International Journal for Multidisciplinary Research (IJFMR)
E-ISSN: 2582-2160 ● Website: www.ijfmr.com ● Email: editor@ijfmr.com

Infrastructural Framework for Green Airports: A Study on Sustainable Airport Development

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Abstract

This piece breaks down the main building blocks behind India's "green" airports, zooming in on a side-by-side look at four heavy hitters: Indira Gandhi International in Delhi, Chhatrapati Shivaji Maharaj in Mumbai, Netaji Subhas Chandra Bose in Kolkata, and Kempegowda International in Bengaluru. It starts by setting the scene on India's push ahead in sustainable flying, nearly a third of its airports are already all-in on renewables, with the government dead set on 100% green power by 2024. The lit review pulls in global stuff like ACI's Airport Carbon Accreditation (ACA) alongside homegrown efforts from MoCA and AAI. Method-wise, it's all secondary data from sustainability reports and accreditation logs, no fancy fieldwork. The results? Delhi, Mumbai, and Bengaluru have hit the gold standard ACA Level 5, fully carbon-neutral. Kolkata's at Level 2+ but ramping up, like with that 57 MW solar addition they're planning to climb higher. Standout infrastructure pops up across the board: big renewable setups (think on-site solar panels plus long-term power purchase agreements), super-efficient terminals (LEDs everywhere, smart HVAC systems), closed-loop water and waste recycling, Delhi's reusing 100% of its wastewater, for one electric ground vehicle with charging stations, and tight carbon tracking protocols. Drawing from that, the paper sketches out a green airport roadmap built on five pillars: Energy, Buildings, Water & Waste, Transport, and Governance. Recommendations feel practical: speed up those renewable rollouts (hello, Kolkata's solar plant), lock in green building codes nationwide, and lean harder on accreditations plus incentives. It's a thorough rundown meant to hand policymakers and airport bosses a playbook for greening things up... though, fair to say, execution varies. Kolkata's lag shows how funding or land constraints can slow the leaders down.

Keywords: Green Airports, Sustainable Airport Infrastructure, Carbon-Neutral Aviation, Renewable Energy Integration, Airport Carbon Accreditation, Water Positivity, Electric Ground Mobility

Introduction

India's aviation world is booming these days, and its airports are really stepping up on the sustainability front to cut down on all that environmental damage. You know, ICAO reports and various industry breakdowns point out how India is kind of leading the pack in airport renewables; nearly a third of them are already running on green energy. The government's right there pushing it too, mandating that every single Indian airport hits 100% renewables by 2024 to match those national climate targets. By late 2023, 66 of them had made the switch completely. And it's paying off in their carbon creds: places like Delhi, Mumbai, Hyderabad, and Bengaluru have nailed the top ACA levels 4+ or even 5, and yeah, they're basically carbon-neutral now. This didn't just happen by magic, though. It's solid policy meshing with real infrastructure moves. The Ministry of Civil Aviation (MoCA) and Airports Authority of India (AAI) laid

down the rules for sustainable designs, carbon tracking, and mandatory green power. Take MoCA's push for new airports: they have to bake in net-zero from the get-go, full renewables no exceptions. Then there's AAI's SUGAM Green Airport Mission, which is all about energy-smart buildings, renewables, and that kind of stuff. Of course, international benchmarks like the ACI's Airport Carbon Accreditation program give them a clear scorecard for measuring progress... though, not everyone agrees it's the perfect metric; some folks argue it overlooks broader supply chain emissions. Anyway, with all that in mind, this study digs into the nuts and bolts of what makes India's green airports tick. Zeroing in on those four big ones, Delhi, Mumbai, Hyderabad, Bengaluru, it breaks down their renewable setups, smart building tech, water and waste handling, ground transport options, and how they govern carbon overall. The idea? Spell out a full blueprint that could steer sustainable upgrades across the country's airports or at least give planners a solid starting point, since scaling this everywhere isn't without its hiccups, like grid reliability or upfront costs.

Literature Review

Airport Carbon Accreditation and International Standards

The Airports Council International's ACA program stands out as the go-to yardstick for how airports handle their carbon footprint. It rolls out six steps up the ladder: Level 1 for just mapping emissions, Level 2 for cutting them back, Level 3 for optimising, 3+ for neutrality tricks, 4 for full transformation, and Level 5, the big one for locking in net-zero long-term. Airports earn their stripes by tracking, slashing, and offsetting greenhouse gases in a structured way. Worldwide, Level 5 is rare; come 2024, only 16 airports had cracked it. India's Delhi and Bengaluru jumped in that year, thanks to their sharp carbon plays (we get the details in Section 4). Top green airports globally swear by infrastructure upgrades, on-site renewables, slick energy-saving designs, and full recycling loops for resources. Cochin in India set the bar early as the world's first fully solar-powered airport, even pumping extra juice back to the grid. Reviews from the industry keep stressing that hardware like solar fields, next-gen terminals, and EV fleets is non-negotiable for hitting those targets. That said, lit on India specifically? Pretty thin. You're mostly sifting government bulletins and trade reports, which is why pulling together real case studies from them feels overdue. Not that global models don't have limits, like ignoring upstream fuel emissions from airlines.

Indian Policy and Missions

India's got a solid policy backbone pushing green airports forward. Here's the rundown on the big pieces: Renewable energy mandates from MoCA and AAI aim for 100% green power across all airports by 2024. AAI's SUGAM mission is all about blanketing grounds with solar and wind setups. New builds have to hit energy-efficient green standards, no shortcuts. They're nudging sustainable transport too, with perks for electrifying airport vehicles and better public transit links. Carbon accounting's standardised now, operators map emissions, plot cuts, the works. And water neutrality? NITI Aayog and CII's framework chases "water positivity," where reused and harvested water beats what you use at Delhi Airport's already there. Past research flags how these policies pave the way for upgrades but skimps on hard case details. So this study steps in, connecting those accreditation levels to the real-world infrastructure at India's top airports. Though policies are one thing, actually funding and rolling them out everywhere? That's where things can snag.

Methodology

This research goes with a comparative case-study vibe, zeroing in on four of India's busiest international hubs: Delhi's Indira Gandhi, Mumbai's CSMIA, Kolkata's Netaji Subhas Chandra Bose, and Bengaluru's

Kempegowda. Picked 'em for their massive traffic and all the green buzz they've got going. Data came from digging deep into the freshest secondary sources out there:

- Official sustainability and annual reports straight from the operators (DIAL, MIAL, BIAL, you name it).
- ACI Asia-Pacific pressers.
- MoCA and AAI announcements.
- Solid industry pubs like CAPA and aviation journals.
- The official Airport Carbon Accreditation news feeds.

For each spot, we pulled details on accreditation level (latest status and when), renewables like solar capacity (on-site or off) and PPAs, efficiency tweaks (lighting, HVAC, smart automation), water/waste setups (harvesting, treatment), transport stuff (EV fleets, chargers, green cabs), and carbon governance (committees, policies, offsets). We lined up the findings across the four to spot what infrastructure bits they all share. That qualitative mash-up forms the backbone for the framework and recs here. Mind you, relying on secondary data means we're piecing together public reports; insider metrics might paint an even sharper picture.

Case Study Findings

Accreditation Status

Delhi's Indira Gandhi International hit Level 5 Transition in 2024, becoming India's trailblazer in its league. That badge means net-zero on Scopes 1 and 2, with a roadmap stretching toward Scope 3 down the line. Mumbai's CSMIA climbed aboard in November 2025, landing in that rare global club, full operational net-zero, plus a sketched-out path to Scope 3 by 2050. Bengaluru's Kempegowda tagged along with Delhi back in 2024 for Level 5, building on earlier Level 4+ wins. Kolkata's Netaji Subhas Chandra Bose sits at Level 2+ (Reduction) these days in the Asia-Pacific scene started with Level 2 Mapping in 2019, bumped to 2+ by 2023 after some solid cuts. Officials there are gunning for 4+ like the others, by scaling up renewables and efficiency plays. You see the pattern: the Level 5 crowd has those renewable and efficiency overhauls locked in, while Kolkata's still stacking the blocks... which makes sense, but also highlights how uneven the rollout can be, traffic volume or private vs. public management might tip the scales.

Renewable Energy Integration

India's green airports are all about going big on solar and renewables; it's practically their signature move. Delhi and Bengaluru lead with hefty solar setups and long-haul PPAs. Delhi's got 7.84 MW on-site, slashing grid reliance through those agreements; Bengaluru mirrors it with its own panels and solar/wind contracts, hitting a 95.6% drop in Scope 1&2 emissions by 2023. Mumbai's CSMIA? Fully 100% green electricity now, courtesy of a massive rooftop solar plant and smart procurement. Kolkata's at about 17 MW so far, but they're gearing up for a 40 MW ground-mounted addition, pushing total to 57 MW and wiping out most fossil fuel hangovers. Across the AAI network, that's ~54 MWp solar installed, plus 53 million kWh snapped up via open-access PPAs, covering 35% of power needs. MoCA says 66 airports are now pure renewables thanks to these rollouts.

Bottom line: these spots bank on sprawling solar (rooftops, ground arrays) paired with PPAs to fuel up cleanly, and yeah, it's the backbone of their carbon-neutral badges. Even if PPAs can sometimes mask true on-site impact, depending on the supplier's chain.

Energy-Efficient Buildings

All four airports have poured money into slick, efficient terminal setups; it's one of those no-brainer moves for cutting energy waste. Take LED lighting and HVAC: Delhi's terminals got a full retrofit with LEDs and smart controls, plus automated building systems that tweak energy on the fly across all those sprawling complexes. Mumbai's right there too, with LEDs and these cool vertical green walls on the facades, which help with insulation, and it ticks MoCA's boxes for efficiency. Then Bengaluru's Terminal 2 takes it up a notch with that "Terminal in a Garden" idea, super-reflective roofs bouncing off solar heat, tons of natural light, automated controls everywhere. It's paid off big: they've hit a water positivity score of 2.36 (way more rainwater collected than used) and racked up serious power savings. All the new terminals chase green certs too, Delhi's 1 and 2 are LEED Gold for instance, and MoCA's pushing eco-materials and daylighting for anything fresh. The point is, this kind of smart infrastructure spending slashes demand right at the source, paving the way for net-zero. Though you wonder if older terminals elsewhere can keep pace without massive overhauls.

Water and Wastewater Management

Water sustainability is baked right into these airports' setups, no half-measures there. Delhi's rainwater game is strong: over 625 harvesting structures feed huge underground tanks (about 9 million litres total) to snag monsoon flows. Bengaluru pulls back around 66% of its water needs the same way. Wastewater? Delhi runs a 16.6 MLD Zero Liquid Discharge plant, recycling every drop, 100% back into HVAC cooling, toilets, and landscaping. That alone guts their freshwater pull. Waste handling's covered too across all four—segregation, composting, recycling stations. Mumbai, say, turns organic scraps into landscaping fertiliser and taps waste heat recovery. Keeps runoff and trash from gunking up the surroundings. Looping water onsite like this, treating sewage in-house, it shrinks their eco-footprint big time... still, during dry spells, you gotta wonder if harvested stocks hold up without dipping into municipal supplies.

Sustainable Transport

Ground transport's getting a serious green overhaul at these airports; it's smart, since cars and buses can rack up emissions fast. Delhi's out front with 57 electric vehicles in its fleet, buses, tugs, cars, and chargers popping up everywhere. Bengaluru jumped in with 175 all-electric airport taxis back in 2024. Kolkata and Mumbai are swapping out shuttles and service rigs for battery power too, bit by bit. Every spot's got multi-point EV chargers now, open to their own fleets and folks driving in. Public transit links help too, metro rails right at Delhi and Mumbai terminals, BRTS setups elsewhere, cutting the carbon from how passengers roll up. Looking ahead, Chennai and Kolkata are testing taxibots, these autonomous tugs that pull planes on the ground without firing up engines, saving fuel on taxiways.

All these vibes with India's big pushes like FAME and electric mobility drives, chipping away at those trickier Scope 3 emissions. Though traffic jams outside the gates might undercut some gains if cities don't catch up.

Carbon Governance and Management

Solid governance setups make sure all that infrastructure actually pays off in carbon cuts; without the right oversight, it's just shiny hardware. Every airport's got a high-level carbon committee calling the shots. Mumbai's MIAL, for one, runs a cross-functional team tied into a full ESG policy that keeps everyone aligned. They track emissions religiously, too: annual GHG inventories, public reports on drops. Mumbai's shaved 95-98% off Scope 1&2 since 2022; Delhi and Bengaluru log steady year-over-year wins. The ACI accreditation grind forces discipline; it's all "measure, manage, reduce, communicate," straight from ACA playbooks. Helps 'em climb and stay put. Collaboration's key as well: airlines, handlers, regulators all in

the mix. Delhi's water neutrality nod from NITI Aayog-CII shows how it ripples city-wide. Put it together, smart builds plus these formal processes, and you've got the real engine behind India's carbon-neutral push... though committees can get bogged down in bureaucracy if leadership wavers.

Proposed Green Airport Framework

Synthesizing the foregoing analysis, this study advances a five-pillar infrastructure framework intended to systematize the development of green airports in India. The framework is not a conceptual abstraction; it is derived from observable patterns across leading airports and aligned with both domestic policy guidance and international accreditation standards.

1. Energy Decarbonization.

Pulling from what works in these top airports, the Energy pillar zeroes in on ramping up renewables and squeezing every bit of efficiency. Start with high-capacity solar PV installs like Delhi's 7.84 MW plant soaking up rays right on-site, then lock in long-term green PPAs to keep the juice flowing steady. Microgrids and energy storage? Throw those in to smooth out supply hiccups, and swap every light and system for LEDs or high-efficiency gear across the board. Delhi's LED networks and solar combo show how it slashes grid pulls overnight. Though you know, cloudy streaks or peak loads can still test those setups if storage lags.

2. Green Buildings.

For the Buildings pillar, it's all about crafting or tweaking terminals to green standards right from the blueprint, passive tricks like maxing natural light and solid insulation to keep things cool without cranking the AC. Pair that with efficient HVAC setups and smart building brains that tweak energy on autopilot. And materials? Pick ones low on embodied carbon, nothing wasteful. Chase LEED or IGBC certs to lock it in Bengaluru's Terminal 2 with its garden vibe and reflective roofs nail this, or Delhi's LEED Gold terminals. Cuts demand hard, sure... but retrofitting ancient structures? That's where budgets groan, and timelines stretch.

3. Water and Waste Circularity.

For the Water & Waste pillar, go full circle on resources roll out ZLD wastewater treatment like Delhi's doing, recycling every drop for cooling towers, toilets, or green spaces. Pair it with massive rainwater harvesting setups, think Delhi's 625 structures and 9 million-litre tanks grabbing monsoon hauls, or Bengaluru's 66% recovery rate. Solid waste? Segregate, treat, and compost onsite. Mumbai turns kitchen scraps into landscaping gold. These loops slash discharge, and freshwater pulls to near-zero. Though in drought-prone stretches, you might still lean on city pipes if the rains ghost you.

4. Sustainable Mobility.

For the Transport pillar, electrify every vehicle the airport owns outright, buses, tugs, cars, the lot, just like Delhi's 57-unit EV fleet or Bengaluru's 175 electric taxis. Roll out chargers everywhere, for staff rigs and public drop-offs alike. Hook into public transit too, metro lines in Delhi and Mumbai or BRTS elsewhere, and experiment with slick taxiing fixes like electric tow tractors (taxibots) to ditch engine idling on runways. It chips away at Scope 3 emissions, syncing with FAME pushes. But if the surrounding roads stay gas-guzzler central, those gains fizzle fast.

5. Governance and Engagement.

For the Governance pillar, build out nonstop carbon management processes that hum along, tracking every emission with regular audits and real-time eyes. Rope in stakeholders from the jump: local communities, regulators, airlines, whoever's in the orbit, keeping lines open like Delhi did for that NITI Aayog-CII water

win. Ride accreditations hard ACA or ISO 14064 for street cred and transparency, and drill sustainability into the culture via training and policies that stick. Mumbai's ESG committee and cross-team setup make it click.

These pillars slot right into MoCA's guidance and the global playbook they're a no-fuss roadmap for any airport eyeing green upgrades. Though without real commitment or cash flow, it's all blueprint, no build.

Recommendations

Drawing from the comparative analysis, the following recommendations are proposed to consolidate and expand India’s green airport trajectory.

1. **Accelerate Renewable Energy Deployment.**

First off, nail those planned solar projects like getting Kolkata's 57 MW ground-mount up and running ASAP, since it's primed to wipe out their fossil fuel leftovers. Wherever feasible, scale 'em further; more panels mean less grid strain long-term. And yeah, throw financing or subsidies at the big installs, whether grants, low-interest loans, or tax breaks to make it less of a wallet-buster for operators, especially smaller AAI spots, not that funding fights ever go smoothly when budgets get sliced.

2. **Institutionalise Green Building Mandates.**

Make green certs like IGBC or LEED mandatory for every airport building and add-on, no exceptions, new or retrofit. Fast-track the approvals for anything hitting or beating national ECBC norms, cutting red tape so projects don't stall in bureaucracy. It'd force that baseline efficiency up across the board... though smaller airports might gripe about the upfront cert costs eating into tight margins.

3. **Leverage Accreditation and Regulatory Incentives.**

Require every operational airport to chase ACI, ACA, or ISO 14064 certs, just like MoCA's been nudging. Link progress there to real perks say, cost recovery on green energy spends or other incentives to light a fire under laggards. It'd sharpen focus and reward the leaders. Though tying strings to regs risks gaming the system if audits aren't ironclad.

4. **Expand Water Recycling and Zero Liquid Discharge Systems.**

Make sure every airport's got sewage treatment and rainwater setups locked in no more half-baked systems. For the older ones playing catch-up to zero liquid discharge, float central funding or tech help their way, easing the load on cash-strapped operators. It'd close those water loops nationwide... but honestly, doling out funds evenly? Politics and priorities could leave some spots in the dust.

5. **Promote Electric Ground and Passenger Mobility.**

Roll out incentives like tax breaks or subsidies to nudge airports into bulking up EV fleets and charger networks think Delhi's 57 units or Bengaluru's taxi push, but everywhere. Ease electric public transport ties too, greasing those metro or bus links. It'd speed the shift on ground ops, still, if city grids can't handle the extra load or roads stay clogged with diesels, you're only greening half the problem.

6. **Strengthen Stakeholder Collaboration and Knowledge Sharing.**

Ramp up those team-ups between airports, airlines, energy folks, and government get 'em sharing notes and resources, no silos. Lean on AAI's SUGAM platform and industry meetups to spread the wins, helping smaller airports copy what the big dogs like Delhi or Bengaluru pulled off. It'd fast-track the scaling. Though collaboration sounds great on paper, egos or misaligned goals can gum up the works if someone's not herding the cats.

Rolling out these steps would lock in India's front-runner spot in sustainable aviation no question. It's already outpacing a lot of the world with those 66 green-powered airports and Level 5 trailblazers. Push

harder here, and yeah, the leadership sticks. Though keeping that edge means watching global rivals like Europe's net-zero hubs don't lap it when funding dips or grids falter.

Conclusion

Indian airports prove you can't just talk a good sustainability game it's gotta be real infrastructure and tight management that seals the deal. Places like Delhi, Mumbai, and Bengaluru hit carbon-neutral by weaving in massive renewables, slick efficient facilities, and sharp resource loops. Even Kolkata, playing catch-up, is closing the gap with stuff like that 57 MW solar push and EV swaps. The five-pillar framework we've sketched pulls those lessons together a ready blueprint for every airport in India. Roll it out with the right policies and team-ups, and they'll keep trimming emissions while handling the passenger boom, not always smooth sailing, since smaller spots might balk at the costs. This rundown, built on solid data and those accreditation wins, should give policymakers and airport heads a clear path to scale up green infrastructure aiming for a future where aviation doesn't choke the planet.

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