Alliance for an™ Energy Efficient Economy

Technologies for Net-Zero Airports

A Blueprint for Sustainable Aviation Infrastructure

2026

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This report is prepared by the Alliance for an Energy Efficient Economy (AEEE).

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Executive Summary

The Indian aviation sector has undergone a profound transformation, evolving from a luxury for the few into a daily necessity for the many. Today, it stands as the third-largest domestic market in the world. However, this success brings a significant challenge: with passenger numbers projected to soar to 572 million by 2037, the industry has reached a critical turning point. India must now scale its infrastructure rapidly while simultaneously optimizing energy requirements and reducing associated emissions. This balance is vital to meeting the national commitment of net-zero emissions by 2070 and the industry's own target of reaching net-zero by 2050.

As global aviation hubs increasingly prioritize energy efficiency as a core pillar of decarbonization, Indian airports are beginning to follow suit. To effectively manage this transition, it is essential to understand that an airport's energy profile is multifaceted. To drive this transformation, key technologies are categorized into three strategic areas:

1. Airside Technologies

The "Airside" domain encompasses activities related to aircraft ground movements and essential support services. By modernizing these operations, airports can drastically reduce their immediate carbon footprint and local environmental impact. Key innovations include:

- **Fixed Electric Ground Power (FEGP):** This technology provides a clean, grid-based "plug-in" power source at the gate, serving as a superior alternative to noisy, fuel-burning Auxiliary Power Units (APUs). Implementation significantly lowers fuel costs while reducing on-ground noise and air pollution.
- **Sustainable Aviation Fuel (SAF):** Recognized as a "drop-in" green fuel produced from waste materials and biomass, SAF can be used in existing aircraft without requiring engine modifications. It is a critical lever for decarbonization, capable of reducing lifecycle emissions by up to 94%.
- **Noise Mapping and Abatement:** To protect the health and well-being of surrounding communities, airports utilize color-coded mapping to identify noise hotspots. These insights allow for the implementation of quieter flight procedures, such as Continuous Descent Approaches.

2. Terminal-Side Technologies

Terminal buildings consume the majority of an airport's electricity, primarily to support passenger comfort and logistics. Key energy-efficient technologies for terminals include:

- **Automated Baggage Handling Systems (ABHS)**: By employing smart sensors and high-efficiency motors, these systems move luggage 30% faster than manual alternatives. They achieve significant energy savings—cutting consumption by up to 15%—by entering "sleep modes" during periods of low activity.
- **Radiant Heating and Cooling**: Traditional AC systems often waste energy by conditioning high, empty volumes of air. In contrast, radiant systems circulate chilled or heated water through floor and ceiling slabs, providing uniform comfort while operating 20–30% more efficiently.

- **Refrigerant Transition:** Modernizing cooling systems by shifting to low-impact chemical fluids is critical for meeting international climate safety standards. This transition is vital for reducing the airport's long-term environmental footprint and ensuring regulatory compliance.
- **Thermal Energy Storage (TES):** Acting as a "thermal battery," TES systems store cooling energy—often in the form of ice or chilled water—during off-peak hours when electricity is cheaper. This stored energy is then deployed during peak usage periods to cool the building, drastically reducing operational costs

3. Landside and Infrastructure

This section explores sustainable construction methods and the electrification of vehicles that transport passengers to and from the terminal.

- "Green" Cement (LC3): By utilizing limestone and calcined clay, LC3 serves as a sustainable alternative to traditional cement. It reduces carbon emissions by 40% and is roughly 9–10% cheaper to produce, all while maintaining standard structural integrity.
- Fleet Electrification: Transitioning airport buses, luggage carts, and taxis to electric power eliminates tailpipe pollution. Furthermore, electric fleets offer significant long-term savings, with maintenance costs up to 75% lower than internal combustion equivalents.
- Chiller Retrofitting: Rather than replacing entire systems, existing cooling plants can be upgraded with smart "Variable Speed Drives." This retrofitting approach costs 40–60% less than new equipment while delivering up to 40% in energy savings.
- HVAC Modernization (VRF/VRV & Heat Pumps): These advanced systems allow for precision climate control across different zones—such as a crowded gate versus an empty lounge. This targeted conditioning results in up to 40% higher energy efficiency.

Strategic Plan for Implementation

This compendium serves as an actionable roadmap for the transformation of energy-intensive facilities into sustainable, climate-resilient, and 'smart' hubs. The transition toward net-zero airport operations is a long-term strategic endeavor that necessitates a balance between immediate financial performance and overarching environmental objectives. Based on an analysis of required capital investment, projected return on investment (ROI), and implementation schedules, this document proposes the following three-phase framework:

- **Phase 1: Foundational Wins (Years 1–3):** Focuses on "low-hanging fruit"—technologies that are easy to implement and generate rapid cost savings to establish a robust energy baseline.
- **Phase 2: Infrastructure Expansion (Years 3–7):** Reinvests accrued savings into larger-scale projects, such as modernizing baggage handling systems and transitioning vehicle fleets to electric power.
- **Phase 3: Advanced Decarbonization (Years 7+):** Implements high-impact, future-proofing solutions, including the adoption of sustainable aviation fuels and low-carbon construction materials.

Technology	Implementation Phase	Financial Payback	Primary Value
Fixed Electric Ground Power (FEGP)	Phase 1 (Foundational)	3–7 Years	Cuts diesel costs; creates revenue
Chiller Retrofit	Phase 1 (Foundational)	3–7 Years	Deep energy savings; longer asset life
Thermal Storage (TES)	Phase 1 (Foundational)	3–7 Years	Lowers expensive peak-hour power bills
Noise Abatement	Phase 1 (Foundational)		Regulatory compliance; community health
Radiant Cooling	Phase 2 (Expansion)	5–10 Years	High comfort; 30% lower energy cost
Baggage Automation (ABHS)	Phase 2 (Expansion)	5–10 Years	Faster check-in; 15% lower power use

Technology	Implementation Phase	Financial Payback	Primary Value
Fleet Electrification	Phase 2 (Expansion)	5–8 Years	Zero emissions; 75% lower maintenance
HVAC (VRF/VRV) Retrofitting	Phase 2 (Expansion)	6–7 Years	Precision zone control; cuts energy waste
Green Cement (LC3)	Phase 3 (Advanced)	Immediate (Cost)	10% lower material cost; 40% less CO_2
Sustainable Aviation Fuel (SAF)	Phase 3 (Advanced)	Long-term	Up to 94% lifecycle carbon reduction
Refrigerant Transition	Phase 3 (Advanced)	6–12 Years	Compliance with global climate mandates

Overall, the technologies highlighted in this compendium are not merely technical upgrades; they are the essential building blocks of a resilient and decarbonized aviation future. Ultimately, this blueprint aims to build knowledge to promote investments—from the cement in the walls to the fuel in the planes—that represent a coordinated step toward building a sustainable, profitable, and climate-resilient aviation sector.

CHAPTER 1

Introduction

Indian aviation sector has witnessed significant expansion, shifting from a privilege for the elite in the early 2000s to what is now recognised as the world's third-largest domestic aviation market. With a population nearing 1.4 billion, India represents one of the fastest-growing air passenger markets globally, driven by sustained infrastructure developments and expected passenger numbers rising annually from 158 million in 2017 to an estimated 572 million by 2037, mainly due to the expanding middle-class demographic and supportive government schemes such as the Ude Desh ka Aam Nagrik (UDAN). [1]

India currently has over 130 operational airports, including 29 international ones, and the number of terminals and capacity utilisation continue to increase to accommodate the rising air travel demand. A large and growing passenger base, along with the resulting expansion of airports, requires substantial energy to operate terminal buildings and associated airport infrastructure. [2]

Aligned with India's national climate goals, including the 'Panchamrit' pledge to achieve net-zero emissions by 2070, the Ministry of Civil Aviation (MoCA) is actively guiding the aviation industry toward sustainable development. This strategic shift is supported by policies aimed at implementing cost-effective carbon mitigation measures and establishing a roadmap to transition airports from fossil fuel-based electricity to 100% renewable energy sources. To support carbon neutrality and net-zero carbon emissions at airports, MoCA has advised most airports to evaluate their carbon emissions and has set the targets of achieving 100% use of green energy by 2025 and net-zero by 2050. [3].

While the aviation sector's sustained growth highlights its economic importance, it also presents a strategic opportunity to advance energy efficiency and environmental stewardship. Adopting energy-efficient technologies offers benefits that extend beyond operational cost savings. These efficient technologies can play a pivotal role in achieving broader sustainability objectives, such as supporting compliance with international climate agreements, including the International Civil Aviation Organisation's (ICAO) Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), as well as India's national net-zero commitments. [4]

1.1 Energy Efficient Technologies for Airports

The energy consumption profile of an airport is multifaceted, encompassing three key areas: airside operations (aircraft handling, fuelling, runways, and taxiways), terminal buildings (passenger processing and comfort systems), and landside infrastructure (transport access, parking, and auxiliary services). In operational and planning practice, airport energy consumption is generally categorised into landside and airside facilities, with the bulk of electricity usage typically concentrated within terminal buildings and associated landside infrastructure. Table 1 highlights the key systems and services that drive energy demand across these areas, while Figure 1 illustrates the spatial distinction between airside and landside areas within an airport.

Table 1: Electricity consumption focus area across the airport

Airport Area	Typical Electricity Consumption Focus
Airside	Air Traffic Control (ATC) facilities, runway/apron lighting, ground support equipment (GSE) charging, and maintenance hangars.
Terminal (Part of Landside)	Terminal buildings, concourses, baggage handling systems, HVAC, lighting, retail spaces, and parking facilities.
Landside and Infrastructure (Broader Area)	Terminal and Landside buildings, support facilities, parking lots, public transport systems, and airport access roads.

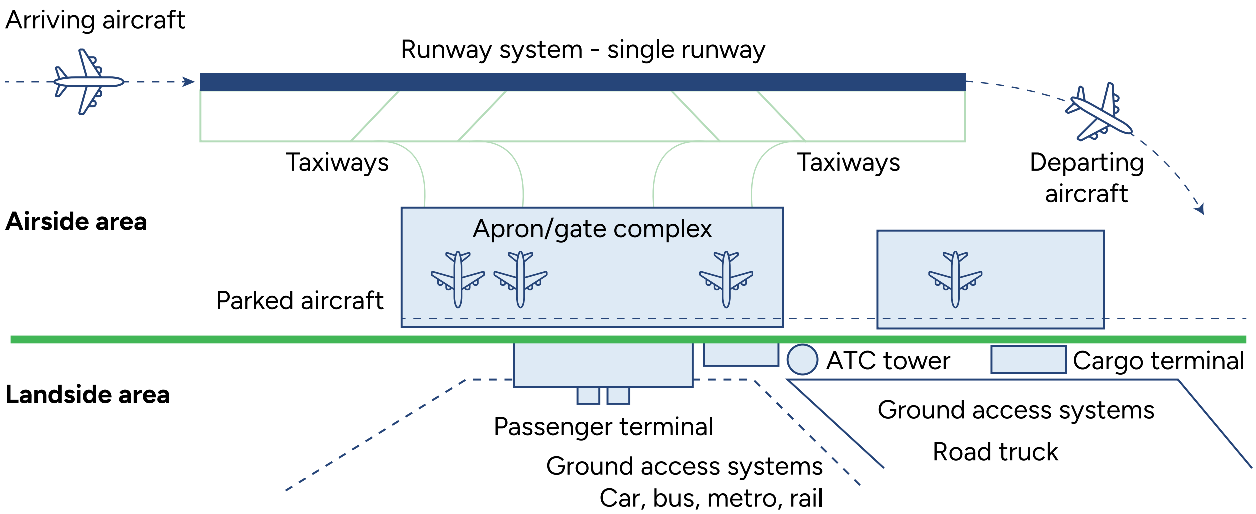


Figure 1: Airside and Landside areas of airports

The relatively high electricity consumption on the landside is primarily driven by the need to maintain passenger and staff comfort through lighting and Heating, Ventilation, and Air Conditioning (HVAC) systems. [5] In addition, a significant share of electricity demand arises from the continuous operation of other necessary airport systems, such as baggage conveyor belts and escalators, which are essential to supporting day-to-day terminal operations. Each of these areas offers significant opportunities for energy efficiency improvements through the adoption of advanced technologies and sustainable practices. This compendium examines these innovations, demonstrating how targeted interventions can mitigate operational inefficiencies and support the transformation of airports into smart, sustainable, and climate-resilient hubs. Accordingly, the compendium is structured around three primary areas of intervention:

Airside Techonologies	Terminal Side Techonologies	Landside & Infrastructure Technologies
The efficiency measures on the air side include: • Fixed Electric Ground Power (FEGP) • Sustainable Aviation Fuel (SAF) • Noise mapping and reduction	The efficiency measures on the terminal side include: • Automated baggage handling systems • Advanced thermal management solutions such as radiant heating and cooling systems to reduce HVAC-related energy consumption.	The efficiency measures on the land and Infrastructure side include: • Limestone Calcined Clay Cement (LC3) • Large-scale electrification of transport fleets • Modernising HVAC infrastructure through chiller retrofits, and deploying advanced VRF/VRV systems.

Improvements across these domains can deliver operational, financial, and environmental benefits simultaneously, while accelerating the Indian aviation sector's progress toward its net-zero ambitions

1.2 The Blueprint for a Net-Zero Airport

The core challenge for every airport operator is transforming high-traffic, energy-intensive infrastructure into resilient, low-carbon assets without compromising safety, service quality, or operational uptime. Achieving this requires a structured, long-term approach that balances immediate efficiency gains with strategic investments in decarbonisation.

A strategic, phased plan that focuses on three primary operational domains – Airside, Terminal, and Landside – and sequences technologies implementation across three strategic phases can provide an effective pathway. In each phase, the implementation of technology can focus on:

- **Phase 1: Foundational Wins (Years 1-3):** This phase prioritises initiatives with high returns on investment (ROI) that can deliver immediate energy savings and operational efficiencies. These measures can establish robust baselines for energy monitoring and management, improve data transparency, and generate financial savings that can be reinvested in subsequent phases.
- **Phase 2: Infrastructure Expansion (Years 3-7):** This phase focuses on reinvesting accumulated savings into larger, capital-intensive projects. These interventions target the transformation of major energy-consuming systems and enable the sustainable expansion and upgrading of airport infrastructure.
- **Phase 3: Advanced Decarbonisation (Years 7+):** This phase focuses on implementing long-term, high-impact solutions that fully integrate renewable energy, establish closed-loop material cycles, and future-proof the entire airport.

By adopting this phased approach, Indian airports can move beyond incremental improvements to achieve a comprehensive net-zero transformation. This roadmap ensures that every investment – from chillers to construction materials – represents a coordinated step toward building a sustainable, economically viable, and climate-resilient hub that meets both national commitments and global industry standards.

Airside Technologies at the Airport

CHAPTER 2

Fixed Electric Ground Power

Fixed Electric Ground Power (FEGP) is a foundational technology for decarbonising airside operations. FEGP offers a high return on investment by providing grid-based 400 Hz electrical power to aircraft parked at the gate. This enables aircraft to shut down their fuel-intensive Auxiliary Power Units (APUs) and reduce reliance on mobile diesel Ground Power Units (GPUs), leading to immediate and substantial reductions in on-ground emissions, noise, and operational costs.

Often described as "shore power for jets," FEGP replaces mobile, fossil-fuel-burning solutions with integrated, grid-based power systems, delivering significant improvements in efficiency, safety, and sustainability. Table 2 presents comparison of different methods for powering options for stationary aircraft.

Table 2: Comparison of different methods for powering options for stationary aircraft

Method	Description	Advantages	Considerations
Auxiliary Power Unit (APU)	A small jet engine in the aircraft's tail that provides power for non-propulsion functions.	• Complete Autonomy: The aircraft is self-sufficient and does not rely on any ground infrastructure. • Universal Availability: Can be used at any airport or remote stand worldwide.	• High Operational Cost: Fuel consumption is extremely high, and maintenance expenses are significant. • High Emissions: Produces significant CO_2, NOx, and particulate matter. • Noise pollution: creates considerable noise on the tarmac.
Diesel Ground Power Unit (GPU)	A mobile generator on a cart supplies power to a parked aircraft.	• Mobility & Flexibility: Can be moved to any aircraft stand as needed. • Lower Cost than APU: Cheaper to operate than running the aircraft's APU. • Lower Initial Cost: The purchase price is much lower than installing FEGP infrastructure.	• Local Pollution: Generates diesel emissions (NOx, particulates) and noise. • Logistical Needs: Requires a constant supply and transport of diesel fuel. • Ramp Congestion: Adds to equipment clutter on the apron.
FEGP (Fixed Electrical Ground Power)	Supplies electricity to a parked aircraft from the airport's power grid via a converter and cable.	• Lowest Operational Cost: Drastically reduces on-ground energy expenses. • Zero On-Site Emissions: Eliminates local air and noise pollution. • High Reliability: Provides stable, clean power.	• High Initial Investment: Requires a substantial upfront capital investment from the airport for infrastructure. • Immobility: It is a fixed installation, only available at equipped gates. • Grid Dependent: Relies on the stability of the local electricity grid.

The benefits of FEGP are amplified when integrated with Pre-Conditioned Air (PCA) systems at the jetway. In this configuration, the FEGP unit powers the PCA system, which supplies cooled or heated air directly into the aircraft cabin. This integrated approach allows the aircraft's main HVAC packs to remain switched off, resulting in further reductions in fuel consumption, emissions, and noise while enhancing passenger and crew comfort from the point of boarding. Figure 2 depicts the schematic diagram of the FEGP system.

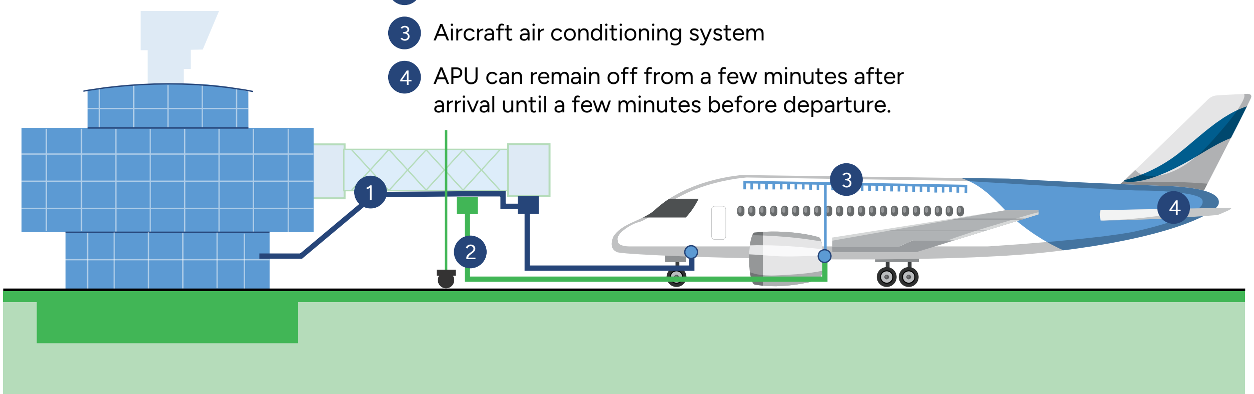


Figure 2: Aircraft connected to Fixed Electric Ground Power (FEGP) at a jetway

2.1 Benefits and Performance Insights

The FEGP represents a fundamental technological shift in ground-based aircraft management. It transitions airports away from mobile, fossil-fuel-dependent solutions toward integrated, grid-based infrastructure, offering significant improvements in efficiency, safety, and sustainability. By replacing mobile diesel-powered units, FEGP significantly enhances operational efficiency, safety, and sustainability. The efficiency gains of FEGP extend beyond basic power delivery to include improved power quality, faster operational turnaround, and long-term cost-effectiveness. As such, FEGP serves as a cornerstone technology for airports aiming to reduce their environmental footprint and progress towards sustainability targets. Key benefits of FEGP are summarised in the accompanying infographic.

FEGP can be deployed by airports during in conjunction with other complementary technologies, to achieve a high ROI. Its implementation delivers substantial ROI for airports through significant reductions in operational expenditures and the potential creation of new revenue streams. By facilitating the systematic shutdown of fuel-intensive APUs and mobile diesel generators while aircraft are at the gate, FEGP considerably reduces on-ground energy costs.

Efficiency	Power Quality and Stability: FEGP systems are designed to deliver "clean power." They use sophisticated solid-state converters to transform standard grid electricity (50 Hz in India) into the precise 400 Hz frequency required by sensitive aircraft avionics, ensuring optimal performance and reducing the risk of power-related faults.
	Operational Efficiency: FEGP streamlines ground handling operations significantly. Rather than requiring ground crews to locate, transport, position, and refuel diesel GPUs, FEGP functions as a "plug-and-play" solution, thereby saving valuable minutes during the turnaround process and enabling ground crews to focus on other critical safety-related tasks.
	Cost Efficiency: Electricity generation through an aircraft's APU is inherently inefficient and costly. By drawing electricity from the national grid, FEGP supplies the same power at a fraction of the cost, resulting in substantial reductions in on-ground energy expenditure.

Safety	Reduction of Fire Hazards: Diesel GPUs are, in essence, mobile fuel tanks with running combustion engines. FEGP mitigates this risk by eliminating liquid fuel from the on-ground power supply process.
	Reduced Ramp Congestion: The airport apron is a highly congested and high-risk operational area, characterised by the continuous movement of baggage carts, catering trucks, service vehicles, and personnel. FGEP helps declutter the apron by removing the need for a mobile GPU at each gate.
	Improved Occupational Health and Safety: The operation of diesel GPUs produces toxic exhaust fumes and high noise levels. FEGP operates quietly and produces zero local emissions, creating a cleaner and safer workplace for ground personnel.
Sustainability	Drastic Reduction in On-Site Emissions: The use of APUs for power generation releases CO_2, Nitrogen Oxides (NOx), and other pollutants directly into the atmosphere. By enabling aircraft to shut down their APUs, FEGP eliminates these on-site emissions, thereby improving local air quality around the airport.
	Significant Reduction in Fossil Fuel Consumption: An APU can burn over 100 kg of jet fuel per hour during operation. FEGP significantly curtails this fuel consumption, resulting in a substantial reduction in the overall carbon footprint of airline and airport operations.
	Alignment with National and Global Green Initiatives: The adoption of FEGP supports airport compliance with increasingly stringent environmental regulations. It also constitutes a key enabler for achieving higher levels of accreditation under the Airports Council International (ACI) Airport Carbon Accreditation (ACA) programme.

2.2 Case Study: Indira Gandhi International Airport (IGIA)

Challenge: As one of the world's busiest airports, Indira Gandhi International Airport (IGIA) faced significant air quality degradation and noise pollution challenges on its aprons due to the extensive use of aircraft APUs. This situation created an unhealthy working environment for ground personnel, increased operational costs for airlines and resulted in a substantial carbon footprint from ground operations.

Solution: As part of a comprehensive sustainability initiative, Delhi International Airport Limited (DIAL) implemented a large-scale programme to install FEGP systems integrated with PCA units across its contact stands. The strategic objective was to provide airlines with a cleaner, quieter, and more economical on-ground power source, enabling the complete shutdown of APUs while aircraft are at the gate. [6]

Quantifiable Outcomes:

- **Carbon Reduction:** The widespread adoption of FEGP served as a cornerstone achievement that helped IGIA to become the first airport in India to achieve the prestigious Level 4+ "Transition" accreditation under the ACI Airport Carbon Accreditation programme for exemplary carbon management performance.
- **Fuel Savings for Airlines:** Airlines operating at IGIA have realised significant financial savings by avoiding the high cost of jet fuel associated with APU operation. This created a compelling business case for adoption and established a win-win financial model, in which the airport generates revenue from FEGP usage while airlines significantly reduce operational expenses.
- **Improved Air Quality & Noise Reduction:** The initiative dramatically improved the working environment for thousands of ground personnel by eliminating direct exposure to jet fuel fumes, particulate matter, and continuous high noise levels generated by APUs.

Key Lesson/Implication for Indian Airports: The success at IGIA provides a robust, evidence-backed blueprint for other Indian airports. It proves that FEGP is not just an environmental initiative but a financially viable technology that enhances operational efficiency and strengthens partnerships between airport operators and airlines. It is a critical first step in any credible airport decarbonization strategy.

2.3 Conclusion and Way Forward

FEGP systems offer a cleaner, quieter, and more energy-efficient alternative to traditional APUs used during aircraft ground operations. By supplying electricity directly from the terminal to the aircraft at the gate, FEGP significantly reduces carbon emissions, noise pollution, and fuel consumption. The experience at Indira Gandhi International Airport clearly demonstrates that FEGP deployment is not only technically feasible but also economically and environmentally advantageous within the Indian aviation context. To enable wider adoption, it is essential to address challenges such as high initial investment, the need for electrical infrastructure upgrades at older terminals and ensuring equipment compatibility across diverse aircraft fleets. A phased rollout targeting major metro airports, supported by targeted financial incentives, concessional financing mechanisms, and clear technical guidelines, can accelerate implementation. Integrating FEGP systems into broader airport sustainability policies and performance metrics will further ensure long-term impact. With appropriate institutional and financial support, FGEP can emerge as a cornerstone technology in India's transition toward greener and more energy-efficient aviation infrastructure. Table 3 presents assessment summary of FEGP.

Table 3: Assessment summary of Fixed Electric Ground Power (FEGP)

Metric	Assessment
Technology Category	Foundational Win (Phase 1)
Capital Expenditure	High; requires significant investment in electrical infrastructure and gate-level equipment.
Typical Payback Period	3-7 years, driven by airline energy payments and reduced GPU maintenance costs
Impact on Operating Expenditure (OpEx)	High positive impact; creates new revenue streams from airlines, eliminates diesel fuel costs, and reduces maintenance on mobile GPUs.
Primary Financial Return	Direct revenue from electricity sales to airlines, extended asset lifespan of ground equipment, and operational cost savings.
Non-Financial Returns	Drastically reduced on-ground emissions and noise, improved air quality for personnel, enhanced airport sustainability credentials (e.g., ACI accreditation), and stronger airline partnerships.
Financing Models	Direct capital allocation, government grants or incentives, and concessional financing.
Key Dependencies	Grid capacity and stability at the airport, airline adoption and operational buy-in, and phased installation planning to minimise operational disruptions.

CHAPTER 3

Sustainable Aviation Fuel

Sustainable Aviation Fuel (SAF) is a safe alternative to conventional fossil-based aviation fuel that can reduce carbon emissions and support the decarbonisation of one of the hard-to-abate sectors – aviation. SAF is a low-carbon synthetic jet fuel that can be used safely in any turbine-powered aircraft, and is derived from sustainable feedstocks, including cellulosic biomass, wastes and residues, waste steel mill gases, and captured carbon monoxide (CO). SAF can reduce lifecycle greenhouse gas (GHG) emissions by up to 94% compared to conventional jet fuel [7]. The adoption of SAFs, including e-fuels, synthetic fuels, green jet fuels, bio jet fuels, and hydrogen-based fuels, is one of the most feasible pathways to mitigate and accelerate reductions in CO_2 emissions from aviation. Consequently, SAF deployment is pivotal to achieving the aviation industry's net-zero target by 2050 [8]. According to the International Civil Aviation Organisation (ICAO), over 360,000 commercial flights have used SAF across 46 airports worldwide, with deployment largely concentrated in the United States and Europe [7]

3.1 Benefits and Performance Insights

Fuel is typically the single largest operating cost for the airline industry, and fluctuations in crude oil prices make long-term operational planning and budgeting challenging. In this scenario, SAF offers a strategic solution, as its production can be geographically diversified and based on multiple feedstocks. This reduces airlines' exposure to fuel cost volatility associated with reliance on a single energy source. Crucially, SAF serves as a "drop-in" solution; it meets the same performance standards as conventional Jet-A or Jet-A1, allowing it to be used in existing aircraft and infrastructure without technical modifications. By leveraging renewable and waste-derived resources, SAF provides a holistic answer to aviation's sustainability challenges. The key advantages of SAF include:

Carbon Emission Reduction	Compared to conventional jet fuel, 100% SAF has the potential to reduce greenhouse gas emissions by up to 94%, depending on feedstock and technology pathway.
Alternative to Conventional Jet Fue	SAF can be blended with conventional jet fuel and can be used in existing aircraft and infrastructure.
Compatible with Existing Aircraft	SAF is an alternative to conventional jet fuel, enabling the production of multiple products from various feedstocks and technologies.
Increasing Energy Security	SAF can diversifies fuel supply and promotes domestic energy production

In addition, SAF delivers economic benefits to regions with marginal land unsuitable for food crops but viable for feedstock cultivation, as well as to areas rich in waste resources like municipal solid waste. Advanced technologies enable SAF production from a diverse array of materials. The specific feedstocks are detailed in the infographic below:

Waste Oils and Fats	These typically come from plant- or animal-based fats and greases that have been used for cooking and are no longer usable for further use (e.g., used cooking oil), as well as waste from food production
Municipal Solid Waste	This includes carbon-based waste materials such as product packaging, grass clippings, furniture, clothing, bottles, food scraps, and newspapers generated from households and businesses.
Cellulosic Waste	This includes lignocellulosic materials such as excess wood, agricultural residues (e.g., corn stalks), and forestry residues including branches and leaves that are not commercailly tradeable.
Rotational Oil Seed and Cover Crops	This includes rotational oilseed crops, leftover 'meal' from the oil extraction, and non-edible oilseed crops with similar promise (such as Carinata).
Non-Biogenic Alternative Fuels	These include 'power-to-liquid' pathways, which typically involve synthesising jet fuel from carbon sources such as industrial point-source waste gases that can be converted into ethanol through biological conversion processes, with the ethanol subsequently upgraded into jet fuel.

There are currently seven SAF production pathways approved by the American Society for Testing and Materials (ASTM) International, with each pathway representing distinct production processes based on feedstock type [9]. Each pathway offers specific benefits such as feedstock availability and cost, total carbon reduction, and processing complexity and associated cost. Some SAF pathways may be more suitable than others in specific geographic regions, depending on local feedstock availability and industrial processing capabilities. The lifecycle pathways of SAF production from waste and other biomass sources are illustrated in Figure 3 [9].

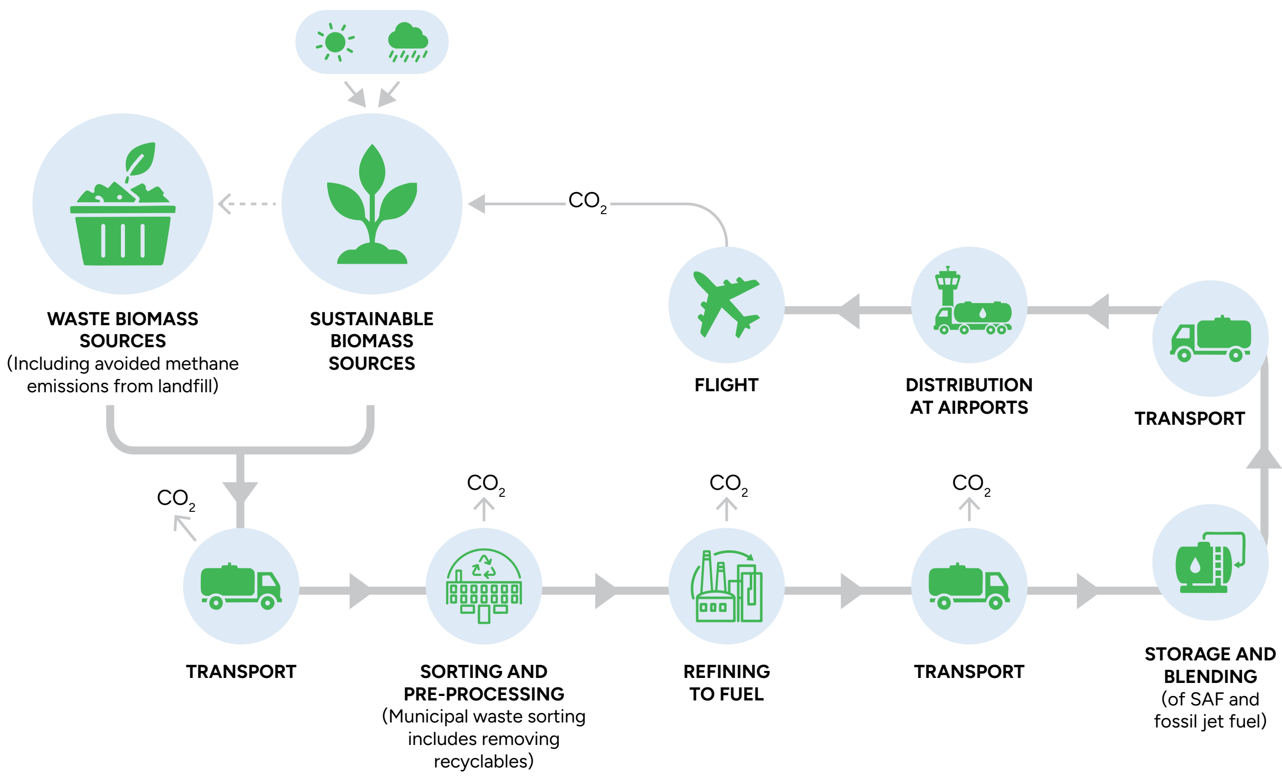


Figure 3: SAF production pathways from waste and other biomass sources

Although blend limits currently exist due to technical and safety reasons, major airframe and engine manufacturers are actively working to ensure that all aircraft can safely operate on 100% SAF by 2030. While technical and safety constraints currently limit blend ratios, major airframe and engine manufacturers are actively targeting 100% SAF compatibility for all aircraft by 2030. The ASTM International-approved pathways for producing this fuel are detailed in Table 4.

Table 4: ASTM International-approved SAF production pathways

Pathway	Feedstock	Certification Name & Blend Limit
Fischer-Tropsch (FT)	Energy crops, lignocellulosic biomass, and solid waste	FT-SPK (up to 50%)
Hydro Processed Esters and Fatty Acids (HEFA)	Waste fats, oils, and greases (FOGs) from vegetable and animal sources	HEFA-SPK (up to 50%)
Direct Sugars to Hydrocarbons (DSHC)	Conventional sugars and lignocellulosic sugars	HFS-SIP (up to 10%)
Fischer-Tropsch with Aromatics (FT+A)	Energy crops, lignocellulosic biomass, and solid waste	FT-SPK+A (up to 50%)
Alcohol to Jet (AtJ)	Sugar, starch crops, lignocellulosic biomass	ATJ-SPK (up to 50%)
Catalytic Hydro Thermolysis Jet (CHJ)	Waste fats, oils, and greases (FOGs) from vegetable and animal sources	CHJ or CH-SK (up to 50%)
HEFA from Algae	Microalgae-derived oils	HC-HEFA-SPK (up to 10%)

3.2 Case Study: SAF Adoption in India

Challenge: A key challenge for the difficult-to-abate aviation sector is identifying a safe, scalable, and environmentally sustainable alternative to conventional fossil-based jet fuel that can be used without requiring modifications to existing aircraft or airport infrastructure. The challenge is further compounded by the lack of local production and the underutilisation of proven domestic feedstocks.

Solution: In a significant step toward validating domestic SAF feasibility, SpiceJet conducted India's first domestic commercial flight using a SAF blend. This pilot flight demonstrated the technical viability of using SAF derived from locally sourced feedstocks within existing aircraft infrastructure. India has the potential to produce 8-10 million tons per year of Sustainable Aviation Fuel (SAF) by 2040, requiring investments of $70-85 billion to achieve this target, according to a new report by Deloitte India. [10]

Quantifiable Outcome:

- **Initial Feasibility:** SpiceJet successfully operated India's first domestic flight using a 25% SAF blend on a Bombardier Q400 aircraft. [11]
- **National Production Potential:** India has the capacity to sustainably produce up to 8-10 million tonnes of SAF annually by 2040. [12]
- **Environmental Impact Potential:** SAF can reduce lifecycle GHG emissions by up to 94% compared to conventional jet fuel.

Key Lesson and Implication for Indian Airports: The successful pilot flight and India's vast production potential confirm that SAF is a technologically feasible and nationally strategic decarbonisation solution. The critical next step for Indian airports is to actively support this transition by focusing on the 'Key Dependencies' for mainstream adoption, which include: developing dedicated SAF blending, storage, and fuelling facilities at major hubs, and actively aligning with the policy push for blending mandates and fiscal incentives. SAF will play a pivotal role in the entire aviation industry to achieve its net-zero goals by 2050.

3.3 Conclusion and Way Forward

Biological and non-biological resources, such as oil crops, sugar crops, algae, and waste oil, serve as the raw materials forming the foundation of the entire production chain of alternative aviation fuels, including synthetic fuels, e-fuels, and bio-jet fuels. The supply of raw materials required for SAF production and the availability of refineries capable of utilising these feedstocks are critical for the overall production capacity and scalability. The availability of SAF at FBOs (fixed-base operators) worldwide continues to grow, with a target production capacity of approximately 3.68 billion gallons by 2030. The sustainable aviation fuel market is projected to grow from USD 219 million in 2021 to USD 15,716 million by 2030, at a Compound Annual Growth Rate (CAGR) of 60.8% during the forecast period, positioning sustainable aviation fuels as a key component in meeting the aviation industry's commitments to offset carbon emissions associated with traffic growth [13]. Although current SAF prices remain significantly higher (2–4 times) than conventional jet fuel, economies of scale, policy incentives, and technological innovation are rapidly improving affordability. Initiatives such as the US SAF Grand Challenge, EU ReFuel Aviation mandate, and India's Bio-Aviation Fuel Roadmap are actively working toward large-scale SAF production and its affordability. Table 5 summarises key deployment metrics providing a clear, data-driven basis for financial evaluation:

Table 5: Assessment summary of Sustainable Aviation Fuel (SAF)

Metric	Assessment
Technology Category	Advanced Decarbonisation (Terminal-side technologies at the airport)
Capital Expenditure	Very high major investments are required for SAF production, blending and storage facilities.
Typical Payback Period	Not explicitly defined; highly dependent on production scale, policy support, and market price differential (currently 2-4 times higher than conventional jet fuel).
Impact on OpEx	Mixed; current SAF prices are significantly higher (2-4 times) than conventional jet fuel. However, diversification of production across multiple feedstocks can reduce exposure to fuel cost volatility.
Primary Financial Return	Long-term: reduced exposure to crude oil volatility, potential cost reductions through economies of scale and policy support, and the ability to meet regulatory mandates (avoiding penalties).
Non-Financial Returns	High; reduces lifecycle GHG emissions by up to 94%, supports the aviation industry's goal of net-zero by 2050, leverages existing infrastructure, and provides environmental benefits through utilisation of waste-derived feedstocks.
Financing Models	Fiscal incentives (e.g., Viability Gap Funding, tax credits) and carbon market credit linkages for SAF.
Key Dependencies	Development of dedicated blending, storage, and fuelling facilities; introduction of SAF blending mandates; securing reliable raw material supply and adequate refinery availability.

CHAPTER 4

Noise Mapping and Reduction

Noise represents one of the most significant environmental challenges associated with aircraft and airport operations. Exposure to high levels of aviation noise poses significant risks to human health, including cognitive development, psychological well-being, and ecological balance. [14] Given the industry's continuous growth and increasing population agglomerations near airports, the population affected by aircraft noise is expected to increase further. Aviation noise is generated from multiple sources, each contributing to the overall acoustic footprint of airport operations. The noise generated during take-off, landing, and ground operations has a measurable impact on the quality of life for surrounding communities. Figure 4 illustrates the major multiple noise sources associated with aircraft operation

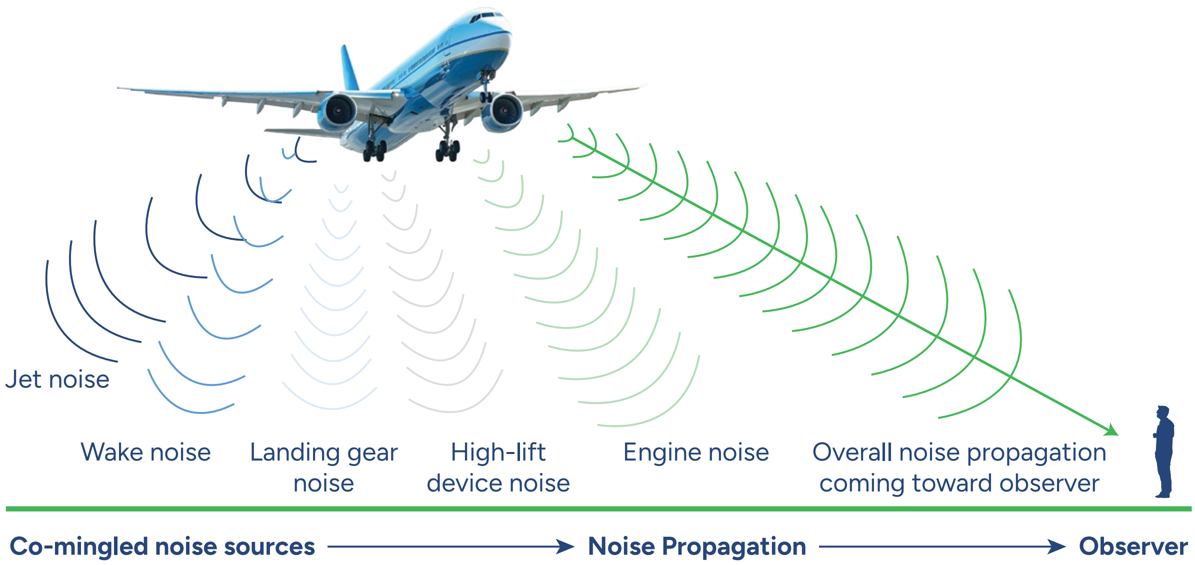


Figure 4: Co-mingled noise sources generated during aircraft operations

The key impacts of high noise include sleep disruption and annoyance, increased risk of hypertension and cardiovascular diseases, and disturbance to wildlife near protected reserves. [14] Accordingly, the primary sources of noise pollution around the airports include:

Aircraft Engines	Noise is generated by combustion during rapid burning of fuel-air mixtures in the combustion chamber, high-speed rotation of fan blades in turbofan engines, and Jet Exhaust noise resulting from turbulence caused by high-velocity exhaust gases
Aerodynamic Noise During Take-off, Landing, and Flight Manoeuvres	Noise is generated due to air flows over aircraft surfaces, especially during landing gear deployment, which creates turbulence and noise due to exposed wheels. The interaction between the wing and fuselage also generates noise during airflow separation at high angles of attack (e.g., during take-off and landing).

Auxiliary Systems such as Auxiliary Power Units (APUs) During Ground Operations	APUs are small gas turbine engines that provide electrical power when the main engines are switched off. The noise produced includes exhaust noise generated by high-frequency sound from the APU exhaust, as well as Intake and compressor noise produced by the air intake flow and mechanical vibrations.
Noise from Ground Support Equipment (GSE)	Noise from Air Start Units (ASU), which provide compressed air for engine starts, and Ground Power Units (GPUs), which use diesel or electric generators to supply aircraft power. Additionally, other ground operations, including aircraft taxiing, aircraft maintenance, and baggage handling, also contribute to noise at airport terminal.

4.1 Benefits and Implementation Procedure

Noise mapping is the process of visualising sound levels in a geographic area using colour-coded maps that reflect varying decibel levels. These maps serve as analytical tools for identifying noise hotspots, informing land-use planning and zoning regulations, and evaluating the effectiveness of mitigation strategies. The typical steps involved in airport noise mapping include the following phases:

1. Noise Mapping and Validation: The foundational step in effective aircraft noise management is establishing a clear understanding of the existing acoustic environment through detailed noise mapping. Airport operators conduct a noise mapping study to assess the current noise levels and identify the population affected within various noise contours. The key requirments for the noise mapping and validation are:

Noise Mapping and Validation

The noise maps must be comprehensive. Therefore, input data should consider the following:

- **Actual air traffic data, including aircraft types, number of movements, and distribution of runway use.**
- **Landing and take-off flight paths.**
- **Meteorological data and, where possible, a 3D terrain model.**
- **Locations of sensitive receptors, such as hospitals and schools.**

Calculated Noise Indices: A variety of noise indices must be calculated to provide a complete picture of the noise environment. These include Lden, Lday, Levening, Lnight, DNL, and LAmax.

Validation and Reporting

A critical component of the process is the validation of the computer-generated models.

- **Field Measurements:** Noise maps must be validated with actual noise measurements collected in the field. For airports with an established Noise Monitoring System (NMS), data from the same year as the model must be used. If an NMS is not available, 24-hour continuous measurements using mobile monitoring units are required.
- **Detailed Report Preparation:** The results are prepared as noise contour maps and include information on the area and population affected within each noise zone. The report also includes a comparison with applicable limits set by the Ministry of Environment and Forests.

2. Noise Reduction Action Plans: Airport operators develop and implement a Noise Management Action Plan. The Action Plan considers noise impacts, identifies problem areas, and formulates measures to reduce noise based on international best practices.

The key noise abatement procedures for airport operators include:

- **Continuous Descent and Climb:** Implement Continuous Descent Approach (CDA) instead of step-down approaches and promote Continuous Climb Operations (CCO).
- **Runway Utilisation:** Optimise the use of all runways on a fixed hourly basis to evenly distribute noise, with the airport operator responsible for identifying sensitive runways and flight paths.
- **Engine Run-up Management:** Designate specific locations for engine run-ups, defining permissible times, maximum thrust levels, and duration.
- **APU/GPU Management:** Develop procedures to minimise the use of Auxiliary Power Units (APU) and Ground Power Units (GPU) by providing Fixed Electrical Ground Power at aircraft parking bays.
- **Noise Monitoring Systems (NMS):** Airport operators establish a fully operational, real-time, permanent Noise Monitoring System (NMS).

Moreover, Noise Reduction Measures for Aircraft Operators include:

- Low Power/Low Drag Operations: Develop procedures for low power and low drag operations.
- **Minimal Reverse Thrust:** Create safe operating procedures for landing with minimal use of thrust reverse, without compromising safety or runway capacity.
- **Adherence to Designated Areas:** Conduct all engine run-ups only at the locations earmarked by the airport operator.
- **Use of Preferential Routes**: Follow noise preferential routes designed by the airport operator/ATC to avoid noise-sensitive areas during departure and arrival.

4.2 Case Study: Indira Gandhi International Airport

Challenge: As one of India's busiest airports, IGIA faced significant challenges in managing aircraft noise to protect surrounding communities. [15] IGIA must adhere to strict maximum permissible noise limits at designated Noise Monitoring Terminals: 105 dB during daytime operations (06:00 to 22:00 hrs) and 95 dB during nighttime operations (22:00-06:00 hrs).

Solution: IGIA implemented a comprehensive noise monitoring and reduction strategy aligned with the ICAO's balanced approach, including:

- Flight Path Optimisation: Design and implementation of Noise Preferential Routes (NPRs) and runways usage strategies to direct aircraft movements away from residential areas.
- Continuous Descent Operations: Aircraft landing at IGIA are instructed through the Aeronautical Information Publication (AIP) to perform Continuous Descent Operations. This approach enables aircraft to descend with minimum engine thrust and avoids step-down flight profiles, to the extent permitted by safe aircraft operation and compliance with published ATC procedures.
- Operational Controls: Promotion of FEGP usage at parking bays to minimise reliance on noisy APUs and GPUs.
- Monitoring System: Operating a fully functional, real-time, permanent NMS across the airport.
- Noise Abatement Procedures: Promoting Continuous Descent Approach (CDA) for arriving aircraft and minimisation of reverse thrust usage during landing to reduce noise.

Quantifiable Outcomes: Airport ensures that the Ambient Air Quality Standards with respect to noise in airport noise zones for a busy airport are maintained at 70 dB during daytime and 65 dB during nighttime [15]. The strict implementation of these measures is essential for IGIA to maintain its status as a major international hub while meeting environmental and social responsibilities.

Key Lesson and Implication for Indian Airports: The success at IGIA demonstrates that a combination of technology (NMS), optimised operational procedures (NPRs, CDA), and infrastructure (FEGP) provides an effective and replicable model for managing aviation noise. It underscores that a proactive noise management strategy is critical for large, rapidly growing airports to sustain their operational licence and long-term growth within sensitive urban environment.

4.3 Conclusion and Way Forward

The primary goal of airport noise management is to control noise from aircraft operations and reduce its adverse effects on people and the environment, without hindering the sustainable growth of the aviation industry. In this context, in India, the Directorate General of Civil Aviation (DGCA) circulars encourage operators to adopt ICAO's balanced approach to aircraft noise management. The ICAO's "Balanced Approach" is structured around four pillars: 1) Reduction of noise at source; 2) Land use planning and management; 3) Noise abatement operational procedures; and 4) Operating restrictions. [16]

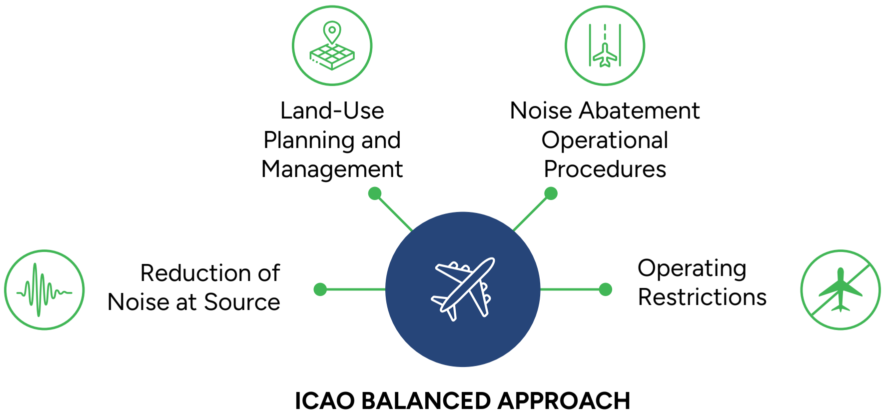


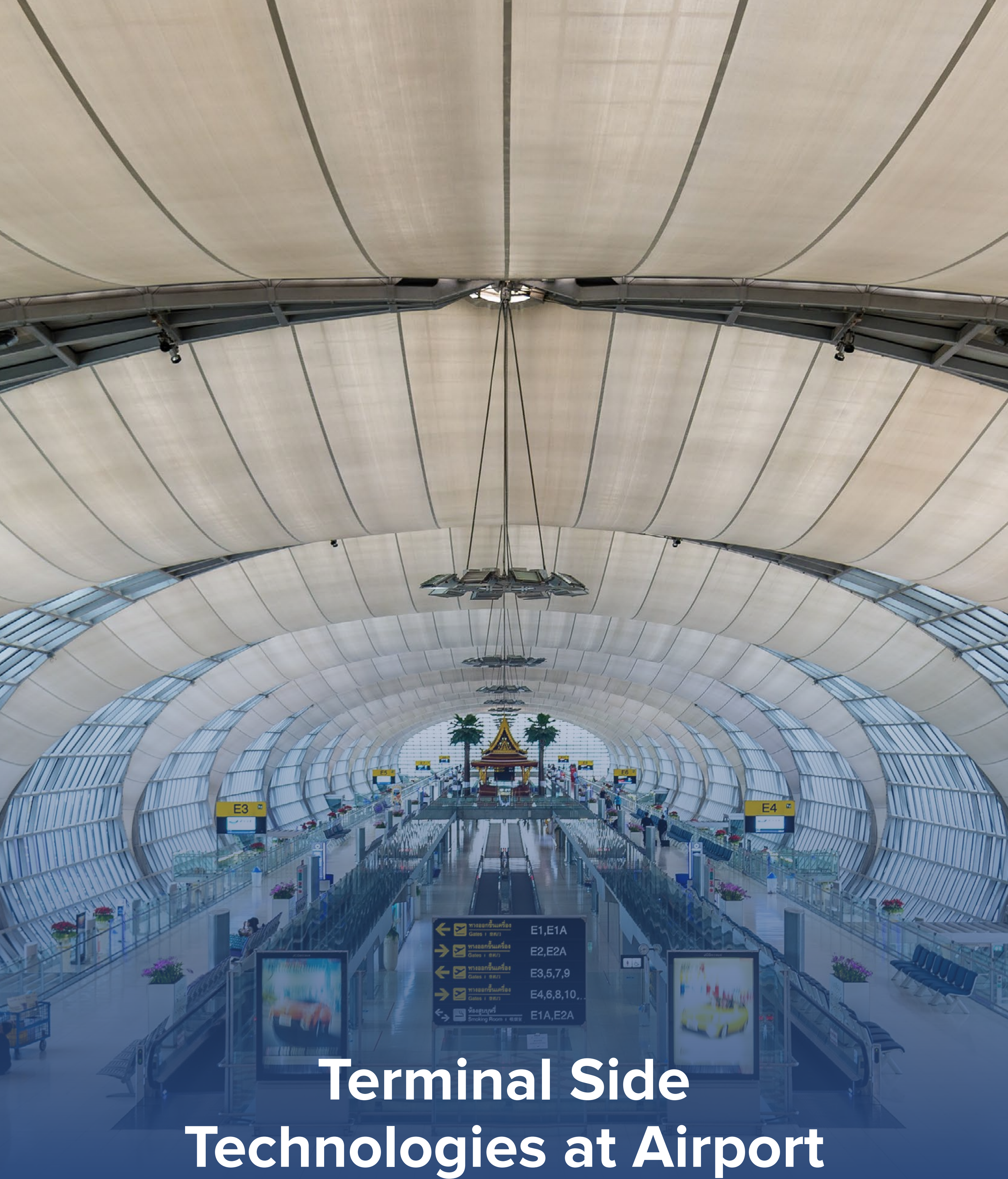
Figure 5: ICAO's "Balanced Approach" to address aircraft noise from airport operations

At the source, the selection of quieter aircraft, incentivising fleet modernisation through landing charge discounts, and retrofitting older aircraft with hush kits or quieter engines can significantly reduce noise emissions. Furthermore, operational measures such as CDA and NPRs designed to avoid populated areas, as well as potential runway rotation or night curfews, can reduce noise generation. Moreover, land-use planning also plays a crucial role, through noise-sensitive zoning to restrict residential and educational developments near airports, soundproofing grants for affected buildings, and optimised airport layouts that reduce overall noise exposure. Overall, the inclusion of robust noise complaint management systems, transparent public disclosure of noise data and mitigation plans, and the integration of noise metrics into Green Airport Ratings under ESG frameworks are essential for effective noise mitigation. Collectively, these measures enable airports to balance aviation growth with environmental protection and public health considerations. Table 6 standardises key deployment metrics, providing a clear, data-driven basis for financial evaluation:

Table 6: Assessment summary of airport noise mapping and abatement measures

Metric	Assessment
Technology Category	**Foundational Win (Phase 1) - Noise Abatement Operational Procedures**
Capital Expenditure	Moderate (for NMS implementation and maintenance)
Typical Payback Period	Not explicitly defined; primary return is non-financial (regulatory compliance, public health protection, and continued operational license).
Impact on OpEx	Mixed; may result in increased OpEx (NMS maintenance, dedicated noise management personnel). Savings may be realised through reduced flight path restrictions, lower litigation or compensation risks, and optimised fuel burn (e.g., Continuous Descent Approaches).

Metric	Assessment
Primary Financial Return	Long-term; avoided costs associated with noise-related litigation, preservation of the public licence to operate, and optimised operational procedures (e.g., fuel savings from Continuous Descent Approach).
Non-Financial Returns	High; reduced public health risks (hypertension, sleep disruption), improved community relations, regulatory compliance, integration of noise metrics into Green Airport Ratings (ESG), and enhanced environmental stewardship.
Financing Models	Direct capital budget, Airport Carbon Accreditation programme-linked funding, and regulatory compliance expenditure.
Key Dependencies	Adherence to ICAO's Balanced Approach (source reduction, land use planning, operational procedures, restrictions); real-time, permanent NMS; cooperation between airport operators, ATC, and aircraft operators; and accurate noise mapping validation through field measurements.



Terminal Side Technologies at Airport

CHAPTER 5

Automated Baggage Handling System

Automated baggage handling systems (ABHS) move checked luggage through an airport using an integrated network of conveyors, sorters, scanners, and computers. When a bag is checked in, it is assigned a unique tag (barcode or RFID), which is automatically scanned by the system. Based on this information, the bag is routed through along conveyors toward security screening and onward to the designated aircraft. Diverters (such as mechanical switches) guide each bag along the correct pathway to its destination. Modern ABHS deployments often rely on individual carrier (tote) systems, in which each bag is placed in a dedicated tray. These tote systems enable the continuous tracking of individual bags from check-in to loading, improving speed and reducing jams. A central control software platform monitors all baggage flows in real time, integrating flight schedules and bag identification data so that luggage can be held or rerouted in response to flight delays or operational changes. ABHS enhance airport efficiency by reducing baggage processing time by up to 30% through smart batching techniques, while achieving energy savings of approximately 10–15% by utilising energy-efficient machinery.

ABHS deployment has also contributed to a significant reduction in baggage mishandling rates, with a reported 63% decrease between 2007 and 2023. [17] At various airports, this software also counts bags, balances load across multiple conveyor lines, and alerts staff in the event of jams or abnormal flow conditions. In short, ABHS utilises a combination of conveyors, automatic scanners, sorters, buffer storage areas, and smart software to ensure the safe, efficient, and reliable movement of baggage from check-in to aircraft loading, and from arrival gates to baggage claim. These advancements result in faster check-ins, fewer lost bags, and improved overall passenger satisfaction, making air travel more efficient and reliable. ABHS can process up to 20,000 bags daily, handling individual weights of up to 50 kg. They reduce processing times by approximately 30%, lower energy consumption by 10–15%, and decrease mishandling rates by 63%. [18] Advanced tote systems combined with high-efficiency motors further conserve energy and enhance flow, increasing overall airport operational efficiency by 20–25% and leading to faster check-in, reduced delays, and more sustainable baggage operations.

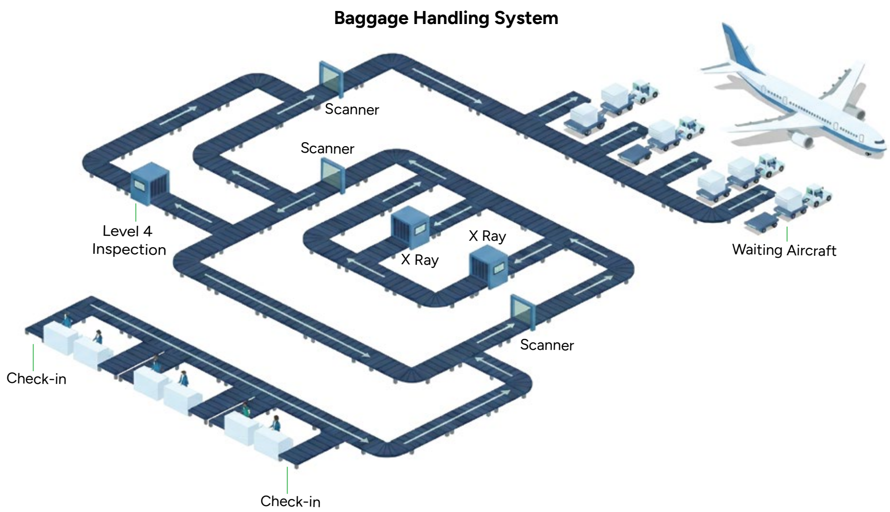


Figure 6: Schematic layout of an automated baggage handling system (ABHS)

5.1 Benefits and Performance Insights

ABHS are a cornerstone of modern, high-performance airport terminals, delivering transformative improvements in operational speed, reliability, and energy efficiency. These systems utilise a sophisticated combination of conveyors, high-speed sorters, scanners, and intelligent software to move checked luggage seamlessly from the check-in counter to the aircraft, and onward to the baggage claim upon arrival

Key Energy-Efficient Features in Automated Baggage Handling Systems

Optimized Motion Planning
Smart routing minimized unnecessary movements

Energy Recuperation During Deceleration
Systems recover and reuse energy

Intelligent Shutdown/ Sleep Modes
Equipment automatically enters low-power state

High-Efficiency Motors and Drives
Advanced motors power consumption

By minimising manual touchpoints and optimising routing, ABHS directly addresses key airport challenges, including reducing baggage mishandling, cutting operational costs, and enhancing the overall passenger experience. Modern energy-efficient features are central to their performance:

- **High-Efficiency Motors and Drives: Utilisation of advanced permanent magnet motors that consume significantly less power than conventional induction motors.**
- **Intelligent Shutdown/Sleep Modes:** Conveyor segments power down automatically when no baggage is present, enabling a "power-on-demand" approach that can reduce energy consumption by over 50% compared to legacy systems.
- **Optimised Motion Planning:** Smart routing software minimises the travel distance for individual bags, reducing unnecessary movements and associated energy use.
- **Energy Recuperation:** Advanced systems can capture kinetic energy during deceleration and convert it into usable electrical energy, further improving overall system efficiency. [19]

5.2 Case Study: London Heathrow Airport, Terminal 5

Challenge: When designing Terminal 5, a major global hub, Heathrow required a baggage handling system capable of managing immense volumes with exceptionally high reliability. The key challenges were ensuring predictable performance under peak operating conditions and efficiently routing tens of thousands of bags daily between the main terminal building and its two satellite piers.

Solution: Heathrow implemented one of the world's most advanced, fully integrated ABHS. The system features a five-level baggage hall with over 18 km of conveyors and high-speed, tote-based technology, in which each bag is placed in an individual tray, enabling 100% tracking and control. The system was designed from the ground up to prioritise resilience and high speed.

Quantifiable Outcomes:

- **High Throughput:** The system can process up to 12,000 bags per hour, ensuring smooth operations even during the peak travel periods.

- **Enhanced Reliability:** The tote-based system has significantly reduced jams and tracking errors, contributing to Terminal 5 being consistently ranked among the world's leading terminals for passenger experience.
- **Operational Efficiency:** The automation has significantly improved baggage flow between terminals, reducing transfer times and supporting on-time departures.

Key Lesson and Implication for Indian Airports: Heathrow's Terminal T5 demonstrates that for large-scale hub airports, a significant upfront investment in a fully integrated and resilient ABHS is not a luxury but a strategic necessity. It highlights that advanced automation is critical for managing complexity, ensuring reliability at scale and delivering a world-class passenger experience. [20]

5.3 Conclusion and Way Forward

ABHS are capital-intensive and complex to deploy. A major airport installation can cost tens of millions of dollars; for example, London Stansted invested approximately £70 million to replace its old conveyors with a new 2.4 km automated system [21]. Such upgrades typically include new hardware (such as conveyors, sorters, scanners, and structural supports), control software, installation, testing, and staff training. Additional costs arise from integrating baggage screening equipment (X-ray and CT machines) into the conveyor system, as well as ongoing operational expenses such as electricity consumption, routine maintenance of motors and belts, and spare parts.

Deployment presents challenges at busy airports (a "brownfield" site), where construction must often occur in phases, during night-time windows, or in sections, to avoid operational disruption. Converting an old system into a new one can disrupt check-in and requires careful planning. Additionally, the location also matters as an installation at a remote, open site (greenfield) is cheaper than at the heart of a live terminal.

Analysts indicate that automated "tote" or ICS can sometimes be more cost-effective in the long run. These systems typically require a smaller physical footprint and modular units that simplify installation [22]. For example, ICS can achieve full tracking with fewer machines and less conveyor length. Energy savings (half the power drawn) and reduced maintenance (fewer jams, less wear) can offset higher upfront costs over time. To estimate ROI, airports commonly assess parameters such as energy use, labour savings, and reduced baggage mishandling costs, with typical payback periods ranging from 5 to 10 years, depending on traffic growth.

In India, airport modernisation has also accelerated; however, baggage automation standards remain a mix of best practices and legacy systems. The Airports Authority of India (AAI) and major private operators (such as Delhi's DIAL, Mumbai's MIAL, Bengaluru's BIAL) follow strict security rules: for example, the Bureau of Civil Aviation Security (BCAS) mandates 100% screening of checked bags, making inline baggage screening (placing scanners in the conveyor system) a standard requirement at all major Indian airports [23]. Inline screening eliminates pre-check-in queues, accelerates check-in, and improves security (GMR's Delhi T3 and Bangalore's terminal have had such systems for years).

Additionally, some Indian airports are introducing user-friendly automation, with Bengaluru (BLR) becoming the first in India to install fully automated self-bag-drop kiosks, which reduce the average check-in time to approximately 45 seconds. To improve the adoption of ABHS in India, policymakers and industry could take several steps. The government can set clear performance standards (for example, requiring airports to track 100% of bags at the four main tracking points, as specified in IATA Resolution 753, marked in red).

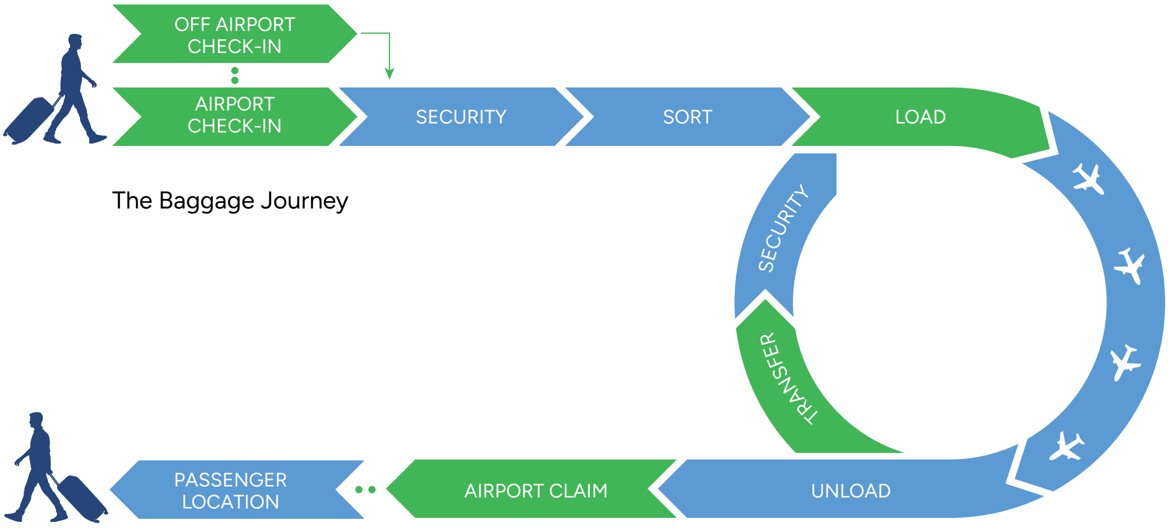


Figure 7: The four key baggage tracking points in an ABHS

Authorities could tie funding or approvals to efficiency goals – for instance, incentives or grants for airports that install energy-efficient tote systems that meet fast-bag-delivery benchmarks. Public-private partnerships (PPPs) should be further encouraged, as existing PPP airports (e.g., Delhi, Hyderabad) demonstrate that private investment brings advanced technology. India could also promote domestic manufacturing of conveyor and RFID tech under "Make in India" to reduce costs. Finally, improved data sharing between airlines and airports would strengthen end-to-end baggage tracking. By combining financial support and collaboration, India can accelerate the deployment of ABHS, improving efficiency and the passenger experience across its airports.

Table7: Assessment summary of automated baggage handling system deployment

Metric	Assessment
Technology Category	Infrastructure Expansion (Phase 2)
Capital Expenditure	Very high; represents a major capital investment involving extensive hardware, software, and integration.
Typical Payback Period	5-10 years, driven by savings in labour, energy, and mishandled baggage costs
Impact on OpEx	High positive impact; reduces annual costs for labour, energy (up to 50% with modern systems), and financial penalties associated with lost or delayed luggage.
Primary Financial Return	Direct savings on operational expenses (staffing, electricity), and reduced compensation payouts for baggage issues.
Non-Financial Returns	Significantly enhanced passenger experience, improved operational speed and reliability, higher baggage throughput, improved staff safety, and adherence to global standards.
Financing Models	Public-private partnership (PPP), Direct capital budget, green bonds.
Key Dependencies	Detailed integration plan with airline and security systems, robust project management to minimise disruption (especially in existing terminals), and significant upfront capital.

CHAPTER 6

Radiant Heating and Cooling

Modern airport terminals and other large public buildings are typically designed with expansive, open-plan interiors featuring high ceilings and wide spans to accommodate public activity while preserving architectural aesthetics. These spaces often lack internal partitions and are enclosed with extensive glass facades or curtain wall systems, resulting in significant solar heat gain and elevated internal surface temperatures during summer conditions. Exposure to strong solar radiation significantly elevates the internal surface temperatures of walls and ceilings in airport terminals. In large buildings, maintaining thermal comfort within occupied zones while minimising energy use in unoccupied upper spaces remains a major challenge. Traditional all-air systems, such as jet air ventilation, deliver conditioned air at high velocities (3.0–7.5 m/s) from heights of 3 to 5 metres, relying heavily on mechanical air movement. As a result, fan energy can account for 30–50% of total HVAC consumption, leading to high operational costs. In addition, high wall and ceiling surface temperatures (30–35 °C) and solar heat gains often push operative indoor temperatures beyond the ISO 7730 comfort range of 24.5 °C ± 1.5 °C. [24][25]

Radiant floor cooling systems offer an efficient and effective solution for airport terminals, particularly in areas with high solar radiation and elevated wall surface temperatures, which challenge conventional HVAC approaches. Unlike all-air systems, radiant floor systems circulate water at temperatures close to indoor setpoints, improving energy efficiency and thermal comfort while significantly reducing fan energy consumption. Advanced dehumidification technologies and dedicated outdoor air systems prevent condensation and maintain air quality. In high-radiation climates, such as India, radiant floor systems have demonstrated cooling capacities ranging from 40 to 140 W/m^2, far exceeding typical design values, making them ideal for large, sunlit spaces dominated by glass facades and skylights.

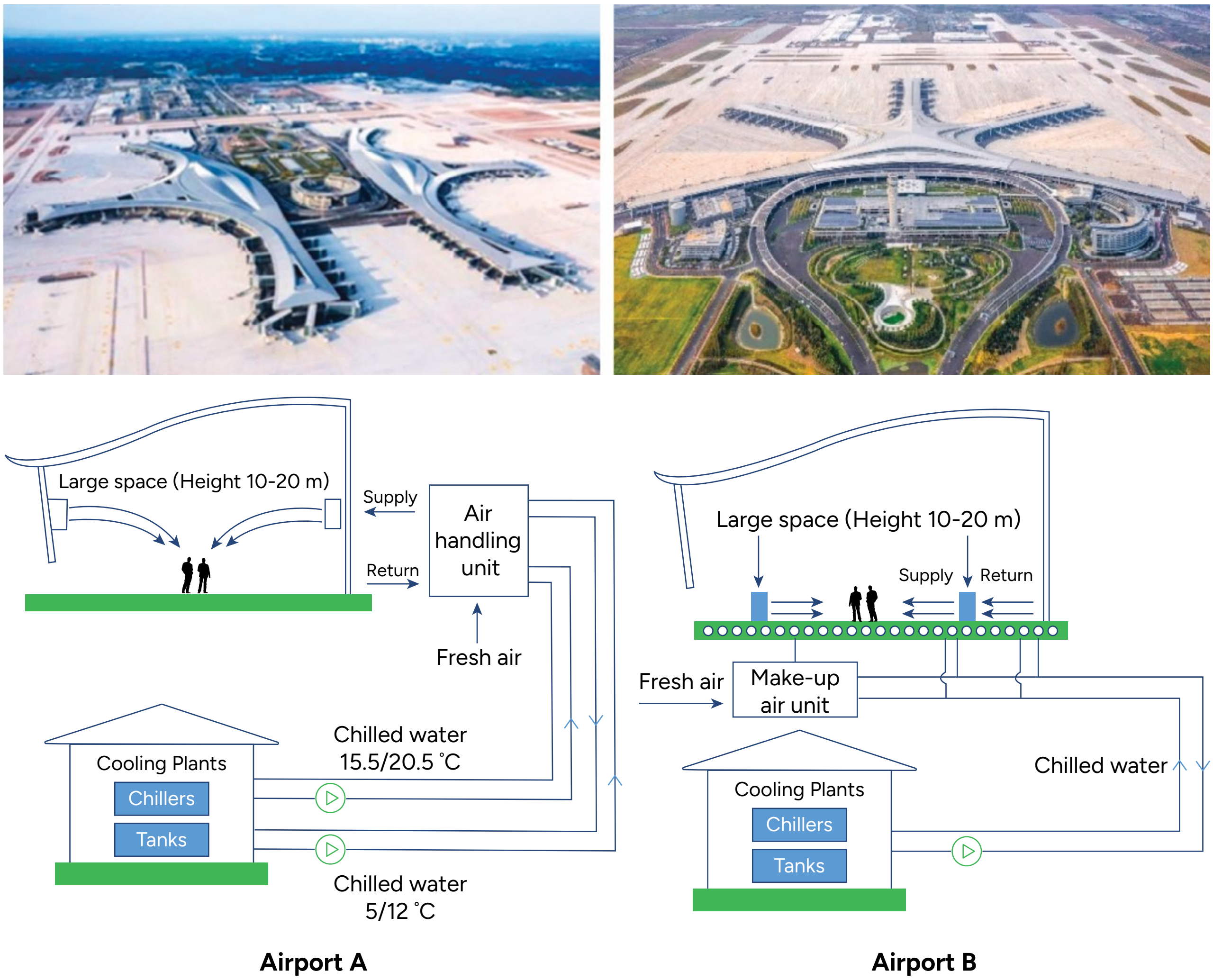


Figure 8: Schematics of all-air and radiant cooling strategies implemented in airport terminals [26]

Radiant cooling operates by circulating chilled water through pipes embedded in the floor or ceiling slabs of a building. These cooled surfaces absorb heat from the surrounding environment through radiative heat transfer, rather than convection. As water can carry 3,400 times more heat than air per unit volume, this approach is inherently more energy efficient. The radiant cooling system (RCS) focuses on handling the sensible heat load, the direct thermal gain from occupants, equipment, and solar radiation, while a separate dedicated outdoor air system (DOAS) manages latent loads (humidity control) and supplies fresh, dehumidified air to maintain indoor air quality. The key components include:

- Chilled water pipes embedded in slabs or ceilings (radiant floor or radiant ceiling pipes)
- Chillers operating at comparatively higher temperatures (12–14°C), which improves the coefficient of performance (COP) and reduces energy consumption
- DOAS units for ventilation and moisture control

This decoupling of cooling and ventilation loads not only enhances system efficiency but also allows quieter, more evenly distributed thermal comfort across terminal areas. The reduction of ductwork and fan energy demand enables radiant systems to increase usable floor space and reduce maintenance requirements, strengthening the case for their adoption in airport infrastructure.

6.1 Benefits and Performance Insights

In comparison to traditional cooling systems, radiant cooling systems achieve higher chiller efficiency because they operate effectively at higher chilled water temperatures, for instance, 12.8°C instead of the 7°C typically required for conventional systems. This elevated operating temperature directly translates into reduced energy consumption and lower operational costs. Additionally, radiant systems transfer heat using water, a far more efficient medium than air, thereby reducing fan energy consumption. The reduction or elimination of large air ducts also frees up valuable building space, offering greater design flexibility and increasing the usable area within terminals.

A compelling real-world comparison from Infosys Hyderabad illustrates these benefits. The radiant-cooled section of the building operates a 325 TR chiller at 12.8°C with a COP of 7.8, whereas the conventionally cooled section runs a 272 TR chiller at 7°C with a COP of 6.4. [27] This comparison shows that radiant systems can support larger thermal loads while delivering superior energy efficiency. Furthermore, radiant cooling offers a more uniform temperature distribution, minimising hot and cold spots, reducing the mean radiant temperature, leading to improved thermal comfort for occupants. In Indian airports, these advantages can lead to significant long-term cost savings, enhanced passenger and staff comfort, and alignment with national sustainability goals. When combined with smart controls and efficient ventilation systems, radiant cooling systems emerge as a highly promising technology for next-generation, energy-efficient airport infrastructure in India.

Moreover, radiant cooling systems offer a high-performance, energy-efficient alternative to conventional jet ventilation in airport terminals. Unlike air-based systems, which consume significant energy by conditioning large volumes, including unoccupied spaces, radiant systems cool surfaces directly in the occupied zone, thereby significantly reducing fan energy use and improving thermal comfort. Operating at higher chilled water temperatures improves chiller efficiency, while water-based heat transfer reduces energy demand. Radiant systems also minimise ductwork, lower operational noise, and enhance spatial and aesthetic design flexibility. When paired with DOAS for ventilation and humidity control, they provide a superior solution tailored to the thermal and architectural demands of large terminals.

Architecturally, radiant systems reduce dependence on bulky ductwork and mechanical air distribution infrastructure, freeing up usable space and minimising visual intrusion. They also produce lower noise levels, enhancing occupant comfort in high-traffic terminal environments. When integrated with modern control systems and DOAS for humidity and ventilation management, radiant systems offer a high-performance, low-energy alternative suited to the unique spatial and thermal requirements of airport terminals, particularly in the context of lifecycle cost, spatial efficiency, and environmental performance.

Table 8: Radiant cooling system vs conventional HVAC system [28]

Parameter	Radiant Cooling System	Conventional HVAC
Heat transfer medium	Water: 3,400 times more heat-carrying capacity than air per unit volume	Air: less efficient, requires higher volume and velocity
Typical chilled water temperature	12–14°C (higher operating temperatures increase chiller COP)	6–7°C (lower temperatures required for effective cooling)
Fan energy use (% of HVAC)	10–20% (lower due to minimal air movement for cooling)	30–50% (significant energy used to drive air jets)
Chiller COP	20-30% higher than conventional	Lower
Cooling load distribution	Focused on occupied zone (within 2 m height); stratified cooling	Mixed cooling of the entire volume, including unoccupied high zones
Thermal comfort index	Higher comfort due to uniform surface temperatures, radiant exchange	Moderate; more drafts and uneven cooling zones

Parameter	Radiant Cooling System	Conventional HVAC
Noise levels	<35 dBA (quiet due to minimal ducting and fan use)	45–55 dBA (depending on air velocity and duct layout)
Visual impact	Hidden systems (pipes embedded in slabs or ceilings), reduced ducting	Bulky ducts, visible terminal infrastructure
Installation cost	~10–20% higher upfront cost than conventional systems	Lower upfront, higher lifecycle operational costs
Lifecycle operational cost	20–30% lower energy cost over lifecycle (due to chiller COP, reduced fan load, low maintenance)	Higher energy cost due to continuous fan and compressor load
Climate suitability	Best in dry or mixed climates; feasible in humid climates with DOAS	Applicable across climates, but with lower energy performance

6.2 Case Study: Radiant Cooling at Bangkok Airport

A notable case study of radiant cooling in airport terminals is Bangkok Airport, where a radiant floor system was implemented to address the challenges of a hot and humid climate. Covering approximately 68% of the floor area with chilled water pipes, the system achieved a cooling capacity of 83 W/m^2 and handled 55% of the indoor sensible load, while displacement ventilation managed humidity control and the remaining heat load.6 Careful control prevented condensation, with floor surface temperatures consistently maintained above the dew-point temperature. Similarly, Xi'an Airport in China implemented radiant floor cooling combined with liquid desiccant-based ventilation. Field data demonstrated effective temperature and humidity control, with cooling capacities increasing from 35–40 W/m^2 to 130–140 W/m^2 under solar exposure, highlighting the system's adaptability and energy efficiency across varying thermal conditions. These results highlight the suitability of radiant cooling systems for large-volume, high-occupancy spaces such as airport terminals, particularly in India's diverse climatic conditions. Table 4 presents the key characteristics of the radiant cooling systems implemented at both airport terminals.

Table 9: Case studies of the radiant cooling systems in airport terminals [29]

Parameter	Suvarnabhumi Airport, Bangkok	Xi’an Airport, Terminal 3, China
Cooling area/type	150,000 m^2 radiant floor cooling	Radiant cooling in the terminal
Climate	Hot and humid	Hot and humid
Cooling capacity (W/m2)	83	35-40 (shaded), 130-140 (sunlit)
Chilled water temp (°C)	13/19 (supply/return)	14 / 19 (supply/return)
Floor surface temp (°C)	~23	~22.4
Indoor conditions	25 °C, 57% RH	23.4–24.3 °C, 60% RH
Integration type	Embedded floor pipes + DOAS	Floor slabs with chilled water + fresh air via a liquid desiccant system
Key benefits over conventional	Reduced fan energy, uniform comfort, and noise reduction	Better thermal stratification, reduced upper zone cooling
Unique features	600 km piping, 7,500 circuits, 3.5 km cooled flooring	Reduced vertical temperature gradient

6.3 Conclusion and Way Forward

Radiant cooling systems typically have slightly higher or comparable initial installation costs compared to conventional all-air systems. For instance, the capital cost of a radiant system reported by Infosys5 was approximately ₹3,302/m^2, while a comparable conventional system cost ₹3,327/m^2. [27] Despite similar upfront costs, radiant systems offer significant long-term savings through reduced energy consumption, particularly in fan operation and chilled water production. Over time, lower energy demand and improved efficiency of radiant systems can offset their upfront investment, making them more cost-effective over lifecycle, especially in large-scale building infrastructure. Table 10 presents assessment of radiant cooling system.

Table 10: Assessment of Radiant cooling system for airport terminals

Metric	Assessment
Technology Category	Terminal-side technologies at the airports (Radiant cooling with DOAS; sensible loads by radiant; latent by DOAS)
Capital Expenditure	Moderate to High (~10–20% higher upfront than conventional all-air HVAC, but comparable in some cases)
Typical Payback Period	5–8 years, driven by reduced operational energy consumption
Impact on OpEx	High positive impact: ~ 20–30 % lower energy use, fan energy reduced to ~10–20 % of conventional HVAC, and lower maintenance costs
Primary Financial Return	Energy savings from higher chilled water operating temperatures (12–14 °C vs 6–7 °C), reduced fan load, deferred ducting infrastructure costs
Non-Financial Returns	Improved passenger comfort (uniform temperature, low noise), reduced architectural constraints (less ducting), enhanced spatial aesthetics, lower mean radiant temperature, and alignment with green building standards.
Financing Models	Direct capital budget, energy service company (ESCO) models
Key Dependencies	Effective humidity and condensation control (via DOAS or liquid desiccant systems), skilled system design and commissioning, integration with existing chiller plants, and effective controls for surface dew-point management

CHAPTER 7

Refrigerant Transition

Airports are complex infrastructures that operate around the clock and require highly controlled thermal environments to ensure passenger comfort. Due to their vast floor areas, high footfall, and the need to maintain thermal comfort across terminals, lounges, and baggage handling zones, airports experience high and continuous cooling demand. On average, airports may require several thousand tons of refrigeration (TR) for cooling, typically ranging from 5,000 to 110,000 TR, depending on the airport's size, design, and passenger traffic. [30] These cooling needs are typically met through air conditioning technologies that rely on refrigerants, chemical working fluids that enable heat transfer within cooling cycles. Centralised water-cooled chiller systems are widely adopted due to their energy efficiency and suitability for large spaces, while variable refrigerant flow (VRF) and packaged direct expansion (DX) systems are deployed for specific zones or auxiliary areas within the airport. [31]

Historically, the refrigeration and air conditioning (RAC) industry has relied on synthetic refrigerants such as chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), and hydrofluorocarbons (HFCs) because of their high thermodynamic efficiency and reliability. [32] However, these refrigerants have been shown to cause significant environmental harm. CFCs and HCFCs contribute to ozone layer depletion, while HFCs, although ozone-safe, have a high Global Warming Potential (GWP) and contribute significantly to climate change. [33] As a result, the aviation sector, including airport infrastructure, is under increasing scrutiny to reduce its environmental footprint, not only from aircraft emissions but also from operations such as HVAC systems. Figure 9 shows the historical evolution and transition of refrigerants used in the RAC sector.

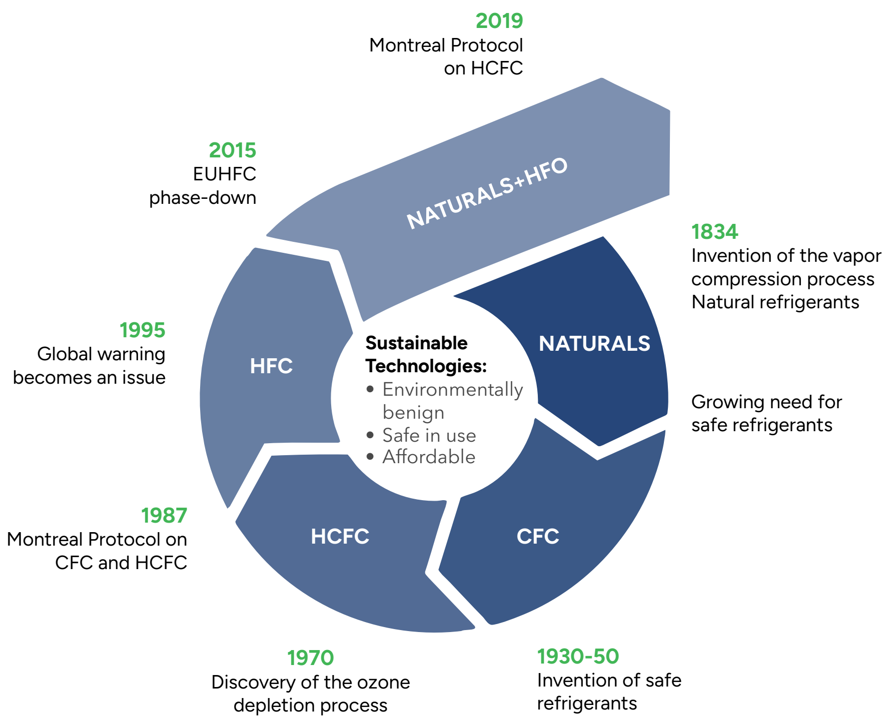
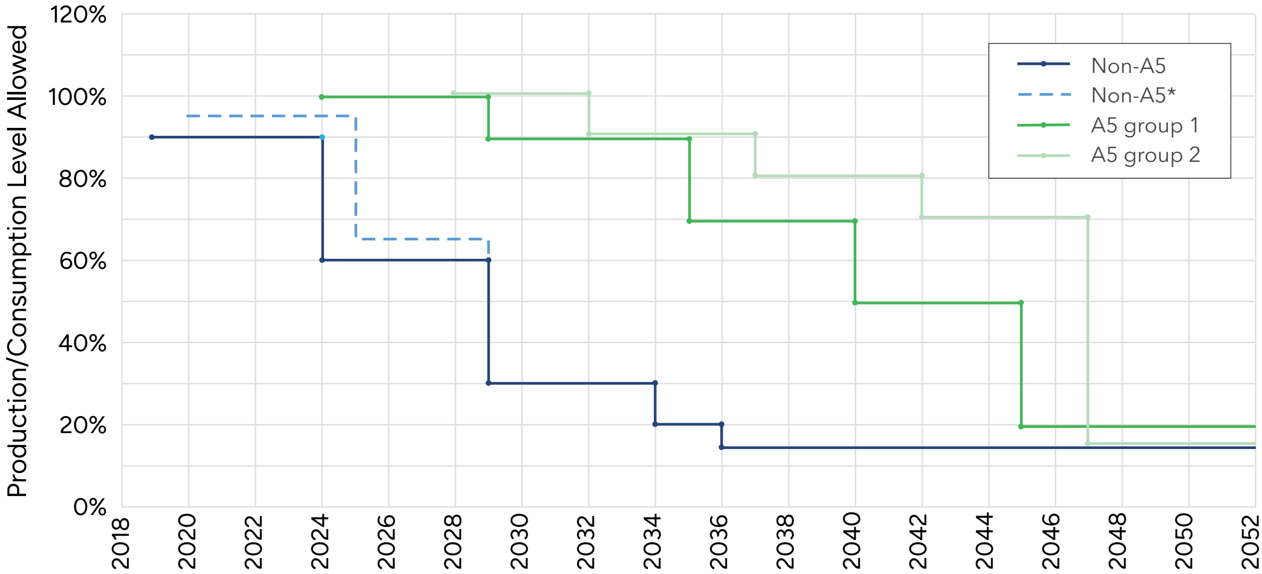


Figure 9: Historical cycle of refrigerants

As a signatory to the Montreal Protocol, India took early action by enforcing the Ozone Depleting Substances (Regulation and Control) Rules, 2000, under the Environment Protection Act, 1986. [34] India has successfully phased out all CFCs and is currently implementing the third stage of the HCFC Phase-out Management Plan (2023–2030), targeting complete HCFC phase-out, with servicing permitted until 2040. In 2021, India ratified the Kigali Amendment to address climate impacts, committing to phase down HFCs – potent greenhouse gases introduced as zero-ODP substitutes for CFCs and HCFCs. Under this framework, India (an Article 5 Group 2 country) will freeze HFC consumption in 2028 and achieve an 85% reduction by 2047, with the first reduction step scheduled for 2032, as shown in Figure 10. The Kigali Amendment adopts a "phase-down" approach, recognising the limited near-term availability of zero-GWP refrigerant alternatives. [35] Importantly, it also includes provisions to promote energy efficiency improvements and research and development, enabling a transition to climate-friendly, low-GWP technologies. This dual focus on refrigerant management and energy efficiency is crucial for achieving meaningful emissions reductions while promoting sustainable cooling performance.



Non-A5 Baseline = Average HFC for 2011–2013 + 15% of HCFC baseline.
Non-A5* Baseline = Average HFC for 2011–2013 + 25% of HCFC baseline.
A5 – Group 1 Baseline = Average HFC for 2020–2022 + 65% of HCFC baseline.
A5 – Group 2 Baseline = Average HFC for 2024–2026 + 65% of HCFC baseline.

Figure 10: HFCs consumption and production reduction schedule [36]

This environmental and regulatory shift presents both challenges and opportunities for Indian airports. Many airport cooling systems still rely on high-GWP HFCs, making refrigerant transition a critical priority, not only for regulatory compliance but also to align with national climate goals and the global aviation sector's net-zero ambitions. However, challenges such as flammability, toxicity, safety compliance, high-pressure operation, and retrofitting costs pose significant barriers to widespread adoption of low-GWP refrigerants, especially in high-occupancy public facilities such as airports.

7.1 Benefits and Perforamance Insights

Refrigerant selection is primarily driven by thermodynamic characteristics such as latent heat of vaporisation, volumetric cooling capacity, pressure levels, and COP, all of which directly impact system efficiency and component design. For instance, R410A operates under pressures ranging from 800 to 3070 kPa, requiring any potential alternative to exhibit comparable pressure and performance characteristics for drop-in or retrofit compatibility. Additionally, factors such as thermal conductivity, boiling point, critical temperature, chemical stability, flammability, toxicity, GWP, and ozone depletion potential (ODP) are also critical in refrigerant evaluation.

In response to India's commitments under the Kigali Amendment to phase down HFCs, the refrigerant landscape in airport HVAC systems is expected to evolve significantly. As per Kumar et al., screw chillers are projected to adopt a 60:40 blend of R134a and R513A. Centrifugal chillers may transition to a more environmentally conscious mix of R134a (45%), R513A (15%), R514A (15%), and R1233zd (25%) [37]. In the VRF segment, manufacturers are increasingly favouring R32 due to its lower GWP and better energy efficiency. Packaged DX systems are similarly expected to shift toward a 70:30 blend of R410A and R32 over the next decade.

Several emerging refrigerants are being considered for chiller applications, including R447A, R452B, R454B, R1234yf, R1234ze, and R1243zf. Among these, R447A and R454B demonstrate energy performance comparable to or better than R410A. R454B, in particular, offers the highest volumetric cooling capacity and favourable compression ratios, making it suitable for high-temperature environments and new-generation systems. However, refrigerants like R1233zd(E) and R1243zf, despite their ultra-low GWP, exhibit higher compression ratios and lower volumetric capacities, which could impact system size, efficiency, and design complexity. [38] While newer HFC blends and HFOs significantly reduce GWP, concerns remain over their environmental persistence and degradation by-products, such as trifluoroacetic acid (TFA), a short-chain per- and polyfluoroalkyl substance (PFAS). In contrast, natural refrigerants like ammonia (R717) and hydrocarbons such as propane (R290) offer near-zero GWP and zero ODP, without contributing to persistent pollution. These refrigerants are increasingly adopted in commercial, industrial, and transport refrigeration sectors and offer viable options for airports seeking long-term sustainability, but are limited to use in airport terminal HVAC systems due to safety concerns.

Retrofitting existing airport HVAC systems with low-GWP refrigerants requires careful redesign, technician upskilling, and effective refrigerant inventory management practices. A well-planned transition can enable airport infrastructure to meet environmental goals under the India Cooling Action Plan (ICAP) and Kigali commitments, ensuring climate-resilient and sustainable operations without compromising system performance or safety. Table 11 provides the safety classification and GWP values of commonly used refrigerants and their potential alternatives.

Table 11: Safety class and GWP of the commonly used refrigerants and available alternatives

Name	Safety class	GWP
Name	Safety class	GWP
R134a	A1	1430
R410A	A1	2088
R407C	A1	1774
R123	B1	77
R513A	A1	631
R514A	B1	2
R1233zd	B1	1
R32	A2L	675
R444A	A2L	286
R452B	A2L	676
R454B	A2L	466
R447A	A2L	53
R152A	A2	124

Name	Safety class	GWP
R1234yf	A2L	4
R1233zd(E)	A1	1
R1234ze	A2L	7

7.2 Case Study: India Trade Promotion Organisation (ITPO), New Delhi

Challenge: The India Trade Promotion Organisation (ITPO) complex at Pragati Maidan is one of India's largest and most prestigious exhibition and convention venues, spanning approximately 150 acres with more than 625,000 m^2 of exhibition space. With a massive built-up area, high footfall, and year-round event operations, the IECC demanded a reliable, energy-efficient cooling system with significantly lower refrigerant-related emissions. Traditional large-capacity chillers using high-GWP refrigerants such as R-134a were incompatible with the sustainability goals and with India's long-term HFC phase-down commitments under the Kigali Amendment.

Solution: The National Building Construction Code (NBCC), acting as the implementing agency, incorporated low-GWP HFO refrigerants into the project specifications. The total cooling demand for the IECC was assessed at 9475 TR. Trane deployed a next-generation chiller plant powered by three 1,650 TR chillers using R1233zd(E) and five 825 TR chillers using R514A, supported by two 200 TR screw chillers. These refrigerants have a GWP of 2, compared to 1,430 for R134a, and all have zero ODP. The multistage centrifugal design, combined with ultra-low leakage rates (<0.5%/year) and high part-load efficiency, delivers substantial operational savings while maintaining supply-air temperatures around 25°C.

Quantifiable Outcomes: The HFO-based chillers offer 13.5% higher energy efficiency, drastically reduce direct emissions, avoid long-term refrigerant lock-in, and ensure compliance with future HFC phase-down timelines. In addition, the short atmospheric lifetime of HFOs (≈26 days) compared to 14 years for R134a further minimises their long-term climate impact.

Key Lesson and Implication for Indian Airports: The ITPO project demonstrates that large-scale Indian facilities can transition to low-GWP refrigerants at scale without compromising safety, reliability, or performance. For Indian airports, this showcases a clear pathway: incorporating low-GWP refrigerant-based chillers in new developments or major retrofits can significantly reduce lifecycle emissions while meeting high cooling demand with superior efficiency.

7.3 Conclusion and Way Forward

The cost and availability of refrigerants critically influence the adoption of low-GWP alternatives. High-GWP HFCs like R134a and R410A remain dominant due to established supply chains and relatively low prices. In contrast, newer low-GWP synthetic refrigerants, mainly HFOs, remain expensive (e.g., R-1234yf ~₹9000/kg vs. R-152a ~₹310/kg), have limited availability, especially outside major cities, and are subject to high import dependency. Their adoption is further hindered by uncertainties around evolving global regulations, patent-related licensing fees, and the limited scale of commercial deployment within India.

The adoption of low-GWP refrigerants is also technically challenging, as most of them are flammable and require improved system designs, enhanced safety measures, trained personnel, and strict compliance with safety regulations. The system cost also varies based on technology maturity, application scale, and the availability of domestic manufacturing capabilities. While several low-GWP refrigerants remain under pilot or early deployment stages, natural refrigerants are increasingly gaining traction in India, supported by favourable policy momentum and increasing domestic production capacity.

As India’s aviation and infrastructure sectors continue to expand, integrating sustainable cooling technologies will be essential for reducing emissions, enhancing energy efficiency, and future-proofing airport infrastructure. Accelerated adoption will require coordinated efforts among technology providers, policymakers, and airport operators to address cost, safety, and system integration challenges, ensuring that India's airports remain climate-resilient and globally competitive. Table 12 presents assessment summary of refrigerant transition in airport HVAC&R.

Table 12: Assessment summary of refrigerant transition in airport HVAC&R

Metric	Assessment
Technology Category	Terminal-side technologies at airports (Refrigerant transition to low GWP alternatives)
Capital Expenditure	Moderate (retrofits cost and safety system upgrades may increase CAPEX)
Typical Payback Period	6–12 years (depending on system type, refrigerant selection, and associated efficiency improvements)
Impact on OpEx	Mixed: higher refrigerant costs initially, offset by potential efficiency improvements and reduced long-term compliance costs under regulations.
Primary Financial Return	Improved chiller energy efficiency in some transitions
Non-Financial Returns	ESG and sustainability compliance, improved climate resilience, reduced airport carbon footprint, and alignment with Kigali commitments
Financing Models	Direct capital budget, ESCO models
Key Dependencies	Technician training and safety compliance, system redesign or retrofit, refrigerant inventory management

CHAPTER 8

Thermal Energy Storage

India's aviation sector is on a trajectory of unprecedented growth, with projections indicating a substantial increase in passenger traffic in the coming years. This expansion necessitates the development of new airports and the modernisation of existing infrastructure, both of which will result in a significant increase in energy consumption. A major portion of this demand is driven by electric HVAC systems required to maintain comfort within terminals, cargo buildings, administrative offices, and lounges, making airports highly energy-intensive facilities. This rapid growth creates a fundamental dichotomy: the need to expand infrastructure to support economic growth versus the national imperative to decarbonise and transition to a sustainable, low-carbon economy. Addressing this challenge requires a strategic approach that integrates efficiency and sustainability from the ground up.

Thermal Energy Storage (TES) is a proven technology that offers a powerful solution to this dilemma. At its core, TES functions as a "thermal battery," storing energy as a heat source or a cold sink for later use. [39] This process effectively decouples the time of energy generation from the time of its use, which is particularly beneficial for large facilities with fluctuating energy demands. By producing chilled water or ice during off-peak hours when electricity is cheaper and less carbon-intensive and then using that stored thermal energy to meet cooling loads during peak demand periods, airports can significantly reduce their reliance on conventional energy sources and the grid. This report provides an in-depth analysis of TES technologies, their financial viability, and their proven applications in both international and domestic contexts. It serves as a guide for strategic decision-makers in the Indian aviation sector, outlining a clear, evidence-based pathway to deploying TES as a cornerstone of their energy strategy.

TES refers to energy stored in a material as a heat source or a cold sink and reserved for use at a different time. TES systems are technically sophisticated yet conceptually simple, utilising a storage medium and equipment for charging and discharging thermal energy. The storage medium may be a naturally occurring structure, such as an underground aquifer, thermally activated building structure, or an engineered solution, such as insulated tanks containing water, ice, or Phase Change Materials (PCMs). [40] TES technologies are broadly categorised into three types based on the physical mechanism used for storage, each offering distinct characteristics, advantages, and limitations: sensible heat storage, which relies on temperature changes in a material; latent heat storage, which uses phase change materials; and thermochemical storage, which involves reversible chemical reactions. Each type offers distinct advantages and is suited to different applications depending on factors such as temperature range, storage duration, and energy density.

- Sensible heat storage: Traditionally, thermal heat storage has been implemented in the form of sensible heat, where energy is stored by increasing the temperature of a medium. Examples of such energy storage include hot water storage (hydro-accumulation), underground thermal energy storage systems (aquifer, borehole, cavern, ducts in soil, pit), and rock-filled storage systems (rock, pebble, gravel). [41]
- Latent heat storage: Latent heat storage is an emerging TES technology that stores energy through a phase change of a material, typically between solid and liquid. Compared to sensible heat storage, latent heat systems offer higher energy density, more compact and near-isothermal operation during phase change. Typical phase change materials (PCMs) used as the storage media include paraffin waxes, esters, fatty acids, salt hydrates, eutectic salts, and water. [42]

- Thermochemical storage: Thermochemical energy storage (TCES) systems store and release heat through reversible chemical reactions, involving three key stages: endothermic dissociation, storage of products, and exothermic recombination. These systems offer higher energy density and lower storage losses than sensible or latent heat storage, making them ideal for space-constrained and long-duration applications. Promising storage materials include $MgSO_4{\cdot}7H_2O$, $Ca(OH)_2$, $CaSO_4{\cdot}2H_2O$, and $FeCO_3$, each paired with a suitable working fluid such as water or CO

TES can also be classified based on applications, ranging from short-term load management to long-term seasonal storage, supporting both conventional and renewable energy sources.

Short-Term Storage	Short-term TES systems are typically designed to store heat for durations ranging from a few hours to a few days. These systems are widely used in buildings and industrial processes to manage peak demand and optimize energy costs. For instance, in solar thermal applications, heat collected during daylight hours can be stored and used during cooler nights. In electrically heated or cooled buildings, TES systems can shift energy use to off-peak hours by storing heat or cold when electricity rates are lower and utilizing it during peak times, thereby reducing electricity bills and easing grid load.
Seasonal Storage	Thermal storage can store energy for days or even months to help address seasonal variability in supply and demand. This is of particular benefit to energy systems in regions that have a significant difference in thermal loads between seasons. Surplus heat produced with renewables like solar PV or wind in the summer can be stored in TES and then used to supplement or meet winter heating demand. Such an initiative would reduce the need for non-renewable sources of heat during peak times. Thermal storage can also be used to store natural cold in the winter to supply space cooling during the summer season. While this particular use case does not directly aid renewables integration, it helps reduce electricity demand during peak times in the summer.

Table 13: Advantages and Limitations of Different TES Technologies

	Sensible Heat Storage	Latent Heat Storage	Thermochemical Storage
Advantages	• Demonstrated large energy capacity (~GWh) • Inexpensive media • Solid media does not freeze and can achieve >1000°C	• Suitable for near-isothermal or low ΔT applications • Can provide high energy density with combined sensible and latent heat storage	• Very high energy densities • Minimal heat losses • Potential for long-term storage • Compact storage system • Oxide TCES stable at high temperatures at > 1000°C
Limitations	• Requires insulation to mitigate heat losses • Lower energy density requires larger volumes • Molten salts freeze at ~200 °C.	• Risk of material corrosion • For larger ΔT, may need cascaded systems (adds costs and complexity) • Low technology maturity	• Higher system complexity • Low technology maturity • Higher capital costs • May require storage of gaseous reaction products

Source: Clifford K. Ho, & Andrea Ambrosini. (n.d.). Thermal Energy Storage Technologies

8.1 Benefits and Use Cases

TES plays a crucial role in enhancing the flexibility, efficiency, and sustainability of energy systems by bridging the gap between energy supply and demand. The diverse application of TES across the sectors are discussed in infographic below: [43]

Buildings	In regions with extreme climatic conditions, TES can enhance the performance of heat pump systems by providing flexibility on the demand side. In warmer climates, TES can help shifting cooling demand to non-peak periods, thereby easing stress on the energy system. Further, thermal storage using water is widely adopted for space heating and cooling in buildings. Additionally, phase change materials (PCMs), solid-state thermal batteries, and ice-based storage systems are used as alternatives to conventional air conditioners, and are also commercially available.
District Heating and Cooling	TES technologies can significantly improve the performance of district heating and cooling systems by offering flexibility over various timescales, from hourly fluctuations to seasonal changes. They help align heat or cooling supply with demand more effectively and enable the use of renewable electricity generated during off-peak periods. In some district cooling networks, ice is generated using renewable electricity and stored for later use, demonstrating a practical application of TES in leveraging clean energy.
Industrial Processes	TES offers strong potential in industrial applications that require both heating and cooling, such as metal processing, textiles, and food production. TES enables recovery and reuse of waste heat and chilled water, improving overall energy efficiency. By decoupling energy generation from use, TES provides operational flexibility, ensuring continuous heating or cooling even when renewable sources like solar or ambient heat are intermittent.
Power Generation	TES can be used to mitigate issues of variability in renewables and improve the short-term (i.e. non-seasonal) supply-side flexibility of the power sector. The key use cases where TES can benefit the power sector by Integration of Variable Renewable Energy (VRE) deployed at or near renewable energy generation sites, such as solar thermal plants using Concentrated Solar Power (CSP), or in conjunction with solar PV and wind installations. The TES helps smooth out short-term and intermittent fluctuations in energy supply—such as cloudy weather for solar or periods of low wind—by storing excess energy and releasing it when generation drops.
Cold Chain and Refrigeration	Thermal Energy Storage (TES) can enhance the integration of renewable energy across entire cold chain—encompassing production, transportation, storage, retail, and end-use—by improving the flexibility of refrigeration systems. This increased flexibility can reduce the need for expensive grid upgrades and enable cold production to align with periods of high renewable energy availability. In cold-chain logistics, TES offers an alternative to diesel-fueled refrigeration units, promoting the decarbonization of transport.

Moreover, TES offers a versatile solution for enhancing energy system flexibility, enabling higher integration of renewable energy sources, improving energy efficiency, and supporting grid stability. By decoupling energy supply from demand, TES can reduce peak loads, lower operational costs, and enhance the reliability of energy systems. However, TES systems also face challenges such as high upfront costs, material availability constraints, space requirements, and system integration complexity, which must be carefully addressed during planning and design stages.

8.2 Case Study: Stockholm Arlanda Airport, Sweden (Underground Thermal Energy Storage) Stockholm Arlanda Airport

Challenge: tockholm Arlanda Airport is uniquely situated atop Brunkebergsåsen, a boulder ridge that houses Sweden's largest known aquifer, an underground lake located 15–25 metres below ground level and insulated by layers of gravel, sand, and stone. As a major Scandinavian aviation hub, Stockholm Arlanda Airport serves over 18 million passengers annually and has a massive roofed area of 450,000 m2. SThis aquifer, with an estimated volume of approximately 600,000 m^3 of water, has been harnessed as a seasonal thermal energy storage reservoir since 2009. [46,47] Its total energy demand is comparable to that of a town with around 25,000 residents, necessitating a strategic and sustainable approach to managing high energy consumption, particularly for HVAC systems.

Solution: The airport implemented one of the world's most prominent Underground Thermal Energy Storage (UTES) systems by leveraging a unique geological feature: a massive underground aquifer beneath the airport. This aquifer functions as a seasonal thermal energy reservoir. During the summer, surplus heat is pumped into the aquifer for use as winter space heating. Conversely, during winter, cold water is stored and later used for summer cooling. Notably, the system operates without conventional chillers, heat pumps, or fossil fuels. [44], [45]

Quantifiable Outcomes: The UTES system delivers an impressive annual energy saving of 19 GWh, equivalent to the energy consumption of 2,000 average Swedish single-family homes. This has resulted in an annual reduction of approximately 7,000 tonnes of CO_2 emissions.

Key Lesson and Implication for Indian Airport: The most significant insight from the Arlanda case is the strategic value of leveraging site-specific natural resources for large-scale, seasonal thermal energy storage. While most Indian airports may not have aquifers, this implies a call to action to conduct thorough geological and environmental assessments to identify similar opportunities. Potential alternatives include exploring ground-source cooling or utilising nearby bodies of water as potential thermal reservoirs. The success of this project demonstrates that a TES solution can be highly effective when custom-engineered to align with local environmental and geological conditions.

8.3 Conclusion and Way Forward

Analysis presented in this chapter confirms that TES is a mature, versatile, and financially viable technology with a critical role to play in the future of India's aviation sector. Its ability to manage high cooling loads, integrate with renewable energy sources, and enhance operational resilience makes it an indispensable component of any modern, sustainable airport strategy. The global and domestic case studies provide a compelling roadmap for implementation, demonstrating that TES can be a large-scale, campus-wide solution, a modular system for specific buildings, or a critical enabler of localised commercial operations. The key to unlocking its full potential lies in adopting a strategic and holistic approach.

Based on this comprehensive research, the following recommendations are proposed for Indian airports seeking to adopt TES:

1. **Conduct Comprehensive Energy Audits:** A successful TES project begins with a detailed understanding of the facility's specific energy profile. Airports should undertake comprehensive energy audits to accurately map their cooling and heating loads. This is a crucial first step and a key dependency for any successful implementation.
2. **Pilot with Scalable Solutions:** To mitigate initial risk, airports should consider a phased deployment strategy. Begin by piloting TES in a single, energy-intensive building, such as a cargo warehouse or administrative office, similar to the Indianapolis or Inficold models. This test-and-learn approach allows for demonstrating efficiency gains and financial returns on a smaller scale before committing to a larger, campus-wide investment.
3. **Explore Innovative Financing Models:** Beyond direct capital investment, airports should actively explore alternative financing mechanisms. Partnerships with ESCOs can allow for project implementation with limited upfront capital expenditure, as the ESCO is paid through a share of the energy savings. Additionally, leveraging Green Bonds offers an increasingly viable option for funding sustainable infrastructure projects, aligning with global and domestic green finance initiatives.
4. **Engage with Utility Providers:** The report's financial analysis revealed a critical causal link between utility rate structures and project payback. Airports should proactively engage with electricity providers to advocate for and adopt favourable tariff structures, such as time-of-use or real-time pricing. Optimising system operations to take advantage of these structures is essential for maximising financial returns.
5. **Develop a Campus-Wide Strategy:** Inspired by the success of the GIFT City DCS, airports should consider the long-term potential of centralised district cooling systems for the entire campus. This model maximises efficiency by consolidating cooling production and offers the potential to serve not only airport facilities but also ancillary developments, such as nearby hotels and commercial complexes.

Table 14 standardises key metrics of TES deployment, providing a clear, data-driven basis for financial evaluation.

Table 14: Assessment summary assessment for TES deployment

Metric	Assessment
Technology Category	Foundational Efficiency (Phase 1)
Capital Expenditure (CapEx)	Moderate (40-60% lower than full replacement); partial-TES implementation cost reported at approximately $215,580 [43]
Typical Payback Period	3-7 years, driven by energy savings and reduced demand charges; potentially as low as 4.83 years under real-time pricing [43]
Impact on OpEx	High positive impact; direct energy cost savings from load shifting and reduced maintenance costs [43]
Primary Financial Return	Direct energy cost savings, demand charge reduction, and extended asset lifespan [43]
Non-Financial Returns	Improved ESG scores, enhanced indoor comfort, and increased energy resilience [44]
Financing Models	Direct capital budget, ESCO models, and green bonds [45]
Key Dependencies	Detailed energy audit, accurate load profiling, and a skilled implementation partner.

Landside and Infrastructure Technologies

CHAPTER 9

LC3 Cement and Low-Carbon Prefab Solutions

Limestone-calcined clay cement (LC3) represents a significant advancement in sustainable construction, offering a smart, climate-resilient alternative to traditional Ordinary Portland Cement (OPC). LC3 is a ternary blended cement, typically composed of clinker (50%), limestone (15%), calcined clay (30%), and gypsum (5%), capable of reducing emissions by up to 40% while maintaining performance standards comparable to OPC. [46]

By blending clinker with calcined clay (metakaolin), limestone, and gypsum, LC3 dramatically lowers clinker content, thereby reducing both energy consumption and process-related CO_2 emissions. What distinguishes LC3 is its ability to achieve these emission reductions without compromising strength, durability, or performance, making it a practical and scalable low-carbon solution for the cement and construction sectors.

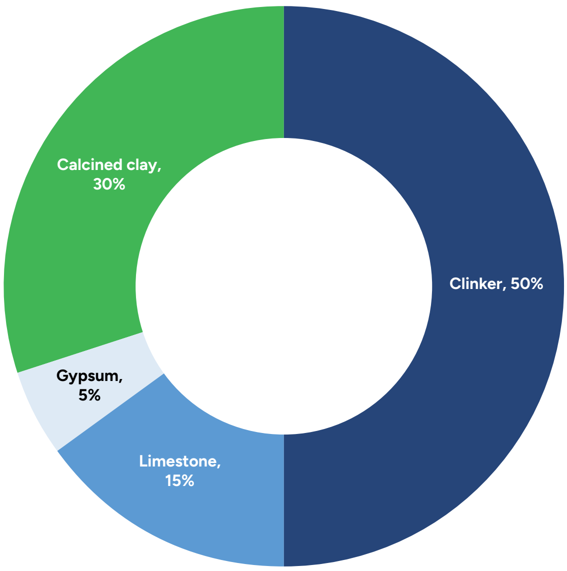


Figure 11: Composition of LC3 Cement

9.1 Benefits and Performance Insights

LC3 achieves significant environmental benefits by reducing clinker usage, a key source of CO_2 emissions. At same time, it also enhancing material efficiency, resource flexibility, and economic viability. Figure 12 illustrates the key advantages of LC3 technology – such as lower carbon emissions, cost-effectiveness, and enhanced durability. These aspects are discussed in detail below.

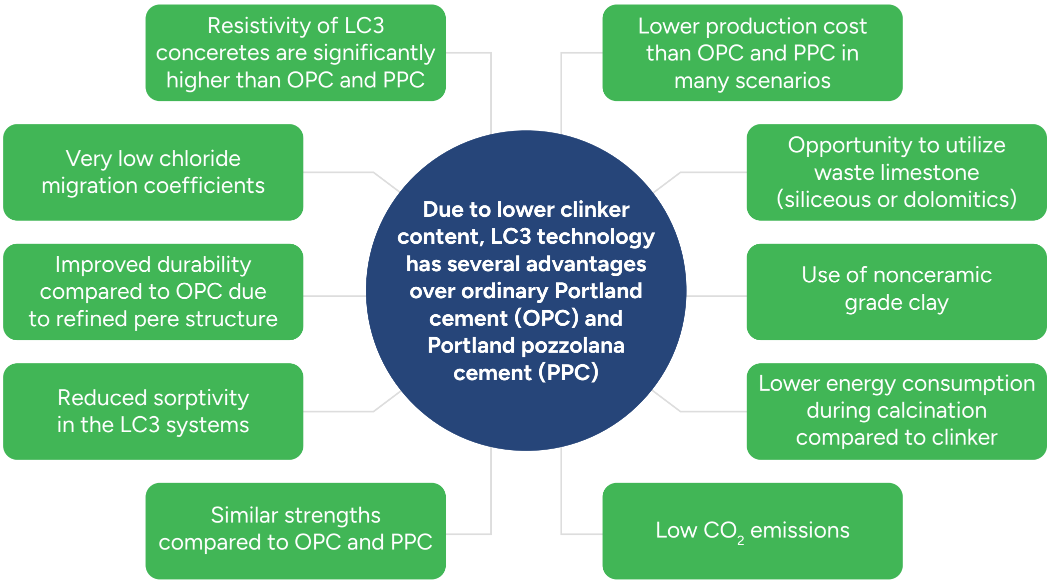


Figure 12: Schematic illustration of multiple benefits of LC3 cement

Emission Reduction

A typical LC3-50 cement blend mixture consists of 50% clinker, 30% calcined clay, 15% limestone, and 5% gypsum. With a clinker content reduction of approximately 45%, LC3 has the potential to lower embodied carbon (EC) in concrete to as low as 0.06 kg CO_2e/kg. Compared to OPC, CO_2 emissions are reduced by up to 40% compared to OPC and approximately 11% relative to PPC as illustrated in Figure 13. [47]

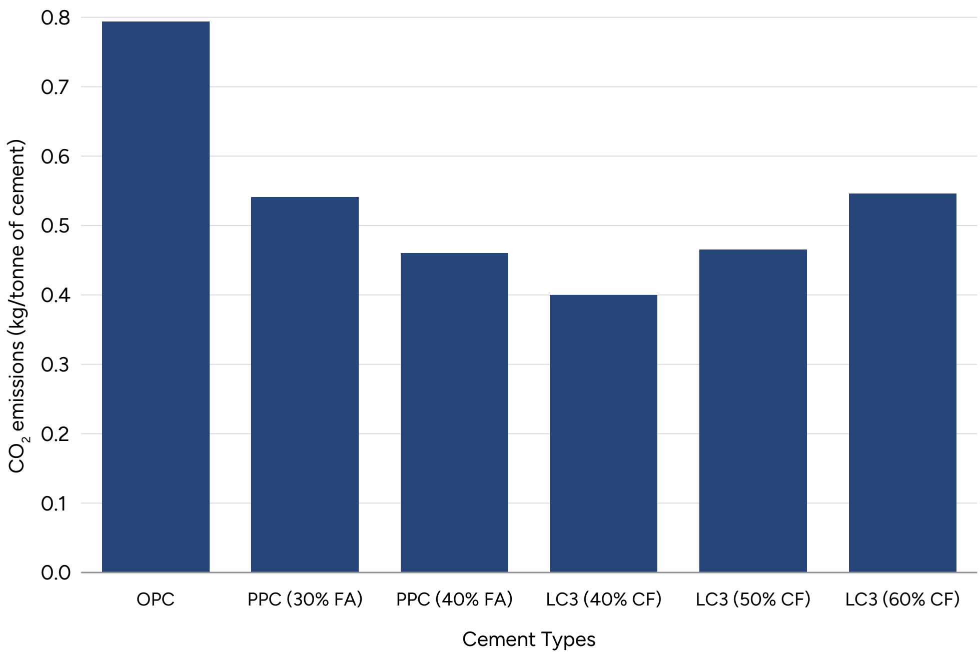


Figure 13: Estimated CO_2 emissions from the production of OPC, PPC and LC3 with varying clinker contents

Cost Reduction

Direct cost estimates for manufacturing per cubic metre of M40 concrete with LC3 and OPC are shown in Figure 14, illustrating a 9% reduction in the cost per cubic metre of M40 concrete when OPC is replaced with LC3 cement. [48]

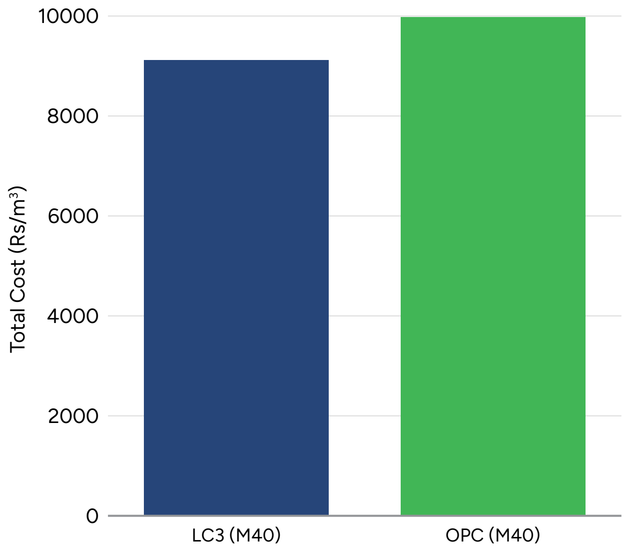


Figure 14: Cost comparison of concrete produced with OPC and LC3 cement

Strength Performance

LC3 not only matches but exceeds OPC in compressive strength at all stages, especially at 28 days, where strength approaches 50 MPa. This superior performance demonstrates LC3's capability to deliver structural reliability while significantly lowering CO_2 emissions. Figure 15 compares the compressive strength development of LC3 and OPC over periods of 3, 7, and 28 days. With higher early and long-term strength, LC3 proves that sustainability and performance can go hand in hand – making it a compelling solution for a low-carbon, climate-resilient construction future. In addition, LC3-based concrete offers superior resistance to chloride ingress and sulphate attack, making it highly suitable for structures in coastal regions. [49] Its lower alkali content also reduces the risk of alkali-silica reactions, thereby enhancing durability, long-term performance, and the service life of infrastructure in aggressive environments.

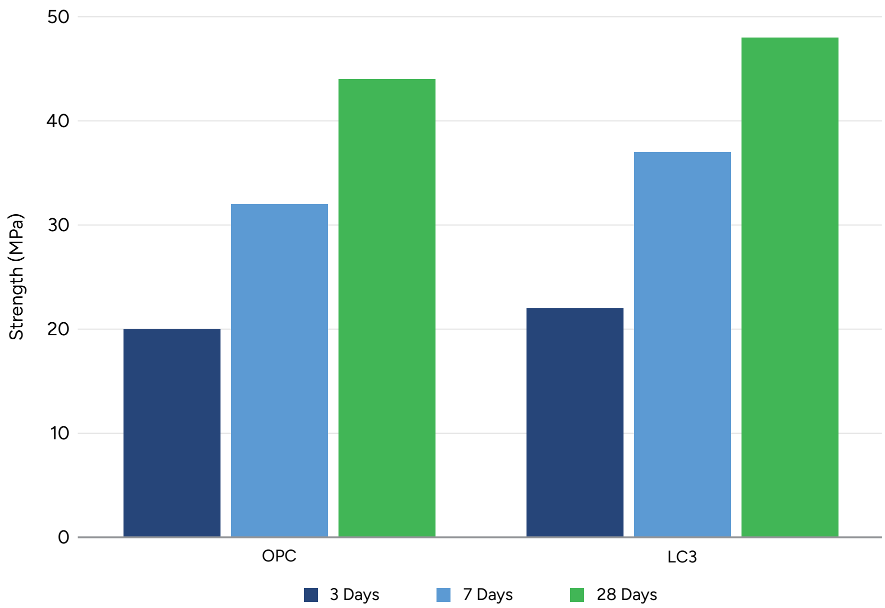


Figure 15: Compressive strength of LC3 and OPC at different curing periods.

Resource Efficiency

From a resource-efficiency standpoint, LC3 utilises locally available raw materials that are widely distributed across India. Policy and Standards

Limestone Reserves: India possesses approximately 185 billion tonnes of limestone reserves, of which 68% are cement-grade. LC3 can additionally utilise dolomitic and low-grade limestone (≥30% CaO), which is typically unusable in conventional clinker production, but readily available in current cement mines.

Clay Resources: While high-purity white China clay (2.4 billion tonnes) is reserved fo r ceramics, LC3 can use lower-grade clays (≥40% kaolinite) and other minerals (e.g., illite, montmorillonite), which are often discarded or underused due to limitations. [50]

This broad availability of alternative materials provides LC3 with a significant scalability advantage over traditional Supplementary Cementitious Materials (SCMs), which are subject to supply chain and location constraints.

Policy and Standards: The Bureau of Indian Standards (BIS) released IS 18189:2023, India's first dedicated standard for LC3 cement. [51] This standard:

- Provides technical specifications for LC3 production and application
- Validates LC3's performance and reliability
- Is expected to accelerate national-level adoption and integration into mainstream construction practices

Additionally, LC3's recent inclusion in India's emerging draft Carbon Credit Trading Scheme (CCTS) and offset mechanisms under the construction sector further enhances its market viability and investment potential. [47]

9.2 Case Study: Swiss Embassy Building in Delhi

In 2017, JK Lakshmi partnered with IIT Delhi to conduct the first-ever full-scale plant trial of LC3 cement at its Jhajjhar unit. This trial showed promising results, with potential CO_2 emission reductions of up to 30% and energy consumption reductions of 20% in cement production . Following successful trials, JK Cement has started commercial-scale production of LC3 cement in its Mangrol Plant. One of the most notable demonstrations of LC3 is the model house in Jhansi, where 98% of the structure was built with LC3, utilising 26.6 tonnes of industrial waste (192 kg/sqm) and achieving a CO_2 reduction of 15.5 tonnes (114 kg/sqm). [53] Another example is the offices of the Swiss Agency for Development and Cooperation within the Swiss Embassy compound in New Delhi, which were constructed using LC3-prefabricated materials.

Figure 16: Use cases of LC3 cement: (a) Model House in Jhansi and (b) Swiss Embassy building in Delhi

9.3 Conclusion and Way Forward

Limited alignment among stakeholders remains a key barrier to scaling low-carbon concrete such as LC3. The initiatives, similar to the Clean Concrete Pledge Initiative, can offer a collaborative framework to accelerate the adoption of LC3 (clinker factor <0.5), reduce emissions, and unlock economic opportunities. The following are some key areas to accelerate the LC3 adoption and Table 15 shows the adoption matrix of LC3 cement for airports.

- Public sector agencies can lead by committing a portion of their annual concrete demand to LC3. AAI can also initiate joint demonstration projects to build market confidence.
- Cement manufacturers and ready-mix concrete producers pledge to meet the resulting demand for LC3 and other low-carbon concretes at scale.
- Policy Support Measures:
- Integrating low-carbon concrete into building codes (e.g., ECBC, ENS), and local byelaws
- Shifting to performance-based standards
- Streamlining regulatory approvals for LC3 plants
- Offering tax incentives

Table 15: Assessment summary of adoption matrix for LC3 cement in airports

Metric	Assessment
Technology Category	Advance decarbonisation measures for new upcoming airport infrastructure and capacity expansion of existing airport terminal buildings
Capital Expenditure	Comparable to conventional cement procurement costs
Financial Benefit	LC3-based concrete offers a lower cost (9-10%) compared to conventional OPC
Non-Financial Benefits	Reduced carbon, improved ESG score of airport terminal buildings
Financing Models	Tax incentives
Key Dependencies	Large-scale production capacity of cement manufacturers to meet the demand

CHAPTER 10

Fleet Electrification (Ground Operations, Cab Services)

In India, the transport sector is responsible for nearly 14% of national GHG emissions. [54] To minimise transportation emissions, a strong push for electric vehicles (EVs) is propelled by a blend of regulatory mandates and economic incentives. Along the same line, airports are also increasingly embracing fleet electrification as a core part of their sustainability strategies, recognising its potential to reduce GHG emissions and improve air quality. [55] Fleet electrification also enhances corporate social responsibility, improving stakeholder perception. India's broader environmental goals, including net-zero emissions by 2070 and 30% EV penetration by 2030, align with targets set by the Ministry of Civil Aviation, such as making 121 airports carbon-neutral by 2025 and achieving 100% green energy usage at major airports by 2024. [56]

Globally, airports are deploying EVs to reduce emissions and improve passenger experiences, particularly through electric shuttles and electrified GSE By 2030 [57], approximately 60% of cargo handling equipment sales are projected to be electric. In India, this trend is already underway. Rajiv Gandhi International Airport, Hydrabad, for example, has installed EV charging stations and adopted EVs as part of its Level 5 Airport Carbon Accreditation. [58] Delhi Airport is leading with India's largest airport EV programme to achieve a net-zero carbon emission status by 2030. [59]

The successful electrification of airport fleets in India hinges on robust and strategically deployed charging infrastructure. Two primary charging technologies are currently driving adoption: high-power DC fast charging and battery swapping. DC fast chargers, such as CCS and CHAdeMO, are critical for minimising downtime in commercial fleets, including electric buses and GSE. India's charging standards accommodate up to 250kW for 4-wheelers, and plans are underway to introduce 360kW ultra-fast chargers for heavy-duty vehicles. [60] Emerging technologies such as the Megawatt Charging System (MCS) are also being explored for future needs. [61] Battery swapping offers rapid turnaround for high-usage vehicles (e.g., two-wheelers, buses), but faces interoperability issues due to proprietary battery designs.

India's EV infrastructure expansion is supported by national programmes such as FAME II and the PM E-Drive scheme, which target to deploy 72,300 public charging stations by FY26, along key corridors and high-traffic areas such as airports. [62] Revised Ministry of Power guidelines have further accelerated deployment by making public EV charging a de-licensed activity. [63] Moreover, private-sector participation is also critical. For example, Tata Power has deployed over 5,300 public/semi-public chargers and 86,000 home chargers across 530 cities. [64] Mumbai Airport (CSMIA) has installed 60–240kW DC fast chargers and operates entirely on renewable energy. [65] Bengaluru's BMTC is developing a dedicated charging hub near Kempegowda International Airport, and AAI has partnered with Terra Charge to expand EV infrastructure for airport GSE fleets. [66]

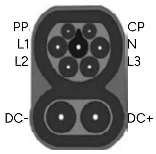
Type of Charging	North America	Japan	EU & rest of the market	China	All markets except EU	India
AC Type1:1-3kW Type2:3-22kW						
Plug Name	J1772 (Type 1)	J1772 (Type 1)	Mennekes (Type 2) IEC62196-2	GB/T		Commando (Type-1): IEC60309 Mennekes (Type-2): IEC62196-2
DC 10-400kW						
Plug Name	CCS1	CHAdeMO	CCS2	GB/T	TESLA	GB/T, CCS2, CHAdeMO

Figure 17: Types of EV charger connectors for vehicles

10.1 Benefits and Perfomance Insights

Adoption of electric vehicles across airport operations spans multiple fleet segments, from specialised ground support equipment to passenger transport and public cab services. This section outlines the current status and specific examples of EV integration across these critical areas in India.

Ground Support Equipment (GSE) Electrification	Electrification of ground support equipment (eGSE) includes a range of vehicles critical to aircraft servicing – such as electric baggage transporters, conveyor belts, mobile stairs, forklifts, aircraft tugs, pushback tractors, belt loaders, container loaders, GPUs, and lavatory and water service vehicles.
Passenger Transport Buses	Passenger transport buses play a vital role in airport mobility, serving both inter-terminal shuttle routes and city-airport connections while delivering quieter, more comfortable rides.
Cab Services (Taxis and Ride-Hailing)	The integration of electric vehicles into airport cab services – spanning traditional taxis and ride-hailing platforms – is rapidly expanding. This combines sustainability with passenger comfort and operational reliability, supported by advanced in-car features and strict safety protocols.

The electrification of airport fleets presents a strong techno-economic and environmental case. Across key vehicle categories – taxis, buses, and GSE, EVs offer significant advantages over internal combustion engine (ICE) vehicles in terms of total cost of ownership (TCO), emissions, and energy efficiency. [68] A comparison of EVs vs. ICE vehicles is provided in Table 16.

Table 16: Comparison of Electric Vehicles (EVs) vs. Internal Combustion Engine (ICE) vehicles

Feature Parameter	Electric Vehicles (EVs)	Internal Combustion Engine (ICE) Vehicles
Upfront Cost	Higher; can be 4-6 times higher for cars, 30-35% higher for GSE, and up to ₹3.5 crore for buses	Lower initial investment (e.g., around ₹1.5 crore for a diesel bus).
Fuel / Energy Cost	Significantly lower and more stable; electricity costs ₹8–20 per kWh	Significantly higher and volatile; diesel costs around ₹90 per L.
Operational Costs	Lower; electric buses operate at ₹7–9 per km; electric GSE can save ~$3,000 annually per vehicle.	Higher; diesel buses operate at ₹20–25 per km.
Maintenance Costs	Substantially lower, approximately 25% of ICE vehicle costs due to fewer moving parts.	Higher due to greater mechanical complexity (engine, transmission, etc).
Total Cost of Ownership (TCO)	Increasingly favourable; already lower for certain cars (e.g., Tata Nexon) and buses over their lifetime; parity for heavy-duty vehicles is expected within 5 years.	Higher over the vehicle's lifetime due to greater fuel and maintenance expenses.
Tailpipe Emissions	Zero tailpipe emissions.	Emits harmful pollutants, including Particulate Matter (PM), Nitrogen Oxides (NOx), and Carbon Monoxide (CO).
Lifecycle Emissions (GHG)	Lower; offers a ~20% CO_2 reduction in India's current grid mix (saving ~10 tonnes of CO_2 per vehicle), with up to 96% with a fully renewable grid.	Higher; the transport sector contributes 14% of India's GHG emissions.
Energy Efficiency	High; converts 60–85% of grid energy to motion; up to 7 times more efficient in low-speed or idling conditions.	Low; converts only 30–40% of fuel energy to motion; inefficient in stop-and-go traffic.
Operational Performance	Smooth acceleration, lower noise, reduced vibrations, and fewer breakdowns lead to a better driving experience.	Noisy operation, engine vibrations, and more frequent breakdowns due to mechanical complexity.
Fleet Management	Excellent; easily integrates with telematics systems for smart fleet management and real-time monitoring.	Integration is possible, but less inherent compared to the electronic nature of EVs.

10.2 Case Study: Fleet Electrification- Delhi Airport

The electrification strategies used by leading airports, for example, Delhi Airport (DIAL), provide valuable lessons about implementation, infrastructure planning, and sustainability outcomes. Delhi Airport, operated by DIAL, has achieved Level 5 Airport Carbon Accreditation in 2024, becoming the first in Asia to do so, and has committed to net-zero carbon emissions by 2030. [69] Since June 2022, it has operated entirely on renewable electricity, achieving a 52% drop in CO_2 emissions and a 36% reduction in emissions per passenger over four years. [70] DIAL has deployed 57 EVs across airside and emergency operations, transitioned its corporate fleet to electric, and introduced electric buses for passenger transfers, with plans to link to Noida International Airport. [71]

Figure 18: Electric AC buses for passenger transportation at Delhi airport

Further, DIAL has also pioneered operational innovations such as TaxiBots – semi-autonomous tugs that save 200–240 litres of ATF and up to 750 kg of CO_2 per taxi-out. By March 2022, over 2,000 TaxiBot missions had saved 371 tons of fuel and reduced 1,173 tons of CO_2 [72] DIAL has also installed 22 EV charging stations and collaborated with private partners such as Tata Power, echoing a broader national push. Collectively, these initiatives underscore the importance of renewable energy sourcing, phased fleet transition, strategic infrastructure investment, and innovation (e.g., TaxiBots) in accelerating airport decarbonisation.

10.3 Conclusion and Way Forward

The transition toward electric fleets in Indian airports is gaining momentum, with growing adoption of EVs in ground support, passenger transport, and cab services. Leading airports like Delhi and Bengaluru, along with private players such as Evera Cabs, are setting strong precedents in electrification. Government schemes, including FAME II and the upcoming PM E-Drive, are further accelerating this shift by supporting vehicle procurement and charging infrastructure. Despite this progress, several challenges persist. High upfront costs, limited grid capacity, space constraints, and the lack of robust battery recycling infrastructure are major roadblocks. Notably, the full environmental benefits of EVs are realised only when paired with a cleaner grid, emphasising the need for integrated energy and transport planning.

To enable a smooth and scalable transition, a multi-pronged strategy is essential. From a policy perspective, sustained incentives tailored to airport fleets, clear electrification mandates, and better coordination among agencies – airport authorities, DISCOMs, and urban planners – can significantly accelerate deployment. From an infrastructure standpoint, investments should prioritise high-power DC chargers, smart grid integration, and renewable-linked microgrids to ensure reliability and emission reduction. Targeted battery swapping pilots should be explored for high-utilisation fleet segments. Simultaneously, developing a domestic battery recycling ecosystem – including second-life applications, local material recovery, and reverse logistics – is critical to manage the upcoming wave of EV battery waste. Public-private partnerships and innovative procurement models such as GCCs can bridge investment gaps, while workforce training and data sharing across airports will help build operational capacity and foster continuous learning. Collectively, these steps can ensure that Indian airports not only electrify their fleets in a manner that is efficient, sustainable, and future-ready.

Table 17: Assessment of fleet electrification – key deployment metrics

Metric	Assessment
Technology Category	Infrastructure Expansion (Phase 2)
Capital Expenditure	High; upfront costs are significant: EV buses cost ~₹3.5 crore vs ₹1.5 crore for diesel; GSE costs 30–35% higher; charging infra adds to costs.
Typical Payback Period	5–8 years, driven by lower fuel cost, reduced maintenance, and favourable TCO parity for buses and GSE within 5 years.
Impact on OpEx	High positive impact; electricity is cheaper and more stable than diesel, and operating costs drop to ₹7–9/km for buses (vs. ₹20–25/km for diesel); maintenance costs ~75% lower.
Primary Financial Return	Reduced fuel expenditure, lower OpEx, and deferred maintenance costs; long-term TCO benefits as fuel and repair savings outweigh upfront cost.
Non-Financial Returns	Significant emissions reduction (~10 tonnes CO_2 saved per EV annually), zero tailpipe pollution, noise reduction, improved ESG score, enhanced passenger experience, and compliance with airport carbon-neutrality goals.
Financing Models	Green bonds, PPPs, Gross Cost Contracts (GCCs), Energy-as-a-Service models, and schemes such as FAME II and PM E-Drive for subsidies.
Key Dependencies	Robust charging infrastructure (DC fast charging, battery swapping pilots), reliable grid capacity with renewable integration, space availability at airports, inter-agency coordination (airport authorities, DISCOMs), and skilled workforce training.

CHAPTER 11

Enhancing Efficiency of Chillers through Retrofitting

Modern airport infrastructure can no longer treat energy efficiency as an isolated initiative – it must be embedded within airport planning, design, and ongoing management. The technologies highlighted throughout this compendium – such as chiller retrofitting, HVAC modernisation through VRF/VRV systems and heat pumps, automated building controls, and future-ready upgrades like thermal energy storage – are not merely technical upgrades but essential building blocks of a resilient, flexible, and decarbonised operating strategy. [73] The rationale for adopting these interventions is threefold:

- **Operational Resilience:** Upgrading legacy systems with advanced, adaptive technologies improves airports' robustness under fluctuating demand and operational stress, reducing the risk of unplanned outages and service disruptions. [74]
- **Financial Prudence:** Life-cycle cost analyses clearly show that investments in energy efficiency and smart controls deliver rapid payback – often within five years – while reducing ongoing maintenance and energy bills, freeing capital for other mission-critical upgrades. [75]
- **Climate Leadership:** As high-visibility global gateways, airports play a leadership role in showcasing climate commitments. Energy-efficient technologies that reduce greenhouse gas emissions and support integration of renewables help airports align with national targets, international best practices, and evolving certifications (LEED, GRIHA), while setting industry benchmarks.

Airports rank among the most energy-intensive public infrastructure facilities, with a significant portion of their energy consumption dedicated to space cooling and maintaining thermal comfort for millions of passengers annually. Chiller systems, forming the backbone of HVAC operations, are critical to achieving this. However, many existing airport chiller plants rely on outdated, inefficient equipment that not only inflates operational costs but also contributes to higher GHG emissions. In this context, chiller retrofitting has emerged as a pragmatic and cost-effective strategy to enhance energy efficiency, reduce emissions, and improve system reliability, without requiring complete equipment replacement.

Chiller retrofitting involves upgrading an existing cooling system with modern, energy-efficient components and intelligent control mechanisms, particularly improving system performance under variable load conditions, which are common in airport operations. One of the most impactful retrofit measures is installing variable-speed drives (VSDs) or inverter kits. The majority of older chillers operate at a constant speed, which makes them inefficient at partial load conditions – a scenario that frequently occurs in large airports where cooling demand fluctuates based on terminal occupancy and weather. By introducing VSDs, the compressor speed can be modulated in real time to match actual cooling demand. This results in leads to energy savings of up to 20% and significantly enhances the chiller's COP. In fact, case studies indicate that annual chilled water supply COPs can improve by up to 20% post-retrofit [76]

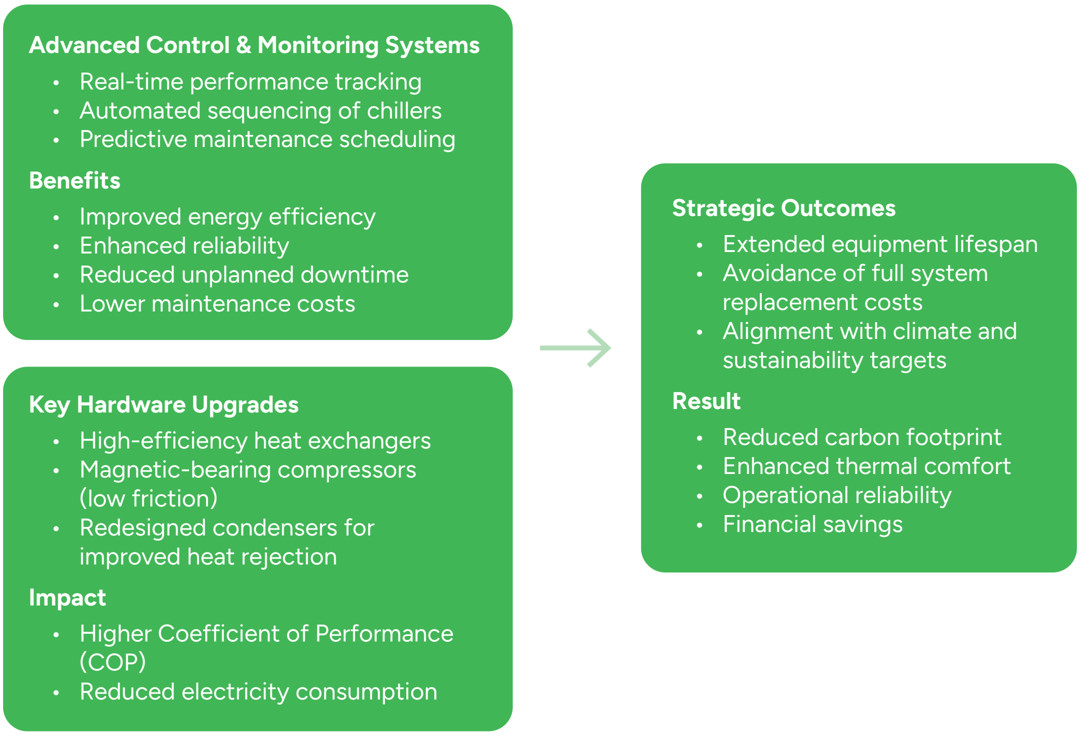


Figure 19: Systematic illustration of retrofit strategy for chiller plants at airports

In addition to mechanical upgrades, advanced control and monitoring systems play a crucial role in optimising chiller plant performance. These intelligent systems enable real-time performance tracking, automate the sequencing of multiple chillers, and schedule maintenance activities based on operational data, improving both the energy efficiency and reliability of the cooling system, while reducing unplanned downtimes and maintenance costs [77]

Another essential component of a successful retrofit strategy involves upgrading key hardware elements. This includes replacing traditional heat exchangers with high-efficiency models, incorporating magnetic-bearing compressors that operate with minimal friction, and redesigning condensers for better heat rejection. Collectively, these enhancements reduce electricity consumption.

Together, these retrofit measures enable airport authorities to extend the lifespan of existing equipment, avoid the capital expense of full system replacements, and align with broader climate and sustainability goals. By upgrading legacy systems with modern technologies, airports can effectively reduce their carbon footprint while ensuring thermal comfort, operational reliability, and financial savings.

11.1 Benefits of Chillers Retrofitting

The global aviation sector is under increasing pressure to decarbonise, not only in in-flight operations but also across airport infrastructure and auxiliary services. As airports expand in scale and operational complexity, their energy demand rises substantially, especially for air conditioning systems, which are critical for ensuring passenger comfort and operational continuity. These systems account for a significant share of an airport's electricity consumption, often relying on ageing, inefficient chillers that waste energy and contribute significantly to GHG emissions.

In this context, retrofitting chillers offers two advantages: improved energy efficiency and a substantial reduction in carbon emissions. By upgrading outdated equipment with high-efficiency components and smarter control systems, airports can reduce the cooling-related energy demand and lower their indirect carbon footprint associated with electricity consumption. These benefits are vital for airports striving to meet energy-efficiency targets, sustainability certifications (such as LEED or GRIHA), or national commitments to climate action.

Studies have shown that energy savings from chiller retrofits typically range from 10% to 40%, depending on the existing system's baseline efficiency and the extent of upgrades implemented. [78] Another major environmental benefit of retrofitting is replacing ozone-depleting refrigerants, such as CFCs, which were commonly used in older centrifugal chillers. These legacy refrigerants not only contribute to ozone layer depletion but also possess very high GWP. Replacing such systems with modern units using non-CFC refrigerants – and achieving an efficiency gain of up to 30% – brings dual benefits. It significantly lowers electricity use, reduces CO_2 emissions, and eliminates CFC leakage risks, contributing to ozone protection.

11.2 Case Study: Infosys Mysuru – Chiller Retrofit Efficiency and Impact

Challenge: Infosys, a leading technology company in India, operates large campuses in warm and humid climates with high cooling demand. The Global Education Centre-1 (GEC-1) at Mysuru relied on legacy chiller plants and pumping systems that were energy-intensive, faced operational inefficiency, and drove up energy costs – a challenge common across Indian commercial buildings.

Solution: Infosys re-engineered and retrofitted its chiller plants to achieve best-in-class energy performance. The approach included:

- Replacing inefficient chillers (4 × 250TR water-cooled screw chillers) and constant-speed pumps with high-efficiency equipment.
- Converting the pumping system from traditional primary-secondary constant flow to variable primary flow using VFDs.
- Integrating smart digital controls for demand-based operation and better load matching.
- Comprehensive metering, monitoring, and controls, allowing for demand-based sequencing and operation.

Figure 20: Infosys campus Mysuru building

Quantifiable Outcomes

- Energy savings: Approximately 200,000 kWh saved in just four months post-retrofit, consistently exceeding expectations.
- Connected Load: Plant room connected load reduced by 70%, lowering peak demand.
- Specific Energy Consumption (SEC): Achieved SEC of 0.6–0.7 kW/ton, outperforming national benchmarks.
- Payback Period: Retrofit project paid back in less than 2 years – making it highly commercially viable.
- Replicability: Infosys implemented over 300 HVAC retrofits across campuses, delivering energy savings of up to 55% in chiller operation and annual energy reductions exceeding 1.5 million kWh on large campuses. [27], [79], [80]

Key Lesson and Implication for Indian Airports: This case demonstrates that Indian organisations can achieve best-in-class efficiency – even in demanding climates – by modernising chiller plants with advanced hardware, controls, VFDs, and metering. The combination of rapid payback, deep energy savings, and operational benefits offers a proven, replicable template for Indian airports and large campuses. Investing in intelligent retrofitting, demand-based operation, and robust monitoring is both financially prudent and environmentally responsible.

11.3 Conclusion and Way Forward

HVAC systems at airports operate year-round and are subject to progressive wear and performance degradation, making energy efficiency an increasingly critical concern. One of the most compelling advantages of chiller retrofitting is its cost-effectiveness compared to full system replacement. On average, retrofitting a chiller plant costs 40% to 60% less than installing a new system. This cost differential is particularly attractive for large-scale facilities such as airports, where capital expenditure decisions are closely scrutinised for ROI. [81] Further, engineered conversions, such as driveline retrofits, typically cost approximately 50% of a new chiller installation, while component-level upgrades – such as replacing compressors, adding controls, or upgrading fan motors – are even more affordable. However, advanced high-efficiency retrofits (e.g., integration of smart controls, premium compressors, and magnetic bearing technologies) can involve up to 20% higher upfront costs than basic replacements. [82] Despite this, these high-performance retrofits deliver substantial long-term savings through reduced energy consumption, fewer equipment failures, and extended operating life. For example, integrated chiller retrofit projects that combine equipment upgrades with system-level improvements – including building load reductions and optimised controls – often achieve payback periods of around 5 years, considerably lower than simple equipment replacement projects, which can exceed a decade without these complementary measures.

Moreover, financial incentives and energy performance contracting models also improve the economic case for retrofits by reducing initial capital burdens and transferring some execution risks to specialised service providers. Beyond cost saving, smart chiller retrofitting enhances system reliability, improves thermal comfort, and aligns airport operations with sustainability mandates, making it a prudent and increasingly necessary business decision. The assessment summary of chiller retrofitting is discussed in Table 18.

Table 18: Assessment summary of chiller retrofitting key deployment metrics

Metric	Assessment
Technology Category	Foundational Efficiency (Phase 1) - Chiller plant retrofitting using VSDs, high-efficiency chillers (magnetic bearing or low-GWP refrigerants), advanced digital controls, and optimised pumping systems.
Capital Expenditure	Moderate; typically, 40–60% lower than full chiller replacement, making retrofit financially attractive, especially for large campuses and airports with existing distribution systems.
Typical Payback Period	3–7 years, depending on local electricity tariffs, baseline efficiency, size of plant, and scope of controls optimisation; projects with digital controls and variable primary flow often achieve payback at the shorter end
Impact on OpEx	High positive impact; annual electrical savings of 15–30% are typical, with some Indian projects (Infosys) reporting up to 55% chiller-plant savings; maintenance and breakdown costs also decline due to upgraded, more reliable components
Primary Financial Return	Significant reduction in recurring energy bills; longer asset life (due to reduced mechanical stress and better controls); delayed need for expensive plant replacement; performance-based incentives may further boost ROI.
Non-Financial Returns	Improved ESG and sustainability ratings for the airport
Financing Models	Direct capital budgets, energy savings performance contracts (ESCOs covering investment and sharing savings), green bonds for sustainability-linked finance, and government or utility incentives where available; Public-private partnerships are often effective for large airports to optimise cash flow
Key Dependencies	• Comprehensive pre-retrofit energy audit and monitoring • Selection of experienced installation and retrofit partners • Strategic, phased implementation plan to guarantee uninterrupted operations and stakeholder buy-in • Robust post-retrofit metering and reporting to verify savings and ensure persistent performance.

CHAPTER 12

HVAC Modernization

Airports are among the most energy-intensive built environments, with nearly 50% of this energy consumed by HVAC systems alone. [83], [84] Conventional airport HVAC systems often rely on fixed-speed chillers, centralized ducting, and outdated control mechanisms, which are poorly suited to respond efficiently to fluctuating occupancy patterns, varying thermal loads, and modern comfort expectations. Adopting advanced HVAC technologies—including variable refrigerant flow (VRF) or variable refrigerant volume (VRV) systems, heat pumps, and geothermal integration systems such as aquifer thermal energy storage (ATES)—is gaining popularity across the globe. These systems offer high energy efficiency, modular design, precision control, and better integration with building automation systems.

HVAC modernization technologies—such as VRF/VRV systems, high-efficiency heat pumps, geothermal integration, and digital controls—are not isolated upgrades. Instead, they are essential tools in a coordinated, sequenced roadmap that airports must adopt to remain operationally resilient, financially competitive, and climate aligned. By combining these solutions, the following benefits can be achieved:

- Ensuring operational resilience, delivering reliable comfort and air quality despite fluctuating occupancy, weather, and demand.
- Achieving rapid financial returns on investment, with energy savings payback often within 3–7 years.
- Leading in climate action and regulatory compliance, supporting international goals and certifications such as net-zero carbon, LEED, or IGBC.

Each modernization step, whether retrofitting a chiller or installing zoned VRF systems fits into a broader strategy aimed at maximizing efficiency, enabling renewable integration, supporting digital facility management, and delivering measurable value for airports, passengers, and their stakeholders. The Indian Society of Heating, Refrigerating and Air Conditioning Engineers (ISHRAE) outlines several foundational principles that are critical for enhancing HVAC efficiency in large facilities like airports:

Integrated System Design	• Energy savings begin at the design stage • Glazing, lighting, chilled water, air distribution must work cohesively
Demand-Supply Matching	• Manage fluctuating loads effectively • Ensure resilient chiller plant operations
Advanced Controls	• Use VFDs in air and water systems • Automated logic for sequencing, unloading, and temperature resets • Reduces peak demand and improves performance
Performance Monitoring	• Conduct regular audits and evaluations • Identify inefficiencies and proactively upgrade systems
Skilled Operations Teams	• Trained personnel are essential • Technology must be paired with proper monitoring and maintenance

Within this framework, VRF/VRV systems and heat pumps have emerged as key technologies for next-generation airport HVAC solutions. These systems use inverter-driven compressors to vary refrigerant flow and operate precisely according to the thermal needs of each zone or terminal area.

Unlike traditional fixed-capacity systems, which operate in on/off cycles, VRF/VRV systems provide continuous modulation, resulting in 30–40% energy savings. [85] They also eliminate the need for fossil-fuel-based boilers by extracting ambient heat from air or water sources, enabling a shift to fully electric, low-carbon HVAC infrastructure. [86]

Each VRF system typically connects one or more outdoor units to up to 50 indoor units, allowing independent temperature control across different zones. This zonal control approach is particularly effective in large, segmented airport terminals where usage patterns vary throughout the day. Each zone can maintain its own temperature setpoint, improving comfort while avoiding the inefficiencies of blanket heating or cooling. [86] A major advantage of modern VRF systems is their ability to support simultaneous heating and cooling. In heat-recovery configurations, waste heat extracted from cooled zones is transferred to areas that require heating, dramatically improving energy performance and user comfort. Noise reduction and lower maintenance requirements also make VRF systems well-suited to airports. With fewer moving parts and advanced control algorithms, these systems are quieter (as low as 27 dB(A)) and more reliable than conventional alternatives, which typically require frequent service and produce higher noise due to centralised ductwork and motor-driven components. [87]

These performance advantages are particularly clear when compared to conventional HVAC systems:

- Traditional HVAC systems typically operate at constant capacity, using fixed-speed compressors and centralised duct networks, leading to energy inefficiencies, especially in underutilised or fluctuating load zones.
- Zonal control is limited, and simultaneous heating and cooling is usually not possible without installing separate systems.
- Higher energy waste, maintenance complexity, and inflexible retrofitting options limit long-term suitability for the evolving needs of airport infrastructure.

Modern HVAC systems, by contrast, are modular, adaptive, and digitally integrated, making them far more aligned with the needs of energy-conscious, future-ready airports. By enabling efficient, zone-wise conditioning, smart load management, and data-driven control, they deliver not only measurable energy savings but also improve occupant comfort, operational control, and system longevity.

12.1 Benefits and Performance Insights

As airports expand and passenger volumes surge, their environmental performance is coming under sharper focus. Regulatory frameworks – both domestic and international – are increasingly mandating measurable reductions in operational carbon emissions. For airport operators, carbon neutrality is no longer a distant goal but a current business imperative, influencing financing, stakeholder perception, and compliance with green building standards such as IGBC and LEED. HVAC systems represent one of the largest and most immediate opportunities for carbon mitigation. Modernising these systems not only reduces electricity consumption but also shifts airports away from refrigerants and technologies with high GWP. The resulting impact is both direct, through lower energy use, and indirect, through electrification and improved readiness for renewable integration. One of the clearest benefits of HVAC modernisation lies in energy efficiency improvements, which directly translate into lower carbon emissions. VRF/VRV systems reduce energy consumption by 30–40% compared to traditional HVAC configurations by dynamically adjusting refrigerant flow in response to real-time demand. These reductions are particularly meaningful in environments with fluctuating occupancy – such as boarding zones, lounges, and check-in areas – where conventional systems tend to over-condition occupied space.

Across several European airports, low-cost actions – including resetting heating controls and replacing faulty sensors – have achieved energy savings of €70,000 per year and avoided 3,500 tonnes of CO_2 emissions annually. Similarly, JFK Terminal 4 identified over $1.57 million in energy savings through HVAC audits and controls optimisation, with a majority of gains attributed to more efficient thermal management. [88] In the UK, Bristol Airport demonstrates how intelligent HVAC management can drive steady decarbonisation. By integrating advanced BMS technologies – featuring remote access and seamless system integration – the airport achieved granular control over HVAC energy use. These efforts have led to a consistent annual reduction of 4.1% in carbon emissions per passenger, reflecting the long-term benefits of digital control infrastructure when paired with efficient HVAC systems. [88]

Another key benefit of HVAC modernisation is the reduction of refrigerant-related emissions. Modern systems phase out outdated refrigerants like R-22, which have high ozone-depletion potential and GWP, in favour of lower-impact alternatives such as R-410A or R-32. This transition supports compliance with the Kigali Amendment and national refrigerant regulations while mitigating long-term climate risks associated with refrigerant leakage. By enabling full electrification of heating and cooling, HVAC modernisation further positions airports to capitalise on renewable energy sources – including on-site solar and utility-scale clean power. This allows for a deeper decoupling from fossil fuels, enabling airports to align with national decarbonisation pathways while future-proofing infrastructure against upcoming carbon pricing and fuel bans.

12.2 Case Study: Tokyo Haneda International Airport

Challenge : Tokyo Haneda Airport's new international terminal was required to maintain high levels of passenger comfort across large open spaces (with ceilings up to 20 metres) and heavy-traffic areas, while limiting energy waste, reducing greenhouse gas emissions, and complying with stringent sustainability standards.

Solution: The terminal's HVAC modernisation featured several key innovations:

- Zoned air-conditioning targeting only occupied areas, combined with an underfloor air distribution system for efficient delivery.
- Geothermal pre-conditioning pits to temper fresh air before mechanical cooling or heating.
- High-efficiency chillers, including three 1,000-RT centrifugal units with inverter technology, achieving COP up to 16.5 at part load.
- Building envelope upgrades, including double glazing and Low-E glass.
- Hybrid wood-steel construction in the north satellite terminal.
- Advanced controls and AI-driven load management.
- Integration of renewables and energy storage, including NaS batteries, solar PV, and cogeneration systems.

Quantifiable Outcomes

- Substantial reduction in HVAC energy load via geothermal pre-conditioning and zoned conditioning strategies.
- Three inverter-driven chillers achieved a COP of up to 16.5 at part load.
- Hybrid construction reduced CO_2 emissions by approximately 2,630 tonnes and improved building resilience.
- Ongoing integration of renewables and large-scale energy storage systems supports grid independence and further emissions cuts. [89], [90], [91], [92]

Key Lesson and Implication for Indian Airports: Tokyo Haneda Airport case study demonstrates that comprehensive HVAC modernisation – combining zonal controls, geothermal integration, envelope upgrades, smart controls, and renewables – can deliver dramatic improvements in energy efficiency and emissions reduction while enhancing system resilience.

12.3 Conclusion and Way Forward

Initial cost of VRF/VRV systems is higher than that of conventional HVAC systems, primarily due to advanced technology, refrigerant piping complexity, and specialised installation requirements. Outdoor units for VRF systems typically range from $3,000 to $10,000 per unit, depending on capacity and configuration, while indoor units cost between $1,000 and $4,000 each. Refrigerant piping and accessory installation can add significantly to the total project budget, with costs averaging around $2.00 to $2.27 per square foot in large projects, and labour requirements ranging from 200 to 490 hours, depending on the system size and complexity. [93] However, despite the higher initial capital expenditure, VRF/VRV systems offer substantial operational savings. Energy consumption reductions of 20–40% compared to traditional systems translate into lower electricity bills, often resulting in payback periods of approximately 5-10 years.

In terms of challenges, the most immediate barrier in HVAC modernisation remains the higher upfront cost compared to conventional HVAC systems, which can constrain budget-conscious airport projects. However, the long-term energy savings and lower maintenance requirements often justify this investment. Design and installation complexity pose additional hurdles for retrofitting. The extensive refrigerant piping required for VRF systems increases the potential for leaks, necessitating strict adherence to safety standards such as ASHRAE Standard 15-2011, which limits refrigerant charge per occupied space (e.g., ≤ 30 pounds per 100 square feet). Leak detection within concealed ductwork or ceiling voids can be difficult, but it is critical to maintaining safety and system integrity. Further, integration with legacy building automation and control systems can also be complicated by proprietary VRF controls that require manufacturer-specific gateways, limiting operational flexibility and increasing integration costs. Additionally, fire codes may require fire-rated insulation for refrigerant piping routed through plenums or evacuation corridors, adding to installation complexity and capital costs.

Potential Mitigation Strategies

- Phased Deployment and Innovative Financing: Adopt modular, zone-wise implementation of HVAC upgrades to spread capital expenditure across multiple budget cycles. Leverage green bonds, concessional loans, or energy performance contracting to offset high upfront costs.
- Capacity Building & Technology Transfer: Invest in upskilling facility management teams and establish long-term partnerships with OEMs to ensure proper design, installation and maintenance.
- Policy Advocacy & Compliance: Collaborate with regulators and industry bodies to standardise safety guidelines, promote incentives for electrification, and fast-track the adoption of climate-friendly refrigerants.
- Grid-Responsive Design: Integrate HVAC modernisation with on-site renewables (e.g., solar PV), battery storage, or microgrid solutions to enhance resilience and smooth peak demand impacts on the local grid.
- Data-Driven Operations: Deploy advanced BMS, comprehensive metering, and digital twins to enable predictive maintenance, early fault detection, and continuous efficiency optimisation.

In conclusion, HVAC modernisation through VRF/VRV systems, heat pumps, geothermal integration, and advanced control technologies represents a transformational opportunity for airports to significantly reduce their energy consumption, operational costs, and carbon footprint. These technologies provide unmatched flexibility, allowing precise temperature control across diverse zones, improved part-load efficiency, and integration with renewable energy sources. Global case studies from leading global airports – such as Schiphol, JFK, and Haneda – demonstrate that these investments deliver measurable CO_2 reductions, lower lifecycle costs, enhanced passenger comfort and improved system resilience. As airports continue to expand and modernise, adopting such future-ready HVAC solutions is not just a sustainability imperative but a strategic investment in operational excellence and climate action. The assessment summary of HVAC modernisation is discussed in Table 19.

Table 19: Assessment of HVAC modernisation – Key deployment metrics

Metric	Assessment
Technology Category	Advanced HVAC Modernisation: VRF/VRV systems, inverter-driven heat pumps, geothermal integrations (e.g., ATES), and digitally integrated building controls providing zonal, load-responsive temperature management.
Capital Expenditure	Higher upfront costs, driven by high-efficiency equipment, piping and integration complexity; system installation, such as floor outlet air-conditioning, double glazing, and geothermal pits, increases capex compared to conventional HVAC.
Typical Payback Period	Typically 6-7 years, depending on system size, efficiency gains, utility tariffs, and scope of modernisation; operational savings (energy, maintenance) are central to recovery of investment, with longer payback for deep envelope/airside upgrades (such as full terminal floor-outlet and double-glazing installations).
Impact on OpEx	High positive impact; reduced electricity consumption through advanced air-conditioning and LED retrofits; focused cooling or heating in populated zones (via floor outlet systems) reduces unnecessary conditioning of high ceilings, cutting energy waste; improved insulation and automation further reduce ongoing expenditure.
Primary Financial Return	Direct energy cost savings from reduced HVAC demand (by cooling/conditioning only occupied areas and using high-efficiency equipment); lower maintenance from modular, smart-controlled systems.
Non-Financial Returns	Improved passenger comfort and indoor environment (zonal control, reduced noise, stabilised temperatures)
Financing Models	Direct capital funding, energy savings performance contracts (ESCOs), green bonds, concessional financing, and grants; phased project implementation allows incremental investment. Utility incentives for electrification and refrigerant upgrades may be leveraged.
Key Dependencies	• Detailed load and occupancy assessment for optimal zoning and system sizing. • Skilled design and commissioning teams with VRF and geothermal expertise. • Phased installation planning to prevent service disruption in active terminals. • Integration capability with existing BMS and legacy systems, considering proprietary VRF controls.

In conclusion, HVAC modernization using VRF/VRV systems, heat pumps, geothermal integration, and advanced control technologies represents a transformative opportunity for airports to significantly reduce their energy consumption, operational costs, and carbon footprint. These systems provide unmatched flexibility, allowing precise temperature control across diverse zones, improved part-load efficiency, and integration with renewable energy sources. Case studies from leading global airports—such as Schiphol, JFK, and Haneda—demonstrate not only substantial reductions in CO_2 emissions and energy bills but also enhanced passenger comfort and system resilience. As airports continue to expand and modernize, adopting such future-ready HVAC solutions is not just a sustainability imperative but a strategic investment in operational excellence and climate action.

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