PUE Calculator — Technical Documentation

Algorithm Reference & Engineering Manual

Complete Manual: Calculation Methodology, Cooling Models, UPS Efficiency Curves, Climate Data & Validation

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CORE 1. Architecture Overview

The PUE Calculator is a single-page, client-side web application that computes Power Usage Effectiveness for data center facilities. It operates entirely in the browser with zero server dependencies, making it suitable for offline use and air-gapped environments. The calculator uses Chart.js for real-time visualization and supports a two-tier access model (Free and PRO).

Tier	Access	Inputs	Outputs
Free	Open	4 input sections (IT Infrastructure, Cooling, Power Distribution, Facility Loads)	PUE, DCiE, total power, annual energy/cost, cooling load, UPS loss, rating, industry comparison, recommendations, 2 charts
PRO	Authenticated	All Free inputs + 2 PRO sections (Advanced Parameters, Seasonal & Growth)	All Free outputs + CO2/year, free cooling hours, percentile ranking, Green Grid level, cost per 0.1 PUE improvement, what-if scenarios, ASHRAE compliance, monthly PUE chart, waterfall chart, PDF export

1.1 Technology Stack

Component	Technology	Purpose

Layout & UI	HTML5, CSS3 (custom properties, grid, backdrop-filter)	Glassmorphism design, responsive from mobile to desktop
Calculation Engine	Vanilla JavaScript (no framework)	All PUE math, interpolation, scenario estimation
Charting	Chart.js (CDN)	Doughnut, bar, line, and waterfall charts
Auth / Session	localStorage (`rz_premium_session` , `dcmoc-auth`)	PRO tier gating, 30-day session persistence
Tooltip System	Custom JS + CSS (`.tooltip-trigger`)	Contextual engineering help on every input
PDF Export	`window.open()` with inline HTML	Print-optimized report generation (PRO only)

1.2 Calculation Flow

```
// Triggered on every input change via oninput/onchange handlers
calculate() {
    // 1. Read all input values from DOM
    // 2. Auto-calculate rack count = ceil(IT_Load / rackDensity)
    // 3. Compute cooling overhead (COP + containment + climate + PRO adjustments)
    // 4. Compute UPS losses (interpolated efficiency curve + redundancy)
    // 5. Compute transformer + PDU losses
    // 6. Compute facility loads (lighting + security + fire)
    // 7. PUE = (IT + cooling + UPS + TX + PDU + facility) / IT
    // 8. Update all UI: PUE display, metrics, rating, comparison, recommendations
    // 9. Render charts (always: doughnut + bar; PRO: monthly line + waterfall)
    // 10. If PRO: render CO2, free cooling, percentile, what-if, ASHRAE
}
```

> **Real-time Computation:** Every input change triggers a full recalculation. There is no "Calculate" button. The architecture ensures sub-10ms computation time on modern browsers, giving users immediate feedback as they adjust parameters. This enables rapid design iteration and what-if analysis.

CORE 2. Input Parameters

2.1 Section 1: IT Infrastructure

Parameter	Type	Options / Range	Default
IT Load (kW)	Number + Presets	50 – 100,000 kW. Presets: 100kW Edge, 500kW Enterprise, 1MW Colo, 5MW Hyperscale, 10MW+ Mega	1,000 kW
Rack Density	Select	Standard (5 kW/rack), Medium (8 kW/rack), High Density (15 kW/rack), AI/HPC (30 kW/rack)	Medium (8 kW)
Rack Count	Number (auto-calculated)	1 – 10,000. Auto: `ceil(IT_Load / rackDensity)`	125 (auto)

2.2 Section 2: Cooling System

Parameter	Type	Options	Default
Cooling Type	Select	CRAC (COP ~2.8), CRAH (COP ~4.0), In-Row (COP ~5.0), RDHX (COP ~8.0), DLC (COP ~15), Immersion (COP ~25)	CRAH
Containment Strategy	Select	None, Hot-Aisle, Cold-Aisle, Chimney Cabinet	Cold-Aisle
Climate Zone	Select	Tropical Humid, Tropical Dry, Subtropical, Temperate, Continental, Cold	Subtropical

2.3 Section 3: Power Distribution

Parameter	Type	Options	Default
UPS Type	Select	Double-Conversion (Online), Line-Interactive, Rotary / DRUPS, Flywheel Hybrid	Double-Conversion
UPS Load Factor	Range slider	25% – 100% (step 5%)	50%
Redundancy	Select	N (no redundancy), N+1, 2N, 2N+1	N+1

2.4 Section 4: Facility Loads

Parameter	Type	Options	Default
Lighting	Select	Minimal (3 W/m²) — LED + sensors, Standard (8 W/m²), High (12 W/m²)	Standard (8 W/m²)
Security Systems	Select	Basic (0.2 kW/rack) — CCTV only, Standard (0.5 kW/rack), Enhanced (1.0 kW/rack) — Full biometric	Standard (0.5 kW/rack)
Fire Suppression	Select	FM-200/Novec (0.1 kW/rack), VESDA + FM-200 (0.3 kW/rack), Water Mist (0.5 kW/rack)	FM-200/Novec (0.1 kW/rack)

2.5 Section 5: PRO Advanced Parameters

Parameter	Type	Options / Range	Default
Utilization	Range slider	10% – 100% (step 5%)	70%
Economizer Mode	Select	None, Air-Side (-15% cooling), Water-Side (-25% cooling)	None
ASHRAE Supply Air Temp	Range slider	18°C – 27°C (step 0.5°C)	20°C
Transformer Loss	Range slider	0.5% – 3.0% (step 0.1%)	1.5%
PDU Type	Select	Basic (98%), Metered (98.5%), Monitored (99%), Switched (99%)	Metered (98.5%)

2.6 Section 6: PRO Seasonal & Growth

Parameter	Type	Options / Range	Default
IT Load Growth/Year	Range slider	0% – 30% (step 1%)	10%
Green Grid Measurement Level	Select	L1 — Annual (utility meter), L2 — Monthly (sub-metering), L3 — Continuous (real-time)	L1
ASHRAE Class	Select	A1 (15-32°C), A2 (10-35°C), A3 (5-40°C), A4 (5-45°C)	A1
Energy Cost ($/kWh)	Number	$0.01 – $1.00	$0.10

CORE

3. PUE Calculation Algorithm

The calculator implements the Green Grid's standard PUE formula with a component-level breakdown that decomposes total facility power into six categories. This enables engineers to identify exactly where overhead originates and target specific subsystems for optimization.

```
Core PUE Formula:
PUE = Total Facility Power / IT Equipment Power

PUE = (IT_Load + Cooling_kW + UPS_Loss_kW + Transformer_kW + PDU_Loss_kW + Facility_kW) / IT_Load
```

3.1 Cooling Overhead Calculation

Cooling is the single largest PUE contributor in most data centers (typically 30-50% of total overhead). The model uses a base cooling overhead factor per technology, modified by containment effectiveness and climate zone.

3.1.1 Base Cooling Overhead Factors

These represent the fraction of IT load required for cooling at the reference climate (subtropical, 1.0x multiplier):

Cooling Type	Overhead Factor	Equivalent COP	Technology Description
CRAC	0.45	~2.2	Computer Room Air Conditioner — DX compressor-based, room-level
CRAH	0.38	~2.6	Computer Room Air Handler — chilled water, room-level
In-Row	0.32	~3.1	Row-level cooling, closer coupling to heat source
RDHX	0.22	~4.5	Rear-Door Heat Exchanger — rack-level passive/active
DLC	0.12	~8.3	Direct Liquid Cooling — cold plates on CPU/GPU
Immersion	0.08	~12.5	Full or partial immersion in dielectric fluid

Engineering Note: The overhead factors in this model represent the total cooling power fraction (including chillers, pumps, fans, and cooling towers) relative to IT load. They are not direct COP inversions because COP measures only the chiller efficiency, while overhead includes the full cooling chain. For example, a CRAH system with a chiller COP of 4.0 still has ~38% overhead due to pump energy, fan energy, and cooling tower parasitic loads.

3.1.2 Containment Reduction Factors

Airflow containment prevents mixing of hot exhaust and cold supply air, directly reducing the cooling energy required:

Containment	Reduction Factor	Effective Saving	Description
None	0.00	0%	Open data hall, no physical separation of air streams
Hot-Aisle	0.10	~10%	Enclosed hot aisle with ceiling return to CRAH/plenum
Cold-Aisle	0.12	~12%	Enclosed cold aisle with raised floor or overhead supply
Chimney Cabinet	0.15	~15%	Rack-integrated chimney exhausting directly to return plenum

3.1.3 Climate Zone Multipliers

Climate Zone	Multiplier	Free Cooling Hours/yr	Example Locations
Tropical Humid	1.15	0	Jakarta, Singapore, Kuala Lumpur
Tropical Dry	1.08	500	Dubai, Phoenix, Riyadh
Subtropical	1.00	1,500	Hong Kong, Sydney, Miami
Temperate	0.92	3,000	London, San Francisco, Tokyo
Continental	0.85	4,500	Chicago, Frankfurt, Beijing
Cold	0.78	6,000	Stockholm, Helsinki, Reykjavik

3.1.4 Complete Cooling Formula

```
Step 1 — Base cooling:
Cooling_kW = IT_Load × (coolingOverhead[type] × climateMultiplier[zone] -
containmentReduction[strategy])

Step 2 — Economizer adjustment (PRO):
if airside: Cooling_kW ×= 0.85  // 15% reduction
if waterside: Cooling_kW ×= 0.75  // 25% reduction

Step 3 — Supply temperature adjustment (PRO):
tempDelta = supplyTemp - 20
Cooling_kW ×= (1 - tempDelta × 0.03)  // 3% per degree above 20°C

Step 4 — Floor:
Cooling_kW = max(Cooling_kW, IT_Load × 0.02)  // minimum 2% of IT load
```

3.2 Calculation Example

```
// Example: 1MW facility, CRAH cooling, cold-aisle containment, subtropical climate
IT_Load = 1000 kW
coolingOverhead[crah] = 0.38
climateMult[subtropical] = 1.00
containmentReduction[cold] = 0.12

// Cooling
Cooling = 1000 × (0.38 × 1.00 - 0.12) = 1000 × 0.26 = 260 kW

// UPS (double-conversion @ 50% load, N+1 redundancy)
UPS_Eff = interpolate('double', 50) = 0.92
UPS_Loss = 1000 × (1/0.92 - 1) × 1.10 = 1000 × 0.0870 × 1.10 = 95.6 kW

// Transformer + PDU
TX_Loss = 1000 × 0.015 = 15.0 kW
PDU_Loss = 1000 × (1 - 0.985) = 15.0 kW

// Facility loads (125 racks, 3 m²/rack = 375 m²)
Lighting = 8 W/m² × 375 m² / 1000 = 3.0 kW
Security = 0.5 kW/rack × 125 = 62.5 kW
Fire = 0.1 kW/rack × 125 = 12.5 kW
Facility_Total = 78.0 kW

// RESULT
```

```
Total = 1000 + 260 + 95.6 + 15 + 15 + 78 = 1463.6 kW
PUE = 1463.6 / 1000 = 1.46
DCiE = 1 / 1.46 × 100 = 68.4%
```

Validation Check: A PUE of 1.46 for a CRAH-cooled, cold-aisle contained, N+1 facility in a subtropical climate is consistent with Uptime Institute survey data showing enterprise average PUE of 1.55 (2023) and best-in-class enterprise at 1.3-1.4. The containment and modern CRAH bring it below average, which is expected.

CORE 4. UPS Efficiency Model

UPS systems are the second-largest PUE contributor in well-cooled facilities, adding 3-12% overhead depending on topology and loading. The calculator models efficiency as a function of UPS type and load factor using discrete data points with linear interpolation between them.

4.1 Efficiency Curves by UPS Type

UPS Type	25% Load	50% Load	75% Load	100% Load	Topology
Double-Conversion	88.0%	92.0%	94.0%	95.0%	AC→DC→AC, always online, highest protection
Line-Interactive	93.0%	96.0%	97.0%	97.5%	Auto-transformer voltage regulation, switches to inverter on failure
Rotary / DRUPS	90.0%	94.0%	96.0%	97.0%	Diesel rotary, kinetic energy storage, integrated generator
Flywheel Hybrid	95.0%	97.0%	98.0%	98.5%	Flywheel kinetic storage + VFD, minimal conversion losses

4.2 Interpolation Algorithm

For load factors between data points, the calculator uses piecewise linear interpolation:

```
function interpolateUPS(type, loadPct) {
    const curve = upsEfficiency[type];
    const points = [25, 50, 75, 100];

    if (loadPct <= 25) return curve[25];     // clamp at minimum
    if (loadPct >= 100) return curve[100];   // clamp at maximum

    // Find the bracket and interpolate linearly
    for (let i = 0; i < points.length - 1; i++) {
        if (loadPct >= points[i] && loadPct <= points[i+1]) {
            const ratio = (loadPct - points[i]) / (points[i+1] - points[i]);
            return curve[points[i]] + ratio × (curve[points[i+1]] - curve[points[i]]);
        }
    }
    return curve[50]; // fallback
}
```

Interpolation Example

```
Double-Conversion at 65% load:
Points: 50% → 0.92, 75% → 0.94
ratio = (65 - 50) / (75 - 50) = 15 / 25 = 0.60
efficiency = 0.92 + 0.60 × (0.94 - 0.92) = 0.92 + 0.012 = 0.932 (93.2%)
```

4.3 UPS Loss Calculation

UPS Power Loss Formula:

```
UPS_Loss_kW = IT_Load × (1 / UPS_Efficiency - 1) × redundancyMultiplier
```

Redundancy Overhead Multipliers

Configuration	Multiplier	Description	Effective Overhead Example (at 92% eff)
N	1.00	No spare modules — all capacity in active use	8.7% of IT load
N+1	1.10	One spare module running at partial load	9.6% of IT load
2N	1.25	Fully mirrored — each path at ~50% capacity	10.9% of IT load
2N+1	1.35	Mirrored plus spare — highest reliability	11.7% of IT load

Why 2N has higher loss than N: In a 2N configuration, each UPS path runs at approximately half load. Since UPS efficiency drops at lower load factors, the aggregate loss is higher than a single path at full load. For example, two double-conversion UPS at 40% load each (89.6% efficiency) produce more total loss than one UPS at 80% load (93.2% efficiency). The multiplier accounts for this non-linear effect.

4.4 UPS Loss Examples by Configuration

UPS Type	Load Factor	Efficiency	Redundancy	Loss (per 1000 kW IT)
Double-Conversion	50%	92.0%	N+1 (1.10)	95.7 kW
Double-Conversion	75%	94.0%	2N (1.25)	79.8 kW
Line-Interactive	50%	96.0%	N+1 (1.10)	45.8 kW
Rotary / DRUPS	75%	96.0%	N+1 (1.10)	45.8 kW
Flywheel Hybrid	50%	97.0%	N+1 (1.10)	34.0 kW
Flywheel Hybrid	75%	98.0%	N (1.00)	20.4 kW

CORE 5. Facility Loads Model

Facility loads represent all non-IT, non-cooling, non-UPS electrical consumption in the data center. While typically only 2-8% of total power, these loads are often overlooked in preliminary PUE estimates and can make the difference between achieving and missing a PUE target.

5.1 Floor Area Calculation

```
Floor Area:
floorArea_m2 = rackCount × 3.0 m²/rack

// 3.0 m²/rack accounts for hot/cold aisle spacing, end-of-row clearance,
// and cable pathways. Industry typical range: 2.5 - 4.0 m²/rack.
```

5.2 Lighting Power

Option	W/m²	Technology	Example (375 m², 125 racks)
Minimal	3	LED with occupancy sensors, dimmable controls	1.13 kW
Standard	8	Standard LED or fluorescent, always-on corridors	3.00 kW
High	12	High-bay fluorescent, legacy lighting, no controls	4.50 kW

```
Lighting_kW = lightingWperM2 × floorArea_m2 / 1000
```

5.3 Security Systems Power

Level	kW/rack	Components	Example (125 racks)
Basic	0.2	CCTV cameras, basic access control at perimeter	25.0 kW
Standard	0.5	CCTV + card access per row + monitoring station	62.5 kW
Enhanced	1.0	Full biometric, mantrap, video analytics, rack-level access	125.0 kW

```
Security_kW = securityKwPerRack × rackCount
```

5.4 Fire Suppression Systems Power

System	kW/rack	Components	Example (125 racks)
FM-200 / Novec	0.1	Detection panel, solenoid valves, VESDA sampling (standby mode)	12.5 kW
VESDA + FM-200	0.3	Active VESDA aspirating detection + suppression, enhanced monitoring	37.5 kW
Water Mist	0.5	High-pressure pump, zone valves, mist nozzles, active pressurization	62.5 kW

```
Fire_kW = fireKwPerRack × rackCount
```

5.5 Total Facility Load

```
Facility_kW = Lighting_kW + Security_kW + Fire_kW
```

PUE Impact: For a typical 1 MW, 125-rack facility with standard settings, facility loads total approximately 78 kW (3 + 62.5 + 12.5), adding 0.078 to PUE. While seemingly small, this is larger than the transformer and PDU losses combined. Upgrading to LED lighting with occupancy sensors and right-sizing security can recover 0.02-0.04 PUE points.

PRO 6. Climate Data & Seasonal Model

The PRO seasonal model adds time-varying PUE analysis by incorporating monthly average ambient temperatures for each climate zone. This enables identification of seasonal cooling peaks and estimation of free cooling potential.

6.1 Monthly Average Temperature Data (°C)

Zone	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Tropical Humid	28	28	29	29	30	30	29	29	29	29	28	28
Tropical Dry	18	20	24	28	33	38	40	39	36	30	24	19
Subtropical	17	17	19	22	25	28	29	29	27	24	21	18
Temperate	5	6	9	12	15	18	20	20	17	13	9	6
Continental	-2	0	5	11	17	22	24	23	18	11	5	0
Cold	-5	-4	0	5	11	16	19	18	13	7	2	-3

6.2 Seasonal PUE Variation Formula

```
Monthly PUE Calculation:
tempFactor[month] = 1 + (monthlyTemp[month] - 20) × 0.008
monthlyPUE[month] = max(1.02, basePUE × tempFactor[month])
```

The 0.008 coefficient means each degree above 20°C increases the base PUE by 0.8%, and each degree below 20°C decreases it by 0.8%. This models the relationship between ambient temperature and cooling energy consumption.

```
// Example: Base PUE 1.46 in Continental climate
// January:  temp = -2°C, factor = 1 + (-2 - 20) × 0.008 = 0.824
//           PUE = 1.46 × 0.824 = 1.20 (cold ambient = free cooling)
// July:     temp = 24°C, factor = 1 + (24 - 20) × 0.008 = 1.032
//           PUE = 1.46 × 1.032 = 1.51 (summer peak)
// Spread:   0.31 PUE variation = significant seasonal impact
```

6.3 Free Cooling Hours

Free cooling hours represent the annual hours when ambient conditions allow the economizer to provide partial or full cooling without mechanical refrigeration (typically when outside air temperature is below 18-22°C):

Climate Zone	Free Cooling Hours/Year	% of Year	Implication
Tropical Humid	0	0%	No free cooling opportunity — mechanical cooling year-round
Tropical Dry	500	5.7%	Brief winter windows — limited economizer benefit
Subtropical	1,500	17.1%	Moderate economizer potential in winter months
Temperate	3,000	34.2%	Strong free cooling — economizer investment pays back quickly
Continental	4,500	51.4%	Majority of year — air-side economizer strongly recommended

Cold	6,000	68.5%	Most of year — some operators run free cooling exclusively

Design Implication: For continental and cold climates, the capital cost of an economizer system (typically $50-150/kW) can pay for itself in 12-24 months through energy savings of 15-25%. In tropical humid climates, economizers provide no benefit and should not be specified.

CORE 7. Industry Comparison & Rating

7.1 PUE Rating Bands

The calculator assigns a letter grade based on the computed PUE, aligned with industry best practices and Uptime Institute survey distributions:

Rating	PUE Range	Color Code	Description	Typical Facility Type
A+	≤ 1.20	Green	Excellent — world-class efficiency	Hyperscale, purpose-built with DLC/immersion
A	1.21 – 1.40	Cyan	Very Good — optimized facility	Modern colocation, well-designed enterprise
B	1.41 – 1.60	Blue	Good — above average	Enterprise with containment, reasonable cooling
C	1.61 – 1.80	Amber	Average — room for improvement	Older enterprise, minimal optimization
D	1.81 – 2.00	Orange	Below Average — significant waste	Legacy facility, no containment, poor cooling
F	> 2.00	Red	Poor — urgent remediation needed	Server closet, unmanaged, no optimization

7.2 Industry Benchmarks

Benchmark Category	PUE Value	Source
Hyperscale Leader (Google/Meta/Microsoft)	1.10	Google Environmental Report 2024
Colocation Best-in-Class	1.20	Equinix Sustainability Report 2024
Enterprise Target	1.40	Uptime Institute Survey 2023
Industry Average (Global)	1.58	Uptime Institute Global Survey 2023

7.3 Comparison Visualization

The results panel renders horizontal bar charts comparing the user's computed PUE against all four benchmarks, with the user's facility highlighted in cyan. This provides immediate visual context for the calculated value.

```
// Benchmark data used for comparison bars
benchmarks = [
    { label: 'Your Facility',      value: calculatedPUE, color: '#06b6d4' },
    { label: 'Industry Average',    value: 1.58,           color: '#94a3b8' },
    { label: 'Enterprise Target',   value: 1.40,           color: '#3b82f6' },
    { label: 'Colo Best-in-Class',  value: 1.20,           color: '#10b981' },
    { label: 'Hyperscale Leader',   value: 1.10,           color: '#22c55e' },
];
```

7.4 Percentile Ranking (PRO)

PUE Range	Percentile	Interpretation

≤ 1.10	p10 (Top 10%)	Among the most efficient facilities globally
1.11 – 1.20	p25 (Top 25%)	Excellent — better than 75% of facilities
1.21 – 1.35	p50 (Median)	Average — at the midpoint of the industry
1.36 – 1.55	p75	Below median — improvement opportunities exist
1.56 – 1.80	p90	Bottom quartile — significant efficiency gap
> 1.80	>p90	Among the least efficient — urgent action needed

PRO 8. PRO Analytics

The PRO tier unlocks advanced analytics that go beyond the core PUE number to provide actionable engineering and financial insights. These metrics are computed in the `renderProOutputs()` function.

8.1 Carbon Emissions (CO2/Year)

```
Annual CO2 Calculation:
annualEnergy_kWh = totalPower_kW × 8,760 hours/year
CO2_tonnes = (annualEnergy_kWh × gridEmissionFactor) / 1,000

// Default gridEmissionFactor: 0.5 kg CO2/kWh (global average)
```

Grid Emission Factor	Region Example	CO2/year (1 MW, PUE 1.5)
0.23 tCO2/MWh	Europe (nuclear/renewable heavy grid)	3,022 tonnes
0.39 tCO2/MWh	USA (mixed grid)	5,124 tonnes
0.50 tCO2/MWh	Global average (calculator default)	6,570 tonnes
0.72 tCO2/MWh	Southeast Asia (coal-heavy grid)	9,461 tonnes

8.2 Data Center Infrastructure Efficiency (DCiE)

```
DCiE = (1 / PUE) × 100%

// DCiE is the reciprocal of PUE expressed as a percentage.
// PUE 1.50 = DCiE 66.7% (meaning 66.7% of total power reaches IT)
// PUE 1.20 = DCiE 83.3% (ideal modern facility)
```

8.3 Cost per 0.1 PUE Improvement

This metric quantifies the annual energy cost savings from incremental PUE reduction, giving engineers a financial justification for efficiency investments:

```
Savings from PUE reduction of Δ:
newPUE = max(1.02, currentPUE - Δ)
newTotalPower = IT_Load × newPUE
newAnnualCost = newTotalPower × 8,760 × energyCostPerKWh
annualSavings = currentAnnualCost - newAnnualCost
```

```
// Example: 1 MW facility, PUE 1.50, energy cost $0.10/kWh
// Current annual energy cost: 1000 × 1.50 × 8760 × $0.10 = $1,314,000/yr
// At PUE 1.40 (-0.10):       1000 × 1.40 × 8760 × $0.10 = $1,226,400/yr
// Savings: $87,600/yr
//
// At PUE 1.30 (-0.20):       1000 × 1.30 × 8760 × $0.10 = $1,138,800/yr
// Savings: $175,200/yr
//
```

```
// At PUE 1.20 (-0.30):       1000 × 1.20 × 8760 × $0.10 = $1,051,200/yr
// Savings: $262,800/yr
```

8.4 Green Grid Measurement Levels

Level	Measurement Method	Accuracy	Recommended For
L1	Annual total from utility meter	±10-15%	Small/edge sites, initial benchmarking
L2	Monthly sub-metering (UPS, cooling, PDU)	±5-10%	Enterprise, colocation (most common)
L3	Continuous real-time (BMS/DCIM integration)	±1-3%	Hyperscale, Tier III/IV with DCIM

> **Important:** Green Grid L1 measurement (annual utility-level) can mask significant seasonal and operational PUE variation. A facility that measures PUE 1.50 at L1 may actually range from 1.30 (winter) to 1.70 (summer peak) when measured at L2/L3. The PRO monthly PUE chart reveals this hidden variation.

8.5 What-If Scenario Analysis

The calculator generates up to three what-if scenarios based on the current configuration, showing the PUE impact of specific upgrades:

```
// What-If Scenario Generation Logic
scenarios = [];

if (coolingType !== 'dlc') {
    // Show impact of switching to Direct Liquid Cooling
    dlcPue = estimatePue('dlc', currentContainment, currentZone, ...);
    scenarios.push({ label: 'Switch to DLC', pue: dlcPue });
}

if (containment === 'none') {
    // Show impact of adding cold-aisle containment
    coldPue = estimatePue(currentCooling, 'cold', currentZone, ...);
    scenarios.push({ label: 'Add Cold-Aisle', pue: coldPue });
}

if (econMode === 'none') {
    // Show impact of air-side economizer
    econPue = estimatePue(currentCooling, currentContainment, currentZone, ..., 'airside');
    scenarios.push({ label: 'Add Air Economizer', pue: econPue });
}
```

8.6 ASHRAE TC 9.9 Compliance Check

ASHRAE Class	Dry-Bulb Range (°C)	Humidity Range (% RH)	Typical Equipment
A1	15 – 32	20 – 80%	Enterprise servers, storage (most restrictive)
A2	10 – 35	20 – 80%	Volume servers, IT networking equipment
A3	5 – 40	8 – 85%	IT equipment designed for broad conditions
A4	5 – 45	8 – 90%	Edge/ruggedized, designed for harsh environments

```
Compliance Check:
isCompliant = (supplyTemp ≥ classRange.min) AND (supplyTemp ≤ classRange.max)

// A1 at 27°C: 27 ≥ 15 AND 27 ≤ 32 → COMPLIANT
// A1 at 34°C: 34 ≥ 15 AND 34 ≤ 32 → NON-COMPLIANT (exceeds max)
```

Design Trade-off: Raising supply air temperature from 20°C to 27°C saves approximately 21% in cooling energy (7 degrees × 3%/degree), translating to a PUE reduction of 0.06-0.10 for typical CRAH-cooled facilities. However, this requires server inlet temperature monitoring, robust airflow management, and confirmation that all IT equipment is rated for A1 or higher class. Do not raise supply temperature without verifying ASHRAE class compliance for all installed hardware.

CORE 9. Chart.js Visualizations

The calculator renders four charts using Chart.js, two available to all users and two gated behind PRO. All charts update in real-time as inputs change.

9.1 Power Breakdown Doughnut (Free)

Segment	Data Source	Color
IT Load	User input (kW)	#06b6d4 (Cyan)
Cooling	Calculated cooling overhead (kW)	#3b82f6 (Blue)
UPS Loss	Calculated UPS loss (kW)	#f59e0b (Amber)
Transformer	IT_Load × txLoss% (kW)	#8b5cf6 (Purple)
PDU Loss	IT_Load × (1 - pduEfficiency) (kW)	#f97316 (Orange)
Facility	Lighting + Security + Fire (kW)	#10b981 (Green)

```
// Doughnut chart configuration
new Chart(canvas, {
    type: 'doughnut',
    data: {
        labels: ['IT Load', 'Cooling', 'UPS Loss', 'Transformer', 'PDU Loss', 'Facility'],
        datasets: [{ data: [itLoad, cooling, ups, tx, pdu, facility], backgroundColor: colors }]
    },
    options: { cutout: '60%', plugins: { legend: { position: 'right' } } }
});
```

9.2 PUE Comparison Bar Chart (Free)

Vertical bar chart comparing the user's PUE against four industry benchmarks. The user's bar is highlighted in cyan while benchmarks use progressively greener colors.

Bar	Value	Color
Your PUE	Calculated	#06b6d4
Industry Avg	1.58	#94a3b8
Enterprise	1.40	#3b82f6
Colo	1.20	#10b981
Hyperscale	1.10	#22c55e

9.3 Monthly PUE Variation Line Chart (PRO)

Displays 12 monthly PUE values based on the selected climate zone's temperature profile. The fill area under the line visually represents the annual PUE variation envelope.

```
Monthly Data Generation:
for each month [Jan..Dec]:
  tempFactor = 1 + (monthlyTemp[month] - 20) × 0.008
  monthlyPUE = max(1.02, basePUE × tempFactor)
```

9.4 PUE Waterfall Chart (PRO)

Stacked bar chart showing how each power component builds up from the IT baseline (1.0) to the final PUE value. This visualization makes it immediately clear which subsystem contributes most to overhead.

```
// Waterfall data construction
waterfallData = [
    { label: 'IT (Base)',    value: 1.0 },
    { label: '+ Cooling',    value: cooling_kW / itLoad },  // e.g., 0.26
    { label: '+ UPS',        value: ups_kW / itLoad },      // e.g., 0.096
    { label: '+ Transformer', value: tx_kW / itLoad },       // e.g., 0.015
    { label: '+ PDU',        value: pdu_kW / itLoad },      // e.g., 0.015
    { label: '+ Facility',   value: facility_kW / itLoad }, // e.g., 0.078
];
// Cumulative = [1.0, 1.26, 1.356, 1.371, 1.386, 1.464]
// Final bar top = PUE (1.464)
```

Chart Implementation Note: The waterfall effect is achieved using a stacked bar chart with two datasets: a transparent "base" dataset that provides the floating offset, and a colored "addition" dataset that renders the visible incremental bar. Each bar is labeled by subsystem and colored to match the doughnut chart segments.

PRO 10. PDF Export & Premium System

10.1 Authentication System

The PRO tier is gated by a client-side authentication system using `localStorage`. The calculator checks two possible session sources at load time:

```
// Session check on page load (IIFE)
(function checkPremiumSession() {
    // Check 1: rz_premium_session (calculator-specific login)
    const session = localStorage.getItem('rz_premium_session');
    if (session) {
        const data = JSON.parse(session);
        if (data.expires > Date.now()) {
            isPremiumUser = true;
            activatePremiumUI();
            return;
        }
    }

    // Check 2: dcmoc-auth (shared session with DC MOC app)
    const dcmocAuth = localStorage.getItem('dcmoc-auth');
    if (dcmocAuth && JSON.parse(dcmocAuth).state?.user) {
        isPremiumUser = true;
        activatePremiumUI();
    }
})();
```

10.2 Session Structure

Storage Key	Format	Fields	Expiry
`rz_premium_session`	JSON	email, tier ("pro"), expires (ISO 8601)	30 days from login
`dcmoc-auth`	JSON (Zustand persist)	state.user (object), state.role	Per DC MOC session

10.3 Valid Credentials

Email	Password	Tier	Access
demo@resistancezero.com	demo2026	PRO	All PRO features, PDF export, PRO charts

> **Cross-Application SSO:** Users who are logged into the DC MOC application (via Zustand `dcmoc-auth`) automatically receive PRO access in the PUE Calculator without needing to log in separately. This provides a seamless experience across the ResistanceZero tool suite.

10.4 PRO Feature Gating

PRO sections use a CSS-based locking mechanism with a JavaScript toggle:

```
// HTML structure for a PRO section
<div class="input-section pro-section locked">
    <div class="pro-overlay">
        <!-- Lock icon, title, "Unlock PRO" button -->
```

```
    </div>
    <!-- Actual PRO content (blurred when locked) -->
</div>

// CSS gating
.pro-section.locked > *:not(.pro-overlay) {
    filter: blur(6px);
    user-select: none;
    pointer-events: none;
}
.pro-section.locked .pro-overlay { display: flex; }

// Unlock on login
function activatePremiumUI() {
    document.querySelectorAll('.pro-section').forEach(s => s.classList.remove('locked'));
}
```

10.5 PDF Export Structure

The PDF export generates a print-optimized HTML page using `window.open()`. The report includes:

1. **Header:** PUE value and rating as the headline metric
2. **Key Metrics:** DCiE, total power, annual energy, annual cost, cooling load, UPS loss
3. **Configuration Summary:** All input parameter values (IT load, cooling type, containment, UPS type, climate zone, etc.)
4. **Industry Comparison:** PUE relative to industry benchmarks
5. **PRO Analytics:** CO2/year, free cooling hours, percentile, Green Grid level, ASHRAE compliance
6. **Recommendations:** Top 3 actionable PUE improvement suggestions with estimated impact
7. **Footer:** Generation date, calculator version, disclaimer

```
// PDF export flow
function exportPDF() {
    if (!isPremiumUser) { handlePremiumTab(); return; }

    // 1. Collect all current values from DOM
    const pueVal = document.getElementById('pueValue').textContent;
    const ratingVal = document.getElementById('ratingText').textContent;
    // ... (all other metrics)

    // 2. Build inline HTML with print-optimized CSS
    const html = buildPdfHtml(pueVal, ratingVal, ...);

    // 3. Open in new window and trigger print dialog
    const win = window.open('', '_blank');
    win.document.write(html);
    win.document.close();
    win.print();
}
```

10.6 Print CSS Considerations

Element	Print Behavior
Navbar, Hero, Premium Controls, Footer	Hidden (`display: none`)
Calculator Grid	Switched to single-column (`display: block`)
PRO locked sections	Blur removed, interaction restored
Results Panel	Static positioning (not sticky)

Page Size	A4 with 1cm margins
Tooltips, Presets, Login Modal	Hidden

Appendix A: Transformer & PDU Loss Models

These two components are often overlooked but contribute a combined 1.5-5% overhead to PUE.

A.1 Transformer Losses

```
Transformer_kW = IT_Load × transformerLoss%

Default: 1.5% (typical dry-type, 95% loaded)
Range: 0.5% (high-efficiency amorphous core) to 3.0% (legacy oil-filled, lightly loaded)
```

Transformer Type	Typical Loss	Application
Amorphous Core	0.5 – 1.0%	New builds, high-efficiency specification
Dry-Type (modern)	1.0 – 1.5%	Standard for indoor data centers
Dry-Type (legacy)	1.5 – 2.5%	Older facilities, oversized transformers
Oil-Filled	2.0 – 3.0%	Outdoor substations, high-capacity

A.2 PDU Efficiency

PDU Type	Efficiency	Loss per MW IT	Features
Basic	98.0%	20.4 kW	Power distribution only, no monitoring
Metered	98.5%	15.2 kW	Inlet/outlet current monitoring
Monitored	99.0%	10.1 kW	Per-outlet monitoring, network-connected
Switched	99.0%	10.1 kW	Per-outlet switching + monitoring (relay loss)

```
PDU_Loss_kW = IT_Load × (1 - pduEfficiency[type])
```

Appendix B: Recommendations Engine

The calculator generates contextual recommendations based on the current configuration. Each recommendation includes a title, description, and estimated PUE impact range.

B.1 Recommendation Triggers

Condition	Recommendation	Impact Range
containment === "none"	Add Containment — hot or cold aisle containment	-0.10 to -0.15 PUE
cooling in [crac, crah] AND PUE > 1.4	Upgrade Cooling — in-row or RDHX	-0.10 to -0.20 PUE
upsType === "double"	Consider Flywheel UPS — higher partial-load efficiency	-0.02 to -0.05 PUE
PUE > 1.5 AND economizer === "none"	Implement Economizer — air-side or water-side	-0.05 to -0.15 PUE
PUE > 1.3	Raise Supply Air Temp — ASHRAE allows up to 27°C	-0.02 to -0.08 PUE
containment in [hot, cold]	Upgrade to Chimney — best containment effectiveness	-0.03 to -0.05 PUE

The engine selects the top 3 most applicable recommendations. If no recommendations trigger (i.e., PUE ≤ 1.2 with optimal configuration), a congratulatory message is displayed instead.

Appendix C: Validation & Data Sources

C.1 Primary Data Sources

Source	Used For	Year
ASHRAE TC 9.9	Thermal guidelines, A1-A4 classes, supply air temperature ranges	2021
The Green Grid	PUE/DCiE definitions, measurement levels (L1-L3)	2014 / updated 2023
Uptime Institute Annual Survey	Industry average PUE (1.58), percentile distribution	2023
Google Environmental Report	Hyperscale PUE benchmarks (1.10)	2024
Equinix Sustainability Report	Colocation best-in-class PUE (1.20)	2024
ASHRAE Fundamentals	COP ranges by cooling technology, psychrometric data	2021
Schneider Electric WP#113	UPS efficiency curves by topology and load factor	2023
IEA World Energy Outlook	Grid emission factors by region	2024
Eureca Climate Data	Monthly average temperatures by climate zone	2020-2024

C.2 Model Limitations

- Cooling overhead factors represent typical full-chain efficiency; actual values depend on chiller staging, water temperatures, and fan static pressure
- UPS efficiency curves are based on published manufacturer data at unity power factor; actual efficiency may be 1-2% lower with non-linear IT loads
- Climate multipliers use zone-level averages; micro-climate effects (urban heat island, altitude, proximity to water) are not modeled
- The seasonal model uses monthly averages and does not capture diurnal variation or extreme weather events
- Facility load calculations (security, fire) use per-rack factors that assume uniform distribution; actual loads may be concentrated at perimeter or control room
- CO2 calculation uses a single grid emission factor; actual carbon intensity varies hourly based on generation mix
- The calculator does not model part-load cooling efficiency (COP variation with load and ambient temperature)

C.3 Recommended Validation Approach

1. Compare calculated PUE against actual PUE measurements from existing facilities with similar configurations
2. Validate cooling overhead against manufacturer performance data for the specific chiller plant design
3. Cross-reference UPS losses with UPS vendor datasheets at the specific load factor being modeled
4. For seasonal analysis, compare monthly PUE projections against 12-month BMS trend data if available
5. Use Green Grid L2/L3 measurement methods for validation rather than L1 annual averages
6. For financial analysis (cost per 0.1 PUE), validate against actual utility rate schedules including demand charges

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