ORINOLYST

COOLING INDIA SUSTAINABLY

BALANCING WATTS AND WEATHER

Leveraging Climate-Responsive Cooling through Innovation and Nature

2025

COOLING INDIA SUSTAINABLY: BALANCING WATTS AND WEATHER

Leveraging Climate-Responsive Cooling through Innovation and Nature

RINOLYST

SciGlyph Exploration Private Limited, Patna, Bihar, India

May 30, 2025

www.rinolyst.com

Collaborators

NetZeroIndia Foundation

Indian Youth Climate Network

Greensapien

Exploring the future of thermal comfort in India through technology, tradition, and ecological intelligence.

CONTRIBUTORS

Sunil Kumar, PhD
RINOLYST, Sciglyph Exploration Private Limited,
Patna, Bihar, India

Sirish Kumar, PhD
RINOLYST, Sciglyph Exploration Private Limited,
Patna, Bihar, India

Manish Ram, MBA, PhD
Independent Climate & Energy Expert,
Ranchi, Jharkhand, India

Achinta Bera, PhD
Assistant Professor, School of Energy Technology,
Pandit Deendayal Energy University,
Raisan, Gandhinagar, Gujarat, India

Kumari Sandhya, PhD
Senior Researcher, Chair of Energy Network Technology
Technical University of Leoben, Austria

Ranjit Kumar Paswan, PhD
Senior Scientist & Assistant Professor (AcSIR)
CSIR-Central Institute of Mining & Fuel Research,
Dhanbad, Jharkhand, India

Gyan Prakash Satyam, PhD
RINOLYST, Sciglyph Exploration Private Limited,
Patna, Bihar, India

Piyush Mishra, BTech, MTech
Former Advisor to MoS, MSME, Government of India.
Founder, NetZero India Foundation,
Greater Noida, Uttar Pradesh, India

Niharika Kapoor,
Board Member, Indian Youth Climate Network
IYCN, Delhi, India

Atul Kumar, MTech
PhD Scholar, Department of Mechanical Engineering,
Indian Institute of Technology (ISM)
Dhanbad, Jharkhand, India

Pooja Agarwal, Mtech
Senior Research Fellow, Department of Design,
Indian Institute of Technology, Delhi, India
EDP (Proj. Management, IIMK)
IGBC AP | GEM CP
Member: IBPSA, ISHRAE

Rahul Kumar, MTech
Centre for Environment and Energy Development (CEED),
Ranchi, Jharkhand, India

Sachin Pratap, MTech
RINOLYST, Sciglyph Exploration Private Limited,
Patna, Bihar, India

Jitendra Raj, MBA
Institute of Rural Management Anand (IRMA),
Anand, Gujarat, India

Jyotsna Chhura, BTech
RINOLYST, Sciglyph Exploration Private Limited,
Patna, Bihar, India

Santosh Kumar Mahto, BTech
Senior software Engineer, JPMorgan & Chase
Glasgow Scotland, United Kingdom

Pramod Raj, BTech
RINOLYST, Sciglyph Exploration Private Limited,
Patna, Bihar, India

This report reflects the insights of dedicated contributors working at the intersection of climate resilience and sustainable development, supported by RINOLYST's commitment to advancing evidence-based solutions through in-house and collaborative research. We sincerely thank all contributors whose expertise has shaped this study. As we continue with our forthcoming reports on ***green hydrogen*** and ***energy efficiency***, we welcome new researchers and professionals to join us in co-developing research that drives meaningful impact. To express interest, please contact us at ***info@rinolyst.com***.

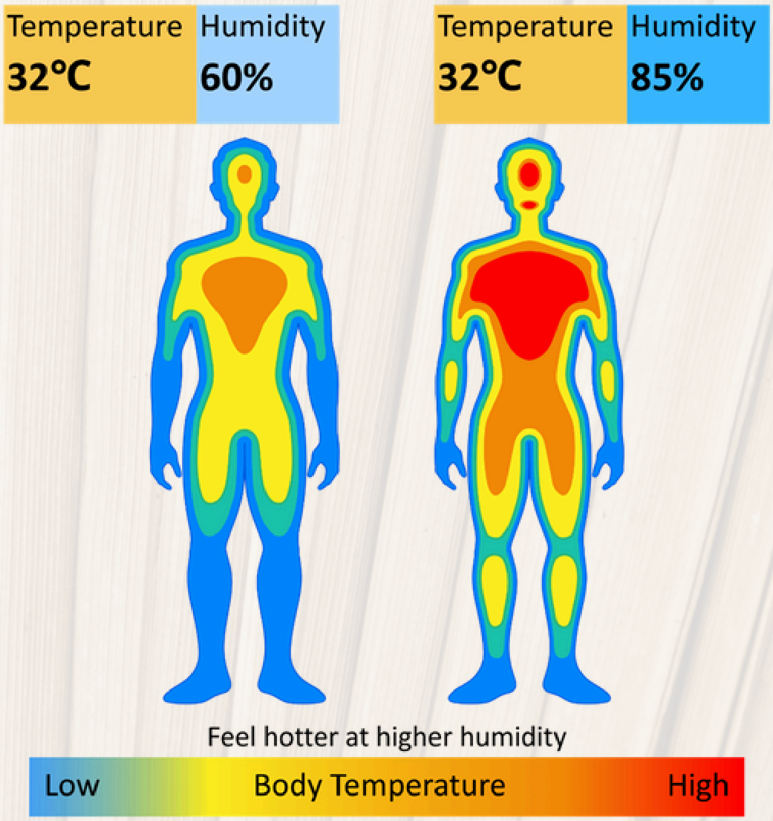
THINK TANK & STRATEGIC ADVISORY PANEL

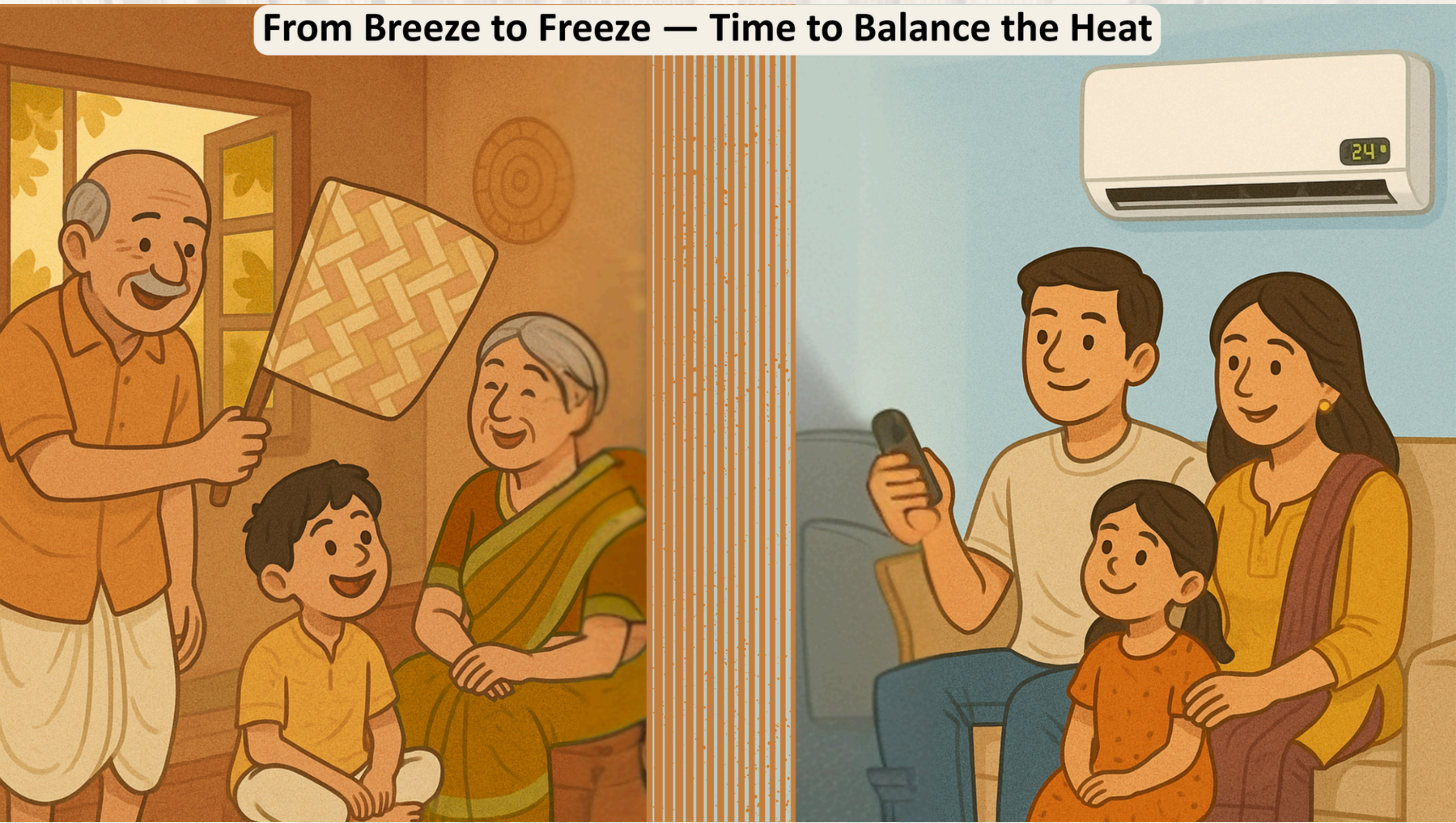
Prof. Tarkeshwar Kumar
Advisor, RINOLYST, Sciglyph Exploration Private Limited, Patna, Bihar, India

Prof. Rakesh Kumar Vij
Advisor, RINOLYST, Sciglyph Exploration Private Limited, Patna, Bihar, India

Prof. Aviral Kumar Tiwari
Advisor, RINOLYST, Sciglyph Exploration Private Limited, Patna, Bihar, India

Dr. Sanjeev Kumar Varshney
Advisor, RINOLYST, Sciglyph Exploration Private Limited, Patna, Bihar, India





Executive Summary

India is heating rapidly, unevenly, and with intensifying consequences. From the Indo-Gangetic Plain to the Deccan Plateau, each passing summer pushes millions closer to the threshold between survivable climate and dangerous heat exposure. India's growing heat burden is not only a national challenge but also an opportunity for transformational change. The country stands at a pivotal intersection of climatic urgency, technological progress, and demographic growth. As heatwaves become more frequent, severe, and lethal, cooling has evolved from a luxury into a critical infrastructure service, deeply tied to energy security, climate resilience, public health, and economic productivity in the world's most populous democracy.

This report offers a comprehensive and data-rich assessment of India's cooling landscape, examining both technology-driven and nature-based solutions to sustainably meet the country's growing thermal comfort needs. The first half of the report focuses on mechanical cooling, particularly the rapid adoption of room air conditioners (ACs). Based on projected growth and a 12-year service life assumption, India's installed AC stock is expected to reach between 150 and 240 million units by 2030. This surge in adoption carries major implications for energy demand and emissions.

If not actively managed, residential cooling alone could contribute 3 to 4 % of India's national emissions by the end of this decade. Including indirect emissions from refrigerant leakage and refrigeration appliances, the sector's footprint may rise to 5–6%. With peak electricity demand projected to exceed 400 gigawatts on the hottest days by 2030, cooling loads will place substantial stress on power infrastructure.

Encouragingly, the market is transitioning toward more efficient technologies. Inverter-based ACs are replacing fixed-speed units, average ISEER ratings are improving, and ultra-low-GWP refrigerants are gaining interest. Yet disparities in access, affordability, and efficiency persist across regions. Advancing equitable, low-emission cooling will require progress in appliance design, consumer financing, public procurement, and decentralized implementation models.

The second half of the report highlights the transformative potential of passive and natural cooling approaches. These strategies, such as reflective roofing, shading, cross-ventilation, thermal mass, evaporative cooling, and vegetated surfaces, can reduce indoor temperatures by 3 to 7 degrees Celsius and lower AC energy use by up to 50 percent. Far from being alternatives for underserved populations, these are sustainable, climate-responsive design principles suitable for all building types and income levels.

The report emphasizes climate-zone-specific applications: radiative and evaporative cooling work well in hot-dry areas like Rajasthan and Gujarat, while humid regions such as Mumbai and Chennai benefit from optimized ventilation, reflective surfaces, and hybrid designs. Integration of smart controls, such as IoT-based cooling, weather-linked pre-cooling, and real-time load monitoring, offers additional efficiency gains. By combining regional climate data, building typologies, and user behaviour patterns, the report presents a highly localized and actionable roadmap. It analyses electricity access, income disparities, and cooling trends to identify high-priority geographies and demographic segments.

India's Energy Conservation Building Code (ECBC) and National Cooling Action Plan (NCAP) provide a strong policy foundation, further supported by developments in domestic manufacturing, energy labelling, and market awareness. India has introduced ultra-efficient ACs into the market, and while the national average ISEER remains around 3.5 to 4.0, the technical potential exceeds 6.0 and global best performers reach 9–12 W/W. This underscores a significant opportunity to narrow the gap between what is available and what is widely adopted through smart incentives, revised labelling, and coordinated innovation.

With India and Africa expected to add over 100 billion square meters of new floor space by 2050, more than 40 percent of all new global construction, the opportunity for market transformation is unprecedented. According to the World Bank, this shift could unlock $1.6 trillion in investment potential and create 3.7 million jobs.

This report, developed by RINOLYST in collaboration with experts from climate science, engineering, architecture, and energy systems, offers a strategic blueprint for India's cooling future. It calls for integrated solutions that align appliance efficiency, nature-based design, equitable access, and industrial competitiveness. Done right, sustainable cooling can serve not just as a climate mitigation strategy, but as a cornerstone of India's inclusive and resilient development.

The Dynamics of India's Cooling Transition

India's cooling demand story begins with the rapid escalation of air conditioner production over the last two decades. As highlighted (later in this report) in our analysis of annual residential AC production trends, India's output of room air conditioners has seen sustained double-digit growth, with future projections diverging sharply depending on market assumptions. This dramatic expansion sets the stage for understanding the forces reshaping the nation's cooling landscape.

Within this surge, the shares of different domestic cooling appliances reveal an important market transformation. While traditional appliances like fans and refrigerators remain vital, the share of energy-intensive but high-comfort solutions, namely air conditioners, is rising steadily. A closer look at the split between fixed-speed and inverter ACs underscores this technological pivot: variable-speed inverter technologies are fast displacing older, less efficient fixed-speed models.

Yet the story of efficiency does not stop with inverter technology alone. India's regulatory push for higher standards is evident in the steady improvement of 5-star rated RACs since 2009, indicating not just greater adoption but better product performance. Top-performing ultra-efficient inverter split ACs today offer models that combine high seasonal efficiency (ISEER) with substantial reductions in annual electricity consumption, setting benchmarks for what sustainable cooling can achieve.

Even among these advancements, there remains significant diversity in product efficiency. Our mapping of ISEER vs. annual energy use across variable-speed split ACs illustrates (later in this report) how room for improvement persists, especially for larger-capacity models where absolute consumption remains high.

The consequences of these shifts at the consumer and system levels are profound. Rising per-capita electricity consumption alongside increasing real incomes foreshadows an impending explosion of cooling demand as households become wealthier and urbanization intensifies. However, state-level disparities in income and electricity access show that not all regions will experience or manage this transition equally. States like

Bihar and Uttar Pradesh face the dual burden of high heat vulnerability and low cooling access, emphasizing the urgent need for inclusive cooling strategies.

At the grid level, the effects are already tangible. Projected electricity demand during extreme heat days demonstrates how widespread cooling adoption could push peak power demand to over 400 GW by 2030, straining infrastructure and challenging India's decarbonization efforts. This is not a hypothetical future; it is an ongoing reality, as seen in the historical growth of June peak demand profiles, where daily electricity loads during heatwaves have nearly doubled in just over a decade, largely driven by rising air conditioning usage.

Demand & Opportunity

As India's energy and economic landscapes evolve, the nature of its cooling challenge is undergoing a profound shift. No longer a seasonal or regional concern, the need for reliable cooling now touches every sector of society, from residential homes and educational institutions to healthcare facilities and industrial hubs. Climate change is intensifying background temperatures across all zones, extending the duration and severity of heat stress well beyond traditional summer months. Rising affluence, urban migration, and a modernizing lifestyle are reshaping expectations for indoor thermal comfort, with aspirations for air-conditioned living becoming widespread even in Tier 2 and Tier 3 cities. Meanwhile, the construction boom is rapidly expanding the built environment, locking in decades of future cooling demand based on today's design choices. The result is a structural and accelerating increase in baseline cooling loads that will profoundly influence India's electricity system, urban planning models, industrial strategies, and climate goals. The opportunity now lies not merely in expanding access to cooling, but in steering that expansion toward efficiency, resilience, and equity. Crafting a sustainable cooling trajectory demands early, coordinated action across appliance innovation, building design, public policy, consumer behaviour, and grid decarbonization, all tuned to India's complex socio-economic and climatic realities.

India's residential air conditioner (AC) production is on a steep upward trajectory, driven by rapid urbanization, rising incomes, and intensifying heatwaves. As shown in the production data and projections, annual AC production is set to increase from around 5 million units in 2015 (Fig. 1) to between 149 and 240 million cumulative installed (Fig. 2) units by 2030, depending on the growth scenario (CAGR ranging from 13% to 22%).

AC Production Trajectory and Emissions Outlook

The Combined and Adjusted Trend, which accounts for COVID-19 disruptions and economic normalization, projects approximately 180 million residential ACs in use by 2030.

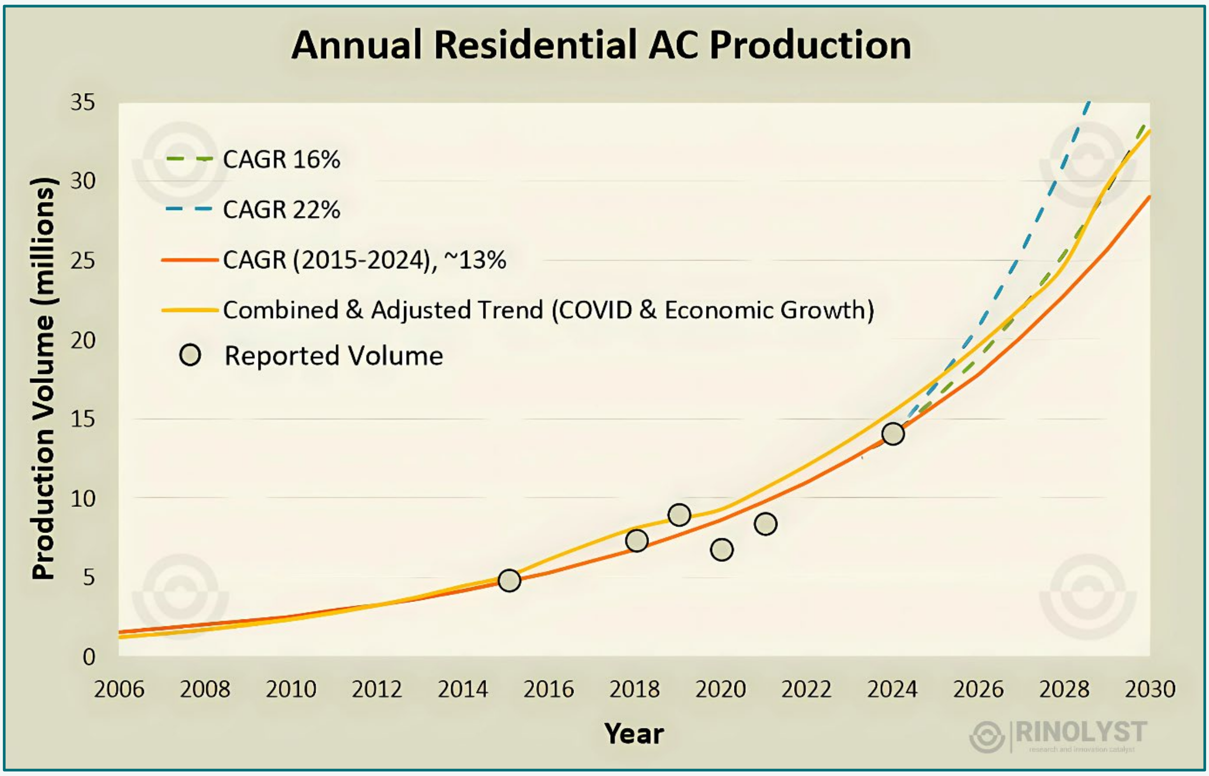


Figure 1: Annual residential air conditioner production in India (projected)[1,2,3,4].

This surge will significantly raise electricity demand and associated greenhouse gas (GHG) emissions: with an assumption of average annual consumption of 750 kWh per unit (see later in this report), emissions from residential ACs alone could reach 0.09–0.15

Gt CO_2 per year by 2030, representing 2.3% to 3.7% of India's projected total emissions for that year, depending on the scenario. These figures are in line with global trends, where air conditioning already accounts for about 3-4% of total GHG emissions and is set to triple in demand by 2050, with India and China leading this growth[5,6]. Notably, these estimates do not include emissions from refrigerators and refrigerant leakage, which could push the cooling sector's share to 5–6% of national emissions by 2030.

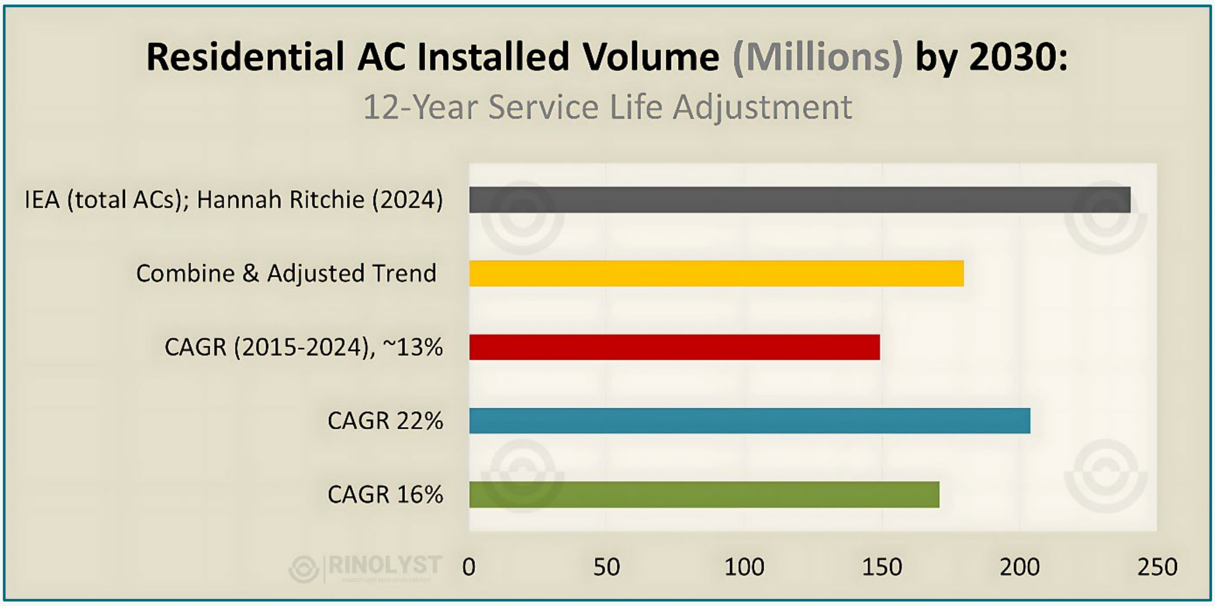


Figure 2: Cumulative residential air conditioner volume in India (projected)[1,2,3,4].

This rapid expansion underscores the urgent need for aggressive improvements in AC energy efficiency, accelerated adoption of low-GWP refrigerants, and integration with renewable energy sources to avoid locking in decades of high emissions. Without such interventions, India risks severe power shortages, higher consumer costs, and a dramatic rise in cooling-related emissions, undermining both adaptation and mitigation efforts. However, with robust policy action-such as doubling AC efficiency standards, incentivizing advanced technologies, and enforcing sustainable building codes-India can meet its cooling needs in a far more energy-efficient and climate-resilient manner, supporting its net-zero ambitions and sustainable development goals.

India's electricity landscape is undergoing a profound transformation under the pressure of intensifying heatwaves and rising ambient temperatures. The seasonal progression of average peak temperatures and corresponding electricity demand from 2014 to 2024 (Fig. 3) reveals a striking and escalating alignment, particularly during the April to June quarter (summer), the nation's most climatically stressful period. As temperatures peak during this interval, so too does the nation's electricity demand, indicating a direct and growing dependence on active cooling solutions to maintain livability across homes, institutions, and workplaces.

Summer & Rising Electricity Demand

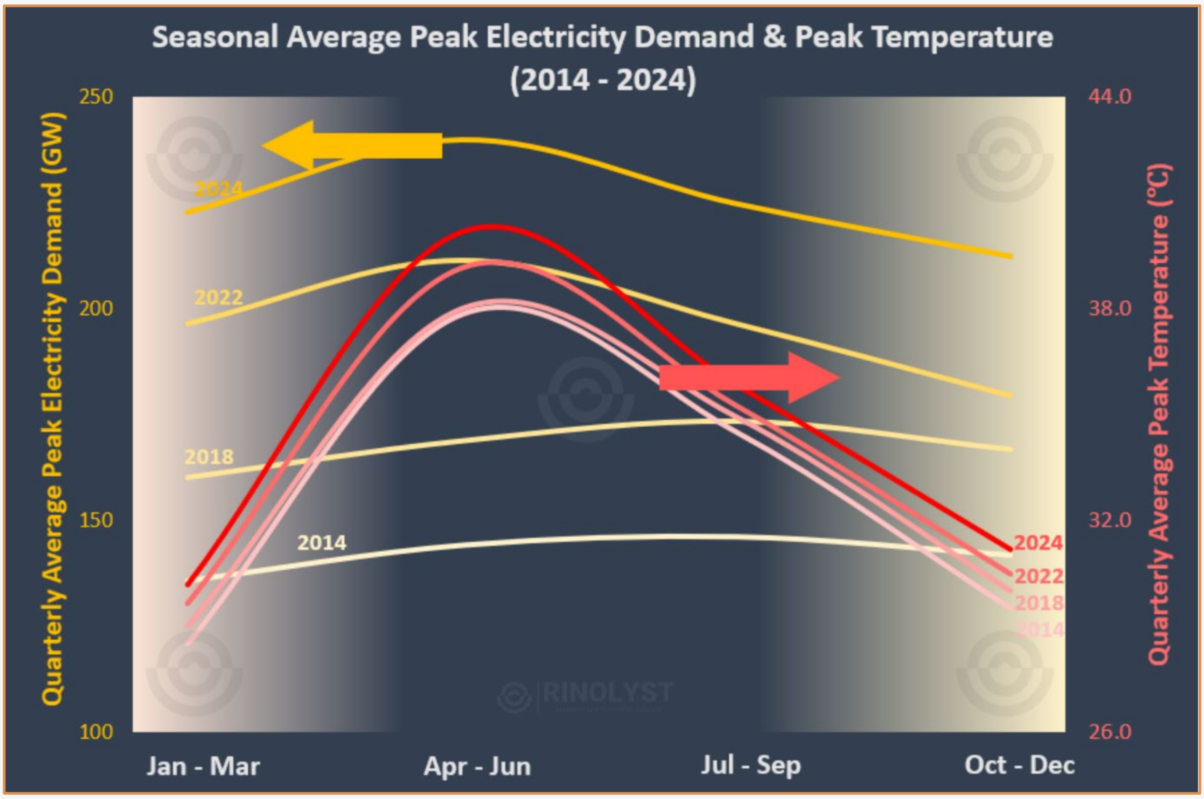


Figure 3: Seasonal average peak electricity demand and peak temperature in the past decade (2014-2024; quarterly average variation) in India[7].

Further compounding this pattern is the projected electricity demand profile on high-temperature days through 2030 (Fig. 4), which anticipates peak requirements more than doubling relative to 2023 levels. These projections not only underscore the accelerating penetration of air conditioning and cooling appliances but also expose the widening variability and uncertainty that grid operators must manage during extreme thermal events. As heatwaves become longer and more intense, the likelihood of daily peak loads exceeding 400 GW within this decade becomes increasingly plausible, placing significant stress on power generation, distribution infrastructure, and pricing mechanisms.

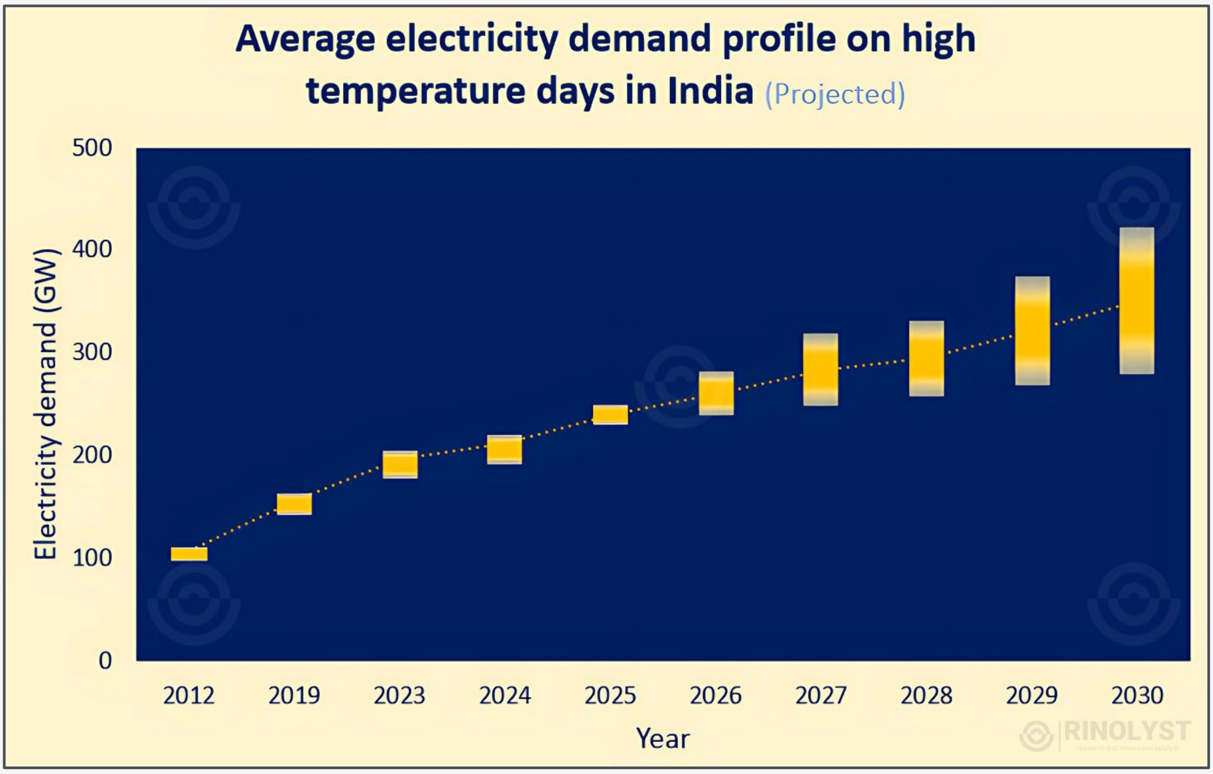


Figure 4: Average electricity demand profile on high temperature day in India (2012-2030; projected)[8,9,10,11].

A deeper look into electricity uses across a typical high-temperature day in June reveals that demand surges are no longer limited to isolated hours. From early morning through late evening, the entire daily load curve has shifted upward, with afternoon and early evening hours experiencing the most pronounced spikes. Between 2012 and 2024 (Fig. 5), these intraday peak demands have effectively doubled, directly tied to the rising use of cooling systems during the hottest parts of the day. This transformation marks a fundamental shift from traditional baseload patterns toward more weather-contingent demand profiles, with cooling acting as the key load driver. Together, these insights present a clear and urgent message: India's energy system is being recalibrated around thermal discomfort. The seasonal, daily, and projected demand trends confirm that rising temperatures are not merely increasing total electricity consumption but are sharply altering when and how that energy is used. This has profound implications for grid planning, capacity expansion, and energy policy. Without coordinated intervention, unmanaged growth in cooling demand could lead to chronic peak load stress, inefficient load balancing, and heightened reliance on carbon-intensive backup generation.

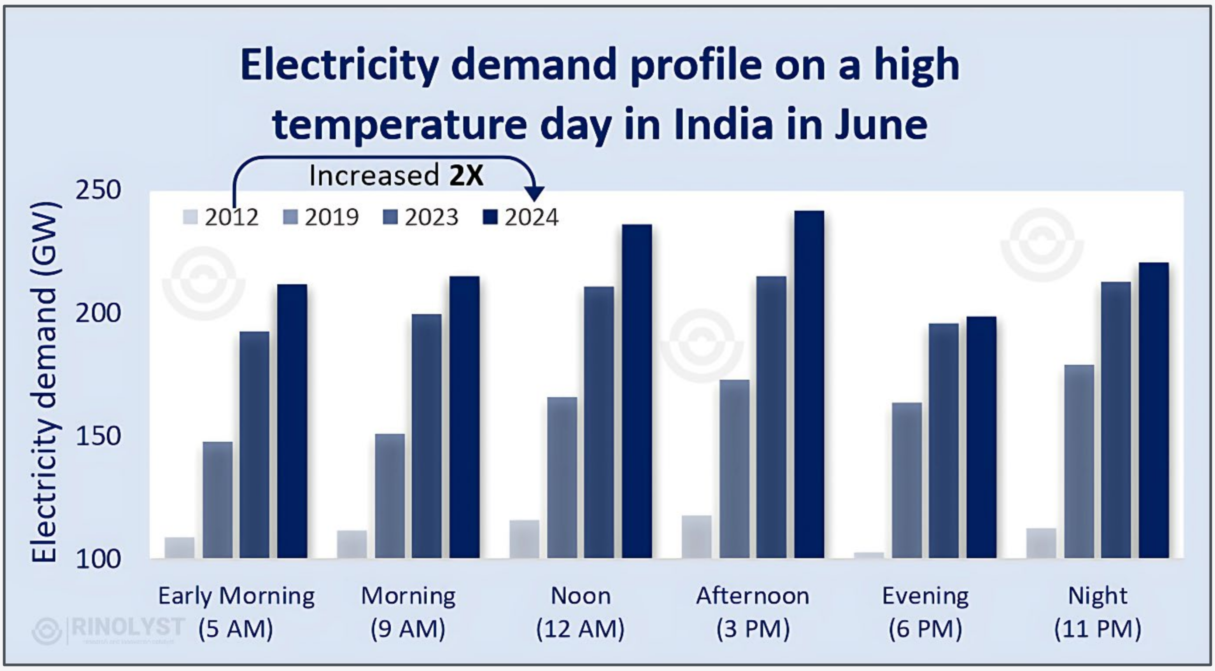


Figure 5: Electricity demand on high temperature day in June in India (2012-24)[8,9,10,11].

The summer quarter has emerged as the pivotal stress point for India's power grid, where even modest rises in temperature now trigger disproportionately large surges in electricity demand. This shift is not merely seasonal but systemic, with climate-induced heatwaves reshaping the country's baseline and peak energy consumption patterns. Cooling loads, particularly from the rapid proliferation of room air conditioners, are driving much of this new demand. As thermal discomfort deepens across geographies and income groups, the imperative to cool is becoming more widespread, yet unevenly accessible. Addressing this growing pressure requires a two-pronged strategy: widespread deployment of super-efficient, regionally adapted cooling appliances and simultaneous investment in passive design, ventilation, and climate-responsive urban planning. Crucially, energy efficiency must take the lead, with India aiming to double the efficiency of its cooling systems while scaling their compatibility with renewable energy, particularly solar[12,13]. Without such integration, India's cooling transition risks becoming a structural burden on energy security, emissions goals, and economic equity. Tracking how the appliance market evolves today will determine whether India's cooling future is one of resilience and sustainability, or growing grid instability and emissions growth.

Improvement in Star Ratings

India's cooling sector has seen a structural transformation in energy performance standards, driven by both technological innovation and regulatory recalibration. Since 2010, the Bureau of Energy Efficiency (BEE) has progressively raised the bar for what qualifies under each star label through multiple revisions of the Minimum Energy Performance Standards (MEPS). These regulatory shifts have ensured that the same star rating today corresponds to significantly higher efficiency than it did a decade ago (Figs. 6 and 7).

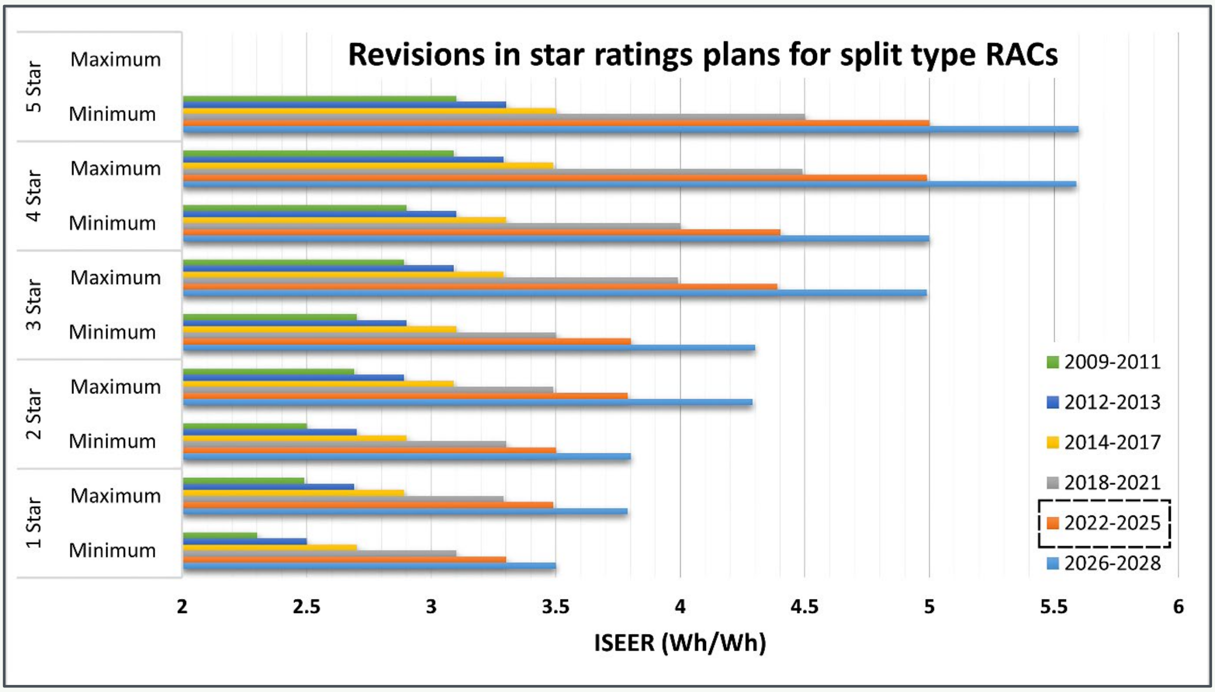


Figure 6: Revision pattern of India RACs (split type) (2009–2028)[14,15].

For example, 5-star split inverter ACs today are around 60% more efficient than their 2010 counterparts, while even the lowest-rated (1-star) split models have improved by about 43% (Fig. 8). This rising baseline, plotted through successive ISEER thresholds, is reshaping the cooling appliance landscape and setting the technical tone for India's energy transition. Despite these gains, the progress is uneven across product types and market segments. Window or unitary ACs, which remain more accessible to low-income consumers, have exhibited far more modest improvements, just 13 to 17 percent since 2010, highlighting a persistent technology and affordability gap. This has real-world consequences: less efficient models not only consume more electricity over their lifetime but also place a disproportionate financial burden on economically vulnerable households.

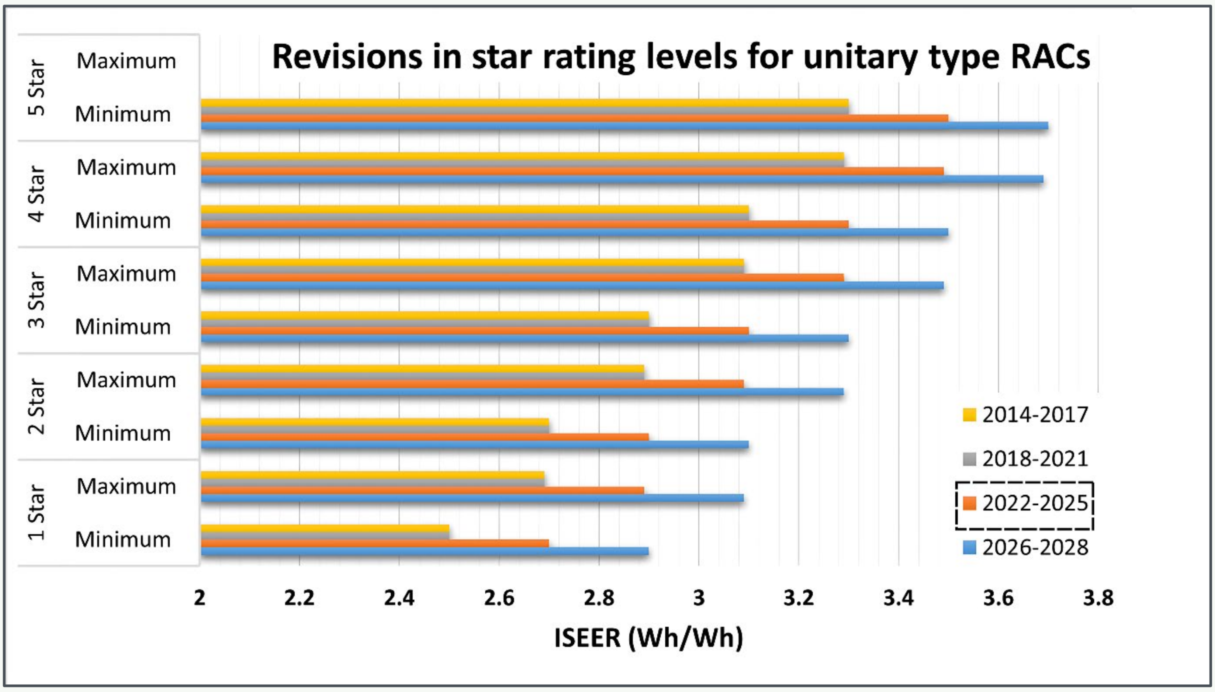


Figure 7: Revision pattern of India RACs (unitary type) (2009–2028)[14,15].

While inverter ACs offer significantly better seasonal performance and long-term savings, their higher upfront cost remains a key barrier to equitable adoption, especially in states

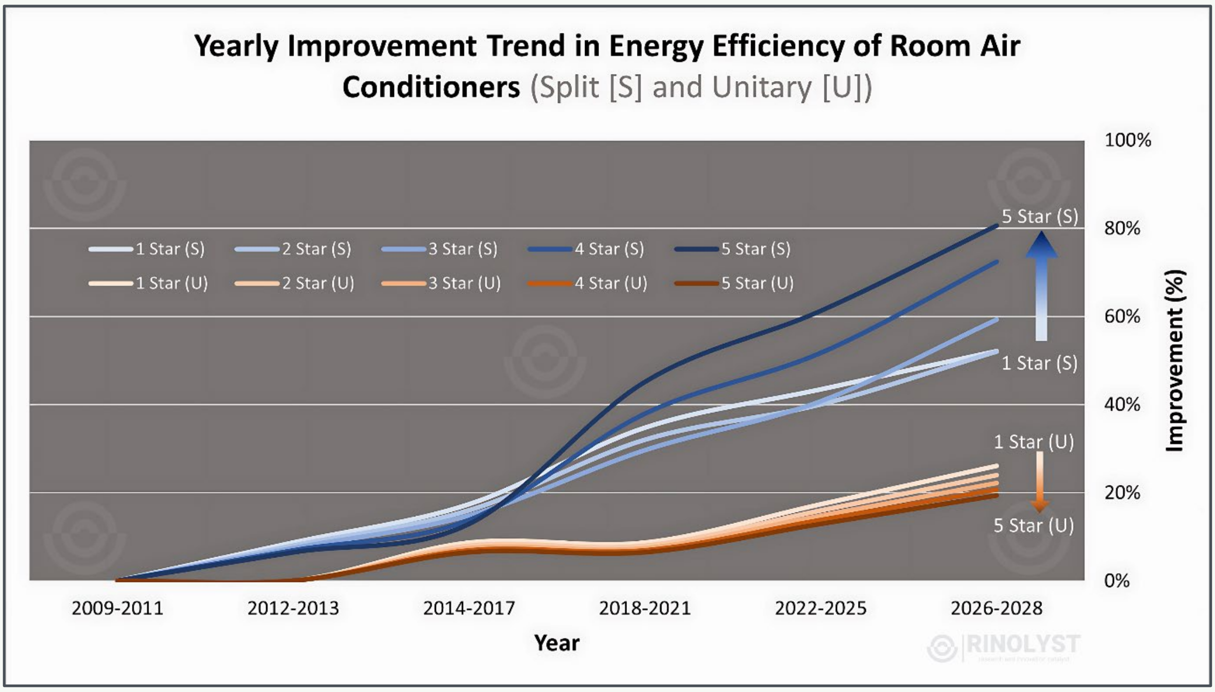


Figure 8: Improvement in energy efficiency of India RACs (2009–2028).

with low per capita income and electricity use. The rapid transformation in market share underscores the success of India's policy interventions. In 2015, inverter-based RACs held just 1% of the market (Fig. 9). By 2023, they accounted for over 77%, displacing fixed-speed units through mandatory labelling, revised efficiency metrics like ISEER, and growing consumer preference for performance and cost-effectiveness. However, this shift also calls attention to the need for continuous support through domestic manufacturing, affordability mechanisms, and smarter financing to scale adoption further.

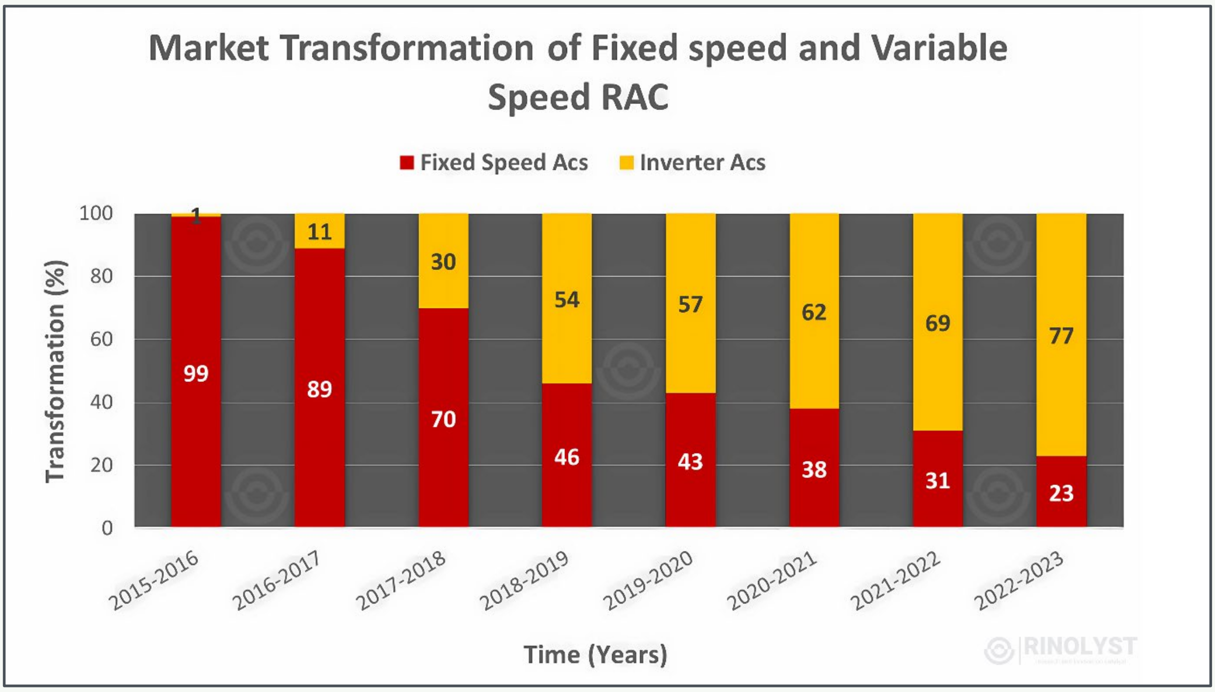


Figure 9: Market transformation of India RACs (2015–2023)[15].

Understanding the shifts in AC production, the changing market shares of unitary and split systems, and the rise of ultra-efficient inverter technologies is essential to assess where India stands in its cooling transformation. These trends not only shape domestic manufacturing and technology pathways but also determine the country's progress toward its broader energy efficiency, emissions reduction, and net-zero ambitions.

As India becomes increasingly vulnerable to heatwaves, essential cooling appliances like ceiling fans, refrigerators, and air conditioners play a vital role in thermal comfort and public health. Between 2018 and 2022, production of domestic cooling appliances was dominated by refrigerators (57%), followed by air conditioners (32%) and ceiling fans (11%), with air conditioner manufacturing showing a clear shift toward variable-speed technology over fixed-speed units (Fig. 9).

Shares of Domestic Cooling Appliances Production (2018-2022)

Room Air Conditioners	2018-19	2019-20	2020-21	2021-22	Total
Fixed Speed	3304280	3797043	2511348	2543997	12156668
Variable Speed	3924884	5050951	4113958	5749914	18839707

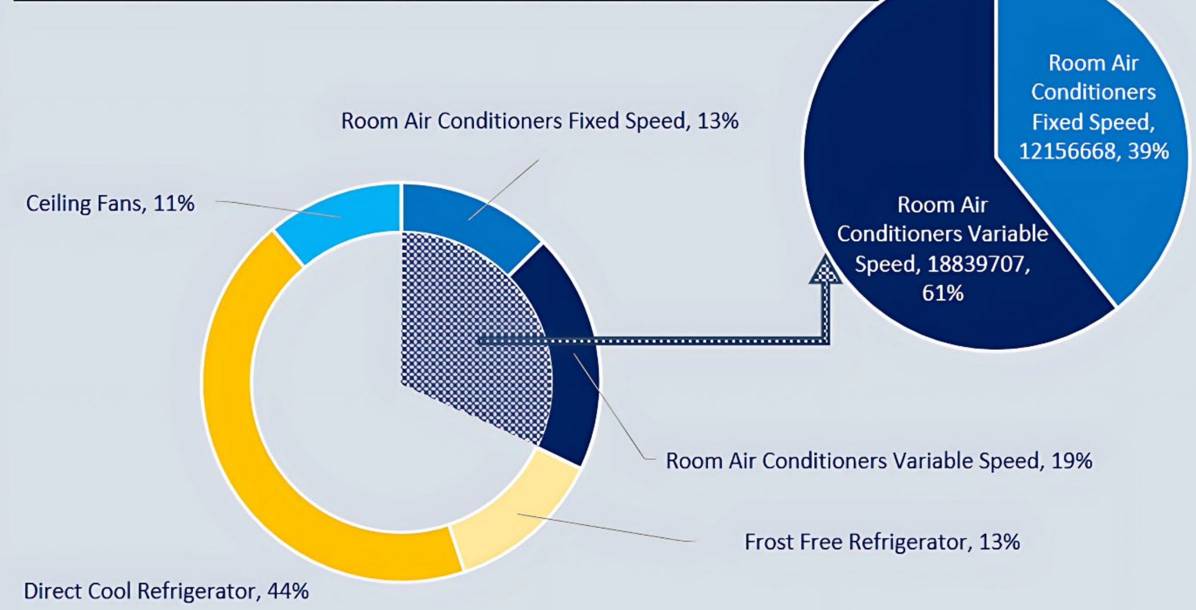


Figure 9: Share of domestic cooling appliances production volume (2018-2022)[1].

India's room air conditioner landscape reveals a complex interplay of performance clustering, pricing strategies, and market segmentation that shapes both the technological progress and energy efficiency outcomes. Among the nearly 2,900 inverter split AC models assessed, a large fraction of the 1-ton and 1.5-ton variants cluster tightly within the 3-star and 5-star bands, while 4-star models remain notably sparse. The 3-star category, defined by ISEER values ranging from 3.8 to 4.39, absorbs the

Ratings, Markets, and Missed Potential: The Efficiency Gap

bulk of production and consumer demand, but this efficiency is often superficial. A striking number of models lie just above the 3.8 threshold, indicating a minimal-effort upgrade from the 2-star tier (Fig. 10). This trend reflects a calculated move by manufacturers to achieve star-label eligibility at the lowest innovation cost, enabling higher pricing without significant performance gains.

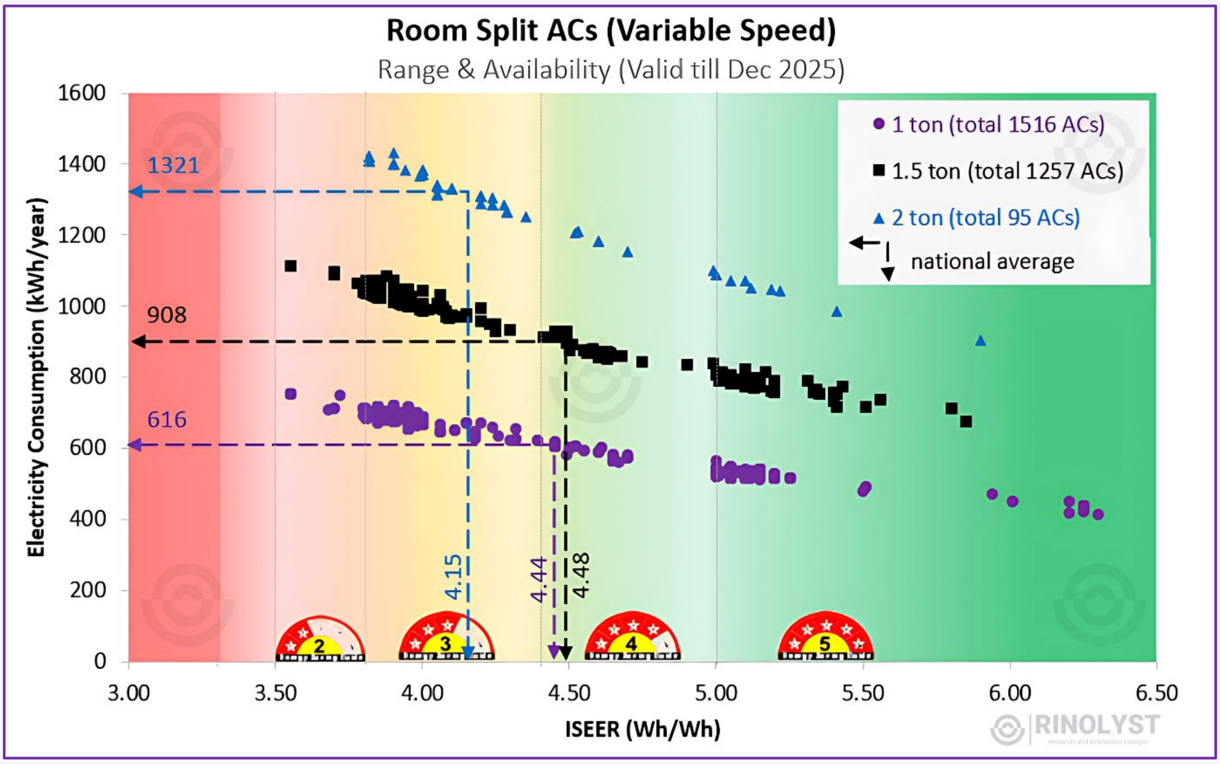


Figure 10: Annual energy consumption and energy efficiency rating (ISEER) of available variable speed RACs (1-, 1.5-, and 2-tons categories) in Indian market[16].

This pattern extends to the 4-star and 5-star tiers as well. In the 4-star bracket (ISEER 4.4 to 4.99), most models cluster just above 4.4. Similarly, within the 5-star category (ISEER ≥ 5.0), the majority barely clear the threshold. While some manufacturers do offer ultra-efficient models with ISEER values well above 6.0 and annual energy consumption as low as 400 kWh/year (Fig. 11), these are outliers rather than the norm. Such units often serve more as technological showcases or premium offerings than as mass-market solutions. As a result, although over 39 percent of 1-ton and 1.5-ton models are labeled as 5-star (Fig. 12), the national weighted average for both capacities hovers precariously near the boundary between 3 and 4 stars (Fig. 10). For 2-ton ACs, the average performance drops more clearly into the 3-star range.

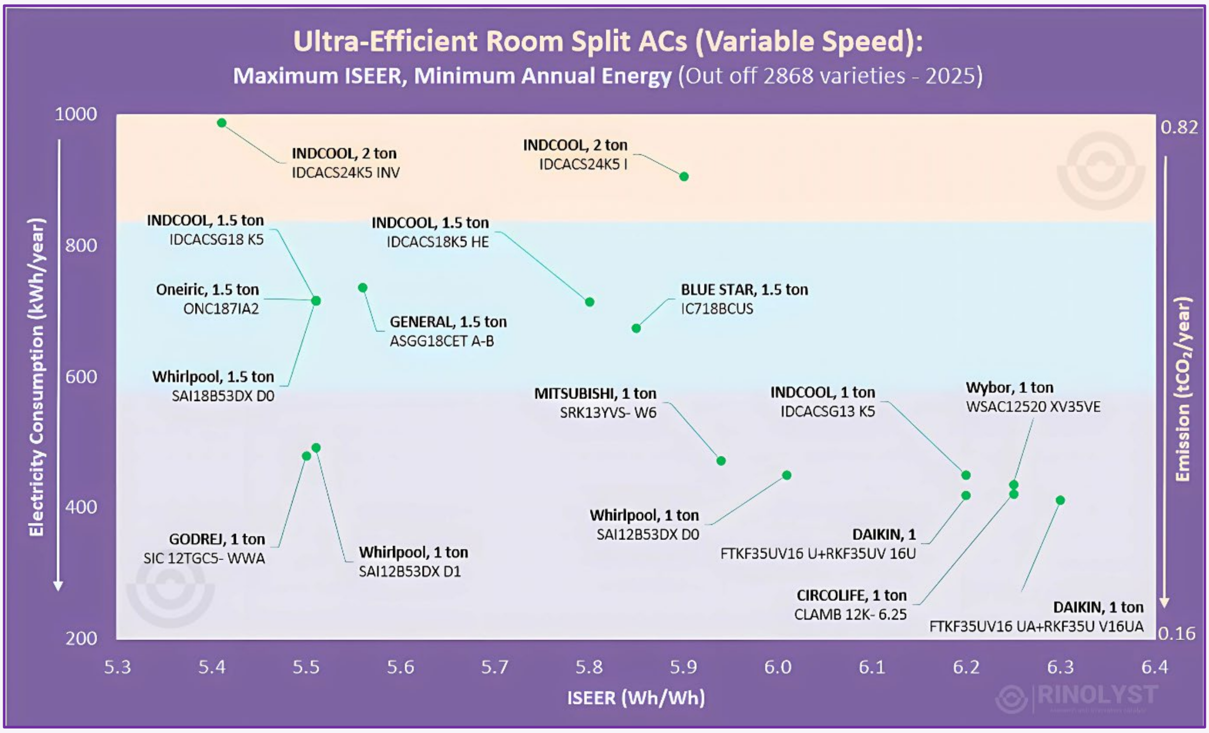


Figure 11: Annual energy consumption and energy efficiency rating (ISEER) of available variable speed RACs (1-, 1.5-, and 2-tons categories) in Indian market[16].

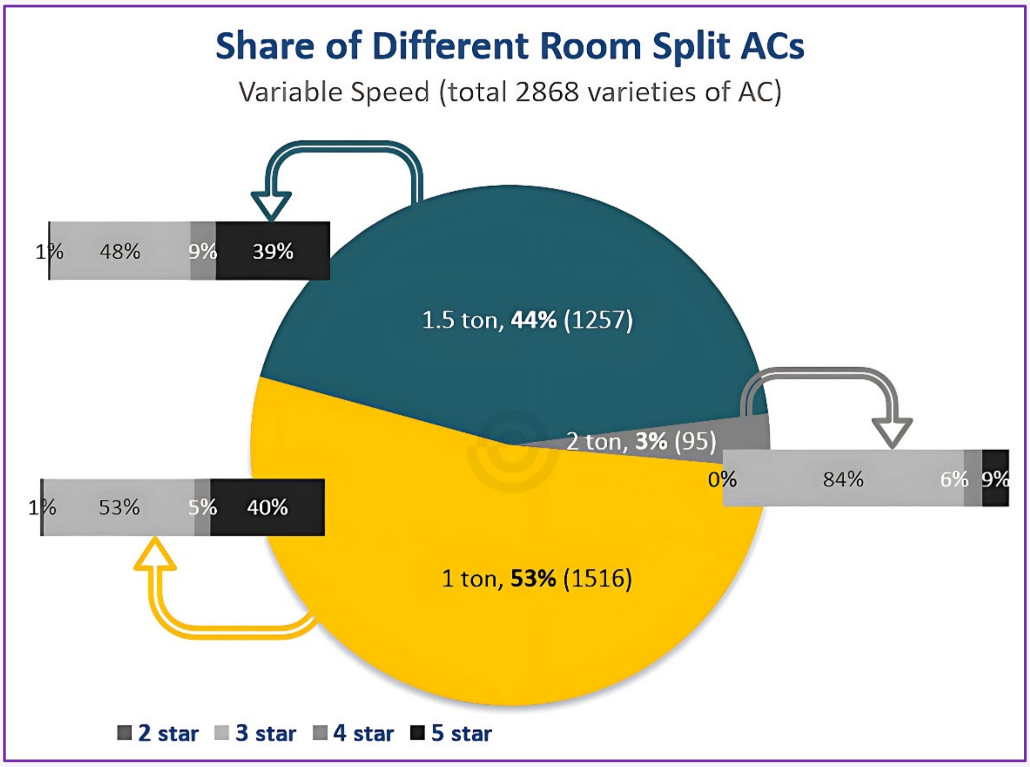


Figure 12: Annual energy consumption and energy efficiency rating (ISEER) of available variable speed RACs (1-, 1.5-, and 2-tons categories) in Indian market[16].

This efficiency gap is further evident when analyzing actual energy consumption. While top-performing 1-ton models consume only around 400 kWh annually, the weighted national average is closer to 616 kWh/year (Fig. 10). In the 1.5-ton segment, efficient units exist at approximately 700 kWh/year, yet the average remains near 908 kWh/year. For 2-ton units, best-in-class performance is around 900 kWh/year, but the national average climbs to 1321 kWh/year. These figures signal that although ultra-efficient technology is being manufactured, it is not widely adopted or purchased, either due to cost, accessibility, or consumer awareness. From the supply side, manufacturers have clearly demonstrated the ability to produce highly efficient ACs. However, the choice to cluster around the lowest edge of star bands reflects a strategic business model: offer a high star rating with minimal cost inputs to maximize perceived value and margin. This approach exploits regulatory thresholds rather than embracing true energy performance. Moreover, since star ratings in India are still broad in scope, consumers are unable to differentiate between a minimally compliant 5-star AC and one with significantly better energy metrics, both labeled the same.

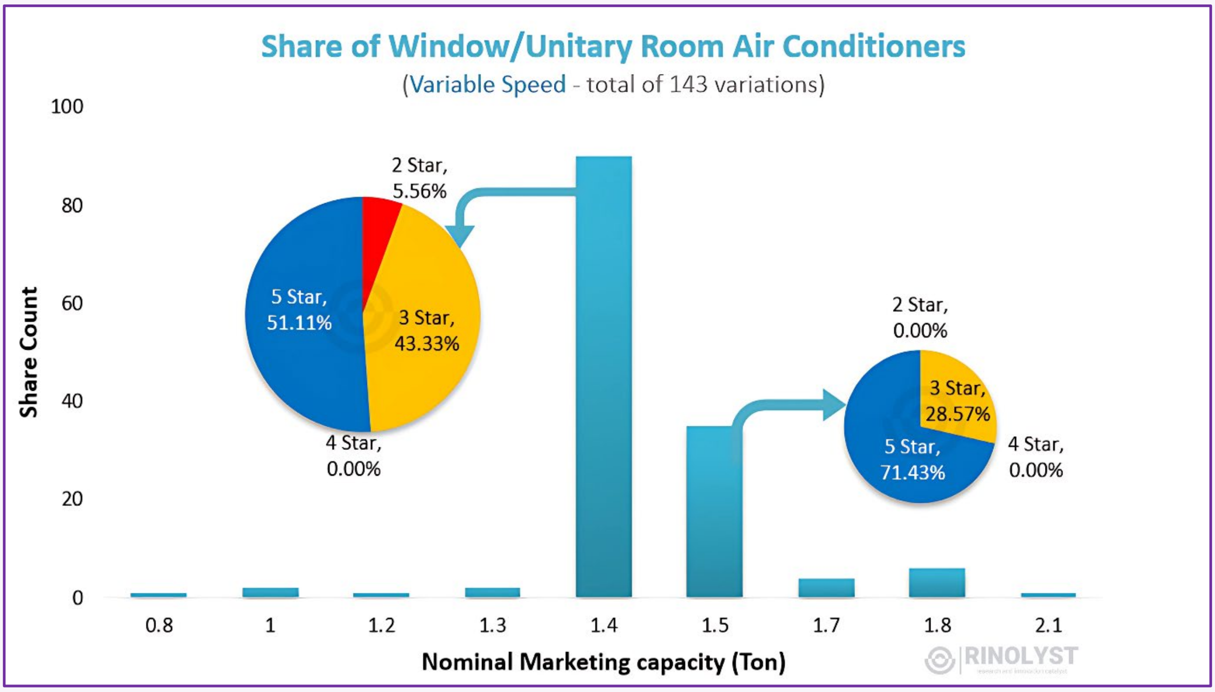


Figure 13: Share of window/unitary variable speed RACs of varying capacity in Indian market (valid till December 2025)[17].

From the demand perspective, consumer behavior reinforces this skew. Price-sensitive buyers, especially in lower and middle-income groups, often base decisions on visible markers like star labels rather than actual kWh consumption. Without clear, simplified disclosures about actual operational efficiency or lifecycle savings, the average buyer gravitates toward the least costly unit within the highest possible star band. The result is a high-volume market for low-end 3-star models that offer nominal compliance but poor long-term performance. This mismatch between policy, product design, and purchasing behavior creates systemic inefficiencies. Most notably, the weighted national ISEER does not reflect the technological potential currently available in the market. Instead, it reflects a market diluted by just-passing models, limited consumer knowledge, and pricing tactics that reward compliance over excellence. Encouragingly, India's push for domestic manufacturing under initiatives like "Make in India" could offer a breakthrough, even some of the startups in this sector have been doing great (Fig. 11). With clear efficiency roadmaps, smart and targeted production incentives, and labelling reforms that go beyond star ratings, India could position its cooling industry for regional leadership. Supporting this ecosystem with buyer-side subsidies linked to actual energy savings, rather than nominal labels, could make ultra-efficient ACs more accessible to low- and middle-income consumers, while expanding the market for performance-driven innovation. Looking ahead, India's energy and climate goals demand a realignment of both supply and demand incentives.

The global comparison of AC efficiency ratings paints a compelling picture of divergence between technological potential and real-world adoption, particularly for India. Globally, India's average efficiecny rating for split ACs stood at just 2.9 in 2012–2013, significantly lower than countries like Japan (4.1), Korea (3.78), and the EU (3.22)[18]. Even by 2020, IEA data shows Indian households continued to favor lower-efficiency units (Fig. 14), averaging around 3.2, compared to 4–5 in the US, Korea, and China, and over 5.0 in Japan and Europe and countries like USA and Eurpoe offer models surpassing 11-12 W/W [19],[20]. It is all driven by aggressive minimum energy performance standards (MEPS), consumer incentives, and innovation ecosystems, India remains stuck at an average ISEER of around 3.5–4.0 W/W despite the domestic availability of units performing above 6.0 W/W. This gap is not due to technical limitations but is symptomatic of policy inertia, weak enforcement, and lack of consumer-centric regulatory design. The persistence of low-efficiency models in the Indian retail ecosystem undermines both climate goals and long-term economic efficiency, given the rapidly growing demand for cooling. While India now offers ultra-efficient models reaching EER values around 6.3 (in 2025), courtnies like

Europe and USA has already advanced beyond 9-14 W/W, highlighting a substantial gap and the need for accelerated efficiency adoption[21].

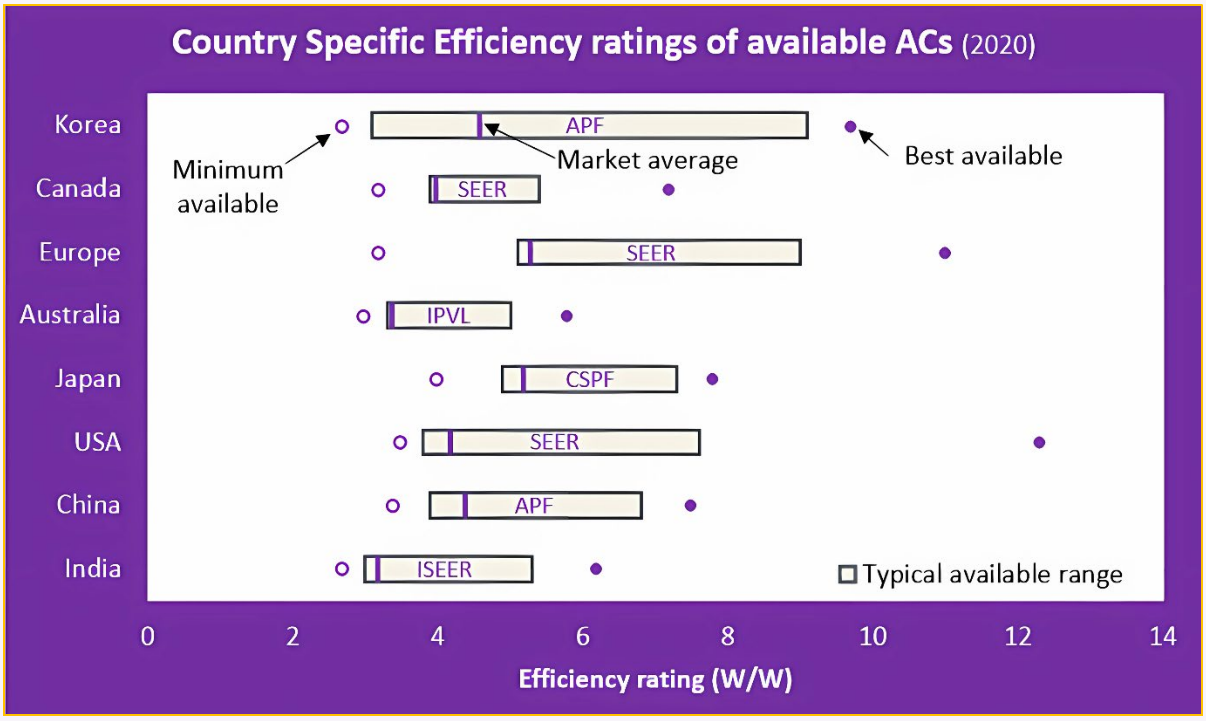


Figure 14: Energy efficiency ratings of ACs in different countries[20].

This global benchmarking underscores the urgent need for India to not just manufacture, but also promote and normalize the adoption of higher-efficiency models to meet its net-zero and energy security targets. As international markets migrate toward next-generation standards like SEER2 in the U.S. (reaching up to 28) and adopt refined labelling structures such as Europe's A+++ to G scale, India's current five-star system, with overly broad banding and insufficient granularity, fails to inform or influence consumer choice meaningfully[21,22,23]. A transition to a modernized labelling framework with 8–10 efficiency categories, enhanced with color coding or tiered 5-star distinctions (e.g., 5-Star+, 5-Star Gold), would provide the nuanced differentiation needed in today's market. To significantly elevate India's national average air conditioner (AC) efficiency and bridge the persistent mismatch between high-efficiency availability and low-efficiency adoption, a deliberate contraction of the typical available efficiency range is both necessary and strategic. Contracting (narrowing) the available AC efficiency range by narrowing the gap between what's technically achievable and what's widely adopted (national average) along with simultaneous increasing this range to higher efficiency rating could be an effective approach. Countries like Japan, Canada, and Australia exemplify how regulatory coherence, performance-focused labelling, and market discipline can yield high average efficiency ratings while maintaining a narrow spread between minimum and maximum performance offerings. Simultaneously, contracting the available range by eliminating sub-3-star models and aligning MEPS to reflect global mid-tier standards would drive the market toward a new equilibrium of high-performance defaults. This shift, supported by green financing, retail interventions, and targeted subsidies, could catalyze a virtuous cycle of demand for efficient appliances, investment in domestic R&D, and competitive innovation. As India stands on the cusp of a massive surge in residential cooling demand, such a realignment is not only urgent but also strategically advantageous, both for decarbonization and for establishing India as a hub for high-efficiency, climate-aligned cooling technologies suited for the Global South.

Ultimately, India's cooling future cannot rely solely on incremental improvements or badge-based marketing. It requires deep structural reforms in labeling, performance disclosure, and consumer awareness, backed by robust incentives and accountability mechanisms. The story told by the current data is not just about efficiency gaps, but also about opportunity, one that remains untapped unless policies, industries, and markets evolve in sync. These findings call for a deeper interrogation of the socio-economic dynamics shaping India's cooling transition. Understanding how income disparities, electricity access, and regional development patterns influence the affordability and adoption of efficient cooling solutions is essential to designing equitable and effective policy responses. This lens is especially vital as India aims to balance its cooling imperative with energy security, climate targets, and inclusive economic growth.

Cooling the Inequality Curve: Income, Electricity, and Emission

The intersection of income and electricity consumption in India reveals an evolving narrative about economic mobility, technological accessibility, and climate responsibility. Analyzing the per-capita electricity consumption against per-capita income (2022–2023) (Fig. 15) unveils a non-uniform distribution of readiness for appliance-based cooling adoption. The quadrant demarcations in the dataset indicates a striking divide. In the upper-right quadrant, shaded distinctly (little darker, Fig. 15) in the plot, lie states like Goa, Delhi, Gujarat, Telangana, and Haryana. These states exhibit high per-capita income as well as elevated electricity consumption, positioning them as regions where households not only can afford cooling appliances but are also more likely to opt for higher ISEER-rated (3-star to 5-star) air conditioners due to better financial capacity and electricity infrastructure. These states are thus primed for accelerated deployment of premium energy-efficient cooling solutions that strike a balance between cost-effectiveness and environmental responsibility.

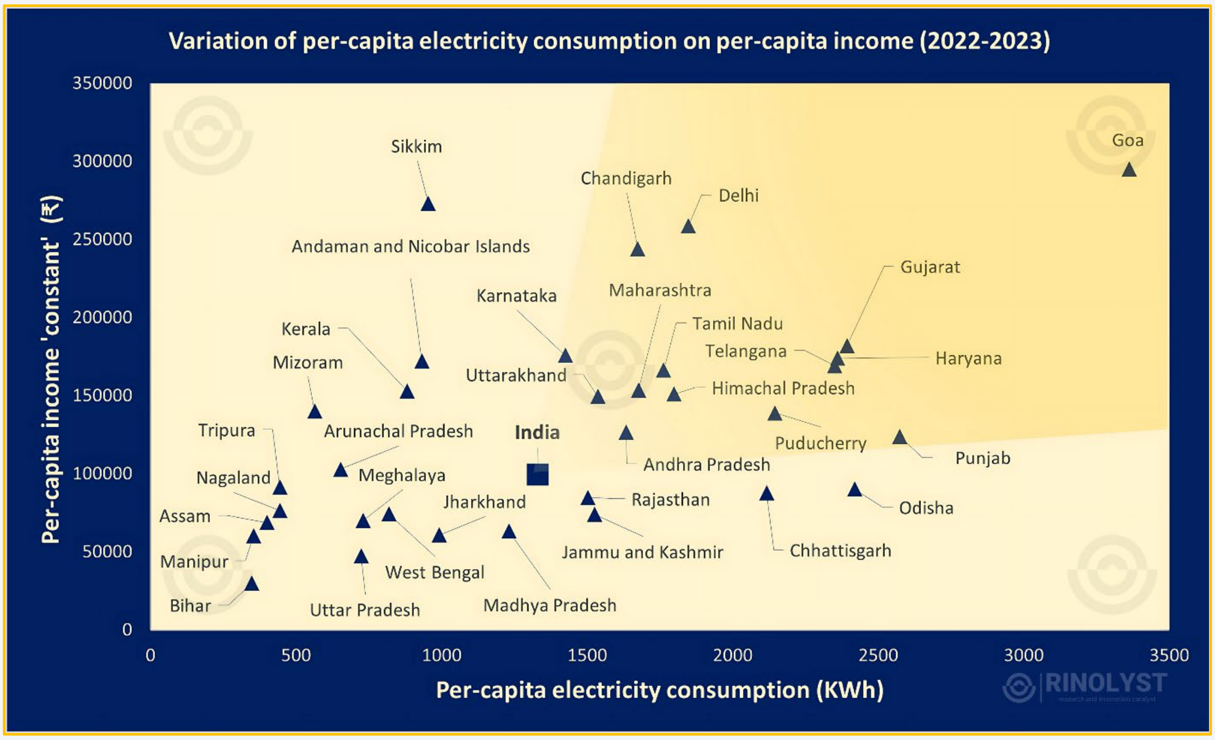


Figure 15: National and state-wise per-capita electricity consumption and per-capita income (at constant price)[24,25,26].

On the opposite end, states clustered in the lower-left quadrant, such as Bihar, Uttar Pradesh, Assam, and Manipur, represent a critical policy conundrum. These states face intense thermal stress and have pressing cooling needs, yet suffer from both low income and limited electricity consumption/access. For these regions, the push must be toward ultra-low-cost, low-power cooling appliances with higher energy efficiency per rupee spent. Here, the cooling transition cannot be a passive market evolution; it must be guided by inclusive industrial policy, targeted subsidies, and equitable energy provisioning. Solutions to bridge these disparities must operate across multiple axes. One critical strategy is a robust push toward "Make in India" for energy-efficient appliances. Domestic manufacturing of low-cost, efficient ACs tailored for low-income, high-heat states could address both affordability and accessibility challenges. Coupling this with production-linked incentives and regional supply chains would also bolster local economies. Furthermore, decentralizing energy sources by promoting solar-powered ACs and encouraging rooftop PV integration, especially in rural and semi-urban areas, can reduce grid dependence and operating costs. Demand-side interventions must complement this. Drawing from the success of the LED distribution program, a centralized bulk procurement mechanism for ACs could dramatically lower prices and catalyse mass adoption. Direct Benefit Transfers (DBTs) linked to energy efficiency purchases, particularly in economically vulnerable states, could help surmount first-cost barriers. Moreover, deploying state-specific cooling action plans, coordinated under a harmonized national framework will allow for targeted strategies that reflect unique climatic, economic, and infrastructural realities. Beyond the technological and economic frontiers lies the imperative of public awareness and behavioural change. Lifespan cost calculators, ISEER labelling literacy, and digital platforms that help consumers choose the best-fit AC based on regional climate and income bracket can empower households to make sustainable choices. Importantly, the cooling transition must be guided by the principle that efficient comfort is a right, not a luxury, a climate adaptation imperative rather than an economic afterthought. At the national level, represented as a bold square marker in the comparative plots, India exhibits a median profile, with per-capita income around ₹99,400 and per-capita electricity consumption close to 1330 kWh for 2022–2023. This centrality masks deep inter-state disparities but offers a baseline for policy calibration.

The longitudinal plot of 2009–2010 to 2022–2023 (Fig. 16) reveals an unmistakable trend: nearly all Indian states have moved upward and to the right, confirming a positive relationship between income growth and electricity usage. However, the steepness of the trajectories varies. First, a handful of states like Goa, Delhi and Chandigarh, shoot almost vertically upward, more than quadrupling their per-capita electricity use even as incomes doubled. These high-affluence, high-consumption outliers signal markets already hungry for comfort, and thus are prime candidates for pilots in smart, solar-coupled cooling systems, time-of-use tariffs and demand-response programs that shave peak load while rewarding efficiency. Second, a broad middle band, Maharashtra, Tamil Nadu, Karnataka, Telangana and West Bengal, shows steady, roughly proportional gains in both income and kWh. Their moderate slopes suggest an emerging mass-market for mid-tier inverter ACs (4-5 stars), so subsidy schemes here should gradually transition from supporting basic

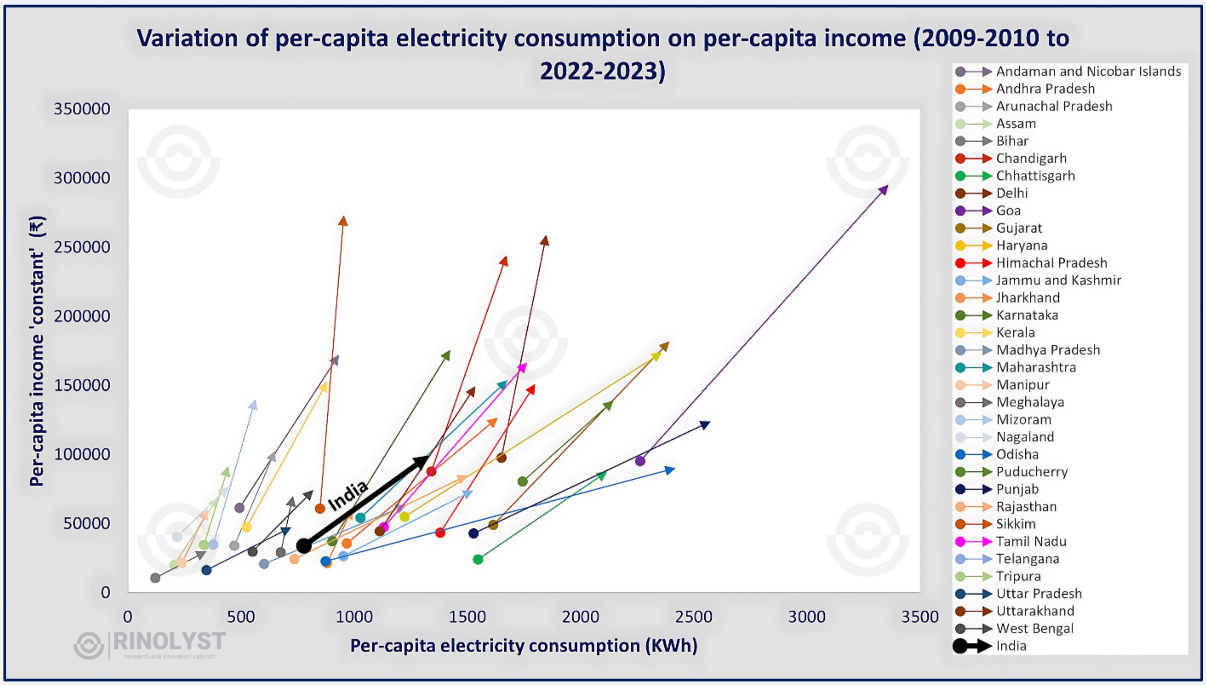


Figure 16: Improvement in national and state-wise per-capita electricity consumption and per-capita income (at constant price) from 2009-10 to 2022-23[24,25,26].

window units toward incentivizing higher-efficiency split systems. Bulk procurement and public-sector lead-by-example (schools, hospitals) in these states could accelerate the efficiency upgrade without distorting nascent market dynamics. Third, In the long tails at the lower left states such as Bihar, Uttar Pradesh, Assam and the Northeast, ambient heat and humidity are already extreme, yet purchasing power and grid access remain limited. Simply promoting fans or evaporative coolers will not suffice in places like Patna, one of the world's most humid cities. Instead, we must deploy ultra-efficient, low-capacity inverter ACs (ISEER ≥ 4.5 Wh/Wh) specifically engineered for minimal power draw

(≤ 500 W at full load) and offer them at heavily subsidized prices, financed through a "cooling equity" rebate tied to a modest carbon-tax surcharge on high-GWP refrigerant imports. Under this scheme, each kilowatt-hour saved by an eligible household would earn a direct bill credit, effectively turning efficiency into an immediate cash-back. Bundled with micro-loan repayment via small monthly surcharges on electricity bills and community-scale solar support, this targeted package would deliver real cooling relief where vulnerability is greatest, aligning public health, equity and climate objectives in one practical program. At the national median (the bold black arrow), India has moved from roughly ₹33 000 and 780 kWh in 2009-10 to ₹99 000 and 1 330 kWh in 2022-23, tripling income and nearly doubling electricity use. This central trajectory underscores that, without differentiation, a one-size-fits-all policy risks overshooting in some states and underserving others. Instead, a three-tiered strategy, premium efficiency pilots in the high-affluence quadrant, efficiency-ladder incentives in the mid-market band, and basic access plus ultra-low-cost cooling in the laggard cluster, will align technology deployment with both climatic urgency and economic capacity, ensuring that India's cooling transition is effective, equitable and climate-responsible.

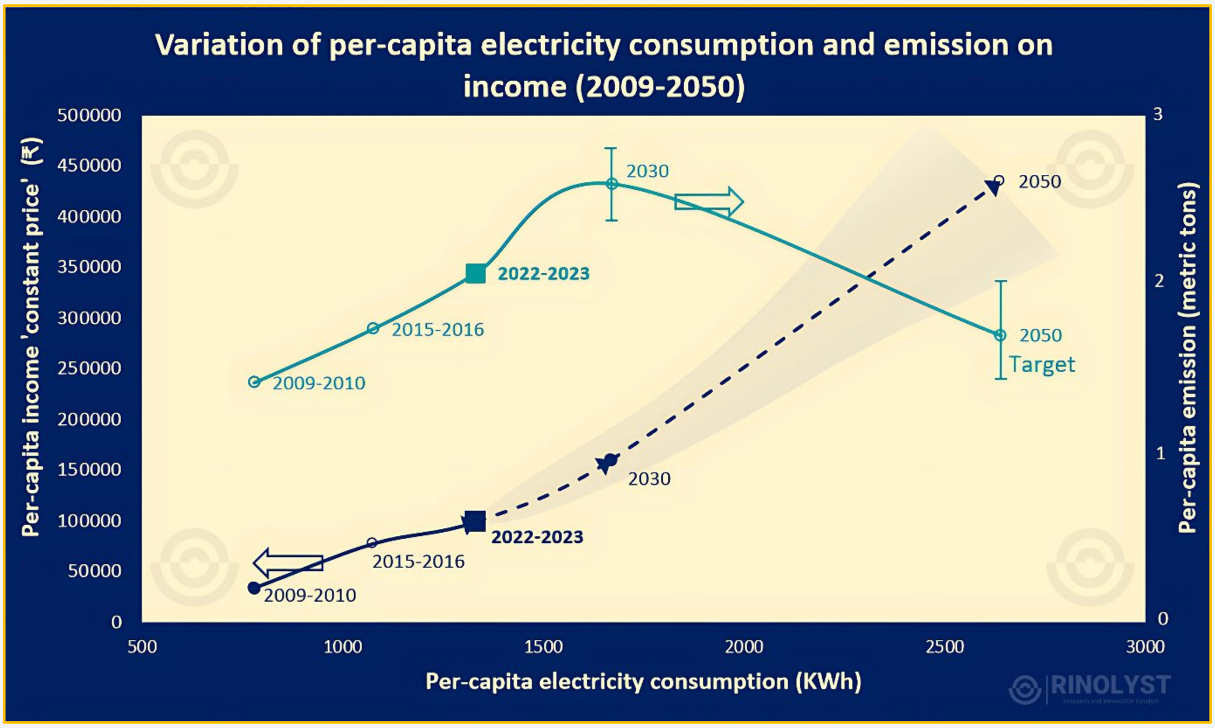


Figure 17: Improvement in national per-capita electricity consumption, per-capita emission, and per-capita income (at constant price) from 2009-2050 (projected with basic adjustment)[24,25,26,27,28,29].

Looking toward 2030 and 2050, the forecasts provide a blueprint of possibilities. By 2030, India is expected to reach a per-capita income of approximately ₹1.6 lakh and electricity consumption of 1670 kWh, with emissions per capita peaking at 2.6 metric tons (Fig. 17). However, the most encouraging trend is the anticipated decline in per-capita emissions to 1.7 metric tons by 2050, despite a surge in income (₹4.35 lakh) and electricity use (2638 kWh). This inflection indicates a probable decoupling of emissions from growth, predicated on a strategic blend of renewable integration and efficiency improvement. This shift is not coincidental but reflects deliberate structural shifts in energy systems and technology deployment. Even, as Indian incomes and household electricity use surge per person by 2030, per-capita CO_2 from that electricity (green curve on the right axis) can peak near 2.3-3 metric tons and then fall toward ~1.3-2 metric tons by 2050 under different scenario. This peak and decline pattern signal a pivotal inflection: although economic growth and electricity consumption continue upward, emissions begin to decouple after 2030, reflecting the projected impact of efficiency gains, cleaner generation, and high-performance cooling technologies. In the context of air-conditioning, this "decoupling" demands three concurrent shifts: first, continue driving the share of high-ISEER inverter ACs well past today's ~77 % of sales, phasing out sub-4 Wh/Wh models; second, pair new AC installations with rooftop solar "cooling kits" and on-site storage so that at least 30 % of cooling load is met by clean power; third, deploy targeted subsidies or carbon-rebate schemes in heat-vulnerable, lower-income states to accelerate replacement of legacy window units with ultra-efficient mini-splits. By merging stringent efficiency standards, solar-coupled operation and equity-focused finance, India can bend the green emissions curve downward even as millions more homes come online with air conditioning. In essence, India stands at a critical juncture where it must "cool smartly", aligning its economic ambitions with environmental stewardship and social equity. If managed correctly, cooling can evolve from an emissions liability into a cornerstone of resilient infrastructure, a driver of green jobs, and a pillar of India's sustainable development agenda. The confluence of economic growth, rising electricity use, and climate targets does not have to be a collision course, it can be a carefully choreographed transition toward a cooler, fairer, and cleaner future.

India's tropical and sub-tropical climates, with prolonged periods of high humidity and temperatures, impose dual burdens on air conditioning systems: removing both sensible (temperature) and latent (humidity) heat; means, simultaneously cooling and dehumidification by overcooling air below its dew point. This process is inherently inefficient and thermodynamically constrained, often leading to excessive electricity consumption and increased emissions from reheating needs and refrigerant loads. As of 2016, the humidity load alone accounted for 599 $MtCO_2eq$, 31% (Fig. 17) of all air conditioning emissions (53% of cooling energy emissions) and over 1% of total global greenhouse gas emissions[5]. By 2050, under business-as-usual scenarios, India's humidity-related cooling emissions are projected to approximately 1,360 $MtCO_2eq$ annually, nearly 35-40 times the the humidy load in 2016[5]. Countries such as India, China, Japan, South Korea, and Indonesia exhibit a higher proportion of latent cooling load (humidity control) compared to sensible cooling load (temperature reduction)[5,32]. Technological innovation offers a powerful lever to counter this trend. Hybrid systems that decouple the handling of sensible and latent loads, combining vapor compression cooling with desiccant-based or membrane-based dehumidification, can deliver 1.5–3 times higher energy efficiency and up to 42% reduction in cooling energy emissions[5]. For instance, systems utilizing liquid desiccants

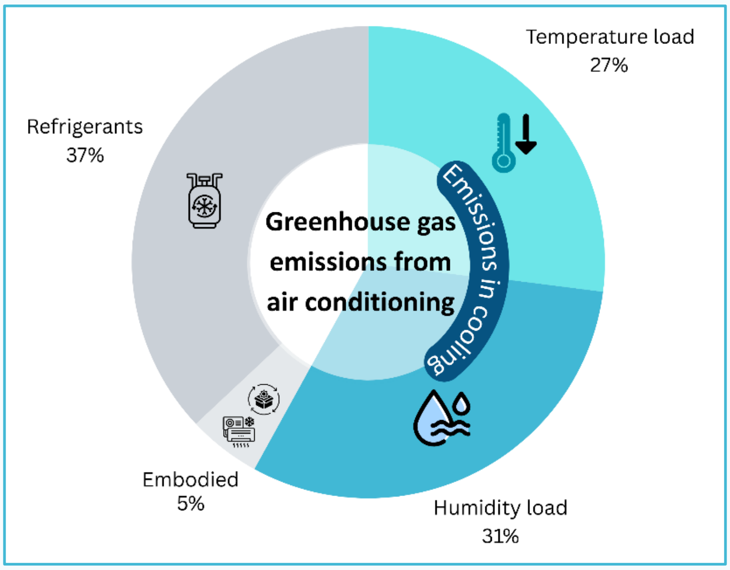


Figure 17: Bifurcation of Greenhouse gas emissions (GHG) from air conditioning (2016)[5].

Decoupling Cooling & Dehumidification

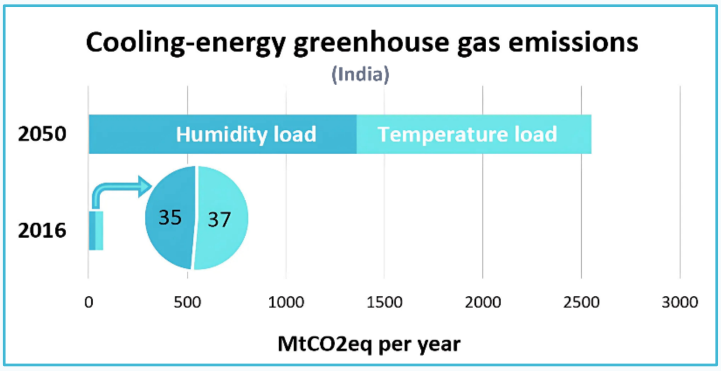


Figure 18: Annual emissions from cooling[5].

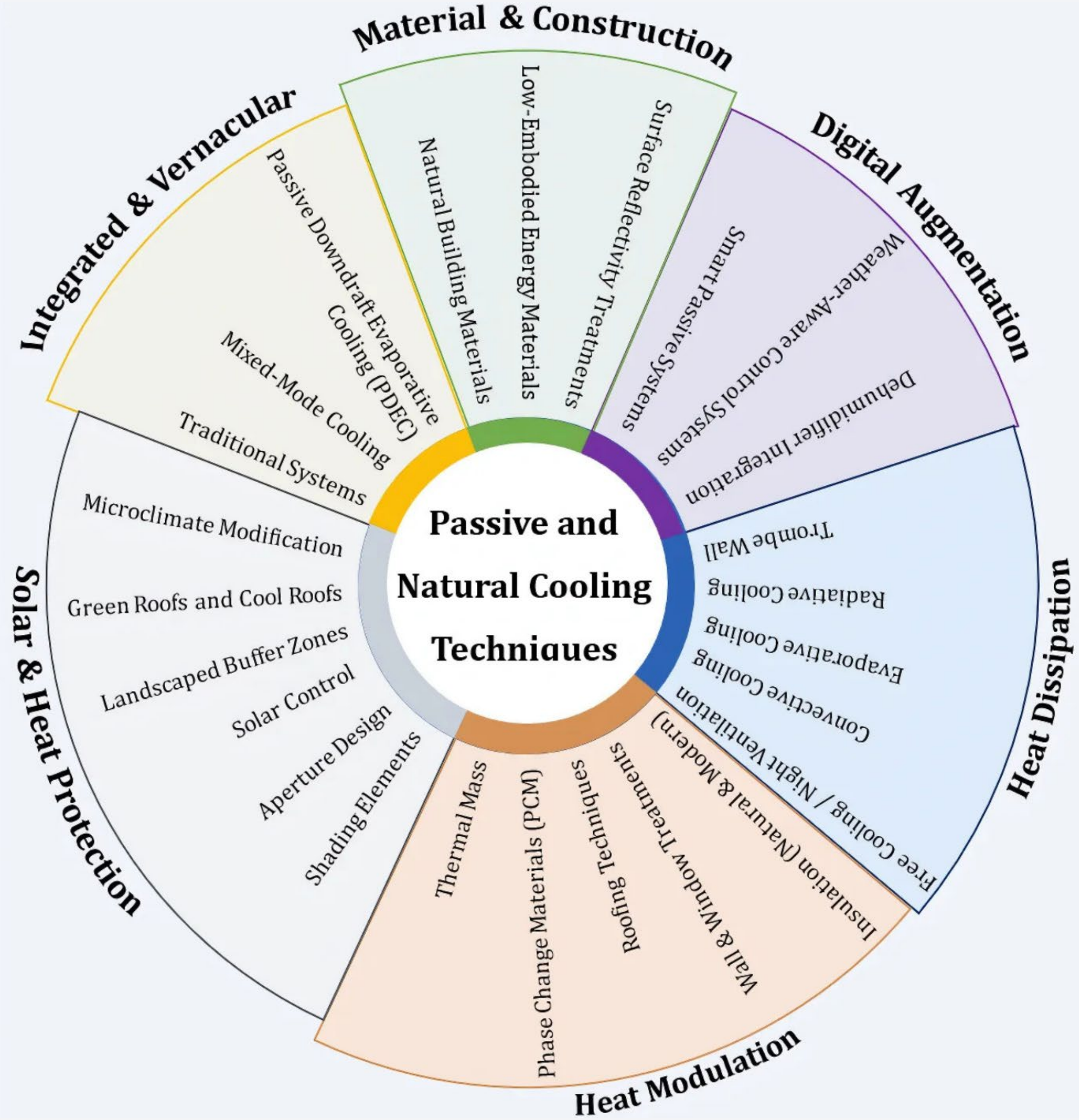
regenerated by solar thermal or industrial waste heat not only shift the energy burden away from the grid but also align with India's renewable energy goals. Furthermore, advanced concepts such as membrane-based vapor compressors, thermo-responsive desiccants, and electrochemical separation of moisture represent a new frontier, potentially bypassing the thermodynamic limitations of cold-surface condensation. Research also points to hybrid systems such as those integrating a liquid lithium chloride dehumidifier with conventional cooling, showing 20–100% improvements in COP under varying climate conditions[30,31]. A membrane-based independent dehumidification system has demonstrated 33% energy savings in simulations, while systems employing hygroscopic-hydrophobic membrane contactors report energy reductions exceeding 60% when latent loads dominate[31]. These systems can be particularly effective in India's coastal cities, where annual relative humidity routinely exceeds 80%[5,31,32]. Realizing the benefits of such decoupled systems requires coordinated policy and market action. It would be valuable for the Indian Cooling Action Plan (ICAP) and the Bureau of Energy Efficiency (BEE) to consider updating efficiency metrics to more effectively capture latent load performance[33,34]. Government procurement programs, such as the integration of Green Room Air Conditioners on the Government e-Marketplace (GeM) and initiatives like ESEAP, are already serving as effective launchpads for demonstrating and mainstreaming energy-efficient technologies across public infrastructure; further expanding these efforts to prioritize region-specific, humidity-adaptive, and decoupled cooling systems could significantly accelerate market transformation and climate alignment[35,36]. Fiscal incentives, such as subsidies and tax rebates for hybrid systems, are crucial to offset higher upfront costs and catalyze market transformation[37]. Moreover, India must invest in workforce development and manufacturing capabilities to support the deployment of advanced AC systems. India's pathway to sustainable and high-performance cooling hinges on fostering a robust, indigenous R&D ecosystem focused on next-generation refrigerants, energy-efficient technologies, and climate-responsive system design. Anchored in the India Cooling Action Plan (ICAP), the country is now strategically positioned to lead in low-GWP refrigerant development, hybrid dehumidification systems, and building-integrated passive cooling solutions through coordinated investments in research institutions such as CSIR, IITs, and IISc. With clear timelines laid out for short-, medium-, and long-term innovation targets, and emphasis on public-private partnerships and mission-aligned initiatives like Mission Innovation and Start-Up

India, India can not only develop cost-effective, climate-aligned solutions for its domestic market but also emerge as a global hub for manufacturing and exporting sustainable RAC technologies[38]. This transition not only serves India's domestic sustainability goals but positions it as a global innovation leader in next-generation cooling technologies.

Geo-Tailored, IoT-Driven Cooling: Smart Branding, Smarter Markets

To future-proof India's cooling sector, air conditioning must evolve into a regionally customized, IoT-driven, and renewable-integrated solution. Cities like Delhi, facing extreme pollution, demand ACs with high-efficiency multi-stage air filtration and smart sensor modules, backed by extended warranties (e.g., 5 years for filters and sensors) to ensure durability under high PM2.5 loads. In humid regions like Chennai or Kolkata, separate mobile-controlled dehumidifiers, operable independently of cooling, can precondition indoor air based on weather app or IMD forecasts, drastically improving energy efficiency and indoor comfort. Arid zones such as Rajasthan need hybrid systems combining passive cooling, reflective insulation, and dust-repellent filters to counter intense heat and dust storms. Embedding solar integration, such as rooftop PV-powered inverter ACs or grid-interactive smart systems, reduces peak load stress and operating costs, particularly during daytime use. Furthermore, mobile-app control coupled with weather-linked automation enables users to pre-cool or pre-dehumidify their space before arrival, reducing overcooling and saving energy. Manufacturers can gain market advantage by branding systems with "Region-Optimized" tags like *Ideal for Delhi* or *Coastal Comfort Chennai*, encouraging informed purchases. These tailored designs, smart controls, and renewable synergies together enhance performance, cut emissions, and reshape India's cooling future into one that is efficient, affordable, and climate-resilient.

Passive and Natural Cooling Techniques in India



In India's intensifying climate crisis, where rising temperatures threaten both public health and electricity grids, passive and natural cooling solutions (Table 1) present a time-tested, energy-efficient, and culturally embedded strategy for thermal comfort. These approaches, rooted in vernacular traditions yet informed by modern simulation models, are increasingly recognized as essential components of a sustainable cooling future. Despite a growing body of evidence supporting their technical and economic viability, their widespread adoption remains limited, largely due to regulatory, behavioural, and market inertia. Passive cooling refers to architectural and material strategies that reduce internal heat gain and promote natural ventilation without the need for mechanical refrigeration. Core techniques include building orientation aligned with prevailing winds, cross and stack ventilation systems, reflective and green roofs, thermal mass through masonry, earth-coupled flooring, evaporative and radiative cooling, and landscape integration like vegetative shading. These elements can collectively reduce indoor temperatures by 3°C to 6°C and significantly delay or replace the need for air-conditioning[39]. Real-world performance data substantiate these claims. For example, high-rise residential buildings in Mumbai and other cities, retrofitted with night ventilation and solar chimneys recorded indoor temperature reductions up to 5.3°C and halved the number of discomfort hours experienced by residents[40,41,42]. In Bhopal, evaporative cooling achieved temperature drops nearing 5–8°C[39]. It is worthy to note that the evaporative cooling is preferrable in hot and dry climatic zones for humidity ranges 40–50%, best for cities like, cities like Ahmadabad, Jodhpur and Bhavnagar[43]. Natural ventilation has shown to be among the most effective passive cooling technology having yearly cooling potential of 30-70% throughout the India; while best for cities like, Thiruvananthapuram (71%), Mumbai (67%), Goa (66%), Chennai (59%), Patna (56%), and Kolkata (55%)[43]. Similarly, hollow clay tile (HCT) roofs have potential to cut heat transmission by up to 60%[44]. Adaptation across India's diverse climatic zones shows how context-specific strategies enhance impact. In hot and dry regions like Rajasthan and Gujarat, the combination of high diurnal temperature variation and low humidity suggests strong potential for passive cooling strategies such as night ventilation, thermal mass integration, and evaporative cooling[39,45,46]. Cities like Jodhpur and Ahmedabad demonstrate huge natural ventilation and thermal mass cooling potentials, making them especially favourable for hybrid passive techniques tailored to local conditions[43]. For humid coastal zones like Mumbai or Chennai, maximizing cross-ventilation, deep verandas, and reflective roofing help mitigate both temperature and humidity stresses. In polluted urban areas like Delhi NCR, where natural ventilation is hindered by air quality concerns, passive stacks and solar chimneys are among the potential techniques to improve indoor air quality and comfort while minimizing reliance on sealed, mechanically cooled spaces[47]. Based on the findings from Panchabikesan et al. (2017), it is evident that India's diverse climatic zones offer significant potential for passive cooling, with hot and dry regions like Jaipur demonstrating the highest combined cooling potential of 251 W/m^2 annually, while warm and humid zones such as Chennai still show a substantial potential of 127 W/m^2, highlighting the feasibility of adopting hybrid passive systems tailored to local conditions to achieve meaningful energy savings and thermal comfort even in challenging climates[48]. Various passive and natural cooling techniques in the context of India are mentioned in table 2.

Table 1: Classification of Passive and Natural Cooling Techniques

Category	Technique	Sub-Methods / Examples	Climatic Suitability
Solar and Heat Protection	Microclimate Modification	Urban forestry, courtyard trees, rooftop gardens, vertical green walls, water bodies, open courtyards	Urban zones (Delhi, Mumbai, Kolkata); semi-arid zones
	Green & Cool Roofs	Lime-wash, cool paints, rooftop vegetation, tile-based systems	High-density urban cities (Hyderabad, Ahmedabad)
	Landscaped Buffer Zones	Shaded setbacks, tree belts, rain gardens	Coastal cities, humid zones (Chennai, Kochi)
	Solar Control	Overhangs, blinds, recessed windows, brise-soleil, east-west façade shading	Hot-humid and composite climates
	Aperture Optimization	Window orientation, clerestory design, optimized Window-to-Wall Ratio (WWR)	Composite, temperate, and hot-dry regions
	Shading Elements	Pergolas, bamboo lattices, trellises, screen walls	Applicable across rural and peri-urban areas
Heat Modulation	Thermal Mass	Thick masonry (brick, adobe, rammed earth), fly ash bricks, lime concrete floors	Rajasthan, Gujarat, Maharashtra, MP, Delhi
	Phase Change Materials (PCM)	PCM plaster or panels in roofs/walls/windows, paraffin-based systems	Maharashtra, Karnataka, urban pilot buildings
	Roofing Techniques	Brickbat coba, ventilated double roofs, hollow clay tiles	Coastal and high-temperature areas (Odisha, Maharashtra)
	Wall & Window Treatments	Cavity walls, double-skin façades, reflective coatings on glass	Metro cities and commercial buildings (Mumbai, Bengaluru)

	Natural/Modern Insulation	Coconut coir, rice husk, sheep wool, CSEBs, EPS boards	North East, South India, green housing
Heat Dissipation	Free Cooling / Night Ventilation	Night air flushing, operable high vents, openable skylights	Hot-dry (Jaipur, Jodhpur), temperate (Bengaluru, Pune)
	Convective Cooling	Solar chimneys, wind towers, ventilated atriums, roof ventilators	Arid zones, coastal cities (Rajasthan, Gujrat)
	Evaporative Cooling	Earthen pot cooling walls, indirect cooling pads, mist sprays, water sprinkling	Rajasthan, Delhi, Gujrat, MP, Maharashtra
	Radiative Cooling	Night-sky exposed surfaces, radiant cooling roofs, cool roof paint	Gujarat, Rajasthan, Maharashtra
	Trombe Wall	Thermal wall with black-painted mass and vented glazing	Hill and cold-humid climates (Ladakh, Shimla)
Integrated & Vernacular	Traditional Systems	Courtyards, jaali walls, verandahs, bamboo mat roofing, chhajjas, mud plastered walls	Rajasthan, Assam, Bihar, Karnataka, Kerala
	Mixed-Mode Cooling	Passive + ceiling fans; ACs with smart pre-cooling and timed ventilation	Urban buildings, institutions
	Passive Downdraft Evaporative Cooling (PDEC)	Downdraft tower with wetted pads, gravity-fed cool air	Heritage buildings in Rajasthan, feasible in dry cities
Material & Construction	Natural Building Materials	Earth blocks, thatch, lime mortar, bamboo, mud brick	Rural and semi-urban areas across India
	Low-Embodied Energy Materials	Aerated concrete, fly ash blocks, recycled glass tiles	Affordable housing, green developments (PMAY, GRIHA projects)
	Surface Reflectivity Treatments	Lime wash, reflective elastomeric paint, radiant barriers	Telangana's cool roof program; Odisha pilot projects
Digital Augmentation	Smart Passive Systems	Motorized vents, automated shading, temperature-humidity sensor-based controls	Smart Cities: Surat, Pune, Indore
	Weather-Aware Control Systems	Weather forecast-linked cooling: automated shutters, fan-on triggers	Green campus buildings; R&D buildings
	Dehumidifier Integration	Standalone solar dehumidifiers, IoT-enabled operation with cooling systems	Coastal zones (Chennai, Mumbai, Goa)

Despite their clear benefits, passive cooling techniques face several implementation challenges. Primary among them is the limited mainstream integration into architectural curricula, design practices, and building codes. While frameworks like the Energy Conservation Building Code (ECBC) and the India Cooling Action Plan (ICAP) now include passive design considerations, these remain largely voluntary and under-enforced[33,38,49]. Furthermore, many developers and end-users perceive air-conditioning as aspirational, leading to underappreciation of passive systems that often render their benefits invisible until rigorously measured. Some states have attempted to break this inertia through targeted policy incentives. Telangana and Gujarat along with other states of India, have implemented state-level cool roof programs that distribute reflective paints to vulnerable community and low-income households[50],[51]. These coatings have shown to reduce indoor temperatures by 2–5°C and highly cost effective which is around ₹0.50-1.5 per square foot. Additionally, PMAY and EWS housing schemes increasingly promote thermally comfortable, climate-smart buildings using sustainable materials and passive design principles, with growing opportunities to strengthen their alignment and implementation across regions[52].

Table 2: Passive and Natural Cooling Techniques in India

Category	Technique	Sub-Method / Description	Relevance to India (climate/region)	Evidence / Practice (source links)
Site Planning & Layout	Building Orientation	Align long axis east–west so facades face north/south; optimize window-wall ratios to minimize direct solar gain.	Critical in hot climates (north–south alignment reduces afternoon sun). Used in government buildings (IPB Delhi oriented N–S) [53].	Indira Paryavaran Bhawan (New Delhi) oriented N–S with central courtyard[53]; CEPT Ahmedabad campus uses shading, cross-ventilation & thermal mass[54].
Building Layout	Central Courtyard	Open central courtyard (often with vegetation/water) provides shaded lightwell and enables stack-driven ventilation.	Common in hot-dry regions (Rajasthan haveli); promotes daytime heat removal at night. Central courtyard in IPB helped stack effect.	IPB Delhi building uses large courtyard for natural stack ventilation[53]; (Traditional examples: Agra Fort, Fatehpur Sikri use ponds/courtyards for cooling).
Shading & Screening	Overhangs / Chajjas	Deep horizontal shades (eaves, verandahs, chajjas) above windows to block high-angle summer sun while admitting winter sun.	Essential in all hot regions (especially Pune/Chennai); Infosys Pune campus uses wide verandahs inspired by Indian wadas[55].	Deep chajjas and verandahs block summer sun, reducing cooling load[55]; NBC/ECBC recommend shading devices[56].
Shading & Screening	Jali / Lattice Screens	Perforated stone/wood screens or brick lattices on windows/facades allow light and airflow but shade direct rays.	Historic in Rajasthan/West Bengal (Hawa Mahal in Jaipur); cools via Venturi effect. (Modern: Piramal Museum Mumbai uses jaali façade.)[55]	Hawa Mahal (Jaipur) has 953 jaalis creating a Venturi-cooled breeze; Piramal Museum (Mumbai) uses jaalis and courtyards for passive cooling[55].
Ventilation	Cross Ventilation	Align operable windows on opposite walls; use internal wind passages to harness prevailing breezes for airflow.	Vital in humid/coastal climates (Mumbai, Chennai) for cooling and air quality. CEPT Ahmedabad campus maintained comfort with cross-ventilation[54,57].	CEPT Ahmedabad campus uses cross-ventilation (with shading and thermal mass) to reduce AC use[54,57]; Karigar House (Delhi) cut AC load ~50% via cross winds and verandahs[55].

Ventilation	Stack/Ventilation (Solar Chimney)	High vents/skylights or solar chimneys to draw hot air up/out, pulling cooler air in at lower levels (night purge).	Effective in composite/dry climates (Delhi, Bengaluru) with cool nights. IPB Delhi uses courtyard stack effect[53].	Indira Bhawan employs stack effect via central atrium[53]; (e.g. solar chimneys studied for residential cooling in India – see research on passive chimney ventilation).
Ventilation	Wind Tower (Windcatcher)	Tall wind tower capturing prevailing winds or buoyancy-driven airflow; channels air into building.	Traditional in hot-arid zones (Rajasthan, Gujarat); reviving in modern designs. Windcatchers historically used in India and West Asia[58,59].	Windcatchers create cross-ventilation and passive cooling; widely used traditionally in India. Modern studies integrate wind towers for natural ventilation in Indian buildings[58,59].
Envelope (Walls)	High Thermal Mass Walls	Thick masonry or stone walls (e.g. brick, rammed earth) store heat during day and release it slowly at night.	Suited to hot-dry/desert regions (high diurnal swing). Used in Chettinad mansions (TN) and Kerala temples. High mass keeps interiors cooler even at 45 °C[55].	Chettinad mansions (TN): thick lime-plastered walls, shaded courtyards kept interiors pleasant in 40–45 °C summers[55]; WEF (World Economic Forum) cites CEPT Ahmedabad's "thermal massing"[54,57].
Envelope (Walls)	Natural Insulation (Mud/Lime Plaster)	Earthen plaster or lime-based finishes on walls provide low-cost insulation and evaporative cooling.	Common in rural/traditional homes (villages, Auroville Earth Institute). Example: Hyderabad Vruksha home kept ~6 °C cooler indoors[55].	Vruksha Home (Hyderabad) with mud walls, lime plaster & water features saw ~6 °C cooler interiors year-round[55]; NDMA notes mud plaster moderates indoor heat[60,61].
Roof	Reflective Cool Roof	High-albedo (white or reflective) roof coatings/surfaces that reflect solar radiation, reducing heat gain.	Adopted in many states (Tamil Nadu cool-roof policy). Indo-Swiss BEEP study: cool roofs cut indoor temp by 3–5 °C[62].	Indo-Swiss study: painted roof kept temperature ~32°C vs ~55 °C conventional[62]; Cool-roof review: 3.2–30.4% energy savings and 2.0–7.0 °C indoor drop in India[63].
Roof	Green Roof (Vegetated Roof)	Plant-covered roofing (green roof) with soil/media; provides shading, evapotranspiration and thermal buffering.	Studied in hot-humid cities (Chennai). Retrofit roof gardens reduce indoor heat and UHI. Chennai shelter: 4–11 °C cooler indoors[64].	Chennai Resilience Centre field study: rooftop garden led to 4–11 °C lower indoor temperatures. (Simulations suggest optimal plant coverage could add ~3–4 °C more.)[64]
Roof	Thatched / Natural Roof Covering	Dried-grass or bamboo roofing (often with reflective top layer) that shades and allows ventilation under roof.	Used in tropical villages (Kerala, Andhra). Provides shade and breathability. Auroville Earth Institute modern mud homes use thatch/straw roofs[55].	Mud+thatched roofs: "Mud's high thermal mass absorbs heat slowly; thatch provides shade+breathability"[55]. Many eco-villages in India build with stabilized mud & thatch for natural insulation.
Vegetation & Landscape	Trees and Landscaping	Strategic planting of trees, green belts and gardens to shade buildings and evaporatively cool surrounding air.	Highly beneficial nationwide. IPB Delhi covers >50% site with vegetation[53]. Urban parks/green belts mitigate heat (Delhi, Chennai).	Indira Bhawan: >50% site under plantation and soft-paved surfaces[53]. CDKN reports green infrastructure (urban forests, parks) as key cooling measure[65].
Vegetation & Landscape	Vertical Green Walls	Living green facades or vine-covered walls that insulate and cool by evapotranspiration.	Emerging practice for urban heat island (UHI) mitigation in cities (Mumbai, Bangalore projects). Acts as wall insulation and air filter.	Green wall systems significantly reduce wall heat gain and improve indoor conditions[66,67]. CEPT research highlights green façades as passive cooling in Indian campuses[54].
Water / Evaporative	Water Features	Courtyard ponds, fountains or misters	Effective in arid/hot regions (Rajasthan, Gujarat). Step-well	Rani ki Vav (Patan stepwell): interior ~6–8 °C cooler due to underground water

	(Fountains/Pools)	that cool the air by evaporation.	examples (Patan) remain ~6–8 °C cooler inside[55].	evaporation[55]. Mughal gardens use water channels[68]; modern "spray/mist parks" for outdoor cooling[69,70].
Subsurface Cooling	Earth-Air Tunnel (Earth Tube)	Buried insulated ducts carrying air through cool/deep soil to pre-cool ventilation air naturally.	Trialed in North India. Ground at ~2–3 m stays ~annual mean (~25 °C) – cooling intake air. Good for dry climates; prevents bringing polluted surface air inside.	BEEP studied a large earth-air tunnel in North India, Clara Swaine Hospital, Bareilly [71,72,73].

India has taken meaningful steps to mainstream passive and climate-responsive building design through programs like the Energy Conservation Building Code (ECBC) and the Eco-Niwas Samhita (ENS), which provide climate-specific design guidelines for thermal comfort and energy efficiency in residential and commercial buildings[49,74]. Additionally, the India Cooling Action Plan (ICAP) lays out a comprehensive vision to reduce cooling demand by promoting passive design strategies across sectors by 2037-38[33,38,75]. While these initiatives are advancing the dialogue and creating institutional momentum, further opportunity lies in aligning incentives and compliance mechanisms with international best practices. For example, Singapore's Green Mark Scheme offers FAR bonuses and grants for buildings that meet passive design benchmarks, California's Title 24 enforces stringent building energy codes tied to passive design performance, and Japan integrates mandatory shading and ventilation design into its building code to improve resilience and reduce cooling loads[76,77,78,79,80]. Drawing from these global experiences, India has the opportunity to strengthen its regulatory framework through a well-integrated mix of incentives, such as tax rebates or fast-track permits and performance-linked building codes that prioritize passive cooling as a foundational strategy rather than a supplementary option.

Moreover, digital augmentation of passive strategies, such as weather-aware smart shading systems, IoT-linked vent controls, and real-time thermal monitoring, can modernize traditional designs while meeting contemporary lifestyle expectations. Integrating passive elements with efficient active technologies (e.g., ceiling fans or inverter-based ACs) in a mixed-mode cooling approach offers a highly scalable model, especially for India's dense urban environments where land and ventilation pathways are constrained. It is better to say that the passive cooling is not an archaic alternative to air-conditioning but a foundational layer upon which modern cooling infrastructure should be built. It is energy-frugal, emissions-light, and deeply attuned to India's climatic diversity. Scaling it demands regulatory will, technical capacity-building, and perceptual shifts, each of which is already underway, but in fragmented ways. With the right policy push and community engagement, passive cooling could form the backbone of India's cooling transition, safeguarding health, reducing emissions, and preserving energy resilience in a warming world.

Looking at the prospect, India is on the verge of a generational opportunity. Together with Africa, it's expected to add over 100 billion square meters of new floor space by 2050, more than 40% of global construction[79]. That's not just growth; it's a chance to shape how the next century of buildings will consume energy. As India's total energy use continues to rise, and cooling alone is set to use more than half of peak electricity by mid-century, the country's 2019 National Cooling Action Plan (NCAP) comes at a crucial moment. The plan doesn't just focus on energy, it aims to transform the entire market, from how buildings are designed to how materials are sourced and jobs are created. The World Bank has estimated that it could unlock $1.6 trillion in investment and generate 3.7 million jobs[79]. Meanwhile, India's Energy Conservation Building Code (ECBC) continues to evolve, laying a foundation for energy-smart construction that suits the country's vast and varied climate zones. Of course, translating these frameworks into everyday practice, especially across states with different capacities and priorities, remains a challenge. But with the right mix of support, innovation, and coordination, India is in a unique position to lead a global shift toward buildings that are not just bigger, but smarter, cleaner, and more resilient.

References

[1] Impact of energy efficiency measures for the year 2021-22, May 2023. Bureau of Energy Efficiency. https://beeindia.gov.in/sites/default/files/publications/files/Impact%20Assessment%202021-22_%20FINAL%20Report_June%202023.pdf

[2] PIB, 10 MAY 2023. Release ID: 1923031. https://www.pib.gov.in/PressReleaseIframePage.aspx?PRID=1923031

[3] Siddhartha Khemka, 2025. The economic times, Mar 14, 2025. AC Demand set to surge in India: Amber Enterprise, Voltas could give 17-23% return in1 year. https://economictimes.indiatimes.com/markets/stocks/news/ac-demand-set-to-surge-in-india-amber-enterprise-voltas-could-give-17-23-return-in1-year/articleshow/119004974.cms?utm_source=contentofinterest&utm_medium=text&utm_campaign=cppst

[4] Air Conditioners – India, Statista. https://www.statista.com/outlook/cmo/household-appliances/major-appliances/air-conditioners/india

[5] Woods, J., et al. (2022). Humidity's impact on greenhouse gas emissions from air conditioning. Joule, 6(4), 726–741. https://doi.org/10.1016/j.joule.2022.02.013

[6] Hannah Ritchie (2024) - "Air conditioning causes around 3% of greenhouse gas emissions. How will this change in the future?" Published online at OurWorldinData.org. Retrieved from: https://ourworldindata.org/air-conditioning-causes-around-greenhouse-gas-emissions-will-change-future

[7] India energy scenario for the year 2023-24, Bureau of Energy Efficiency, December 2024. https://beeindia.gov.in/sites/default/files/BEE_India_Energy_Scenario_Report-2024_web_version-rev2.pdf

[8] Can efficient cooling help manage fast rising electricity demand in India and achieve thermal comfort for all? In, IEA (2023), Energy Efficiency 2023, IEA, Paris. https://www.iea.org/reports/energy-efficiency-2023/can-efficient-cooling-help-manage-fast-rising-electricity-demand-in-india-and-achieve-thermal-comfort-for-all

[9] Operational performance report for the month of June -2024, Grid Controller of India Limited. https://posoco.in/en/download/monthly_report_jun_2024/?wpdmdl=58607

[10] Operational performance report for the month of June -2012, Power System Operation Corporation LTD. https://posoco.in/en/download/june-2012-monthly-report/?wpdmdl=4466

[11] Rishi Ranjan Kala, 2024. India's power demand to grow at over 4% y-o-y till 2050: IEA. The Hindu businessline, October 16, 2024. https://www.thehindubusinessline.com/economy/indias-power-demand-to-grow-at-over-4-y-o-y-till-2050-iea/article68760945.ece

[12] IEA (2024), From Taking Stock to Taking Action, IEA, Paris https://www.iea.org/reports/from-taking-stock-to-taking-action, Licence: CC BY 4.0. https://www.iea.org/reports/from-taking-stock-to-taking-action/executive-summary

[13] World Energy Transitions Outlook 2023 VOLUME 1. https://www.irena.org/Digital-Report/World-Energy-Transitions-Outlook-2023

[14] Room Air Conditioners, Notification on 16th July, 2024. Bureau of Energy Efficiency, Ministry of Powe, Government of India. https://www.beestarlabel.com/Content/Files/AC_Notification.pdf.

[15] PIB, 10 May 2023, Release ID: 1923031, Ministry of Power. https://www.pib.gov.in/PressReleaseIframePage.aspx?PRID=1923031

[16] Room air conditioner (variable speed), search and compare tool, Bureau of Energy Efficiency. https://www.beestarlabel.com/SearchCompare

[17] Room air conditioner (window/unitary), search and compare tool, Bureau of Energy Efficiency. https://www.beestarlabel.com/SearchCompare

[18] Phadke, A., 2014. Avoiding 100 new power plants by increasing efficiency of room air conditioners in India: opportunities and challenges. https://www.osti.gov/servlets/purl/1136779

[19] Hannah Ritchie (2024) - "Air conditioning causes around 3% of greenhouse gas emissions. How will this change in the future?" Published online at OurWorldinData.org. Retrieved from: https://ourworldindata.org/air-conditioning-causes-around-greenhouse-gas-emissions-will-change-future

[20] IEA (2020), Efficiency ratings of available AC units by regional metric, IEA, Paris https://www.iea.org/data-and-statistics/charts/efficiency-ratings-of-available-ac-units-by-regional-metric, Licence: CC BY 4.0. https://www.iea.org/data-and-statistics/charts/efficiency-ratings-of-available-ac-units-by-regional-metric

[21] What are seasonal energy efficiency ratings? https://www.midtechservices.co.uk/what-are-seasonal-energy-efficiency-ratings/

[22] The Most Energy Efficient HVAC Systems. https://bkvenergy.com/blog/most-energy-efficient-hvac-systems/

[23] Midtech news & insight, What are seasonal energy efficiency ratings? https://www.midtechservices.co.uk/what-are-seasonal-energy-efficiency-ratings/

[24] ICED dashboard, Per capita income at state and national level. https://iced.niti.gov.in/economy-and-demography/key-economic-indicators/socio-economic

[25] All India Electricity Statistics, Data for the Year 2022-23, General Review 2024. Government of India, Ministry of Power, Central Electricity Authority. https://cea.nic.in/wp-content/uploads/general/2024/GR_2024.pdf

[26] ICED dashboard, Per capita electricity consumption. https://iced.niti.gov.in/economy-and-demography/key-economic-indicators/socio-economic

[27] Per capita carbon dioxide (CO_2) emissions from fossil fuels in India from 1970 to 2023, Statista. https://www.statista.com/statistics/606019/co2-emissions-india/

[28] Sunita Narain, 2021, India's new climate targets: Bold, ambitious and a challenge for the world. 02 Nov 2021, DownToEarth. https://www.downtoearth.org.in/climate-change/india-s-new-climate-targets-bold-ambitious-and-a-challenge-for-the-world-80022

[29] Gambhir, A., Napp, T.A., Emmott, C.J. and Anandarajah, G., 2014. India's CO2 emissions pathways to 2050: Energy system, economic and fossil fuel impacts with and without carbon permit trading. Energy, 77, pp.791-801. https://doi.org/10.1016/j.energy.2014.09.055

[30] Conde, M.R., 2004. Properties of aqueous solutions of lithium and calcium chlorides: formulations for use in air conditioning equipment design. *International Journal of Thermal Sciences*, *43*(4), pp.367-382. https://doi.org/10.1016/j.ijthermalsci.2003.09.003

[31] Chua, K.J., Chou, S.K., Yang, W.M. and Yan, J., 2013. Achieving better energy-efficient air conditioning–a review of technologies and strategies. *Applied energy*, *104*, pp.87-104. https://doi.org/10.1016/j.apenergy.2012.10.037

[32] IEA (2018), The Future of Cooling: Opportunities for energy-efficient air conditioning, IEA, Paris, https://doi.org/10.1787/9789264301993-en.

[33] ICAP 2024, India Cooling Action Plan, 14 FEBRUARY 2024. National Disaster Management Authority (India). https://ndma.gov.in/sites/default/files/PDF/Heatwave-workshop/14012024/session6/ICAP.pdf

[34] BEE 2025, Energy-efficient retrofit manuals: transforming existing buildings, Residential, February 2025, Bureau of energy efficiency, Ministry of Power, Government of India. https://beeindia.gov.in/sites/default/files/publications/files/BEE_EB_Retrofit_Residential_Cold%20Climate%20CTC%2017%20%281%29.pdf

[35] PIB 2021, New product category of Green Room Air Conditioners launched on Government e-Marketplace (GeM) to mark the World Environment Day today. PIB Delhi 05 JUN 2021, Ministry of Commerce & Industry, India. https://www.pib.gov.in/PressReleasePage.aspx?PRID=1724823

[36] Shah, N.K., Park, W.Y. and Gerke, B., 2017. Assessment of commercially available energy-efficient room air conditioners including models with low global warming potential (GWP) refrigerants. https://escholarship.org/uc/item/01h8g7zb

[37] Du Can, S.D.L.R., Leventis, G., Phadke, A. and Gopal, A., 2014. Design of incentive programs for accelerating penetration of energy-efficient appliances. *Energy Policy*, *72*, pp.56-66. https://doi.org/10.1016/j.enpol.2014.04.035

[38] ICPA 2019, India Cooling Action Plan, March 2019, Ozone Cell Ministry of Environment, Forest and Climate Change Government of India. https://ozonecell.nic.in/wp-content/uploads/2019/03/INDIA-COOLING-ACTION-PLAN-e-circulation-version080319.pdf

[39] Bhamare, D.K., Rathod, M.K. and Banerjee, J., 2019. Passive cooling techniques for building and their applicability in different climatic zones—The state of art. Energy and Buildings, 198, pp.467-490. https://doi.org/10.1016/j.enbuild.2019.06.023

[40] Stasi, R., Ruggiero, F. and Berardi, U., 2024. Influence of cross-ventilation cooling potential on thermal comfort in high-rise buildings in a hot and humid climate. Building and environment, 248, p.111096. https://doi.org/10.1016/j.buildenv.2023.111096

[41] Lal, S., Kaushik, S.C. and Bhargava, P.K., 2013. A case study on solar chimney-assisted ventilation for residential building in India. International Journal of Energy Sector Management, 7(4), pp.478-490. http://dx.doi.org/10.1108/IJESM-01-2013-0003

[42] Asadi, S., Fakhari, M., Fayaz, R. and Mahdaviparsa, A., 2016. The effect of solar chimney layout on ventilation rate in buildings. Energy and Buildings, 123, pp.71-78. https://doi.org/10.1016/j.enbuild.2016.04.047

[43] Bhamare, D.K., Rathod, M.K. and Banerjee, J., 2020. Evaluation of cooling potential of passive strategies using bioclimatic approach for different Indian climatic zones. Journal of Building Engineering, 31, p.101356. https://doi.org/10.1016/j.jobe.2020.101356

[44] Vijaykumar, K.C.K., Srinivasan, P.S.S. and Dhandapani, S., 2007. A performance of hollow clay tile (HCT) laid reinforced cement concrete (RCC) roof for tropical summer climates. Energy and Buildings, 39(8), pp.886-892. https://doi.org/10.1016/j.enbuild.2006.05.009

[45] Pathways to Green India, section 2: Innovative Ideas for Public Spaces Volume II. https://www.earthday.org/wp-content/uploads/2020/06/Pathways-to-Green-India_-Volume-II-Innovative-Ideas-for-Public-Spaces.pdf

[46] Gupta, N. and Tiwari, G.N., 2016. Review of passive heating/cooling systems of buildings. Energy Science & Engineering, 4(5), pp.305-333. https://doi.org/10.1002/ese3.129

[47] Lal, S., Kaushik, S.C. and Bhargav, P.K. (2013), "Solar chimney: A sustainable approach for ventilation and building space conditioning", International Journal of Development and Sustainability, Vol. 2 No. 1, pp. 277-297. https://isdsnet.com/ijds-v2n1-20.pdf

[48] Panchabikesan, K., Vellaisamy, K. and Ramalingam, V., 2017. Passive cooling potential in buildings under various climatic conditions in India. Renewable and Sustainable Energy Reviews, 78, pp.1236-1252. http://dx.doi.org/10.1016/j.rser.2017.05.030

[49] Energy Conservation Building Code, June 2017. Bureau of Energy Efficiency. https://beeindia.gov.in/sites/default/files/BEE_ECBC%202017.pdf

[50] NRDC, December 2023. Telangana and Gujarat, for instance, have implemented state-level cool roof programs that distribute reflective paints to low-income households free of cost. Natural Resources Defense Council. https://www.nrdc.org/sites/default/files/2023-12/cool-roofs-policy-factsheet-20231207.pdf

[51] NRDC, July 2019. Keeping it cool, How Cool Roofs Programs Protect People, Save Energy and Fight Climate Change, Models to develop city cool roof programs in India. Natural Resources Defense Council. https://www.nrdc.org/sites/default/files/keeping-it-cool-roofs-india-fs.pdf

[52] Pradhan Mantri Awas Yojana - Urban 2.0. Housing for All Mission. Scheme Guidelines, September 2024. Ministry of Housing & Urban Affairs Government of India. https://pmay-urban.gov.in/uploads/guidelines/Operational-Guidelines-of-PMAY-U-2.pdf

[53] Indira Paryavaran Bhawan Ministry of Environment and Forest (MoEF). https://nzeb.in/case-studies/nzebs-in-india/nzebs-in-india-case-studies-list/ipb-case-study

[54] Net Zero Energy Building A Living Laboratory CEPT University, Ahmedabad, December 2017. https://carbse.org/wp-content/uploads/2019/06/NZEB-Report.pdf

[55] How Traditional Indian Architecture Can Solve Modern Cooling Problems, 26 April, 2025, CivilEngineerDK. https://civilengineerdk.com/how-traditional-indian-architecture-can-solve-modern-cooling-problems/

[56] Report of the sub-committee for development of National Sustainable Habitat parameters for energy efficiency in Residential and Commercial Buildings. May, 2011. https://mohua.gov.in/upload/uploadfiles/files/Energy_Efficiency.pdf

[57] How to decarbonize urban India with climate-conscious strategies, May 8, 2025, World Economic Forum. https://www.weforum.org/stories/2025/05/decarbonize-urban-india-with-climate-conscious-strategies

[58] Saadatian, O., Haw, L.C., Sopian, K. and Sulaiman, M.Y., 2012. Review of windcatcher technologies. Renewable and Sustainable Energy Reviews, 16(3), pp.1477-1495. https://doi.org/10.1016/j.rser.2011.11.037

[59] Windcatcher. https://en.wikipedia.org/wiki/Windcatcher#:~:text=A%20windcatcher%2C%20wind%20tower%2C%20or,can%20also%20function%20without%20wind

[60] Samuel, D.L., Dharmasastha, K., Nagendra, S.S. and Maiya, M.P., 2017. Thermal comfort in traditional buildings composed of local and modern construction materials. International Journal of Sustainable Built Environment, 6(2), pp.463-475. https://doi.org/10.1016/j.ijsbe.2017.08.001

[61] National Disaster Management Guidelines for Cultural Heritage Sites and Precincts, September 2017. New Delhi A publication of the National Disaster Management Authority, Government of India. https://nidm.gov.in/PDF/pubs/NDMA/20.pdf

[62] A ready-reckoner for cool roofs, Reference manual for cool roof use, Indo-Swiss Building Energy Efficiency Project (BEEP). https://www.beepindia.org/wp-content/uploads/2022/12/Ready-Reckoner-Cool-Roofs-_English-Version_24-02-2023.pdf

[63] Rawat, M. and Singh, R.N., 2021, July. Energy saving opportunities in buildings using cool roofs for India: A review. In AIP Conference Proceedings (Vol. 2358, No. 1). AIP Publishing. https://doi.org/10.1063/5.0057915

[64] Visvanathan, G., Patil, K., Suryawanshi, Y., Meshram, V. and Jadhav, S., 2024. Mitigating urban heat island and enhancing indoor thermal comfort using terrace garden. Scientific Reports, 14(1), p.9697. https://doi.org/10.1038/s41598-024-60546-0

[65] CDKN Global, 13th July 2021. Strengthening heat resilience in cities: Insight from India. https://cdkn.org/story/feature-strengthening-heat-resilience-in-cities-insight-from-india

[66] Nesci, V., Ballarini, I., Rando Mazzarino, P. and Corrado, V., 2024. Living Walls and Green Façades: An Implementation Code for Energy Simulation. Buildings, 14(7), p.2040. https://doi.org/10.3390/buildings14072040

[67] Rakhshandehroo, M., Mohd Yusof, M.J. and Deghati Najd, M., 2015. Green façade (vertical greening): benefits and threats. Applied Mechanics and Materials, 747, pp.12-15. http://dx.doi.org/10.4028/www.scientific.net/AMM.747.12

[68] TOI News Desk, Cooling techniques from Mughal architecture before the invention of AC, Jul 30, 2024. https://timesofindia.indiatimes.com/india/cooling-techniques-from-mughal-architecture-before-the-invention-of-ac/articleshow/112110553.cms

[69] Wang, P., Lu, S., Wu, X., Tian, J. and Li, N., 2024. Mist Spraying as an Outdoor Cooling Spot in Hot-Humid Areas: Effect of Ambient Environment and Impact on Short-Term Thermal Perception. Buildings, 14(2), p.336. https://doi.org/10.3390/buildings14020336

[70] Truemist, June 27, 2023. Why misting system is the best choice for Outdoor Cooling. https://truemist.in/why-misting-system-is-the-best-choice-for-outdoor-cooling/

[71] Singh, R., Sawhney, R.L., Lazarus, I.J. and Kishore, V.V.N., 2018. Recent advancements in earth air tunnel heat exchanger (EATHE) system for indoor thermal comfort application: A review. Renewable and Sustainable Energy Reviews, 82, pp.2162-2185. https://doi.org/10.1016/j.rser.2017.08.058

[72] Earth Air Tunnel, BEEP. https://www.beepindia.org/technologies-n-tools/earth-air-tunnel

[73] Mihalakakou, G., Souliotis, M., Papadaki, M., Halkos, G., Paravantis, J., Makridis, S. and Papaefthimiou, S., 2022. Applications of earth-to-air heat exchangers: A holistic review. Renewable and Sustainable Energy Reviews, 155, p.111921. https://doi.org/10.1016/j.rser.2021.111921

[74] Eco-Niwas Samhita 2021. Code Compliance and Part-II: Electro-Mechanical and Renewable Energy Systems. Bureau of Energy Efficiency, Ministry of Power, Government of India. https://beeindia.gov.in/sites/default/files/Eco%20Niwas%20Samhita%202021%20Part-%202.pdf

[75] PIB 2022. India Cooling Action Plan, 14 MAR 2022, Ministry of Environment, Forest and Climate Change. https://www.pib.gov.in/PressReleaseIframePage.aspx?PRID=1805795

[76] Green mark gross floor area incentive scheme for private developments that achieved higher-tier green mark ratings. Circular no. BCA/GM GFA/2009-04-TD01. https://www.ura.gov.sg/Corporate/Guidelines/Circulars/dc09-04

[77] Building energy efficiency standards for residential and nonresidential buildings, 2022. California energy commission. https://www.energy.ca.gov/sites/default/files/2022-12/CEC-400-2022-010_CMF.pdf

[78] California energy code, 2025. https://www.energy.ca.gov/sites/default/files/2024-12/2025_Energy_Code_Summary_ADA.pdf

[79] World Bank. 2025. Unlocking Efficiency – The Global Landscape of Building Energy Regulations and their Enforcement. https://documents1.worldbank.org/curated/en/099718504112546491/pdf/IDU-1d303826-4a43-4eff-8649-1052aa316783.pdf

[80] The Japan's policy and strategy in the building sector towards "Carbon Neutrality", February 2023. Energy Efficiency and Renewable Energy Department Agency For Natural Resources and Energy (ANRE), Ministry of Economy Trade and Industry (METI), Japan. https://energyefficiencyhub.org/wp-content/uploads/2023/02/S1-1.pdf

Read our latest studies on Heatwaves (inhouse), Hydrogen (Elsevier), & Decarbonization (Elsevier)

Every initiative at RINOLYST is grounded in scientific integrity, driven by rigorous research and robust data, and propelled by our unwavering commitment to accelerating progress through research that matters.

RINOLYST,
Sciglyph Exploration Private Limited,
Patna, Bihar, India

Visit us: www.rinolyst.com
Contact us: info@rinolyst.co