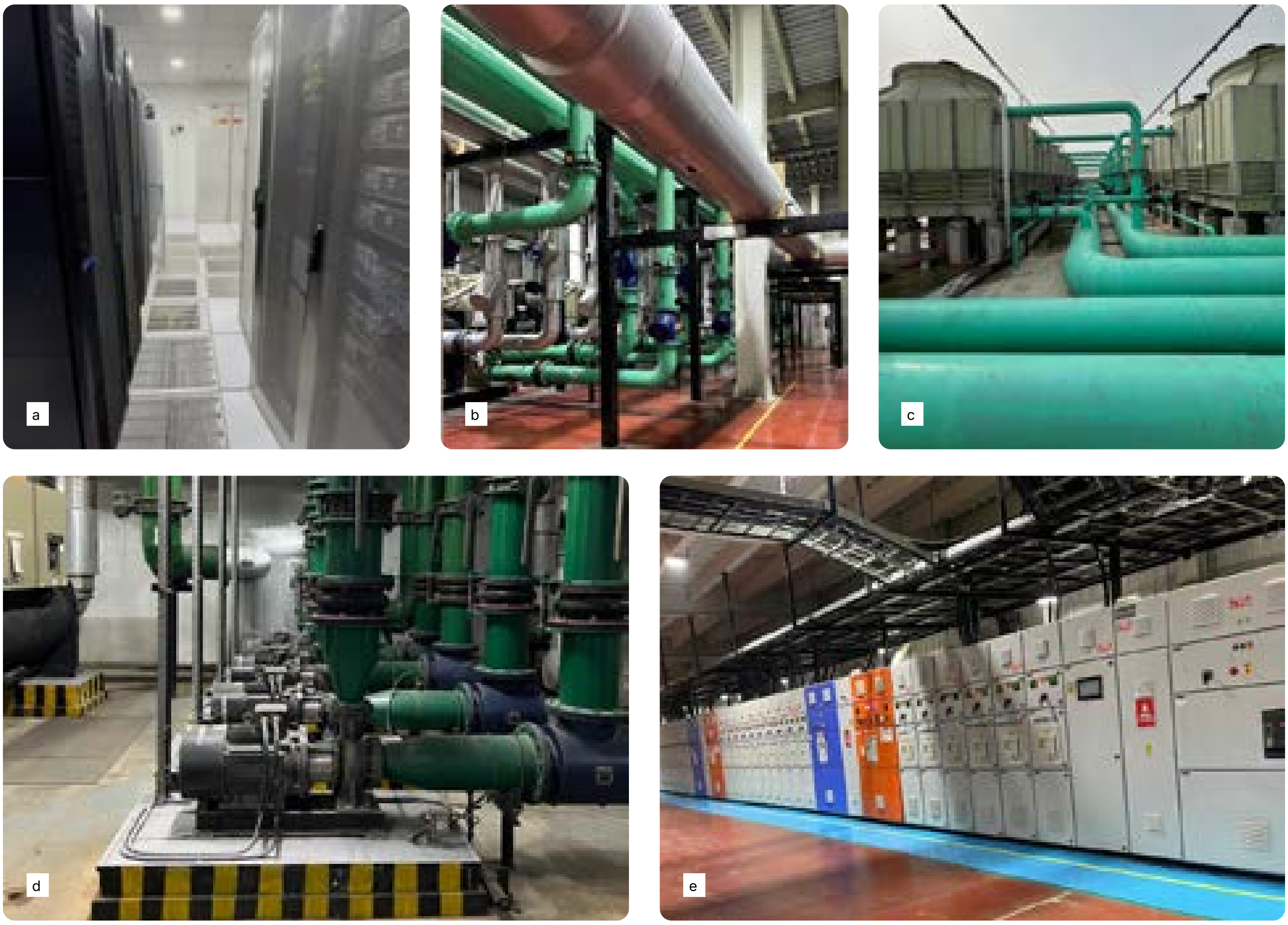


Figure 2: Representative photographs of DC facilities(a) inter area of DC facility; (b) compressor bank (c) outdoor chiller plant; (d) chiller water supply and return lines (e) electrical power distribution and switchgear infrastructure

1.1.2 Data Centre Energy Consumption Footprint

The typical electricity consumption pattern of DC is shown in Figure 3[13]. distributed across five categories: servers, storage, network, cooling, and other infrastructure. In traditional enterprise facilities, cooling accounts for a substantial share of total energy use, around 33% reflecting older designs and lower operational efficiency. In modern hyperscale facilities, by contrast, computing dominates with servers accounting for around 76% of total energy, with other infrastructure making up the remainder, and cooling reduced to a much smaller share. This does not mean hyperscale facilities require less cooling; rather, they deliver the same cooling function far more efficiently, through optimised design, higher operating temperatures, and advanced cooling architectures. The key implication is that the cooling share of a facility's energy is a direct reflection of its overall efficiency, as captured by Power Usage Effectiveness (PUE). A lower cooling share corresponds to a lower PUE and a larger fraction of energy reaching productive computing. This underscores the central premise of this study, improving cooling efficiency is the single most effective lever for reducing the energy intensity of DCs and the gap between traditional and hyperscale facilities illustrates how much efficiency potential remains untapped in India's existing stock.

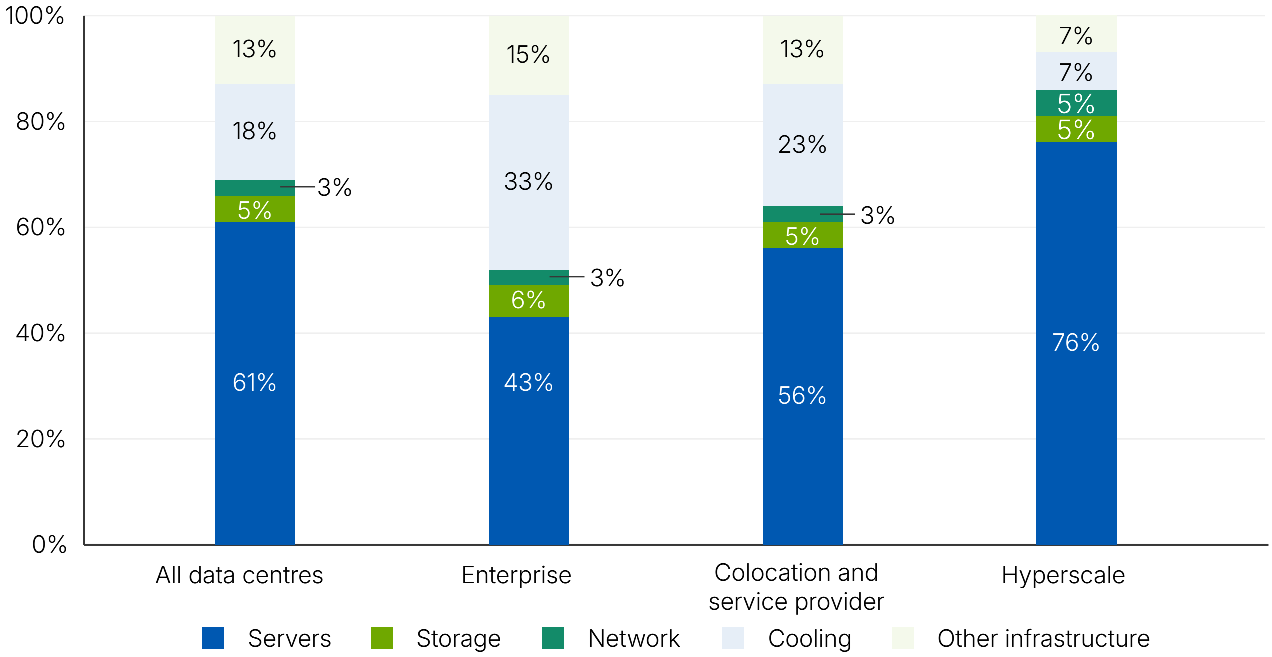


Figure 3: Share of electricity consumption by data centre and equipment type

DCs were predicted to account for approximately 2% of global electricity consumption, totalling 536 terawatthours (TWh) in 2025. Figure 4 highlights the rising electricity demand of DCs across major economies by 2026[14]. The United States leads with ~220 TWh, followed by China at ~80 TWh, while India's consumption is ~10 TWh, which is less than 1% of national energy demand but is expected to grow rapidly with expanding DCs. Furthermore, with the current rapid expansion of power-intensive generative AI (Gen AI) training and inference surpassing other applications, global DC electricity consumption could nearly double to 1,065 TWh by 2030[15].

DCs and data transmission networks that support global digitalisation accounted for approximately 330 million tons of CO_2 eq. emissions in 2020, including embodied emissions. This represented nearly 0.9% of global energy-related GHG emissions and around 0.6% of total global GHG emissions[16].

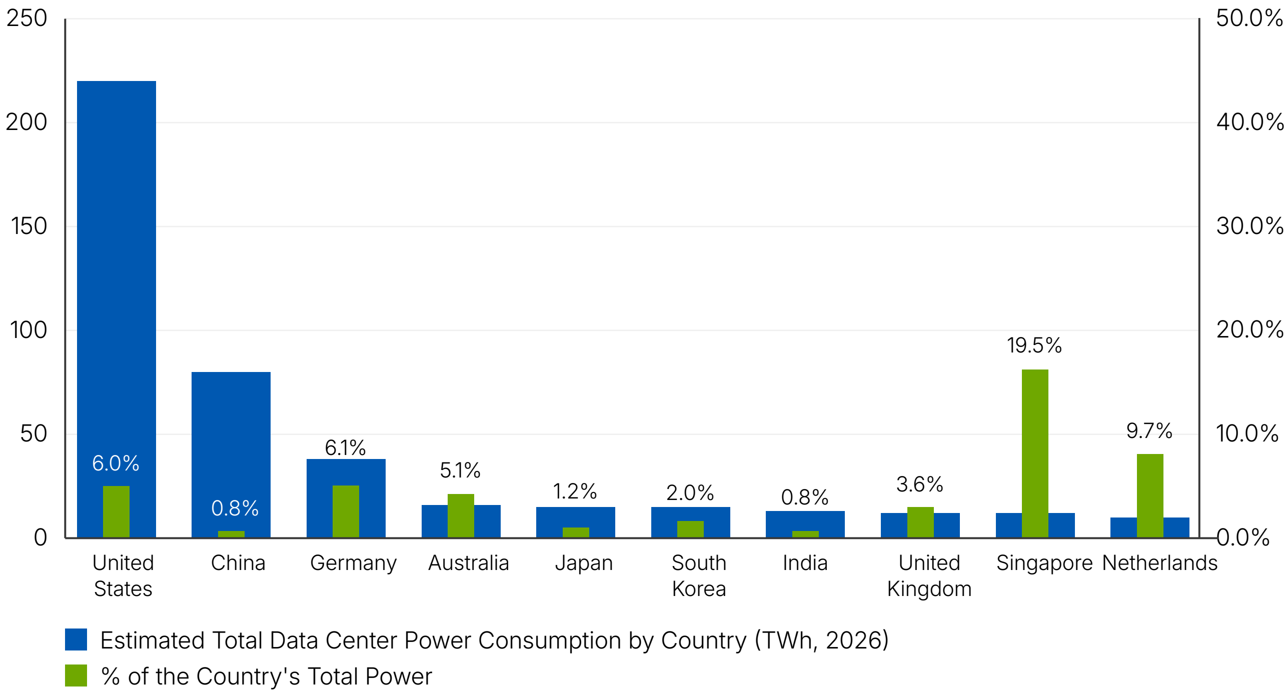


Figure 4: 2026 Global Data Centre Electricity Consumption and National Grid Impact

1.1.3 Market Overview and Investment Trends

The global DC sector is expected to add nearly 97 GW of new capacity between 2026 and 2030, increasing total installed capacity to approximately 200 GW by 2030, according to JLL's 2026 Global DC Outlook. The Americas (AMER) account for about 50% of global capacity and are projected to grow at a 17% CAGR, with the U.S. contributing nearly 90% of regional capacity. In Asia-Pacific (APAC), capacity is expected to increase from 32 GW to 57 GW by 2030 (12% CAGR), while Europe, the Middle East, and Africa (EMEA) is projected to grow at a 10% CAGR (Figure 5)[17], adding around 13 GW of new capacity.

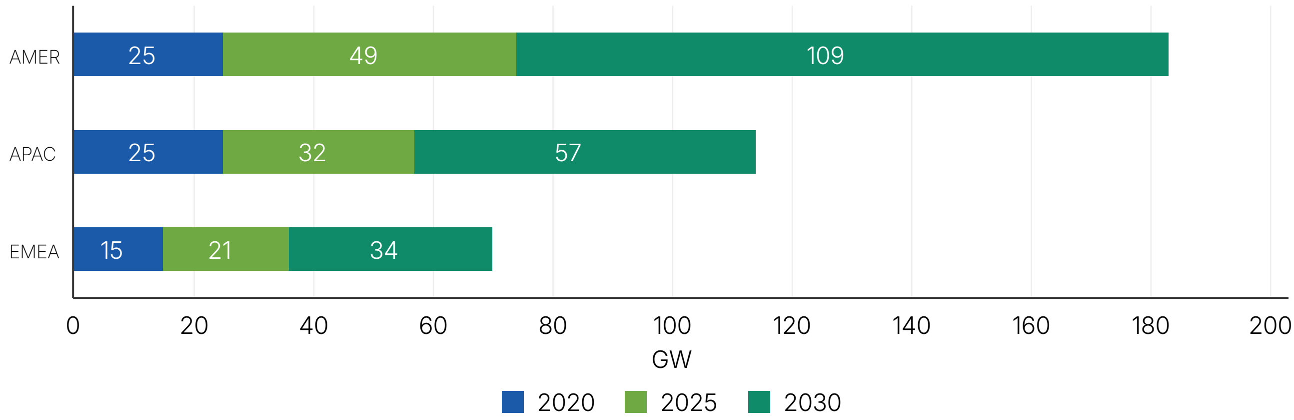


Figure 5: Global data centre supply forecast by region (GW)

Growth across all regions is being driven by hyperscale cloud expansion, AI adoption, and increasing demand for digital infrastructure. As of April 2026, the United States had over 4,184 DCs, the highest globally, followed by the United Kingdom (515) and Germany (514)[18] (Figure 6).

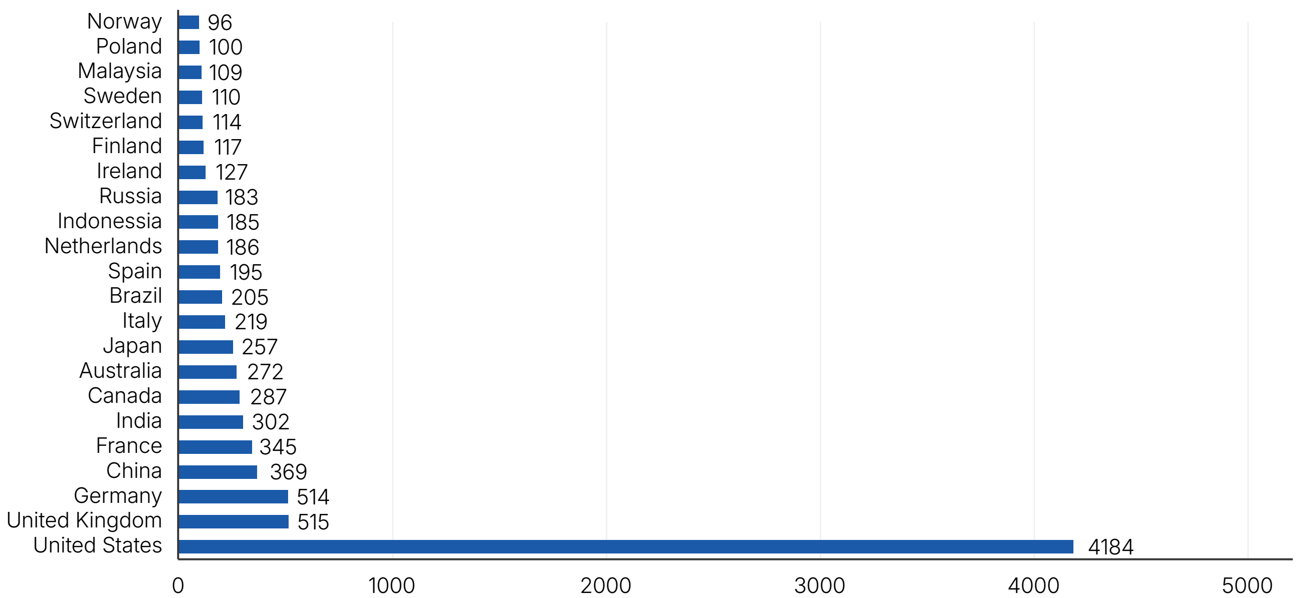


Figure 6: Global number of data centre

India's data centre market is on a massive growth trajectory, as shown in Figure 7. The country's IT capacity has already surged from 375 MW in 2020 to 1,500 MW in 2025 and is expected to reach 3,000 MW in 2026.

Earlier industry estimates, made in early 2026, projected that capacity would grow to around 9 GW by 2032. However, following a wave of major capacity announcements through 2026, these estimates have risen sharply.

Announced projects now put the 2032 pipeline at approximately 17 GW and with further announcements likely, capacity could reach as much as 20 GW. Extrapolating this trend, AEEE's baseline estimate suggests capacity could reach at least 25 GW by 2037, with the potential to rise to as much as 32 GW.

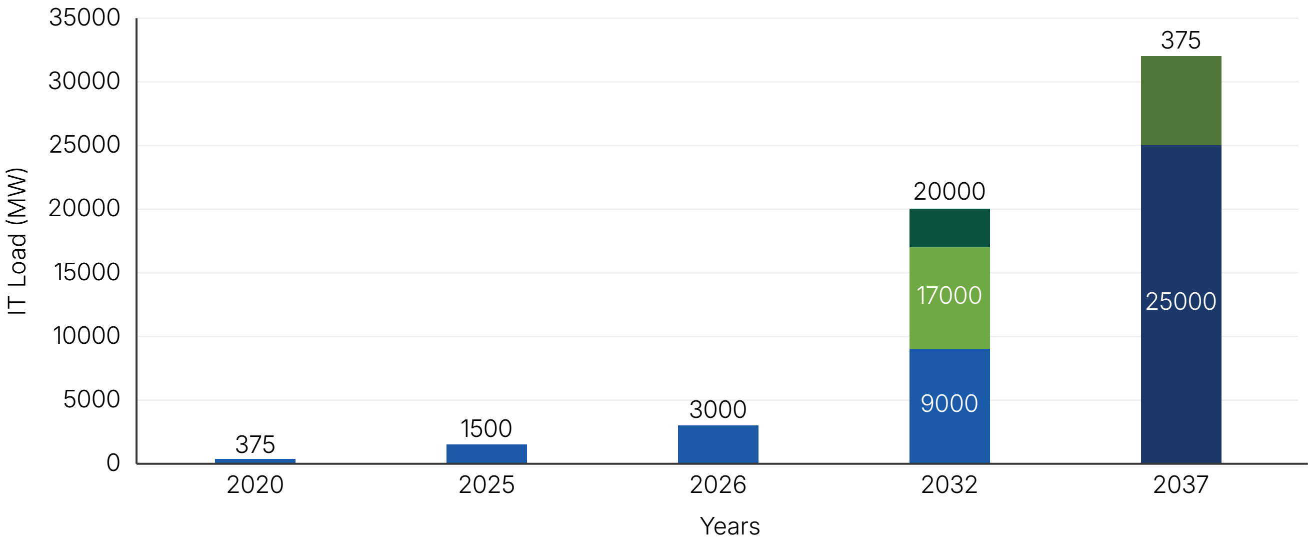


Figure 7: India's Data Centre Market (IT Load) [AEEE research]

Driven by recent large-scale investments from hyperscalers, the number of data centres currently around 302 in 2026 is projected to reach only about 350 by 2032, even as total IT load capacity expands significantly from 3,000 MW to approximately 17,000 MW over the same period. This reflects a fundamental shift in facility scale, unlike the largely small and mid-sized facilities that make up today's fleet, upcoming data centres are being built predominantly by hyperscalers at a far larger IT capacity per site. Consequently, the average capacity per facility will increase nearly 4.8 times, rising from around 10 MW per data centre in 2026 to about 48 MW by 2032 (Figure 8).

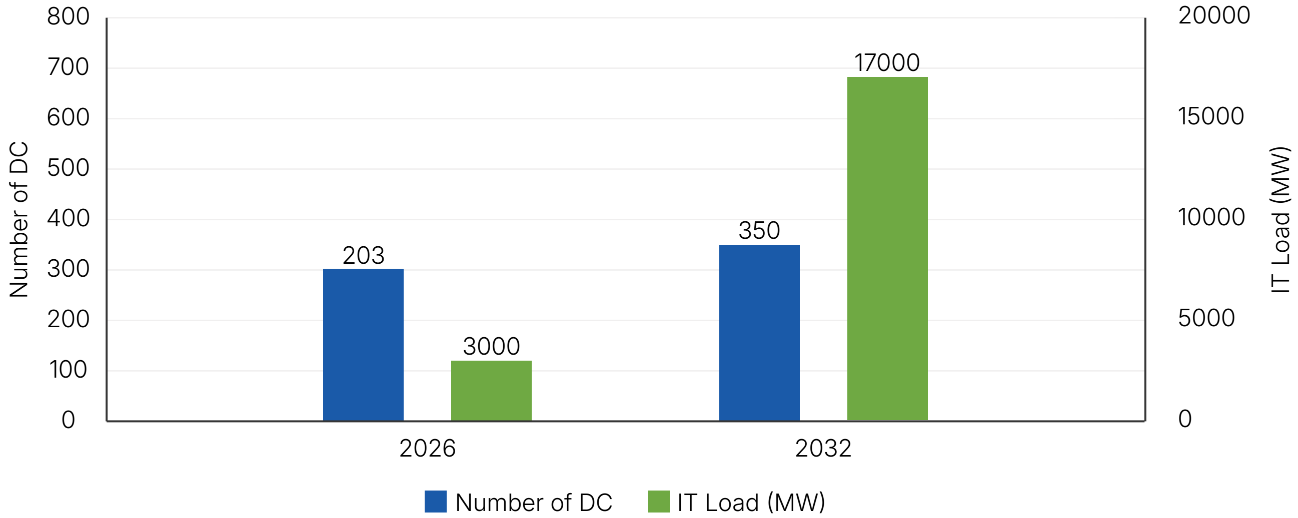


Figure 8: Number of data centres and IT load

Between 2018 and 2023, India secured commitments exceeding USD 40 billion from both global and domestic investors[19]. In February 2026, the Ministry of Electronics and Information Technology (MeitY) announced that India is expected to attract over USD 200 billion (approximately INR 18.33 lakh crore) in DC investments. Investment proposals worth around USD 90 billion have already been received, with nearly USD 70 billion worth of projects entering the construction phase[20].

1.1.4 India's Data Centre Ecosystem

India's DC ecosystem is expanding rapidly, supported by growing digital infrastructure investments and favourable policy initiatives. This section examines the geographic distribution of DC hubs, major growth drivers, and the domestic policy and regulatory framework shaping the sector.

1.1.4.1 India's Geographic Distribution

An analysis of operational DC number in various states in Figure 9. The distribution of data centres across India is highly uneven, with a strong concentration in a few major states and metropolitan technology hubs, while deployments remain relatively limited across most other states. This concentration reflects the importance of established digital infrastructure, reliable power supply, connectivity and commercial demand in determining data centre locations

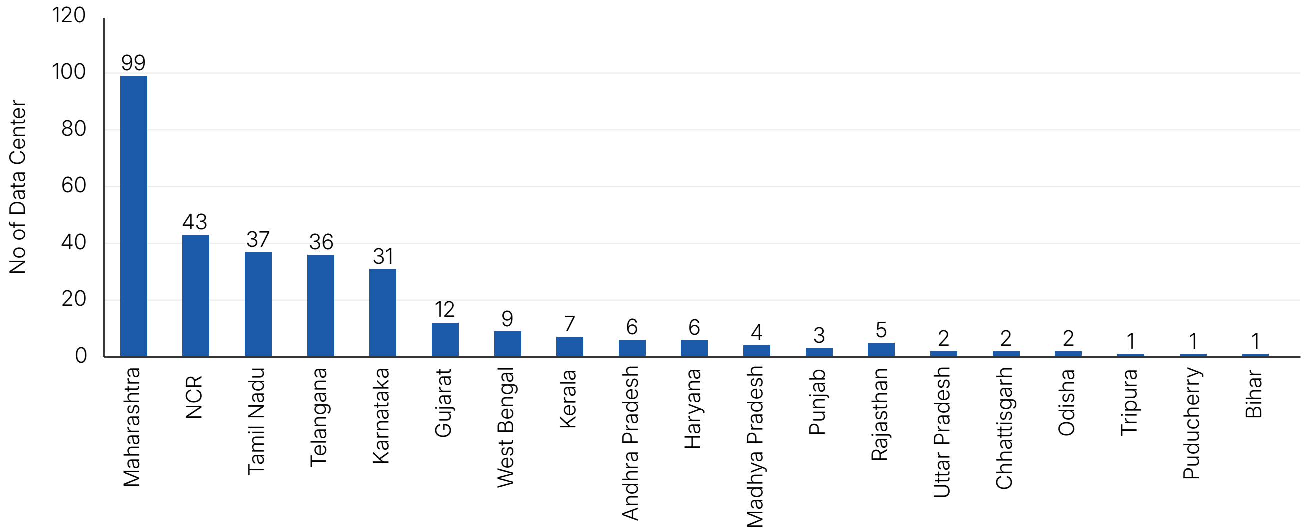


Figure 9: Number of data centres across India

The IT capacity shown in Figure 10, reveals a pronounced geographic concentration. More than 60% of India's current operational capacity is located in Maharashtra and Tamil Nadu, reflecting the early-mover advantage of Mumbai and Chennai as established connectivity hubs with access to submarine cable landing stations, and other favorable factors. Regions in northern, eastern, and central India currently account for comparatively lower shares of deployed capacity.

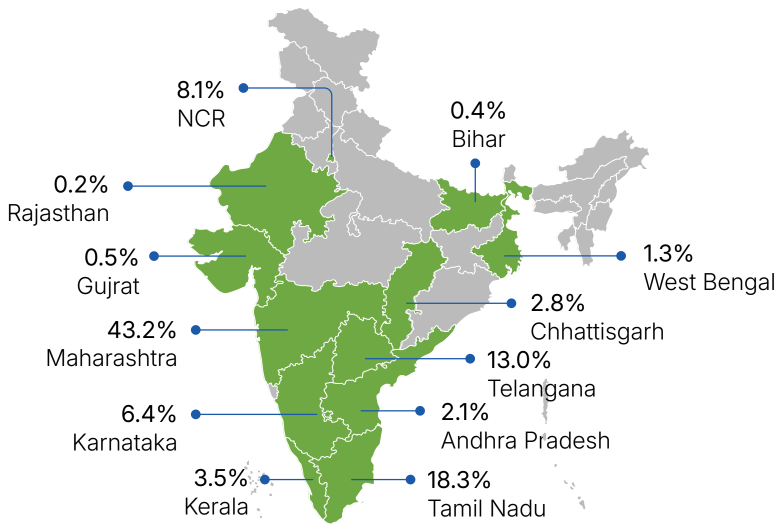


Figure 10: State-wise share of operational data centre capacity (IT Load) [AEEE Research]

Considering the recent announcements, this concentration is expected to persist in the near term. As shown in Figure 11, over 93% of announced future capacity is announced across Maharashtra, Telangana, and Gujarat. Maharashtra continues to account for the largest share of the pipeline, followed by Telangana and Gujarat, with Gujarat's rising share reflecting the emergence of newer investment destinations. Figure 11 presents the distribution of upcoming announced DCs across Indian states, highlighting the geographic concentration of the sector[21].

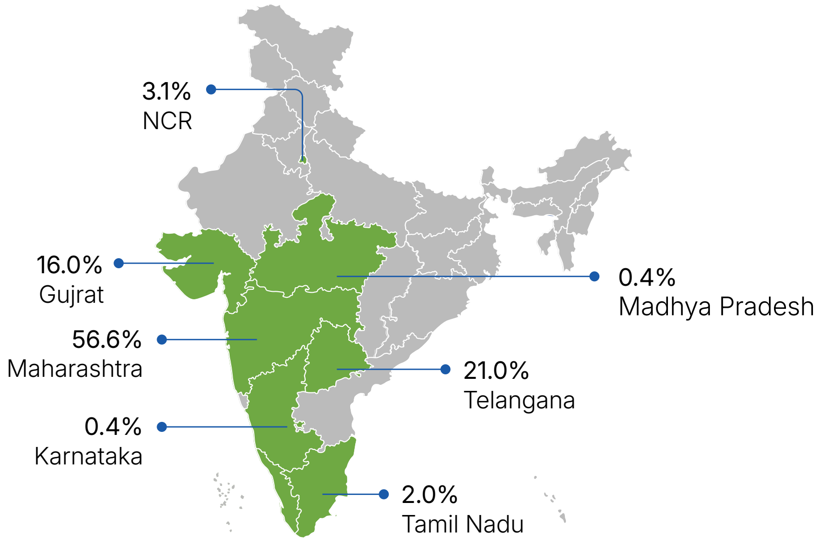


Figure 11: State-wise share of upcoming data centres capacity (IT load) [AEEE Research]

1.1.4.2 Growth Catalysts

India's DC capacity is expanding under a convergence of demand-side and regulatory drivers, each of which places distinct requirements on domestic infrastructure rather than offshore hosting. The key drivers include:

- **Rising data consumption:** A large and growing internet user base, rapid 5G adoption, and a surging OTT streaming audience are generating unprecedented data traffic, exposing an infrastructure gap that requires domestic capacity expansion.
- **Enterprise cloud migration:** A rapid shift by enterprises to cloud and Software-as-a-Service (SaaS) models is driving sustained demand for colocation and hyperscale capacity.
- **Artificial intelligence and high-performance computing:** The localised integration of AI requires high-density computing power that traditional infrastructure can no longer sustain, creating demand for a new generation of AI-ready facilities.
- **Policy and regulatory support:** Supportive government policies, data localisation requirements, and infrastructure status for the sector are encouraging domestic investment.
- **Global hyperscaler demand:** Rising investment from global cloud and hyperscale operators is positioning India as a strategic DC hub in Asia.

India's DC sector, as outlined above, is on a rapid growth trajectory. This expansion, while central to India's digital ambitions, carries resource and environmental implications that must be addressed for the sector to grow sustainably. Foremost among these is cooling. Because IT equipment generates heat continuously, DCs require uninterrupted cooling which is the largest determinant of its energy and water intensity. As computing densities rise with AI workloads, efficient cooling becomes increasingly critical. However, a range of sustainable approaches including liquid cooling, free cooling, thermal energy storage, renewable integration, and waste-heat recovery, etc. offer significant potential to improve efficiency and reduce environmental impact.

As cooling is closely linked to refrigerant choice and DCs have traditionally relied on high-global warming potential (GWP) refrigerants and transitioning to lower-GWP alternatives is now a defining challenge, aligned with India's commitments under the Montreal Protocol to phase out hydrochlorofluorocarbons (HCFCs) by 2030 and its Kigali Amendment to phase down hydrofluorocarbons (HFCs) from 2028. As cooling plant operates over a 15-to-20-year lifecycle, the choices made during the current expansion will shape the sector's footprint and India's compliance for decades. In this context, the following sections define the study's objectives and scope in Section 1.2 and methodology in Section 1.3.

1.2 Study Objectives and Scope

The primary objective of this study is to assess current cooling technologies, refrigerant usage patterns, operational practices, and emerging sustainable cooling solutions in Indian DCs, and to recommend strategies for promoting low-GWP and energy-efficient cooling pathways.

The study covers the following areas:

- Assessment of current cooling technologies and refrigerant usage in Indian DCs;
- Analysis of cooling energy demand and operational practices related to thermal management;
- Review of sustainable cooling approaches, including low-GWP refrigerants and energy-efficient technologies;
- Examination of national and international standards, guidelines, and regulatory frameworks relevant to DC cooling;
- Documentation of global and Indian case studies on sustainable cooling adoption;
- Identification of barriers, challenges, and enabling factors for technology transition; and
- Development of recommendations and best practices for promoting sustainable cooling in DCs.

The study also includes stakeholder consultations and workshops involving government agencies, industry representatives, technology providers, researchers, and other relevant stakeholders to validate findings and encourage knowledge exchange.

1.3 Study Methodology

The study followed the phased approach presented in Figure 12. It began with an inception phase to define the analytical framework, assessment indicators, data sources, and case-study criteria. These covered cooling technologies, refrigerants, energy performance, O&M, and regulatory requirements. A desk-based assessment then reviewed cooling technologies, refrigerant trends, energy performance, standards, and low-GWP solutions. The Indian DC market was sized using a bottom-up mapping of facilities across major operators. This was validated through top-down estimates and triangulated with corporate disclosures, government sources, industry databases, and technology reports. Targeted facilities were then assessed against key parameters, including IT load and utilisation, cooling systems, PUE and cooling energy share, thermal conditions, chilled-water performance, airflow and containment, water and refrigerant use, control systems, and O&M practices. Sustainability measures such as renewable energy, thermal energy storage, and free cooling were also examined. Stakeholder consultations and workshops were held to validate the findings and identify key technical, operational, and market barriers. The combined findings were then synthesised into evidence-based recommendations for sustainable DC cooling pathways.

Inception, Framework Development, and Alignment	• Develop the analytical framework, assessment parameters, and data sources for the study. • Finalise field visit and case study selection criteria. • Conduct an inception consultation with MoEFCC to validate the study approach.
Desk Research and Assessment	• Bottom-up aggregation: Maps ~25 operator individual facilities (operational and incoming) and standardize capacity to IT load in MW. • Top-down Validation: Cross checks facility totals against macro industry benchmarks and national projections to ensure market completeness. • Conduct assessment of cooling technologies, refrigerants, energy use, and O&M practices. • Review relevant standards, regulations, and global best practices.
Field Visits and Case Study Documentation	• Conduct targeted field visits and stakeholder consultations to collect information on cooling systems, refrigerant use, and operational practices. • Document anonymised case studies on the adoption of sustainable, low-GWP, and energy-efficient cooling technologies.
Integrated Analysis and Recommendations	• Analyse findings from the desk review, field visits, and case studies to identify key gaps and opportunities. • Develop recommendations and best practices for sustainable, low-GWP, and energy-efficient cooling in data centres.
Workshops and Knowledge Dissemination	• Organise two virtual stakeholder workshops to present findings, validate recommendations, and facilitate knowledge exchange. • Incorporate stakeholder feedback into the final report.

Figure 12: Study Methodology

02

Cooling Approaches in Data Centres

DCs are highly energy-intensive facilities, with most electricity consumed by IT equipment ultimately converted into heat that must be continuously removed to maintain reliable operating conditions. Heat is generated primarily by CPUs, GPUs, memory, storage, and networking equipment, with additional contributions from electrical infrastructure such as UPS, PDUs, transformers, and switchgear due to conversion and distribution losses, as well as from cooling equipment, pumps, fans, and compressors; auxiliary systems such as lighting and security contribute comparatively little (Figure 13). The rapid growth of cloud computing, AI, and HPC is driving higher processor and rack power densities, making cooling increasingly critical to DC energy efficiency, reliability, and environmental performance. Cooling technology selection depends on heat load, rack density, climate, reliability requirements, and sustainability objectives. While conventional air cooling remains widely used for low- and medium-density facilities, increasing AI and HPC workloads are accelerating the adoption of liquid, hybrid, and other advanced cooling technologies.

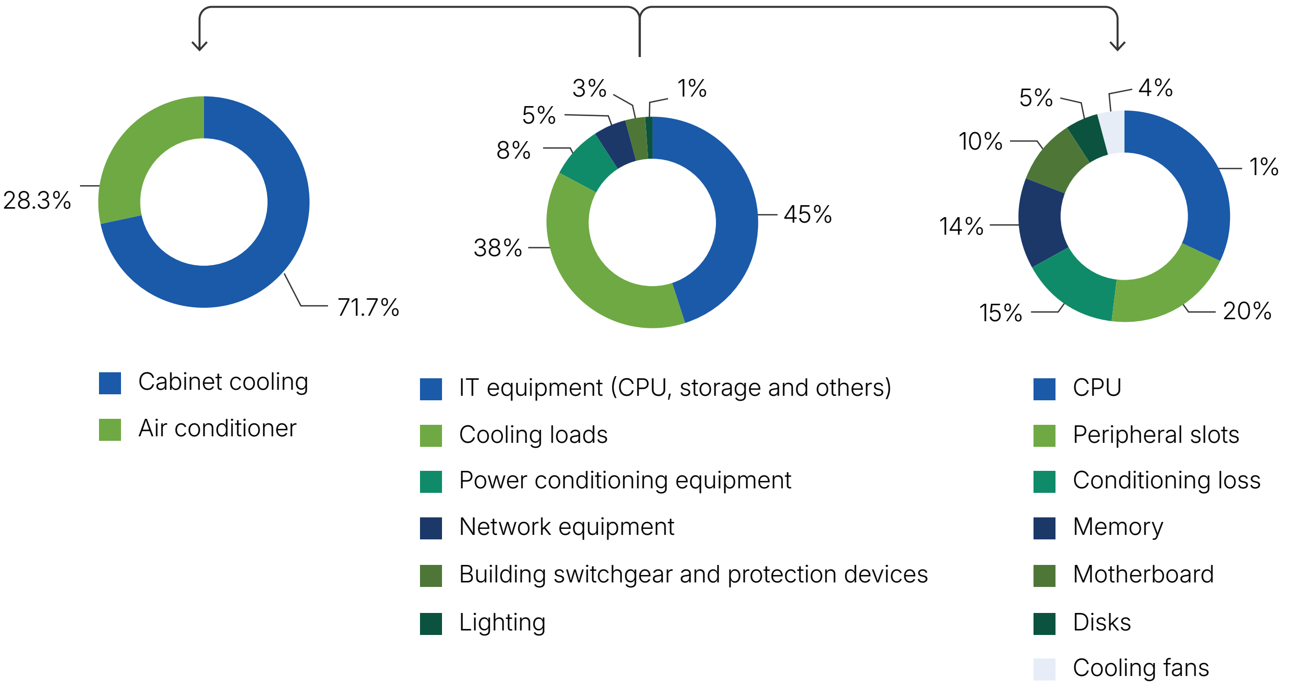


Figure 13: Component-wise energy consumption of a data centre

2.1 Overview of Data Centre Cooling System

Regardless of the cooling technology, DC cooling systems perform two fundamental functions: heat collection and heat rejection. Heat collection involves removing heat from IT equipment either indirectly through conditioned air or directly through chilled water or liquid coolants using cold plates, rear-door heat exchangers, or immersion systems. In liquid-cooled systems, a coolant distribution unit (CDU) circulates and regulates the coolant and transfers the collected heat to the facility cooling loop through a heat exchanger while maintaining hydraulic separation between the two circuits. The heat is then rejected to the ambient environment using chillers, cooling towers, dry coolers, condensers, or adiabatic systems. Thus, cooling performance depends on the effective integration of heat collection, coolant distribution, and heat rejection while maintaining required operating conditions with minimum energy and water consumption. Based on these functions and system architectures, DC cooling technologies can be broadly classified into three categories:

2.1.1 Free Cooling

Uses ambient air or water (via air-side/water-side economizers, indirect heat exchangers, or heat pipes) to reject heat with little or no mechanical refrigeration (Figure 14), cutting energy use and emissions. It's widely adopted in large-scale and hyperscale facilities, often paired with conventional cooling.

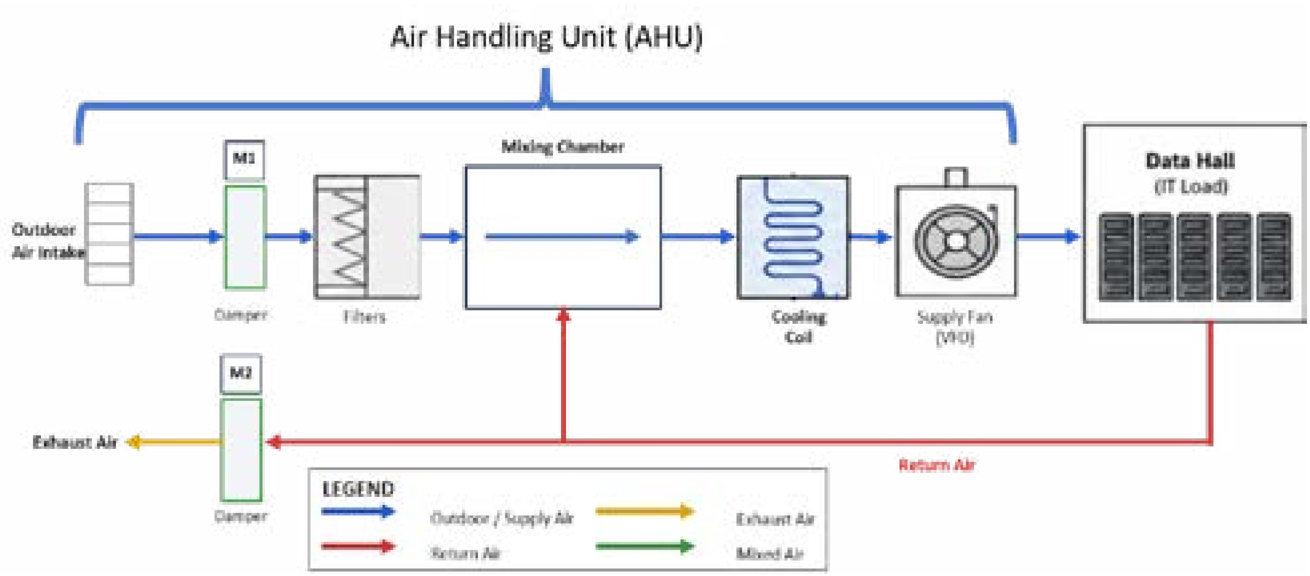


Figure 14: Free cooling in data centre

2.1.2 Air Cooling

The default when free cooling isn't sufficient, or climate is unfavorable, circulates conditioned air through CRAC/CRAH units, supported by raised-floor/overhead distribution and hot-aisle/cold-aisle containment (Figure 15). Its simplicity and low capital cost make it dominant in small- to medium-sized facilities with low- to moderate-rack density.

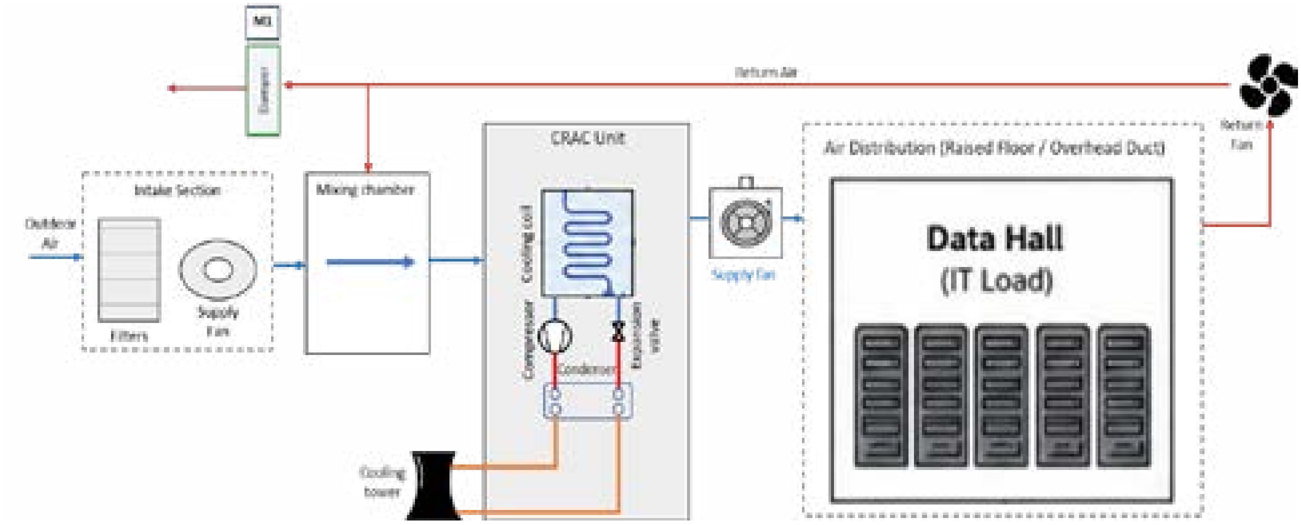


Figure 15: Air cooling in data centre

2.1.3 Liquid Cooling

Increasingly necessary as AI/HPC rack densities climb, uses water or other coolants with far higher heat-transfer capacity than air. Key variants: chilled-water cooling, cold plate cooling, rear-door heat exchangers, and immersion cooling. The cooling architectures are further expanded and illustrated in Figure 16.

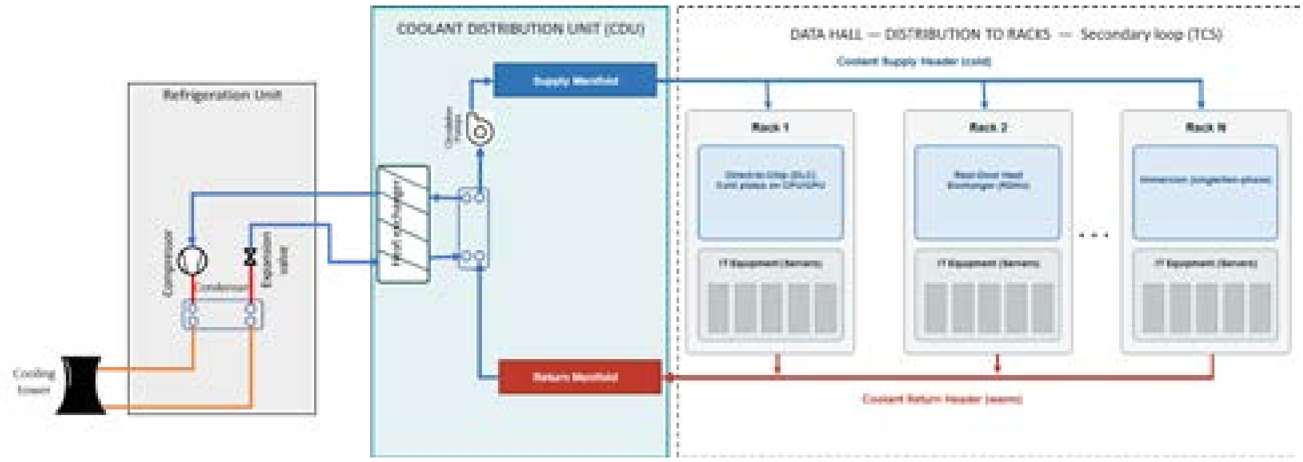


Figure 16: Liquid cooling in data centre

No single architecture or technology fits every case; the right choice depends on IT load, rack density, climate, water availability, and operational requirements. That's why comparative performance assessment, weighing thermal performance, energy efficiency, water consumption, cost, and implementation complexity, matters for selecting the right cooling approach for a given facility.

After heat is collected from the IT equipment, it is transferred to the heat rejection system, where it is discharged to the ambient environment. The choice of heat rejection technology has a significant influence on cooling energy consumption, water use, and overall system performance.

2.1.4 Evaporator Side Technologies

Evaporator-side cooling architectures can be classified into four tiers based on their proximity to the IT load:

2.1.4.1 Room-based cooling

In these systems, conditioned air is supplied to server racks to absorb heat generated by IT equipment, while the heated air is collected, cooled, and recirculated through cooling units such as Computer Room Air Conditioners (CRACs) or Computer Room Air Handlers (CRAHs) (Figure 17). To enhance cooling effectiveness, airflow management strategies such as raised-floor distribution, hot-aisle/cold-aisle configurations, and containment systems are commonly employed. Owing to their relatively simple design, lower capital costs, and operational familiarity, air cooling systems are predominantly used in small- and medium-sized DCs as well as facilities with low to moderate rack power densities

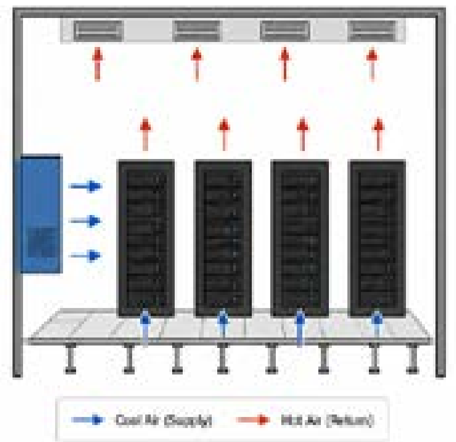


Figure 17: Schematic of room-based cooling

2.1.4.2 Row-based cooling

Row-based cooling positions cooling units close to the IT racks, typically within or adjacent to rack rows, using approaches such as in-row cooling and overhead row cooling (Figure 18). By reducing the distance between cooling supply and heat generation, these systems provide improved airflow control, better temperature uniformity, and higher cooling efficiency compared with room-based systems. They are commonly adopted in medium- to high-density DCs, although they require higher capital investment and more complex piping and control systems. technologies for high-performance computing applications[22],[23].

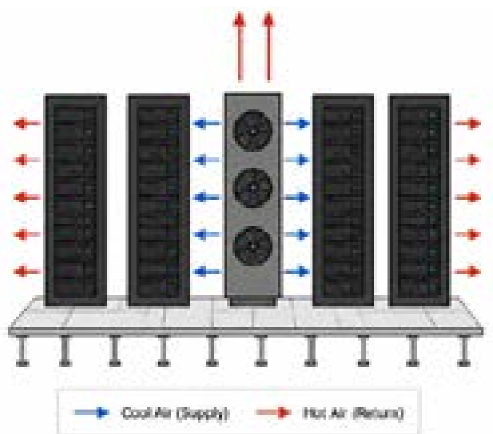


Figure 18: Schematic of row-based cooling

2.1.4.3 Rack-based cooling

Rack-based cooling provides cooling directly at the rack level through technologies such as rear-door heat exchangers (RDHx) and in-rack cooling units (Figure 19). These systems minimise airflow dependence at the room level and are suitable for high-density computing applications, including artificial intelligence (AI) and high-performance computing (HPC) environments. However, they involve higher installation complexity, increased maintenance requirements, and greater infrastructure integration compared with room- and row-based cooling approaches. Overall, air cooling remains effective for conventional DCs; however, its scalability becomes limited as rack power densities increase. This has accelerated the adoption of liquid cooling.

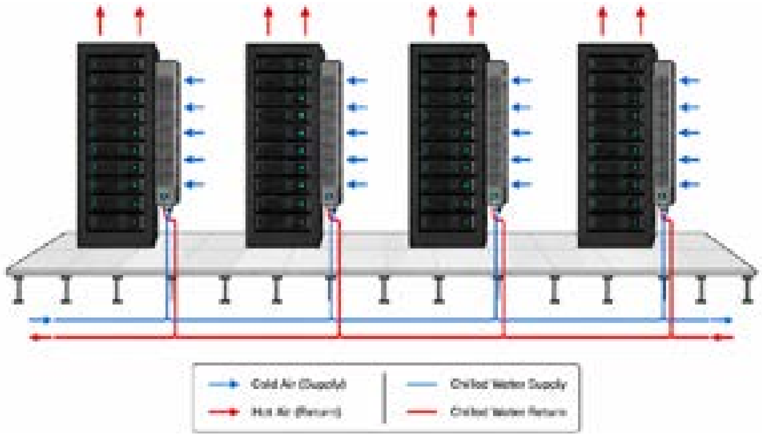


Figure 19: schematic of rack-based cooling

2.1.4.4 Direct chip cooling

Direct-to-chip cooling removes heat directly from high heat density components, such as CPUs and GPUs, using liquid-cooled cold plates connected to a closed coolant loop (Figure 20). The heated coolant transfers the absorbed heat to a CDU, which subsequently rejects it through a secondary cooling system, such as a dry cooler, cooling tower, or chiller. By cooling the primary heat-generating components directly, direct chip cooling significantly higher heat removal capacity and energy efficiency than conventional air cooling, making it well suited for high-density AI and HPC workloads with rack power densities exceeding the practical limits of air cooling. Although direct chip cooling substantially reduces fan energy consumption and enables higher rack densities, it requires specialized liquid distribution infrastructure, leak management, and compatibility between IT equipment and cooling hardware, resulting in higher capital costs and greater system integration complexity.

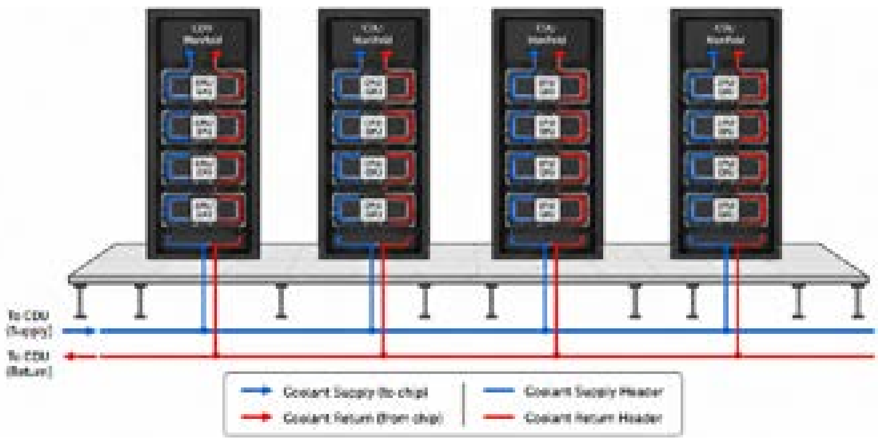


Figure 20: schematic of direct chip cooling

Figure 21 presents a broad classification of DC cooling technologies, categorised according to the level at which heat is collected from the IT equipment. The selection of an appropriate cooling architecture depends on factors such as rack power density, climatic conditions, water availability, operational reliability, and overall energy efficiency requirements.

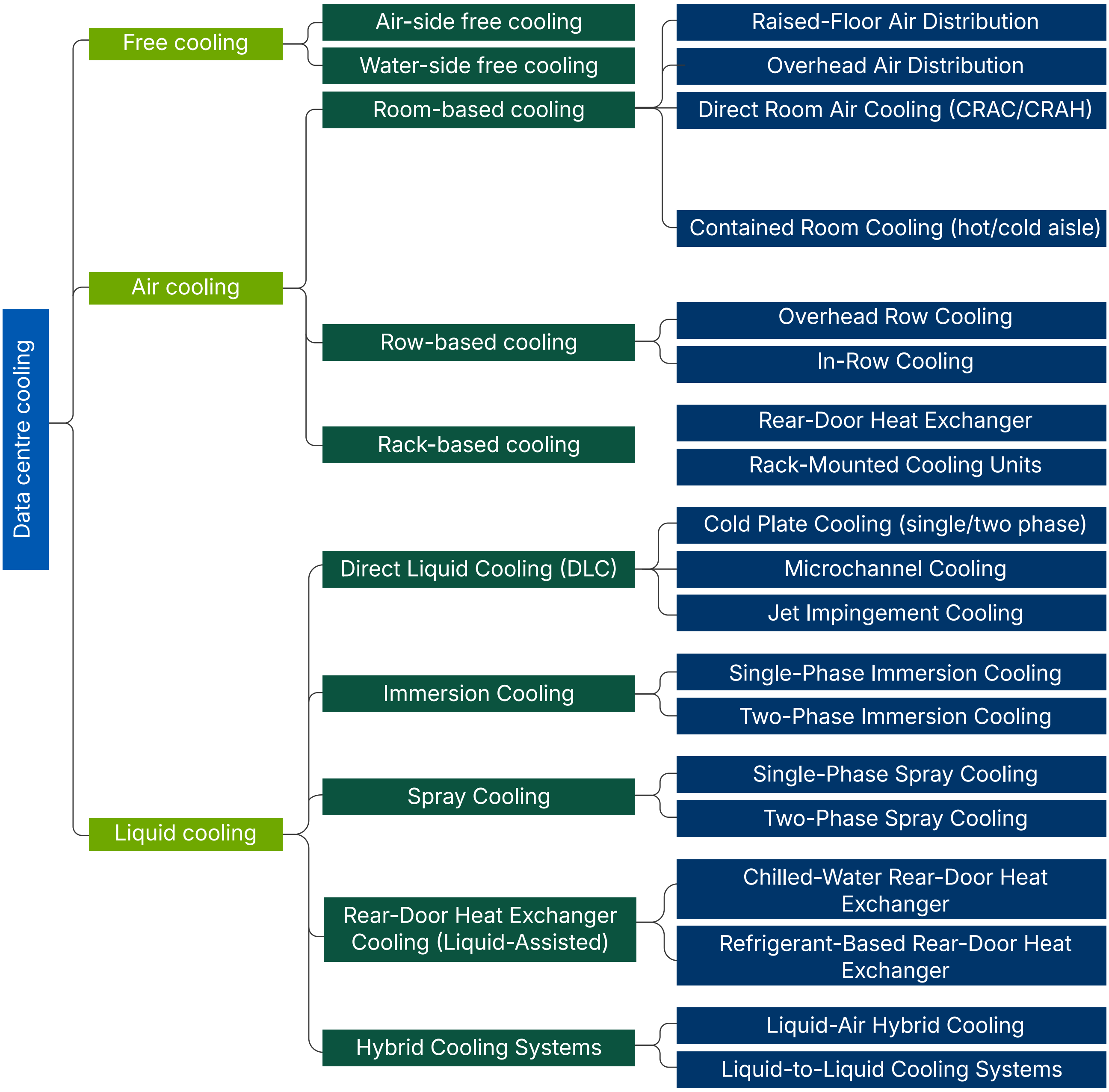


Figure 21: Cooling architectures of a data centre

2.1.5 Condenser Side Technologies

On the condenser side, cooling system architectures are generally categorized into four tiers according to their heat rejection approach:

2.1.5.1 Air Cooled Condenser

Heat is rejected directly to the ambient air through finned heat exchangers using forced convection. Dry coolers (Figure 22) operate without water consumption, resulting in low maintenance and simplified operation. However, their heat rejection capacity decreases as ambient temperature rises, making them less effective in hot climates unless combined with adiabatic assistance.

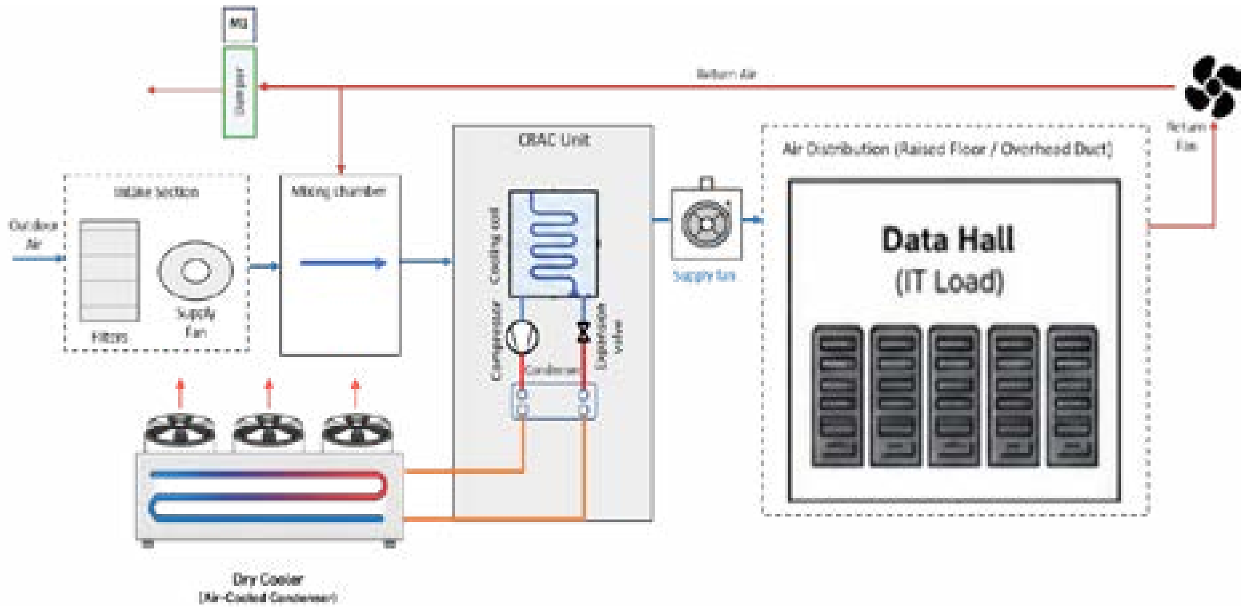


Figure 22: Dry air-cooled condenser equipped system

2.1.5.2 Water Cooled Condenser

Cooling towers (Figure 23) reject heat through evaporative heat transfer, where warm condenser water is cooled by direct contact with ambient air. Owing to the lower achievable approach temperatures, cooling towers provide higher heat rejection efficiency and lower condensing temperatures than dry coolers, improving chiller performance. Their operation, however, requires continuous water supply, water treatment, blowdown management, and regular maintenance to prevent scaling, corrosion, and biological growth.

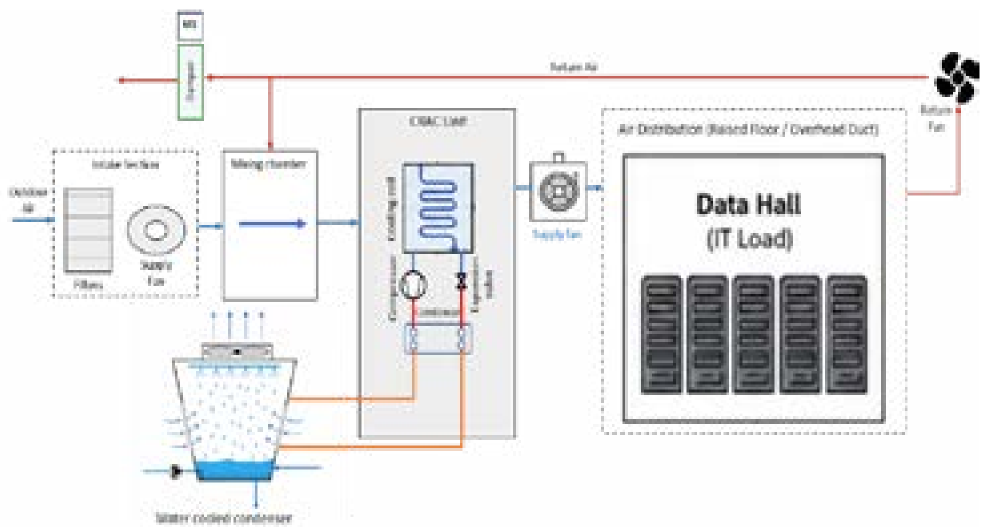


Figure 23: Water cooled condenser equipped system

2.1.5.3 Adiabatic and Evaporative Condenser

Conventional dry coolers used in liquid-cooled DCs can become ineffective at high ambient temperatures, particularly when the dry-bulb temperature approaches the required coolant supply temperature. Adiabatic and evaporative cooling (Figure 24) improves heat rejection by evaporatively cooling the inlet air, thereby increasing the temperature difference across the heat exchanger. Performance depends on the wet-bulb depression and is therefore highest in hot, dry climates but decreases under humid conditions. Rising ambient temperatures and more frequent heatwaves are driving wider adoption of evaporative-assisted dry cooling to improve energy efficiency and cooling reliability.

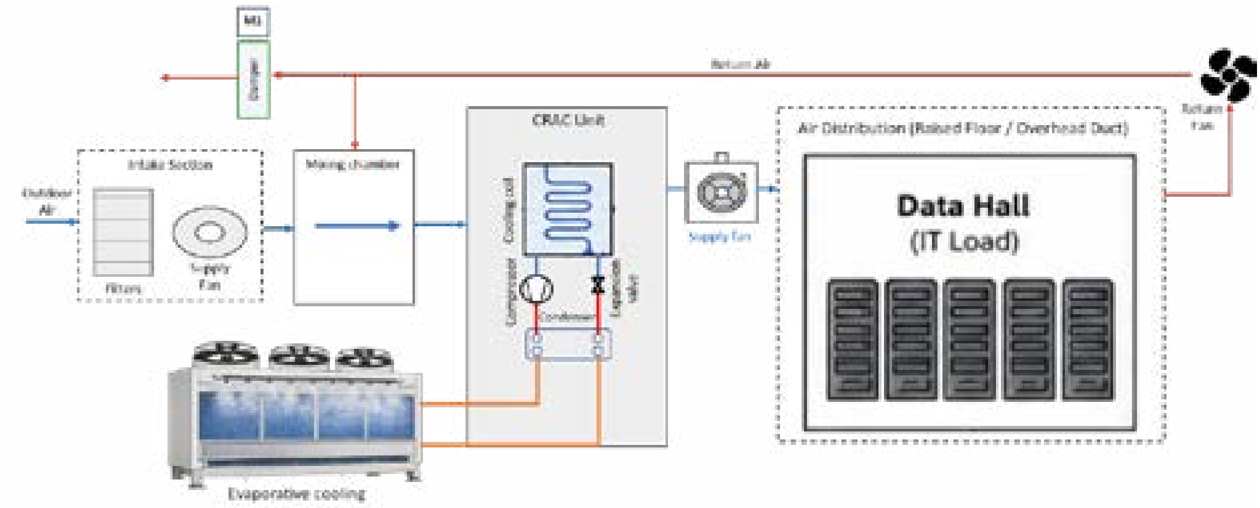


Figure 24: Evaporative cooled condenser equipped system

2.1.5.4 Hybrid Closed-Loop Condenser

Hybrid closed-loop cooling (Figure 25) combines dry and evaporative cooling to optimise energy and water use under varying climatic conditions. The system operates in dry mode during cooler periods and switches to evaporative mode during high ambient temperatures or peak cooling loads to maintain the required coolant temperature. Hybrid closed-loop cooling is increasingly adopted in DCs, particularly in water-stressed regions, as it provides an effective balance between energy efficiency, water conservation, and operational reliability. Hybrid cooling towers can achieve up to 80% water savings, depending on climatic conditions and operating profiles, through intelligent wet/dry mode switching.

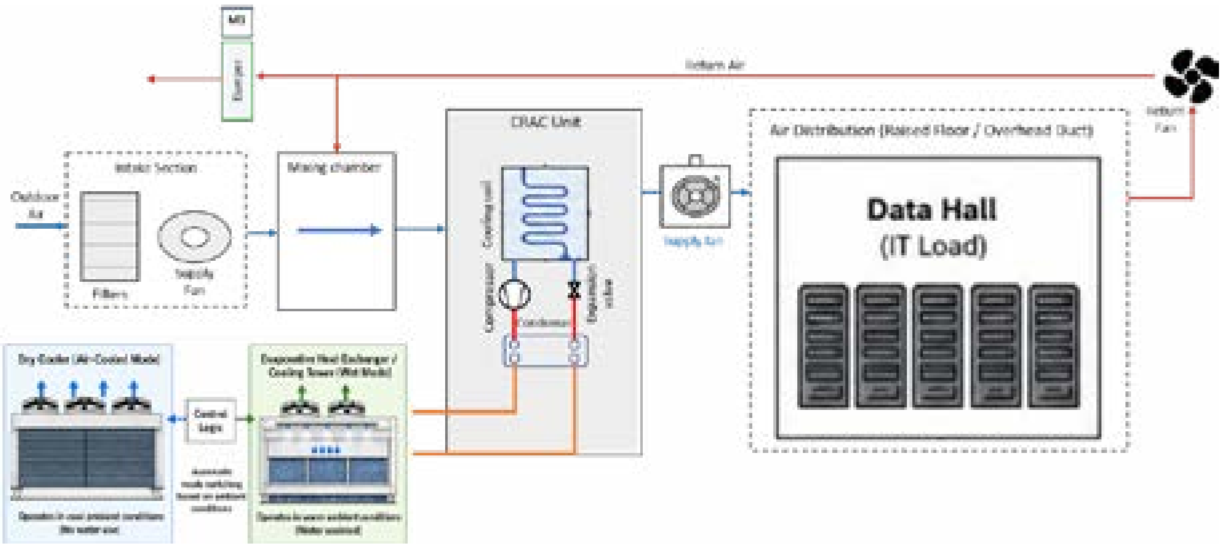


Figure 25: Hybrid air-water cooled condenser equipped system

2.2 Cooling Capacity and Heat Density Suitability

A major trend in DC cooling is the shift from conventional room-level air cooling to liquid cooling at the rack and chip level. While CRAC/CRAH systems remain widely used for conventional IT equipment, increasing rack power densities and higher GPU heat loads (Figure 26) are driving the adoption of rear-door heat exchangers (RDHE), direct-to-chip liquid cooling (DLC), and immersion cooling (Figure 27). Liquid cooling can deliver 8% server-level energy savings and 30–40% facility-level cooling energy savings, translating to overall DC energy savings of 10–21% compared with conventional cooling systems[24].

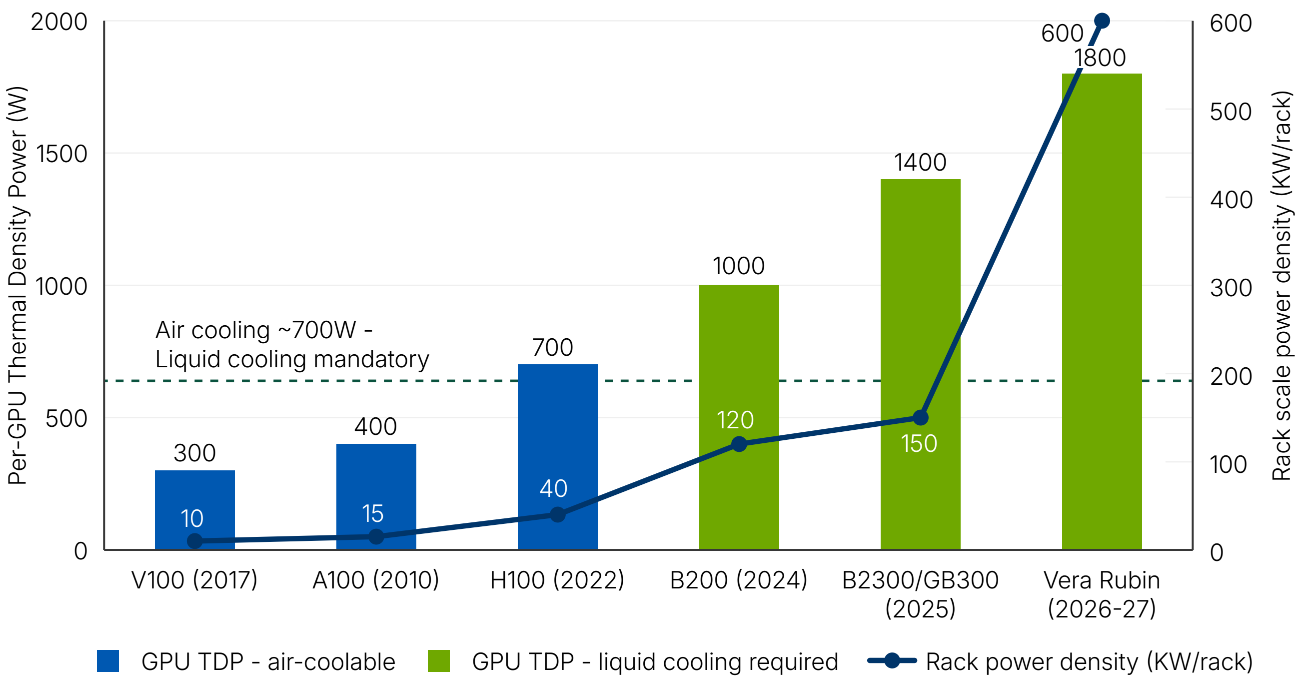


Figure 26: Thermal density of the chip[25, 26, 27, 28]

The environmental and physical footprint of a DC is fundamentally dictated by the silicon processors inside it. To deliver the mathematical computing power required for AI training and inference, chip manufacturers have sharply increased per-processor thermal output. The rapid growth of cloud computing, hyperscale facilities, artificial intelligence (AI), and high-performance computing (HPC) has fundamentally changed the thermal characteristics of modern DCs. Increasing computational intensity has led to a substantial rise in server and rack power densities, resulting in significantly higher heat fluxes that conventional air-cooling systems were not originally designed to dissipate. However, beyond a per-chip power threshold of approximately 700 W, air physically cannot carry away thermal energy fast enough without consuming prohibitive amounts of fan energy or room space[29].

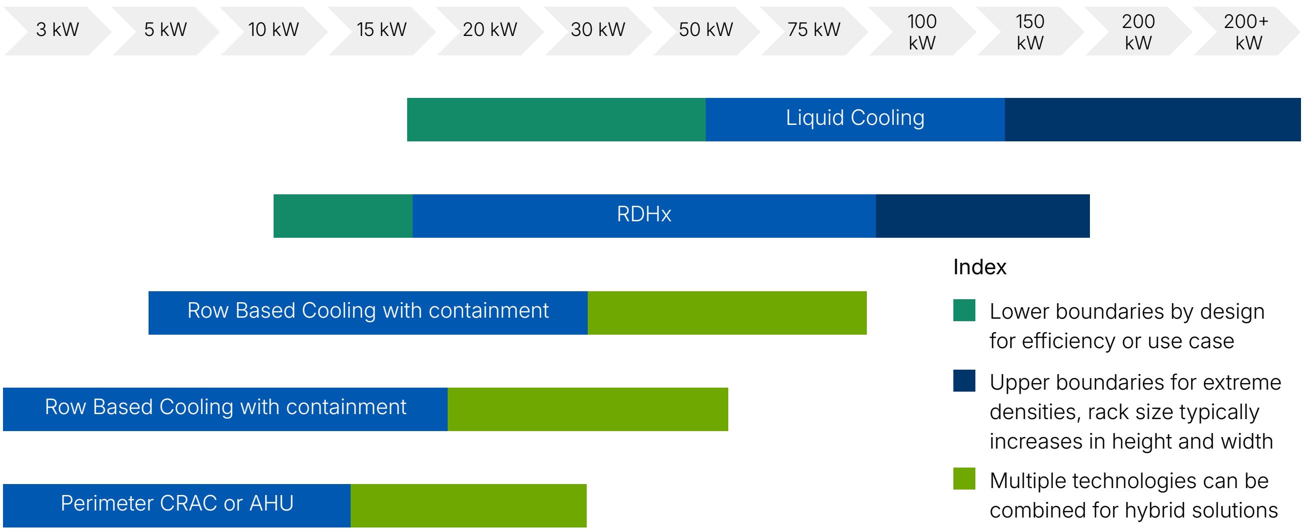


Figure 27: Rack density ranges and corresponding cooling technique

The rapid growth of AI and cloud computing is driving DC electricity demand to unprecedented levels, increasing pressure on grid capacity and connection timelines. This is accelerating the adoption of "Bring Your Own Power" (BYOP), or behind-the-meter (BTM) generation, where operators use on-site or co-located power sources such as gas generation, renewables, batteries, fuel cells, and microgrids to supplement grid supply[30]. In the USA, this approach is gaining momentum as grid interconnection delays can extend to several years, with around 50 GW of BTM gas generation announced globally in 2025 and more than 35 GW of self-generated DC power projected by 2030[31]. BYOP is generally considered complementary to the grid, providing near-term capacity and resilience while long-term grid connections are developed.

In India, the model could help address long transmission and grid-connection timelines in major DC hubs such as Mumbai, Chennai, Hyderabad, and Delhi-NCR. Captive renewables, group-captive arrangements, open-access PPAs, and battery-based microgrids can support faster deployment while reducing grid dependence. However, the sustainability benefits depend on the energy source: renewable generation with storage can improve REF and reduce CUE, whereas fossil-fuel-based generation increases direct Scope 1 emissions. India should therefore encourage BYOP models centred on renewable and low-carbon generation.

2.3 Refrigerant Use in Data Centres

Refrigerants are used in DC cooling systems such as CRAC units, chillers, heat pumps, and precision cooling systems to transfer heat from IT equipment to the ambient environment. Refrigerant selection affects cooling efficiency, operating pressure, safety, equipment design, and lifecycle environmental impact. With the upcoming phase-down of high-GWP HFCs under Kigali Amendment of Montreal Protocol. DCs are increasingly considering low-GWP HFOs and natural refrigerants.

In India, R134a, R410A, and R407C remain common in existing DC cooling systems because of their established equipment base, supply chains, and operational familiarity. However, low-GWP alternatives are gaining attention, particularly for new-generation cooling systems. Importantly, the shift towards liquid cooling does not necessarily require a different refrigerant, since direct-to-chip, rear-door, and immersion systems primarily change the method of heat collection on the IT side; the refrigerant may remain within the central chiller or heat-rejection system. The relevance and key considerations of major refrigerants for DC cooling are summarised in Table 3.

Table 3: Current Refrigerant usage and low GWP alternatives

Equipment Type (Data Centre Use)	Current Refrigerant Use	Alternative Low-GWP Refrigerants
Centrifugal & Screw Chillers (main chilled-water plant, large DCs)	R134a, R1234ze, R513A	R1233zd, R1234ze, R513A, R514A, R515B, R744
Scroll Chillers / CRAC-CRAH Rooftop Units (room-level, packaged cooling)	R407C, R410A, R32, R452B/R454B	R452B/R454B, R290, R515B

For Indian DCs, HFO-based refrigerants, particularly R1234ze(E), offer the most immediate low-GWP pathway for large chiller applications. Natural refrigerants such as CO_2, ammonia, and propane can provide further environmental benefits, but face application-specific challenges related to pressure, toxicity, or flammability. Their wider adoption will depend on equipment availability, safety requirements, skilled workforce, and supporting infrastructure.

03

Data Centre Performance and Sustainability

As computing demand grows, evaluating DC performance requires moving beyond simple energy metrics to a broader sustainability framework. This section presents the key performance indicators used to assess energy, water, and carbon performance, along with benchmark comparisons across cooling technologies and DC types. It then examines the trade-offs between energy efficiency and water consumption, and outlines the core strategies for sustainable operation, including energy efficiency measures, advanced cooling systems, waste heat recovery, renewable energy integration, refrigerant transition, thermal energy storage, AI-driven cooling optimisation, and water sustainability practices.

3.1 Data Centre Performance Metrices

DC sustainability assessment requires metrics that capture not only energy efficiency but also carbon emissions, water consumption, renewable energy use, and resource utilisation. Power usage effectiveness (PUE) remains the most widely used facility-level metric, with a theoretical minimum of 1.0, but it does not capture IT utilisation, workload efficiency, or the carbon intensity of electricity. Complementary indicators therefore provide a broader assessment: Carbon Usage Effectiveness (CUE) measures operational carbon emissions, Water Usage Effectiveness (WUE) measures water consumption, Energy Reuse Effectiveness (ERE) quantifies beneficial waste-heat recovery, Renewable Energy Factor (REF) captures the share of renewable electricity, and Water Reuse Effectiveness (WRE) evaluates water reuse and recycling. Data Centre Infrastructure Efficiency (DCIE) measures the proportion of total data centre energy consumption that is used by IT equipment. For AI and HPC facilities, workload-based metrics such as energy per computational task or queries per kWh are also becoming important. Together, these indicators provide a more comprehensive assessment of DC energy, carbon, water, and resource performance. The definitions and formulations of the key metrics are summarised below in Table 4.

Table 4: Key Performance Parameters for Data Centre Cooling Systems

Metrices	Formula	Relevance	Typical Range / Interpretation
PUE	$\dfrac{\textit{Total energy consumption by data centre}}{\textit{Energy consumption by IT components}}$	• Overall energy efficiency indicator — total facility energy vs. IT energy • Covers cooling, power distribution, lighting, UPS losses & auxiliary infra • Lower is better, but ignores server utilisation, workload & carbon intensity	• Min possible: 1.0 | Global avg: ~1.57 • Typical split: IT 50–65%, cooling 30–40%, power/aux 5–10% • Hyperscale: 1.1–1.5 | Older facilities: >2.5
WUE	$\dfrac{\textit{Annual Water Usage (litres)}}{\textit{IT equipment energy (kWh)}}$	• Tracks water use, mainly from cooling systems • Depends heavily on cooling technology & climate • Lower = better sustainability, less freshwater draw	• Best-in-class: 0.1–0.3 L/kWh | Evaporative cooling: 1–2 L/kWh • Arid/water-intensive: >4 L/kWh | Air-cooled: ~0 L/kWh • No universal target
CUE	$\dfrac{\textit{Total}CO_2\textit{ emissions (kg)}}{\textit{IT equipment energy (kWh)}}$	• Measures carbon emissions from IT energy use • Complement PUE by adding a carbon lens, not just energy	• No fixed range — lower is always better • Fully renewable facility → approaches 0
DCIE	$\dfrac{\text{IT Power consumed by IT equipment}}{\text{Total facility power consumption}} \times 100$	• Inverse of PUE percentage of power actually reaching IT equipment • Higher = more efficient infrastructure	• Range: 0–100% • Efficient facilities: 65–90% (≈ PUE 1.1–1.5)
ERE	$\dfrac{\textit{Total facility energy consumption-reused energy}}{\textit{Power consumed by IT components}}$	• Extends PUE by crediting waste-heat reuse (district heating, hot water, industrial use) • Lower = more heat recovered & reused	• Min: 0 (full waste-energy reuse) • U4E target: 30% by 2025 → 60% by 203132.
REF	$\dfrac{\textit{Renewable energy consumption (kWh)}}{\textit{Total energy consumption}}$	• Share of electricity from renewables — key driver of lower carbon emissions • Best assessed annually to capture seasonal shifts	• Range: 0–1 | REF = 1.0 → fully renewable • U4E target: 50% by 2025 → 80% by 2031.
WRE	$\dfrac{\text{Total volume of water reused}}{\text{Total volume of water supplied to the data centre}}$	• Measures re[32]liance on reclaimed/recycled/harvested water • Complements WUE — reuse rate rather than total consumption	• Range: 0–1 | Higher = more reuse • WRE = 1.0 → zero freshwater dependence

Table 5 presents a comparative overview of the typical Power Usage Effectiveness (PUE) associated with the major cooling technologies employed in modern DCs, compiled from the available literature. The comparison highlights the progressive improvement in energy efficiency from conventional air-based cooling systems to advanced liquid cooling technologies. While traditional perimeter CRAC/CRAH systems generally exhibit the highest PUE, the adoption of airflow management strategies, free cooling, rack-level cooling, and liquid cooling technologies has enabled substantial reductions in facility energy consumption. Among these, direct liquid cooling and immersion cooling demonstrate the highest energy efficiency due to their superior heat removal capability and significantly lower cooling power requirements. It should be noted, however, that PUE is a facility-level performance metric influenced by several factors, including climatic conditions, IT load, electrical infrastructure, cooling system design, operational practices, and the degree of system optimisation. Therefore, the reported values should be considered representative benchmarks derived from the literature rather than definitive performance limits for individual cooling technologies.

Table 5: Cooling Technologies and Corresponding Power Usage Effectiveness (PUE)

Cooling Technology	Typical PUE
Perimeter CRAC/CRAH Units[33]	1.6–2.0
Hot-Aisle / Cold-Aisle Containment[34]	1.2–1.5
Free Cooling / Economiser Modes[35]	1.08–1.56
Rear-Door Heat Exchangers (RDHE)[36]	1.25–1.33
In-Row Liquid Coolers[37]	1.2–1.4
Direct Liquid Cooling[38]	1.02–1.05
Single-Phase Immersion Cooling[39]	1.07–1.1
Two-Phase Immersion Cooling[40]	1.04-1.06

Table 6 compares key technical metrics, such as rack density, power capacity, and energy efficiency (PUE), across different types of DCs. It highlights the main differences in scale and efficiency between enterprise, colocation, hyperscale, and edge facilities

Table 6: Comparative Performance and Power Metrics Across Data Centre Types

	Enterprise DCs	Colocation DCs	Hyperscale DCs	Edge DCs
Rack density	Commonly run 3-5 kW/rack[41]	Low-Density: 2–5 kW/rack, Mid-Density: 6–9 kW/rack, High-Density: 10–50 kW/rack[42]	50 kW and even higher[43]	3 - 20 kW per rack (Edge optimised)
Power required	0.5-20 MW	500 kW – 20 MW[44]	50-500+ MW[45]	1-10 MW[46]
PUE	1.5-1.8	1.3-1.6	1[47].09-1.20	1.5-2.0

3.2 Energy and Water Saving Potential and Corresponding Emissions

Cooling condenser selection creates a clear trade-off between energy and water efficiency as presented in Figure 28. Under comparable climatic and operating conditions, air-cooled condensers typically show the highest PUE or lowest efficiency, at approximately 1.6, but near-zero water use; water-cooled condensers, by contrast, typically achieve the lowest PUE, around 1.25, at the highest WUE, approximately 3.0. Hybrid and evaporative systems offer intermediate performance, with indicative PUE values of around 1.45 and 1.35, and WUE values of around 0.9 and 1.15, respectively. These values are indicative and can vary depending on local climatic conditions, ambient temperature and humidity, facility design, and operating parameters; direct comparisons are most meaningful when technologies are evaluated under similar climatic and operational contexts.

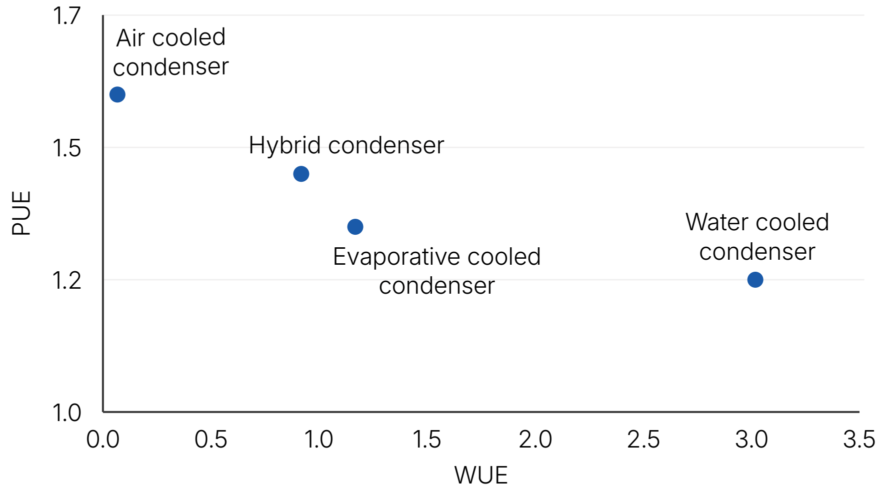


Figure 28: Trade-off Between PUE and WUE

At the current industry-typical PUE of 1.6 in air-cooled condensers, facility energy consumption is projected to nearly double between 2032 and 2037. Shifting to water-cooled condensers with PUE of 1.25 meaningfully reduces this demand, and the benefit compounds over time, the earlier the transition, the greater the cumulative saving by 2037.

This efficiency gain, however, is not without cost. As the Figure 29 shows, the same shift that lowers PUE also raises WUE toward higher side, making water-cooled systems by far the most water-intensive option, while air-cooled systems though the least energy-efficient consume minimal water. PUE and WUE therefore cannot be optimised simultaneously within a single condenser technology, improving one comes directly at the cost of the other.

In 2032, for instance, reducing PUE from 1.60 to 1.25 lowers projected facility energy consumption from approximately 167 TWh to 130 TWh, a saving of about 37 TWh. This saving alone is roughly equivalent to Delhi's current annual electricity consumption, illustrating the scale of energy efficiency gains achievable through cooling system selection for the entire DC fleet.

Over the same shift, water consumption rises sharply, from near-negligible levels under air-cooled operation to as much as 331 billion litres per year under water-cooled operation, equivalent to roughly one-fifth of Delhi's current total annual water supply. At the scale of India's projected 2032 DC pipeline, this represents a substantial additional claim on water resources, particularly significant given that many of India's largest DC hubs are themselves located in water-stressed regions.

These results demonstrate an inherent trade-off between energy and water efficiency in condenser selection and underline that cooling strategy should be guided by local resource availability rather than PUE alone. In water-stressed regions in particular, hybrid or lower-water cooling solutions may offer a more sustainable balance between energy and water outcomes.

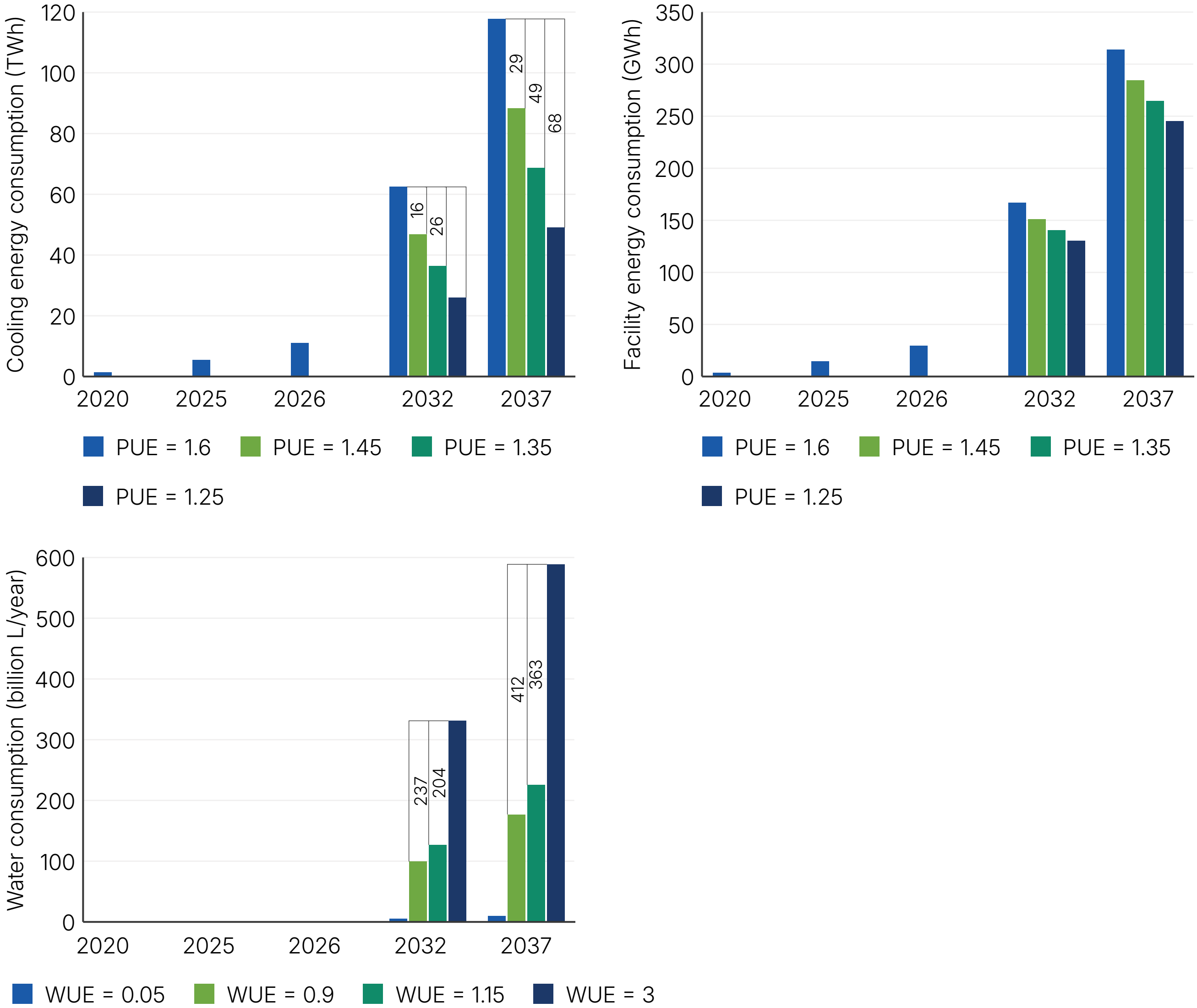


Figure 29: Energy and water consumption pattern

The energy savings from improved cooling efficiency translate directly into lower carbon emissions, since reduced electricity consumption is the principal driver of a DC's GHG footprint. Renewable energy (RE) integration acts as a complementary lever, reducing the carbon intensity of the electricity consumed. It should be noted that the RE share referred to here represents the proportion of DC's own total power or energy supply sourced from renewables, for instance, through captive generation, open access, or power purchase agreements, and not RE penetration in the broader grid mix.

As shown in Figure 30, lowering PUE from 1.60 to 1.25 consistently reduces emissions across all RE scenarios, demonstrating that efficiency improvements alone deliver significant mitigation potential, independent of the electricity mix. At the same time, increasing the RE share in DC's own supply from 0% to 50% further lowers emissions at every efficiency level, reinforcing that efficiency and RE adoptionare mutually reinforcing rather than competing strategies.

Combined, the two levers deliver the largest reduction as CO_2-equivalent emissions fall from approximately 126 million tons at a PUE of 1.6 with no RE, to approximately 49 million tons when PUE is improved to 1.25 and the DC's RE share is raised to 50%, a reduction of over 60%. This underscores that neither efficiency nor RE alone is sufficient; the greatest mitigation potential lies in pursuing both simultaneously.

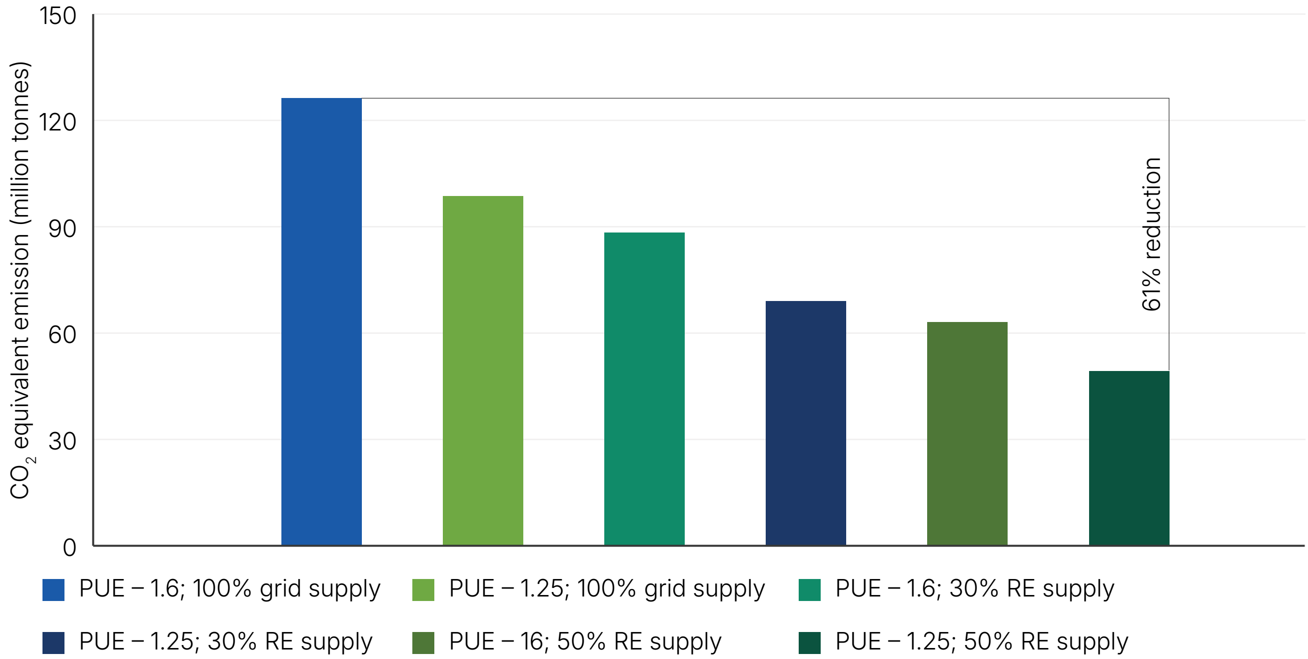


Figure 30: Carbon emission by 2032

3.3 Sustainable Practices in Data Centre Operation

Sustainable and low-carbon DC operation requires a holistic approach that combines multiple strategies to reduce energy consumption, greenhouse gas emissions, and resource use. As shown in Figure 31, key decarbonisation strategies include renewable energy integration, energy efficiency measures, advanced cooling technologies, low-GWP refrigerants, waste heat recovery, wastewater recovery, and thermal energy storage, which collectively improve environmental performance and operational resilience.

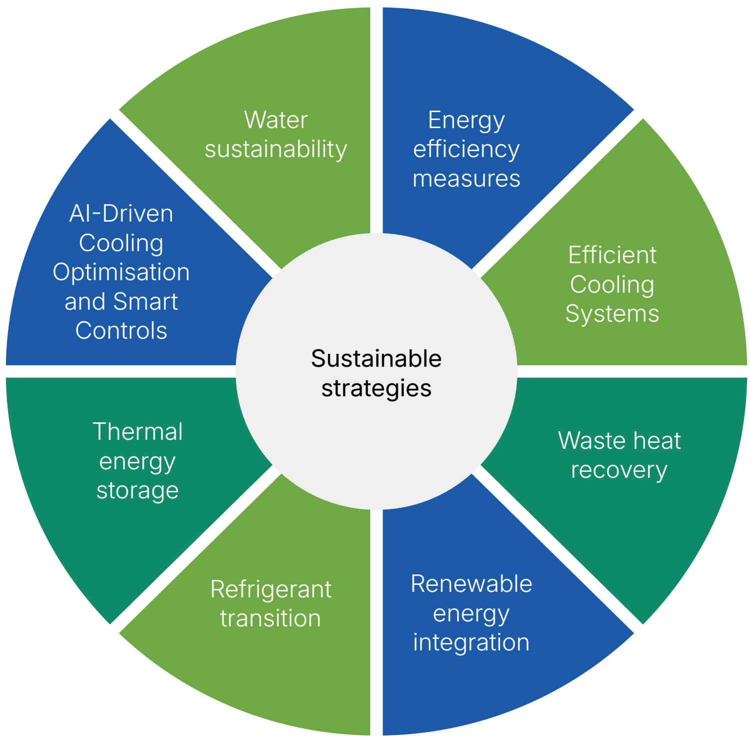


Figure 31: Sustainability strategies in data centre

3.3.1 Energy Efficiency Measures

Power distribution infrastructure (Figure 32), including motors, UPS systems, and transformers, represents a significant opportunity for energy savings.

- Air/water flow: Optimise fan and pump operation to reduce bypass, recirculation, and distribution losses.
- UPS: Use high-efficiency UPS systems compliant with IEC 62040; efficiency improvements can reduce conversion losses by 30–55%.
- IT utilisation: Use virtualisation and dynamic workload management to reduce idle servers and associated cooling demand.
- Power supplies: SiC/GaN-based PSUs can achieve up to 97.5% efficiency and reduce power losses by over 50%[48,49].

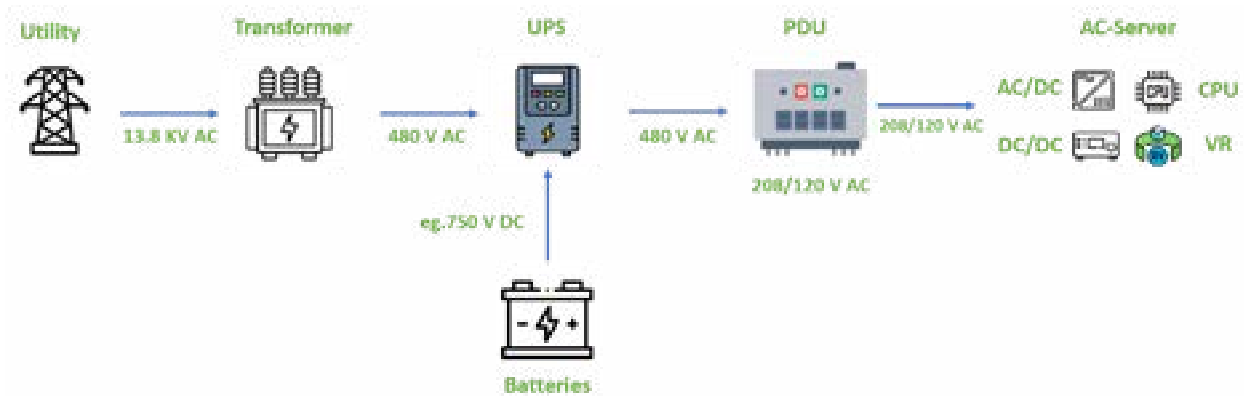


Figure 32: Power flow architecture in an AC-powered data centre

3.3.2 Efficient Cooling System

Cooling systems are among the most energy-intensive components of a DC and play a critical role in maintaining reliable IT operation. Improving cooling efficiency is therefore a key strategy for reducing energy consumption and enhancing overall sustainability. Modern DCs employ several advanced cooling techniques, including:

- **Hot/Cold Aisle Containment:** Physical separation of hot and cold air streams prevents air mixing, improves airflow management, reduces fan energy consumption by 20–25%, and lowers overall energy use by 5–10%50.
- **Free Cooling and Economisers:** In suitable climates, outdoor air or water can be used for cooling, significantly reducing mechanical refrigeration requirements. For example, Facebook's Oregon DC achieved a PUE of 1.08 using direct air-side economisation[50].
- **Liquid and Immersion Cooling:** These technologies remove heat directly from high-power-density IT components, providing superior thermal performance. Immersion cooling can reduce cooling energy consumption by up to 50% and decrease space requirements by approximately two-thirds compared **with conventional air cooling51.**
- **Evaporative Cooling:** By utilising the cooling effect of water evaporation, evaporative cooling can consume up to 80% less energy than conventional air-conditioning systems, making it particularly effective in dry climates, provided that water resources are managed efficiently[52].

3.3.3 Waste Heat Recovery

Nearly all the electrical energy consumed by IT equipment is ultimately converted into low-grade heat, which is conventionally rejected to the ambient environment through air- or liquid-cooling systems. This continuous dissipation of thermal energy represents a significant loss of valuable energy resources and has motivated the development of heat recovery technologies to improve the overall energy efficiency and sustainability of DCs (Figure 33).

- Waste heat is typically available at about 25–45 °C from air-cooled systems and 40–60 °C from liquid-cooled systems, often requiring heat pumps for integration with conventional district-heating networks.
- Liquid cooling, particularly direct-to-chip and immersion cooling, produces higher-temperature waste heat and therefore offers greater heat-recovery potential than conventional air cooling.
- Recoverable heat can be used for space heating, hot water, greenhouses, industrial processes, desalination, and absorption cooling; heat pumps can raise the temperature for higher-temperature applications.
- District heating can replace part of fossil-fuel-based heat supply, while direct supply to nearby buildings or industries can reduce transmission losses and improve economic viability.
- Key barriers include low heat temperature, mismatch between heat supply and demand, seasonal variation, infrastructure costs, and heating networks.

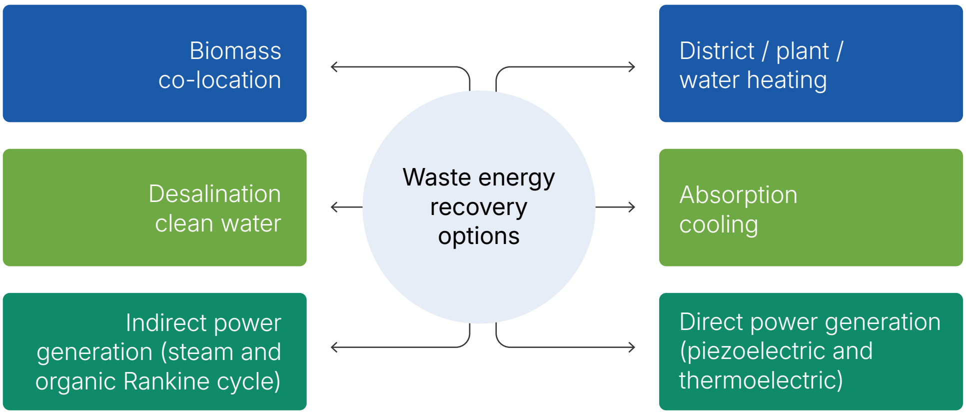


Figure 33: Waste heat recovery options

3.3.4 Renewable Energy Integration

Renewable energy integration is emerging as a key pathway for reducing the carbon footprint of DCs, particularly in regions such as India where electricity grids continue to rely significantly on fossil fuels. Since DCs operate continuously with high electricity demand, replacing conventional grid electricity with renewable sources can substantially reduce Scope 2 emissions, improve energy price stability, and support long-term decarbonisation targets (Figure 34).

- **Carbon reduction:** Replacing grid electricity with renewable energy can substantially reduce Scope 2 emissions and support long-term decarbonisation.
- **Procurement pathways:** Renewable electricity can be sourced through on-site generation, power purchase agreements (PPAs), and renewable energy certificates (RECs).
- **On-site generation:** Solar PV is the most practical option for many DCs, while wind and other sources can be deployed where local resources permit.
- **Storage and flexibility:** Battery energy storage systems (BESS), thermal energy storage (TES), and energy management systems can address the variability of solar and wind and better match generation with continuous IT loads.

- **Site-specific planning:** Renewable system design depends on resource availability, land constraints, grid connectivity, and facility load profile; the optimal solution may combine generation, storage, grid supply, and backup systems.
- **Future relevance:** As DC electricity demand continues to grow, combining physical renewable generation with contractual procurement will be increasingly important for low-carbon operation.

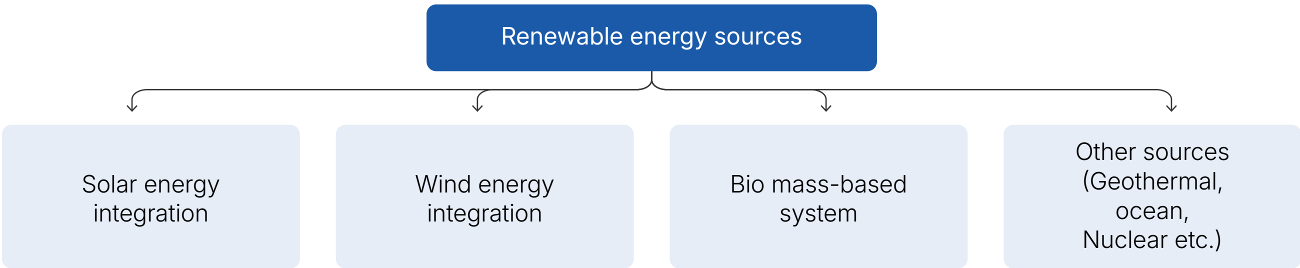


Figure 34: Renewable energy sources

Where direct renewable generation is not feasible due to space limitations or resource constraints, DCs increasingly rely on PPAs, green tariffs, and RECs to procure renewable electricity. In 2024, global DC operators contracted approximately 17 GW of clean energy, primarily through renewable PPAs[53]. These mechanisms enable operators to achieve renewable energy targets while supporting additional renewable generation capacity.

3.3.5 Refrigerant Transition

The refrigerant transition in DC cooling is being driven by the need to reduce the climate impact of high-GWP refrigerants such as R134a, R407C, and R410A. Low-GWP HFOs and natural refrigerants are emerging as alternatives, but their suitability depends on system design, safety, equipment compatibility, and availability[54]. The transition therefore requires a balance between environmental performance and practical system requirements.

- Low-GWP alternatives: R1234yf, R1234ze(E), and R454B can significantly reduce GWP while providing comparable cooling performance when systems are appropriately designed[55].
- Natural refrigerants: CO_2 (R744) and R290 offer very low environmental impact but require specialised designs to address high operating pressure and flammability, respectively.
- New systems vs retrofits: HFOs are generally more suitable for new equipment, while lower-GWP alternatives such as R454B may be considered for selected R410A systems[56],[57].
- System implications: Differences in pressure, cooling capacity, and volumetric properties can affect compressor sizing, heat exchangers, equipment cost, and retrofit feasibility.
- Key consideration: Refrigerant selection should consider GWP, energy efficiency, safety, equipment compatibility, availability, and lifecycle cost rather than GWP alone.

3.3.6 Thermal Energy Storage

Thermal Energy Storage (TES) is emerging as an effective strategy for improving the sustainability and resilience of DC cooling. By storing cooling energy in the form of chilled water, ice, or phase change materials (PCMs), TES provides cooling during power outages and peak demand periods, reducing reliance on diesel generators (DGs), which are associated with high greenhouse gas emissions, air pollution, and maintenance requirements. TES ensures uninterrupted cooling during short-duration power interruptions by maintaining chilled water supply until grid power or backup systems are restored, thereby protecting IT equipment from thermal stress. It also enables load shifting by producing cooling during off-peak periods or when renewable electricity is abundant and utilising the stored cooling during peak demand. This reduces electricity costs, lowers carbon emissions, enhances grid stability, and supports greater integration of renewable energy. In countries such as India, where time-of-day tariffs and renewable energy penetration are increasing, TES offers a practical pathway for low-carbon and energy-efficient DC operation.

3.3.7 AI-Driven Cooling Optimisation and Smart Controls

Artificial intelligence (AI) enables predictive and adaptive cooling by analysing real-time operational data using machine learning (ML), deep learning (DL), and reinforcement learning (RL) algorithms to optimise chillers, pumps, cooling towers, CRAC units, and airflow management systems according to changing workloads and environmental conditions. AI-based cooling systems optimise supply air temperature, chilled water temperature, fan speed, coolant flow rate, and equipment sequencing, reducing cooling energy consumption while maintaining thermal reliability. Studies indicate that conventional manual control leaves 25–30% of potential energy savings unrealised[58], whereas AI-driven optimisation improves energy efficiency, reduces PUE, and enables predictive maintenance through early fault detection and equipment health monitoring. The integration of digital twins, Internet of Things (IoT) platforms, and advanced analytics further enhances real-time monitoring and autonomous system optimisation. Despite these benefits, large-scale deployment remains constrained by the need for high-quality operational data, robust sensing and communication infrastructure, cybersecurity, model interpretability, computational requirements, and integration with existing building management systems. Nevertheless, AI-driven thermal management is emerging as a key technology for improving the energy efficiency, reliability, and sustainability of next-generation DCs.

3.3.8 Water Sustainability

Water is a critical resource for DC cooling, making its efficient management essential for sustainable operation, particularly in water-stressed regions. Modern DCs are increasingly adopting wastewater reuse, rainwater harvesting, and closed-loop cooling systems to reduce dependence on freshwater. A 1 MW DC can consume up to 25.5 million litres of water annually for cooling[59], highlighting the need for effective water conservation strategies. To improve water efficiency, the U4E DC Guidelines recommend achieving a Water Usage Effectiveness (WUE) of ≤1.5 L/kWh by 2025 and ≤1.0 L/kWh by 2027 through efficient cooling technologies and robust water management practices (Table 7).

Table 7: Minimum water use effectiveness requirements

Year	2025	2027	2029	2031
WUE	≤ 1.5 L/kWh	< 1 L/kWh	≤ 0.5 L/kWh	≤ 0.2 L/kWh

Key water conservation strategies for DCs include the use of air-cooled, hybrid, and advanced liquid-cooling systems, along with treated wastewater, recycled greywater, and rainwater as alternatives to freshwater. Closed-loop cooling and on-site treatment systems such as STP/RO can further reduce freshwater demand and blowdown losses, while smart monitoring enables leak detection and optimisation of water use. These measures can improve water resilience, particularly in India, where seasonal water stress and opportunities for wastewater reuse and rainwater harvesting vary widely across regions.

04 Operations and Maintenance Practices

Effective operation and maintenance (O&M) are essential for ensuring efficient cooling system performance, reducing refrigerant leakage, and maintaining reliable operation. Regular inspection, preventive maintenance, leak detection, refrigerant recovery, and proper servicing help minimise direct greenhouse gas emissions, improve system efficiency, extend equipment life, and ensure compliance with environmental regulations.

4.1 Temperature and Humidity Management

Precise thermal control is essential for reliable and energy-efficient DC operation. ASHRAE classifies IT equipment into different environmental classes based on their thermal requirements. For conventional air-cooled equipment (Classes A1–A4)[60], the recommended inlet air temperature is 18–27 °C, while high-density computing equipment (Class H1) requires a tighter range of 18–22 °C. For liquid-cooled systems, recommended coolant supply temperatures generally range from 17–27 °C for lower-temperature classes, while higher-temperature classes can operate at approximately 32–45 °C or above. Higher coolant temperatures enable greater use of free cooling, reduce compressor operation, and improve waste-heat recovery, although high AI and HPC heat loads may require lower coolant temperatures. Maintaining stable conditions within the recommended ranges therefore helps minimise cooling energy while protecting IT equipment from thermal stress and degradation.

4.2 Refrigerant Management Practices

Effective refrigerant management is essential for reducing direct greenhouse gas emissions, ensuring safe operation of DC cooling systems, and supporting compliance with evolving environmental regulations. A comprehensive refrigerant management approach covers the entire refrigerant lifecycle, from procurement and storage to charging, leak detection, recovery, recycling, reclamation, and final disposal. Proper handling by trained personnel and the use of appropriate equipment are critical, particularly for flammable, toxic, or high-pressure low-GWP refrigerants. Regular leak detection and preventive maintenance can minimise refrigerant losses during operation, while recovery and reclamation at equipment servicing or end-of-life prevent refrigerants from being vented to the atmosphere and reduce the need for virgin refrigerant. Accurate record-keeping of refrigerant type, charge, additions, recovery, and disposal further supports emissions accounting and regulatory compliance. As DCs transition towards low-GWP refrigerants and more advanced cooling technologies, robust refrigerant management will become increasingly important for achieving both environmental and operational objectives.

4.3 Preventive Maintenance

Preventive maintenance of DC cooling systems is essential to maintain continuous cooling, energy efficiency, and IT reliability. Key parameters such as temperature, pressure, flow rate, power consumption, vibration, etc. should be routinely monitored to identify performance degradation before failure occurs. Maintenance should also include refrigerant recovery and leak testing, water-quality management, filter and coil cleaning, and functional testing of redundant cooling equipment. Tools including refrigerant leak detectors, pressure sensors, gas detection sensors are essential.

4.4 Technician Skills, Training, and Certification

India's rapidly expanding DC sector is creating a growing demand for specialised HVAC&R professionals capable of maintaining highly reliable and energy-efficient cooling infrastructure. Unlike conventional cooling applications, DCs require technicians with advanced skills in precision cooling systems, chilled water plants, controls and automation, airflow management, and continuous monitoring to ensure uninterrupted operation. Cooling systems in DCs operate as mission-critical infrastructure, where failures can result in significant operational and financial losses. Therefore, technicians require not only fundamental refrigeration knowledge but also sector-specific competencies in preventive maintenance, fault diagnosis, refrigerant management, energy optimisation, and compliance with stringent reliability and safety requirements. The following sections discuss the current skill landscape, training pathways, and competency gaps affecting the DC cooling workforce in India.

4.4.1 Current State of Technician Training

India has an established HVAC&R training ecosystem through ITIs, polytechnics, Skill India, Sector Skill Councils, OEM programmes, and HPMP-supported initiatives, covering core skills in refrigeration, installation, servicing, troubleshooting, and refrigerant handling. However, these programmes are largely oriented towards general HVAC&R applications and do not adequately reflect the requirements of DC cooling. DCs require additional competencies in precision cooling, airflow and containment, chilled-water and DX systems, advanced controls and BMS, liquid cooling, redundancy, continuous monitoring, and preventive maintenance. This gap is becoming more important with the transition to low-GWP refrigerants, which requires knowledge of A2L, A3, and high-pressure refrigerants, along with safe handling, leak detection, recovery, and reclamation. The existing training ecosystem can therefore be strengthened by introducing dedicated DC cooling modules covering these technical areas, supported by hands-on training through OEMs, DC operators, ITIs, and accredited centres. Competency-based certification and periodic upskilling would further ensure that technicians can safely operate and maintain increasingly advanced and efficient DC cooling systems.

4.5 Field Assessment Observations

The study team conducted field audits across seven Indian DCs to assess prevailing O&M practices, cooling system operation, and energy management strategies. The audits indicate that O&M practices are predominantly reliability-oriented, with high system availability taking precedence over energy optimisation. While all facilities have established preventive maintenance programmes and comprehensive monitoring infrastructure, several operational practices present significant opportunities to improve energy efficiency without compromising reliability. The key field observations are summarised in Table 8.

Table 8: Summary of Key Field Observations from Site Assessments

Area	Field observations
Monitoring and maintenance	All audited facilities use BMS and/or DCIM for real-time monitoring of electrical, cooling, environmental, alarm, and equipment parameters. Preventive maintenance is routinely undertaken for chillers, CRAH/PAC units, pumps, cooling towers, UPS, transformers, DG sets, and associated equipment.
Cooling reliability	N+1 redundancy, hot-/cold-aisle containment, rack blanking panels, and continuous monitoring of server inlet temperature and relative humidity are widely adopted.
Cooling operation	Cooling units generally operate with conservative supply-air and chilled-water setpoints, and multiple units often remain in operation at relatively low loading to maintain redundancy.
Airflow management	Containment systems are present, but bypass airflow, air recirculation, unsealed cable penetrations, missing blanking panels, and sub-optimal perforated floor-tile placement were observed at some facilities.
Chilled-water operation	Supply temperature, return temperature, and chilled-water ΔT are monitored, although these parameters are not consistently used for adaptive plant control.
Instrumentation	Extensive temperature, humidity, pressure, flow, and differential-pressure instrumentation is installed; however, periodic sensor calibration is not consistently integrated into energy management practices.
BMS/DCIM utilisation	BMS/DCIM platforms are primarily used for equipment monitoring, alarms, and fault management, with relatively limited use of advanced performance analytics and continuous energy optimisation.
Overall O&M approach	O&M practices across the audited facilities are predominantly reliability-oriented, with system availability given higher priority than operational energy optimisation.

Overall, the audits demonstrate that Indian DCs have robust maintenance practices, and future efficiency improvements are more likely to come from intelligent operational control, adaptive cooling strategies, and performance-based O&M than from major infrastructure upgrades.

4.5.1 Field Assessment Report

This section presents field-assessment findings from seven Tier III DCs across Mumbai, Pune, and Delhi NCR, commissioned between 2015 and 2024. The portfolio includes two enterprise and five hyperscale facilities using chiller–CRAH, DX-PAC/CRAC, and hybrid cooling systems with under-floor or mixed-air distribution. Key observations from the site assessments are summarised below.

- **Cooling and redundancy:** All facilities use N+1 redundancy to maintain cooling availability during equipment outages.
- **Thermal conditions:** Server inlet temperatures are maintained within the ASHRAE-recommended 18–27 °C range, typically at 20–24 °C or 22–26 °C. Relative humidity is generally maintained at 40–60%, within the broader 20–80% controlled range.
- **Conservative setpoints:** Despite IT equipment being rated up to 35 °C, operating temperatures are maintained well below this level, indicating potential for further cooling optimisation.

- **Airflow management:** Cold- or hot-aisle containment and rack blanking panels are widely used to limit recirculation and improve cooling effectiveness.
- **Cooling equipment and refrigerants:** Facilities employ scroll, fixed- and variable-speed screw, and centrifugal compressors, predominantly using R134a and R407C.
- **Refrigerant management:** Annual refrigerant leakage was relatively low at 1.8–2.7%. Leak detection is incorporated, with recharge undertaken after leak rectification.
- **Efficiency measures:** Older facilities include aisle sealing, fan-speed optimisation, equipment scheduling, motion-based lighting controls, and chiller replacement, while recently commissioned facilities have not yet undertaken major cooling upgrades.

The DCs audited exhibited considerable variation in the average installed IT capacity per rack across the audited facilities ranged from 6 to 18 kW/rack, while the corresponding utilised IT load varied between 2.3 and 11 kW/rack.

The field assessment reveals that cooling performance varies considerably across the surveyed DCs and that facility size alone does not determine energy efficiency. A key observation is the different relationship between PUE and the cooling energy share across facilities. DCs with relatively similar PUE values can have substantially different contributions from cooling, indicating that the efficiency of non-cooling infrastructure, such as power distribution and UPS systems, also influences overall PUE. Therefore, PUE should not be interpreted in isolation when identifying cooling-related improvement opportunities.

The results further indicate that cooling becomes a particularly important efficiency lever in facilities where its contribution to total energy consumption is high. However, a high cooling-energy share does not necessarily correspond directly to the highest PUE, suggesting that cooling performance is influenced by the interaction of IT load, cooling system configuration, operating conditions, and other facility loads. This distinction is important because simply reducing cooling energy may not proportionally translate into the same reduction in PUE. For DC 4 and DC 7, the relatively high PUE is primarily associated with their very low IT utilisation, which is only around 4–6%. Despite the low IT load, the cooling systems continue to operate to maintain the required environmental conditions, resulting in significant cooling energy consumption under part-load conditions and consequently higher overall PUE.

The comparison also suggests that some facilities have already achieved relatively efficient overall operation despite substantial cooling requirements, whereas others exhibit a stronger coupling between cooling demand and facility energy consumption. This indicates a clear opportunity for targeted interventions rather than a one-size-fits-all approach. Facilities with a higher cooling contribution should be prioritised for measures such as airflow optimisation, containment, variable-speed operation, intelligent controls, free cooling, heat recovery, and higher-efficiency cooling technologies.

Overall, the field results (shown in Figure 35 (a) and (b)) establish that cooling is a major but highly site-dependent contributor to DC energy performance. More importantly, the variation between facilities demonstrates that the greatest efficiency gains are likely to come from identifying the specific causes of excessive cooling demand at each site rather than applying generic energy-efficiency measures. The findings therefore provide a practical basis for benchmarking the surveyed facilities and subsequently selecting technology interventions according to their individual cooling-performance characteristics.

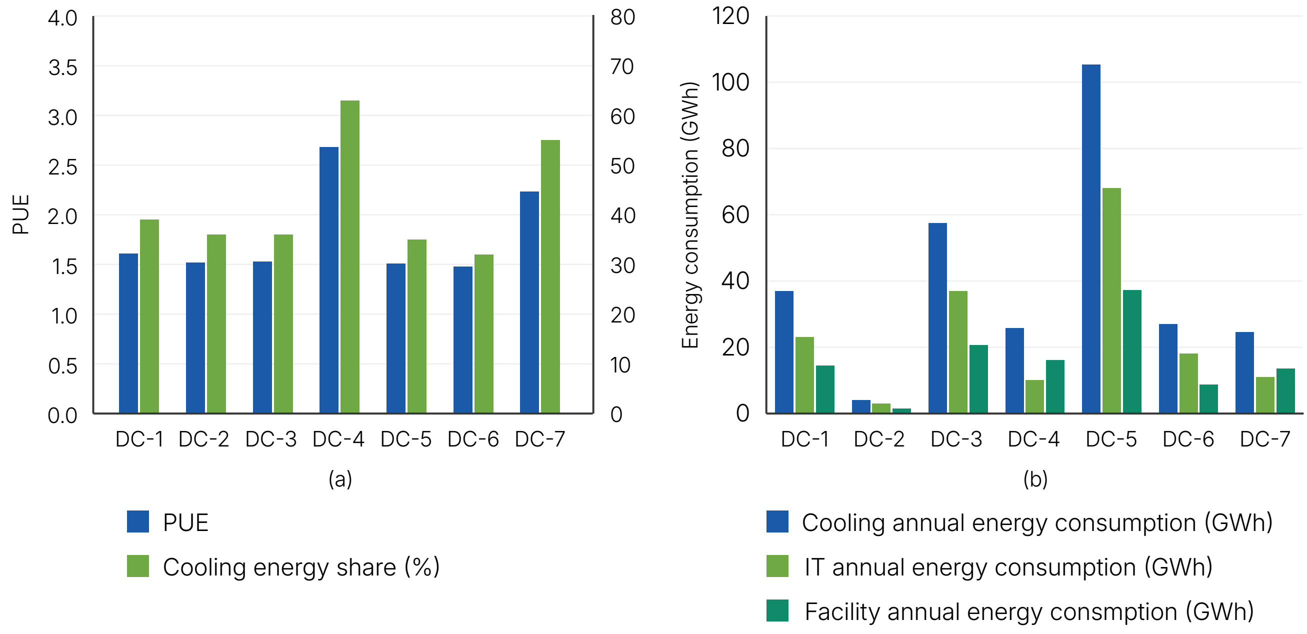
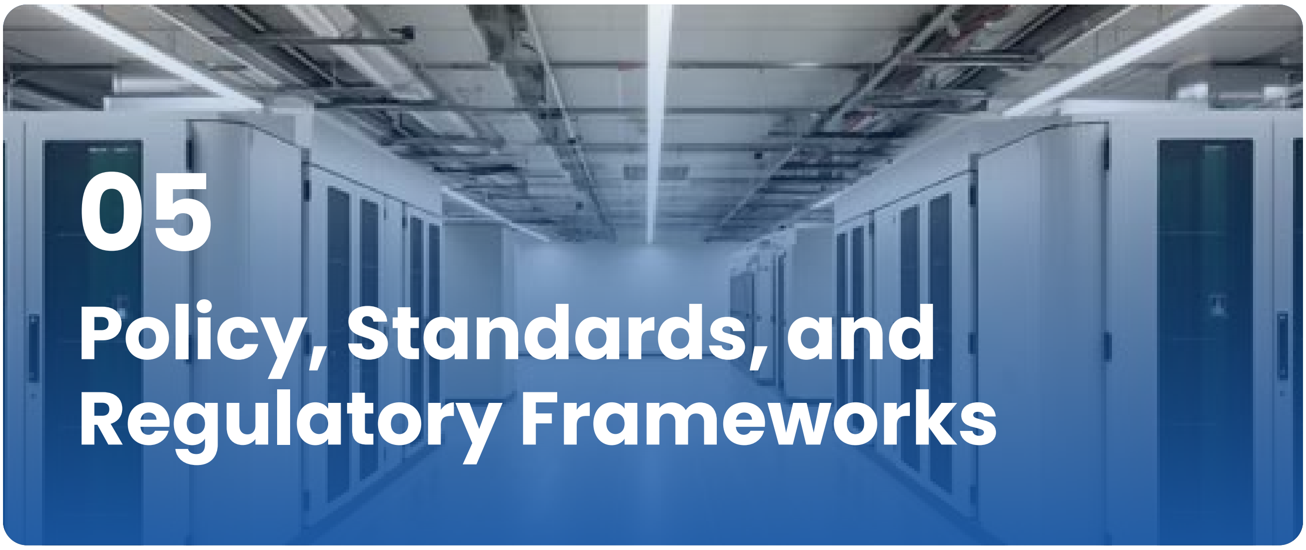


Figure 35: Field Study Results: (a) PUE and Cooling Energy Share, and
(b) Overall Energy Consumption Pattern

Overall, effective O&M provides a practical and near-term pathway for improving the sustainability and reliability of data centre cooling systems without compromising operational resilience. The field assessment indicates considerable scope for improvement through optimisation of operating conditions, continuous performance-based monitoring, adaptive control, and a proactive preventive maintenance approach. Cooling performance is influenced not only by facility size but also by IT load utilisation, operating setpoints, airflow management, and cooling plant configuration. Accordingly, BMS/DCIM capabilities and performance analytics should be used more effectively to support continuous monitoring and optimisation of temperature, humidity, chilled-water, and airflow conditions, while preventive maintenance should increasingly be based on system condition and performance. Improved refrigerant lifecycle management and technician competency will also become increasingly important with the adoption of low-GWP refrigerants and advanced cooling technologies. In addition, facility load utilisation should be explicitly considered, as maintaining cooling infrastructure at very low IT utilisation can increase cooling energy intensity and overall PUE. The findings therefore support targeted, site-specific O&M interventions, particularly in facilities with low IT utilisation or a high cooling-energy contribution, to achieve sustained efficiency improvements while maintaining the high reliability required for mission-critical operations.



05

Policy, Standards, and Regulatory Frameworks

5.1 Global Policy and Regulations

As DC capacity has expanded worldwide, countries have responded with a range of policies and regulatory measures to manage the sector's growing energy, water, and environmental footprint. These responses fall into two broad and complementary streams. The first comprises data-centre-specific policies that govern efficiency, resource use, and siting including performance benchmarks, disclosure requirements, and spatial-planning measures. The second concerns the transition away from high-GWP refrigerants, driven by the Montreal Protocol and its Kigali Amendment, which shapes cooling and refrigerant choices across all sectors, including DCs. The following sub-sections examine each in turn, drawing out the lessons most relevant to India's own policy development.

5.1.1 Global data centre policies

Governments and regulatory agencies are rapidly introducing frameworks to improve DC sustainability, focusing on energy reduction, efficient cooling, and renewable integration. Table 9 evaluates these shifts across four primary regulatory pillars: (i) primary strategies and regulatory frameworks establishes the foundational laws and national visions used to guide digital infrastructure growth, (ii) efficiency standards and PUE targets set operational limits and reporting thresholds to eliminate energy waste, while (iii) renewable energy and sustainability mandates enforces green requirements like sourcing renewable power and reusing waste heat. Lastly (iv) grid, land use, and location policies manage physical zoning and heavy utility demands to optimize placement.

Global DC policies have shifted to strict regulatory mandates, with hubs hardcoding maximum PUE limits (≤1.2 to <1.3), enforcing waste heat recovery, and using zoning incentives to decentralised facilities away from strained urban grids. As India continues to scale its DC infrastructure, these international frameworks offer valuable reference points for balancing sectoral growth with sustainability objectives. The forthcoming National DC Policy presents an opportunity to move from the current state-level approach toward a more cohesive national framework. In doing so, India may draw on relevant international experience including the adoption of climate-appropriate efficiency metrics suited to tropical conditions, as demonstrated by Singapore, and the use of geographic or zoning-based approaches, as seen in China, to guide high-density compute loads toward regions with adequate renewable energy or surplus power capacity, thereby easing pressure on established hubs.

Table 9: Comparative Analysis of Global Data Centre Policy Frameworks

Region	Primary Strategies and Regulatory Frameworks	Efficiency Standards and PUE Targets	Renewable Energy and Sustainability Mandates	Grid, Land Use, and Location Policies
European Union (EU)	* Revised Energy Efficiency Directive (EED), 2023[61] * Draft DC Energy Efficiency Package (Expected Q2 2026) * EU Taxonomy Regulation	* Establishes a common EU-wide sustainability rating scheme to compare facility performance. * Facilities with ≥500 kW IT power must report energy performance data.	* Promotes renewable energy use, waste heat recovery, and efficient water/refrigerant management. * AI Act encourages voluntary energy efficiency codes. * Battery Regulation mandates recycling for storage systems.	* Focuses on enhancing overall grid efficiency. * Funds digital infrastructure via programmes like EuroHPC JU (EURO 7 billion budget for 2021–2027)[62].
United States (US)	* Federal Executive Order (July 2025) to accelerate development *Fragmented landscape across state and local jurisdictions[63]	* California: Facilities with PUE > 1.5 must reduce PUE by ≥10% annually. * State compliance reporting loads can be as low as 10 MW (vs. federal > 100 MW threshold)[64].	* California: Mandates 60% renewable electricity by 2030, 100% by 2045. * Illinois: Requires 40% renewable energy usage by 2030 and battery storage integration.	* Federal level streamliners permitting for large/national security facilities (>100 MW or >USD 500 million). * Grid Funding: Illinois requires 15% funding for grid upgrades; Ohio requires paying for 85% of subscribed capacity and 10–20% of grid upgrades.
Singapore[65]	* Green DC Roadmap (GDCR) * DC-Call for Application (DC-CFA) framework	* SS 715:2025: Promotes efficient IT equipment to reduce energy consumption by ≥30%. * SS 697:2023 (Tropical DC Standard): Sets operating temps to ≥26C to save 2–5% cooling energy per 1 C increase.	* Green Mark for DCs 2024 (GDMC:2024): Certifies sustainable operator practices. * Provides Energy Efficiency Grants for lifetime carbon abatement >350 tonnes.	* Highly structured due to land constraints. * GDCR aims to add ~300 MW near-term capacity.
China[66]	* Policy Guidelines (March 2025) * Three-Year Action Plan on New DCs * "Data in the East, Computing in the West" project	* Utilisation rate target must exceed 60% per new facility. * Large-scale DC PUE must be <1.3 (and <1.25 in extremely cold regions)[67].	* 2025 guidelines mandate newly built national hub DCs to source ≥80% of electricity from renewables by 2030, tracked using Green Electricity Certificates (GECs).	* Relocates computing power from resource-scarce eastern regions to resource-abundant western regions. * Special Economic Zones (e.g., Hainan) offer 15% tax rates and zero tariffs.

Region	Primary Strategies and Regulatory Frameworks	Efficiency Standards and PUE Targets	Renewable Energy and Sustainability Mandates	Grid, Land Use, and Location Policies
United Kingdom (UK)[68]	* Critical National Infrastructure (CNI) Designation (Sept 2024) * National Planning Policy Framework (NPPF) updates (2024/2025) * AI Growth Zones (AIGZ) Initiative (2025)	* Specific operation-based PUE limits are not highlighted, but the framework targets large/hyperscale developments via specific local vs. national regimes.	* Green/Grey Belt exceptions are evaluated based on whether benefits outweigh the environmental impact (e.g., Abbots Langley and Court Lane approvals).	* CNI sites are exempt from emergency planned power cuts. * Very large projects can request the Nationally Significant Infrastructure Projects (NSIP) consenting route. * AI Growth Zones (AIGZs) (Oxford, North East) fast-track grid access and planning for AI infrastructure.
Japan	* Act on the Rationalisation of Energy Use and Shift to Non-Fossil Energy * GX 2040 Vision (Feb 2025) * Watt-Bit Collaboration Framework	* Mandates minimum efficiency standards for new DCs: PUE of 1.4 by 2030, and PUE of 1.3 for facilities built from 2029 onwards[69].	*USD 1.29 billion in subsidies to cover 50% of CAPEX for 100% renewable/nuclear sites * GX-ETS (Emissions Trading Scheme) goes live in fiscal 2026 (>100k tons CO2 emissions)[70].	* Subsidies up to USD 0.18 million for regional infrastructure (≥10 hectares)[71].
Saudi Arabia	* DC Services Regulations (DCSR), 2024 * National DC Strategy 2025–2030 * Cloud First Policy	* Standard (Tier II) and Advanced (Tier III) facilities are mandated to submit specific energy management and sustainability plans to reduce consumption[72].	* National DC Strategy mandates compliance with green technologies for energy efficiency. * Planned investments of over USD 18 billion in DC and renewable energy projects.	* Aims to build 1.5 GW of capacity by 2030. * Registration with CST is required, valid for 3 years (no fees). * New Tier II/III centres must be Carrier Neutral. * Sets up a dedicated "Cloud Computing Special Economic Zone"[73].
Germany	* National DC Strategy (March 2026) * Energy Efficiency Act (EnEfG), 2023	* Applies to facilities ≥300 kW. * New DCs: PUE must be ≤1.2. * Existing DCs: PUE 1.5 by 2027; PUE 1.3 by 2030. * Mandates registration in the Energy Efficiency Register[74].	* Renewable Obligations: Cover 50% electricity from renewables since 2024, rising to 100% by Jan 1, 2027[75]. * Waste Heat Reuse: New DCs (from July 2026) must reuse ≥10% energy, rising to 15% (2027) and 20% (2028). * Violations fined up EUR 100,000[76]	* National Strategy targets doubling general capacity and quadrupling AI/HPC capacity by 2030[77]. * Intends to fund at least one AI Gigafactory. * Mandates certified Energy Management Systems (DIN EN ISO 50001) for facilities ≥1 MW[78].

Region	Primary Strategies and Regulatory Frameworks	Efficiency Standards and PUE Targets	Renewable Energy and Sustainability Mandates	Grid, Land Use, and Location Policies
Australia	* National AI Plan (Dec 2025) - federal anchor for DC & AI policy * Mandatory National DC Framework (Jul 2026) - net-generation, grid cost & water rules * Office of AI established in PM&C to co-ordinate all DC regulation * Legislation to Parliament early 2027; National Cabinet alignment Aug 2026[79]	* NABERS 5-Star mandatory for all govt. DC providers from 1 Jul 2025 and target a PUE below 1.4. * DTA Panel requires energy reporting & emissions reduction plans[80]	* Large DCs must be net-generators - contribute ≥ energy consumed to the grid * Must underwrite new renewables; offsets not permitted * Must fund own grid connection costs & any water infrastructure needed * Must minimise water use and meet water efficiency requirements[81]	* AEMC draft rule: new technical grid connection standards for large DCs (2026) * DCs must reduce power draw during grid strain events * Foreign DC investment subject to FIRB review[82]

To support its rapid data growth, India could further strengthen its domestic framework by considering a gradual transition from voluntary state-level incentives towards nationally harmonised, climate-responsive efficiency standards. These could include statutory PUE benchmarks, informed by international practices, along with temperature thresholds suited to tropical conditions. Further, greater emphasis could be placed on renewable power procurement, coordinated inland siting of data centres to support balanced distribution of computing capacity, and clear Water Usage Effectiveness (WUE) guidelines. Complementary provisions for grid co-funding could also help support efficient resource use while maintaining grid stability.

5.2 Domestic Policy Frameworks, and Regulations

The Union Budget 2026–27 proposed a tax holiday until 2047 for eligible foreign cloud service providers using India-based DCs to attract hyperscale cloud and AI investments[83]. The enactment of the Digital Personal Data Protection Act, 2023, along with the Reserve Bank of India (RBI) data localisation requirements for payment systems, has further reinforced India's data protection framework by mandating domestic storage of critical data and regulating cross-border data sharing.

The regulatory framework is further supported by sector-specific policy initiatives. The Telecom Regulatory Authority of India (TRAI) has recommended a DC Incentivization Scheme (DCIS), a single-window clearance mechanism, a DC Readiness Index (DCRI), and the establishment of DC Economic Zones (DCEZs) across selected states to accelerate sector growth.[84] In October 2022, DCs were granted infrastructure status under the Harmonised Master List, improving access to institutional finance.[85] More recently, the Sustainable Harnessing and Advancement of Nuclear Energy for Transforming India (SHANTI) Act, 2025 aims to support reliable low-carbon power supply for emerging sectors, including AI and DCs, through the future deployment of small modular and micro nuclear reactors[86].

5.2.1 State Data Centre Policies

Table 10 presents the key DC policy provisions across major Indian states, covering fiscal incentives, power and connectivity support, and sustainability-related measures.

Table 10: Overview of State-Level Policies [87]

S.no	State Policies	Stamp duty and land incentives	Electricity and renewable energy incentives	Employment and other subsidies
1	Haryana State DC Policy 2022	100% SDV reimbursement;	100% electricity duty exemption for 20 years; power bill reimbursement up to 25% of Net SGST for electricity from Haryana DISCOMs for 3 years; 50%-75% Net SGST reimbursement for 10 years.	Employment generation subsidy of INR 48,000/ employee/year for 10 years for bona fide residents.
2	Karnataka DC Policy 2022	10% subsidy on land up to 10 acres outside Bengaluru Urban district; One-time 7% capital subsidy up to INR 10 crores on fixed assets.	Electricity duty exemption; subsidy on renewable energy and land conversion fees	Customised incentives for investments above INR 4,000 crores.
3	Maharashtra IT/ITES Policy 2015	100% exemption on stamp duty.	100% electricity duty exemption; Power tariff subsidy of INR 1/unit for 5 years; Assistance to establish captive power farms.	Additional FSI: Financial assistance for transmission lines.
4	Tamil Nadu DC Policy 2021	50%-100% SDV exemption in different districts for land purchase/lease.	Subsidy on renewable energy.	Training subsidy; Assistance for large investments.
5	Odisha State DC Policy 2022	Capital subsidy of 20% of fixed assets (excluding land), up to INR 25 crore; 100% SDV on first transaction.	100% exemption on electricity duty; Power bill subsidy of 30% for 5 years, up to INR 2 crore.	SGST, land conversion, energy audit, green initiatives, employment, interest, infrastructure development subsidies, and Internet bandwidth reimbursement.
6	Uttar Pradesh DC Policy draft 2026	25%–50% land subsidy based on region (applies to captive solar land); 100% stamp duty exemption on first lease/purchase against Bank Guarantee.	Reimburses cost of 1 out of 2 required power grids; 50%–75% transmission/wheeling charge exemption for 25 years; 10-year electricity duty waiver for smaller units Green Boosters: Extra subsidy increments for RE share (>20 % to >70 %) and top Green DC certifications.	60% interest subsidy (max ₹50 Cr) for Parks; 7% capital subsidy (max ₹20 Cr) for Units; PUE Boosters (Subsidies): PUE +₹4 Cr (Parks) / +₹2 Cr (Units), 1.35 PUE 1.45: +₹2 Cr (Parks) / +₹1 Cr (Units), 1.45 PUE < 1.60: +₹1 Cr (Parks) / +₹0.5 Cr (Units)
7	West Bengal DC Policy 2021	100% exemption from stamp duty and registration fees.	Electricity duty waiver for five years.	- -
8	Gujarat DC Policy 2026-29	100% exemption on stamp duty and registration fees for land lease/purchase; permits first instance of sub-leasing without transfer fees/stamp duty.	RS 1/unit power tariff subsidy (20 years); 100% electricity duty reimbursement (20 years); mandates ≥ 51% green/renewable energy usage for core operations	Up to 4% interest subsidy (max ₹25 Cr/year for 10 years); 100% SGST reimbursement on plant, machinery (8 years) and operational revenue (20 years); 2.5% capital subsidy exclusively for Dholera region

Recognising the costs incurred in relation to municipal building approvals, the policies formulated by Telangana and Odisha provide for rebates on building fees and building plan approval costs. Other states like Andhra Pradesh, Gujarat, Madhya Pradesh, Punjab, Rajasthan, Himachal Pradesh, and Chhattisgarh provide various land, utility, and infrastructure subsidies, reduced power tariffs, and tax exemptions.

5.2.2 Montreal Protocol Implementation

In March 1991, India acceded to the Vienna Convention for the Protection of the Ozone Layer and ratified the Montreal Protocol on Substances that Deplete the Ozone Layer in June 1992. India has also ratified all the amendments to the Montreal Protocol including the London amendment in 1992, Copenhagen, Montreal, Beijing amendments in 2003 and Kigali Amendment for phase-down of HFCs in 2021. As a party operating under Article-5 of the Montreal Protocol, India is committed to phase out Ozone Depleting Substances (ODSs) including HCFCs by 2030 in accordance with the accelerated phase out schedule of the Montreal Protocol.

India has taken progressive measures to phase out designated controlled substances and is following the Montreal Protocol control phase-out schedule. This has been successfully accomplished through assistance from the MLF for implementation of the Montreal Protocol by undertaking technology conversions, technical assistance, training and capacity building, information dissemination and awareness-raising, management, and coordination. India has also established an effective policy and regulatory framework for phase out production and consumption of ODSs. The regulatory framework for ODSs is set forth in the Ozone Depleting Substances (Regulation and Control) Rules, 2000 that are amended from time to time to align with the Amendments to the Montreal Protocol and National Policies & Regulations. The final version of the rules has been amended to align with the accelerated phase-out of HCFCs and complete phase-out of HCFC-141b in polyurethane foam manufacturing sector.

India had taken proactive steps for implementation of the accelerated phase-out schedule of HCFCs, in line with the decision XIX/6 of the 19th Meeting of Parties of the Montreal Protocol. India had prepared a roadmap as early as 2009, describing the long-term vision and action plan, including the policy instruments, for phase-out of production and consumption of HCFCs in the country. It took into account expected availability of technologies that are sustainable and have minimum cost impact on industry and consumers. The current initiative focused on building construction industry is the next step in this direction. India has been implementing in close cooperation with industry stakeholders the HPMPs and successfully meeting the phase out targets of production and consumption by converting the manufacturing of RAC equipment based on HCFCs to non-ODS and low-GWP technologies.

5.2.3 Kigali amendment to the Montreal protocol

India ratified the Kigali amendment to the Montreal protocol in 2021. The Amendment requires India to gradually reduce the production and consumption of HFCs, many of which have high GWP. India phase-down will begin with a freeze in 2028, followed by phase down of production and consumption of HFCs in four steps from 2032 onwards with reduction of 10% from the baseline of production and consumption in 2032, 20% in 2037, 30% in 2042 and 85% in 2047 respectively. The Kigali amendment marks the next stage of the refrigerant transition from high GWP refrigerant to alternative low GWP refrigerants to support the HFC phase down.

5.2.4 India Cooling Action Plan (ICAP)

The transition towards energy-efficient and lower-GWP cooling technologies also supports India's broader sustainable cooling objectives. The India Cooling Action Plan (ICAP), launched in 2019, provides a long-term framework for addressing the country's growing cooling requirements. Its objectives include reducing cooling demand, refrigerant demand and cooling-related energy consumption, while promoting access to sustainable cooling technologies and strengthening capacity in the cooling sector. Space cooling in buildings is one of the key areas addressed under ICAP, and DCs are an important and growing application within this sector. As data-centre capacity and computing requirements continue to grow, particularly with increasing deployment of high-performance computing and AI, the demand for efficient and sustainable cooling is also expected to increase.

5.2.5 Energy Conservation Building Code (ECBC)

The Energy Conservation Building Code (ECBC), administered by the Bureau of Energy Efficiency (BEE), sets minimum energy-performance standards for commercial buildings, including provisions for building envelopes, HVAC systems, lighting, and electrical infrastructure. DCs fall within the Code's scope based on their connected load; however, they are currently addressed through generic provisions developed for conventional commercial buildings rather than as a distinct, high-intensity building typology. Given the continuous operation, high heat densities, and cooling-dominated energy profile of DCs, there is an opportunity to strengthen the Code's applicability to the sector through dedicated, performance-based provisions that reflect the specific operational characteristics of DC cooling and infrastructure.

5.2.6 Standards and Labelling (S&L) Programme

The BEE Standards and Labelling (S&L) programme promotes energy efficiency by rating appliances and equipment on a star scale, enabling informed procurement and driving market transformation toward more efficient products. Several categories of equipment directly relevant to DC cooling are covered under the programme, including chillers, air conditioners, motors, and other HVAC components that form part of the cooling chain. However, the programme operates at the level of individual equipment rather than the DC as an integrated system, and a dedicated star-rating framework for DCs anchored to system-level metrics such as PUE and WUE could complement the existing equipment-level ratings and provide a more holistic measure of facility performance.

India has established a strong foundation for DC growth through the grant of Infrastructure Status, data localisation provisions, and state-level fiscal incentives. As the sector matures, a comparison of domestic policy with international frameworks highlights several areas that merit further attention to support sustainable growth. The first relates to regulatory harmonisation. In the absence of a finalised National DC Policy, operators currently navigate varying provisions across states. The forthcoming national policy offers an opportunity to provide greater consistency and predictability across jurisdictions. The second concerns sustainability performance. Several countries have adopted efficiency benchmarks such as Power Usage Effectiveness (PUE) and Water Usage Effectiveness (WUE), along with waste-heat recovery provisions. India's current framework, which focuses primarily on fiscal and land-related incentives, could be complemented by performance-oriented measures to strengthen energy and water efficiency outcomes. The third relates to infrastructure and spatial planning. There is an opportunity to develop mechanisms for shared grid investment and a national spatial-planning approach that guides high-density compute loads toward regions with adequate power, water, and connectivity, thereby easing pressure on metropolitan grids and enabling more balanced regional development.

06

Case Studies and Industry Experiences

Case studies and industry experiences provide valuable insights into the practical implementation of sustainable, resilient, and energy-efficient DC practices across different regions and operating environments. They highlight successful technology deployments, innovative cooling and power strategies, operational challenges, and lessons learned from real-world applications. Examining these examples enables stakeholders to understand proven approaches, evaluate emerging solutions, and identify best practices that can be adapted to improve the performance, reliability, and environmental sustainability of future DC developments.

6.1 Indian Case Studies

6.1.1 Free Outside Air Cooling at Data Centre

i. **Baseline:** A conventional chilled-water cooling system was used to support a 4.26 MW design IT load (currently ~0.96 MW), with a design PUE of 1.30 and capacity for up to 532 racks. Reliance on mechanical cooling resulted in higher cooling energy consumption.

ii. **Intervention:** An automated air-side economizer was integrated with the chilled-water system to utilise filtered outdoor air when ambient conditions were favourable. The system operates in four modes: 100% free cooling, free cooling with return-air mixing, partial free cooling with chilled-water support, and full mechanical cooling. Full free cooling is enabled when outdoor temperature is <23.9°C and RH is <80%. The facility also uses hot/cold aisle containment, high-efficiency filtration, 116 kWp rooftop PV, and renewable electricity procurement.

iii. **Outcome:** The facility was designed to operate in 100% free-cooling mode for ~20% and partial free-cooling mode for ~78% annually, with full mechanical cooling required for only ~2% of the year. During free-cooling periods, monthly PUE reached approximately 1.35–1.38. More than 75% of annual electricity is supplied from renewable sources, demonstrating the potential of climate-responsive free cooling to reduce cooling energy, operating costs, and carbon emissions in data centres.

6.1.2 Free Cooling with Hybrid Closed-Loop Cooling Tower

i. **Baseline:** The 48 MW Tier III data centre was designed with a rack power density of approximately 72 kW/rack and relied on CRAH units, fan-wall units, CDUs and AHUs supported by an R134a-based chiller system. Increasing rack heat loads resulted in substantial cooling demand and chiller energy consumption.

ii. **Intervention:** A Hybrid Closed Loop Cooling Tower (Hybrid CLCT) was integrated upstream of the chiller as a primary heat-rejection and pre-cooling stage. It operates in two modes: full free cooling, where the Hybrid CLCT provides approximately 100% of the cooling requirement without chiller operation, and pre-cooling, where it partially removes the heat load before the chiller. Automatic staged control enables mode switching based on ambient conditions and cooling demand. Tertiary-treated STP water is used instead of freshwater for evaporative heat rejection.

iii. **Outcome:** The Hybrid CLCT provides full free cooling for approximately 40% of operating time, while pre-cooling is used during the remaining period. PUE decreased from 1.45 to 1.23, corresponding to approximately 15% lower power consumption. Cooling-system emissions decreased from approximately 68,573 to 24,000 tCO_2e/year, a reported reduction of ~65%. Reported annual energy and cost savings are 61,700 megawatt hour (MWh) and approximately ₹37 crore, respectively, with a simple payback period of ~15 months against a capital investment of approximately ₹45–50 crore. The use of tertiary-treated STP water also reduces dependence on freshwater, although WUE increased from 0.35 to 1.2 L/kWh due to the use of recycled water for evaporative cooling.

6.1.3 PUE Improvement through Airflow Optimisation[88,89]

i. **Baseline:** An Indian data centres had an average PUE of approximately 1.82, with cooling energy consumption affected by inefficient airflow management and HVAC operation.

ii. **Intervention:** A portfolio-wide airflow and cooling optimisation programme was implemented, including cold-aisle containment (CAC), HVAC optimisation, variable frequency drives (VFDs), smart controls, and continuous monitoring through the Facilities Infrastructure Management (FIM) programme. In total, 125 energy-efficiency opportunities were identified across HVAC, UPS, lighting, and IoT-enabled monitoring, of which 91 projects were completed.

iii. **Outcome:** The average PUE of Indian facilities improved from approximately 1.82 to 1.76 in FY 2020–21 and subsequently to approximately 1.60 for facilities managed by the FIM team. The company's global average PUE reached approximately 1.56 in FY 2022–23. The 91 completed projects delivered annual electricity savings of approximately 5.57 million kWh and energy cost savings of ₹4.82 crore, demonstrating the potential for airflow and operational optimisation to improve data centre efficiency without major IT infrastructure modifications.

6.1.4 Integrated Low-GWP Cooling Design[90,91]

i. **Baseline:** New hyperscale data centres require high cooling capacity to support increasing IT and AI workloads, while conventional cooling systems can contribute significantly to energy consumption and refrigerant-related emissions.

ii. **Intervention:** A greenfield hyperscale data centre was designed with energy-efficient chilled-water cooling, advanced airflow management, and scalable thermal infrastructure. Low-GWP refrigerant technologies such as R-454B were also incorporated into new cooling systems, supported by inverter-driven compressors, indirect free cooling, and intelligent controls.

iii. **Outcome:** The facility achieved a reported design PUE below 1.5 while providing scalable cooling capacity for future high-density workloads. The integration of low-GWP refrigerants and energy-efficient cooling technologies supports reduced cooling energy consumption, lower refrigerant-related emissions, and improved long-term environmental compliance.

6.1.5 Thermal Energy Storage for Chilled-Water Backup

i. **Baseline:** A Tier III data centre with a 37.69 MW IT load relied on a conventional chilled-water cooling system, with backup cooling during power interruptions dependent on mechanically driven chillers supported by diesel generator (DG) power.

ii. **Intervention:** A thermal energy storage (TES) tank was integrated with the chilled-water system to provide backup cooling during power failures and emergencies. The tank uses thermal stratification, with warm and cold water maintained in separate layers to enable chilled-water delivery without active refrigeration during discharge. CFD analysis was used to validate the stratification behaviour and cooling performance. The TES can also be charged during off-peak periods and discharged during peak demand or grid-stress conditions.

iii. **Outcome:** The TES provides an independent passive cooling buffer, improving cooling redundancy and reducing the risk of thermal excursions during power interruptions. It also enables cooling-load shifting and can reduce the need for DG-supported chiller operation during outages, potentially lowering diesel consumption and associated CO_2 emissions. However, the magnitude of DG runtime and emissions reduction requires site-specific operational data and has not been quantified.

6.2 International Case Studies

6.2.1 Case Study: Singapore's Sustainability Moratorium[92,93,94,95,96]

i. **Baseline:** Rapid data centre growth led to data centres accounting for more than 7% of Singapore's electricity consumption, prompting a moratorium on new data centre construction in 2019. The resulting constraint highlighted the need to improve energy efficiency, renewable energy use, and sustainable cooling before allowing further capacity expansion.

ii. **Intervention:** The moratorium was partially lifted in 2022 through a competitive Data Centre Call for Application (DC-CFA) process with stringent sustainability requirements. These included a PUE of ≤1.30, an initial capacity allocation of 80 MW, and, in subsequent allocation rounds, a requirement to source 50% renewable/green energy. Approved facilities were also required to use liquid cooling for at least 60% of the IT load and develop waste-heat-recovery plans.

iii. **Outcome:** The policy enabled controlled expansion of data centre capacity while embedding energy efficiency, renewable energy, liquid cooling, and heat recovery into new developments. However, the allocated capacity remained substantially below market demand, creating a reported supply gap of more than 500 MW. This accelerated regional expansion into neighbouring Johor Bahru, Malaysia, and Batam, Indonesia, supported by dedicated low-latency fibre connectivity to Singapore.

6.2.2 F-Gas Regulation and Refrigerant Transition in DCs[97,98]

i. **Baseline:** Data centre cooling systems have traditionally used high-GWP HFC refrigerants, including R-410A and R-134a, contributing to refrigerant-related greenhouse gas emissions and creating long-term regulatory risks.

ii. **Intervention:** The revised F-Gas Regulation (EU) 2024/573, effective from March 2024, introduced a progressive phase-down of HFCs with the objective of eliminating their use by 2050. This is driving the adoption of lower-GWP alternatives, including R-454B, R-513A, R-1234ze(E), and natural refrigerants where technically feasible. Large data centres are also subject to sustainability reporting requirements covering refrigerants, energy, renewable energy, water, and waste-heat recovery.

iii. **Outcome:** The regulatory framework is accelerating the transition towards low-GWP refrigerants and integrating refrigerant management with broader data centre sustainability objectives. This supports reduced refrigerant-related emissions while encouraging improvements in energy efficiency, renewable energy utilisation, water management, and waste-heat recovery.

6.2.3 Green Data Centre Roadmap Implementation

i. **Baseline:** Singapore's limited land and energy resources, combined with rapidly growing data centre demand, created challenges for sustainable expansion. Conventional approaches focused primarily on facility-level energy efficiency, without a broader framework integrating cooling, IT equipment, renewable energy, and supporting infrastructure.

ii. **Intervention:** The Green Data Centre Roadmap, launched in 2024, established a national framework to support additional data centre capacity while improving energy efficiency and increasing green energy use. The roadmap targets at least 300 MW of additional capacity and promotes advanced cooling technologies, high-efficiency IT equipment, intelligent software optimisation, and low-carbon energy. Supporting measures include Green Mark for Data Centres 2024, the Energy Efficiency Grant, and Singapore Standard SS 715:2025 for energy-efficient IT equipment.

iii. **Outcome:** The roadmap provides a coordinated pathway for expanding data centre capacity while improving energy and environmental performance. SS 715:2025 targets energy savings of at least 30% through improved IT equipment selection and operation, while the overall framework promotes advanced cooling, efficient IT infrastructure, and renewable energy integration to support lower-carbon data centre growth.

6.2.4 Waste Heat-Driven Absorption Cooling in an AI Data Centre

6.2.4.1 Combined Heat and Power with Waste Heat-Driven Absorption Cooling for AI Infrastructure[99]

i. **Baseline:** High-density AI data centres have substantial cooling requirements and typically depend on electricity-intensive vapour-compression cooling systems. Conventional CHP systems may also reject useful waste heat rather than recovering it for cooling.

ii. **Intervention:** A combined heat and power (CHP) system was integrated with waste heat-driven lithium bromide absorption chillers. Recovered high-temperature CHP waste heat drives 23 absorption chiller units with a combined cooling capacity of approximately 46,000 TR. The chilled water is supplied to direct liquid cooling (DLC) and rear-door heat exchanger (RDHx) systems for high-density AI servers.

iii. **Outcome:** The integrated system converts CHP waste heat into useful cooling, reducing dependence on electricity-intensive vapour-compression cooling and improving overall energy utilisation. The large-scale deployment demonstrates the potential of waste heat-driven absorption cooling to reduce cooling-related electricity demand and support efficient thermal management of high-density AI data centres.

6.2.4.2 Absorption Chiller with Waste Heat Recovery

i. **Baseline:** AI data centres require substantial cooling capacity, with conventional electrically driven cooling increasing facility power demand. A significant portion of energy from on-site power generation is also rejected as waste heat.

ii. **Intervention:** A waste heat-driven absorption chiller system was integrated with on-site power generation to recover waste heat and convert it into useful cooling. The architecture recovers approximately 57% of energy otherwise lost as waste heat and provides thermally driven cooling for AI workloads. The modular design can scale from 100 MW campuses to gigawatt-scale facilities.

iii. **Outcome:** The system can reduce cooling-related electricity demand by up to 44% and cooling-system CO_2 emissions by up to 43%. A reference 1 GW AI facility achieves a PUE as low as 1.23 and can free up to 97 MW of additional computing capacity without increasing on-site power generation. The approach demonstrates the potential to decouple cooling growth from electrical demand growth in high-density AI data centres.

6.2.5 Ultra-Low-Grade Waste Heat-Driven Absorption Cooling for Data Centres[100]

i. **Baseline:** Liquid-cooled data centres generate low-grade waste heat, typically around 50°C, which is difficult to utilise with conventional absorption chillers requiring heat sources above 80°C. Air-cooled components may therefore continue to rely on conventional mechanical cooling.

ii. **Intervention:** A triple-stage LiBr–H_2O absorption chiller was developed to utilise 50°C waste heat from the liquid-cooling loop. The system delivers 50 kW of chilled water at 18°C and incorporates stage-switching control to adjust operation according to waste heat availability. The recovered cooling is used for air-cooled components within the data centre.

iii. **Outcome:** For a data centre with a 200 kW liquid-cooling load and 100 kW air-cooling load, the system reduced the mechanical cooling load by up to 80.5% and achieved annual electricity savings of approximately 78 MWh under Guangzhou climatic conditions. The approach demonstrates the potential of ultra-low-temperature absorption cooling to recover low-grade server waste heat and reduce cooling electricity demand.

The case studies demonstrate that sustainable data centre cooling requires an integrated approach, combining efficient cooling, operational optimisation and low-GWP refrigerants with integral technologies such as thermal storage, renewable energy and heat recovery. Rather than pointing to distinct regional solutions, the Indian and international examples reviewed illustrate different facets of this same portfolio. Free cooling, heat rejection technologies, airflow optimisation and the transition to liquid cooling as rack densities rise, together with the policy frameworks, refrigerant transitions and waste-heat utilisation, are relevant across markets as AI and HPC workloads intensify. What varies by geography is the specific combination each facility adopts, shaped by local climate, water availability, grid conditions and IT heat density. As rack densities and cooling loads continue to rise globally, this integrated approach, addressing efficiency, resilience and decarbonisation together, is set to become the standard framework for data centre cooling worldwide.

07 Gaps, Challenges and Recommendations

The earlier chapters have reviewed cooling technologies used in DCs, refrigerant use, energy and water requirements, operations and maintenance practices, international developments and selected case studies. Based on these findings, this chapter identifies the key gaps and challenges that may need to be addressed to support sustainable cooling in the DC sector.

The findings suggest that sustainable cooling in DCs is not only a matter of selecting efficient cooling equipment. It is also linked to refrigerant choice, energy and water use, availability of skilled personnel, DC siting, grid requirements, financing and coordination among different stakeholders.

Table 11 summarises the key gaps identified through the study and highlights their relevance to sustainable cooling in DCs. The areas are presented to support greater awareness and understanding of the considerations that may influence the sustainability and long-term performance of DC cooling systems.

7.1 Key Gaps and Challenges

Table 11: Key Gaps Relevant to Sustainable Cooling in Data Centres

Area	Kay Gaps	Relevance to Sustainable Cooling
Cooling technologies	Conventional DCs continue to rely largely on air cooling, while higher-density AI and HPC applications, with rack densities reaching 100–200 kW and in some cases above 600 kW, are driving interest in liquid and hybrid cooling. The increasing adoption of these technologies presents an opportunity to build awareness of their design, installation, operation, maintenance and potential application in existing facilities.	The choice and efficiency of cooling technology directly affect energy use, cooling performance and the ability of DCs to meet increasing thermal loads.
Refrigerant transition	DCs being developed today may operate for 15–20 years, while India's HFC phase-down under the Kigali Amendment begins in 2028. This creates an opportunity to increase consideration of low-GWP and non-ODS refrigerants in new and replacement cooling systems.	Refrigerant choice can influence the climate impact of cooling systems over their operating life. The transition to lower-GWP options can therefore be an important part of sustainable cooling.

Area	Kay Gaps	Relevance to Sustainable Cooling
Skills and workforce	The transition towards low-GWP refrigerants and newer cooling technologies is accompanied by evolving skill requirements across the cooling sector. Greater awareness and knowledge of refrigerant safety, refrigerant management, liquid-cooling systems and monitoring could support technicians, facility engineers and MEP professionals.	Appropriate technical knowledge and skills are important for the safe installation, efficient operation, maintenance and long-term performance of cooling systems, including effective refrigerant management. ICAP identifies servicing-sector capacity as a key area requiring strengthening.
Energy and power consumption	The growth of DCs, particularly AI-driven growth, is increasing electricity requirements and placing greater importance on cooling efficiency. There is an opportunity to improve understanding of the relationship between cooling performance and overall energy consumption.	Cooling accounts for approximately 30–50% of DC energy consumption, with higher shares in older facilities. Improving cooling efficiency can therefore contribute to reducing overall power requirements and improving facility performance.
Water use and efficiency	Cooling systems can have significant water requirements, particularly where evaporative cooling is used. There are opportunities to improve awareness of water-use efficiency, including the potential role of efficient cooling technologies and treated wastewater or greywater reuse.	Improving the efficiency of water use in cooling systems can help reduce water consumption while maintaining required cooling performance. A single 100 MW facility using evaporative cooling can draw close to 2 million litres per day, which is material in water-stressed locations.
Waste heat and energy reuse	DCs generate significant amounts of waste heat, while its productive use remains relatively limited. India's predominantly warm climate may limit some applications, but opportunities may exist for heat-to-cooling, industrial process heat, desalination and other suitable uses.	Recovery and productive use of waste heat could improve the overall resource efficiency of DC cooling and reduce the need for energy in other applications where technically and economically suitable.
Data and monitoring	Information on PUE, WUE, refrigerant inventories and leakage is limited, and there is at present no common national format in which such information is reported. This presents an opportunity to improve understanding of resource use and cooling performance across the sector.	Measurement and monitoring can help identify variations in cooling performance, energy and water use, and refrigerant management, providing a basis for benchmarking and improvement.
Access to finance	Access to concessional or dedicated finance for cooling-system upgrades and low-GWP refrigerant transitions is limited, particularly for edge, colocation and mid-sized operators.	Where affordable capital is not available, operators may default to lower-cost cooling options with higher long-term energy, water and refrigerant intensity, particularly in the price-sensitive colocation segment.
Siting and local conditions	DC siting is influenced by factors such as grid availability, connectivity, land and renewable-energy potential. Greater consideration of water availability and other local resource conditions could provide opportunities for more resource-efficient development.	Location influences the choice and performance of cooling systems, as well as their energy and water requirements. Tier-2 and Tier-3 locations with land availability, renewable-energy potential and grid headroom remain relatively underutilised.

Area	Kay Gaps	Relevance to Sustainable Cooling
Policy and institutional coordination	Several existing frameworks and initiatives, are relevant to DC energy efficiency, cooling and refrigerant management, and currently operate largely independently of one another. These provide an opportunity for greater alignment and knowledge sharing across the different stakeholders involved.	Coordination and information sharing can help improve awareness of sustainable cooling technologies, refrigerant options, efficiency practices and emerging approaches across the sector.
Grid integration	The rapid growth in DC electricity demand may increase pressure on local and regional power systems. At the same time, cooling and other facility loads may offer opportunities for optimisation, storage, demand management and renewable-energy integration.	More efficient and flexible management of cooling-related electricity demand could support both DC energy efficiency and more efficient integration with the wider electricity system.

The chapter therefore highlights five broad areas that are relevant to promoting awareness and understanding of sustainable cooling opportunities in the DC sector.

7.2 Recommendations

The gaps and opportunities identified in the study point to several areas that could support greater awareness and wider consideration of sustainable cooling practices in India's DC sector. The following areas are presented as broad suggestions for consideration by relevant stakeholders.

Four considerations underpin these recommendations. First, they should build on existing frameworks rather than create parallel mechanisms. Second, implementation should progress from awareness and voluntary benchmarking towards more established practices as the sector matures. Third, cooling technology and refrigerant choices should be addressed together, recognising their interdependence. Finally, the recommendations should remain applicable across hyperscale, colocation, enterprise and public-sector facilities, which vary significantly in their technical and financial capacities.

7.2.1 Low-GWP Refrigerants and Advanced Cooling

Greater consideration could be given to low-GWP and non-ODS refrigerants and to emerging cooling approaches such as liquid and hybrid cooling, particularly as DC rack densities increase. Awareness could also be strengthened on appropriate refrigerant and cooling-technology selection, safety considerations, and the suitability of different approaches for new and existing DCs. Further emphasis may be placed on safe refrigerant handling, operation and maintenance, leak detection and reporting, and good refrigerant management practices, particularly for systems above a significant refrigerant charge.

Indicators of progress: share of new DC cooling capacity specified with non-ODS, low-GWP refrigerants; number of facilities operating liquid cooling and their measured PUE; reported refrigerant leakage rates.

7.2.2 Energy and Water Efficiency

PUE reporting in India is largely voluntary, with average reported levels of around 1.5–1.6. Leading international hyperscalers report PUE levels of around 1.1–1.3, providing useful benchmarks for improving energy efficiency in DCs. As set out in Chapter 3, narrowing this gap across the projected 2032 fleet corresponds to approximately 37 TWh of avoided electricity consumption annually comparable to Delhi's current annual electricity use.

The use of common indicators such as PUE and WUE could be encouraged to support benchmarking and comparison of energy and water performance across DCs, reported in a standardised national format. Greater awareness of the links between cooling-system design, energy and water consumption, and equipment efficiency could support informed technology and procurement choices. Reporting of energy and water performance, including for existing facilities, along with appropriate incentives, could further encourage continuous improvement in DC efficiency.

The field assessments undertaken as part of the study indicate that a significant share of the efficiency improvement potential can be achieved through better operational practices rather than capital replacement. Facilities assessed maintained server inlet temperatures well below the equipment's rated tolerance, operated multiple cooling units at low loading, and used BMS and DCIM platforms primarily for alarm management rather than performance optimisation. Greater awareness of adaptive setpoint management, airflow containment integrity and analytics-led operation could therefore deliver efficiency gains at limited cost.

Indicators of progress: share of new DC capacity reporting PUE and WUE, and the annual trend; number of states referencing common national indicators in their DC policies.

7.2.3 Skills, Information and Collaboration

DCs require technicians with advanced skills in precision cooling systems. Greater emphasis needs to be placed on skill development and upskilling of service technicians involved in the installation, operation and maintenance of DC cooling systems, particularly to support the safe and effective use of low-GWP refrigerants and advanced cooling technologies, including liquid and hybrid cooling systems. Training and capacity-building programmes could strengthen technicians' knowledge of refrigerant handling, leak detection and management, system operation and maintenance, and safety practices.

Alongside skills, the study points to value in shared information and coordination. A common national repository for PUE, WUE and refrigerant-inventory information would reduce duplicative reporting across agencies and give the sector a basis for benchmarking. ICAP identifies the servicing sector as one of its thematic areas and recognises the need for skill development and capacity building of servicing technicians in the cooling sector. The action points under the servicing sector have been finalised by mapping them with relevant ongoing government schemes and programmes.

Indicators of progress: number of technicians trained on low-GWP refrigerant handling and liquid-cooling operation and maintenance; setting up the forum and deciding how often it will report.

7.2.4 Water-Sensitive Planning and Siting

Water availability and local water-stress conditions need to be considered when planning DC locations and selecting cooling systems. Greater awareness of water-use performance, including through indicators such as WUE, can help make better decisions about energy and water use. Water-efficient cooling approaches, such as air-cooled, closed-loop and dry or adiabatic systems, together with the potential use of treated wastewater and rainwater harvesting, could also be explored where appropriate to local conditions.

An important consideration is that energy and water efficiency cannot be optimised at the same time through condenser selection alone. As discussed in Chapter 3, condenser configurations with lower PUE generally use more water, while air-cooled systems use less water but require more energy. Therefore, cooling technology should be selected based on local water and energy availability rather than PUE alone. In water-stressed areas, hybrid and low-water cooling options may provide a better balance between energy and water use.

Data from the Central Ground Water Board (CGWB) and Central Water Commission (CWC) on groundwater availability, surface water resources and water-stress conditions can help DC developers assess local water availability when selecting sites and cooling systems. Developers can also adopt appropriate water-conservation measures in line with government policies and requirements for the use and management of groundwater and surface water.

DC siting decisions also depend on grid capacity, access to renewable energy, connectivity and land availability. Tier-2 and Tier-3 locations with adequate land, renewable energy potential and available grid capacity may offer better resource efficiency than further expansion in metros, where power and water resources are already under pressure.

Indicators of progress: percentage of new DCs assessing local water availability and water stress; percentage of DCs reporting WUE.

7.2.5 Waste Heat and Energy-System Integration

There are opportunities to explore the productive use of DC waste heat for applications suited to local conditions, including industrial processes, cooling and other potential uses. Greater awareness of demand flexibility, renewable energy integration and energy storage could also support more efficient interaction between DCs and the electricity system.

Given the limited experience in India so far, feasibility studies at two or three large facilities, particularly in industrial clusters and coastal or water-stressed areas, would help assess which applications are suitable under Indian climate and demand conditions.

Indicators of progress: number of operating waste-heat reuse installations at DCs; DC load participating in demand-flexibility arrangements.

7.3 Sequencing of Opportunities

The areas described above differ in how quickly they can be taken forward. Table 12 sets out an indicative sequencing across near-, medium- and long-term horizons. It is intended as a reference for stakeholders rather than as a schedule, and several of these areas can be progressed in parallel. The sequencing reflects the timing of India's HFC phase-down under the Kigali Amendment, which begins in 2028, and the 15–20 year operating life of cooling systems being installed in the current build-out.

Table 12: Summary of Key Recommendations

Area	Near-term (0–2 years)	Medium-term (2–5 years)	Long-term (5+ years)
Refrigerants and cooling	Technical guidance on low-GWP refrigerant options, A2L and A3 handling, and liquid cooling	Harmonisation of relevant BIS codes and standards; support for domestic manufacture of key liquid-cooling components	Low-GWP refrigerants as established practice for new facilities; liquid and hybrid cooling widely applied in high-density AI and HPC facilities
Energy and water performance	Common indicators and a standardised disclosure format available for voluntary use	Wider adoption of benchmarking, particularly among larger facilities	Performance information available across the sector, including existing facilities, and reflected in incentive frameworks
Water and siting	National DC water-stress advisory using CGWB and CWC data	Wider use of WUE reporting and of treated-wastewater and air-cooled design in water-stressed districts; greater consistency across state siting incentives	Water-neutral and water-positive design established as good practice in stressed basins
Waste heat and grid integration	Feasibility studies and pilots on heat-to-cooling, industrial heat and desalination; initial demand-response pilots with DISCOMs	Connection and tariff approaches for flexible DC loads; scale-up of proven heat-reuse applications	Grid-interactive, renewable- and storage-linked facilities, with waste-heat recovery integrated into suitable industrial clusters
Skills, information and coordination	Coordination forum convened; technician training modules developed and launched	RAC and liquid-cooling skilling scaled through NSDC and Skill India; financing mechanisms established	Sustained certification, financing and information ecosystem supporting continuous improvement across the sector

India's DC sector is entering a period of rapid change, with the growing use of AI increasing the need for cooling, electricity and water. Technologies such as liquid and hybrid cooling, low-GWP and non-ODS refrigerants, waste-heat reuse, grid-interactive and water-efficient systems are already available internationally and are increasingly being adopted in India. The key priority now is to better coordinate existing policies, institutions and skills so that energy and cooling performance, refrigerant management, water use, grid integration and workforce development are addressed together rather than separately.

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