



Adaptation and Mitigation Measures for Climate Change in Airport Sustainability

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Abstract

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<p>This thesis considers the crossroads of climate change and sustainability in aviation, focusing on implementing comprehensive strategies of adaptation and mitigation to address the escalating environmental concerns within the aviation sector. With the deteriorating impacts of climate change on airport infrastructure and operations, the necessity for immediate and proactive sustainability measures is apparent. This work employs a mixed-methods research approach, integrating in-depth literature analysis with empirical case studies to explore a broad spectrum of techniques for enhancing airport resilience and sustainability.</p> <p>The thesis identifies critical mitigation strategies, such as the adoption of solar energy solutions and the integration of green building standards in terminal design, alongside the shift toward electrically powered ground support equipment. It also details various adaptation options, including strengthening coastal defenses against rising sea levels and improving drainage systems to handle increased rainfall. These initiatives are vital not only for diminishing the environmental footprints of airports but also for augmenting their resilience to climate perturbations.</p> <p>Moreover, the thesis underscores the significance of policy and regulatory frameworks in bolstering airport sustainability efforts. It advocates for the establishment of consistent policies that foster green innovation, incentivize investment in sustainable technologies, and facilitate multi-stakeholder collaboration. Emphasizing the importance of engaging local communities and stakeholders in sustainability discussions, the thesis argues for inclusive and effective strategy formulation and execution.</p> <p>In conclusion, the research demonstrates that, despite the significant challenges posed by climate change to airport sustainability, thoughtful and cohesive adaptation and mitigation measures can enable airports to counter these threats. The findings offer vital insights for airport executives, policymakers, and the broader aviation industry, charting a course toward a more sustainable and resilient aviation future.</p>
Key words Airport Sustainability, Climate Change Adaptation, Climate Change Mitigation, Renewable Energy, Infrastructure Resilience, Environmental Policy

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1 Introduction

Background on Climate Change and Its Impact on the Aviation Sector

Climate change manifests through rising global temperatures, severe weather events, and escalating sea levels, presenting significant challenges across industries, notably aviation. As a substantial greenhouse gas emitter, aviation faces heightened risks. For instance, the aviation sector in Europe has recently contended with increased extreme weather events—devastating floods in Belgium and Germany, rampant wildfires, and unprecedented heatwaves causing infrastructure damage and operational disruptions. (Rachel Burbidge 2023). In 2022, extreme heat led to runway deformities, while violent storms triggered widespread flight irregularities and infrastructural damage, exemplifying the sector's vulnerabilities. The United Nations Intergovernmental Panel on Climate Change anticipates the intensification of such events, urging aviation to adopt resilient and adaptive strategies. The anticipated 40% flight increase by 2050, as projected by EUROCONTROL(2024), accentuates the urgency for preparedness against escalating climate-induced disturbances that threaten operational efficiency, safety, and infrastructure.

The Interlinked Dynamics of Aviation and Climate Change

The aviation sector's contribution to climate change is a critical concern, given its feedback loop dynamics: aviation emissions aggravate climatic conditions that, in turn, intensify the sector's vulnerability. This cyclical relationship necessitates robust resilience and adaptation measures within aviation to mitigate worsening feedback impacts.

The Imperative of Sustainable Airport Operations

Sustainable airport operations are pivotal, mitigating environmental impacts while enhancing resilience to climate-induced variations. Citing Greer, Rakas, and Horvath (2020), sustainable practices—renewable energy adoption, energy efficiency improvements, and sustainable resource management—are vital for reducing airports' carbon footprints and ensuring operational continuity during adverse events. Airports, as crucial nodes in the global transport network, are instrumental in the aviation sector's broader climate response, setting benchmarks for sustainability, shaping regulatory expectations, and influencing community and industry standards.

Thesis Aims and Research Scope

This thesis explores adaptation and mitigation strategies within airport sustainability frameworks, addressing climate change challenges. It aims to:

1. Chart the prevailing impacts of climate change on aviation, focusing on airport operations.
2. Analyze viable adaptation strategies for enhancing airport resilience to climate phenomena.
3. Investigate mitigation approaches for airports to lower carbon emissions and contribute to global mitigation endeavors.
4. Assess the integration of adaptation and mitigation within airport sustainability planning.
5. Offer cogent recommendations for airports to elevate their sustainability practices in light of climate adaptation and mitigation.

Employing a detailed examination of peer-reviewed literature and case study analyses, this study endeavors to elucidate the multifaceted challenges and opportunities for advancing airport sustainability against the backdrop of climate change, spanning dimensions of infrastructure, energy, water, waste, and stakeholder collaboration.

In closing, this thesis anticipates delivering insightful, actionable strategies fostering robust, sustainable airport operations amidst climatic uncertainties, contributing valuable perspectives to the academic discourse and practical frameworks within the aviation sustainability domain.

Literature Review

Climate Change and the Aviation Sector

The relationship between aviation and climate change is intricate and layered. The aviation sector stands as a significant contributor to carbon emissions, representing a considerable share of global CO₂ emissions. Concurrently, it is profoundly affected by the ramifications of climate change, notably through operational interruptions triggered by adverse weather conditions (Greer et al., 2020). This dichotomy underscores the need for a nuanced approach that addresses both the industry's role in climate change and its susceptibilities to its impacts.

Adaptation Measures for Airport Sustainability

Effective adaptation measures are crucial for boosting airport resilience to the impacts of climate change. Berry et al. (2015) underscore the significance of considering cross-sectoral consequences, noting how adaptation efforts at airports reverberate across local biodiversity, water resources, and communities. The essentiality of fortifying infrastructure is emphasized, with recommendations for elevating and reinforcing airport facilities to counter sea-level rise and severe weather threats, as discussed by Zhao et al. (2018). Moreover, Greer, Rakas, & Horvath (2020) delve into strategic planning for enhancing airport infrastructure resilience, advocating for a holistic strategy.

In particular, Madeira Airport's deployment of engineering measures to curb flooding showcases inventive resilience tactics, providing a valuable model for airports encountering analogous issues. Logan (2021) further investigates the use of cool pavements at airports, elucidating their role in diminishing heat-associated repercussions and bolstering airport sustainability.

Mitigation Measures for Airport Sustainability

Mitigation measures play a pivotal role in lessening the environmental impact of airport operations, particularly focusing on reducing greenhouse gas emissions through a concerted strategy that emphasizes renewable energy, energy efficiency, and sustainable transportation. Greer, Rakas, and Horvath (2020) note that utilizing renewable sources like solar and wind power significantly curtails airports' carbon footprints by substituting traditional energy sources with cleaner alternatives. Moreover, enhancing energy efficiency within airport infrastructure, such as adopting energy-efficient lighting and HVAC systems, is vital as it profoundly affects operational energy consumption and associated emissions. These initiatives not only advance environmental sustainability but also yield economic advantages by lowering energy expenditures.

Choufani (2016) highlights Hong Kong International Airport's energy conservation success through LED lighting upgrades and chiller system enhancements, illustrating the potential for substantial energy and cost savings. Furthermore, transitioning to electric ground support equipment signifies a broader industry movement toward curbing direct emissions from airport activities, in alignment with overarching goals to minimize the aviation sector's environmental footprint.

Beyond energy-centric tactics, the integration of water management and conservation practices is gaining recognition for its contribution to airport sustainability. Efficient water use strategies, including rainwater harvesting and wastewater recycling as examined by Jaiyeola (2017) and Krop et al. (2016), empower airports to reduce dependency on municipal water sources and address the environmental ramifications associated with water utilization and wastewater processing.

Integration of Adaptation and Mitigation Strategies

The integration of adaptation and mitigation strategies presents a strategic avenue to boost airport resilience and sustainability. Watkiss, Benzie, and Klein (2015) highlight the synergistic potential of these approaches, suggesting that their combined implementation can optimize advantages while reducing negative consequences. In the context of airports, this strategy involves crafting infrastructure that not only withstands climate-related challenges but also curtails carbon emissions. This dual-benefit approach is epitomized in the design of buildings that are both energy-efficient and resistant to flooding, demonstrating how infrastructure can simultaneously address resilience and emission reduction. Such holistic planning underscores the imperative of a comprehensive perspective in developing airport facilities that are sustainable in the face of evolving climate conditions.

Zhao et al. (2018) emphasize the critical need for airports to align their adaptation and mitigation strategies effectively to combat climate change. By integrating these efforts, airports can enhance their operational resilience and robustness, ensuring that initiatives to reduce emissions also improve their adaptability to climate change. This integrated approach fosters more sustainable and efficient airport operations, reflecting a forward-thinking commitment to environmental stewardship.

The concept of integration here is defined as a strategic coordination where the different facets of airport sustainability—adaptation and mitigation—are woven together, not treated in isolation. For instance, Ayers and Huq (2009) highlight the benefits of waste-to-compost initiatives that not only curb methane emissions but also bolster soil quality nearby, addressing both mitigation and adaptation goals. Similarly, Berry et al. (2015) suggest that creating green spaces at airports can concurrently support biodiversity (an adaptation benefit) and aid in carbon sequestration (a

mitigation benefit), exemplifying the potential to harness cross-sectoral synergies for broader environmental impact.

Policy and Regulatory Frameworks

Policies and regulations play a crucial role in guiding the sustainability efforts of airports, providing the necessary standards and motivations for the adoption of eco-friendly practices. Iglesias and Garrote (2015) highlight the significance of policy backing in the context of sustainable water management, underlining that such principles are vital throughout various facets of airport operations. In a similar vein, Zhao et al. (2018) stress the need for integrated strategies that blend adaptation and mitigation efforts, advocating for policy structures that support these approaches to bolster airport resilience and sustainability. This underscores the essential role that well-designed policies and regulations play in not only encouraging but also structuring the sustainable evolution of airport infrastructure and operations.

Worldwide, aviation regulatory bodies like the FAA (2021) and the UK's Civil Aviation Authority are establishing and promoting standards and initiatives that advocate for the use of renewable energy, aim at reducing emissions, and foster environmental stewardship within the aviation sector. A case in point is Edmonton International Airport, which is pioneering solar energy initiatives, exemplifying adherence to and proactive engagement with these regulatory mandates. Such actions by airports not only demonstrate compliance with current regulations but also indicate a broader commitment within the aviation industry to align operational practices with environmental sustainability objectives, responding constructively to the global call for greener aviation solutions. (UK Civil Aviation Authority 2019)

Indeed, policy and regulatory frameworks act as critical catalysts for embedding sustainable practices within airport operations. They highlight the indispensable need for collaborative efforts between government entities and the aviation industry to realize substantial environmental advancements. Such frameworks not only set the benchmarks and guidelines for sustainable actions but also encourage innovation and accountability across the sector, emphasizing that collective efforts are essential for driving meaningful environmental improvements within aviation. This synergy between policy mandates and industry practices is fundamental in steering the sector towards more sustainable and environmentally responsible operations.

Stakeholder Engagement and Collaboration

Stakeholder engagement plays a pivotal role in the realm of airport sustainability, serving as a linchpin that brings together varied perspectives to shape effective and holistic sustainability strategies. Uysal & Sogut (2017) underscore the significance of involving an array of

stakeholders—ranging from airport operators and airlines to passengers, local communities, and regulatory bodies. Such inclusive engagement is instrumental in fostering innovation and ensuring that sustainability initiatives are well-aligned with the wider spectrum of expectations and necessities.

A testament to the power of collaborative engagement is seen in the sustainability efforts of Seattle-Tacoma International Airport (SEA). The airport's adoption of renewable natural gas and shift towards electric ground support equipment are exemplary initiatives that illustrate how concerted efforts among stakeholders can culminate in significant environmental and operational enhancements. These initiatives not only demonstrate SEA's commitment to sustainability but also highlight the transformative potential of stakeholder collaboration in driving substantial progress.

Hence, stakeholder engagement and collaboration are essential pillars of effective airport sustainability programs. By integrating diverse insights and expertise, airports can devise and enact comprehensive strategies that adeptly tackle various environmental challenges, ensuring these strategies resonate with and meet the expectations of all stakeholders involved, thereby promoting a more sustainable and inclusive future for the aviation sector.

2 Methodology

This section delineates the structured approach employed to investigate adaptation and mitigation measures for climate change in the realm of airport sustainability. It outlines the research design and approach, explicates the data collection methods, and delineates the criteria for evaluating the effectiveness of these measures, ensuring a comprehensive examination of strategies to enhance airport sustainability amidst climatic challenges.

A. Research Design and Approach

Research Strategy: The study adopts a mixed-methods approach to capture both the quantitative impact of specific measures and the qualitative insights from their implementation. This strategy enables a holistic understanding of the effectiveness of adaptation and mitigation efforts in airports.

Conceptual Framework: The research is underpinned by a conceptual framework that identifies key areas of airport operations affected by climate change (e.g., energy consumption, infrastructure resilience) and maps out potential adaptation and mitigation measures within these areas. This framework serves as the basis for investigating the interplay between climate change impacts and sustainability initiatives at airports.

Research Questions: The primary research questions are:

What adaptation measures are airports implementing to enhance resilience to climate change?

What mitigation strategies are airports adopting to reduce their environmental footprint?

How effective are these measures in promoting airport sustainability?

B. Data Collection Methods

Literature Review: A systematic literature review will be conducted to identify existing adaptation and mitigation measures within the aviation sector, focusing on peer-reviewed journals, industry reports, and policy documents. The review will also help identify benchmarks and best practices in airport sustainability.

Case Studies: Multiple airport case studies will be selected based on their geographic diversity, size, and commitment to sustainability. For each case study, data will be collected on implemented adaptation and mitigation measures, including any available performance data.

Quantitative Data: Quantitative data on emissions, energy use, and other sustainability indicators will be collected from airport reports and possibly direct data requests. This data will provide a basis for assessing the impact of various measures.

C. Criteria for Evaluating the Effectiveness of Adaptation and Mitigation Measures

Effectiveness Indicators: Key indicators for effectiveness will include reduced greenhouse gas emissions, energy efficiency improvements, increased use of renewable energy, enhanced infrastructure resilience, and cost-effectiveness of implemented measures.

Benchmarking: These indicators will be benchmarked against industry standards, best practices, and, where available, pre-implementation data to assess improvements and identify performance gaps.

Data Analysis: Statistical analyses will be applied to quantitative data to evaluate the effectiveness of adaptation and mitigation measures. Qualitative data from interviews and case studies will be analyzed using content analysis to extract themes and insights related to implementation processes and outcomes.

Validity and Reliability: To ensure the study's validity, data from different sources (quantitative data, case studies, interviews) will be cross-validated. Any assumptions made during the analysis will be clearly stated, and sensitivity analyses may be conducted where appropriate.

Limitations: Potential limitations, such as data availability, the comparability of measures across different airports, and the potential for unreported factors influencing the effectiveness of measures, will be acknowledged and discussed.

3 Adaptation Measures for Airport Sustainability

This section of the thesis examines various adaptation strategies employed by airports to enhance their resilience and sustainability amid climate change. Leveraging data analysis, authoritative research, and case studies, it delineates how these methodologies counteract the impacts of climate change on airport operations and infrastructure. By integrating data and conclusions from recent studies, the discussion underscores the critical nature of these interventions. Through case study examinations, this analysis not only consolidates current understanding but also pinpoints research lacunae, proposing directions for future inquiry that illuminate the complex interplay between climate change and airport sustainability.

3.1 Infrastructure Resilience Planning

In anticipation of escalating climate threats, notably sea-level rise and extreme weather events, airports globally are proactively reinforcing their critical infrastructure. Strategic resilience planning in infrastructure development is pivotal for airport adaptation, mitigating severe weather and climatic alterations' ramifications. Among such strategies, Zhao et al. (2018) delineate a suite of adaptation initiatives including elevating vital structures, fortifying runways and terminals, and embedding climate risk assessments within strategic planning frameworks.

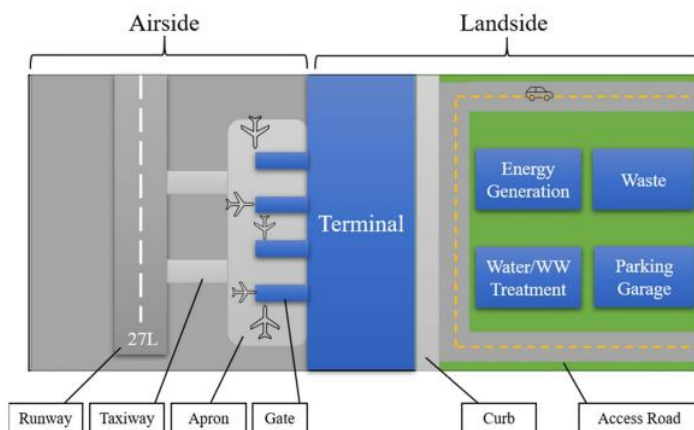


Figure.1. Plan view of airport system boundary. Key infrastructure features are identified. (Greer, Rakas, & Horvath, 2020)

1. Elevation of Infrastructure:

Runways and Taxiways: Highlighting specific cases, particularly those with low-lying coastal proximities, prioritize runway and taxiway elevation. Such measures, as observed by Kaklugin (2024), involve engineering enhancements like the addition of layered fill materials, capped with robust surfacing, to avert flood-induced impairments.

Terminals and Support Buildings: This section explores how architectural ingenuity and engineering advancements converge in elevating terminals and ancillary edifices, safeguarding them from storm surges and flooding. Instances include the integration of raised foundational platforms and protective flood barriers, ensuring uninterrupted operational continuity during adverse weather events (Mlit.go.jp, 2011).

Mitigating Flood Risks at Airports: Comprehensive Strategies and Case Studies

The strategic significance of flood risk mitigation extends beyond preserving airport operations; it is integral to maintaining global connectivity, regional economic stability, and effective disaster response mechanisms. Effective flood mitigation strategies protect not only the physical assets but also ensure the continuity of critical services that airports provide.

Airports, as strategic infrastructural entities, must maintain operational integrity under severe climatic duress. This narrative delves into a gamut of flood risk mitigation tactics, substantiated by empirical research and practical deployments:

1. Whole Premises Fortification

Fortifying the entire airport premises is an overarching strategy that offers extensive protection and can transform the airport into a safe haven during flooding events. This approach ensures that all components, including runways, terminals, and support structures, are protected against flood risks.

Infrastructure Protection: Fortification encompasses various structural enhancements, such as elevating buildings, reinforcing levees, and installing advanced drainage systems. For instance, at Bangkok's Suvarnabhumi Airport, the construction of a 23.5-kilometer perimeter dike, combined with an extensive network of drainage canals, exemplifies how such infrastructure can mitigate the impact of flooding. Post-implementation assessments revealed a significant reduction in vulnerability to surrounding water levels, highlighting the strategy's effectiveness. (PRNewswire 2011)

Runways and Taxiways: Ensuring the resilience of runways and taxiways is critical for maintaining airport operations during floods. The fortification might include elevation, improved drainage, and the use of permeable materials. As demonstrated at New Orleans Lakefront Airport, raising runway elevations and enhancing surrounding drainage systems successfully mitigated historical flooding issues, offering a model for similar at-risk airports. (New Orleans Lakefront Airport 2021)



Figure.2. LAKEFRONT AIRPORT STORMWATER PLAN, (MICHAEL BAKER, 2021)

2. Specific Mitigation Techniques

Wet and Dry Proofing: These methods are applied primarily to buildings and critical infrastructure within the airport but are not suitable for runways. Wet proofing allows water to enter structures without causing significant damage, whereas dry proofing prevents water entry altogether.

Elevation: Raising the construction site is a common strategy to mitigate flood risks. Although runways are typically not elevated on pillars, Madeira Airport provides an exceptional case where the runway is supported by approximately 180 pillars, each 70 meters tall, to combat its challenging terrain and vulnerability to flooding (Mlit.go.jp, 2011).



Figure.3. Supporting pillars under the airport runway extension(Madeira Airport 2023b)

Protective Mounds and Floating Airports: Building protective mounds around airport perimeters is a straightforward yet effective strategy. Japan's experimentation with floating airports, such as the Mega-Float, illustrates an innovative approach to reduce costs and enhance flood resilience compared to traditional land reclamation methods (Mlit.go.jp, 2011).



Figure.4. 1000m Mega-Float floating airport model in Tokyo Bay(Mlit.go.jp, 2011)

3. Case Studies of Implemented Solutions

Temporary Barriers: Vermeer (2012) highlights the installation of a \$24 million temporary barrier system at Saint Paul's downtown airport as a scalable and effective flood mitigation measure. Capable of being deployed within 48 hours, this system has proven its worth during multiple flood events. In evaluating the \$24 million investment in a temporary barrier system at Saint Paul's downtown airport, it is imperative to scrutinize its cost-effectiveness and long-term sustainability. Although the system's rapid deployment capability and historical efficacy are notable, the

justification for such substantial expenditure on a temporary measure warrants careful consideration.



Figure.5. Temporary barrier at St. Paul’s Airport, USA (Nelson 2023).

The imperative for airports to evolve from reactive entities to proactive fortresses against the escalating threats of flooding. The strategic and operational insights derived from examining comprehensive premises fortification and specific mitigation techniques illuminate a pathway for airports worldwide to enhance their resilience and sustainability.

3.2 Heat Resilience:

In response to rising global temperatures, airports are proactively implementing measures to ensure operational integrity and protect infrastructure against the challenges posed by heat. These initiatives not only aim to maintain functionality and safety but also to enhance passenger experience and infrastructure longevity amid escalating temperatures.

Heat-Resistant Materials: Innovative material choices are paramount for infrastructure resilience. For instance, advanced heat-resistant materials used in runways and terminal constructions can significantly mitigate the effects of high temperatures. Airports are increasingly adopting highly reflective pavement coatings that decrease temperature absorption, thus preventing runway degradation and ensuring structural integrity. An illustrative example includes the use of such coatings at Phoenix Sky Harbor International Airport, where they have successfully reduced surface temperatures, demonstrating the material's efficacy in extreme heat conditions.(Landrum ,2023)

Green Spaces: The strategic incorporation of green spaces within airport areas serves dual functions: they mitigate temperature increases and enhance aesthetic appeal, contributing to

overall environmental quality and passenger well-being. A prime example is Hamad International Airport in Qatar(2019), which integrates indoor gardens and water features to create a cooler, more pleasant environment for travelers, thereby reducing reliance on energy-intensive air conditioning systems.



Figure.6. Indoor garden and water feature at Hamad International Airport in Doha(TheDesignAir – Doha’s Hamad International Airport expansion features indoor gardens and water features. A “growing” trend? 2019)

Cool Roofs and Green Roofs:

Adopting cool and green roofing technologies is another effective strategy to combat heat. Cool roofs reflect more sunlight and absorb less heat compared to standard roofing materials, significantly lowering indoor temperatures. Concurrently, green roofs, which are covered with vegetation, provide natural insulation, reducing heat transfer into the building and supporting biodiversity. They not only reduce the urban heat island effect but also promote energy savings by enhancing roof longevity and reducing cooling needs. An exemplar of green roofing can be found at Chicago's O'Hare International Airport, where green roof installations have demonstrated tangible benefits in terms of energy conservation and operational efficiency.

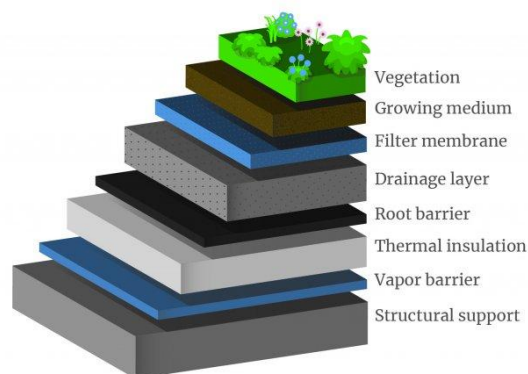


Figure.7.Common Green Roof Layers (US EPA 2014)

3.3 Community and Ecosystem-Based Approaches

The airports cannot work in isolation and are a part of an environment and communities among them. In this context, several airports develop their approaches based on community and ecosystems to further regional climate resilience. The strategies assist in the operations of the airport but contribute equally to the well-being of the community around and ecosystems within.

1. Collaboration with Local Communities:

Engagements: Active engagement with local communities fosters trust and ensures that airport operations are in harmony with local needs and aspirations. For example, San Francisco International Airport's community roundtables serve as a model where diverse stakeholders, including residents and local business owners, engage in meaningful dialogues, shaping airport policies and practices toward community-friendly outcomes. (SFO Airport/Community Roundtable, 2024)

Local Project Support: Airports can play a pivotal role in supporting local climate adaptation and resilience projects. An exemplar of this is Amsterdam Schiphol Airport's partnership with local authorities and NGOs to enhance urban green spaces and water management systems, benefiting both the airport and its surrounding area by reducing urban heat islands and improving stormwater management.

Shared benefits: Projects offering mutual advantages, such as joint airport-community green initiatives, not only address climate resilience but also enhance community welfare. A case in point is Boston Logan International Airport's collaboration with the local community to develop a harborwalk, providing public recreational space while also serving as a protective barrier against sea-level rise.

2. Biodiversity and Ecosystem Services:

Green Infrastructure: Incorporating green infrastructure like parks, green roofs, and vegetated swales not only embellishes airport aesthetics but also bolsters ecosystem services. Chicago O'Hare's eco-friendly initiatives, including a green roof and apiary, exemplify how airports can support local biodiversity while mitigating their environmental footprint.

Biodiversity Conservation: Airports are adopting comprehensive strategies to conserve local biodiversity. For instance, Auckland Airport's native vegetation conservation program demonstrates a commitment to preserving local flora and fauna, enhancing ecological connectivity, and fostering biodiversity within and around the airport perimeter.

Ecosystem-Based Adaptation: Utilizing natural ecosystems to mitigate climate impacts exemplifies forward-thinking adaptation strategies. The restoration of mangrove habitats adjacent to Cancun International Airport not only shields against coastal erosion and storm surges but also provides critical wildlife habitat, illustrating how airports can contribute to larger ecological resilience.

Monitoring and Stewardship: Ongoing monitoring and stewardship ensure the effectiveness and sustainability of implemented strategies. Engaging airport personnel and community volunteers in these programs fosters a shared sense of responsibility and stewardship. For example, Glasgow Airport's biodiversity monitoring initiative, involving local schools and conservation groups, encourages community involvement in tracking local wildlife, fostering a collaborative approach to environmental stewardship.

Through these community and ecosystem-based approaches, airports can position themselves as leaders in climate adaptation, showcasing how integrated, collaborative strategies can address the multifaceted challenges of climate change. Such initiatives not only protect airport operations but also enrich community well-being and environmental integrity, highlighting the airport's role as a proactive, responsible actor in the broader socio-ecological landscape.

3.4 Best Practices and Lessons Learned from Jewel Changi Airport Case Study

Jewel Changi Airport exemplifies the integration of sustainability and climate resilience within its operational blueprint, setting a global benchmark for airports. Its design and operational strategies embody advanced green principles and resilience against climate change, offering valuable insights for airports worldwide.

SWOT Analysis:

Strengths:

Innovative Infrastructure: Jewel Changi's infrastructure, including its advanced drainage system and climate-resilient runway design, exemplifies cutting-edge solutions to mitigate climate-related risks such as increased rainfall and sea-level rise. (Changi Airport 2023)

Comprehensive Risk Management: The airport's proactive approach to climate risk, addressing a range of factors from temperature fluctuations to wind speed changes, demonstrates a robust framework for climate resilience.

Weaknesses:

Operational Adaptability Limits: Despite its comprehensive strategies, Changi faces challenges in scaling its operational adaptability to meet unpredictable climate conditions, highlighting the need for ongoing adaptative strategy refinement.

Data Integration Gaps: Enhancing the integration of climate data into operational and strategic planning is identified as a critical area for further development, potentially enabling more informed decision-making processes.

Opportunities:

Technological Advancements: Emerging technologies present Changi with new pathways to bolster resilience and sustainability, such as through energy-efficient cooling systems or AI for weather predictions.(Keeping Changi cool with less energy 2023)

Collaborative Initiatives: Engaging in partnerships with global climate resilience entities can advance Changi's strategies and serve as a model for airport sustainability.

Threats:

Escalating Climate Risks: The accelerating pace of climate change poses continuous adaptation challenges.

Regulatory Dynamics: Evolving international climate policies may necessitate swift adaptations to meet new standards.



Figure.8. Different activities across Changi contribute to the carbon footprint of the whole airport(Keeping Changi cool with less energy 2023)



Figure.9. Changi Airport’ s runways are grooved to reduce the danger of aquaplaning and runway excursions during thunderstorms.(Building climate resilience to ensure smooth operations 2023)

Table.1. Changi Airport Group Sustainability and Operational Performance Targets
FY2022/23(Changi Airport 2023)

MATERIAL MATTER(S)	TARGETS	PERFORMANCE FY2022/23
Airport Experience & Passenger Satisfaction	Achieve good yearly performance for the Customer Satisfaction Index of Singapore (CSISG)	81.7 out of 100 in 2020
Airport Safety	Zero employee work-related fatalities, yearly	Achieved
	Deficiency-free rating from the International Federation of Air Line Pilots’ Associations (IFALPA), yearly	

Contribution to the Economic	Completion of Terminal 2 (T2) Expansion Project	On track
Development Of Singapore	Build capacity ahead of growth with Terminal 5 (T5) planning and development	Ongoing effort

3. Implementation Guidance:

Drawing from Jewel Changi's experience, airports looking to fortify their adaptation measures can adopt the following strategies:

Early and Integrated Planning: Establish a foundational planning process that incorporates long-term climate data and sustainability objectives, ensuring that infrastructural and operational designs are future-proofed.

Comprehensive Risk Assessments: Employ regular and thorough evaluations of climate-related risks to prioritize and tailor adaptation strategies effectively.

Adaptive Infrastructure Design: Invest in resilient infrastructure that anticipates future climate scenarios, ensuring continued functionality and safety.

Operational Flexibility: Foster an adaptive operational culture that can respond dynamically to changing climate conditions, integrating innovative technologies and processes where applicable.

Human-Centric Focus: Prioritize the health and safety of both employees and passengers by implementing comprehensive measures against climate-induced stressors, such as heatwaves or air quality degradation.

Collaboration and Partnership: Cultivate partnerships across sectors and with local communities to share knowledge, resources, and strategies, enriching the airport's adaptive capacity.

Continuous Monitoring and Evaluation: Establish robust monitoring and evaluation frameworks to assess the efficacy of adaptation strategies, facilitating iterative improvement and responsiveness to new insights.

Conclusion:

The case study of Jewel Changi Airport underlines the paramount importance of proactive climate adaptation strategies in maintaining airport resilience. By identifying and mitigating climate risks

through strategic planning and comprehensive risk assessments, airports can enhance their sustainability and operational robustness. Jewel Changi's commitment to innovative infrastructure, technological adaptation, and human-centric approaches serves as a model for airports globally, encouraging a holistic view of sustainability that includes ecosystem well-being and collaborative efforts. This case study offers a practical framework for airports seeking to navigate the challenges of climate change, contributing to broader climate action and sustainable development goals.

4 Mitigation Measures for Airport Sustainability

As airports strive to reduce their environmental footprint and contribute to global efforts to combat climate change, implementing effective mitigation measures is paramount. These strategies are designed to reduce greenhouse gas emissions, enhance energy efficiency, and promote sustainable resource use, all while supporting the airport's operational and economic goals.

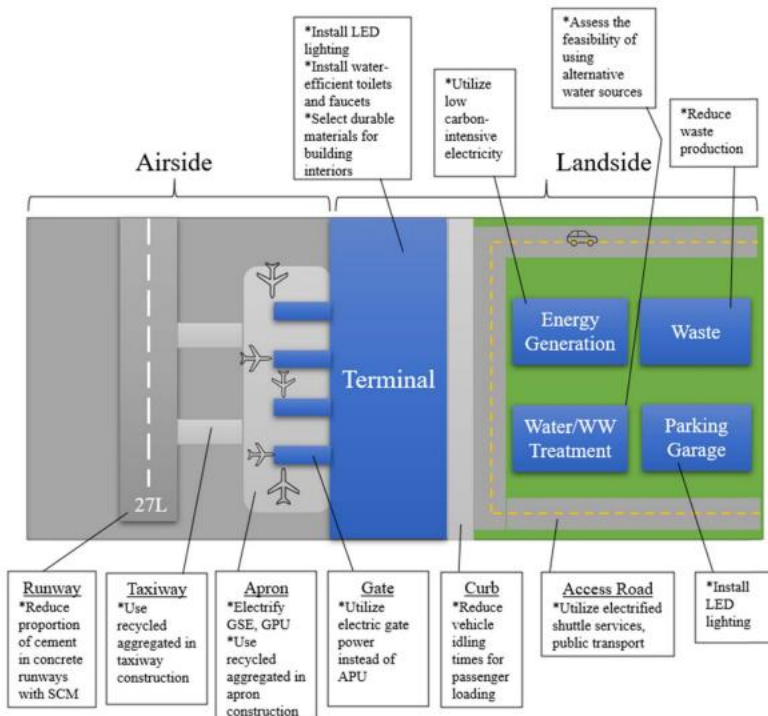


Figure.10. Suggested best practices for improving airport environmental sustainability(Greer, Rakas & Horvath 2020)

4.1 Energy Efficiency and Renewable Energy Adoption

Infrastructure Energy Efficiency in Airport: Energy efficiency in airport infrastructure has been ranked very important with regard to emission control by Greer, Rakas, and Horvath (2020). Most of the airports applied the use of modern energy management systems as an approach. Such systems effectively optimize energy use across varying operations in the airport and, therefore, contribute to cutting down on wastages while enhancing efficiency. Better insulation provides a way through which the aviation service sector can reduce energy demand for heating and cooling the associated CO₂. Also, the replacement of energy-efficient lighting and HVAC (Hejson) systems is considered key interventions, since the ability of the equipment to reduce operational energy consumption from the airport can be huge and, therefore, assist in saving money from energy costs as part of the airport's sustainability goals.

The largest share in energy consumption at an airport is formed by lighting, heating, ventilation, and air conditioning (HVAC). Introducing energy-efficient systems in lighting, heating, ventilation, and air conditioning (HVAC) and improving operations are anticipated to cut down the use of energy by over 60% and associated emissions. For instance, the implementation of LED lighting and smart building technologies has significantly increased energy efficiency in all airport facilities.

Renewable Energy Sources: As is outlined by Greer et al. (2020), adoption of renewable energy technologies to minimize environmental impacts, coupled with achieving energy independence, should be among the major sources of pride for the airport. The integration of solar energy systems, for instance, can leverage the vast expanses of land and rooftops at airports, providing a substantial area for solar panel installation. Such systems can generate clean electricity, reducing dependence on fossil fuel-based power sources. Wind energy also presents a viable option, especially for airports located in regions with favorable wind conditions. Geothermal energy, while less common, offers additional potential for airports situated in geothermally active zones. By harnessing these renewable resources, airports can significantly diminish their carbon emissions and move towards a more sustainable and resilient energy portfolio, aligning with broader environmental and sustainability objectives.

Table.2. Example energy conservation practices at airports as reported in Baxter et al (2018a, 2018c).

Airport	Copenhagen (CPH)	Kansai (KIX)
Energy conservation practices at airports	<ul style="list-style-type: none"> • Reliance on fixed electrical ground power for parked aircraft • Optimized energy consumption from airport's ventilation systems • Energy conservation measures related to tenant and concessionaire activities • Use of solar PV • Use of LEDs 	<ul style="list-style-type: none"> • Control air conditioning • Use of ceiling fans • Using electricity from renewable sources (solar PV, wind) • Installation of LEDs • Driving low-emission vehicles • Reliance on fixed electrical ground power for parked aircraft

	<ul style="list-style-type: none"> • Monitor energy consumption • Utilize sensor-controlled escalators • Use of groundwater for heating and cooling • Reduce voltage for site's equipment 	<ul style="list-style-type: none"> • Reducing vehicle idling times
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4.2 Electrification of Ground Support Equipment

Transition to Electric Vehicles: The electrification of ground support equipment is a critical initiative for airports to lower their greenhouse gas emissions and mitigate local air pollution. By transitioning to electric-powered baggage handlers, tugs, and service vehicles, airports can significantly reduce the combustion of fossil fuels on the airfield and in operational areas, directly cutting down emissions of CO₂ and other harmful pollutants. Electric vehicles (EVs) offer a cleaner alternative, contributing to improved air quality and reduced greenhouse gas emissions.

This transition not only aligns with global sustainability goals but also supports the aviation industry's broader ambitions to reduce its carbon footprint. Electric ground support equipment can also yield operational cost savings over time, attributable to the lower maintenance and energy costs associated with electric vehicles compared to their internal combustion counterparts.

Moreover, the adoption of electric ground support equipment can enhance the airport's environmental image and compliance with increasingly stringent environmental regulations. It demonstrates a tangible commitment to sustainability, which can bolster the airport's reputation among passengers, regulatory bodies, and the community. By investing in electric ground support equipment, airports take a significant step forward in their journey toward more sustainable and responsible operations, contributing to the broader transition towards a low-carbon future in aviation.

4.3 Case study: Energy Efficiency and Renewable Energy Adoption at Hong Kong International Airport

Background: Hong Kong International Airport (HKIA), situated in a region with a hot and humid climate, faces significant energy demands, particularly for air conditioning. The deployment of a water-chilled Variable Air Volume (VAV) system, which is optimized to address the specific needs

of high-ceiling areas, stands as a testament to HKIA's commitment to energy conservation and efficiency.(Choufani 2016)

Key Strategies and Implementations;

Infrastructure (Primary Activity):

LED Lighting Retrofit:The transition of 100,000 lights to LED technology at HKIA represents a substantial energy-saving initiative, reducing energy consumption by 18.2 million kWh annually. This project not only demonstrates the operational and financial benefits of energy-efficient lighting but also serves as a model for similar large-scale retrofits globally.

Chiller Systems Integration:By amalgamating two separate chiller systems into a single entity that now serves both terminals, HKIA enhanced its efficiency, accommodating fluctuating temperatures and loads, resulting in annual savings of 6.1 million kWh.

Technology Development (Support Activity):

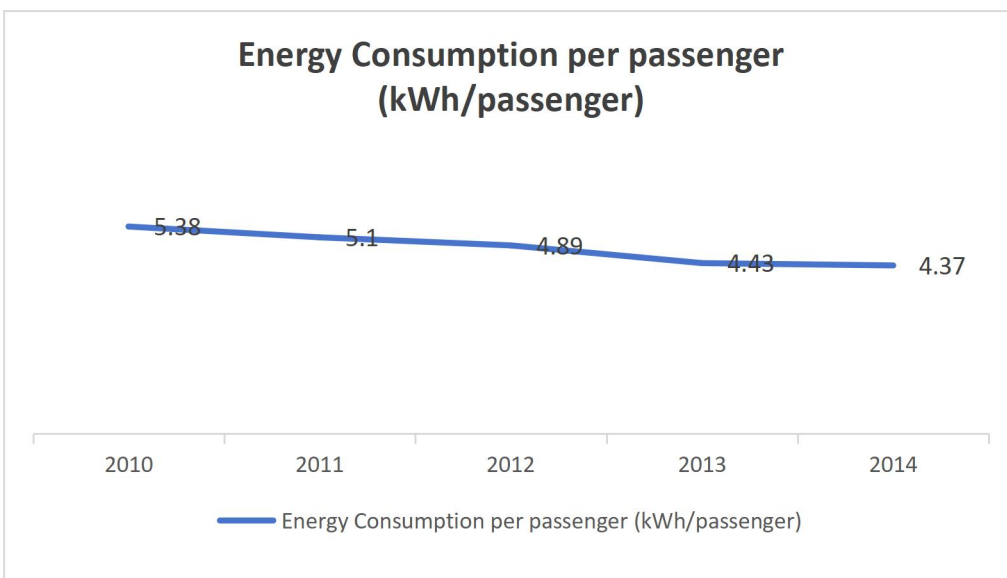
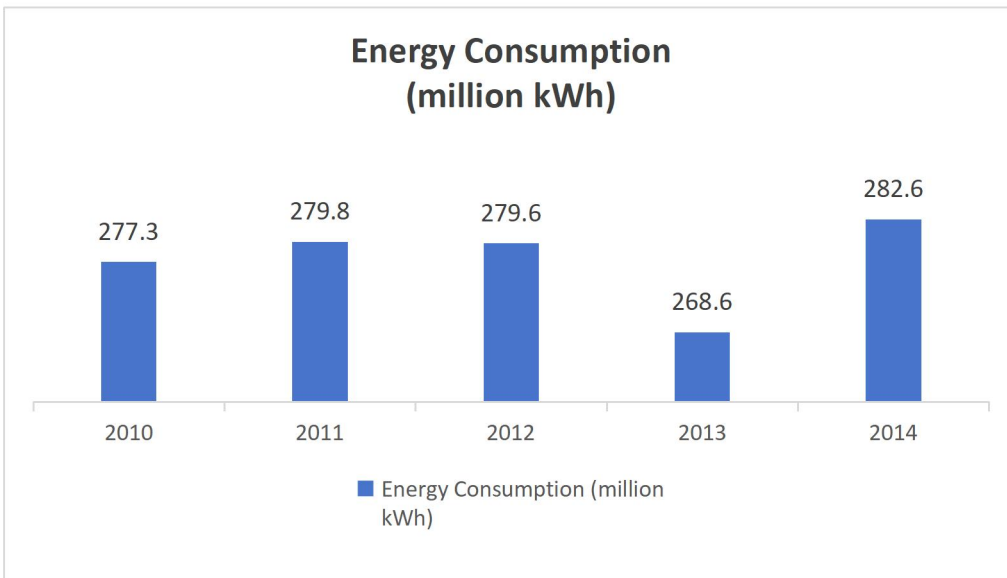
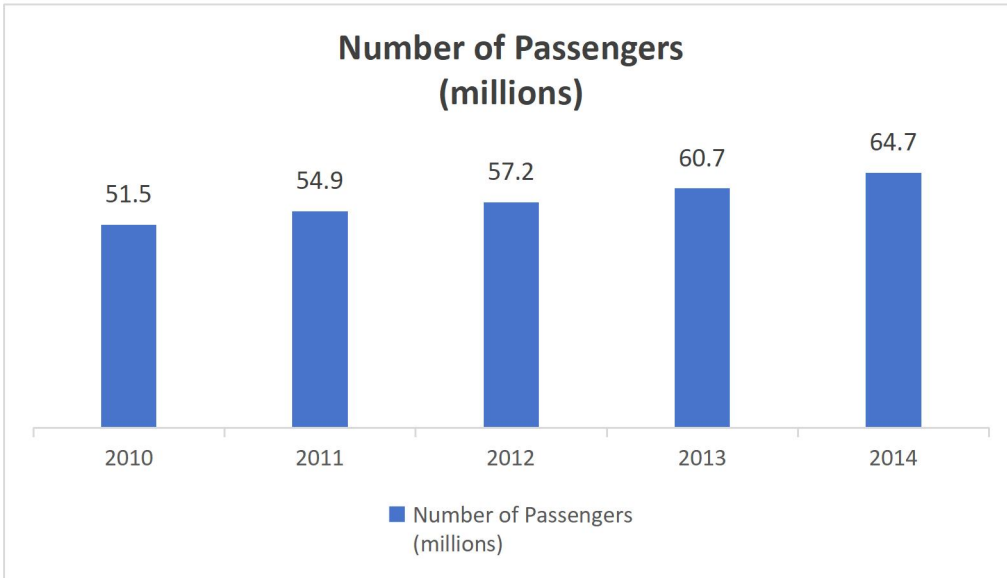
Sub-metering and Intelligent Systems:The implementation of sub-metering provided essential data that pinpointed opportunities for energy savings. The ongoing exploration of cloud-based energy management systems represents HKIA's forward-thinking approach to harnessing technology for sustainability.

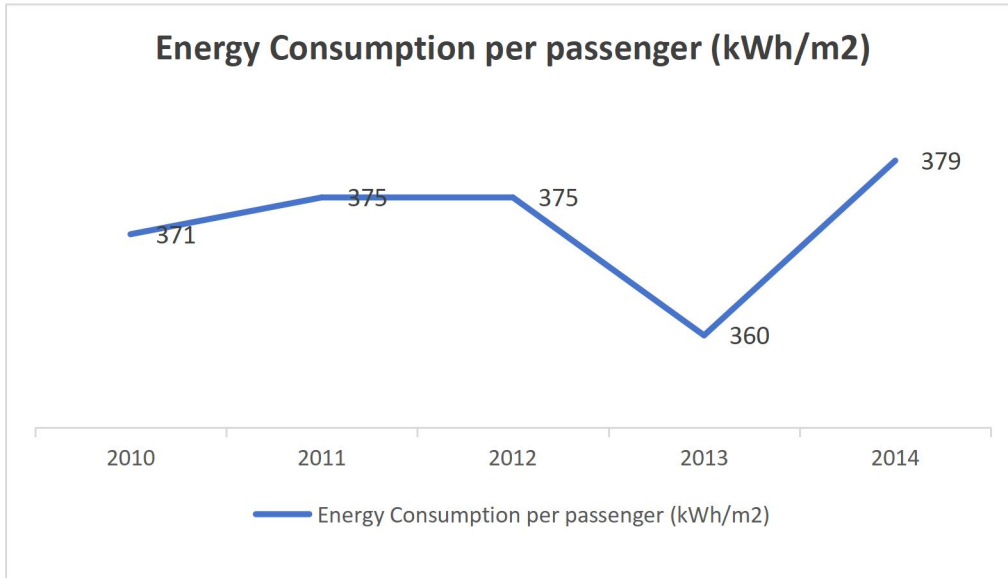
Procurement (Support Activity):

Auxiliary Power Units (APU):The prohibition of fixed ground power units in 2014 led to the integration of APUs, providing air and power to parked aircraft, which, while increasing the airport's own energy use, significantly lowered aircraft carbon emissions.

Benchmarking and Impact:

Table.3. Despite a 35% increase in passenger traffic over five years, HKIA witnessed only a marginal rise in energy consumption, achieving a substantial 25.4% reduction in energy use per passenger. This was attained without expanding the terminal's floor area, illustrating a nuanced improvement in energy efficiency even as services expanded.(Choufani 2016)





The above graphs are based on data received from the Hong Kong Airport engineering team and are for the terminal buildings only.

Key Learnings:

1. Strategic Investment and Cost Management via LED Lighting Retrofit:

The transition to LED lighting at HKIA facilitated a discernible reduction in energy consumption, quantified as an 18.2 million kWh yearly decrease. This transition is substantiated by empirical data, delineating the direct correlation between technological upgrade and energy efficiency.

The LED retrofit exemplifies a paradigmatic shift towards energy-conscious infrastructure, underpinning the premise that strategic investments in energy-efficient technologies not only engender operational savings but also expedite return on investment. HKIA's initiative underscores the imperative of integrating cost-effective technologies to mitigate energy expenditures while accentuating the intrinsic value of data-driven decision-making in operational enhancements.

2. Enhancement of Operational Efficiency through Chiller System Integration:

The effective result in the consolidation of these two dissimilar chiller systems into one, optimized system, showed a reduction of energy consumption of 6.1 million kWh annually.

Such an integration epitomizes the very essence of operational efficiencies, depicting that incisive analysis and strategic reengineering of the existing systems can bring abundant energy savings. The broad explanation is that with infrastructural agility, the recontextualization of the existing assets requires the two for a sustainable operational paradigm.

3. Leveraging Technological Innovation for Competitive Advantage:

HKIA is proactive in implementing a sophisticated, cloud-based system using sub-metering for stronger energy management; such a system demonstrates the interface of operational effectiveness and interfacing of technological innovation.

What delineates strategic foresight beyond the traditional operational framework is the HKIA engagement with state-of-the-art technologies to offer them a competitive edge in the market. This further explains the greater story, whereby it is important to have acceptance and adoption of the constant improvement in efficiency of energy and technological innovation to set up a foundation for adaptive resilience facing changed and still-changing technological landscapes.

4. Operationalizing Sustainability:

The strategic deployment of Auxiliary Power Units (APU) and other energy-efficient initiatives at HKIA signifies a conscientious integration of sustainability within operational protocols, notwithstanding the augmented energy usage attributed to APUs.

This integration reflects an operational ethos where sustainability is not peripheral but integral, advocating for a coherent strategy that synergizes immediate operational exigencies with long-term environmental stewardship. The narrative promulgated by HKIA accentuates the viability of embedding sustainable practices within the core operational framework, thereby manifesting a pragmatic confluence of operational efficiency and environmental accountability.

4.4 Water Management and Conservation

Efficient water use in airport operations is critical to reducing environmental impact and increasing sustainability. Water-saving technologies, therefore, call for the use of both technologies and techniques of conservation that would enable the airport to save water and hence minimize to a great extent the water footprint of the airport, which will also help save such an important resource. An example is inciting airports to minimize the use of water by looking for other sources of water and utilizing them in their facilities, which may include rainfall or treated wastewater (Carvalho et al., 2013). Rainwater collection is a significant possibility for airports to improve their water sustainability. In the collection of harvested rainwater, airports can use the water in various non-potable uses, including irrigation of landscapes, washing of vehicles, and flushing of toilets by intercepting and re-using the runoff from airport infrastructures, comprising buildings, pavements, and others. That is the approach that helps in the conservation of the precious potable water supplies and reduction of stormwater runoff to diminish the impact on the environment.

However, recycling of wastewater looks to be a very important strategy for improved water efficiency at airports. Wastewater can be reused at airports through advanced treatment techniques for underage use, for example, agriculture, landscaping, and flushing toilets. The decentralized approach to wastewater treatment is a system design within an urban setup that is meant to lessen the use of fresh water supplies while simultaneously limiting the discharge of untreated waste into the natural environment (Krop et al., 2016).

Airports that incorporate these water management and conservation measures implement an important operational feature that takes them one step further toward more sustainable operations, thereby lessening their environmental footprints and preparing for any future potential water scarcity. Most importantly, such efforts often result in long-term financial gains that would emanate from reduced water use and wastewater treatment costs, hence showing the twin benefits of environmental stewardship and economic prudence (Sattler, 2015). If accompanied by their operational framework, these new approaches may eventually allow for a balance between environmental responsibility and operational efficiency to preside and give way to the standard of aviation sustainability.

4.5 Case Study: Water Management and Conservation at Changi Airport

The Changi Airport Group (CAG) is going to intensify water management across its terminals to ensure that they become a water-resilient future, especially with increased passenger and public footfall. This case study elaborates on the water optimization strategy of Changi Airport Group with an aim to reduce consumption and bring efficiency to benchmark levels for sustainable airport operations.

CAG's Water Optimisation Strategy

The CAG has also infused an effective water optimization strategy that aims at reducing the use of both potable and non-potable water to a bare minimum while ensuring that all airport operations are executed most efficiently. This includes a set of strategies applied, ranging from those brought by infrastructure to the involvement of the community; the main point is to reduce the use of water in the airport and promote a culture of conservation in the airport ecosystem. .

Water-Saving Measures at Changi Airport

1. Potable Water:

Retrofitting Water Taps: At Changi Airport, over 170 manual taps in terminal airside washrooms have been retrofitted with contactless alternatives that reduce water flow from five liters per minute to just two, thus attaining substantial water savings.

Leakage Management: A very responsive system for leakage reporting and repair has been introduced, guaranteeing timely detection and rectification to minimize losses due to water leakages.

Community Engagement: CAG promotes active water conservation through public awareness campaigns, involving airport users and the broader airport community to foster a collective responsibility towards water stewardship. .

2. Others:

Innovative Cleaning Solutions: The adoption of purified pH12.5 ionized alkaline 'Z Water,' produced on-site using advanced Japanese technology, exemplifies Changi's innovative approach to reducing water usage in cleaning processes.

3. Non-Potable Water:

Cooling System Efficiency: By monitoring and maintaining cooling towers with high-efficiency designs and water treatment systems, Changi Airport optimizes water use in its cooling infrastructure. This includes the exploration of technologies to decrease building cooling loads, thereby reducing reliance on air-conditioning and associated water consumption.

Rainwater Harvesting: The implementation of rainwater harvesting systems for irrigation and the use of recycled condensate water in cooling towers illustrate Changi's commitment to utilizing alternative water sources. Notably, the Jewel's Rain Vortex, which uses harvested rainwater, stands out as an iconic feature demonstrating this commitment.

Chiller Plant Upgrades: Upgrades to Terminal 1's chiller plant are projected to save over 11,000 m³ of water annually, showcasing the tangible benefits of such initiatives.

Performance and Impact:

The ensuing data table exhibits a progressive decline in potable and overall water consumption at Changi, juxtaposed against an uptrend in passenger footfall, thus demonstrating the efficacy of its water conservation measures

Text.2. Water Consumption Metrics(FORGING A SUSTAINABLE CHANGI 2023)

Water Consumption	FY18/19	FY19/20	FY20/21	FY21/22
Potable water	1,050,000 m3	818,000 m3	448,000 m3	463,000 m3
NEWater	2,176,000 m3	2,454,000 m3	861,000 m3	783,000 m3
Total Consumption	3,226,000 m3	3,272,000 m3	1,309,000 m3	1,245,000 m3
Water Discharge	2,273,000 m3	2,064,000 m3	904 000 m3	815,000 m3

Changi Airport's water management and conservation efforts exemplify a comprehensive and proactive approach to sustainability. Through strategic investments in technology, infrastructure, and community engagement, CAG significantly enhances its water efficiency, setting a precedent for airports worldwide. These initiatives not only contribute to environmental sustainability but also demonstrate Changi's leadership in operational excellence and responsible resource management.

5 Integration of Adaptation and Mitigation Strategies

Literature Insight:

Watkiss, Benzie, and Klein (2015) provide valuable perspectives on how integrated solutions can be developed and implemented in airport operations.

It is asserted that airports need to implement integrated strategies that harmonize adaptation and mitigation measures to effectively address climate change challenges (Zhao et al., 2018).

Strengthening operational frameworks through exploiting synergies between these areas can enhance airport resilience. This strategy ensures that actions aimed at reducing greenhouse gas emissions (mitigation) simultaneously bolster the airport's adaptability and recovery capacity from climate-related disturbances (adaptation). Such an approach promotes more sustainable and efficient airport operations, demonstrating proactive environmental stewardship.

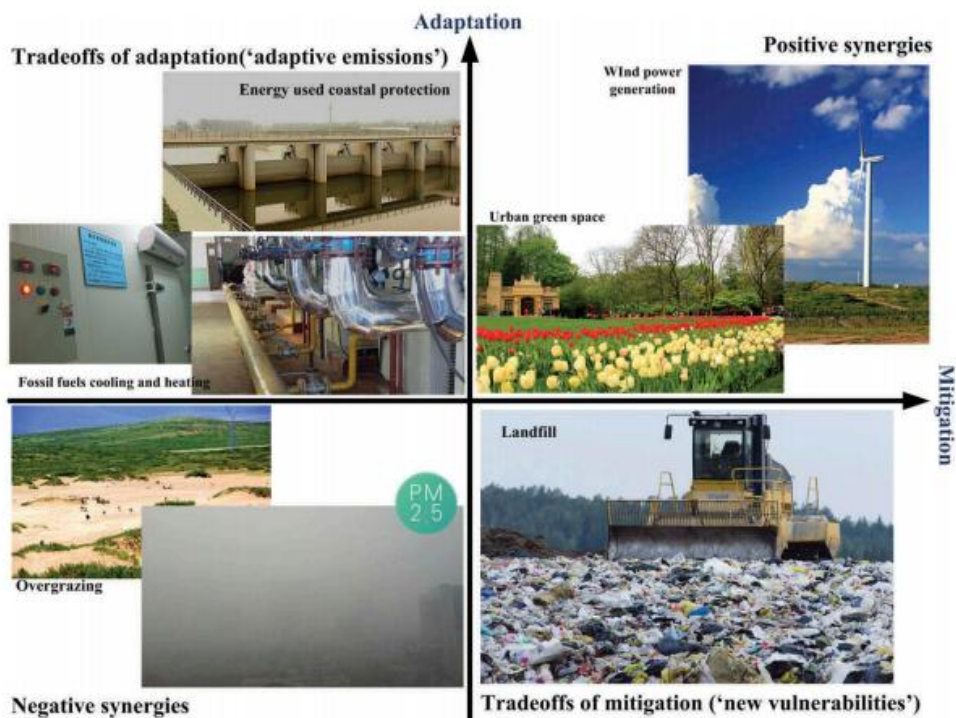


Figure.11. Significance and mechanism of synergies and trade-offs.(Zhao & al. 2018)

5.1 Defining Integration:

Integration in the context of airport sustainability engrosses a malleable approach where adaptation and mitigation measures are aptly developed and applied in a synergistic manner rather

than in isolation. This approach enhances the airport's resilience to climate change impacts and its contribution to sustainability.

Holistic Approach: Inspired by a case study in Bangladesh, airports can introduce waste-to-compost projects that serve triple purposes: reducing methane emissions (mitigation), improving soil in adjacent drought-prone areas (adaptation), and contributing to sustainable development (Ayers & Huq, 2009). Berry et al. (2015) emphasize leveraging cross-sectoral synergies, particularly in biodiversity and water management. For example, green space development can enhance biodiversity (adaptation) and act as a carbon sink (mitigation). Innovative water management practices like rainwater harvesting and wastewater recycling can boost water resilience (adaptation) and reduce energy consumption for water services (mitigation).

5.2 Synergies and Conflicts

A. Identifying and Leveraging Synergies:

Integration of Renewable Energy: Adopting renewable energy sources, like solar panels, at airports creates synergies between mitigation (reducing reliance on fossil fuels and decreasing greenhouse gas emissions) and adaptation (enhancing energy resilience). For instance, on-site solar generation can sustain critical operations during disruptions to the traditional power grid due to extreme weather, offering dual benefits in resilience and emission reduction.

Sustainable Water Management: Advanced water management systems can save water resources and lower energy consumption (mitigation) while ensuring sufficient water supply at airports during droughts (adaptation). Practices like rainwater harvesting and wastewater recycling align with both goals, decreasing reliance on municipal water systems and addressing water scarcity impacts.

Green Infrastructure: The development of green spaces and infrastructure at airports can provide cooling effects, reducing the urban heat island effect and energy costs for cooling (mitigation) and enhancing the airport's resilience to heatwaves (adaptation). Additionally, these green spaces can absorb stormwater, reducing flood risks and associated disruption.

B. Addressing Potential Conflicts

Land Use Considerations: While biofuel production might be considered a renewable strategy with potential mitigation benefits, dedicating large areas of land around airports for biofuel crops could conflict with local biodiversity and conservation efforts (adaptation). It's crucial to balance these considerations, perhaps by identifying land that provides low ecological value for biofuel cultivation or exploring alternative, less land-intensive renewable energy options.

Infrastructure Upgrades: Upgrading airport infrastructure for greater energy efficiency or resilience can have upfront carbon costs or environmental impacts. For instance, construction activities associated with retrofitting facilities can lead to temporary increases in emissions or disturbances to local ecosystems. Mitigation strategies should account for and minimize these initial impacts to ensure that long-term benefits are realized.

Operational Changes: Efforts to reduce emissions through operational changes, such as altering flight patterns to reduce fuel use, need to be carefully evaluated for their impact on airport adaptability and resilience. For example, while such changes can lower carbon footprints, they must not compromise the airport's ability to adapt to changing climate conditions, such as increased frequency of extreme weather events.

6 Policy and Regulatory Frameworks

6.1 Role of policy and regulation in supporting airport sustainability efforts

The pivotal role of policy and regulatory frameworks in guiding airport operations towards sustainability has been substantiated in numerous studies, which call for strategic, adaptive approaches to integrate sustainability into core airport operations. Notably, the integration of energy efficiency and renewable energy technologies, as advocated by Kaszewski and Sheate (2004), signifies a foundational step towards green transportation and architecture within airports. The empirical analysis of Greer, Rakas, and Horvath (2020) underscores the necessity for thorough environmental sustainability assessments, linking strategic energy management to tangible outcomes in renewable resource adoption.

A comparative analysis between the initiatives like the FAA's sustainability programs and the UK's CAA Environmental Sustainability Strategy reveals divergent impacts on local and national scales. For example, while FAA initiatives have led to a marked enhancement in sustainable aviation fuel (SAF) adoption across American airports, the UK's focus has catalyzed advancements in noise management and airspace modernization, as reflected in reduced noise pollution levels around Heathrow and Gatwick airports.

6.2 Establishing Sustainability Standards:

Globally, aviation authorities are instituting sustainability benchmarks, aiming to mitigate environmental impacts across pivotal areas: emissions, energy, water, and waste. The U.S. FAA, through its array of initiatives—ranging from SAF project funding to the EAGLE initiative—has catalyzed a notable shift towards sustainable practices. A detailed case study of the FAA's impact, analyzing emission reductions at pilot airports, would provide concrete evidence of these policies' efficacy.



Figure.12. Eliminate Aviation Gasoline Lead Emissions(FAA 2021)

Similarly, in the UK, the CAA's strategy not only emphasizes carbon footprint reduction but also pioneers Jet Zero technologies. By examining the operational shifts at UK airports post-strategy implementation, one can quantify the strategy's direct benefits, particularly in emissions and local environmental quality.(UK Civil Aviation Authority 2019)

Airports themselves are adopting innovative approaches to sustainability. For example, airports like Edmonton International and Melbourne Airport are investing in large-scale solar farms to generate clean energy, significantly reducing their reliance on non-renewable power sources.(casey s.a.)Furthermore, the Roundtable on Sustainable Biomaterials (RSB) offers guidance to airports on integrating SAF into their operations, which aligns with broader goals of reducing greenhouse gas emissions and promoting a sustainable bioeconomy(SAF Sustainability Guidance for Airports – RSB 2023) .

These initiatives collectively represent a global movement toward greener aviation, emphasizing collaborative efforts between governments, aviation authorities, and airport operators to meet ambitious sustainability targets and mitigate the environmental impact of airport operations and aviation at large.

6.3 Incentivizing Green Investments:

Financial incentives play a crucial role in catalyzing sustainable transitions at airports. By dissecting tax credit impacts, one can elucidate their significant role in diminishing the upfront costs of green technology adoption, as posited by Kaszewski and Sheate (2004). Through detailed financial analyses, the direct correlation between tax incentive structures and increased investments in renewable energy at airports like Edmonton International can be demonstrated, showcasing a model for broader application.

Furthermore, examining the leverage of grants and subsidies in facilitating infrastructure upgrades reveals a nuanced landscape of opportunity and challenge. For instance, the efficacy of grants in promoting advanced water recycling technologies at airports can be evaluated through specific project outcomes, detailing the enhancements in water conservation and management.

Through these mechanisms, policy frameworks can effectively encourage airports toward sustainability, promoting environmental conservation and climate change mitigation. These incentives not only facilitate the adoption of green technologies but also foster a culture of sustainability within the aviation sector.

7 Stakeholder Engagement and Collaboration

7.1 Importance of Engaging Stakeholders in Sustainability Initiatives

Stakeholder engagement is a crucial component of successful airport sustainability initiatives, providing a platform for the exchange of ideas, concerns, and expectations. Uysal & Sogut (2017) emphasize the significance of integrating various stakeholders in the energy management process within airports, suggesting that such collaboration can lead to more effective and widely supported sustainability outcomes. Engaging stakeholders—including airport authorities, airlines, passengers, local communities, environmental groups, and regulatory bodies—ensures a holistic approach to sustainability, incorporating diverse perspectives and expertise.

- **Inclusive Decision-Making:** Involving stakeholders in the decision-making process fosters a sense of ownership and commitment to sustainability goals. By considering the input and feedback from a broad range of stakeholders, airports can develop more comprehensive and feasible sustainability strategies.
- **Building Trust and Transparency:** Regular communication and collaboration with stakeholders build trust and transparency, essential elements for the successful implementation of sustainability initiatives. Open dialogue helps mitigate potential conflicts and aligns airport sustainability efforts with broader community and environmental objectives.
- **Leveraging Expertise and Resources:** Collaboration with stakeholders allows airports to leverage external expertise, resources, and networks, enhancing the effectiveness and scope of sustainability projects. For example, partnerships with energy companies can facilitate the adoption of renewable energy technologies, while collaboration with local governments and NGOs can support conservation and community engagement initiatives.

7.2 Case Examples of Effective Stakeholder Collaboration in Airport Sustainability Projects

Seattle-Tacoma International Airport (SEA) exemplifies the power of stakeholder collaboration in driving substantial sustainability achievements. By partnering with tenant airlines, service providers, and the local community, SEA has launched several pioneering initiatives, demonstrating a commitment to environmental stewardship and collaborative action within the aviation sector. (Climate and Air Quality 2021)

1. **Renewable Natural Gas (RNG) Adoption:** SEA's pioneering move to purchase thermal RNG, derived from landfill waste, for heating the terminal and powering its bus fleet marks a significant

stride towards reducing carbon emissions. This switch not only contributes to a substantial reduction in SEA's carbon footprint but also advances its emission reduction targets significantly ahead of schedule.

Objective: Transition to thermal RNG derived from landfill waste for heating and powering the bus fleet.

Impact: This transition is projected to cut SEA Airport's carbon emissions by 50% in 2024, achieving a target set for 2030 ahead of schedule.

Emission Reduction Equivalence: The use of RNG is expected to mitigate emissions comparable to heating 40,000 homes or removing 24,000 passenger vehicles from the roads.

SEA's initiatives to promote sustainable ground transportation options illustrate a forward-thinking approach to reducing emissions. However, the effectiveness of these measures hinges on user adoption and operational integration. The actual environmental impact may vary, necessitating a closer examination of user behavior and system efficiencies. Assessing the long-term effects of these transportation initiatives on emissions, local traffic patterns, and public adoption is essential. Such studies could identify gaps and opportunities for enhancing the effectiveness of sustainable transportation solutions in airport contexts.



Figure.13. Natural Gas (RNG) Adoption(Climate and Air Quality 2021)

2. Electric Ground Support Equipment (eGSE): By installing numerous eGSE charging stations, SEA has facilitated a transition from petroleum-fueled to electric-powered ground support equipment. This shift is poised to cut down nearly a million gallons of petroleum usage annually, save on fuel costs, and notably decrease greenhouse gas emissions.

Infrastructure: Installation of nearly 300 charging stations, aiming for 561 to cover every gate by 2021.

Savings: Anticipated reduction of nearly 1 million gallons of petroleum annually and about \$2.8 million in fuel costs.

Emission Reduction: Estimated decrease of 10,000 metric tons of greenhouse gases per year.

The installation of eGSE charging stations at SEA represents a commendable effort to reduce petroleum dependency. Nonetheless, the environmental benefits of eGSE are contingent on the electricity source. In regions where the power grid relies heavily on fossil fuels, the net reduction in carbon emissions may be less significant. It is crucial to investigate the integration of eGSE with renewable energy sources, ensuring that the electricity used is as green as the technology it powers. Comparative studies on the adoption barriers and success factors across airports can provide actionable insights for broader implementation.



Figure.14. Electric Ground Support Equipment(Climate and Air Quality 2021)

3. Greener Transportation Options: SEA's collaborations with ground transportation providers to introduce vehicles with higher MPG, alternative fuels, and ridesharing options reflect its commitment to offering sustainable transport solutions. These measures are aimed at reducing emissions from the broader transportation network associated with the airport.

Partnerships: Collaborations with providers to offer high MPG taxis, alternative fuel shuttles, and eco-friendly rideshare options.

Innovations: Inclusion of the state's first large CNG fueling station and mandates for high environmental standards in airport contracts for taxis and rideshares.

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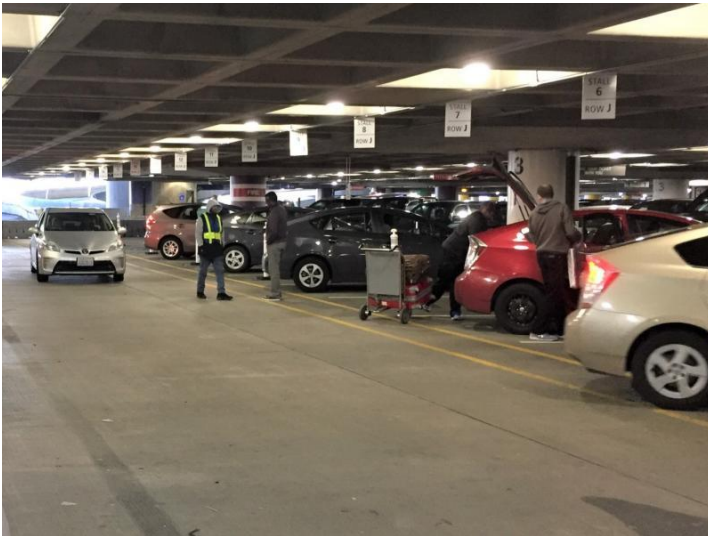


Figure.15. CNG fueling station(Climate and Air Quality 2021)

4. Pre-Conditioned Air and Ground Power: The installation of PC Air and ground power units at each gate underscores SEA's dedication to improving operational efficiency and reducing the environmental impact of aircraft while parked. This technology not only lowers fuel consumption and emissions but also cuts operational costs for airlines.

Function: Supply of cooled or heated air and electrical power to aircraft at gates, allowing for auxiliary engine shutoff.

Benefits: Reduction of 5 million gallons of fossil fuel usage and \$15 million in airline fuel expenditures annually.

Emission Reduction: Cut down of 73 tons of NO_x and 40,000 metric tons of greenhouse gases each year.

While the implementation of PC Air and ground power units at SEA aims to reduce aircraft idling emissions, the technological, operational, and financial barriers to adoption by other airports warrant consideration. The success of such systems at SEA may not directly translate to airports

with different sizes, resources, or infrastructure. Comparative research on the deployment of these technologies across various airport settings could elucidate factors that facilitate or hinder their widespread adoption. Understanding these dynamics is key to formulating strategies that ensure the broader applicability and effectiveness of such emissions-reducing technologies.



Figure.16. The installation of PC Air and ground power units(Climate and Air Quality 2021)

These initiatives highlight the airport's proactive approach to environmental stewardship, showcasing how collaborative efforts can yield substantial benefits in terms of sustainability, economic efficiency, and community well-being. SEA's strategies serve as exemplary practices for other airports and organizations aiming to enhance their environmental performance and operational efficiency.

8 Conclusion

This thesis reflects a deep dive into the critical sector of adaptation and mitigation in airport sustainability, particularly in the context of climate change. This research has not only academically researched the subject, but it has also provided actionable insights that airports may use to forge a sustainable future in a period of climatic uncertainty.

Initially, this analysis explored the multifaceted consequences of climate change for the aviation sector, identifying airports as crucial nodes requiring robust solutions to combat environmental adversity. With the increase in extreme weather phenomena, there is an urgent need for airports to preemptively armor their infrastructure and operational modes to ensure continuous functionality and passenger welfare.

The exploration into adaptation strategies unraveled a spectrum of approaches—from buttressing infrastructure against severe weather to innovating against the escalating threats of flooding and heat. Such proactive measures aren't just about resilience; they signify a forward-thinking ethos, preparing airports to navigate the turbulent skies of tomorrow.

On the flip side, the dialogue on mitigation measures cast a spotlight on the imperative of slashing airports' ecological footprints. Embracing energy-efficient practices, pivoting towards renewable energy, and championing resource stewardship not only align with the global environmental crusade but also make eminent business sense. These transitions promise a dual boon: mitigating ecological impact while potentially paring down operational expenditures.

Moreover, the discourse accentuated the linchpin role of policy frameworks and stakeholder synergy in elevating airport sustainability. The call for policies that incentivize green initiatives, coupled with collaborative stakeholder engagement, underscores a collective momentum towards reimagining airport operations within a sustainable framework.

This research synthesizes the dual avenues of adaptation and mitigation as integral, interwoven threads in the tapestry of airport sustainability. It advocates for a holistic, integrated strategy that marries resilience with environmental stewardship, positioning airports as vanguards of sustainable aviation in the climate-challenged epoch ahead.

Looking forward, the thesis beckons further scholarly exploration to distill deeper insights into specific adaptive and mitigative strategies, assessing their viability, scalability, and impact. Such progressive inquiries are pivotal for sculpting a knowledge repository that airports worldwide can tap into, inspiring informed, impactful sustainability strategies.

To conclude, this thesis has aspired to inject a fresh perspective into the sustainable aviation dialogue, urging airports to not merely weather the storm of climate change but to emerge as beacons of sustainability. By charting a course that melds resilience with eco-consciousness, airports can indeed ascend to the forefront of the global sustainability vanguard, crafting a legacy of environmental stewardship for generations to come.

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