# Brazil

# EPIC Deploy: Brazil Cooling assessment[1]

POLITECNICO MILANO 1863

Ministero dell'Ambiente e della Sicurezza Energetica

UN environment programme

[1] **Scope and use:** This report provides contextual and screening-level information to support the preparation of applications. It is not a technical design standard, legal opinion, official national inventory or substitute for site-specific due diligence. Applicants remain responsible for validating demand, baseline conditions, equipment sizing, regulatory compliance and expected emission reductions for the proposed project.

# Cooling Demand Taxonomy

Brazil is one of the world's most complex cooling markets. It combines one of the cleanest electricity systems globally with rapidly increasing cooling demand, a large domestic RAC manufacturing base and one of the highest populations exposed to cooling poverty in Latin America. The principal country framework conditions are summarised in Table 1 for quick reference, and each dimension is developed in the sections that follow.

*Table 1 – Brazil: key cooling taxonomy data*

| **Economics and Demographics** | | **Climatic conditions** | |
|---|---|---|---|
| GDP (2024) | approx. USD 2,200 B [1] | National avg. Cooling Degree Days (18°C base) | 2,901 °C·day/yr [2] |
| GDP per capita | approx. USD 10,300 [1] | Range of biome average temperatures | ≈ 16–29 °C [3] |
| GDP growth rate (medium-term) | 3.4%/yr [1] | Additional hot days per year increase by mid/late century | +133 to +327 days (SSP2-4.5) [4] |
| Total population (2024) | approx. 212.6 M [5] | Hot days projected by mid-century | up to 45% of days/yr [4] |
| Population growth rate | 0.5%/yr [5] | Projected warming by 2050s | +1.2 to +2.2 °C [6] |
| Urban population share | approx. 87% [7] | Growth in residential cooling $CO_2$ emissions under +4 °C warming | +190% vs today [8] |
| Urban growth rate | ≈ 0.9%/yr [7] | | |
| Population in favelas / comunidades | 16.4 M (8.1%) [9] | | |
| Growth-driving sectors | Services, agribusiness, industry [1] | | |
| **Energy infrastructure** | | **Regulatory framework** | |
| National electrification rate | 100.0% (rural 97.3%) [10] | MEPS for cooling appliances | In force (IDRS; Res. 1/2022) [11] |
| Total electricity production | 751.3 TWh generated in 2024 [12] | HCFC consumption phase-out target | 2030 [13] |
| Hydropower share of supply | 56.1% [12] | HFC phase-down (Kigali Amendment) | Decreto 11.666/2023 [14] |
| Renewable share of generation | 88.3% [12] | National Cooling Action Plan | Drafting started Mar 2026 [15] |
| Grid reliability | 10.24 h/yr; 4.89 interruptions/yr [16] | NDC emissions reduction target | −59 to −67% by 2035 vs 2005 [17] |
| Residential electricity tariff | Varies by distribution area; verify current B1 tariff in ANEEL database [18] | Import conformity requirement | INMETRO conformity assessment and ENCE labeling, where the product is regulated [19] |
| Grid emission factor | 0.0599 kg$CO_2$eq/kWh [20] | Energy efficiency regulation | Lei 10.295/2001; PBE/PROCEL [19] |

The electricity-generation total and mix are based on IEA 2024 data [12], while the grid emission factor and service-continuity metrics are supported by EPE and ANEEL sources [16][20][21]. Brazil generated 751.3 TWh of electricity in 2024 [12], while final electricity consumption was 650.4 TWh [20]. Sector shares in this report are therefore compared with final electricity consumption. The screening-level grid emission factor used throughout the chapter is 59.9 kg CO2e/MWh (BEN 2025, base year 2024) [20].

# General Overview

## Geography and climate

Brazil extends across almost half of South America and encompasses six terrestrial biomes that differ sharply in temperature, humidity and population density, producing correspondingly different cooling needs. The country's climatic heterogeneity is governed chiefly by latitude and continentality: an equatorial, humid north in Amazônia; a hot, semi-arid interior in the north-east within the Caatinga; an extensive tropical savanna in the Cerrado; and a more temperate, densely populated south and south-east spanning the Mata Atlântica and Pampa. The biome breakdown in Table 2 and the map in Figure 1 provide a reference framework used throughout the assessment.

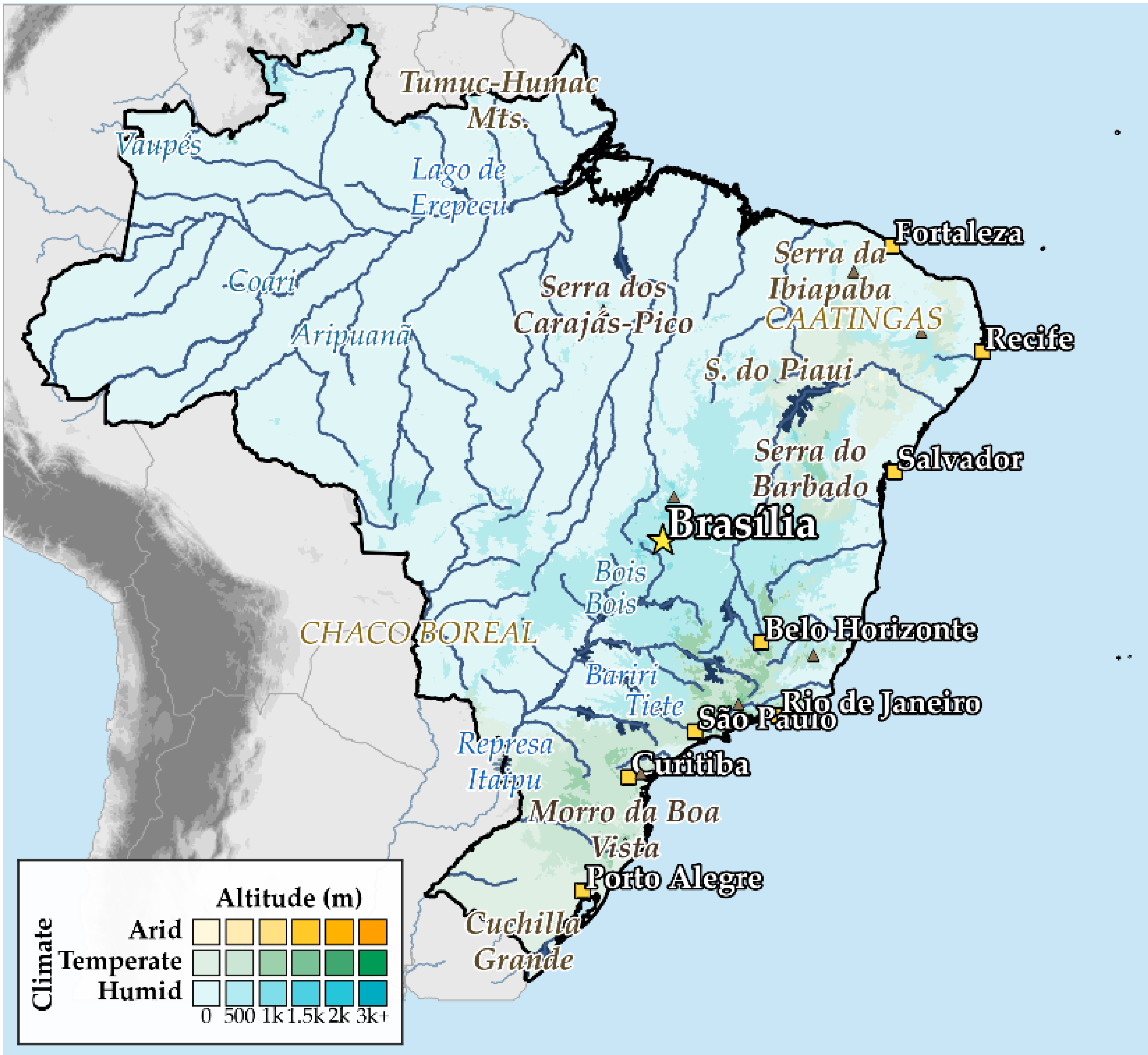


*Figure 1 – Brazil: geography and climate*

*Table 2 – Brazil: climatic zones general data*

| Biome | Area share [22] | Average temperature [3] | Climate | Key cooling relevance |
|---|---|---|---|---|
| Amazônia | 49.5% | ≈ 26–28 °C | Equatorial, hot-humid, high RH | High latent loads; isolated and off-grid systems in the North; humidity-driven discomfort |
| Cerrado | 23.3% | ≈ 22–26 °C | Tropical savanna, marked dry season | High sensible cooling demand; agribusiness and cold-chain heartland |
| Mata Atlântica | 13.0% | ≈ 18–24 °C | Tropical to subtropical | Largest population and cooling market (SP, RJ, MG, South); urban heat islands |
| Caatinga | 10.1% | ≈ 26–29 °C | Semi-arid, highest ambient temperatures | Highest per-capita thermal stress; lower incomes; concentrated vulnerability |
| Pampa | 2.3% | ≈ 16–20 °C | Subtropical, seasonal | Lower cooling demand; heating also relevant |
| Pantanal | 1.8% | ≈ 24–27 °C | Tropical wetland, hot | Sparse population; niche demand |

Climate projections raise cooling requirements across every biome. Under intermediate and high-emissions scenarios, mean temperatures are projected to rise by between 1.2 °C and 2.2 °C by mid-century [6], with larger increases in the continental interior towards the end of the century. The number of hot days rises steeply: projections indicate between 133 and 327 additional hot days per year (TX90p) under SSP2-4.5, and up to 234 to 328 under SSP5-8.5 by 2100, with effects concentrated in the North and North-East and on vulnerable populations [4]. According to a Brazil-specific study of the residential sector space-cooling $CO_2$ emissions could increase by roughly 70% at 1.5 °C of warming and by as much as 190% at 4 °C relative to today [8]. Cooling demand is therefore both large in absolute terms and rising rapidly.

The national average Cooling Degree Days on an 18 °C base, calculated from the World Bank Climate Change Knowledge Portal, is about 2,901 [2]. A visual representation of the spatial distribution of this indicator is provided in Figure 2.

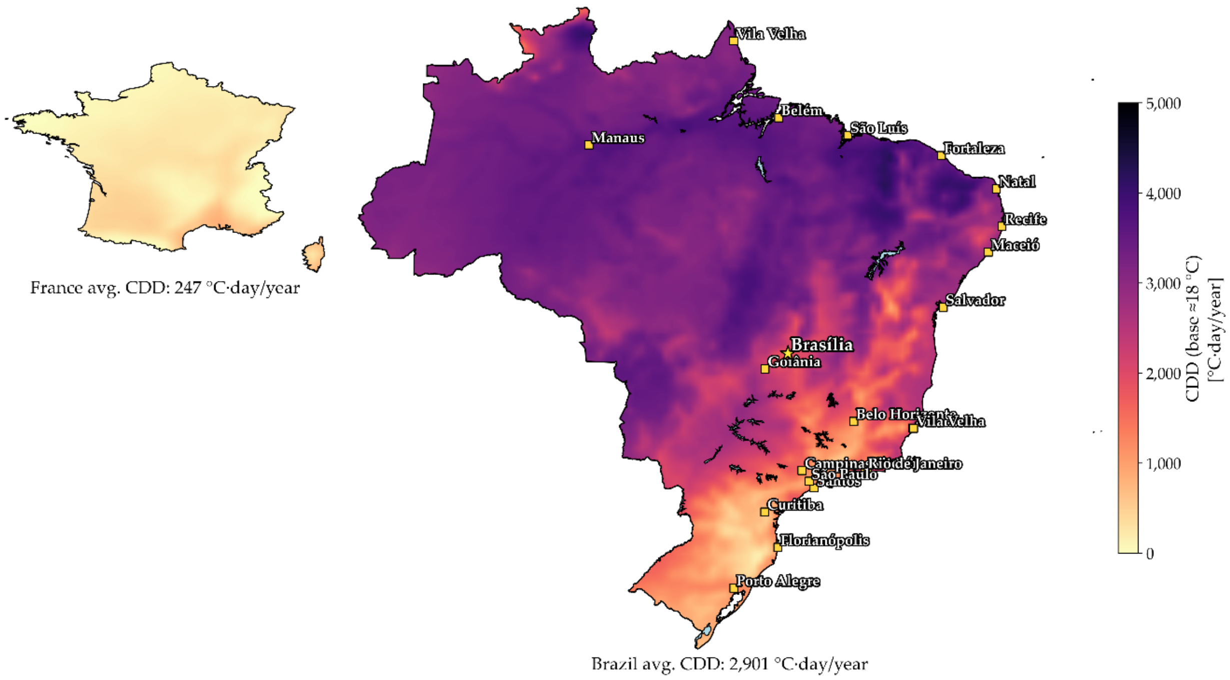


*Figure 2 – Brazil: cooling degree days 18°C spatial distribution*

## Population, Urbanisation and Vulnerability

Brazil is already highly urbanised, with roughly 87% of the population living in cities [7]. The dominant cooling-relevant dynamic is therefore not rapid urban in-migration but the thermal vulnerability of dense, established urban settlement, set against an ageing and slow-growing population whose annual growth is close to 0.5% [5]. Key demographic and vulnerability indicators are reported in Table 3.

*Table 3 – Brazil: general demographic data*

| Indicator | Value |
|---|---|
| Total Population (2024) | 212.6 M [5] |
| Population growth rate | 0.5%/yr [5] |
| Urban population share | approx. 87% [7] |
| Population in favelas / comunidades urbanas | 16,390,815 (8.1%) [9] |
| Number of favelas / comunidades urbanas | 12,348 [9] |
| States with highest favela share | Amazonas 34.7%, Amapá 24.4%, Pará 18.8% [9] |
| Most populous favela | Rocinha, RJ (72,021) [9] |

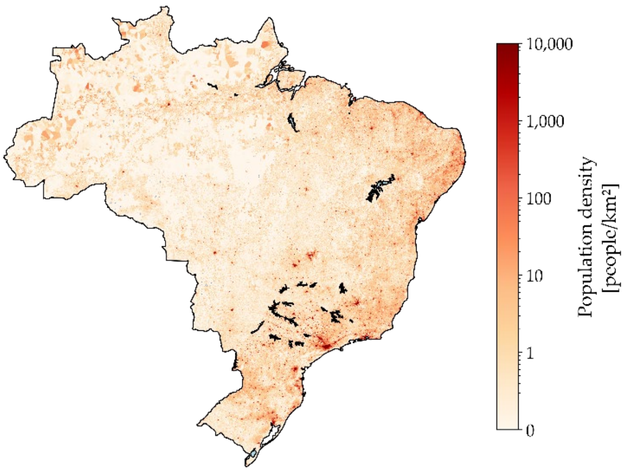


*Figure 3 – Brazil: population density*

Brazil's population is highly concentrated, with most urban areas clustered along the Atlantic coast and in the Southeast, a region that alone accounts for roughly 42% of the population on just 11% of the national territory, while the vast Amazonian interior remains sparsely settled [7].

## Building Stock and Thermal Exposure

In Brazil's dense urban centres the built environment is a primary determinant of heat risk. Favelas and comunidades urbanas, home to 16.4 million people [9], combine lightweight and poorly insulated construction with high density and limited vegetation, which amplifies indoor overheating during heat waves. Urban heat-island intensity in the largest metropolitan areas is material: in the Rio de Janeiro metropolitan region, more than 60% of municipal schools stand in heat-island zones where mean annual temperatures exceed 32 °C [23].

Construction practice compounds the exposure. Much of the lower-cost housing and public building stock relies on fibre-cement or thin concrete roofing with little thermal mass and minimal shading, so internal temperatures track outdoor peaks closely [24]. Passive measures such as reflective coatings, roof insulation, cross-ventilation and shading therefore carry significant potential, particularly in the hot interior and the North-East, where their cost is modest relative to mechanical cooling.

## Economy and Energy Poverty

In Brazil the binding constraints on cooling are affordability and equity rather than an absolute lack of grid access. Near-universal electrification, at close to 100% nationally and 97.3% in rural areas [10], coexists with rising real electricity tariffs and with access gaps that fall on lower-income, informally housed and rural-poor households. SEforALL classifies 34.2 million Brazilians as at high risk from a lack of access to cooling, the largest such population in Latin America and the Caribbean, of whom about 4.3 million are rural poor [25]. Indicators relevant to cooling market potential and to financing are reported in Table 4.

*Table 4 – Brazil: main economic indicators*

| Indicator | Value | Source |
|---|---|---|
| GDP (2024) | approx. USD 2,200 B | [1] |
| GDP per capita | approx. R$ 55,250 | [1] |
| Population at high risk from lack of cooling | 34.2 M | [25] |
| Rural poor in population at high risk from lack of cooling | approx. 4.3 M | [25] |
| AC share of residential electricity (2023) | approx. 17% | [21] |
| Reported fruit-and-vegetable losses | Highly variable by commodity and supply-chain stage | [26][27] |
| Cold-chain logistics market (2026 est.) | approx. USD 5.64 bn (commercial est.) | [28] |

## Electricity system

The Brazilian electricity system is large, overwhelmingly renewable and hydro-dominated, which keeps the indirect, grid-related emissions of cooling comparatively low but exposes cooling demand to hydrological and seasonal risk.

As represented in Figure 4, hydropower supplied about 56.1% of electricity and renewables about 88.3% of the generation mix in 2024, while wind and solar together reached approximately 23.7% [12]. Total generation was 751.3 TWh [12] and final electricity consumption was 650.4 TWh [20]. The grid emission factor was correspondingly low, at 59.9 kg $CO_2e$/MWh [20]. This profile shifts the climate case for efficient cooling toward the management of direct refrigerant emissions and peak demand. Final electricity consumption rose by 5.5% year on year, with the residential segment up 8.0%, a movement attributed in part to more intensive use of fans and air conditioners during heat waves [20][21]. Key indicators are reported in Table 5.

*Table 5 – Brazil: electricity system key indicators*

| Indicator | Value | Source |
|---|---|---|
| National electrification rate | approx.100% (rural 97.3%) | [10] |
| Renewable share of electricity | approx. 88.3% | [12] |
| Hydropower share of supply | 56.1% | [12] |
| Wind + solar share of generation | approx. 23.7% | [12] |
| Grid reliability — DEC, avg. interruption duration (2024) | 10.24 h/yr avg. interruption | [16] |
| Grid reliability — FEC, avg. interruption frequency (2024) | 4.89 interruptions/yr | [16] |
| Residential electricity tariff | Varies by distribution area and tax treatment | [18] |
| Yearly residential electricity consumption growth | +8% | [20] |
| Grid emission factor | 59.9 $kgCO_2eq/MWh$ (2024) | [20] |

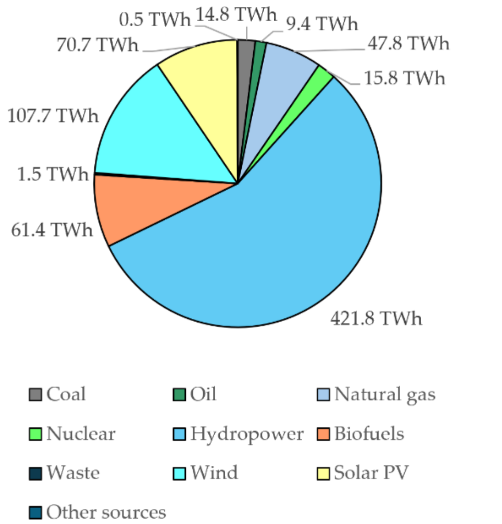


*Figure 4 – Brazil: electricity production share [12]*

## The Manaus Free Trade Zone and the domestic RAC industry

A structural feature of the Brazilian market is that most room air conditioners are manufactured domestically, largely through assembly of semi-knocked-down and completely-knocked-down kits in the Manaus Free Trade Zone (Zona Franca de Manaus) [29]. This shapes the available policy levers. Minimum performance standards and refrigerant transitions act on local production lines and a domestic supply chain rather than on a stream of finished imports. Fiscal incentives are tied to the Free Trade Zone regime rather than to import tariffs alone and the HFC phase-down interacts directly with industrial conversion programmes for compressors and charging lines. The wider refrigeration and air-conditioning industry is economically significant: the industry association forecast turnover of approximately R$ 41 billion for 2024 [30]. Because production capacity already exists onshore, efficiency and refrigerant policy can be implemented through the domestic industrial base, which is treated further in the market-entry section.

# Regulatory Framework

## Key legislation

Brazil has a long-established framework for appliance energy efficiency and for the ozone and HFC agenda. It does not yet have a dedicated national cooling plan in force: the participatory preparation of the Plano Nacional de Ação pelo Resfriamento was formally launched in March 2026 [15]. Energy efficiency rests on the Energy Efficiency Law (Lei 10.295/2001) and is implemented through PROCEL and the Brazilian Labeling

Program (PBE) administered by INMETRO. Refrigerant controls operate through the Brazilian HCFC Elimination Program (PBH), IBAMA import procedures and the Montreal Protocol and Kigali instruments.

The principal instruments are summarised in Table 6.

*Table 6 – Brazil: list of administrative key provisions*

| Instrument | Year | Key provision |
|---|---|---|
| Energy Efficiency Law 10.295 | 2001 | Legal basis for minimum efficiency levels of energy-using equipment |
| PBE / ENCE labelling | ongoing | Mandatory ENCE energy labeling for regulated AC and refrigerator categories, administered by INMETRO [19] |
| INMETRO Portaria 269, as amended | 2021–2025 | IDRS-based AC energy classification and conformity requirements; current consolidated scope must be checked [19] |
| CGIEE Resolution No. 1 (Programa de Metas) | 2022 | Minimum IDRS levels for room ACs; removes lowest classes from the market [11] |
| Programa Brasileiro de Eliminação dos HCFCs (PBH) | 2010–2030 Stage III | HCFC phase-out schedule; final stage targets 100% consumption elimination by 2030 [13] |
| Decreto 11.666 (Kigali Amendment) | 2023 | Promulgation of the HFC phase-down commitments [14] |
| Plano Nacional de Ação pelo Resfriamento | under preparation from 2026 | Participatory intersectoral cooling strategy; not yet in force [15] |

The revision of the Brazilian Energy Labeling Program for air conditioners began with INMETRO Ordinance No. 234 of 29 June 2020 and was consolidated by Ordinance No. 269 of 22 June 2021, subsequently amended, including by Ordinance No. 672 of 2025 [19]. These measures introduced the IDRS-based classification and conformity framework. The corresponding binding minimum-performance thresholds were approved by the CGIEE through Resolution No. 1 of 29 April 2022 [11]. Applicants should use the current consolidated INMETRO text and product tables rather than relying on an earlier label class or an isolated ordinance.

## MEPS in force for cooling appliances

Minimum energy performance requirements and PBE/ENCE labeling apply only to products within the relevant regulated scope. Room air conditioners and specified refrigerator and freezer categories are covered, but conformity assessment, registration and labeling requirements remain product-specific. Commercial refrigeration equipment should therefore be checked against the current INMETRO scope before procurement [11][19][21]. Technical standards issued by ABNT should be treated separately from product-market authorization: their applicability may arise through regulation, building and fire requirements, procurement documents, contracts or professional duties and must be confirmed for the specific project.

*Table 7 – Brazil: MEPS in force for cooling appliances*

| Product | Instrument | Key requirement |
|---|---|---|
| Room air conditioners | INMETRO 269/2021, as amended, + CGIEE Res. 1/2022 | IDRS-based label and mandatory minimum performance levels; use the current consolidated requirements [11][19] |
| Regulated refrigerators and freezers | PBE / ENCE, where covered | Energy labeling, minimum performance and registration apply only to covered categories; verify the exact product scope [19][21] |
| Conformity / market entry | INMETRO conformity assessment, where regulated | For regulated products, certification or registration and ENCE are required before sale, as applicable [19] |

## Refrigerant transition timeline

Brazil follows the Montreal Protocol and the Kigali Amendment. HCFCs, including R-22, are governed by the PBH and IBAMA controls, and the final PBH stage targets elimination of HCFC consumption by 2030. HFC consumption was frozen in 2024 and is scheduled for phased reductions through 2045 [13][14]. R-32 and lower-GWP or natural refrigerants such as R-290, CO2 (R-744) and ammonia (R-717) are technology pathways rather than blanket legal prescriptions. IBAMA quota and authorization procedures apply to controlled HCFCs, HFCs and mixtures as specified by the applicable rules; natural refrigerants are not subject to HFC or HCFC quotas solely because they are used as refrigerants, although product, safety, transport, installation and maintenance requirements remain applicable [13]. The milestones are set out in Table 8.

*Table 8 – Brazil: refrigerant transition targets*

| Milestone | Target |
|---|---|
| HCFC consumption reductions (PBH) | −39.3% (2020), −51.6% (2021) vs baseline [13] |
| HCFC total elimination | 2030 [13] |
| HFC phase-down (Kigali): freeze | 2024 [14] |
| HFC phase-down, reductions | −10% (2029), −30% (2035), −50% (2040), −80% (2045) [14] |
| Common transition option in split ACs | R-32, subject to product and safety requirements [13] |
| Lower-GWP options in commercial/industrial systems | R-290, CO2 (R-744) and NH3, subject to application-specific requirements [13] |

## Key institutions

Oversight is distributed across several federal authorities, summarised in Table 9.

*Table 9 – Brazil: cooling key authorities*

| Authority | Role for cooling |
|---|---|
| MME / EPE | Energy policy and planning; Balanço Energético Nacional; efficiency analysis [20][21] |
| INMETRO | PBE labelling, MEPS, conformity assessment and product registration for regulated categories [19] |

| Authority | Role for cooling |
|---|---|
| ANEEL | Electricity tariffs and distribution service quality (DEC/FEC) [16][18] |
| MMA / IBAMA | PBH, HFC phase-down and import controls for refrigerants and other Montreal Protocol substances [13][14] |
| Receita Federal | Customs, import tax (II), IPI, PIS/COFINS-Importação [31] |
| ANVISA | Health-product cold chain and medical-device regulation in the health sector [32] |

The customs and tariff functions operate within a domestic-manufacturing and Mercosur setting rather than a pure import-conformity regime, which reflects the weight of local production noted earlier.

## Market entry: what to do before importing or installing equipment in Brazil

Because a large share of the room-AC market is assembled domestically in Manaus [29], direct importation is only one route to market. Imported equipment is classified under the Mercosur Common Nomenclature (NCM) and may be subject to Import Duty (II), IPI, PIS/COFINS-Importação and state ICMS. INMETRO conformity assessment applies only where the specific product falls within a regulated scope. Table 10 is therefore indicative: exact tariff treatment, licensing and conformity requirements must be checked using the current eight-digit NCM and the applicable product regulation before budgeting [19][31][33][34].

*Table 10 – Brazil: indicative import requirements and charges*

| Charge | Working assumption |
|---|---|
| Import duty (II), ACs (NCM 8415) | Indicative rate often 10–20%; confirm the exact eight-digit NCM and current TEC [31][33][34] |
| Import duty (II), refrigeration (NCM 8418) | Indicative rate often 10–20%; confirm the exact eight-digit NCM and current TEC [31][33][34] |
| IPI (excise) | Product-specific; often 0–15%, to be confirmed by NCM and current TIPI [31][33] |
| PIS/COFINS-Importação | General goods rate commonly 2.1% + 9.65%, subject to legal exceptions and product treatment [31][33] |
| ICMS (state VAT) | State-specific; often 17–25%, with the rate and calculation rules varying by state and transaction [31][33] |
| INMETRO conformity | Required only for products within an INMETRO-regulated scope; certification or registration and ENCE apply as specified [19] |
| Refrigerant import | HCFCs, HFCs and other controlled substances require the applicable IBAMA authorisation and quota or registration procedures [13] |
| Manaus Free Trade Zone | Tax incentives for local assembly, distinct from the import regime [29] |
| Ex-Tarifário (duty relief) | Temporary II reduction for eligible BK/BIT goods without equivalent domestic production; advance application required [35] |
| Importer of record | A Brazilian legal entity or importer is generally required for Siscomex habilitation and the applicable import declaration; conformity requirements remain product-specific [33][34] |
| INMETRO certification planning | Product-, documentation- and laboratory-dependent; confirm the pathway and timing with an accredited certification body before procurement [19] |

| Charge | Working assumption |
|---|---|
| Smart controls, BMS, IoT | ANATEL homologation is required where radio-frequency or telecommunications functionality falls within the regulated product scope [36] |
| Pressure / industrial systems | NR-13 applies to covered pressure equipment and piping; regulated engineering services require CONFEA/CREA responsibility and ART [37][38] |
| Climate / efficiency financing | BNDES Fundo Clima may support eligible climate-aligned machinery and projects; state incentives are case-specific [31][39] |

Routing to market in practice normally requires a Brazilian legal entity or importer habilitated in Siscomex. The applicable import declaration is the DUIMP or, during the system transition, the DI, depending on the operation and current implementation timetable [33][34]. For products within an INMETRO-regulated scope, Brazilian conformity assessment, registration and ENCE labeling must be completed as applicable; CE marking and foreign test reports do not replace these requirements, although technical evidence may support the conformity process [19]. Certification timing is product-, documentation- and laboratory-dependent and should be confirmed with an accredited Brazilian certification body before procurement. Wireless or radio-frequency controls require ANATEL homologation where they fall within the telecommunications-product scope [36]. NR-13 applies to covered boilers, pressure vessels, piping and metallic storage tanks, while regulated engineering services require a responsible professional and the relevant ART under the CONFEA/CREA system [37][38]. Imports of controlled HCFCs, HFCs and covered mixtures require the applicable IBAMA authorization, registration and quota procedures [13].

Several mechanisms can lower landed cost. The Ex-Tarifário regime can temporarily reduce import duty for eligible capital goods and information-technology or telecommunications goods, including qualifying parts and components, where there is no equivalent national production; eligibility is not automatic and the process requires advance planning [35]. BNDES Fundo Clima may finance eligible machinery, equipment or investment projects linked to greenhouse-gas reduction and climate adaptation [39]. State ICMS incentives, where available, remain project- and state-specific [31][33].

# Behavioural Context

Cooling in Brazil is shifting in perception from a comfort and status good towards a necessity, but it does so from a higher baseline of ownership than in most lower-income markets and within a highly unequal distribution. Air-conditioner ownership remains comparatively low overall, at roughly 20% of households against near-universal refrigerator ownership of about 98% [21], and it is strongly stratified by income, reported above 60% in the highest bracket and far lower among poorer households, so any policy that lowers the cost of efficient cooling carries a direct equity dimension [21][30]. Heat-wave episodes now produce visible spikes in residential electricity use [20][21], and exposure falls disproportionately on favela residents, outdoor and informal workers, the elderly and pregnant women. Brazil's continental climate, deep inequality, clean grid and domestic appliance industry together set the conditions for the sectoral demand examined in the following chapters.

# Tertiary-Sector Cooling

# Healthcare

## System infrastructure and facility inventories

Brazil operates the Sistema Único de Saúde (SUS), a universal and decentralised system spanning the federal, state and municipal levels, alongside a substantial private and supplementary sector [40]. Facilities and beds are recorded in the National Registry of Health Establishments (CNES) maintained by DATASUS. National provision stands at about 2.5 hospital beds per 1,000 inhabitants [41], under the global average of 3.3, with wide regional dispersion, with provision falling below the national average across much of the North and North-East and reaching the upper end of the range at about 2.71 in Rio Grande do Sul, 2.78 in the Federal District and 3.01 in Rondônia per 1,000 [42]. On the basis of the Ministério da Saúde open dataset, the estate with inpatient capacity comprises about 7,200 facilities and roughly 522,000 beds and cots, of which just under 3,000 facilities are hospitals with more than 50 beds [43]; the CNES universe of establishments is far larger once primary-care units without beds are included [42]. A facility-type breakdown by size band, with counts and bed capacity, is proposed in Table 11.

*Table 11 – Brazil: healthcare facilities classification (elaboration on Ministério da Saúde open data, "Hospitais e Leitos" [43])*

| **Healthcare Facility Type** | **Description** | **Facilities** | **Total capacity**<br>Hospital beds + cots | **Average capacity**<br>Hospital beds + cots |
|---|---|---|---|---|
| Community / Basic Healthcare Facility | Not a hospital or Hospital beds ≤ 50 | 4,228 | 101,046 | 23.90 |
| Small district hospital | 50 < Hospital beds ≤ 150 | 2,083 | 181,176 | 86.98 |
| Medium hospital | 150 < Hospital beds ≤ 300 | 680 | 139,563 | 205.24 |
| Large hospital | 300 < Hospital beds ≤ 500 | 173 | 64,139 | 370.75 |
| Referral / Tertiary sector hospital | Hospital beds > 500 | 48 | 35,678 | 743.29 |

The geography of provision matters for cooling because the regions with the highest thermal stress, in the North and North-East, are also those with comparatively thinner hospital infrastructure and tighter municipal budgets, as represented in Figure 5.

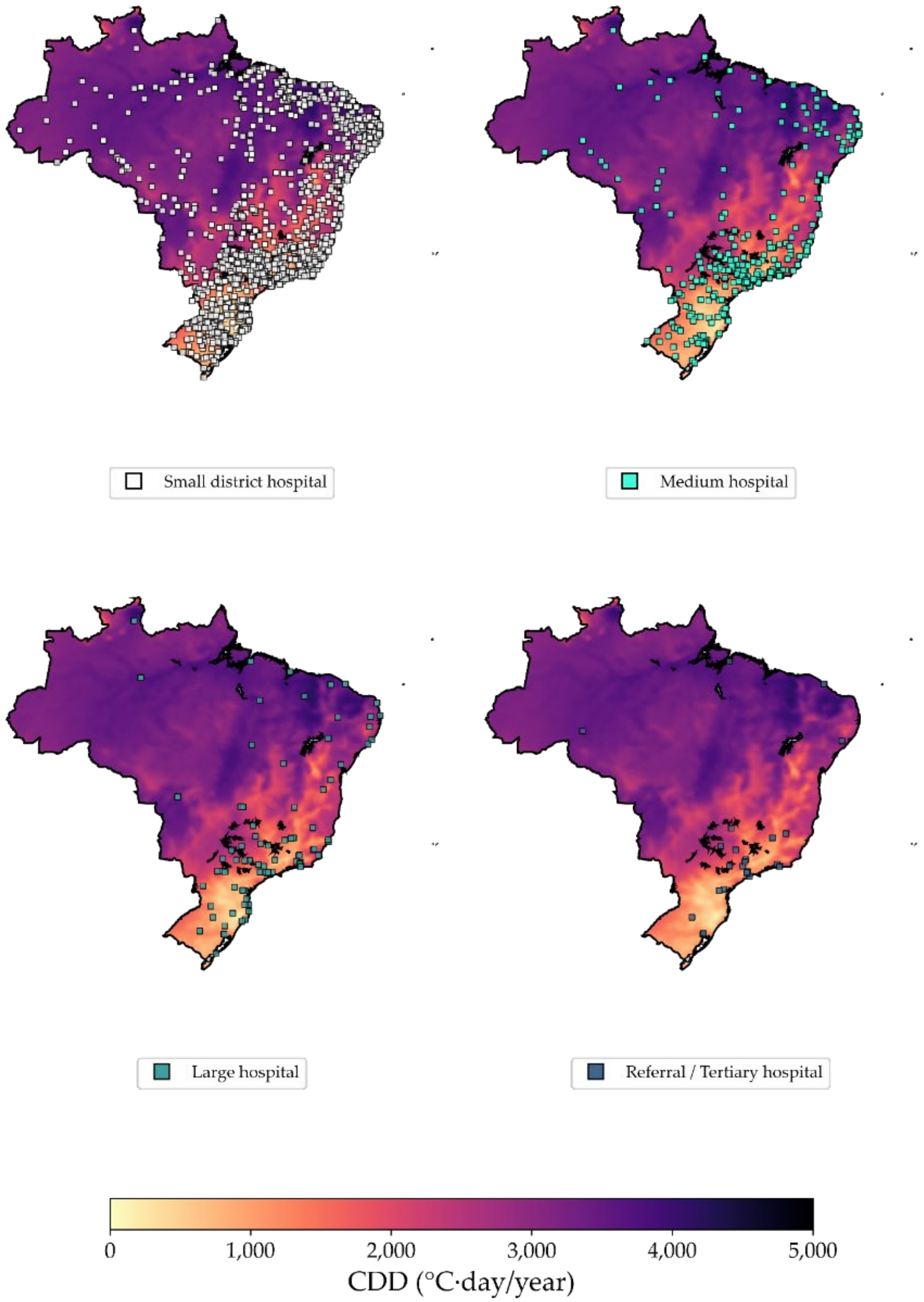


*Figure 5 – Brazil: hospital facilities location vs cooling degree days 18°C distribution*

Any expansion of capacity in these regions will embed new cooling load, and the specification of that load at the design stage will determine operating costs and emissions for decades. The supplementary private hospital sector, by contrast, is concentrated in the wealthier south-east and continues to expand, which drives demand for higher-specification climate control in new and refurbished units [44].

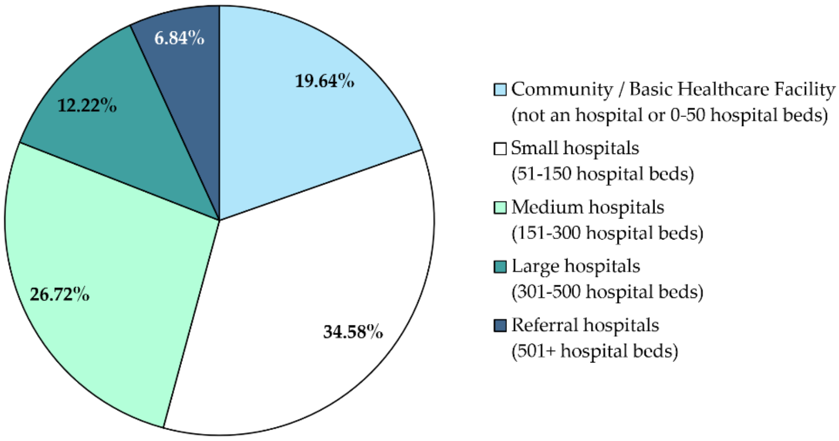


*Figure 6 – Brazil: inpatient bed distribution across facilities [43]*

The distribution of facilities is strongly skewed. The large majority are small community and basic-health units, while hospitals with more than 50 beds, and especially medium and large hospitals, are comparatively few yet hold most of the inpatient and specialised capacity. This mirrors the design of the SUS, which pairs a broad, capillary network of primary-care units for first-contact and preventive care with a smaller set of mid- and high-complexity hospitals concentrated in the larger cities, predominantly in the South-East [40][45]. For cooling, it implies that basic-comfort and vaccine-storage needs are dispersed across many small facilities, whereas clinical-grade air treatment and chilled-water cooling are concentrated in the larger hospitals.

## The cooling deficit and clinical consequences

In healthcare, cooling is an operational requirement rather than a matter of comfort, and its functions fall into three domains summarised in Table 12.

*Table 12 – Brazil: healthcare cooling applications*

| Domain | Requirement | Evidence / response |
|---|---|---|
| Vaccine cold chain (2 – 8 °C) | Continuous temperature control across the PNI rede de frio | The national central store (CENADI) operates about 17,600 m³ of refrigerated capacity at +2/+8 °C and about 2,646 m³ at −20 °C; immunobiologicals flow from CENADI through the 27 state central stores and municipal networks down to local vaccination rooms, with every tier dependent on continuous refrigeration [40][46]. |
| Medical storage & labs | 24-hour climate control for pharmaceuticals, blood products and reagents | Storage and transport of temperature-controlled medicines are governed by ANVISA good-practice rules (RDC 430/2020); blood components are regulated by RDC 34/2014. Both require documented, continuous temperature control, so a refrigeration failure interrupts pharmacy, laboratory and transfusion services [32]. |
| Clinical thermal comfort | Stable temperature and humidity in wards, ICU and surgery; air changes and pressurisation per NBR 7256. | A nationwide study covering 1,814 cities (2000–2015) found that hospitalisation risk rises by 4.0% for every +5 °C of daily mean temperature in the hot season, with about 6.2% of hot-season admissions attributable to heat; the burden peaks in the centre-west and the interior north-east, the same regions with the highest cooling demand [47]. |

The vaccine cold chain is anchored by the National Immunization Program (PNI), which operates a temperature-controlled 'rede de frio' from national and state stores to local vaccination units; the current PNI manual is the sixth edition published in 2025 [40][46]. The clinical estate also imposes requirements beyond simple temperature setpoints. Operating rooms, intensive-care units and isolation rooms require controlled humidity, air-change rates and, for specific spaces, pressurization. ABNT NBR 7256:2021, including Amendment 1:2022, is the principal Brazilian technical reference for air treatment in healthcare establishments [48]. Its project-specific legal or contractual applicability should be confirmed. In the hot-humid North and coastal zones, dehumidification represents a substantial part of the load, so latent capacity and air quality, not temperature alone, drive equipment sizing.

## Current market conditions and technology

Common technology configurations in medium and large hospitals include central chilled-water plants, while VRF, direct-expansion split and self-contained units are used in wards, clinics, administrative areas and smaller facilities. The precise configuration varies by facility, climate and clinical function. Manufacturer documentation confirms that current product pathways include R-513A options for selected chillers and R-32 options for several unitary and VRF product families [49]. Indicative performance ranges are reproduced in Table 13 and should be verified against the current equipment class, rating conditions and applicable efficiency requirements.

*Table 13 – Brazil: healthcare cooling technology benchmark*

| Technology | COP | EER [W/W] | Notes |
|---|---|---|---|
| Modern centrifugal chillers | > 6.0 | > 5.5 | Indicative high-efficiency range for large chillers; verify equipment class, rating conditions and the current ASHRAE 90.1 edition [50] |
| Inverter VRF | 4.0–5.0 | 3.5–4.5 | Indicative part-load range; not a universal minimum requirement [50] |
| Conventional split | 3.0–3.4 | 2.8–3.2 | Indicative rated range for the PBE-labeled segment; verify current IDRS class [19] |
| Automation / predictive control | +15–20% | +15–20% | Operational optimisation; industry estimates [30] |

## Infrastructure demand projections

The calculation is an illustrative capacity-expansion scenario. It combines expected population growth with a selected benchmark of approximately 3.3 hospital beds per 1,000 inhabitants and preserves the current modeled distribution of facilities by size band [41]. It is not a forecast of approved hospital construction or a statement of a legally required capacity level; actual investment needs will depend on service organization, occupancy, outpatient provision and regional access.

*New facilities = (population growth × current hospital beds per capita × current facility-type ratio) / average facility size*

Holding the modeled facility-type mix constant, Figure 7 shows the additional facilities implied by this illustrative 2050 scenario. The values are screening outputs, not an approved investment pipeline or a regional allocation.

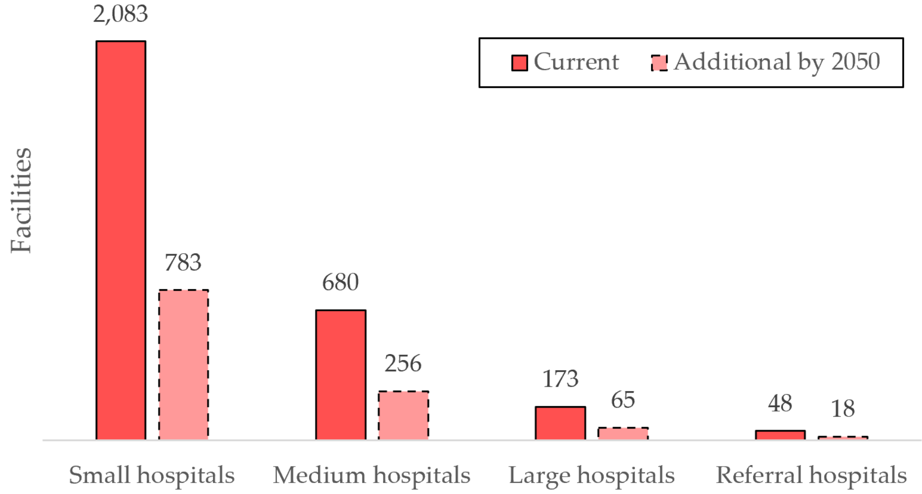


*Figure 7 – Brazil: current and additional facility number by size*

Under the illustrative scenario, preserving the current modeled distribution of facility types yields approximately 783 additional small district hospitals, 256 medium hospitals, 65 large hospitals and 18 referral hospitals by 2050. These values indicate the order of magnitude of potential capacity expansion and associated cooling demand; they are not a forecast or a minimum construction requirement, and no regional allocation has been modeled.

## Technology baseline and refrigerant mix

The current technology baseline in Brazil's healthcare cooling sector reflects a market at an early stage of transition, with a predominance of low-efficiency equipment and a refrigerant mix still weighted toward higher-GWP options. Key indicators are summarised in Table 14.

*Table 14 – Brazil: healthcare cooling technology indicators*

| Indicator | Value | Source |
|---|---|---|
| HVAC share of electricity, large hospitals | ≈ 41% | [45] |
| Cooling share of electricity, facilities > 50 beds | ≈ 28.6% | [45] |
| Specific total energy consumption (large-hospital sample, monthly) | ≈ 3,301 kWh/bed·month | [45] |
| Dominant plant type, medium and large hospitals | Central chilled-water plants | [45] |
| Reference refrigerant, centralised chillers | R-134a; transition to R-513A under way | [49] |
| Dominant technology, wards and small units | DX split and VRF on R-410A; transition to R-32 | [49] |

Despite the dominance of split units, the centralised chiller segment is growing.

## Energy implications

It has been estimated in this assessment, using the hospital electricity intensities in Table 15 [45], that electricity consumption in facilities with more than 50 beds is about 6.24 TWh/yr, of which cooling accounts for roughly 28.6%, or 1.78 TWh/yr, equivalent to about 4% of national public-services electricity consumption [20]. Applying the 2024 grid emission factor and the refrigerant-leakage assumptions below, the cooling-related GHG emissions are about 0.327 Mt $CO_2$eq/yr (0.220 direct plus 0.107 indirect) [20][45][51].

Energy consumption and emissions in the healthcare sector are parameterized using hospital bed count as the primary proxy. At the national level, beds per 1,000 inhabitants is a widely available indicator of healthcare-system capacity. At facility level, bed capacity is associated with infrastructure complexity, but it does not capture climate, occupancy, clinical services or operating practice. Primary-care practices and pharmacies are excluded from the quantified energy assessment. The 28.6% cooling share and the annual electricity intensities in Table 15 are derived by converting the published study's monthly total-energy benchmarks using its reported electricity and air-conditioning shares [45]. Because the study is based on an older facility sample and the size-band model uses different service assumptions, its values are used as screening benchmarks rather than as a current national metered inventory; applicants should validate loads and intensities at site level.

The corresponding energy consumption values used, along with their respective references and explanation, are presented in Table 15:

*Table 15 – Healthcare reference specific energy consumption [45]*

| Healthcare Facility Type | Level | Hospital electricity consumption [kWh/bed·yr] | Hospital electricity consumption for cooling [kWh/bed·yr] | Notes |
|---|---|---|---|---|
| Small district hospital | 1 | 8,875.07 | 2,204.57 | Brazilian average for small district hospitals. |
| Medium hospital | 2 | 18,344.88 | 4,995.31 | Brazilian average for medium hospitals with high comfort level. The underlying hypothesis is that overall comfort level has increased in the hospital band with 150-450 hospital beds |
| Large hospital | 3 | 18,344.88 | 4,995.31 | Brazilian average for medium hospitals with high comfort level |
| Referral / Tertiary sector hospital | 4 | 25,193.23 | 10,334.26 | Brazilian average for large hospitals |

Facility-level GHG emissions are assessed as the sum of indirect contributions (electricity consumption) and direct contributions (refrigerant leakage).

Indirect emissions are calculated as the product of electricity consumption and the national grid emission factor.

For direct emissions, the estimated facility stock and modeled plant sizes are used to construct a screening scenario. The system type, specific refrigerant charge and annual service-emission factor shown in Table 16 are explicit model assumptions rather than observed Brazilian national averages. Project applications should replace them with equipment-specific charge, service records and leakage data wherever available.

*Table 16 – Healthcare cooling plant characteristics used as screening assumptions*

| Healthcare Facility Type | Level | Typical cooling system | Assumed average plant size [MW] | Assumed specific refrigerant charge [kg refrigerant/kW installed] | Assumed annual service-emission factor [kg refrigerant leaked/kg charge·yr] |
|---|---|---|---|---|---|
| Small district hospital | 1 | Mostly VRF and DX split units; one or two small modular chillers with AHUs and fan-coils may serve the operating block and the ICU | 0.75 | 0.14 | 22% |
| Medium hospital | 2 | Chilled water plants | 2.5 | 0.14 | 22% |
| Large hospital | 3 | Chilled water plants | 5.7 | 0.14 | 22% |
| Referral / Tertiary sector hospital | 4 | Chilled water plants | 15.3 | 0.14 | 22% |

Emission figures are calculated taking R-134a as the reference refrigerant across centralised chiller installations, giving an average GWP of about 1,430 [51], with an electricity grid emission factor of 0.06 $kgCO_2eq/kWh$ [20]. On this basis the sector's cooling-related emissions are about 0.327 Mt $CO_2eq$ per year, of which roughly 0.220 Mt is direct (refrigerant leakage) and 0.107 Mt indirect (electricity). Although modest in national terms, these values underline the importance of embedding energy-efficient and low-GWP refrigerant standards in any healthcare infrastructure investment programme, both to contain facility operating costs and to support alignment with Brazil's NDC commitment [17].

## Structural barriers to investment

The principal barriers and the corresponding pathways are summarised in Table 17.

*Table 17 – Brazil: barriers to the deployment of cooling technologies in the healthcare sector*

| Barrier | Detail |
|---|---|
| Low-efficiency installed base | Conventional fixed-speed splits and ageing chillers dominate the installed base. As HCFC supply tightens under the PBH quotas, servicing costs rise and replacement becomes unavoidable [13]. |
| High upfront capital cost for small and medium SUS units | Municipal and small SUS units operate under constrained capital budgets and lowest-price procurement, which selects against higher-efficiency equipment with lower life-cycle cost; financing costs are high for private operators as well [44]. |
| Direct refrigerant emissions dominate under a clean grid | With a grid emission factor near 0.06 $kgCO_2eq/kWh$ [20], leakage of high-GWP refrigerants outweighs indirect emissions, so refrigerant choice, leak-tightness and end-of-life recovery become the primary mitigation levers [14]. |
| Resilience of the PNI rede de frio to outages | Average distribution outages of 10.24 hours per year (DEC, 2024) [16], higher in the North, expose vaccine and pharmaceutical stores to temperature excursions unless backup power, autonomy and monitoring are specified [46]. |

## Technology pathways

Brazil's national cooling plan (Plano Nacional de Ação pelo Resfriamento) is still being drafted, with the process launched in March 2026 [15]. Pending its publication, the directions below draw on the PBH and Kigali instruments [13][14], on the INMETRO efficiency framework [11][19]and on current sector practice. For project developers they provide a procurement reference and a basis for demonstrating regulatory alignment in climate-finance applications. The recommended pathways are summarised in Table 18.

*Table 18 – Brazil: technology pathway for healthcare cooling applications*

| Application | Recommended technology direction |
|---|---|
| General space cooling: wards, clinics and administrative areas | Inverter-driven splits, VRF, mini-chillers |
| Central plants and critical areas (ICU, operating theatres) in medium and large hospitals | Semi-centralised systems with heat recovery, enthalpic recuperators, TES; target 21–23 °C, 40–60% RH |
| Medical and pharmaceutical storage, laboratories | High-efficiency units, R290 or $CO_2$, digital monitoring, 2–8 °C continuous |
| Vaccine cold chain (PNI rede de frio), remote and outage-prone units | Solar Direct Drive (SDD) refrigerators with battery/thermal storage |

## Quick summary

The key barriers and enablers for sustainable cooling investment in the healthcare sector are summarised in Table 19.

*Table 19 – Brazil: healthcare cooling quick summary*

| Dimension | Barriers | Enablers |
|---|---|---|
| Technology | Stock dominated by fixed-speed splits and ageing chillers | Inverter VRF, high-efficiency chillers, low-GWP refrigerants (R-32, R-513A, R-290, $CO_2$) [13][14][49] |
| Economics and finance | High upfront cost for SUS units; lowest-price procurement | Cooling-as-a-service, on-bill repayment, development finance aligned with the NDC [17][44] |
| Regulation | No sector cooling plan yet in force; Plano Nacional de Ação pelo Resfriamento in preparation [15] | INMETRO MEPS and labelling in force [11][19]; NBR 7256 air-treatment standard [48] |
| Infrastructure and resilience | Supply is generally reliable (distribution outages at 10.24 h/yr), but even short outages can compromise critical vaccine and blood cold chains, which justifies battery or solar backup for those loads [16] | Solar-assisted and battery-backed cold chain, SDD refrigerators, digital monitoring [46] |
| Data | Healthcare-specific stock, refrigerant mix and R-22 share not quantified | CNES-based facility inventory and submetering programmes [42][43] |

# Education

## System structure and context

Brazil's basic-education system enrols about 47.1 million students across roughly 179,300 schools, supported by 2.4 million teachers [52]. The regions of highest cooling demand in the North, North-East and central interior coincide with weaker infrastructure, but the sector's distinctive problem is the low and highly unequal penetration of classroom climatisation within a system that is otherwise close to universally electrified. Key indicators are summarised in Table 20.

*Table 20 – Brazil: education sector key indicators*

| Indicator | Value | Source |
|---|---|---|
| Basic-education enrolment | 47.1 M | [52] |
| Number of schools | 179,300 | [52] |
| Classrooms with cooling/AC (national) | 41.1% public / 53.2% private (≈ 44.9% overall) | [53] |
| Worst state penetration (SP state network) | ≈ 4.1% (São Paulo capital municipal network 1.2%) | [53] |
| Classrooms without mechanical cooling | ≈ 55% (fans and natural ventilation only) | [53] |
| Basic infrastructure (water/energy/sanitation) | Water, electricity and sanitation are near-universal in the school network; the remaining deficits concern thermal comfort and digital connectivity, which lag despite electrification | [54] |

A further Brazilian feature compounds the exposure. Most public schools operate on multiple daily shifts, so a large share of teaching takes place in the afternoon, when indoor temperatures peak. The combination of afternoon occupancy, lightweight roofing and limited shading means that the hours of greatest learning effort frequently coincide with the hours of greatest heat stress.

An analysis of the 2024 INEP School Census microdata reports that 41.1% of classrooms in public schools and 53.2% in private schools were recorded as climatised, approximately 44.9% overall [52][53]. The Census variable includes functioning equipment used to maintain thermal conditions and should not be interpreted as proof that every classroom is air-conditioned or that design ventilation requirements are met. The regional distribution remains strongly unequal, and the reported regional adoption rates are used as model inputs below.

Figure 8 maps facilities against thermal stress.

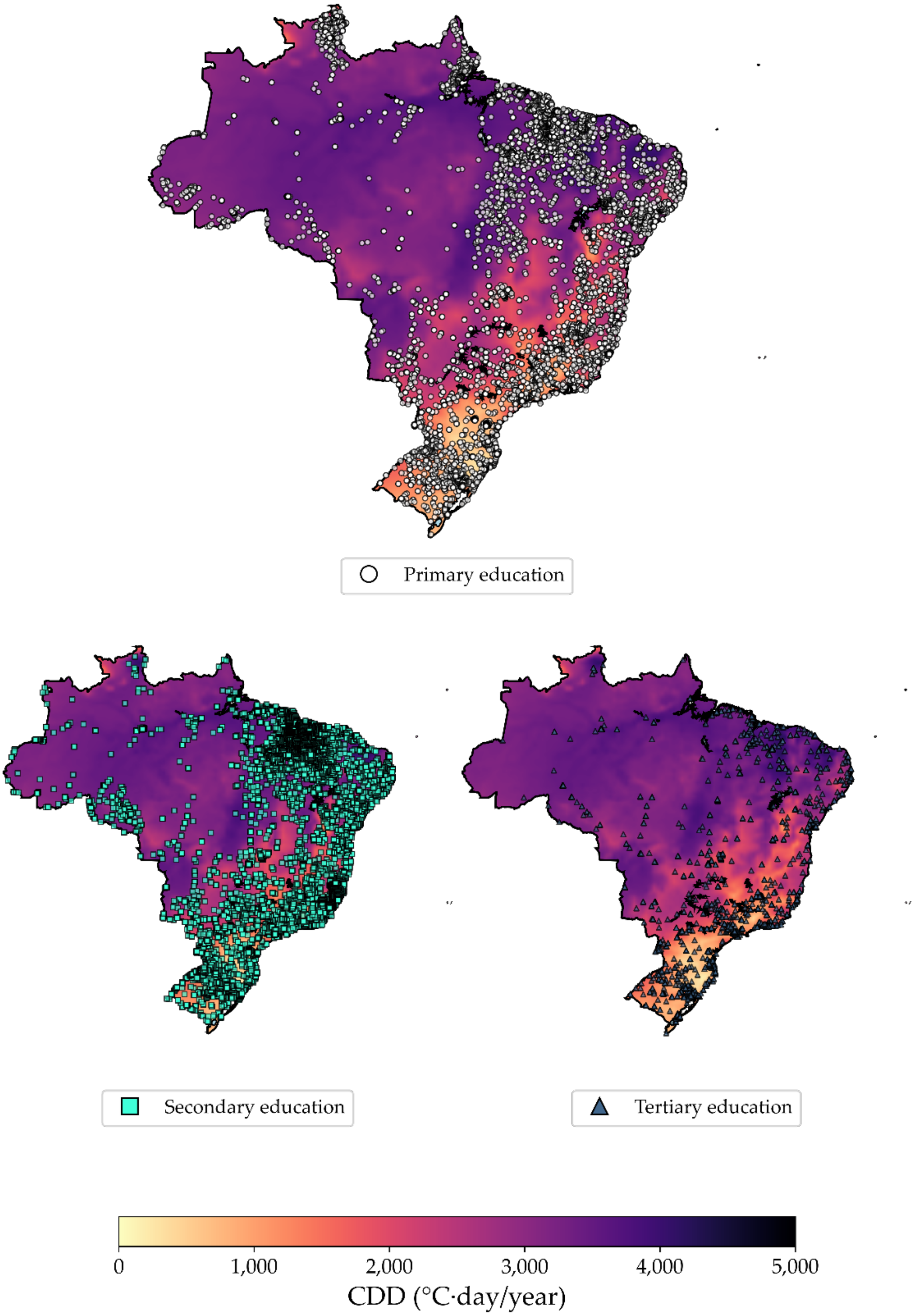


*Figure 8 – Brazil: Education facilities location vs cooling degree days 18°C distribution*

The overlay shows that many schools lie in the high-CDD North and North-East, where cooling needs are greatest while climatisation rates and grid resources are weakest. Education cooling demand is therefore concentrated where the system is least able to meet it, reinforcing the regressive pattern noted above.

## The thermal problem

Brazilian classrooms experience pronounced overheating, a problem widely described in public debate as 'saunas de aula'. Mechanical cooling is absent from over half of classrooms (≈ 55% nationally on the 2024 Census microdata)[52], and where it is missing the only mitigation is fans [53][55]. Excess heat is associated with reduced cognitive performance and weaker learning outcomes, and the burden is regionally regressive, since the hottest areas are also the least climatised [23][53]. Where air conditioning is installed, cooling becomes one of the dominant electricity end uses in Brazilian schools, substantially increasing overall building energy consumption, particularly during periods of extreme heat [56][57]. Several states and municipalities have launched classroom-climatisation programmes in response, although coverage remains partial and uneven [53].

## Market trajectory

Indicative efficiencies, consistent with the PBE/INMETRO labelled ranges, are given in Table 21 [19].

*Table 21 – Brazil: education cooling technology benchmarks*

| Technology | EER [W/W] | Notes |
|---|---|---|
| Modern inverter split | 3.5–4.2 | Up to 40% less energy than conventional units [19] |
| Conventional split (on/off) | 2.6–3.0 | Common in lowest-price tenders [19] |
| Window AC (ACJ) | 2.4–2.8 | Obsolete on efficiency and noise [19] |
| Evaporative cooler | n/a | Up to 90% lower energy; limited cooling effect [19] |

Demand is widely expected to rise steeply, and classroom cooling demand could roughly triple by 2050 as warming and the expansion of climatised floor space combine [58][59]. The procurement model matters as much as the equipment: lowest-price public tenders tend to favour conventional on/off units, which locks in low efficiency for the equipment's full service life, so efficiency criteria in tender design are a decisive lever.

## Demand Estimation Methodology

Cooling energy demand was estimated through a bottom-up model structured around Brazil's educational system. Two distinct methodologies are applied, reflecting the different cooling technology assumptions for university and non-university facilities. For universities, a centralised chiller system is assumed as the reference technology. For all other education levels, split and multi-split systems serving individual classrooms are used as the reference configuration.

For non-university facilities, the methodology follows three sequential steps: thermal-load characterization per classroom, estimation of annual operating hours by macro-region and aggregation by education level. Plant load is the sum of net outdoor-air load, internal gains and envelope transmission. Three climatic zones are distinguished with zone-specific design conditions. The 7.4 and 10.3 L/s per person cases use values reported in the 2024 edition of ABNT NBR 16401-3 for the stated classroom density [60]. That edition was subsequently suspended in 2025; the values are therefore retained only as transparent illustrative ventilation benchmarks, not presented as current mandatory requirements. Applicants must verify the standard edition and legal or contractual requirements in force when designing a project. The prevailing hi-wall split stock generally recirculates room air and introduces little dedicated outdoor air, so the installed-stock case is reported separately.

*Table 22 – Brazil: assumed design parameters for an education plant*

| Parameter | Value | Reference |
|---|---|---|
| Ventilation rate | 7.4 l/s per person (700 ppm); 10.3 (500 ppm) | Illustrative values from ABNT NBR 16401-3:2024; that edition was suspended in 2025, so current status must be verified [60] |
| Indoor set-point temperature | 24 °C | Model design assumption; verify the applicable comfort and health requirements |
| Outdoor design temperature | 35 / 37 / 33 °C (Z1 / Z2 / Z3) | Design assumption by zone |
| Indoor absolute humidity | 12 $g/m^3$ (24 °C, ≈55% RH) | Design assumption |
| Outdoor absolute humidity | 23 / 16 / 15 $g/m^3$ (Z1 / Z2 / Z3) | Design assumption by zone |
| Building envelope U-value (average) | 4 $W/m^2K$ | Design assumption |
| Average split system COP | 3.1 | Stock average, PBE/INMETRO labelled ranges [19] |

The resulting plant sizes by education level, derived from occupant loads, ventilation loads, and transmission loads, are reported in Table 23; values are zone-weighted averages on the climatised stock (42.9% Z1, 11.4% Z2, 45.6% Z3), and the outdoor-air column is net of the supply-air cooling credit.

*Table 23 – Brazil: classroom characteristics (zone-weighted averages from the classroom thermal model)*

| Level | Occupants per classroom | Occupant load [$kW_{th}$] | Net outdoor-air load [$kW_{th}$] | Transmission load [$kW_{th}$] | Total thermal load [$kW_{th}$] | Electrical plant size [$kW_{el}$] |
|---|---|---|---|---|---|---|
| Primary | 20 | 4.00 | 4.26 | 1.24 | 9.49 | 3.06 |
| Secondary | 25 | 5.00 | 5.32 | 1.55 | 11.87 | 3.83 |

Tertiary education is treated separately with the centralised-plant approach; only the in-person share of enrolment generates classroom cooling demand, with distance learning excluded [61].

Annual cooling hours are estimated by weighting the five macro-regions by their share of classrooms. The AC adoption rate is not assumed but measured: it is taken region by region from the 2024 School Census microdata, public and private networks combined [53]. The share of school days with active cooling is assigned per region by climate. The school year is set at 200 teaching days, the statutory minimum under the LDB (Lei 9.394/1996, art. 24) [62], with 8 building-operation hours per day reflecting the prevalent two-shift pattern, in which the afternoon shift coincides with peak heat. The regional assumptions are set out in Table 24.

*Table 24 – Brazil: assumed cooling technologies adoption and utilization [53]*

| Climatic zone | Share of classrooms | AC adoption rate | Days with active cooling |
|---|---|---|---|
| North | 8.5% | 69.9% | 95% of school days |
| North-East | 27.4% | 48.7% | 80% of school days |
| Centre-West | 7.5% | 68.5% | 75% of school days |
| South-East | 40.5% | 28.0% | 50% of school days |

| Climatic zone | Share of classrooms | AC adoption rate | Days with active cooling |
|---|---|---|---|
| South | 16.1% | 56.9% | 40% of school days |
| **Weighted average** | 100% | 44.9% | 65.7% of school days (weighted on climatised classrooms) |

The resulting annual cooling hours, weighted on the climatised stock, are about 1,051 hours per year. The classroom count is converted from class groups (turmas) to physical rooms through a multi-shift factor of 0.93, anchored to the 1,509,908 classrooms recorded by the 2024 School Census [52][53].

*Energy [GWh] = No. classrooms × adoption rate × electrical plant size [kW$_{el}$] × annual cooling hours [h] × load factor*

Where the load factor (0.7) reflects compressor cycling and modulation below nameplate output during operating hours.

For the tertiary sector, consumption is estimated from the in-person enrolment of about 5.0 million students, i.e. 49.3% of approximately 10.23 million total enrolments: distance learning, which surpassed in-person enrolment in 2024, generates no classroom cooling demand [61]. A specific load of 200 W per student is applied, with a design oversizing factor of 1.15, a distribution efficiency of 0.9, an annual equivalent occupancy of 630 hours and a centralised-plant COP of 2.8. The resulting energy consumption breakdown by education subsector is illustrated in Figure 9.

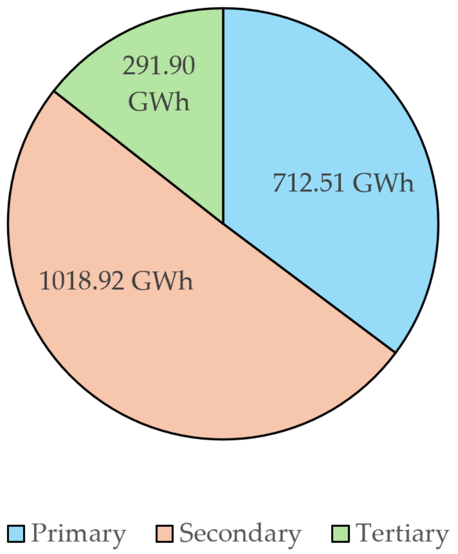


*Figure 9 – Brazil: Cooling energy demand by education subsector*

The estimated current installed-stock consumption is approximately 1,667 GWh per year (Table 27). Applying the illustrative 7.4 L/s per person ventilation benchmark raises the model result to approximately 2,023 GWh per year: 713 GWh in primary, 1,019 GWh in secondary and 292 GWh in tertiary facilities. This is approximately 0.31% of Brazil's 2024 final electricity consumption [20]. The implied average for primary and secondary education is about 2,750 kWh per climatised classroom per year, consistent with the stated equipment size and approximately 1,000 annual operating hours under the model assumptions.

## Emissions Estimation

Total emissions are the sum of indirect emissions from electricity consumption and direct emissions from refrigerant leakage. Indirect emissions apply the Brazilian grid emission factor of 0.0599 t CO2e/MWh (2024) [20] to the estimated consumption, yielding about 121 kt CO2e per year. Direct emissions are calculated as installed electrical cooling capacity × specific refrigerant charge × annual leakage rate × mixture-weighted GWP. For schools, the screening scenario assumes 0.56 kg of refrigerant per kW installed and 15% annual leakage, with the split-system mix in Table 25. For centralised tertiary plants, it assumes 0.90 kg/kW and 10% annual leakage with an illustrative equal mix of R-134a, R-410A and R-513A. These are explicit modelling assumptions, not measured national averages; the product pathways are informed by current technical documentation [49], and GWP values use a consistent IPCC AR4 basis [51].

*Table 25 – Brazil: assumed split and multi-split refrigerant mix for the emissions scenario*

| Refrigerant | Assumed share | GWP (AR4) |
|---|---|---|
| R-410A | 65% | 2,088 |
| R-32 | 30% | 675 |
| R-22 (legacy) | 5% | 1,810 |
| Weighted average GWP | 100% | 1,650 |

The resulting emissions breakdown is summarised in Table 26.

*Table 26 – Brazil: modeled education-sector emissions summary*

| Emission component | Value [ktonCO2/year] |
|---|---|
| Indirect emissions – electricity consumption | 121.2 |
| Direct emissions – refrigerant leakage (schools) | 324.8 |
| Direct emissions – refrigerant leakage (tertiary, centralised plants) | 57.3 |
| Total estimated emissions | 503.3 |

Total estimated emissions of approximately 503 ktonCO2eq per year are dominated by refrigerant leakage, which accounts for about 76% of the total. With a grid emission factor an order of magnitude below fossil-heavy systems, the climate impact of school cooling in Brazil is primarily a refrigerant question rather than an electricity question, which points to low-GWP refrigerants, leak-tight installation and end-of-life recovery as the first-order levers. The estimate is also a lower bound on latent demand: with adoption measured at 44.9% of classrooms [53], convergence towards full climatisation under current technology would more than double school consumption and direct emissions, before accounting for climate-driven growth in cooling hours.

*Table 27 – Brazil: modeled education cooling consumption and emissions under illustrative ventilation scenarios*

| Ventilation scenario | Outdoor air [l/s·person] | Cooling consumption [GWh/yr] | Total emissions [ktonCO$_2$eq/yr] |
|---|---|---|---|
| Estimated current installed-stock consumption (recirculation, infiltration only) | 4.0 | 1,667 | 415 |
| Illustrative 7.4 L/s·person ventilation benchmark (2024 edition; current status to be verified) | 7.4 | 2,023 | 503 |

| Ventilation scenario | Outdoor air [l/s·person] | Cooling consumption [GWh/yr] | Total emissions [ktonCO$_2$eq/yr] |
|---|---|---|---|
| Illustrative enhanced ventilation benchmark (10.3 L/s·person; current status to be verified) | 10.3 | 2,328 | 579 |

## Intervention logic

The estate divides into two segments that call for different responses. The first comprises schools in hot regions with constrained municipal budgets and, in parts of the North, less reliable power supply. Here the priority is passive: reflective or insulated roofing to cut the dominant transmission load through lightweight fibre-cement roofs, cross-ventilation and ceiling fans, external shading of glazing, and vegetation in school grounds. These measures cost a fraction of mechanical cooling per degree of indoor temperature reduction, remain effective during outages, and their investment case rests on learning outcomes and resilience rather than on energy savings; they are natural candidates for FNDE infrastructure programmes and align with the regressive geography of the deficit, since the hottest networks outside the North are also the least climatised.

The second segment, urban and institutional schools with reliable grid access, is the near-term market for efficient mechanical cooling: inverter hi-wall splits and, in larger buildings, VRF systems, procured under INMETRO label classes A with low-GWP refrigerants such as R-32. Procurement design is the decisive lever in this segment: tenders awarded on lowest purchase price systematically select on/off units whose lifetime electricity cost exceeds the capital saving, so award criteria should weight life-cycle cost, seasonal efficiency (IDRS) and a maintenance plan that limits refrigerant leakage. Aggregated purchasing across municipal networks can compress prices for high-efficiency equipment.

In this second segment, on-site solar generation is a natural complement: the net-metering framework of Lei 14.300/2022 allows schools to offset daytime cooling load with rooftop photovoltaics, whose generation profile coincides with school hours and with the afternoon cooling peak [63], and Brazil already has a large distributed-generation base [21]. Sequencing matters: passive measures first, since they shrink the plant size every subsequent investment must serve; efficient equipment second; generation third.

## Quick summary

The key barriers and enablers for sustainable cooling investment in the education sector are summarised in Table 28.

*Table 28 – Brazil: education sector cooling quick summary*

| Dimension | Barriers | Enablers |
|---|---|---|
| Technology | Over half of classrooms lack mechanical cooling; lowest-price tenders entrench on/off splits | Inverter splits (EER 3.5–4.2) and VRF; R-32 transition; evaporative cooling in dry zones [19][49] |
| Economics and procurement | Constrained municipal budgets; awards on purchase price ignore life-cycle cost | Life-cycle and IDRS criteria in tenders; aggregated purchasing; cooling-as-a-service; FNDE and development finance [17] |
| Regulation | No school-climatisation standard; national cooling plan still in drafting [15] | INMETRO MEPS and labelling in force [11][19]; net metering for school PV under Lei 14.300/2022 [63] |
| Infrastructure and resilience | Afternoon shifts coincide with peak heat; outages in the North expose schools [16] | Passive envelope measures; rooftop PV matched to the cooling peak; ceiling fans as baseline [63] |

| Dimension | Barriers | Enablers |
|---|---|---|
| Data | Climatisation tracked only through Census microdata; no consumption metering | Censo Escolar microdata [53]; school submetering |

# Food Cold Chain

## Structure: agribusiness exports, maritime reefers and a fragmented domestic chain

Brazil's cold chain is defined by its scale and strong export orientation, but it extends from industrial processing to fragmented domestic distribution [64]. Agribusiness exports reached approximately USD 164 billion in 2024, close to half of Brazilian exports, and meat, poultry, soy, sugar, coffee and fruit are major export flows [65][66][67]. Alongside export-oriented freezing and cold storage, domestic dairy, horticulture, fish and retail-ready food move mainly by road through wholesale markets, supermarket distribution centers and small operators. Brazilian studies and older technical sources report substantial fruit-and-vegetable losses, but estimates vary by commodity, supply-chain stage and method; the 40% value used later is therefore an explicit screening assumption rather than an official current national loss rate [26][27]. The maritime, industrial and domestic segments are contrasted in Table 29.

*Table 29 – Brazil: export/logistics vs domestic cold chain*

| Dimension | Export/maritime segment | Domestic segment |
|---|---|---|
| Maturity | Large, capital-intensive, growing | Fragmented; high losses at farm and retail |
| Key products | Beef, poultry, soy, sugar, coffee and fruit [65][66][67] | Dairy, horticulture, fish, retail-ready food |
| Logistics | Ports (Santos, Paranaguá/TCP, Itajaí–Navegantes), reefer ships, cabotage [68][69] | Road-dominated; CEASA wholesale hubs; modular cold rooms; retail distribution |
| Post-harvest losses | driven by logistics and handling | Substantial and highly variable by commodity and stage; no single current national rate is used as an observed value [26][27] |
| Refrigerants | R-134a moving to R-513A, with CO2 (R-744) in newest reefers [49] | Ammonia and CO2 in large industrial systems; HFC and hydrocarbon solutions vary by application [13][49][70] |

The maritime segment is large and expanding. Brazil's ports handled a record 1.32 billion tonnes of cargo in 2024, and containerized cargo grew strongly [68]. Refrigerated exports are concentrated in specialized corridors. The Paranaguá Container Terminal (TCP) reports 5,268 reefer plugs after its 2024 expansion and describes the yard as the largest in South America [69]. Coastal shipping is being expanded under the BR do Mar program (Lei 14.301/2022), which is intended to increase cabotage capacity [71]. Published reefer-fleet and throughput figures vary by source, so project preparation should prioritize ANTAQ and terminal-authority data over undated trade estimates [68][69].

The industrial side of the cold chain is also significant. Large meat and poultry processors operate blast-freezing and cold-storage capacity at industrial scale. Ammonia (R-717) is a long-established refrigerant for large food-processing and cold-storage plants, while CO2 (R-744) is used in cascade and transcritical configurations in appropriate applications [70]. These systems are concentrated near production centers and are priority areas for efficiency, heat recovery, leak detection and safe refrigerant management. Under the screening calculation below, in-plant process refrigeration is the largest quantified electricity load in the selected cold-chain segments.

## Export cold chain: key logistics vulnerabilities

Despite the relative maturity of the export segment, several infrastructure bottlenecks introduce systematic cold-chain risks that individual project developers cannot resolve unilaterally but must design around [68]. The domestic distribution chain faces a different set of constraints, including sparse cold storage for horticulture, last-mile gaps and less reliable inland power, which are taken up in the barriers and priorities below. The principal export-side vulnerabilities, their impact on cargo integrity, and the recommended interventions are identified in Table 30.

*Table 30 – Brazil: export cold-chain infrastructure bottlenecks [68]*

| Bottleneck | Impact | Addressable solution |
|---|---|---|
| Long interior-to-port road haul (Centre-West to Santos/Paranagua, 1,500-2,000 km) with limited refrigerated rail | Genset reliance, higher transport cost and emissions, temperature-excursion risk | Modal shift to coastal shipping (BR do Mar) and refrigerated rail; reefer telemetry [71] |
| Congestion at the Port of Santos in peak export season | Extended dwell and peaks in reefer-plug demand | Reefer-plug expansion, off-peak scheduling, diversion to Paranagua/TCP and Itajai-Navegantes [68] |
| Limited shore power for berthed reefer vessels at several terminals | Auxiliary-engine diesel use and emissions during berthing | Shore power (cold ironing) at reefer berths |
| Phytosanitary and customs throughput (MAPA / Receita Federal) at peak | Weekend and holiday bottlenecks for perishables | Continuous inspection service at major reefer terminals |
| Export-heavy meat lanes create reefer repositioning imbalance | Empty-reefer positioning cost | Triangulation and non-operating-reefer (NOR) use on return legs |
| Reefer fleet and throughput data partly from trade press | Weak basis for capacity planning | Consolidate ANTAQ and port-authority statistics [68] |

These bottlenecks are not marginal operational inconveniences. For temperature-sensitive cargo, each gap in the cold chain translates directly into product loss, market rejection, or reduced export value. Project developers should treat infrastructure redundancy and temperature monitoring as non-negotiable design requirements rather than optional enhancements.

## Energy footprint of cold chain operations

Cold chain operations generate a significant and growing energy and emissions footprint across all segments. Estimated energy demand and GHG emissions for the main segments of Brazil's cold chain are presented in Table 31.

*Table 31 – Brazil: estimated operational cold-chain electricity demand and electricity-related emissions*

| Segment | Estimated energy demand | Notes |
|---|---|---|
| Domestic cold storage (perishables) | 89 GWh/yr | 16.35 Mt refrigerated domestic perishables; dwell 12 days |

| Segment | Estimated energy demand | Notes |
|---|---|---|
| Export pre-shipment cold storage | 95 GWh/yr | 10.5 Mt refrigerated exports (meat + fruit); dwell 20 days |
| Maritime reefers (export) | 309 GWh/yr | Export tonnage via TEU; 2.1 kW/TEU over in-country refrigeration period |
| Industrial process refrigeration (meat) | 3,998 GWh/yr | ~29 Mt meat throughput; chilling + freezing + plant cold storage; ammonia plants [65][66][70][72][73] |
| Total cold-chain electricity | 4,491 GWh/yr | ≈ 0.69% of 2024 final electricity consumption (650.4 TWh) [20] |
| Operational electricity-related emissions | ≈ 0.27 Mt CO2e/yr | 4,491 GWh × 0.0599 t CO2e/MWh [20] |
| Product-loss-associated lifecycle emissions | Not quantified | Requires commodity-, stage- and site-specific evidence; report separately [27][74] |

Cold-chain energy estimates cover four components. Maritime reefer consumption is derived from approximately 10.5 Mt/yr of refrigerated exports, converted at 12 tonnes per TEU and 2.1 kW per reefer [65][66]. The resulting 309 GWh/yr corresponds to an assumed in-country energized period of approximately seven days per TEU, covering port dwell and connected inland stages; this is a model assumption that should be replaced by corridor-specific dwell data where available. Cold-storage consumption uses 165 kWh per tonne-year applied to average inventory inferred from dwell time. Export pre-shipment storage is assigned 20 days and domestic perishables 12 days. The domestic flow is an illustrative modeled stream based on production and loss assumptions reported in the cited Brazilian literature [26][27], not an official cold-store inventory.

A fourth and larger component is industrial process refrigeration in meat and poultry plants. It is estimated from approximately 29 Mt of 2024 meat production [65][66]multiplied by refrigeration-specific electricity intensities. A published European meat-industry assessment reports 149 kWh per tonne of hot standard carcass weight for slaughterhouses [72]; this report applies a central modeling assumption that refrigeration accounts for 50% of that electricity, then adds product-specific freezing increments from the comparative meat-processing literature [73]. The resulting screening intensities are about 165 kWh/t for poultry, 99 kWh/t for beef and 121 kWh/t for pork. Because technology, product mix and plant utilization differ between Europe and Brazil, these values are transferable engineering benchmarks rather than measured Brazilian national averages. Dairy, fish, further-processed foods, retail refrigeration and internal refrigerated transport are excluded.

The resulting cold-chain electricity demand is about 4,491 GWh per year. By far the largest component is industrial process refrigeration at the meat and poultry plants, at roughly 4,000 GWh. The logistics and storage of perishables account for the remainder, about 309 GWh for maritime reefers, 95 GWh for export pre-shipment storage and 89 GWh for domestic cold storage.

Operational electricity-related emissions from the quantified cold-chain segments are approximately 0.27 Mt CO2e per year, using the 2024 average grid factor of 0.0599 t CO2e/MWh [20]. Product-loss-associated lifecycle emissions are not added to this operational footprint. Their calculation requires commodity-specific production footprints, the stage and cause of loss, and evidence of the share that a proposed cold-chain intervention could avoid [27][74]. Applicants may quantify avoided product losses at project level, but should report them separately from equipment electricity and refrigerant emissions and document the causal baseline.

## Market drivers and projections

Several structural forces are converging to drive cold chain market growth in Brazil over the coming decade. The key drivers and their projected impact are summarised in Table 32.

*Table 32 – Brazil: food cold chain market drivers [28][69]*

| Driver | Detail |
|---|---|
| Export volume growth | Record meat exports (beef 2.89 Mt, poultry 5.29 Mt, pork 1.35 Mt in 2024) [65][66]; reefer handling at record levels, led by frozen meat, with TCP (South America's largest reefer yard, 5,268 plugs) the leading corridor [69] |
| Modal shift to cabotage | BR do Mar (Lei 14.301/2022) expands coastal-shipping capacity, shifting refrigerated volumes from long-haul road to lower-emission sea freight [71] |
| Urbanisation-led domestic demand | ~87% urban population; rising demand for fresh, retail-ready and processed food expands refrigerated retail and distribution |
| Climate adaptation | Warming of +1.2 to +2.2 °C by 2050 compresses the harvest-to-spoilage window and widens the addressable market [6] |
| Projected market value | Cold-chain logistics market ≈ USD 5.64 bn (2026), growing ~4.15%/yr to 2031 [28] |

Taken together, these drivers create a demand signal that is both large and durable. The combination of export growth, urbanisation-led domestic consumption, and climate-driven market expansion means that cold chain investment in Brazil is not dependent on any single growth vector, reducing the risk profile for long-term infrastructure commitments.

## Barriers and technology priorities

The principal barriers constraining cold chain development in Brazil are identified in Table 33.

*Table 33 – Brazil: food cold chain investment barriers*

| Barrier | Detail |
|---|---|
| High and uneven post-harvest losses in parts of the domestic chain [26][27] | Reported values vary by commodity, location and supply-chain stage; domestic horticulture remains fragmented and cold storage is concentrated in export-oriented agribusiness |
| Energy and refrigerant footprint of reefers and ports | Maritime reefers draw ~309 GWh/yr; industrial plants use ammonia and reefers commonly use R-134a, with lower-GWP transition options including R-513A and R-744; under a near-decarbonised grid, refrigerant leakage dominates the energy-related climate impact |
| Refrigerant transition under Kigali | Decreto 11.666/2023 implements the HFC phase-down. Controlled HFC/HCFC imports are subject to applicable IBAMA procedures; natural refrigerants are instead governed by product- and site-specific safety and conformity requirements [13][14] |
| Data quality on losses and the reefer fleet | Brazil has not reported to the FAO Food Loss Index; reefer-fleet and throughput figures are partly from trade press and should be consolidated against ANTAQ and EMBRAPA datasets [26][68] |

The financing barrier deserves particular attention. At the smallholder end of the market, the constraint is not the absence of suitable technology but the inability to mobilise upfront capital. Interventions that address this through service-based procurement models and cooperative aggregation are likely to achieve greater scale and sustainability than those focused on equipment supply alone.

## Technology and intervention priorities

The recommended technology and intervention priorities, organised by axis and target segment, are set out in Table 34.

*Table 34 – Brazil: cold chain technology and intervention priorities [13]*

| Technology/intervention axis | Target segment | Key design requirements |
|---|---|---|
| Solar and hybrid modular cold rooms, cooperative aggregation and cooling-as-a-service | Domestic smallholder and horticulture | Off-grid or hybrid PV, low-GWP refrigerants (R-290, R-600a), simple operation and maintenance, output-linked financing |
| CO2 (R-744) and R-513A reefers, shore power and technician training on leak reduction [49] | Export and maritime segment | Low-GWP reefers, cold ironing at reefer berths, leak-tight design and reefer telemetry |
| Natural-refrigerant industrial systems and controlled-substance compliance [13][14][70] | Meat and poultry processing (industrial) | Ammonia and CO2 systems, heat recovery, leak detection and safe end-of-life management; verify IBAMA procedures only for controlled substances |
| Consolidation of official ANTAQ and EMBRAPA datasets [26][68] | Sector governance and policy | Reefer-fleet registry, food-loss monitoring and cold-store submetering |

The two segments identified in Table 29 require distinct intervention logics: the export segment demands precision, compliance, and integration with international cold chain standards, while the domestic segment demands affordability, operational simplicity, and solutions designed for grid-unstable or off-grid deployment.

## Quick summary

The key barriers and enablers for sustainable cold chain investment in Brazil are summarised in Table 35.

*Table 35 – Brazil: food cold chain quick summary*

| Dimension | Barriers | Enablers |
|---|---|---|
| Energy infrastructure | Electricity tariffs vary by distribution area; diesel reliance persists for long inland reefer haul and gensets [18] | ~88% renewable grid and very low grid emission factor (0.0599 tCO2/MWh); abundant solar; cooling-as-a-service [20] |
| Logistics & port infrastructure | Santos congestion; long interior-to-port road haul; limited refrigerated rail; shore-power gaps | Paranagua/TCP (5,268 reefer plugs) and Itajai-Navegantes; cabotage expansion under BR do Mar [69][71] |
| Financing & affordability | Upfront capital for domestic and smallholder cold rooms; fragmented demand | Cold-chain market ~USD 5.64 bn (2026) [28]; cooling-as-a-service and development finance |
| Regulatory & compliance | HFC phase-down requires fleet transition; refrigerant servicing and leakage | Decreto 11.666/2023 (Kigali) and IBAMA quotas [13][14]; national cooling plan in drafting [15] |
| Market structure | Fragmented domestic chain; food-loss rates vary by product and stage and are not treated as operational cooling emissions [26][27] | Record meat exports [65][66]; record reefer handling led by frozen meat [69]; modal shift to cabotage [71] |

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