

Maine Data Center Advisory Council – Environment Pre-Read

June 23, 2026, 2:00pm-5:00pm

Location: Virtual via Zoom

Registration link: https://cbi-org.zoom.us/webinar/register/WN_G_3WmF0JQymqAAyRDqLCKw

About the Council

The [Maine Data Center Advisory Council](#) was established by Executive Order of Governor Janet Mills to evaluate issues related to large-scale data center development in Maine and make recommendations to protect ratepayers, maintain electric grid reliability, minimize environmental impacts, and enable responsible economic development.

Council meetings will be open to the public. Additional meetings will be held throughout 2026, with a final report due to the Governor and Legislature by January 29, 2027. Meetings will be recorded and posted along with slides and summaries on the [Council webpage](#).

Meeting Pre-Read

To help inform the discussion, the Council Co-Chairs are providing the following background information related to environmental considerations associated with large data centers in Maine. This information will be presented and discussed during the June 23 meeting, with information provided in advance for those who are interested in delving deeper into the scientific and regulatory topics that the Council will discuss.

At the Kickoff meeting on June 3, Department of Environmental Protection Commissioner Melanie Loyzim presented core areas of focus as well as current environmental safeguards and processes in place at the federal, state, and local level. Core areas of focus include the following:

- Siting
- Water withdrawal and discharge
- Habitat, wetlands
- Air emissions, including greenhouse gases
- Cooling fluids, refrigerants
- Fuel Storage
- Lighting, noise, infrasound
- Stormwater
- Brownfields
- Solid, hazardous, and e-wastes

A meeting summary containing key points raised by Council members during the June 3 meeting can be found online at maine.gov/energy/datacentercouncil. The June 23 meeting will include a detailed discussion of data center environmental considerations and applicable safeguards and processes. The June 23 meeting agenda can also be found at the link above.

To inform the discussion, the following information is included as a pre-read for Council Members and the public. Attachments begin on page 3 of this document.

Attachment 1. Data Center Advisory Council Environmental References

- This is a list of some of the laws and rules that apply to the potential environmental impacts from data center development and operations in Maine. This is not an exhaustive list. Applicability depends on site and project-specific details.

Attachment 2. Maine's Site Location of Development Act (SLODA)

- MRS Title 38, §481. FINDINGS AND PURPOSE

Attachment 3: Cooling Systems in Data Centers: A Technical Review of Water-Based Methods, Emerging Alternatives, and Environmental Considerations.

Authors: Kazi Tamaddun, Tara Goldberg, Dave Goodman.

- This contains a research summary of data center cooling systems and impacts, including traditional cooling methods, non-water-based cooling alternatives, efficiency and sustainability metrics and trade-offs, innovation and future technologies, emerging regulatory trends, and conclusions and opportunities.

Maine Data Center Advisory Council Environmental References

This is a list of some of the laws and rules that apply to the potential environmental impacts from datacenter development and operations. This is not an exhaustive list. Applicability depends on site and project-specific details.

Acronyms used in this document: Maine Department of Environmental Protection (DEP), National Oceanic and Atmospheric Administration (NOAA), Maine Department of Agriculture, Conservation, and Forestry (DACF), Maine Center for Disease Control (CDC), Maine Land Use Planning Commission (LUPC), Maine National Pollutant Discharge Elimination System (NPDES), Clean Air Act (CAA), Clean Water Act (CWA), Spill Prevention, Control, and Countermeasure (SPCC), Maine Endangered Species Act (MESA), Maine Natural Resources Protection Act (NRPA), Site Location of Development Act (SLODA), Hydrofluorocarbons (HFCs), National Emission Standards for Hazardous Air Pollutants (NESHAP), Per-and polyfluoroalkyl substances (PFAS).

Law or Rule	Subject	Citation	Agency
Federal Laws			
Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA)	pesticide, herbicide use	7 U.S.C. §§ 136 et seq.	US Environmental Protection Agency
Farmland Protection Policy Act	prime farmland conversion	7 U.S.C. §§ 4201-4209	US Dept. of Agriculture - Natural Resources Conservation Service
Toxic Substances Control Act	PCBs, asbestos	15 U.S.C. §§ 2601 et seq.	US Environmental Protection Agency
Bald and Golden Eagle Protection Act	eagles	16 U.S.C. §§ 668-668d	US Fish & Wildlife Service
Migratory Bird Treaty Act	migratory birds	16 U.S.C. §§ 703-712	US Fish & Wildlife Service
Coastal Zone Management Act	coastal zone development	16 U.S.C. §§ 1451-1465	NOAA; Maine Coastal Program
Endangered Species Act	endangered species	16 U.S.C. §§ 1531-1544	US Fish & Wildlife Service
Rivers and Harbors Act	water intake and outfalls, navigable waters	33 U.S.C. § 403	US Army Corps of Engineers
Clean Water Act (CWA)	water quality	33 U.S.C. § 1251 et seq.	US Environmental Protection Agency; some delegated to Maine DEP
Safe Drinking Water Act	public water systems	42 U.S.C. §§ 300f et seq.	US Environmental Protection Agency; Maine CDC
National Environmenal Policy Act	major federal actions	42 U.S.C. §§ 4321 et seq.	US Environmental Protection Agency
Resource Conservation and Recovery Act	wastes, underground storage tanks	42 U.S.C. §§ 6901 et seq.	US Environmental Protection Agency; some delegated to Maine DEP
Clean Air Act (CAA)	air emissions	42 U.S.C. § 7401 et seq	US Environmental Protection Agency; some delegated to Maine DEP
Small Business Liability Relief and Brownfields Revitalization Act	Brownfields	42 U.S.C. §§ 9601 et seq.	US Environmental Protection Agency
National Historic Preservation Act (Section 106 Review)	historic, archaeological resources	54 U.S.C. § 306108	Advisory Council on Historic Preservation; Maine Historic Preservation Commission
Federal Rules			
Nationwide Permit Program (General Permits)	wetlands, Waters of the US	33 C.F.R. Part 330	US Army Corps of Engineers
New Source Performance Standards (NSPS)	air emissions, new sources	40 C.F.R. Part 60	US Environmental Protection Agency; delegated to Maine DEP (06-096 CMR Ch. 143)
Electric Utility Steam Generating Units	power plant air emissions	40 CFR 60 Subpart Da	US Environmental Protection Agency; delegated to Maine DEP (06-096 CMR Ch. 143)
Industrial/Commercial/Institutional Steam Generating Units	boiler air emissions	40 CFR 60 Subpart Db - Dc	US Environmental Protection Agency; delegated to Maine DEP (06-096 CMR Ch. 143)
Stationary Compression Ignition Internal Combustion Engines	diesel generator emissions	40 CFR 60 Subpart IIII	US Environmental Protection Agency; delegated to Maine DEP (06-096 CMR Ch. 143)
Volatile Organic Liquid Storage Vessels	storage tank emissions	40 CFR 60 Subpart Kb	
Stationary Combustion Turbines	turbine air emissions	40 CFR 60 Subpart KKKKa	
National Emission Standards for Hazardous Air Pollutants (NESHAP)	hazardous air pollutants	40 C.F.R. Part 63	US Environmental Protection Agency; delegated to Maine DEP (06-096 CMR Ch. 144)
Industrial, Commercial and Institutional Boilers and Process Heaters (major sources)	boiler air emissions	40 CFR 63 Subpart DDDDD	US Environmental Protection Agency; delegated to Maine DEP (06-096 CMR Ch. 144)
Industrial, Commercial and Institutional Boilers (area sources)	boiler air emissions	40 CFR 63 Subpart JJJJJJ	US Environmental Protection Agency; delegated to Maine DEP (06-096 CMR Ch. 144)

Industrial Process Cooling Towers	cooling tower emissions	40 CFR 63 Subpart Q	US Environmental Protection Agency; delegated to Maine DEP (06-096 CMR Ch. 144)
Reciprocating Internal Combustion Engines	combustion engine emissions	40 CFR 63 Subpart ZZZZ	US Environmental Protection Agency; delegated to Maine DEP (06-096 CMR Ch. 144)
Stationary Combustion Turbines	combustion turbine emissions	40 CFR Part 63 Subpart YYYY	US Environmental Protection Agency; delegated to Maine DEP (06-096 CMR Ch. 144)
Risk Management Program (CAA § 112(r))	chemical accident prevention	40 C.F.R. Part 68	US Environmental Protection Agency
State Operating Permits Program	major sources	40 C.F.R. 70	US Environmental Protection Agency; delegated to Maine DEP
Greenhouse Gas Reporting Program	GHG emissions reporting	40 C.F.R. Part 98	US Environmental Protection Agency
Oil Pollution Prevention (SPCC Rule)	oil spill prevention	40 C.F.R. Part 112	US Environmental Protection Agency
NPDES Stormwater Discharge Regulations	construction stormwater permits	40 C.F.R. Part 122	US Environmental Protection Agency; delegated to Maine DEP
National Pollutant Discharge Elimination System	wastewater discharge permits	40 C.F.R. 125	US Environmental Protection Agency; delegated to Maine DEP
Cooling Water Intake Structures (CWA § 316(b))	cooling water intake	40 C.F.R. Part 125, Subpart J	US Environmental Protection Agency; delegated to Maine DEP (06-096 CMR Ch. 526)
Underground Injection Control Program	underground injection wells	40 C.F.R. Parts 144-148	US Environmental Protection Agency
Universal Waste Rule	universal waste handling	40 C.F.R. Part 273	US Environmental Protection Agency; delegated to Maine DEP (06-096 CMR Ch. 858)
All Appropriate Inquiries (Phase I & II Environmental Site Assessments)	remediation	40 C.F.R. Part 312	US Environmental Protection Agency
National Flood Insurance Program	floodplain development	44 C.F.R. Parts 59-77	Federal Emergency Management Agency
Incidental Take Permits	endangered species	50 C.F.R. Part 17	US Fish & Wildlife Service
State of Maine Laws			
Use Regulation Law (LUPC zoning jurisdiction)	Unorganized Territory zoning	12 M.R.S. Ch. 206-A, §§ 681 et seq.	Maine Dept. of Agriculture, Conservation & Forestry - Land Use Planning Commission
Maine Endangered Species Act (MESA)	endangered and threatened species	12 M.R.S. §§ 12801-12810	Maine Dept. of Inland Fisheries & Wildlife
Maine Historic Preservation Commission Act	historic, archaeological resources	27 M.R.S. §§ 501-511	Maine Historic Preservation Commission
Solar Energy Development Decommissioning	solar facility decommissioning	35-A M.R.S. §§ 3491-3497	Maine DEP; Maine Land Use Planning Commission
Battery Storage System Decommissioning	battery storage decommissioning	35-A M.R.S. §§ 3498-3499	Maine DEP; Maine Land Use Planning Commission
Water Pollution Control Law / Maine Pollutant Discharge Elimination System (MEPDES)	wastewater discharge permits	38 M.R.S. §§ 413-414	Maine DEP (delegated NPDES authority)
Erosion and Sedimentation Control Law	erosion, sediment control	38 M.R.S. § 420-C	Maine DEP
Stormwater Management Law	stormwater management	38 M.R.S. § 420-D	Maine DEP
Mandatory Shoreland Zoning Act	shoreland development	38 M.R.S. §§ 435-449	Maine DEP; municipalities
Floodplain Management (Federal Flood Insurance)	floodplain development	38 M.R.S. § 440	Maine DACF; municipalities
Natural Resources Protection Act (NRPA)	wetlands, waterways, natural resources	38 M.R.S. §§ 480-A - 480-JJ	Maine DEP
Site Location of Development Act (SLODA)	large development review	38 M.R.S. §§ 481-490	Maine DEP
Pollution and corruption of waters and lands of the State prohibited	oil spills and discharges	38 M.R.S. § 543	Maine DEP
Electronic Waste	e-waste recycling	38 M.R.S. § 1610	Maine DEP
Hydrofluorocarbons (HFCs)	HFC refrigerants	38 M.R.S. § 1613	Maine DEP
PFAS in Products	PFAS in products	38 M.R.S. § 1614	Maine DEP
State of Maine Rules			
Land Use Districts and Standards	Unorganized Territory land use	01-672 C.M.R. Ch. 10	Maine DACF - Land Use Planning Commission
Permits for Aboveground and Underground Propane and Natural Gas Storage Facilities	propane, natural gas storage	02-658 C.M.R. Ch. 12	Maine Fuel Board
Processing of Applications and Other Administrative Matters	permit application procedures	06-096 C.M.R. Ch. 2	Maine DEP
Rules Concerning the Conduct of Licensing Hearings	licensing hearing procedures	06-096 C.M.R. Ch. 3	Maine DEP
Products Containing Perfluoroalkyl and Polyfluoroalkyl Substances	PFAS in products	06-096 C.M.R. Ch. 90	Maine DEP
Definitions Regulation (Air Quality)	air quality definitions	06-096 C.M.R. Ch. 100	Maine DEP
Visible Emissions Regulation	visible air emissions	06-096 C.M.R. Ch. 101	

Major and Minor Source Air Emission License Regulations	air emission licensing	06-096 C.M.R. Ch. 115	Maine DEP
Emission Statements	emissions reporting	06-096 C.M.R. Ch. 137	Maine DEP
Part 70 Air Emission License Regulations	major source licensing	06-096 C.M.R. Ch. 140	Maine DEP
New Source Performance Standards (NSPS)	air emissions, new sources	06-096 C.M.R. Ch. 143	Maine DEP
National Emission Standards for Hazardous Air Pollutants (NESHAP)	hazardous air pollutants	06-096 C.M.R. Ch. 144	Maine DEP
Stationary Generators	backup generator emissions	06-096 C.M.R. Ch. 169	Maine DEP
Wetlands and Waterbodies Protection	wetlands, waterbodies	06-096 C.M.R. Ch. 310	Maine DEP
Assessing and Mitigating Impacts to Existing Scenic and Aesthetic Uses	visual impacts	06-096 C.M.R. Ch. 315	Maine DEP
Significant Wildlife Habitat	wildlife habitat protection	06-096 C.M.R. Ch. 335	Maine DEP
Significant Groundwater Wells	large groundwater withdrawals	06-096 C.M.R. Ch. 342	Maine DEP
No Adverse Environmental Effect Standards (Site Location of Development Act)	adverse effect standards	06-096 C.M.R. Ch. 375	Maine DEP
Beneficial Use of Solid Wastes	solid waste reuse	06-096 C.M.R. Ch. 418	Maine DEP
Stormwater Management	stormwater management	06-096 C.M.R. Ch. 500	Maine DEP
Definitions for the Waste Discharge Permitting Program	waste discharge definitions	06-096 C.M.R. Ch. 520	Maine DEP
Applications for Waste Discharge Licenses	discharge license applications	06-096 C.M.R. Ch. 521	Maine DEP
Application Processing Procedures for Waste Discharge Licenses	discharge license procedures	06-096 C.M.R. Ch. 522	Maine DEP
Waste Discharge License Conditions	discharge license conditions	06-096 C.M.R. Ch. 523	Maine DEP
Criteria and Standards for Waste Discharge Licenses	discharge license standards	06-096 C.M.R. Ch. 524	Maine DEP
Cooling Water Intake Structures	cooling water intake	06-096 C.M.R. Ch. 526	Maine DEP
Rules to Control the Subsurface Discharge of Pollutants	subsurface wastewater discharges	06-096 C.M.R. Ch. 543	Maine DEP
Regulations Relating to Temperature	thermal water discharge	06-096 C.M.R. Ch. 582	Maine DEP
Surface Water Quality Criteria for Toxic Pollutants	toxic pollutant water criteria	06-096 C.M.R. Ch. 584	Maine DEP
In-stream Flows and Lake and Pond Water Levels	water levels and flows	06-096 C.M.R. Ch. 587	Maine DEP
Rule for Underground Oil Storage Facilities	underground oil storage	06-096 C.M.R. Ch. 691	Maine DEP
Siting of Oil Storage Facilities	oil storage facility siting	06-096 C.M.R. Ch. 692	Maine DEP
Universal Waste Rules	universal waste handling	06-096 C.M.R. Ch. 858	Maine DEP
Guidelines for Municipal Shoreland Zoning Ordinances	shoreland zoning standards	06-096 C.M.R. Ch. 1000	Maine DEP
Rules Relating to Drinking Water	public water systems	10-144 C.M.R. Ch. 231	Maine CDC
Subsurface Wastewater Disposal Rule	septic system disposal	10-144 C.M.R. Ch. 241	Maine CDC

§481. Findings and purpose

The Legislature finds that the economic and social well-being of the citizens of the State of Maine depends upon the location of state, municipal, quasi-municipal, educational, charitable, commercial and industrial developments with respect to the natural environment of the State; that many developments because of their size and nature are capable of causing irreparable damage to the people and the environment on the development sites and in their surroundings; that the location of such developments is too important to be left only to the determination of the owners of such developments; and that discretion must be vested in state authority to regulate the location of developments which may substantially affect the environment and quality of life in Maine. [PL 1987, c. 812, §§1, 18 (AMD).]

The Legislature further finds that certain geological formations particularly sand and gravel deposits, contain large amounts of high quality ground water. The ground water in these formations is an important public and private resource, for drinking water supplies and other industrial, commercial and agricultural uses. The ground water in these formations is particularly susceptible to injury from pollutants, and once polluted, may not recover for hundreds of years. It is the intent of the Legislature, that activities that discharge or may discharge pollutants to ground water may not be located on these formations. [PL 1981, c. 449, §3 (NEW).]

The purpose of this subchapter is to provide a flexible and practical means by which the State, acting through the department, in consultation with appropriate state agencies, may exercise the police power of the State to control the location of those developments substantially affecting local environment in order to insure that such developments will be located in a manner which will have a minimal adverse impact on the natural environment within the development sites and of their surroundings and protect the health, safety and general welfare of the people. [PL 1989, c. 890, Pt. A, §40 (AFF); PL 1989, c. 890, Pt. B, §84 (AMD).]

The Legislature further finds that noise generated at development sites has primarily a geographically restricted and frequently transient impact that is best regulated at the municipal level pursuant to a municipality's economic development and land use plans. It is the intent of the Legislature that regulation of noise from developments be primarily the responsibility of local municipal governments. [PL 1993, c. 383, §2 (AMD); PL 1993, c. 383, §42 (AFF).]

SECTION HISTORY

PL 1969, c. 571, §2 (NEW). PL 1971, c. 613, §1 (AMD). PL 1971, c. 618, §12 (AMD). PL 1979, c. 466, §11 (AMD). PL 1981, c. 449, §3 (AMD). PL 1983, c. 513, §1 (AMD). PL 1987, c. 346, §1 (AMD). PL 1987, c. 812, §§1,18 (AMD). PL 1989, c. 890, §§A40,B84 (AMD). PL 1993, c. 383, §2 (AMD). PL 1993, c. 383, §42 (AFF). PL 1995, c. 704, §A2 (AMD). PL 1995, c. 704, §C2 (AFF). PL 1999, c. 468, §5 (AMD).

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Cooling Systems in Data Centers: A Technical Review of Water-Based Methods, Emerging Alternatives, and Environmental Considerations

Kazi Tamaddun, Tara Goldberg, Dave Goodman For additional information and full references, contact: kazi.tamaddun@pnnl.gov

1.0. Introduction

Data centers are growing rapidly due to AI and cloud services, driving steep increases in energy and cooling demand. Traditional cooling systems struggle with rising rack densities and growing water and energy constraints, prompting a shift toward liquid, hybrid, and advanced cooling solutions. This report reviews these technologies and the trade-offs that shape their performance and sustainability.

2.0. Traditional Cooling Methods

2.1. Water-Based Cooling Systems

- Chilled Water Systems:** Central chillers supply 6–12 °C water to Computer Room Air Handlers (CRAHs); cools server intake air and returns warm water to the plant. Efficiency improves with warmer setpoints and economizer use.
- Cooling Towers:** Evaporative towers reject heat from condenser-water loops; greatly reduce chiller load but consume significant water (4–7 L/kWh). Most effective in dry climates (Fig. 1).
- Free Cooling (Economizers):**
 - Water-Side:** Cooling tower + heat exchanger cools return water without compressors when wet-bulb temperatures are low (Fig. 1).
 - Air-Side:** Uses filtered outside air to bypass mechanical cooling (Fig. 1).
 - Refrigerant/DX Economizers:** Passive condensing of refrigerant using outdoor conditions inside Direct Expansion (DX) systems.

2.2. Air Distribution & Containment

- CRAC/CRAH Systems:** Computer Room Air Conditioner (CRAC) = DX cooling; CRAH = chilled-water coils. CRAH dominates hyperscale designs; effective to ~20–30 kW/rack before airflow limits emerge (Fig. 2).
- Airflow Management:** Hot-aisle/cold-aisle layouts reduce mixing; raised floor or overhead plenums deliver supply air (Figs. 3–4).
- Aisle Containment:** Cold- and Hot-Aisle Containment Systems (CACS/HACS) physically separate supply and exhaust air, improve cooling efficiency by ~10–20%, and support higher supply-air temperatures (Fig. 5).
- In-Row Cooling:** Units between racks capture hot exhaust and deliver localized cold air—improves performance in high-density zones (Fig. 6).
- In-Rack Cooling (RDHx):** Rear-door heat exchangers (RDHx) remove heat at the rack; best air-compatible option for >30 kW/rack (Fig. 6).

4.0. Non-Water-Based Cooling Alternatives

- Air-based cooling (DX/CRAC, dry coolers, sealed refrigerant loops)** enables near-zero **Water Use Effectiveness (WUE)** and remains viable at moderate rack densities with proper airflow and controls.
- Advanced air-only systems:** Containment and higher allowable inlet temperatures reduce recirculation and cut cooling energy; high-performance sites demonstrate very low **Power Usage Effectiveness (PUE)** using outside air.
- Direct Expansion (DX):** Water-free refrigerant loops suited for small–medium facilities; efficiency depends on airflow discipline, part-load compressor control, and optional economizers or thermosyphon dry coolers.
- Hybrid air–liquid cooling:** Adds localized liquid loops (RDHx, cold plates, Coolant Distribution Units [CDUs]) while rejecting heat to dry/adiabatic coolers, supporting higher rack densities without evaporative towers.
- Air-side & indirect economizers:** Use favorable outdoor conditions to bypass compressors, delivering major energy savings where climate allows.
- Passive solutions:** Heat pipes, vapor chambers, and Phase-Change Materials (PCMs) buffer rapid thermal spikes; containment and envelope strategies further stabilize airflow.
- AI-assisted airflow optimization:** ML/RL systems adjust fan speeds, airflow paths, and economizer modes in real time, reducing cooling energy by ~14–40%.
- Trade-offs:**
 - Water:** All approaches achieve WUE ≈ 0.
 - Density:** Air-only≈20–30 kW/rack; hybrid≈40–50 kW/rack; higher loads require liquid cooling.
 - Energy/carbon:** Strongly climate- and control-dependent.

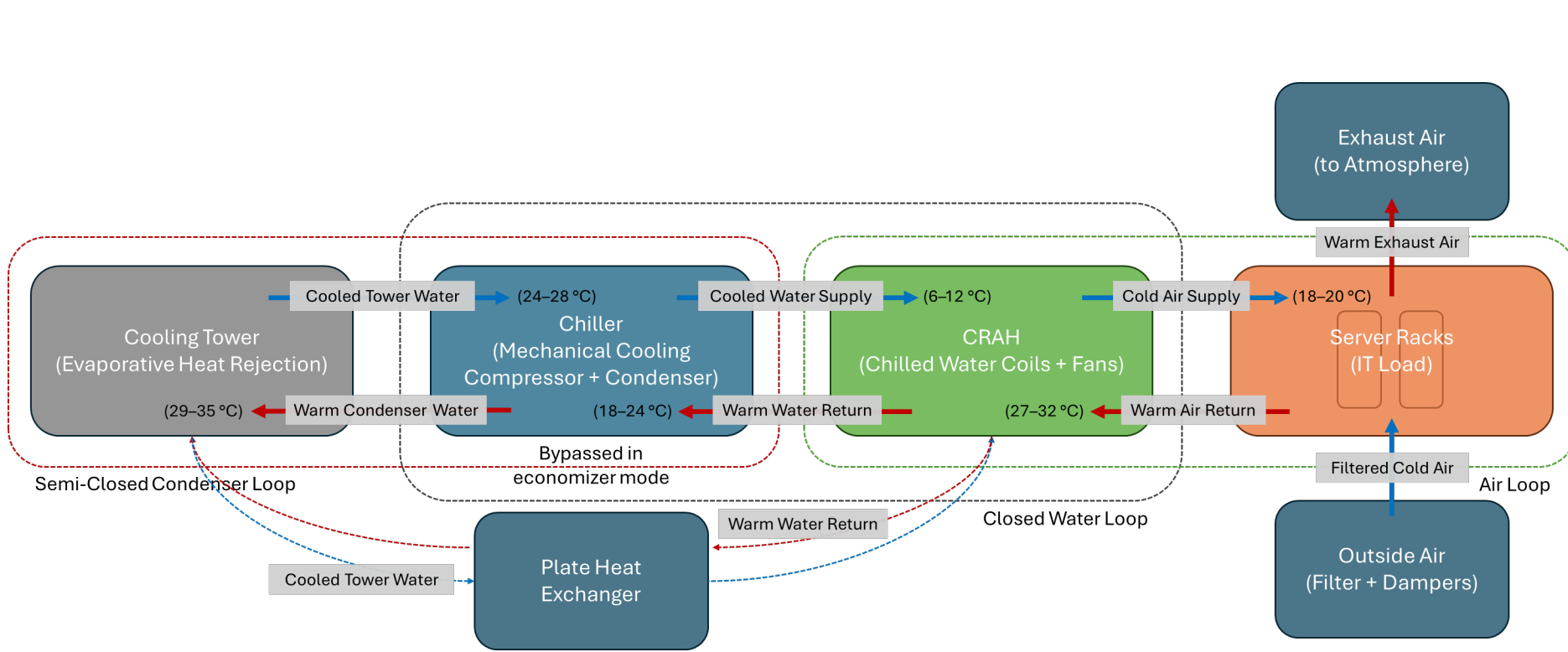


Fig. 1: Schematic of water-side and air-side economizer operation.

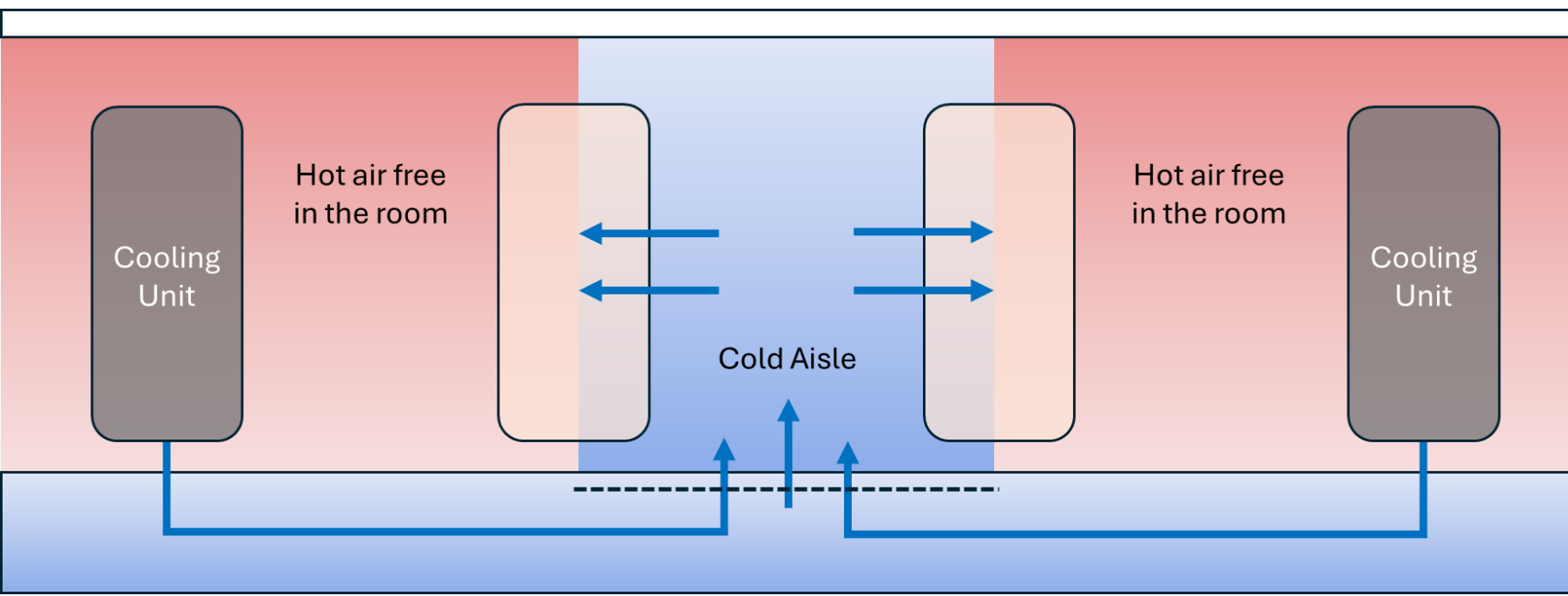


Fig. 3: Schematic of cold aisle containment strategies (CACS).

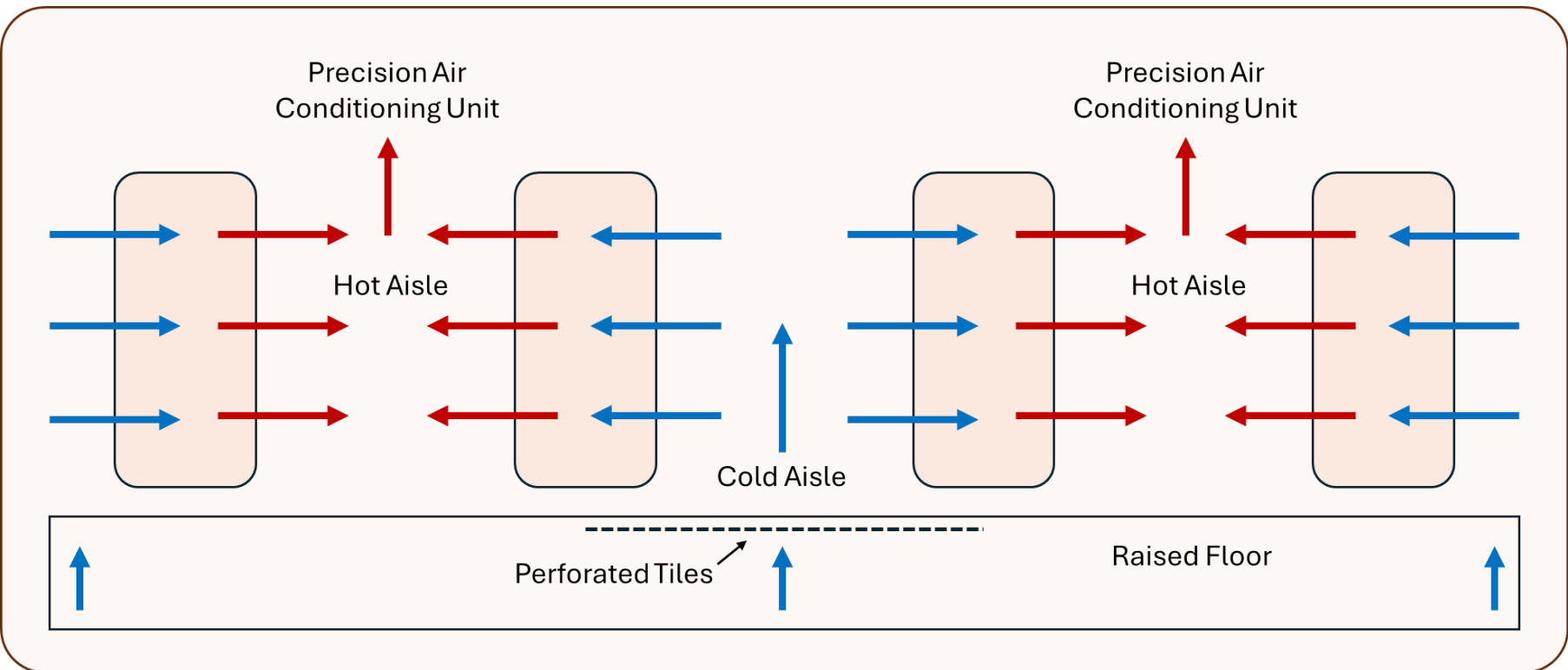


Fig 5: Schematic of hot aisle/cold aisle arrangement.

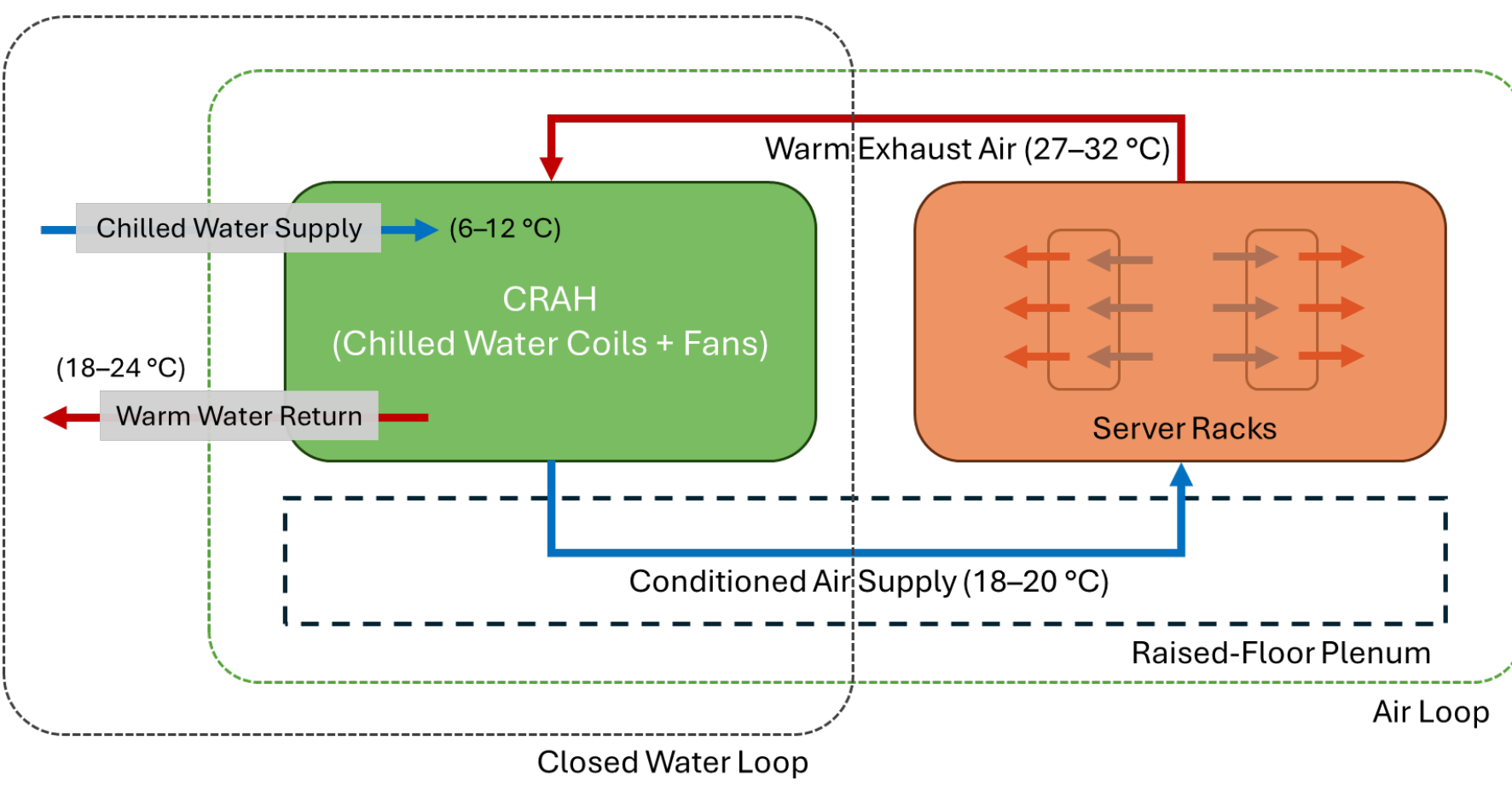


Fig. 2: Schematic of CRAH-based air distribution in a raised-floor system.

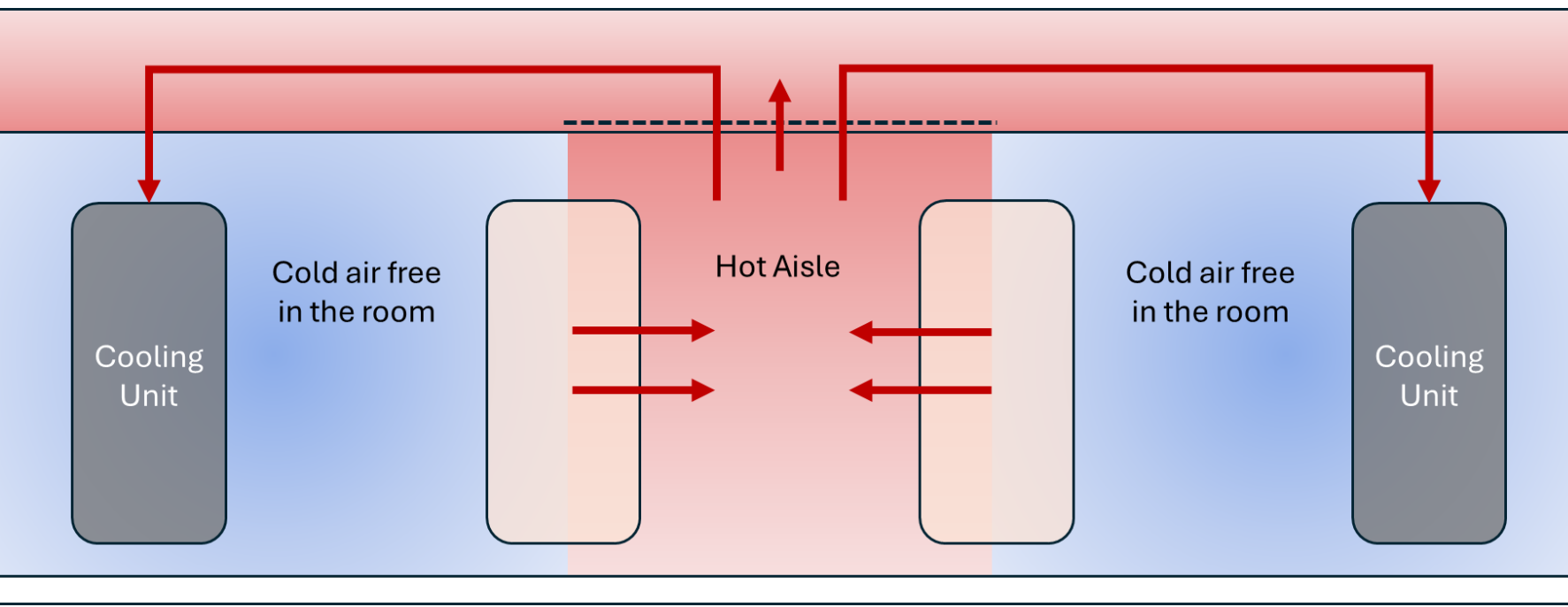


Fig. 4: Schematic of hot aisle containment strategies (HACS).

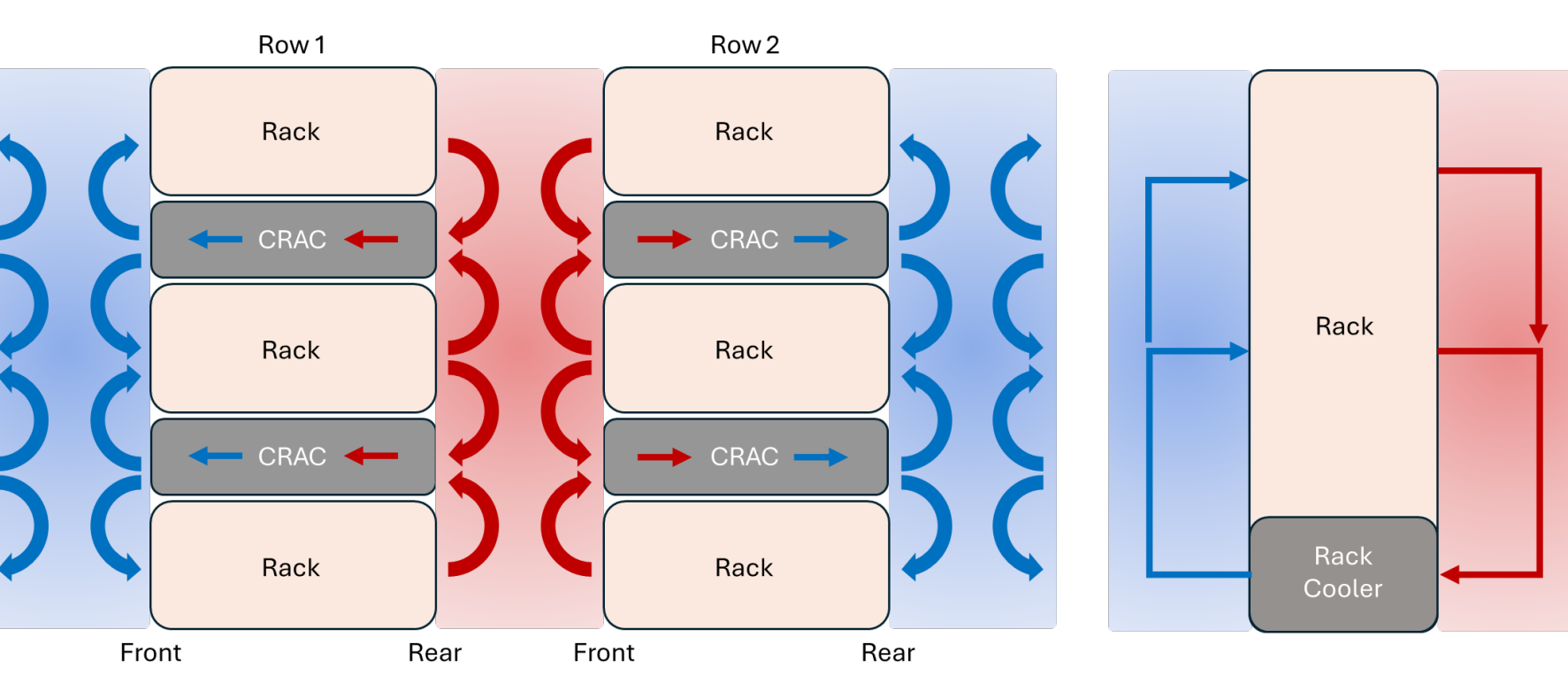


Fig. 6: Schematic of in-row and in-rack cooling strategies.

5.0. Innovations & Future Cooling Technologies

- Shift driven by AI densities:** Rapid growth in AI/ML workloads and higher rack power (>50–100 kW/rack) is accelerating adoption of **liquid, hybrid, and thermally integrated cooling systems** beyond traditional air cooling.

5.1. Near-Term Technologies (3–5 years)

- D2C Cold Plates:** Liquid plates on CPUs/GPUs enable warm-water cooling, high rack densities, major energy/GHG/water reductions, and support **heat reuse** (Figs. 8–9).
- Waste-Heat Recovery:** Warm-water liquid cooling exports heat to buildings or district heating; demonstrated **up to ~80% heat reuse**.
- Immersion Cooling (Single & Two-Phase):** Uniform fluid cooling allows extreme densities and very low PUE (~1.02) (Figs. 10–11). Two-phase systems face **PFAS-related environmental and regulatory constraints**.
- Rear-Door Heat Exchangers (RDHx):** Liquid-cooled rear doors remove rack exhaust heat with minimal retrofit; capacities now reach **30–80+ kW/rack**.
- AI-Assisted Cooling Optimization:** ML/RL controls dynamically reduce cooling energy use (~14–40%) by leveraging outdoor conditions, with no hardware changes.
- Prefabricated / Modular Cooling:** Factory-built pods with liquid loops or immersion tanks shorten deployment time and become **cost-competitive** at higher densities.

7.0. Conclusions and Opportunities

- Water-based cooling** (chilled water, towers, water-side economizers) remains highly energy-efficient and scalable but is increasingly constrained by **water scarcity**, permitting, and climate dependence.
- Non-water-based systems** (DX air cooling, air-cooled chillers, hybrid air–liquid, immersion cooling) reduce freshwater use and improve resilience in **water-stressed regions** but often require higher electrical input or added design complexity.
- Systems integration** (district cooling, heat reuse, and coordinated water–energy planning) creates major opportunities for lowering lifecycle carbon and improving community resilience.

3.0. Efficiency & Sustainability Metrics

- PUE:** Energy efficiency of full facility; improves with economizers, containment, and warmer water/air setpoints.
- WUE:** Water use tied mainly to cooling towers; air-side and DX systems use ≈0 L/kWh.
- CUE:** Carbon intensity depends on compressor/fan energy and grid mix; reduced by economizers and higher setpoints (Fig. 7).
- ERE:** Heat-reuse potential requires warm-water loops; limited in conventional chilled-water and air-cooled systems.

PUE Power Usage Effectiveness $\frac{\text{Total facility energy}}{\text{IT energy}}$	WUE Water Usage Effectiveness $\frac{\text{Water use}}{\text{IT energy}}$
ERE Energy Reuse Effectiveness $\frac{\text{Total energy} - \text{Reused energy}}{\text{IT energy}}$	CUE Carbon Usage Effectiveness $\frac{\text{CO}_2 \text{ emissions}}{\text{IT energy}}$

Fig. 7: Efficiency and sustainability metrics for data centers.

5.2. Mid- to Long-Term Concepts (5–10 years)

- Saline / Non-Potable Water Cooling:** Uses seawater, river water, or wastewater to eliminate potable-water demand; requires corrosion control and environmental permitting (Fig. 12).
- Thermal Energy Storage (TES):** Chilled water, ice, or PCMs shift cooling load, improving resilience and reducing **peak demand by ~20–30%**.
- Subsea Data Centers:** Sealed underwater modules provide efficient natural cooling (PUE ~1.07) and show **significantly lower failure rates**, but servicing remains challenging (Fig. 13).

5.3. Cross-Cutting Considerations

- Regulatory pressures:** PFAS phase-outs and refrigerant transitions affect immersion fluids and chiller designs.
- Climate & water constraints:** Heat, drought, and water-stress regions limit use of evaporative and once-through cooling.
- Infrastructure alignment:** Benefits of heat reuse, TES, and modular cooling depend on site context (district heating, microgrids, coastal access, etc.).

5.4. Technology Maturity Variations:

- TRL 9:** Direct-to-chip cold plates, modular cooling, rear-door heat exchangers.
- TRL 7–8:** Single- and two-phase immersion, AI-assisted optimization, hybrid air–liquid cooling.
- TRL 5–6:** Thermal energy storage (TES), saline cooling, subsea concepts.

Global innovation is expanding, with significant advances from Europe and Asia in immersion, warm-water reuse, and modular liquid systems.

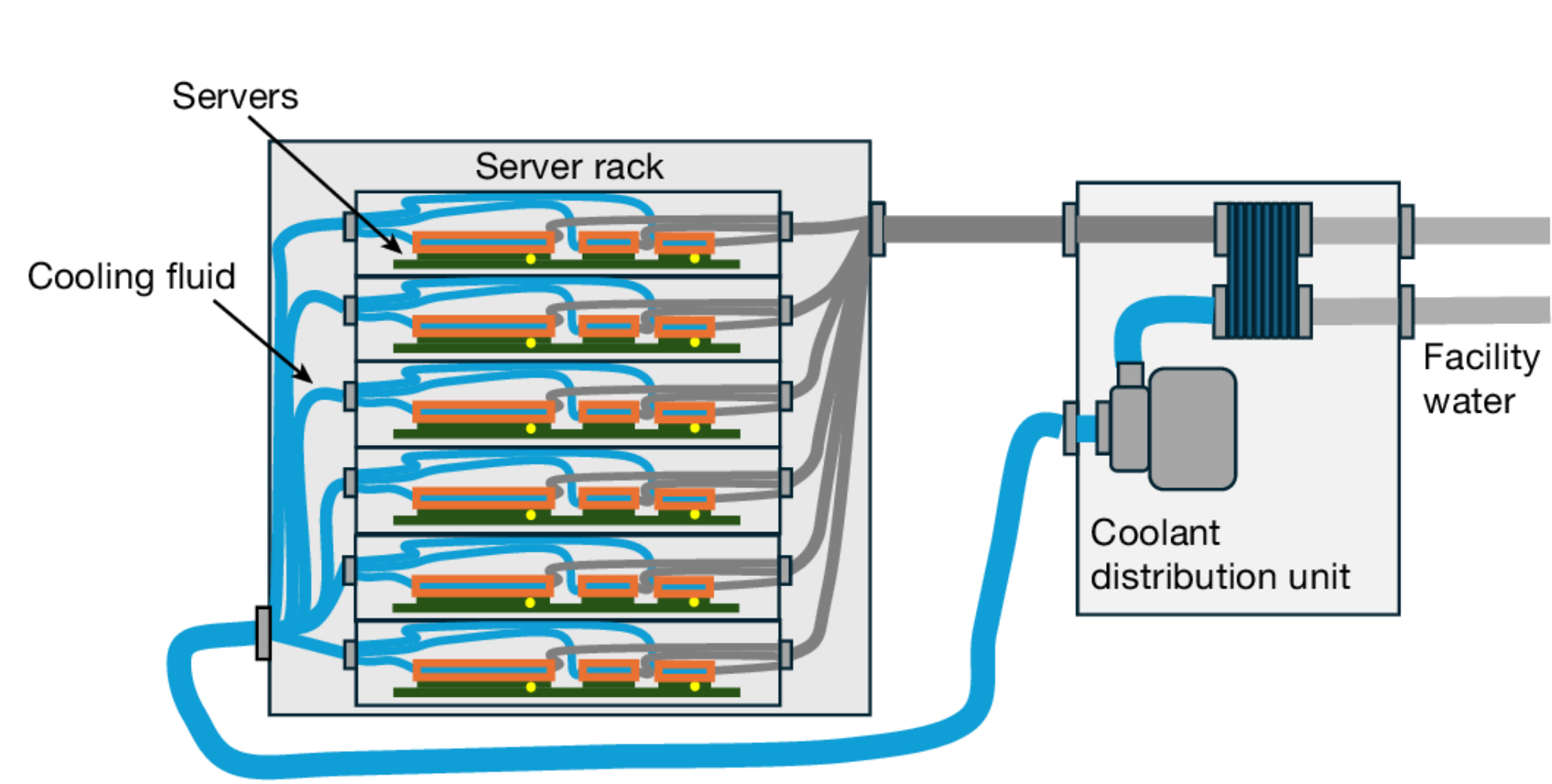


Fig. 8: Schematic of direct-to-chip (D2C) cold-plate cooling. Source: [Alissa et al. \(2025\)](#).

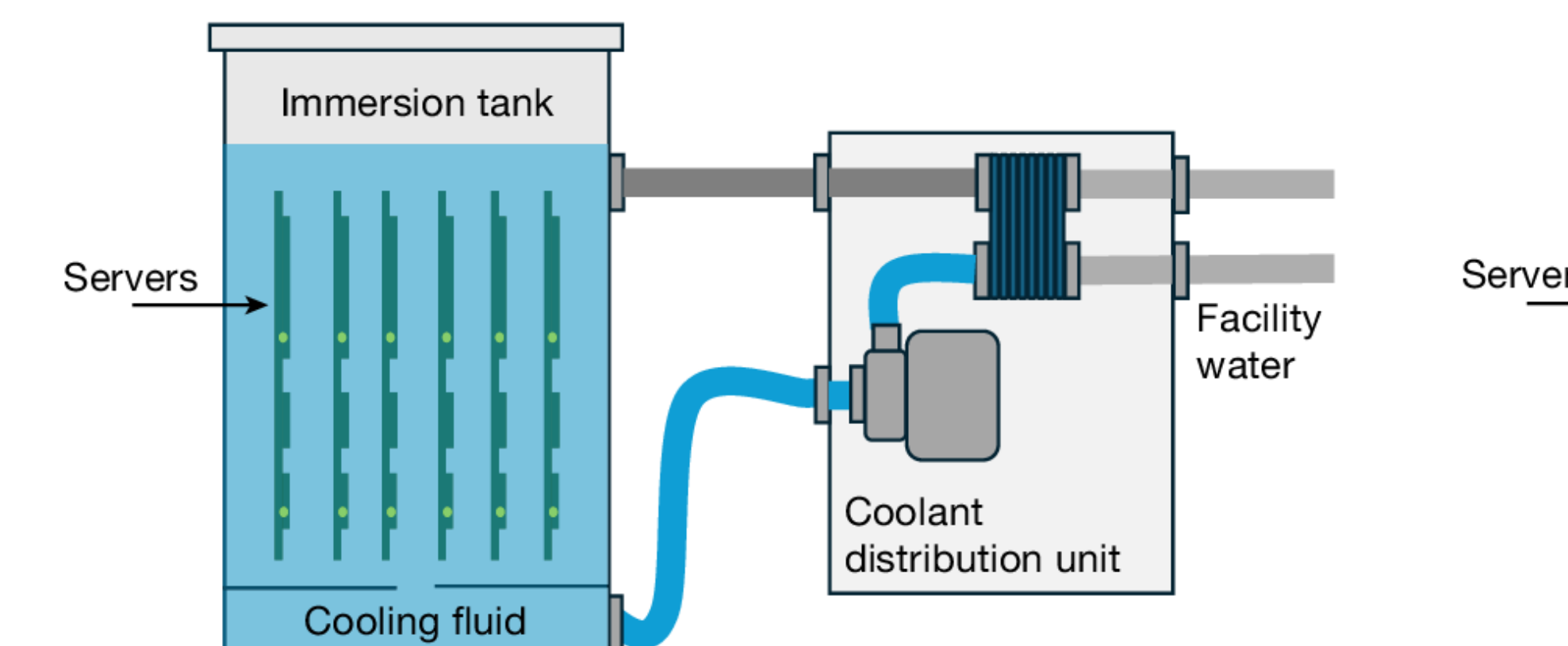


Fig. 10: Schematic of one-phase immersion system. Source: [Alissa et al. \(2025\)](#).



Fig. 12: Nautilus Data Technologies' Stockton1 facility, CA. Source: [Nautilus \(2021\)](#). [Saline/Non-potable water cooling]



Fig. 9: Water-cooled IBM BladeCenter QS22. Source: [Zimmerman et al. \(2012\)](#).

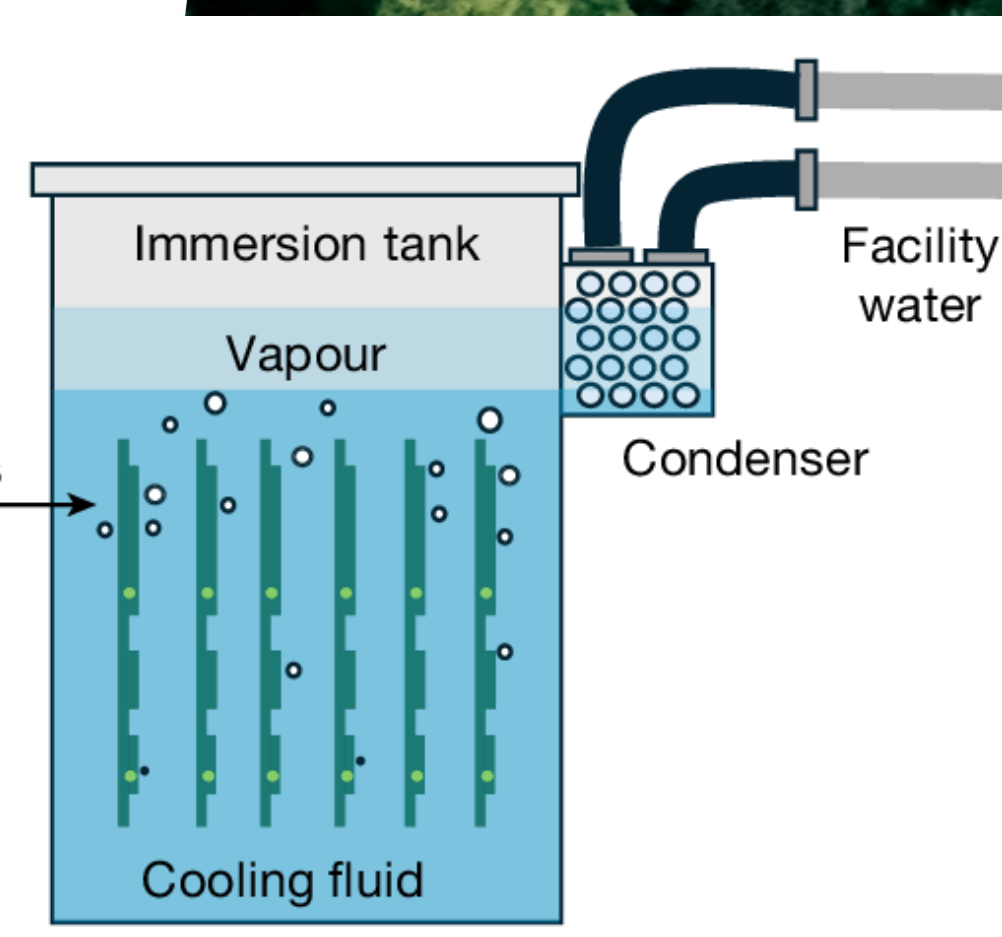


Fig. 11: Schematic of two-phase immersion system. Source: [Alissa et al. \(2025\)](#).



Fig. 13: Microsoft Project Natick, Orkney Island, Scotland. Source: [Microsoft \(2020\)](#). [Subsea data center cooling]

6.0. Regulatory & Compliance Trends Affecting Cooling Systems

- Stricter energy-efficiency codes:** ASHRAE 90.4, Title 24, and EU EN 50600 now require **demonstrated cooling-system efficiency**, not just design claims. Cooling choices must meet climate-zone-specific performance thresholds.
- Expanding water-stewardship rules:** Federal Clean Water Act (CWA) permits, and new state/municipal limits increasingly restrict **high-volume withdrawals and thermal discharges**, placing pressure on evaporative and once-through systems and favoring **low-water liquid cooling**.
- Mandatory reporting & transparency:** EU Energy Efficiency Directive and U.S. federal Data Center Optimization Initiative frameworks require disclosure of **PUE, WUE, and GHG emissions**, creating compliance and reputational challenges for **water-intensive or inefficient systems**.
- Safety, environmental, and resiliency standards:** NFPA 75/76, ISO 14001, and ASHRAE TC 9.9 now extend compliance into **continuous monitoring of fire safety, environmental impacts, and thermal resilience**, especially important for liquid-cooled facilities.
- Circular-economy & carbon policies:** EU waste-heat rules and California's CALGreen embodied-carbon limits incentivize **heat reuse** and penalize **material-intensive tower systems**, shifting preference toward **liquid cooling with higher-grade heat output**.
- Digital oversight & AI-driven compliance:** Emerging policies (EU AI Act, CA AB-222) and DOE guidance increasingly expect **real-time metering, analytics, and AI/RL optimization** as part of regulatory compliance and system verification.
- Overall implication:** Cooling decisions now directly influence **permitting feasibility, environmental compliance, lifecycle carbon, and long-term regulatory risk**, making **liquid cooling and closed-loop systems** better aligned with future policy trajectories.