A COMPARATIVE STUDY ON SUSTAINABLE AVIATION MANAGEMENT: Transitioning Indian Airports Toward Renewable Energy

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1. ABSTRACT

The rapid expansion of India's civil aviation sector has intensified energy demand and carbon emissions, making sustainable airport management an urgent national priority. This study presents a comparative analysis of renewable energy adoption and sustainability performance at Cochin International Airport (CIAL) and Indira Gandhi International Airport (IGIA), supplemented by a regulatory comparison between India's Directorate General of Civil Aviation (DGCA) and the European Union Aviation Safety Agency (EASA). Primary survey data from 120 respondents measure passenger awareness and behavioural intent, while secondary data are drawn from official sources including DGCA reports, CIAL Annual Reports 2024–25, EASA's European Aviation Environmental Report 2025, and ACI accreditation records. Findings reveal that 70% of India's 157 operational airports remain dependent on grid electricity; India lacks a binding Sustainable Aviation Fuel (SAF) mandate and a standardized Monitoring, Reporting and Verification (MRV) framework; and a 7-point regulatory maturity gap separates India from the EU on SAF mandates and legal enforceability. Conversely, India holds three of only four global ACI Level 5 Net Zero airports, and solar deployment at Tier 2 and Tier 3 airports achieves disproportionately high CO_2 avoidance per MW due to India's carbon-intensive grid. The study proposes four evidence-based policy recommendations targeting grid independence, SAF mandates, MRV integration, and domestic carbon pricing.

Keywords - *Sustainable aviation; renewable energy; CIAL; IGIA; DGCA; EASA; SAF; CORSIA; airport decarbonization; India civil aviation*

2. INTRODUCTION

India's civil aviation sector ranks among the world's fastest-growing, with passenger volumes reaching 237.42 million and air cargo handling rising to 2.28 million metrics tons during FY 2025–26 (April–October 2025). Airport infrastructure has expanded from 74 airports in 2014 to 163 currently operational, while aircraft movements increased to 2.87 million by October 2025 [DGCA Traffic Report, 2025]. Despite this expansion, airport operations remain energy-intensive, contributing substantially to national carbon emissions through terminal management, airfield lighting, and ground handling systems.

The aviation sector contributes approximately 2–3% of global CO_2 emissions, with airport-level operations accounting for a measurable share of that total. India's airports consumed an estimated 4.2 billion kWh annually as of FY 2024–25, predominantly sourced from coal-intensive state electricity grids at an average carbon intensity of 0.72 kg CO_2/kWh—approximately twice the EU average of 0.37 kg CO_2/kWh [AAI Annual Report, 2024–25; EASA EAER, 2025]. This differential amplifies the climate return on renewable energy investment at Indian airports.

High capital expenditure requirements, technological integration constraints, and the absence of binding policy frameworks remain principal barriers to decarbonization. This study addresses these challenges through a structured comparative analysis of CIAL and IGIA, a regulatory maturity assessment of DGCA and EASA, and primary survey data capturing passenger attitudes. The research yields four targeted policy recommendations for advancing India's aviation sustainability agenda.

II. LITERATURE REVIEW

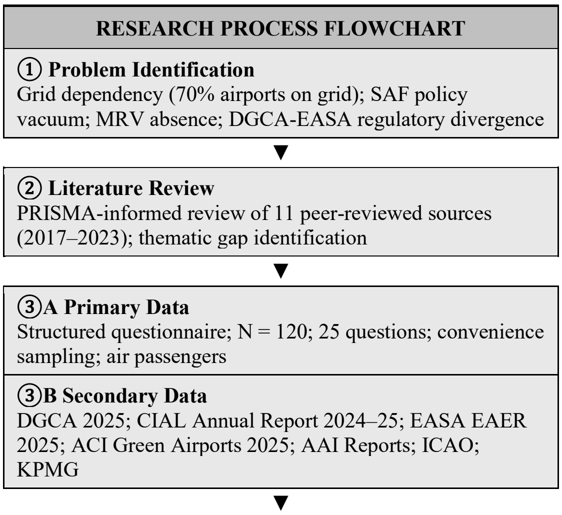
The academic literature on airport sustainability converges around several distinct thematic gaps. El Zein, Karimipanah, and Ameen (2023) established that most aviation sustainability research prioritizes SAF while renewable energy integration in airport infrastructure receives comparatively limited academic attention. Sukumaran and Sudhakar (2017) demonstrated through operational data from CIAL's 12 MWp plant that large-scale solar deployment can achieve energy sufficiency while significantly reducing emissions, though their single-case scope limits generalizability. Khanna (2022) identified social sustainability passenger well-being, employee welfare, and community engagement as underrepresented relative to environmental metrics.

Thummala and Hiremath (2023) applied a netnographic approach to Indian airlines and found that fuel efficiency improvements and carbon offsetting dominate corporate sustainability strategies, with limited coordinated action between airlines and government bodies. Pitter and Iqbal (2022) conducted a systematic Life Cycle Assessment review and concluded that practical LCA implementation remains sparse in developing-country airports. Raimundo, Baltazar, and Cruz (2022) identified a framework gap: integrated sustainability models linking environmental, economic, and operational performance remain underdeveloped. Abdi, Li, and Camara-Turull (2022) found that higher financial performance may paradoxically reduce airline ESG engagement, with particular relevance to state-owned Indian carriers.

These collective gaps comparative infrastructure analysis, social dimensions, policy enforceability, MRV systems, and integrated frameworks constitute the research space that this study addresses through its multi-method design.

III. RESEARCH METHODOLOGY

This study employs a mixed-methods research design integrating primary quantitative data with secondary qualitative and quantitative sources. The research design is structured around five sequential phases, as represented in the flowchart below.



RESEARCH PROCESS FLOWCHART

① **Problem Identification**
Grid dependency (70% airports on grid); SAF policy vacuum; MRV absence; DGCA-EASA regulatory divergence

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② **Literature Review**
PRISMA-informed review of 11 peer-reviewed sources (2017–2023); thematic gap identification

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③**A Primary Data**
Structured questionnaire; N = 120; 25 questions; convenience sampling; air passengers

③**B Secondary Data**
DGCA 2025; CIAL Annual Report 2024–25; EASA EAER 2025; ACI Green Airports 2025; AAI Reports; ICAO; KPMG

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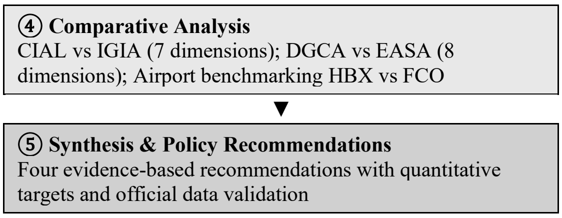

④ **Comparative Analysis**
CIAL vs IGIA (7 dimensions); DGCA vs EASA (8 dimensions); Airport benchmarking HBX vs FCO

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⑤ **Synthesis & Policy Recommendations**
Four evidence-based recommendations with quantitative targets and official data validation

Fig. 1. Research Process Flowchart — Five-Phase Mixed-Methods Design

The primary survey employed a structured questionnaire with 25 questions administered to 120 air passengers. Respondents were drawn using convenience sampling across departure and arrival zones. The secondary data framework prioritizes official institutional sources: DGCA traffic and regulatory reports (2024–25), CIAL Annual Reports and sustainability disclosures (2024–25), EASA's European Aviation Environmental Report 2025, ACI Asia-Pacific & Middle East Green Airports Recognition 2025, AAI Annual Reports, ICAO DGCA60 Conference Papers, and KPMG's India SAF Report (2025). Data validation follows a triangulation approach, cross-referencing survey findings with case study evidence and regulatory benchmarking.

IV. DATA ANALYSIS AND RESULTS

A. Primary Survey Findings

The 120-respondent survey reveals a well-informed cohort with a clearly progressive disposition toward sustainable aviation. Environmental awareness (Q4) is strong, with 61.7% rating themselves as moderately or highly aware of aviation's environmental footprint. Renewable energy literacy (Q7) is meaningful, with 58.3% confirming knowledge of airport solar deployments. An overwhelming 86.6% rated sustainability in aviation as very important or moderately important (Q11), establishing a robust social mandate for decarbonization.

Behaviourally, 75% indicated that sustainability credentials would strongly or moderately influence airport selection (Q16) Willingness to pay a supplementary fee for sustainable infrastructure was expressed by 72.5% (Q18), while 93.4% collectively affirmed support for the systemic transition of Indian airports toward sustainable practices (Q25) - a finding with direct policy implications for public acceptance of carbon pricing instruments.

B. CIAL vs IGIA: Comparative Analysis

Parameter	CIAL (Kochi)	IGIA (Delhi)
Solar Installed Capacity	50 MWp (5 technology streams)	13.14 MW (onsite)
Renewable Source Mix	Solar PV + 4.5 MW hydro (owned)	94% hydropower PPA (until 2036)
Grid Dependency	Zero - surplus fed to KSEB	Eliminated via PPA procurement
Annual CO_2 Avoidance	66,000 t CO_2/yr (solar +hydro)	200,000 t CO_2/yr (scale-adjusted)
Electricity Savings	Rs. 40 Cr/yr	Rs. 28 Cr/yr (PPA rate savings)
ACI Level (2024–25)	Level 4+ (Net-Zero Energy, Dec 2025)	Level 5 Net Zero (2024)

Parameter	CIAL (Kochi)	IGIA (Delhi)
ZLD Capacity	Standard treatment	16.6 MLD Zero Liquid Discharge
Unique Initiative	Agro-PV: 90 MT vegetables/yr	TaxiBot: 8,000 t CO_2/yr saved

Table I. CIAL vs IGIA: Comparative Sustainability Performance (FY 2024–25) Sources: CIAL Annual Report 2024–25; DIAL Sustainability Disclosures 2024–25; ACI Green Airports 2025

CIAL achieved generation sovereignty through five diversified PV technology streams ground-mounted rooftop carport canal-top and floating reaching 50 MWp total installed capacity by FY 2024–25. Cumulative output of 436 million kWh has generated approximately Rs. 170 crores in value through avoided grid costs and net-metering revenue [CIAL Annual Report, 2024–25]. IGIA's PPA-based model, procuring 94% of renewable supply from a Himachal Pradesh hydropower producer (contract valid until 2036), reflects a rational response to its constrained urban campus, dense pollution environment, and scale mismatch handling 50 million+ passengers versus CIAL's 10–12 million [DIAL Sustainability Report, 2024–25].

On a per-passenger basis, CIAL's carbon avoidance is structurally embedded in owned physical assets rather than contractual procurement. Delhi's winter AQI routinely exceeds 400–491 with PM2.5 reaching 200 $\mu g/m^3$, degrading photovoltaic efficiency by an estimated 15–30% without regular cleaning [DGCA Environmental Compliance Data, 2024–25], making aggressive onsite solar deployment structurally infeasible. Hubballi Airport's (HBX) 8 MWp cluster powering three airports and exporting surplus electricity worth ₹12.32 crore to the state grid in FY 2024–25 demonstrates the replicable model for Tier 2/3 contexts [AAI Press Release, April 2025].

C. DGCA vs EASA: Regulatory Maturity Assessment

Regulatory Dimension	EASA/EU	DGCA India	Gap
SAF Mandate	9/10	2/10	7
Carbon Pricing	8/10	1/10	7
Legal Enforceability	9/10	2/10	7
MRV / Data Reporting	9/10	3/10	6
Technology R&D Investment	8/10	3/10	5
CORSIA Alignment	8/10	6/10	2
Green Airport Standards	7/10	6/10	1
Renewable Energy Deploy.	7/10	7/10	0

Table II. Regulatory Maturity: EASA/EU vs India DGCA (Score /10, 2025) Sources: EASA EAER 2025; DGCA India 2025; ReFuelEU Reg. EU 2023/2405; ICAO DGCA60

The EU's ReFuelEU Aviation Regulation (EU 2023/2405), in force from January 2025, mandates SAF blending escalating from 2% (2025) to 70% (2050), with a financial penalty of at least 2× the SAF shortfall market value for non-compliance [EASA, 2025]. India has zero commercially produced domestic SAF as of 2025 and no binding blending mandate, rendering all targets aspirational. The EU ETS, operating at €60–70 per tonne CO_2 in 2025, creates a structural market signal absent in India's CORSIA-only framework. The Clean Aviation JU- a €4 billion public-private partnership (2021–2031) funds hybrid-electric and hydrogen-powered aircraft demonstrators, contrasting sharply with India's limited aviation R&D budget [EASA EAER, 2025].

India demonstrates credible leadership where governance remains voluntary: holding 3 of only 4 global ACI Level 5 airports as of 2024–25, achieving near-parity in renewable energy deployment, and demonstrating 17.2% of airports running on 100% green energy [ACI Asia-Pacific, 2025; AAI Annual Report, 2024–25]. The critical deficit lies in legal enforceability—the defining characteristic of the EU's transformational regulatory model.

D. SAF Policy Divergence: Long-Term Trajectory

Year	India SAF (%)	EU ReFuelEU (%)	Gap (pp)
2025	0%	2%	2
2027	1% (aspirational)	2%	1
2030	5% (aspirational.)	6%	1
2035	Undefined	20%	20
2040	Undefined	34%	34
2050	ICAO-aligned	70%	~70

Table III. SAF Policy Divergence: India vs EU ReFuelEU (%, 2025–2050) Sources: ReFuelEU Reg. EU 2023/2405; MoCA/ICAO ACT-SAF; KPMG India SAF Report 2025

V. DISCUSSION

A. Structural Asymmetry and Scale Context

The comparative analysis reveals a fundamental structural asymmetry that prevents direct equivalence between CIAL and IGIA's sustainability models. CIAL's 94-acre ground-mounted installation was enabled by Kerala's latitude 10°N, yielding year-round high irradiance, clean coastal air minimizing panel soiling, and contiguous land availability conditions simply not replicable within IGIA's dense urban campus [CIAL Annual Report, 2024–25]. Conversely, IGIA's operational scale handling 50+ million passengers versus CIAL's 10–12 million demands a procurement-led model to achieve energy sufficiency that individual onsite generation cannot practically match.

The Hubballi multi-airport cluster model reframes the national deployment strategy. Each MW of solar installed at HBX avoids approximately 2,044 tonnes of CO_2 annually four times the ~500 t CO_2/MW achieved at Rome Fiumicino (FCO) due to India's higher grid carbon intensity (0.72 vs 0.37 kg CO_2/kWh) [AAI Press Release, 2025; EASA EAER, 2025]. This disproportionate climate return makes accelerated deployment across 70 grid-dependent Tier 2/3 UDAN airports not merely desirable but strategically imperative.

B. Regulatory Gap and Policy Transition

India's regulatory position reflects a governance architecture optimized for voluntary achievement rather than systemic transformation. The 7-point SAF mandate gap (EASA 9/10 vs DGCA 2/10) and the equivalent gaps in carbon pricing and legal enforceability indicate that the structural instruments required to drive commercial SAF production fiscal incentives, blender tax credits, penalty frameworks remain absent [EASA EAER, 2025; DGCA, 2025]. The 2025 SAF Feasibility Study (MoCA/ICAO/EU) confirms adequate domestic feedstock availability from used cooking oil, agricultural residue, and municipal solid waste; the constraint is policy rather than resource.

India's CORSIA operational phase entry in 2024–2026 as a mandatory participant represents genuine regulatory progress reflected in the ICAO Council President Certificate awarded to the DGCA Director General in September 2025 but CORSIA compliance alone generates offset expenditure rather than structural fuel transition. Without a domestic carbon pricing signal equivalent to the EU ETS (€60–70/tonne CO_2), investment flows remain directed toward offset markets rather than SAF production infrastructure [ICAO DGCA60, 2025].

The MRV gap (EASA 9/10 vs India 3/10) has direct systemic consequences. India's 127 of 157 airports outside the ACI accreditation framework cannot be systematically benchmarked or incentivized under a voluntary reporting architecture. EASA's mandatory annual SAF uplift disclosure, lifecycle GHG savings reporting, and EU ETS verification chain demonstrate that MRV is not merely administrative overhead but the data infrastructure enabling evidence-based policy calibration [EASA EAER, 2025].

C. Financial Viability and Investment Context

The financial evidence supports both models as economically rational within their respective operating environments. CIAL's Rs. 260 crore capital outlay across its 50 MWp solar portfolio achieved payback within 5–7 years, with annual electricity savings of Rs. 40 crores continuing well into the 2040s [CIAL Annual Report, 2024–25]. Cumulative output of 436 million kWh has created Rs. 170 crores in total value through avoided grid costs and net-metering revenue to KSEB Ltd. The agro-photovoltaic model generating 90 metric tonnes of pesticide-free vegetables annually from inter-panel land adds Rs. 0.5 crore per year, demonstrating that sustainability investment can simultaneously serve energy, carbon, and food security objectives with no additional land footprint.

IGIA's financial gains are structurally distributed across multiple stakeholders. The Zero Liquid Discharge plant reduces freshwater procurement costs by an estimated Rs. 12 crores annually, TaxiBot eliminates engine-on taxiing contributing to 8,000 tonnes of CO_2 savings per year while saving Rs. 15 crores in airline fuel costs, and ISO 14001-driven operational efficiencies contribute a further Rs. 18 crores in terminal savings [DIAL Sustainability Report, 2024–25]. These figures underscore that the business case for sustainability is robust across airport types, scales, and ownership structures an important signal for the 70 grid-dependent airports yet to commence renewable energy investment.

VI. RECOMMENDATIONS AND CONCLUSION

A. Recommendations

No.	Problem	Recommended Solution	Evidence Base
1	70% of 157 airports on grid electricity	Replicate Hubballi cluster model; target 150 MWp under UDAN by 2027	HBX: ₹12.32 Cr surplus exported; 65.8% survey support
2	No binding SAF mandate; zero domestic SAF (2025)	Binding blending: 1% by 2027, 5% by 2030; 2× penalty for shortfall	DGCA SAF 2/10 vs EASA 9/10; 20 pp gap by 2035
3	No mandatory MRV; fragmented reporting	Mandatory sustainability MRV via DGCA eGCA platform (1M+ pax airports)	India MRV 3/10 vs EASA 9/10; 127 airports outside ACI
4	No domestic aviation carbon pricing	Voluntary ETS pilot for major carriers or international departure carbon cess	India pricing 1/10 vs EASA 8/10; EU ETS €60–70/t CO_2

Table IV. Consolidated Problem–Solution–Evidence Matrix Sources: This study; AAI Annual Report 2024–25; EASA EAER 2025; DGCA 2025; ACI Green Airports 2025

B. Conclusion

This study establishes that sustainable aviation in India has advanced substantially but unevenly. CIAL's generation-sovereign solar model and IGIA's procurement-led carbon neutrality demonstrate that decarbonization is achievable through institutionally distinct strategies calibrated to specific geographic, operational, and regulatory contexts. India's voluntary sustainability leadership is credible: 3 of 4 global ACI Level 5 airports, 27 airports on 100% green energy, and solar investments yielding disproportionately high climate returns relative to EU counterparts due to grid carbon intensity differentials [ACI Asia-Pacific, 2025; AAI, 2024–25].

Nevertheless, three structural deficits relative to the EASA framework constrain systemic transformation: the absence of legally binding SAF mandates, no domestic aviation carbon pricing mechanism, and fragmented sustainability reporting without standardized MRV. The primary survey reinforces the policy case, with 93.4% of respondents endorsing systemic transition and 72.5% expressing willingness to pay for sustainable infrastructure. Targeted legislative reform—binding SAF mandates with enforceable penalties, eGCA-integrated MRV, and a domestic carbon pricing pilot is the prerequisite for converting India's renewable energy leadership into an internationally competitive and systemically enforceable decarbonization regime.

C. Scope for Future Research

Several avenues warrant deeper investigation beyond the scope of this study. First, the analytical framework applied to CIAL and IGIA should be extended to greenfield UDAN airports, PPP-privatized hubs, and cargo-centric facilities, enabling the development of context-sensitive sustainability typologies applicable across India's heterogeneous airport ecosystem. Second, a comprehensive quantitative Life Cycle Assessment (LCA) encompassing construction materials, operational energy systems, water infrastructure, and waste management would provide a more empirically robust foundation than the secondary data-dependent framework employed here.

Third, a longitudinal passenger awareness survey tracking changes in environmental cognition, willingness-to-pay, and behavioural intent over multiple years would enable rigorous impact measurement of policy interventions and public communication initiatives. Fourth, dedicated research into SAF supply chain feasibility in India, including economic modelling of feedstock cost trajectories and blender incentive structures for used cooking oil, agricultural residue, and municipal solid waste pathways, is urgently needed to operationalize aspirational blending targets. Fifth, extending the regulatory comparison to the FAA (United States), CAAC (China), and CASA (Australia) would yield a comprehensive global benchmarking framework. Finally, the limited adoption of Electric Ground Support Equipment (E-GSE) and nascent green hydrogen infrastructure at Indian airports including the BPCL–CIAL green hydrogen partnership warrant dedicated feasibility and pilot-program research with emphasis on total cost of ownership and airside integration.

D. Key Survey Findings Summary

Survey Question	Key Response	%
Q4 — Environmental awareness of aviation	Moderately or highly aware	61.7%
Q7 — Awareness of airport solar energy	Yes, confirmed knowledge	58.3%
Q11 — Importance of aviation sustainability	Very or moderately important	86.6%
Q12 — Should airports invest in renewables?	Yes	65.8%
Q13 - Should airlines reduce carbon emissions?	Agree or strongly agree	90.8%
Q15 - Prefer eco-friendly airport infrastructure?	Strongly prefer or prefer	85.0%
Q16 - Would sustainability influence airport choice?	Strongly or moderately yes	75.0%
Q18 - Willing to pay fee for green infrastructure?	Definitely or possibly willing	72.5%
Q23 - Reducing grid dependency important?	Very important or important	84.1%
Q25 - Support transition to sustainable aviation?	Strongly support or agree	93.4%

Table V. Key Survey Findings — Passenger Awareness & Attitudes (N = 120) Source: Primary survey data, this study (2026)

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