Life-Cycle Environmental and Economic Management of Airport Infrastructure and Operations

by

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Abstract

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The airport infrastructure system, which is comprised of runways, taxiways, aprons, and terminal buildings, air traffic control/surveillance, maintenance, and parking facilities, supports the global movement of passengers and goods. Although sustaining a vital mode of transportation, the system enacts a strain on Earth's resources and emits pollutants that directly contribute to impacts on climate, human health, and ecosystems. This dissertation explores both impacts from and potential mitigation opportunities for the construction and operation of the airport infrastructure system. Opportunities for minimizing system impacts, such as electrification, are inspired by actions undertaken by existing airports and by the building sector. Integrative life-cycle methods are employed to comprehensively assess the scope of impacts from the airport infrastructure system.

A detailed review is conducted of the metrics and methods found in academic literature and used by industry professionals to assess the environmental sustainability of airports. Articles are grouped according to the six categories (Energy and Atmosphere, Comfort and Health, Water and Wastewater, Site and Habitat, Material and Resources, Multidimensional) of an existing airport sustainability assessment framework. A case study application of the framework is evaluated for its efficacy in yielding performance objectives, finding that an objective, evidence-based, quantitative framework is necessary. Prominent research themes include analyzing the greenhouse gas (GHG) emissions from airfield pavements and energy management strategies for airport buildings. Research on water conservation, climate change resilience, and waste management is more limited, indicating that airport environmental accounting requires more analysis. A disconnect exists between research efforts and practices implemented by airports. Effective practices such as sourcing low-emission electricity and electrifying ground transportation and gate equipment can in the short-term aid airports in moving towards sustainability goals. Future research must emphasize stakeholder involvement, life-cycle assessment, linking environmental impacts with operational outcomes, and global challenges (e.g., resilience, climate change adaptation, mitigation of infectious diseases).

The scope of annual, life-cycle GHG emission savings associated with gate electrification is quantified for commercial airports at two scales: (1) the 24 busiest airports by aircraft movements and (2) the 2,354 airports that provide most of the commercial service in the

world. Complete electrification could yield GHG reductions of 63%–97% per gate operation relative to current practice, with greater reductions correlated with low-carbon electricity. Economic payback periods average just 1–2 years. Shifting to complete gate electrification could save a high-traffic airport an average of \$5–6 million in annual climate economic damages relative to estimates of current practice. 10–12 million metric tons of annual GHG emissions could be saved if most airports in the world electrified gate operations, costing the 24 busiest global airports on average \$25–30, United States airports \$60–70, and non-United States airports \$80–90 per metric ton of CO_2 mitigated, in some cases comparable to carbon-market prices. Annual GHG savings are on the order of 34 million metric tons relative to a worst-case scenario where all gate operations are powered by fossil fuel-combusting equipment. Environmental benefits depend primarily upon electricity sources and operational parameters such as aircraft fleet composition.

A novel decision-support tool is created that is intended to provide insight into the climate change and human health impacts from airport terminal and ancillary structure construction and operation. The tool, known as Airport Terminal Environmental Support Tool (ATEST), incorporates user input, default data, and life-cycle methods to estimate annual baseline and mitigated GHG and criteria air pollutant emissions for four modules. The modules are: (1) building/structure materials; (2) operational energy; (3) water and wastewater; and (4) solid waste management. Emissions are related to climate change and human health indicators, using the Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) impact factors. Annual operating costs and monetized climate change damages are also calculated for each module. The tool is tested on various hub airports in the United States to assess its efficacy in yielding varying results.

This dissertation adds to the wider body of knowledge on sustainability of infrastructure systems by incorporating life-cycle methods to assess environmental and economic impacts from the construction and operation of airports. Evidence-based frameworks and holistic analysis will support and improve the decision making for airport environmental management, sustainability, and facility planning teams, as well as for other stakeholders including airlines, transportation planners, and regulators. Improved insight will allow for stakeholders to make decisions that will result in less energy- and emissions-intensive airports.

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List of Abbreviations

ACERT	Airport Carbon and Emissions Reporting Tool
ACI	Airports Council International
ACRP	Airport Cooperative Research Program
APU	auxiliary power unit
ATEST	Airport Terminal Environmental Support Tool
CAP	Criteria air pollutant
CO_2	carbon dioxide
CO_2e	Carbon dioxide equivalent
EF	Emission Factor
eGRID	Emissions and Generational Resource Integrated Database
EIO-LCA	Economic Input-Output Life-cycle Assessment
EPA	U.S. Environmental Protection Agency
EUI	Energy use intensity
FAA	Federal Aviation Administration
GHG	Greenhouse gas
GSE	Ground service equipment
GPU	Ground power unit
GWP	Global warming potential
HVAC	Heating, ventilation, air conditioning
IATA	International Air Transport Association
ISO	International Organization for Standardization
LCA	Life-cycle assessment
LCI	Life-cycle inventory
LCIA	Life-cycle impact assessment
LEED	Leadership in Energy and Environmental Design
LTO	Landing and take-off
PCA	Pre-conditioned air
$PM_{2.5}$	Fine particulate matter
$PM_{2.5}e$	Fine particulate matter formation potential
SCC	Social Cost of Carbon
TRACI	Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts
WARM	Waste Reduction Model

Glossary

Auxiliary Power Unit – A non-propulsive rear engine in an aircraft that provides electrical and mechanical power. Commonly used to support ventilation and thermal comfort for passengers when aircraft are parked during boarding/off-boarding procedures.

Gate electrification – The practice of using electrically-powered equipment to provide thermal comfort and ventilation needs for passengers when aircraft are parked during boarding/off-boarding procedures.

Greywater – Water collected from non-organic sources (e.g., restroom sinks, showers, washing machines) from within a building. Can be treated to an acceptable level for reuse in toilets/urinals or in irrigation.

Ground power – Electricity supplied from 400Hz ground power cables.

Life-cycle assessment – Environmental accounting method, standardized as a four-step process under ISO 14040, that assesses inputs (energy, water, materials) and outputs (wastes, pollution) associated with all life stages (raw material extraction/processing, construction/manufacturing, transportation/logistics, operation and maintenance, end of life) of a product, process, or project.

Life-cycle impact assessment – The step in a life-cycle assessment that involves relating the life-cycle inventory to changes in impact categories such as climate change, human health, or water toxicity.

Life-cycle inventory – The step in a life-cycle assessment that involves documenting all inputs and outputs associated with a system boundary.

On-site reuse – The practice of collecting, treating, and using non-potable sources of water at a decentralized location.

Pre-conditioned air – External systems used to deliver fresh air into parked aircraft for the purpose of providing ventilation for passengers.

Rainwater – Water collected from precipitation events. Can be treated to an acceptable level for reuse in toilets/urinals or in irrigation.

Social Cost of Carbon – An estimation of the economic damage and harm caused by climate change.

TRACI – A life-cycle impact assessment tool developed by the United States Environmental Protection Agency. TRACI contains characterization factors for a database of pollutants which can be used to relate life-cycle inventories to impact categories.

Waste diversion – The practice of diverting solid waste from landfills to other waste management pathways such as recycling facilities, composting facilities.

Waste reduction – The practice of reducing waste generation at a location of interest, such as at an airport terminal.

Waste substitution – The practice of switching one type of waste product for another (e.g., switching from a non-recoverable product to a compostable or recyclable product).

Wastewater – Water containing wastes collected from residential, commercial, or industrial sources.

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Chapter 1. Introduction

The airport infrastructure system, which is comprised of runways, taxiways, aprons, and terminal buildings, air traffic control/surveillance, maintenance, and parking facilities, supports the global movement of goods and passengers. Although sustaining a vital mode of transportation, the system enacts a strain on Earth's resources and emits pollutants that directly contribute to impacts on climate, human health, and ecosystems. This dissertation explores both impacts from and potential mitigation opportunities for the construction and operation of the airport infrastructure system. Opportunities for minimizing system impacts, such as electrification, are inspired by actions undertaken by existing airports and by the building sector. Integrative life cycle methods are employed to comprehensively assess the scope of impacts from the airport infrastructure system.

1.1 Motivation

The airport infrastructure system provides a means for economic growth through commerce and employment at airports and supporting industries. The system aids in fulfilling societal needs by transporting high priority goods, supporting medical and emergency operations, and connecting diverse populations. Prior to the COVID-19 pandemic, which began in January 2020, demand for air travel was expected to rise at a fast rate, although not uniformly across regions. Air travel growth was forecasted to be stagnant in more mature markets in the United States and Europe (IATA, 2018a). Consistent with global population trends (Cave et al., 2021), travel in newer markets such as Asia and Africa were expected to dominate growth in the coming decades. Demand has been volatile throughout the pandemic, with periods of historically low air travel. Almost two years into the pandemic, trends point towards recovery (IATA, 2021a). Without a doubt, airports will continue to be a critical component of society's infrastructure systems.

1.1.1 Impacts on Climate Change, Local Health, Resource Use

Air travel and supporting infrastructure such as terminal buildings, runways, air traffic control/surveillance facilities, and parking structures are energy and resource intensive in their construction and operation. Relative to other sectors, aviation accounts for approximately 3% of global anthropogenic greenhouse gas (GHG) emissions and is a significant source of exposure to pollutants that can have serious health consequences for those working and living within the airport system boundary.

Impacts from the construction and operation of airport infrastructure are important to assess because going forward they will likely represent a larger portion of global GHG emissions and continued source of localized pollution for a variety of reasons. Sources of climate change-causing and localized pollution from other sectors will be lowered due to targeted regulatory policies and technological advances related to electrification at scale. To function properly, airports require continuous updates to meet changes in capacity, health and building codes compliance, and customer satisfaction levels. Such updates result in construction activities and modifications to how the airport operates.

1.1.2 Stakeholders

Stakeholders, defined as federal/state/local governmental bodies, airport environmental and sustainability teams, and airport strategic planning boards need better understanding of the scope of impacts from airport construction and operation on global and local emissions, and consumption of energy and other natural resources. Improved insight will allow for stakeholders to make decisions that will result in less energy- and emissions-intensive airports.

1.2 Background

Scope of Environmental Impacts

Unlike for some infrastructure systems, where data are tracked and reported more thoroughly and openly, there is no defined global estimate of how much certain impacts and resource uses are attributable to airports. Conversely, airlines receive most of the attention and scrutiny. Current estimates state that the aviation industry is responsible for anywhere from 2 to 3% of annual anthropogenic GHG emissions (IATA, 2021b), but this estimate likely does not comprehensively consider the aggregate impact from all sources of airports' emissions. Increasing anthropogenic GHG emissions are of concern because of their impact on global climate change. It is common industry practice to categorize GHG emissions as either Scope 1, Scope 2, or Scope 3. Each Scope corresponds to ownership of emission sources, with airport operators owning Scope 1 (airport-controlled sources) and Scope 2 (purchased energy), and airlines and other third parties owning Scope 3 emissions (e.g., ground support equipment, concession operations). The Scope designation of GHG emissions does not explicitly account for embodied and supply chain emissions, which are emissions attributable to construction, materials, and transportation associated with the construction, maintenance, and end of life of airport infrastructure. Embodied and supply chain emissions can provide a more complete overview of the life-cycle impacts of airport construction and operation.

There are no estimates of cumulative electricity, natural gas, and freshwater consumption from all commercial airports, making it difficult to track the airport industry's progress in achieving environmental performance targets or identifying areas of potential concern and opportunity. There is no extensive evaluation of cumulative, life-cycle GHG emissions associated with the construction and operation of all commercial airports, limiting the ability of the aviation industry to accurately meet GHG reduction targets. The cumulative amount of fine particulate matter ($PM_{2.5}$) intake, which is the mass of inhaled fine $PM_{2.5}$, from the construction and operation of individual or multiple airports is also not known at a high level of precision, although recent estimates provide a broad overview of intake from fine $PM_{2.5}$ for airports in California (Apte, 2019). Inhalation of $PM_{2.5}$ can lead to cardiovascular and lung diseases.

Part of the reason why there is an information gap lies with the inherent nature of an airport. There is some degree of similarity among airports; there are typologies in the layouts of runways (e.g., single, parallel, intersecting), geometries of terminals (e.g., linear, pier, satellite), and configurations of terminal spaces (e.g., check-in, security, boarding). However, individual airports or groups of airports even within similar regions can be distinct due to factors such as capacity, topographic/geographic features and land size, and regulatory climate. This uniqueness can potentially make it difficult to scale up global comprehensive assessment of impacts as compared to more standardized infrastructure systems such as road transport or electric power generation.

1.2.1 Efforts to Monitor and Address Environmental Impacts

An estimate of the entire range of impacts from all airports is currently unavailable. However, individual airports do internally track and publish data on some of their environmental effects. In general, there is a lack of standardization across reporting practices for publicly available sustainability/annual/financial reports. The data included in public reports might not be as useful for research or environmental accounting purposes as the data that airports might track, for example, for regulatory purposes. Whether an airport does monitor, report, or publish environmental data might depend upon local or regional regulatory status, market forces, and type of environmental impact.

1.2.1.1 GHG Emissions

As an example, San Francisco International Airport (SFO) must comply with the city of San Francisco’s ordinance that all city-owned property meets a GHG reduction target of 61% below 1990 levels by 2030 (San Francisco, 2021). The European Commission mandates, with its Green New Deal framework, for airports to fulfill its goal of carbon neutrality by 2050 through a range of measures related to aircraft and airport operation (European Commission, 2021; Finger et al., 2021). Commercial airports both in the United States and abroad might keep an inventory of Scope 1, 2, and 3 GHG emissions to meet certification requirements from the Airport Council International (ACI) (Airport Carbon Accreditation, 2021) or business environmental reporting initiatives from the Global Reporting Initiative (GRI, 2021).

1.2.1.2 Criteria Air Pollutants

In the United States, airports are required to monitor criteria air pollutant (CAP) emissions from operation to comply with the Clean Air Act. Under the National Environmental Policy Act (NEPA) and in compliance with FAA purview, airport operators must complete an environmental impact review of proposed new construction, expansion, or remodeling projects (FAA, 2021c). Relevant environmental impact categories that may be considered include air quality, biological resources, hazardous materials, land use, noise, visual pollution, and water resources (FAA, 2021e). Airports outside of the United States might be subject to similar monitoring and compliance depending upon national and regional regulations.

1.2.1.3 Assessment Frameworks

Industry organizations and individual airports have developed frameworks and methods aimed at assessing the sustainability of airports. ACI created the Airport Carbon Accreditation framework, which is comprised of multiple levels of accreditation. Certified airports typically map their Scope 1, 2, and 3 GHG emissions and identify and implement mitigation strategies to achieve higher accreditation levels. SFO initiated a framework, explored more in-depth in Chapter 2, for implementing mitigation strategies for multiple categories of environmental impacts during the planning, design, and construction phases of building projects at airports. Both the ACI and SFO frameworks have their strengths and weaknesses and can be viewed as works in progress.

What is needed, given information gaps and current frameworks, is an evidence-based approach to finding the most important mapping and mitigation opportunities on which stakeholders should concentrate their resources such that airports, which are hubs of localized pollution and contributors to global climate change, can be managed as environmentally efficiently as possible.

A more detailed background on the environmental impacts from airports is explored in Chapter 2. Holistic quantification that encompasses supply chain and regional variations is introduced. It complements and improves upon existing frameworks for tracking environmental effects from the construction and operation of airports.

1.3 Research Overview

This dissertation assesses impacts from the construction and operation of airport infrastructure, developing a comprehensive model and focusing on two detailed, interrelated projects:

- Chapter 3: Quantifying the GHG emissions, payback periods, levelized annual costs, and monetized climate change damages associated with various gate electrification scenarios for the busiest airports in the world. Estimating the cumulative GHG emissions savings and mitigation costs for complete gate electrification at most commercial airports in the world.

- Chapters 4 and 5: Developing a decision-support tool that quantifies unmitigated (baseline) and mitigated GHG and CAP emissions, operational and monetized damage costs, and climate change and human health indicators for the construction and operation of airport terminals and supporting infrastructure. Applying the decision-support tool to small, medium, and large hub airports in the United States.

Reliable and robust individual airport- and regionally specific data and life-cycle assessment (LCA) methods are used to model, quantify, and analyze impacts. Airport infrastructure refers to the physical structures, features, and operations emblematic of an airport. This dissertation does not focus on or assess aircraft operations for air travel.

The scope of impacts from airport infrastructure construction and operation is studied less than those from aircraft manufacturing and flying. Filling the gap in research is crucial so that stakeholders can accurately address impacts. It is also easier to assess mitigation strategies, especially electrification, for airport infrastructure because they are currently more economically and efficiently implementable at airports than for aircraft operation. Many of the airports used as case studies in the dissertation are in the United States. Foreign airports are also included to compare differences in how stakeholders manage environmental impacts and implement reduction actions.

1.3.1 Research Questions

The following questions form the foundational research of this dissertation:

- What does it mean for an airport to be sustainable?
- What feasible, readily deployable, cost-effective strategies should stakeholders implement to reduce an airport's: (1) energy consumption; (2) GHG emissions; (3) CAP emissions; (4) economic costs; (5) monetized damages; (6) human health impacts?
- How should strategies be implemented when policy goals, for example, climate change mitigation or pollutant exposure reduction, might be in conflict?
- How do strategies practically get implemented? Which strategies are the most important depending upon a range of criteria, such as meeting policy goals or reducing inequity?
- What are constraints in how some environmental impacts, particularly GHG emissions, are managed?

Questions specific to each research project are provided in their respective chapters.

1.3.2 Objectives

The objectives of this research are to:

- Perform a systematic, environmental life-cycle assessment of distinct airport infrastructure and operational activities;
- Provide a better understanding of how the scope of impacts, particularly GHG emissions, from airport infrastructure and operations change with respect to regional variation and scale of operations;
- Provide robust data and results so that airport stakeholders (regulators, planning and development/sustainability/environmental teams) can identify the strategies that yield the best outcome according to performance criteria (lowest emissions, cheapest, lowest damages, maintaining operations) and under changing circumstances (energy supplies, operations, etc.);

- Improve airport-industry practices by moving beyond sustainability efforts/systems like the Scope designation and Leadership in Energy and Environmental Design (LEED);

- Create a novel decision-support tool for airport capital investment, sustainability, planning, and management teams, as well as for other industry professionals, regulators, or researchers, to use in preliminarily estimating GHG and CAP emissions, operational costs, and monetized climate damages associated with constructing and operating airport terminals.

1.3.3 Targeted Dissertation Contributions

As explained in more detail in Chapter 2, gaps in the comprehensive mapping of environmental impacts from airport infrastructure prevent stakeholders from making informed, efficient mitigation decisions. Filling this gap is important at both global and local scales. An accurate understanding of the scope of GHG emissions from the aviation industry is needed so that cities, regions, states, and countries can appropriately plan and meet climate change mitigation goals. As noted, the scope of GHG emissions from the aviation industry is better documented for aircraft operations than for airports themselves. At local scale, understanding the environmental impacts from the construction and operation of airports is vitally important for addressing health impacts for ecosystems and people in the surrounding communities. This research is targeting the following contributions which bolster the wider body of knowledge on airport infrastructure systems by:

- Providing a systematic, environmental life-cycle assessment of components of an infrastructure system (i.e., an airport) that is (1) often neglected in environmental accounting of the aviation industry and (2) critical for meeting GHG emissions goals of the aviation industry.

- Offering insight into how environmental impacts vary for different regions and different airport scales (small, medium, large airports). This is vitally important because a common trend is for airports to adopt “best practices” after another airport’s successful implementation. However, what works for one airport might not be as effective for another, and both airports may be underperforming against optimal or ambitious criteria. There needs to be rigorous appraisals of “best practices” for each airport so that regional variations (e.g., in energy supplies, climate conditions) and supply chain considerations can be accounted for. Additionally, understanding the scope of impacts for airports of different scale is especially useful from a policy perspective because it helps identify potential areas to focus on (e.g., impacts from medium airports, which outnumber large airports, could be more significant than from large airports).

- Most previous LCA studies on airport components only consider GHG emissions. While it is important to consider GHG emissions, especially in the context of meeting legislative requirements (e.g., Assembly Bill 32 in California) or obtaining funding grants from the Federal Aviation Administration (FAA), it is just as important to consider the localized impacts of a strategy. Considering localized impacts, such as exposure to pollution, is important for assessing the potential health impacts to local populations. An inventory of CAP emissions is the first step in determining the exposure levels of fine $PM_{2.5}$ for specific populations. An inventory can help airports and regulatory agencies identify specific strategies to put in place to minimize pollution concentrations and mitigate exposure.

- Understanding the relationship among the airport components, their respective environmental impacts, and the managing stakeholder groups is critical because it leads to identifying which groups must act to mitigate environmental impacts.

- Investigating the potential to electrify key aspects of the airport system boundary which matters in broader policy context of electrification of major infrastructure systems.

- Developing a customizable, scalable tool for holistically assessing environmental footprints and potential mitigation opportunities for airport terminal projects, improving the pre-planning and design process for airport decision makers

1.4 Dissertation Organization

The dissertation chapters are organized as follows:

- Chapter 2 presents a detailed review of the metrics and methods found in academic literature and used by industry professionals to assess the environmental sustainability of airports. Articles are grouped according to the six categories (Energy and Atmosphere, Comfort and Health, Water and Wastewater, Site and Habitat, Material and Resources, Multidimensional) of an existing airport sustainability assessment framework. A case study application of the framework is evaluated for its efficacy in yielding performance objectives. Research gaps are outlined and suggestions for new research directions are provided.

- Chapter 3 quantifies, using LCA, annual GHG emission savings associated with the electrification of gate operations at commercial airports at two scales: (1) the 24 busiest airports by aircraft movements and (2) the 2,354 airports that provide most of the commercial service in the world. Two economic assessments are conducted. Payback periods associated with purchasing gate electrification infrastructure are calculated. The levelized annual operating and maintenance costs from gate electrification are compared to costs of gate operations with fossil fuel-combusting equipment. Monetized climate change damages, using the social cost of carbon, are estimated for various gate operation scenarios.

- Chapter 4 outlines the creation of a novel tool that is intended to provide insight into the climate change and human health impacts from airport terminal and ancillary structure construction and operation. The tool, known as Airport Terminal Environmental Support Tool (ATEST), incorporates user input, default values, and life-cycle methods to estimate annual baseline and mitigated GHG and CAP emissions for four modules. The modules are: (1) building/structure materials and construction; (2) operational energy; (3) water and wastewater; and (4) solid waste management. Emissions are related to climate change and human health indicators, using the Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) impact factors. Annual operating costs and monetized climate change damages are also calculated for each module.

- Chapter 5 builds upon the framework and decision-support tool outlined in Chapter 4 and tests its function on multiple airports in the United States.

- Chapter 6 finishes with key conclusions from the dissertation, how research objectives lead to contributions, and recommendations for future work.

Chapter 2. Literature Review of Airports and Environmental Sustainability

The following chapter is adapted from Greer, F., Rakas, J. and Horvath, A., 2020. Airports and environmental sustainability: a comprehensive review. Environmental Research Letters, 15(10), p.103007, with permission from Jasenka Rakas and Arpad Horvath. Copyright 2020, The Authors. Published by IOP Publishing Ltd.

Over 2,500 airports worldwide provide critical infrastructure that supports 4 billion annual passengers. To meet changes in capacity and post-COVID-19 passenger processing, airport infrastructure such as terminal buildings, airfields, and ground service equipment require substantial upgrades. Aviation accounts for 2.5% of global greenhouse gas (GHG) emissions, but that estimate excludes airport construction and operation. Metrics that assess an airport's sustainability, in addition to environmental impacts that are sometimes unaccounted for (e.g., water consumption), are necessary for a more complete environmental accounting of the entire aviation sector. This review synthesizes the current state of environmental sustainability metrics and methods (e.g., life-cycle assessment, Scope GHG emissions) for airports as identified in 108 peer-reviewed journal articles and technical reports. Articles are grouped according to six categories (Energy and Atmosphere, Comfort and Health, Water and Wastewater, Site and Habitat, Material and Resources, Multidimensional) of an existing airport sustainability assessment framework. A case study application of the framework is evaluated for its efficacy in yielding performance objectives. Research interest in airport environmental sustainability is steadily increasing, but there is ample need for more systematic assessment that accounts for a variety of emissions and regional variation. Prominent research themes include analyzing the GHG emissions from airfield pavements and energy management strategies for airport buildings. Research on water conservation, climate change resilience, and waste management is more limited, indicating that airport environmental accounting requires more analysis. A disconnect exists between research efforts and practices implemented by airports. Effective practices such as sourcing low-emission electricity and electrifying ground transportation and gate equipment can in the short-term aid airports in moving towards sustainability goals. Future research must emphasize stakeholder involvement, life-cycle assessment, linking environmental impacts with operational outcomes, and global challenges (e.g., resilience, climate change adaptation, mitigation of infectious diseases).

2.1 Introduction

Airport infrastructure is a vital component of society's transportation network. There are more than 40,000 airports worldwide (CIA, 2016). Around 2500 airports processed over 4 billion passengers in 2018 (IATA, 2018b). The onset of COVID-19 has drastically decreased air traffic levels (IATA, 2020). It is likely that air travel will recover over the next couple of years and continue to rise. In the United States, massive investment is required (ACC, 2020; ASCE, 2021) to modernize and retrofit aged, inadequate airport infrastructure (e.g., terminals, airfields, service equipment). Similar expansion projects and necessary reconfiguration projects for post COVID-19 processing of passengers are occurring worldwide. Airports are not solely transport nodes. The onset of 'airport cities' make this critical infrastructure a catalyst for economic, logistical, and social development (Appold & Kasarda, 2013).

The environmental impacts attributed to airport construction and operational activities (e.g., building operation, ground service equipment (GSE)) are significant to consider, especially in light of the fact that as other transport sectors go 'green,' the air transport sector will face more challenges in reducing their environmental impacts. It is estimated that the aviation industry accounts for approximately 2.5% of global greenhouse gas (GHG) emissions in 2018 (IEA, 2021), but that estimate excludes the impacts from airport construction and operation. An analysis of 2019 data for San Francisco International Airport (SFO, 2018, 2021) reveals an approximate annual breakdown of 85% for aviation GHG emissions and 15% for airport GHG emissions. Although not accounting for life-cycle impacts and not representative of every airport, this breakdown offers a sense of scope of how GHG impacts are divided between aviation (i.e., flights) and airport activities. The environmental impact of airport infrastructure/operations is not just limited to their GHG emissions. Airport construction and operation also results in emissions of air pollutants such as carbon monoxide (CO), nitrogen oxides (NO_x), and particulate matter (PM), displacement of and damage to natural ecosystems, generation of waste, and consumption of resources such as water.

In the public policy sphere, airport sustainability is an emerging area of interest. The aviation and airport communities recognize the important role that airport infrastructure plays in promoting beneficial environmental and human health outcomes. However, how the public sector addresses airport sustainability is fragmented and lacks rigorous appraisal of suggested best practices. Oftentimes, airport operators rely on other airports' existing sustainability guidelines for selecting 'green' practices that are not explicitly defined and quantified (Setiawan & Sadewa, 2018). This review offers the public aviation sector, in particular, a much-needed overview of relevant sustainability indicators and methods for airport infrastructure and guidance in pursuing future research and implementation of sustainable practices and projects.

The expected increase in demand for air travel and the necessary upgrades for airport infrastructure compound the environmental impacts of airport construction and operation. In designing and operating the next generation of airport infrastructure (e.g., terminal buildings) there must be a systematic way for evaluating the resulting environmental impacts. Measures that assess the sustainability of the design, construction, and operation of airport infrastructure offer a potential solution for airport operators to consider.

2.1.1 History and background

Sustainability, as defined in the United Nations' Brundtland Report, states that present society must manage and consume resources so as not to compromise future society's needs (Brundtland & Khalid, 1987). While the Brundtland definition acknowledges human activity's environmental impact, it does not offer concrete guidance for achieving sustainability. A less abstract framework is the 'triple bottom line' approach, which aims to identify solutions that balance environmental, social, and economic interests (Elkington, 1994).

Sustainability indicators, or metrics, can be used to measure the 'sustainability performance' of an airport. Metrics are critical because they allow for:

- Comparing the sustainability of one airport (or one type of airport) against another;
- Identifying the weak points or opportunities for improvement in airport infrastructure;
- Measuring progress towards meeting targeted goals.

A standardized, empirical metric is also crucial for making decisions about sustainable design and operation of airport infrastructure (Longhurst et al., 1996). Stakeholder involvement in developing these indicators is necessary (Upham & Mills, 2005). Sustainability metrics are a component of a larger- scale sustainability plan. Ideally, formalized sustainability plans developed by airports should incorporate metrics for tracking progress towards goals.

Airport sustainability, as defined by the aviation industry, incorporates the 'triple bottom line' concept with a fourth pillar focused on operational efficiency. Airport Council International (ACI) to this approach to sustainability as EONS (Martin-Nagle & Klauber, 2015; Prather, 2016). Common subcategories of EONS are shown in Table 1. An important research dimension of the airport industry is the United States National Academies of Sciences' Airport Cooperative Research Program (ACRP), which researches and publishes synthesis reports and guidance for current sustainability practices at airports. ACRP reports are largely compiled through literature reviews of airports' published sustainability reports and through interviews, surveys, and questionnaires with airport operators. Recent topics of ACRP reports include:

- overall sustainability (Delaney & Thomson, 2013; Lurie et al., 2014; Malik, 2017; Prather, 2016; Program, Administration, & Brown, 2012);
- feasibility of on-site energy provision (S. B. Barrett et al., 2014; Lau et al., 2010) and microgrids (Heard & Mannarino, 2018);
- GHG emission reduction strategies (S. Barrett, 2019; Program et al., 2011);
- air quality impacts (Kim et al., 2014, 2015; Lobo et al., 2013; Transportation Research Board, 2012);
- water efficiency (Krop et al., 2016) and stormwater management (Jolley et al., 2017);

- habitat management (Belant & Ayers, 2014);
- sustainable ground transport (Kolpakov et al., 2018);
- sustainable construction practices (Transportation Research Board, 2011);
- waste management (Transportation Research Board, 2018a);
- climate change adaptation of airports (Marchi, 2015).

Table 1. Airport industry concept of sustainability or EONS, as defined by Prather, 2016.

Economic Viability	**Operational Efficiency**	**Natural Resource Conservation**	**Social Responsibility**
• Economic vitality	• Delivering services in a cost-effective manner • Accounting for life-cycle costs	• Air quality enhancement/climate change • Energy conservation/renewable energy • Noise abatement • Water quality protection & water conservation • Land & natural resources management • Land/property use • Pavement management • Materials use & solid waste reduction/recycling • Hazardous materials & waste management/reduction • Surface transportation management • Buildings/facilities	• Socioeconomic benefits • Community outreach & participation

The definition of environmental airport sustainability in the academic literature varies with some defining it according to multiple categories of environmental impacts (Chao et al., 2017; Ferrulli, 2016; Gomez Comendador et al., 2019; S. Kilkis & Kilkis, 2016) and others limiting that definition to traditional environmental aviation impacts such as emissions and noise (Lu et al., 2018). Environmental sustainability is assessed using both quantitative and qualitative metrics/measures, and using both generalized, average airports (M. V. Chester & Horvath, 2009) and data from operating airports (Chao et al., 2017; S. Kilkis & Kilkis, 2016; Li & Loo, 2016).

In both industry and academic research, environmental impacts are often disaggregated according to the airside and landside components of the airport system boundary. Figure 1 shows a plan view schematic of the typical features included in the airport system boundary. It should be noted that energy generation, water/wastewater (WW) treatment, and waste management infrastructure can be located within airport-owned property (i.e., decentralized) or within the surrounding community of the airport (i.e., centralized). Table 2 identifies the purpose and primary stakeholders for each airport component. Understanding the scope of airport infrastructure aids in identifying the most relevant environmental impacts and the stakeholders best equipped to mitigate those impacts.

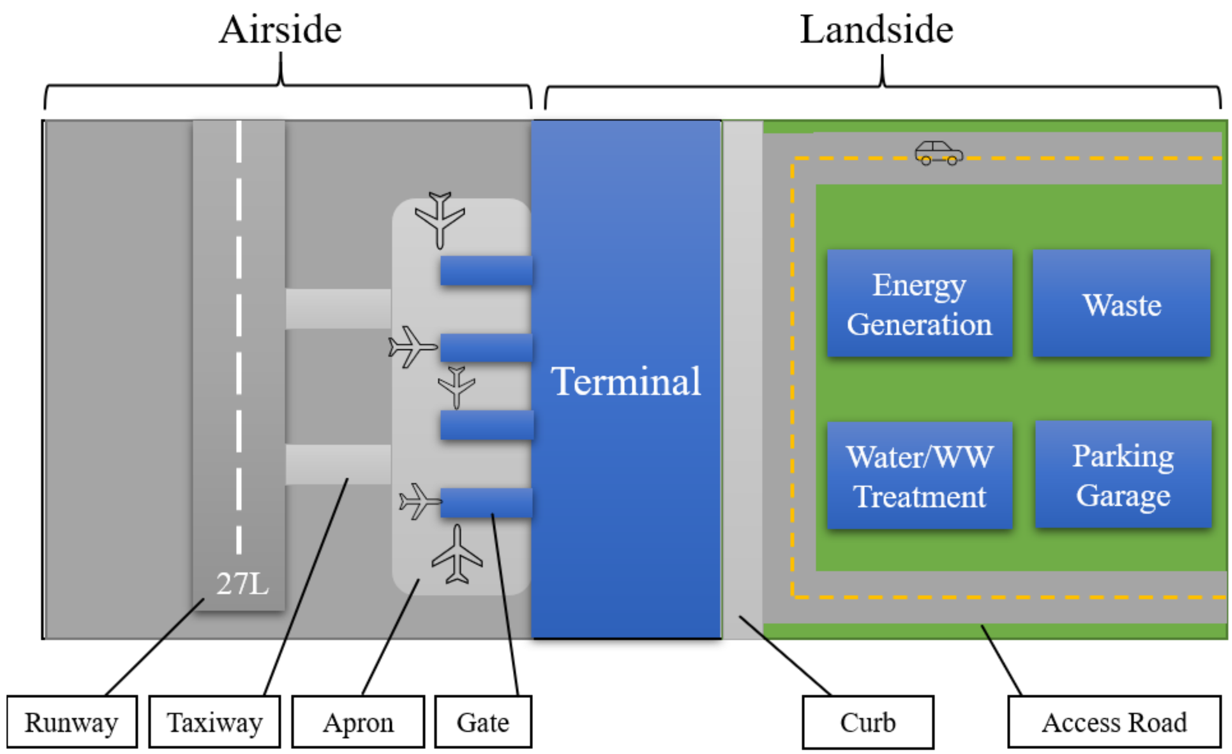


Figure 1. Plan view of airport system boundary. Key infrastructure features are identified.

Table 2. Purpose and primary stakeholders of key airport infrastructure.

Component	Infrastructure	Purpose	Primary Stakeholder
Airside	Runway	Support aircraft take-off/landing	Aviation regulatory agency
	Taxiway	Move aircraft from gate to runway	Aviation regulatory agency
	Apron	Passenger boarding/aircraft maintenance	Airline
	Gate	Connect passengers from terminal to aircraft	Airline
Landside	Terminal	Process passengers from landside to airside	Airport
	Curb	Passenger drop-off/pick-up	Airport
	Access Road	Transport passengers/employees to/from airport	Airport/Local Community
	Energy Generation	Provide energy for airport operation	Airport/Local Community
	Water/WW Treatment	Provide safe water for airport operation Treat effluent	Airport/Local Community
	Waste	Manage waste from airport operation	Airport/Local Community
	Parking Garage	Provide space for passenger/employee parking	Airport

2.1.2 Research Objectives

While previous studies have examined sustainability practices of individual airports (Berry et al 2008, Prather 2016), this work represents the first comprehensive systematic review of academic and industry literature on airport environmental sustainability. The five objectives of this research are: (1) synthesize the existing literature on environmental sustainability indicators and metrics for airports; (2) review the application of sustainability indicators developed for the construction of terminals and other airport facilities at a case study airport (San Francisco International Airport also known as SFO); (3) identify gaps in the literature; (4) recommend what sustainability indicators/metrics should be employed at airports based upon the results of the literature review; (5) provide recommendations for future directions of research. Sustainability indicators are grouped according to the SFO framework: Energy and Atmosphere, Comfort and Health, Water and Wastewater, Site and Habitat, Materials and Resources. These five categories provide a framework for stakeholders to begin exploring the scope of relevant environmental impacts. The breadth of the five categories also highlights that sustainability encompasses more than one type of impact (e.g., GHG emissions) and underscores that airports have multiple priorities in addressing their environmental impacts. The expected outcome from this review is the identification of gaps in the existing literature and practice as it pertains to evaluating the sustainability of airport infrastructure. Recommendations for future research directions will provide those in the academic realm, as well as in the public aviation sector, a robust assessment of what metrics, practices, and methods should be applied to achieve optimal performance outcomes.

2.2 Methods

The foremost criterion in selecting peer-reviewed research articles and technical reports is that they pertain to indicators (i.e., metrics or measurements) for environmental sustainability. Although the concept of sustainability also includes economic and social factors, they are outside the scope of this review. We excluded corporate sustainability reports published by individual airports as data from these reports often appear in non-standard formats. However, individual airport sustainability practices were explored as part of the review of academic and ACRP literature. We iteratively searched for peer-reviewed research articles and technical reports in Web of Science, Google Scholar, and the National Academies of Science' ACRP database that were relevant to 'airport sustainability,' using the key terms of 'airport' and variations of 'sustainability' including 'environmental sustainability,' 'sustainable development,' and 'environmental impact.'

Searches were conducted with key terms related to the five categories of the SFO framework (i.e., Energy and Atmosphere, Comfort and Health, Water and Wastewater, Site and Habitat, Materials and Resources). Additional searches also included articles that incorporated life-cycle assessment (LCA), a method for assessing the 'cradle-to-grave' environmental impacts of a product, process, or project. We elected to also include search terms for Scope 1, Scope 2, and Scope 3 GHG emissions. Table 3 summarizes the definitions and examples of Scope GHG emissions.

Characterizing GHG emissions according to the three Scopes aligns with airport industry practice of allocating responsibility for GHG emissions among airport stakeholders (Airport

Carbon Accreditation, 2021). Exact search terms for all criteria are provided in Appendix A. Articles that were relevant to at least more than one of the five sustainability categories were considered as part of a Multidimensional category. Articles that focused on sustainability indicators for the construction and operation of physical airport infrastructure were prioritized. Articles were excluded if they concentrated on aircraft, aircraft fuel, or on aircraft operations within the airport boundary such as taxiing, queuing, and the landing and take- off (LTO) cycle. The rational for this exclusion is that aircraft-related sustainability is an already extensively reviewed subject (Agarwal, 2010; Blakey et al., 2011; Sarlioglu & Morris, 2015). However, articles pertaining to aircraft servicing operations at airports (e.g., ground service equipment or GSE, de-icing) were included. All screening criteria are listed in Table A2 in Appendix A. Note that the time period of 2009 to 2019 is selected to provide a meaningful analysis of the academic literature, as interest in airport environmental sustainability as a research field began in earnest at the end of the 2000s.

The searches yielded a total of 108 articles grouped according to Energy and Atmosphere (n = 22), Comfort and Health (n = 25), Water and Wastewater (n = 14), Site and Habitat (n = 16), Materials and Resources (n = 18), Multidimensional (n = 13). Common themes of sustainability indicators for each category are depicted in Figure 2. Section 3 provides a trend analysis of the articles included in the systematic review.

Table 3. Summary of GHG scope emissions for airports.

	Scope 1	**Scope 2**	**Scope 3**
Definition	GHG emissions come from on-site sources that airport owns	GHG emissions come from purchase of off-site energy	GHG emissions come from on-site sources that are controlled by tenants
Examples	• On-site natural gas combined heat and power plant • Airport-owned vehicles	• Utility-supplied electricity	• GSE owned by airlines • Concessionaire activities • Passenger/employee transportation to and from airport

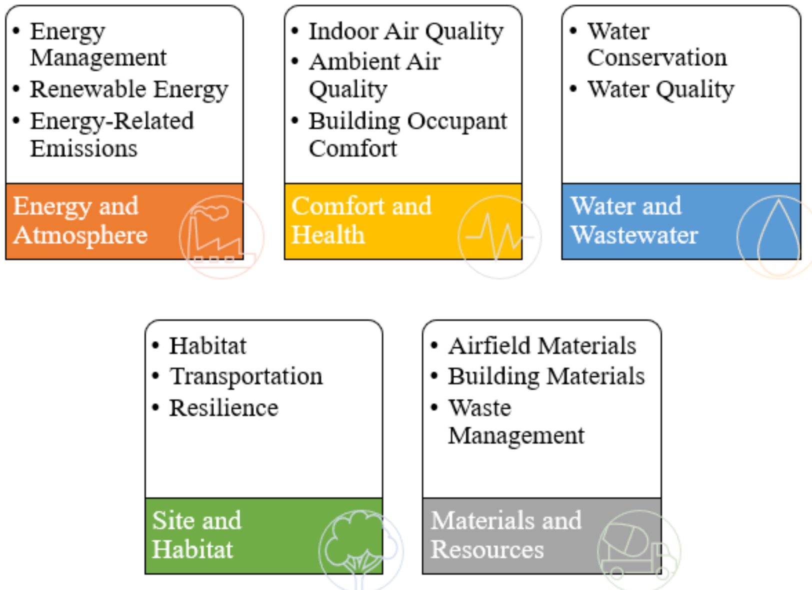


Figure 2. Themes for each of the five sustainability categories.

2.3 Results

2.3.1 Characterization of systematic literature review

A trend analysis of the reviewed articles indicates that interest in airport environmental sustainability has steadily increased over the period of 2009 to 2019 (Figure 3). Article counts in each category theme (Figure 4) reveal that research among the various categories is relatively balanced, with some prominent exceptions. Article counts for 'Ambient Air Quality,' 'Airfield Materials,' and 'Multidimensional' research themes are the highest. The high article counts for 'Ambient Air Quality' and 'Airfield Materials' suggests that research in the field of airport environmental sustainability largely focuses on the characteristics of an airport that are most prominent and apparent (i.e., the runway, taxiway, and apron). The high article count for the 'Multidimensional' category indicates that the research community is beginning to recognize that airport sustainability is comprised of multiple environmental impacts across multiple airport functions. In categories such as 'Waste Management' and 'Building Materials,' the small article counts imply that these specific subjects are still emerging as relevant research areas.

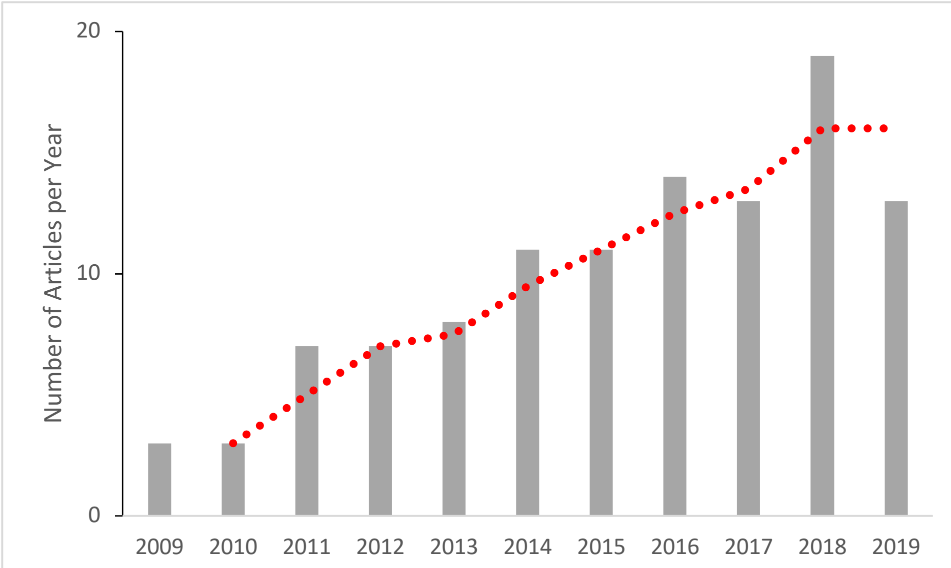


Figure 3. 'Airport environmental sustainability' article count by year (Dotted line = moving average).

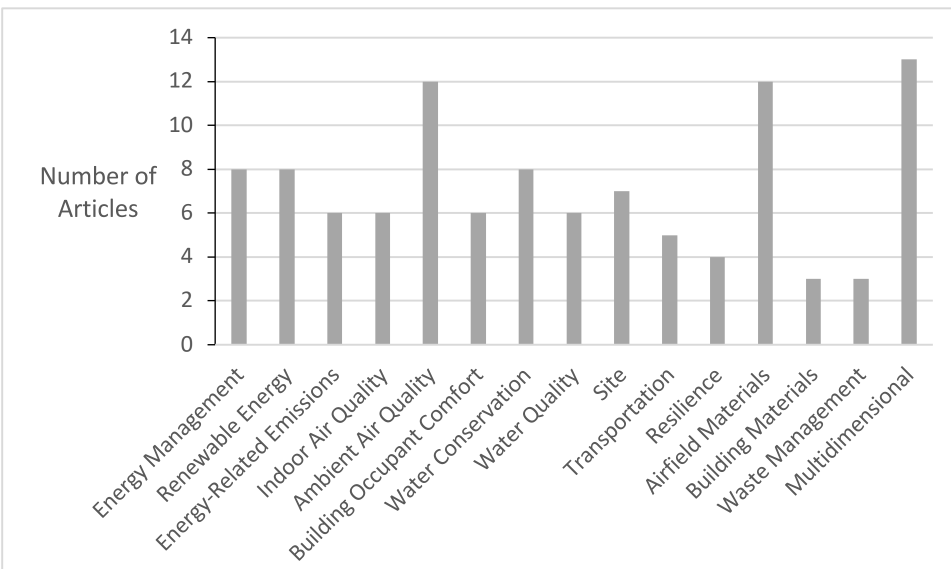


Figure 4. Cumulative articles by theme.

2.3.1.1 Synthesis of research by category

2.3.1.1.1 Energy and atmosphere

Common themes among the articles featured in the Energy and Atmosphere category include energy management of airport infrastructure, use of renewable energy on-site, and energy-related air emissions.

2.3.1.1.1.1 Energy management

Energy management refers to a process by which airports can characterize and monitor their energy consumption and enact measures to reduce it. Airports use fossil fuels (natural gas, petroleum) and electricity to perform various operational requirements such as controlling the thermal environment of buildings, lighting runways and buildings, and fueling airport ground equipment and vehicles. Using Seve Ballesteros-Santander Airport in Spain as a case study, it is estimated that most of the energy consumption at an airport is attributable to the terminal building with heating, ventilation, air conditioning (HVAC) and lighting being the most energy-intensive practices (Ortega Alba & Manana, 2017). A best practice for energy management is implementation of an energy monitoring system (Lau et al., 2010). Although not analyzed from an environmental perspective, airports represent an opportunity for exploring the implementation of microgrids, which allow for on-site energy generation and storage (Heard & Mannarino, 2018).

Some literature indicates that if an airport has implemented specific energy management practices, then those practices are a marker of sustainability. A sample of practices that are considered sustainable and have been implemented at two case study airports (Baxter et al., 2018c, 2018b) is provided in Table 4. An airport that implements a standardized energy management system is considered sustainable (Uysal & Sogut, 2017). Implementation of specific practices depends upon site characteristics including climate, occupancy level, and operating hours (Malik, 2017). An analysis of energy related to the lighting of a Turkish airport terminal indicates that indoor lighting is a critical energy consumer (Kiyak & Bayraktar, 2015).

Table 4. Example energy conservation practices at airports as reported in Baxter et al. (2018a, 2018c).

Airport	Copenhagen (CPH)	Kansai (KIX)
Energy Conservation Practices at Airports	• 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 • Monitor energy consumption • Utilize sensor-controlled escalators • Use of groundwater for heating and cooling • Reduce voltage for site's equipment	• 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 • Reducing vehicle idling times

2.3.1.1.1.2 Renewable energy

Implementation of on-site renewable energy is another typical indicator of sustainability as discussed in the literature. There are safety concerns (e.g., glare, radar interference) with some forms of renewable energy such as solar and wind (S. B. Barrett et al., 2014), but airports are ideal candidates for employing on-site renewables because of their expansive land areas (Lau et al., 2010). Metrics for evaluating the efficacy of on-site renewable energy such as solar photovoltaic (PV) systems include percentage of energy demand met by on-site renewables (Dehkordi et al., 2019) and exergy (B. Kilkis & Kilkis, 2017; Sukumaran & Sudhakar, 2018). Exergy, as it relates to provision of on-site solar PV, refers to the quality of the energy delivered; solar power tends to have high thermal losses unless cooling intervention is taken. In assessing the emissions impact from different energy sources in a district heating system at Schiphol Airport in the Netherlands, it is argued that GHG emissions should be estimated by accounting for both the first and second laws of thermodynamics (B. Kilkis & Kilkis, 2017). Accounting for GHG emissions from both the quantity (first law) and quality (second law) of energy provides a more realistic analysis of the feasibility for achieving practices that are considered sustainable (e.g., net zero-carbon airport terminal buildings). Another metric for assessing environmental impacts from renewable energy at airports is absolute reduction of fossil fuel consumption, which is applied to evaluate a solar PV and battery storage project at Cornwall Airport Newquay in the United Kingdom (Murrant & Radcliffe, 2018). Modeling of a solar PV farm at a rural United States airport indicates that this form of renewable energy can meet both the airport's and local community's electricity needs without compromising pilot or airspace safety (Anurag et al., 2017). A groundwater source heat pump was found to meet indoor thermal requirements in a more energy-efficient manner (i.e., a higher coefficient of performance) than conventional heat pumps for a Tibetan airport (Zhen et al., 2017). LCA is used to inventory the GHG emissions from using a biomass-fired combined heat and power plant at London Heathrow Airport to meet terminal building heating needs (Tagliaferri et al., 2018).

2.3.1.1.1.3 Energy-related emissions

Recommended GHG emission reduction strategies related to energy use at airports pertain to designing building envelopes to be more energy efficient, using energy efficient equipment and fuels, relying on renewable energy, and managing use of refrigerants (S. Barrett, 2019; Program et al., 2011). GHG emissions from annual airport energy consumption are a typical sustainability evaluation metric (Baxter et al., 2018c, 2018b; Monsalud et al., 2015). In practice, GHG emissions are often inventoried according to a framework developed by ACI, which recognizes that an airport is under direct control of GHG emissions from Scope 1 sources (e.g., on-site power generation) and Scope 2 sources (e.g., purchase from grid electricity), and only able to influence Scope 3 sources (e.g., emissions from an airline's GSE) (Ozdemir & Filibeli, 2014; Program et al., 2011). The ACI framework accounts for the annual amount of electricity and natural gas consumed and the amount of fuel used to power airport ground vehicles. A similar method allocates emissions to each macro unit (e.g., GSE) at an Italian airport (Postorino & Mantecchini, 2014). A more holistic approach for measuring an airport's energy consumption accounts for the loss of a carbon sink from the deforestation of the site on which Istanbul International Airport was built (B. Kilkis, 2014).

2.3.1.1.2 Comfort and health

The Comfort and Health themes in the literature include building occupant comfort and health impacts related to ambient and indoor air quality.

2.3.1.1.2.1 Building occupant comfort

Passengers and airport/airline employees spend a considerable amount of time inside airport buildings such as terminals, maintenance facilities, and control towers. Occupant comfort in these buildings is relevant for environmental sustainability because aspects of comfort (i.e., thermal, ventilation, lighting) are directly related to metrics such as energy consumption. Research into novel air conditioning and heating systems in terminals at Chinese airports indicates that thermal and ventilation comfort can be satisfied while saving energy (X. Liu et al., 2021; Meng et al., 2009; Zhang et al., 2013; K. Zhao et al., 2014). An investigation of preferences at airports in the U.K. demonstrates that occupants tolerate higher thermal levels and prefer natural lighting, which have energy-saving implications (Kotopouleas & Nikolopoulou, 2018). Designing airport buildings to emphasize natural lighting should incorporate the functional operational characteristics of air travel (i.e., operational peaks occur in the early morning and early to late evening) (Clevenger & Rogers, 2017).

2.3.1.1.2.2 Indoor air quality

Exposure to air pollutants is known to cause negative human health impacts including increased risk of respiratory illness, cardiovascular disease, and death(Apte et al., 2012; Transportation Research Board, 2012). Indoor air quality(IAQ) research focuses on the pollutants and factors (e.g., ventilation systems, building design) that contribute to occupant exposure while inside facilities such as terminals and control towers. Research on exposure in indoor settings at airports has been limited to the concentrations of nitrogen dioxide (NO_2) and volatile organic compounds (VOCs) in a maintenance room at a Lebanon airport (Mokalled et al., 2019), PM in a terminal building at a Chinese airport (Ren et al., 2018), VOCs, PM, odorous gases, and carbon dioxide (CO2) at an Italian airport terminal (Zanni et al., 2018), and CO, VOCs, and PM in a control tower at a Greek airport (Helmis et al., 2009; Tsakas & Siskos, 2011). One study linked IAQ at eight large Chinese airports with passenger satisfaction, finding that IAQ satisfaction is correlated with CO2 concentration (Z. Wang et al., 2015).

2.3.1.1.2.3 Ambient air quality

Ambient, or outdoor, air quality at airports is a function of both aircraft and non-aircraft operations. Sources of non-aircraft emissions include the equipment used to clean, load, or reposition parked aircraft (i.e., GSE) or used to provide power to parked aircraft (i.e., ground power units or GPUs). Another source of emissions from parked aircraft is the auxiliary power unit (APU), an external rear engine on the aircraft which provides electrical power and thermal conditioning (Lobo et al., 2013; Program, Administration, & Associates, 2012). Other outdoor sources include emissions from construction (Kim et al., 2014) and operation of airport ground access vehicles (e.g., maintenance trucks, firetrucks). Much of the exposure to pollutants such as black carbon (a component of PM) occurs on the airfield's apron where aircraft are often positioned for passenger boarding and luggage loading (Targino et al., 2017). Outdoor exposure to VOCs near a United States airport revealed higher-than-expected concentrations of toluene (Jung et al., 2011). Construction of a terminal building at a major airport in Spain was a critical contributor to ambient levels of PM (Amato et al., 2010).

A review of airport contributions to ambient air pollution suggests that research on emissions related to GSE, GPU, and APU operations is more limited relative to research on emissions from aircraft (Masiol & Harrison, 2014). Concentrations of CO2, CO, PM, hydrocarbons, NOx, sulfur dioxide, sulfate, and black and organic carbon are estimated for APU and GSE use at 20 U. K. airports (Yim et al., 2013), emissions of CO, hydrocarbons, and NOx from APUs and GSE are calculated for turnaround operations at major European airports (Padhra, 2018), and concentrations of NOx and PM for APUs and GSE at Copenhagen Airport are calculated (Winther et al., 2015). Provision of fixed electrical power and external air conditioning units is considered a sustainable solution for mitigating PM and NOx emissions from APU, GPU, and GSE operation (Padhra, 2018; Preston et al., 2019; Program, Administration, Corporation, et al., 2012; Winther et al., 2015; Yim et al., 2013). Use of alternative fuel (hydrogen) for powering GSE is considered another sustainable measure to improve ambient air quality on the airport apron (Testa et al., 2014).

2.3.1.1.3 Water and wastewater

The major themes related to Water and Wastewater in the reviewed articles include water conservation strategies at airports and water quality concerns related to airport activities.

2.3.1.1.3.1 Water conservation

Airports consume water for indoor operations such as toilet-flushing, food preparation, and HVAC systems and for outdoor operations including irrigation and aircraft/infrastructure washing and maintenance (Krop et al., 2016). The amount of water that major airports consume is not insignificant and is on par with consumption patterns of small and medium-sized cities (Carvalho et al., 2013). A typical metric for assessing airport water consumption is volume per day (Baxter et al., 2019), but this metric fails to offer a broader picture of what sources of water are consumed and what management practices yield the best results (do Couto et al., 2013). The water conservation techniques proposed for airports include monitoring of water consumption, use of water efficient fixtures/fittings, reducing irrigation demand, and use of alternative water sources (e.g., rainwater, greywater, recycled wastewater).

An important point in the literature is that much of airport water consumption is for activities that do not require potable water. There is an opportunity for airports to rely upon alternative sources of water which have been studied for: rainwater harvesting at an Australian airport (Somerville et al., 2015); wastewater reclamation for a Brazilian airport (Ribeiro et al., 2013); greywater usage at a Brazilian airport (do Couto et al., 2013, 2015); seawater and greywater use at an airport in Hong Kong (Leung et al., 2012). These studies assess the efficacy of alternative sources in terms of demand met.

2.3.1.1.3.2 Water quality

Water quality concerns related to airport activity can be categorized as persistent, seasonal (e.g., from de-icing operations), and accidental (e.g., fuel spills) (Baxter et al., 2019). Airports make efforts to prevent hazardous pollutants and fluids from entering groundwater or surface water bodies. Stormwater management strategies include use of bioretention basins, green roofs, harvesting, porous pavement, sand filters, and wetland treatment systems (Jolley et al., 2017). The academic literature focuses on water quality issues stemming from de-icing activities, a necessary operation for aircraft and runways in cold-weather climates. De-icing fluid runoff can create negative surface water quality effects that impact aquatic flora and fauna by causing higher levels of chemical oxygen demand and lower levels of dissolved oxygen (Fan et al., 2011; Mohiley et al., 2015). Potential mitigation measures for managing aircraft de-icing include utilization of novel soil filters (Pressl et al., 2019) and treatment with constructed wetlands (Higgins et al., 2011). Most studies assess the water quality impact of de-icing fluid, but one article examined the GHG impact from forgoing collection and treatment of de-icing fluid at a wastewater treatment plant and instead using on-site recycling (Johnson, 2012).

2.3.1.1.4 Site and habitat

Major themes of the Site and Habitat category in the literature refer to the impact airport construction and operation have on existing natural ecosystems, the effects from on-site and public transportation options, and the implications of airport resilience to climate change.

2.3.1.1.4.1 Site

Airport development and operation requires suitable land area. In regions where existing land is not suitable, land reclamation is used to create a suitable airport environment. Research into the effects of land reclamation on existing ecosystems focus on impacts to soil, water, air, and animal species (Yan et al., 2017; B. Zhao et al., 2019). Another indicator in the literature refers to efficiency of airport land utilization, or how many aircraft operations occur per given unit area (Janic, 2016). Airport operation and its impacts on wildlife populations is another area of research, with the goal of finding specific strategies to discourage and accommodate wildlife populations on airfields, airport water resources, terminal buildings, and control towers (Belant & Ayers, 2014). Work done in the academic literature focuses on identifying the factors that attract avian species to green roofs (Washburn et al., 2016), on the impacts of solar arrays on avian species (DeVault et al., 2014), and on the effects of airport expansion on bat populations (Divoll & O'Keefe, 2018).

2.3.1.1.4.2 Transportation

Sustainable transportation, as it relates to airports, refers to the modes of transportation for shuttling passengers from terminals to parked aircraft and for bringing passengers to airports. Common sustainability practices for on-site transportation include: use of alternative vehicles (e.g., electric vehicles); restriction of vehicle idling; and reducing the number of empty trips (Kolpakov et al., 2018). One study examined the use of an underground rapid transport system (URTS) for transporting airport passengers the long distances from main terminal buildings to satellite and midfield concourse terminals (M.-B. Liu & Liao, 2018). This study did not include specific environmental indicators but noted that use of URTS is sustainable because it frees up congestion from passenger transport on the airfield concourse. Sustainable public transport options might include using automated vehicles (Y. Wang & Zhang, 2019), encouraging passengers to use existing public transport options by enhancing their capacity, discouraging private vehicle use, integrating with other transport hubs (Budd et al., 2016), or installing dedicated electric vehicle charging infrastructure (Silvester et al., 2013).

2.3.1.1.4.3 Resilience

The resilience of airports to climate change impacts is a significantly under-researched subject. Relevant risks that airports in coastal locations will face include impacts from sea-level rise and increased frequency of flooding events (Burbidge, 2016; Marchi, 2015; Poo et al., 2018). Another site implication related to climate change is that increased mean air temperatures will make it harder for aircraft to generate lift, thereby necessitating the construction of longer runways (Coffel et al., 2017).

2.3.1.1.5 Materials and resources

Themes from the literature for Materials and Resources center around selection of materials for the construction of airfield (e.g., runway, taxiway, apron) and terminal building infrastructure, as well as management of waste from airport construction and operation.

2.3.1.1.5.1 Airfield materials

Estimation of environmental effects of airfield pavements is a fairly well-researched subject area, relative to other airport infrastructure. Airfields are either made from asphalt or concrete, which are known major sources of GHGs (Horvath, 2004; Miller et al., 2016; Santero et al., 2011). The sustainability of airfield pavements is constrained by structural integrity requirements and safety standards (Pittenger, 2011).

Evaluation metrics for sustainable airport pavement can be general, such as implementing suggested best practices, including: using recycled aggregate in pavement mixes; using locally sourced construction materials; reducing idling times of construction equipment (Hubbard & Hubbard, 2019). More specific critical factors of a sustainable airport pavement relate to its construction (i.e., the raw materials and equipment used, transportation, waste management) and its operation, which is a function of the pavement's structural characteristics (Babashamsi et al., 2016). Table A3 in Appendix A highlights the specific sustainable practices and assessment methods/metrics found in the literature as they pertain to different parts of the airfield. Example sustainable practices include use of supplementary cementitious materials (SCM) in concrete runways and use of recycled aggregates in taxiway and apron construction. LCA is frequently used in measuring the environmental sustainability of airfield pavements. The scope of most of the LCAs is limited to impacts from the raw material and construction phases of the airfield.

2.3.1.1.5.2 Building materials

Relative to the airfield, environmental impact analysis of other airport infrastructure (e.g., terminal buildings) is much more limited. LCAs have been performed to determine the optimum level of thermal insulation for terminal buildings at two Turkish airports with a focus on selecting a design that reduces GHG emissions (Akyüz et al., 2017; Kon & Caner, 2019). An extensive overview of construction methods and building materials that are standard practice (e.g., using locally sourced materials) among the green building community is applied for airports (Transportation Research Board, 2011). It is common practice, as mentioned in the ACRP literature, for airports to aim for green building certification from groups such as the United States Green Building Council's Leadership and Energy in Environmental Design (LEED) like LEED provides a checklist framework where building owners (municipalities in the case of airports) earn points for choosing 'green' building materials and design attributes, among other criteria. There are over 200 LEED certified airport buildings worldwide (USGBC, 2021), with SFO's Terminal 2 the first LEED Gold airport terminal in the United States (SFO, 2011).

2.3.1.1.5.3 Waste management

Analysis of waste management at airports is another emerging research area. Waste sources at airports include food waste from retailers/concessionaires, construction waste, and aircraft-related (Transportation Research Board, 2018a). Metrics applied for analyzing waste at a major international airport include quantity of waste, waste source fraction, and waste amount per operation (Baxter et al., 2018a). One article assessed the life-cycle impact, in terms of air emissions, of six waste management scenarios at Hong Kong International Airport determining that on-site incineration with heat recovery yielded optimal results (Lam et al., 2018).

2.3.1.1.6 Multidimensional studies

Sustainability, as expressed in ACRP reports (Delaney & Thomson, 2013; Lurie et al., 2014; Malik, 2017; Prather, 2016; Program, Administration, & Brown, 2012), encompasses many categories including energy and climate, water, waste, natural resources, human well-being, transportation, and building design and materials. Many of the metrics that the ACRP literature use to assess the specific categories of sustainability mirror those described in the academic literature. A theme among the ACRP work is the evaluation of sustainability practices from an economic and practical perspective, recognizing that implementation can yield economic benefit but takes concerted, coordinated effort.

Table 5 identifies metrics used for quantifying impacts and strategies used to reduce impacts. These metrics and strategies are extracted from the multidimensional journal articles included in the systematic review. Each metric or strategy is prioritized to the one of the five categories of interest. While the focus of this review paper pertains to metrics/strategies that evaluate the sustainability of physical airport infrastructure, and not does focus on environmental impacts related to the aircraft LTO cycle, some of the multidimensional papers include indicators for evaluating those specific environmental impacts (e.g., noise from near-airport aircraft operations). The indicators in Table 5 range from explicit, quantifiable metrics (e.g., tonnes CO2 per passenger) to more vague best practices (e.g., conserve energy in airport buildings). The metrics and strategies that are explicit and quantifiable are more informative for enacting policy measures than are vague strategies such as 'conserve energy' or 'reduce emissions.' It is also more effective for metrics and strategies that connect environmental impacts to operational outcomes and level of service (e.g., number of passenger-miles traveled). Connecting impacts to level of service allows for airports to track how efficiently they are managing their impacts as numbers of operations increase.

Indicators from each multidimensional paper do not always span all five categories of environmental sustainability, suggesting that consensus building on the definition of environmental sustainability needs to occur. The Energy and Atmosphere category dominates with metrics often related to reducing airport building and airfield energy consumption and air pollutant emissions. Of the eight journal articles included in Table 5, all include metrics for addressing noise pollution in the Comfort and Health category, but none provide explicit metrics for assessing indoor air quality for airport buildings. The indicators in the remaining three categories vary in level of specificity. As an example, in the Materials and Resources category, four of the articles suggest airports use 'green building materials' but only one article (Ferrulli, 2016) identifies in some detail what that means.

A theme that emerges from the multidimensional papers are the different methods utilized in determining the overall sustainability of an airport. Utility-based methodologies are utilized in two of the multidimensional articles (Chao et al., 2017; Lu et al., 2018) in the ranking of the most critical indicators by weights applied from expert opinion. Another method for assessing an airport's environmental sustainability is the application of a checklist-based point system where the most sustainable airport implements the most indicators with the highest level of points (Gomez Comendador et al., 2019). One method incorporates cost-benefit analysis where each environmental indicator for an airport development project is transformed into a financial amount and the highest benefit-cost ratio yields the most sustainable outcome (Li & Loo, 2016). A composite ranking indicator is created by normalizing indicators across all categories to compare the environmental sustainability of multiple airports (S. Kilkis & Kilkis, 2016). Only one method applies life-cycle assessment in inventorying the environmental impact from the LTO cycle, APU and GSE operation, de-icing activities, lighting, and construction of an airport terminal, airfield, and parking lot (M. V. Chester & Horvath, 2009).

Table 5. Sustainability indicators from multidimensional papers.

Citation	Energy and Atmosphere	Comfort and Health	Water and Wastewater	Site and Habitat	Materials and Resources
Gomez Comendador et al. 2019	• Control emissions of NO_x, So_x, CO, PM, VOCs, CO_2Limit use of APUs & GPUs • Use ecological cars • Offer infrastructure to support biofuels use • Manage energy consumption • Use renewable energy • Control air conditioning equipment for energy conservation • Use efficient indoor lighting	• Create noise map & mitigation plan • Take steps to isolate community buildings from noise pollution • Acoustic efficiency (number of people exposed per annual number of aircraft movements) • Restrict engine testing during certain time periods • Monitor indoor air quality	• Control water consumption • Reduce indoor/outdoor water consumption • Reduce water consumption in handling • Manage stormwater runoff • Treat wastewater	• Integrate with public/private transport • Select a site that meets aeronautical safety requirements • Measure soil quality • Protect native flora & fauna • Reduce light pollution • Reduce heat island effect	• Treat hazardous waste from maintenance activities • Recycle waste • Implement a construction/maintenance/demolition plan for infrastructure • Choose green building materials
Lu et al. 2018	• Carbon emission reduction & energy conservation	• Prevention & monitoring of noise			• Green Building Practices
Chao et al. 2017	• Conserve energy in buildings • Use ground power units over auxiliary power units • Use low-emission vehicles • Use energy-savings control devices • Use renewable energy • Monitor air quality	• Monitor noise	• Install water-saving devices • Use recycled water • Recycle wastewater	• Practice ecological conservation	• Use green building materials • Engage in waste reduction, reuse, & recycling

Citation	Energy and Atmosphere	Comfort and Health	Water and Wastewater	Site and Habitat	Materials and Resources
	• Shorten runways to reduce queuing time				
Ferrulli 2016	• Design airside layout to minimize aircraft emissions • Design infrastructure & buildings to minimize CO_2 emissions • Reduce building-level energy consumption • Reduce outdoor energy consumption • Use alternative & renewable energy	• Design airside layout to reduce noise impact • Provide physical mitigation barriers between operating areas & surroundings	• Landscape & design to reduce water use • Design for water efficient use • Design to maximize water harvesting, recycling, reuse • Design to reduce stormwater quantity • Design to improve stormwater quality	• Reduce parking footprint • Integrate infrastructure for public transport • Avoid destruction of sensitive habitats • Avoid attracting certain species • Design to reduce heat island effect • Design to reduce light pollution	• Design for storage & collection of recyclables • Design for deconstruction, reuse & recycling • Use recycled, bio-based, & rapidly renewable materials • Use materials with a high design service life
Kilkis & Kilkis 2016	• Energy Consumption (toe) • Energy Consumed per Passenger (toe/Passenger) • ISO 50001 Certification[a] • Implementation of Energy-Saving Measures • Use of On-site Energy • CO_2 Emissions	• Noise abatement for decibels ≤ 60	• Water Withdrawal (m3) • Percentage of utilized recycled water	• Amount of Conserved Area (hectares)	• ISO 14001 Certification[c]

Citation	Energy and Atmosphere	Comfort and Health	Water and Wastewater	Site and Habitat	Materials and Resources
	(tonnes) • CO_2 per Passenger (tonnes/Passenger) • CO_2 Emissions per Unit Energy (tonnes /toe) • Recognition under ACI's Airport Carbon Accreditation[b] • Aiming for CO_2 Neutrality • Concentration of PM_{10} ($\mu g/m^3$) • Use of low-emission ground vehicles				
Li & Loo 2016	• Mass of CO_2, SO_2, NO_x, PM, VOCs, HC, NH_3 per annual operations	• Level of Noise Pollution	• Amount of Water Pollution	• Amount of Habitat Loss	
Janic 2010	• Energy Efficiency (Energy consumption per annual WLU[d]) • Air Pollution Efficiency (Total air pollution per annual WLU)	• Noise Efficiency (Number of households, population, or area exposed to specified noise level per year)		• Land Use Efficiency (Number of aircraft operations per unit area per year)	• Waste Efficiency (Amount of waste generated per annual WLU)
Chester & Horvath 2009	• CO_2 emissions per passenger-kilometer-traveled (PKT) • Energy consumption per PKT • CO, SO_2, NO_x per PKT				• CO_2 emissions per passenger-kilometer-traveled (PKT) • Energy consumption per PKT • CO, SO_2, NO_x per PKT

The multidimensional articles that include case study airports are listed in Table 6, along with each airport's location. All the case study airports are considered major international hubs, averaging millions of passengers per year. Their locations span the primary airport markets including Asia, Europe, and the United States, but do not reflect the emerging markets of Latin America and Southeast Asia. By comparing airports of a similar operational capacity, the multidimensional papers offer some insight into how varying regions influence environmental impact. However, more case study airports are necessary to capture local impacts. Insight is lacking on whether the sustainability indicators developed in these multidimensional articles result in distinct environmental outcomes for disparate levels of airport service (e.g., small, regional airports; medium hub airports). Modeling environmental impacts from an average airport (M. V. Chester & Horvath, 2009) allows for generalization of results, which might yield more far-reaching outcomes (i.e., sustainability indicators can be applied to a greater range of airports).

Table 6. Case study airports/locations from multidimensional papers.

Citation	Case Study Airport (Code)	Location
Chao, Lirn, & Lin 2017	• Narita (NRT) • Incheon (ICN) • Kaohsiung (KHH) • Istanbul (IST) • Miami (MIA)	• Japan • South Korea • Taiwan • Turkey • United States
Kilkis & Kilkis 2016	• Amsterdam (AMS) • Ataturk (IST) • Barcelona (BCN) • Frankfurt (FRA) • Gatwick (LGW) • Heathrow (LHR) • Munich (MUC) • San Francisco (SFO) • Seoul (ICN)	• the Netherlands • Turkey • Spain • Germany • United Kingdom • United Kingdom • Germany • United States • South Korea
Li & Loo 2016	• Hong Kong (HKG)	• Hong Kong
Chester & Horvath 2009	• Average airport modelled after Dulles International Airport (IAD)	• United States

2.3.1.2 Summary of trends in existing research

Figure 5 shows a word cloud diagram of the article titles included in each of five sustainability categories and the multidimensional category. Frequently used words appear larger relative to less frequently used words. Figure 5 provides a visual representation of the key themes for each category. A summary of key trends in the five sustainability categories and the multidimensional category include:

- Energy and atmosphere: Articles focus on investigating the efficacy of on-site renewable energy at various case study airports. Common sustainability indicators are total energy consumed and mass of GHG emissions from energy consumption. Best practices are considered as: monitoring of energy consumption; utilization of energy efficient HVAC equipment and lighting; installation of on-site renewable energy. There is some effort, particularly in the ACRP literature, to evaluate best practices from a practical perspective (e.g., addressing the safety implications of PV installations). Use of LCA in this category is limited.

- Comfort and health: Most of the research is focused on indoor comfort and health indicators like preferences for thermal and lighting conditions and concentrations of PM, VOCs, CO, and CO2. Studies on exposure to ambient air pollutants from non-aircraft sources are limited. Most of the research on ambient air quality aggregates emissions from all sources. There is recent effort to investigate the impact from non-aircraft sources such as APUs, GSE, and GPUs and to identify possible solutions for these equipment (e.g., use of external electrical power and air conditioning units).

- Water and wastewater: Articles focusing on estimating the potential utilization of alternative water sources at airports dominate. Water quality research pertains to impacts from stormwater and de-icing fluids. A typical article in the Water and Wastewater category includes annual water consumption per passenger or flight operation. There is discussion in the literature on whether a disaggregated metric (e.g., indoor water consumption per passenger, outdoor water consumption per passenger) might be a more effective performance indicator.

- Site and habitat: This category is the least explored in the literature. Few articles offer measurable indicators, with most of the quantifiable metrics relating to land use efficiency and destruction of wildlife habitat. There is need for quantifiable indicators for research in on-site, public/private transport and for climate change adaptation practices.

- Materials and resources: Research on the environmental sustainability of airfield pavements dominates this category. LCA is the most frequently used assessment methodology, with life-cycle GHG emissions and energy consumption the most common assessment metrics.

- Multidimensional: Research that investigates airport sustainability from a multidimensional perspective is grouped according to efforts by ACRP and by the academic community. ACRP largely defines environmental sustainability across the five categories (i.e., energy and atmosphere, comfort and health, water and wastewater, site and habitat, materials and resources), but often focuses on economic and practical factors of implementing sustainability best practices. These best practices are often identified through interviewing and surveying United States airports. Sustainability indicators in the academic literature predominantly focus on energy consumption and GHG emissions. Sustainability is assessed with several methodologies (e.g., utility-based theories, cost-benefit analysis, LCA), suggesting that within the academic community there is a lack of consensus on what attributes and indicators make an airport sustainable.

Figure 5. Word cloud diagram of article titles included in systematic review. Frequently used terms appear larger relative to less frequently used terms.

Application of an airport sustainability assessment

This section reviews the application of the SFO environmental sustainability framework on an existing infrastructure project at the airport.

2.3.2.1 Selection of case study airport

San Francisco International Airport (SFO) is one of the United States' large hub airports and it serves major domestic and international routes. The airport ranked seventh among busiest airports in 2018, with enplanements totaling close to 28 million (FAA, 2021d). The airport was an early adopter in implementing sustainability efforts and in developing metrics to assess the sustainability of construction and operation of airport infrastructure projects (FAA, 2021a; SFO, 2021). A review of the implementation of SFO's sustainability framework answers two critical questions: (1) how sustainability efforts practically get implemented at airports, and (2) how their implementation is or is not effective in yielding measurable benefits. Featuring SFO as a case study offers stakeholders (e.g., regulators, airport operators, the public) insight into what is considered best practices, or acceptable methods, for managing environmental impacts for major international airports. Additionally, it provides some understanding of how sustainability measures at an airport like SFO might not work as well for other airport types (e.g., small hub, regional, general aviation, etc.).

2.3.2.2 Development of sustainability indicators

SFO is redeveloping their Terminal 1 as part of a capacity-enhancement upgrade for the entire airport; the upgrade will increase the terminal's total number of annual enplanements to 8.8 million. Sustainability indicators were developed in conjunction with SFO's planning, design, and construction guidelines as a measurable index for determining whether the Terminal 1 project will comply with the airport's overarching environmental goals (e.g., achieving GHG emission reductions relative to a baseline year). Each sustainability indicator is grouped according to relevant themes in the five categories of Energy and Atmosphere, Comfort and Health, Water and Wastewater, Site and Habitat, and Materials and Resources. Indicators are either considered 'Mandatory Requirements' or 'Expanded Requirements.' 'Mandatory Requirements' outline metrics and practices that must be achieved according to applicable federal, state, regional building codes and city-wide mandates (e.g., meeting LEED requirements). 'Expanded Requirements' are voluntary metrics and practices that project participants (i.e., contractors) are obligated to implement where feasible. For example, a city-wide 'Mandatory Requirement' in the Energy and Atmosphere category mandates 40% reductions below 1990 GHG emissions by 2025. An example 'Expanded Requirement' calls for reduced GHG emissions from natural gas consumption by using automated HVAC systems.

2.3.2.3 Implementation of indicators

The indicators are intended to be used for the planning, design, construction, and operation/maintenance phases of airport facilities. An additional level of evaluation is applied to each 'Expanded Requirement.' Requirements are rated as 'Baseline,' 'Baseline Plus,' or 'Exceptional Project Outcome.' Per the previous 'Expanded Requirement' example, 'Baseline,' 'Baseline Plus,' or 'Exceptional Project Outcome' ratings would be given to 10%, 20%, and 30% reductions in GHG emissions, respectively. Such a rating system allows SFO to discern between project outcomes that are more 'sustainable' than others.

The results of an analysis of the projected reduction in annual GHG emissions per square meter from implementing Energy and Atmosphere 'Expanded Requirements' in SFO's Terminal 1 project are shown in Figure 6. The specific 'Expanded Requirements' include practices that rely on reduced natural gas and electricity consumption in terminal buildings (e.g., energy-efficient escalators, dynamic glazing, radiant heating and cooling). It is projected that these 'Expanded Requirements' will reduce Terminal 1's energy use intensity (EUI). The EUI indicates how much natural gas and electricity is consumed by buildings. By converting the EUI to an equivalent amount of GHG emissions per square meter, it can be shown that the GHG intensity of the Terminal 1 project will be less than the average of other SFO buildings. The blue bars in Figure 6 show the amount of GHG emissions per square meter, while the dotted outline indicates the amount of annual GHG savings per square meter in the Terminal 1 project. The GHG emissions account for the upstream processes related to natural gas provision and electricity generation. See Appendix A for the complete methodology in producing Figure 6. The savings represent an approximate 57% reduction relative to the average GHG intensity for all SFO airport building infrastructure.

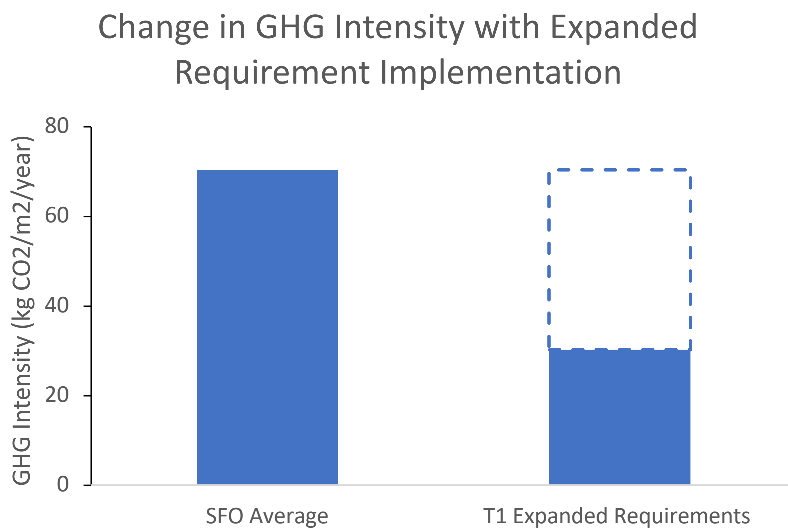


Figure 6. Reductions in GHG Intensityassociated with implementing energy reducing ‘Expanded Requirements’ in Terminal 1 (T1) project relative to the SFO average. Savings are relative to 2018 data.

2.4 Discussion

2.4.1 Limitations and gaps of existing research

With few exceptions on airport energy (B. Kilkis & Kilkis, 2017; Tagliaferri et al., 2018), overall sustainability (M. Chester & Horvath, 2012; M. V. Chester & Horvath, 2009; Taptich et al., 2016), and airfield pavements, much of the research fails to holistically analyze the environmental impacts through supply chains and regional variations. While the ACRP literature provides a sample representation of current best practices at airports, its analysis is sometimes limited by the responses it receives from case study airports. For both the ACRP and academic literature, analysis of sustainability indicators is often limited by the scope of a case study airport, so it is difficult to link research results with suggested practice or policy outcomes.

The literature in the Energy and Atmosphere category lacks a broader understanding of how much energy is used at different airports, what it is used for, and where it comes from. Current estimates are limited by the number of existing case study airports. With an exception (Ozdemir & Filibeli, 2014), the academic literature limits its characterization of GHG emissions according to Scope 1, Scope 2, and Scope 3. This limitation in the literature indicates that there is a slight disconnect between the academic research community and the airport industry and stakeholders as the Scope characterization is how the industry thinks about and manages GHG emissions. Research that investigates different energy sources (e.g., solar; bioenergy) and energy provision strategies (e.g., grid versus on-site storage) is just beginning, and more effort in this area is needed. Additional gaps in the research include:

- Environmental impacts of energy consumption in terms of other pollutants besides GHG emissions;
- Environmental assessment of airports and supply chains using local and regional models and data (Cicas et al., 2007);
- Characterization and environmental impact assessment of energy consumption patterns for specific airport infrastructure and equipment by region (e.g., United States airport terminals are focused on food consumption; European/Asian airports serve as retail/recreational centers); and
- Energy consumption impacts from construction of new airport expansion/retrofitting projects.

As with the Energy and Atmosphere category, research in the Comfort and Health category could be broadened to include more research and innovative and exploratory case studies. In light of COVID-19, more research is urgently needed to investigate how terminal building design and ventilation equipment might influence spread of infectious diseases. Ambient air quality research tends to aggregate sources, which makes it difficult to determine if mitigation policies are effective. Additional gaps in the research include:

- More human health-focused exposure studies related to operation of non-aircraft equipment, such as GSE, GPUs, APUs, and ground access vehicles;
- Investigation of air pollutant concentrations related to landside operations, such as passenger pick-up and drop-off;
- Research on human health impacts from airfield and terminal building maintenance, retrofit, and construction; and
- Air quality impacts related to selection of different building materials and cleaning/daily maintenance procedures.

As suggested in the Water and Wastewater literature, assessing an airport’s water consumption in terms of volume per day provides minimal insight. More research should be conducted to provide a thorough overview of disaggregated water consumption at the airport level so that sustainable practices can be implemented appropriately. A major gap in the literature is the complete lack of research into the linkage between water consumption, water quality, energy needed to convey, treat and heat water, and the resulting GHG and other environmental emissions and impacts. This water-energy nexus is particularly relevant in examining the environmental sustainability of using alternative sources of water at airports, especially with respect to potable versus non-potable demands and options.

Much of the literature in the Site and Habitat category lacks explicit, quantifiable sustainability indicators and there is vast room for investigation into the following gaps:

- Energy and environmental implications of constructing resilience infrastructure, such as sea walls and stormwater systems;

- Environmental impacts of onsite transportation systems, such as underground rapid transit systems;

- Overview of the types of suitable, environmentally efficient transportation modes within and outside of the airport boundary, which is dictated by airport configuration and location; and

- Environmental trade-offs between site selection and terminal building orientation and layout of runways.

Research in the Materials and Resources category is predominantly focused on environmental impacts of airfield pavement construction and maintenance, with life-cycle energy consumption and GHG emissions as common metrics. Within the theme of airfield pavements, more research regarding innovative designs and maintenance techniques are warranted. There is a lack of understanding on what sustainable pavement practices can be implemented at airports of different operational capacities. Small and medium-sized airports might be good candidates for testing out innovative practices because their load or volume requirements tend to be smaller than those of larger airports. In terms of sustainable materials and design for airport buildings, research results are limited. In practice, it is more common for airports to strive for LEED certification of airport buildings. LEED, for practical purposes, is a relatively easy standard to implement, but is not sufficient for meeting quantified performance goals throughout the life cycle of airports. Additional gaps in the research include:

- Environmental impact of conventional and alternative construction materials in terminal building infrastructure;

- Sustainability impacts of supply chains and sourcing of airport construction materials; and

- Deeper understanding leading to defensible actions on waste generation and waste management techniques at airports, especially in the context of waste-management policies such as ‘zero-waste’ and bans of single-use plastics.

A review of articles in the Multidimensional category indicates that there is no cohesive, agreed-upon definition of airport environmental sustainability. Gaps in the research include:

- Determining optimal methods for achieving overall environmental sustainability at an airport, also integrated with achieving specified city, regional-level, airline, or civil aviation targets;

- Integration of life-cycle, or holistic, thinking within a specified time horizon into decision making (e.g., should an airport implement an electricity-based strategy if the electricity is generated from fossil fuels?);

- Specifying environmental sustainability indicators in the context of airport operational safety;

- Investigating the overlap between environmental sustainability and airport resilience;

- Rigorous analysis of environmental sustainability and operational parameters; and

- Integration of actions in achieving societal sustainable development (economic, environmental, social) with airport, airline, air traffic control, and in general, civil aviation goals.

2.4.2 Efficacy of case study application

A projected 57% reduction in annual GHG emissions per square meter from consuming natural gas and electricity on-site within the airport terminal buildings suggests that SFO's sustainability assessment indicators have the potential to be effective. A more meaningful expression of results would relate saved GHG emissions to the airport's level of service (e.g., GHG emissions per passenger or per revenue dollar). There are limitations to stating one airport's efforts as 'best practice.' It should be emphasized that applicability from the results of the case study is dependent upon local factors. For SFO, implementing energy-efficient strategies saves more GHG emissions because SFO's electricity is supplied from hydropower, which is less carbon-intensive relative to the state average. Utilizing low carbon-intensive energy is a key sustainability performance indicator. While post-facto analysis would be able to confirm actual GHG reductions from implementing 'Expanded Requirements,' the project is still ongoing. Some important observations can still be made regarding SFO's sustainability indicators.

In discussions with parties involved with the Terminal 1 reconstruction projects, having sustainability criteria at the outset of project development is crucial. All involved parties must be aware of their specific commitments. It is a good practice going forward for project contracts to incorporate strong sustainability performance indicators. SFO plans to integrate language more thoroughly into the Architectural and Engineering standards and guidelines that specifically align with two of SFO's guiding environmental priorities, namely climate change and human and ecological health. Regarding the former, the new contract language will explicitly require that decarbonization be reflected in project design and procurement. For example, instead of a voluntary consideration as part of an 'Expanded Requirement,' low-carbon structural steel would have to be selected as a building material. The voluntary aspect of the framework (i.e., the 'Expanded Requirements') and the evaluation of 'Expanded Requirements' as baseline, baseline plus, and exceptional project outcome are rather subjective. Such subjectivity does not necessarily result in a completed project with the best environmental performance. Additionally, the SFO framework relies upon building codes that while they are 'state of the art' compared to building codes outside of California, represent a minimum standard. If interested in attaining a facility or project that meets a specified, quantifiable environmental outcome, the subjectivity of a rating system or checklist is not the most effective approach.

SFO's sustainability indicators do not explicitly consider the tradeoffs that potentially occur with prioritizing one criteria over the other; it is a rather static framework that could benefit from incorporating spatial and temporal factors. For example, electing to use a decentralized recycled water source (which is an 'Expanded Requirement' in the Water and Wastewater category) is sometimes an energy-intensive process which can result in increased GHG emissions while enhancing resilience. In this anecdotal example, there is a potential tradeoff between achieving water conservation and reducing GHG emissions. While the SFO framework might work well for an airport that explicitly prioritizes overarching goals (e.g., reducing GHG emissions and climate change impact), it might need to be reevaluated for airports that must equally consider sometimes conflicting environmental priorities.

2.4.3 Suggestions for direction of future research

The roadmap for future research of airport environmental sustainability emphasizes increased stakeholder involvement, more life cycle-based analysis, linkage of environmental impacts with operational outcomes, and addressing major challenges such as adaptation to climate change and mitigation of infectious diseases like COVID-19.

Airport environmental sustainability is often addressed at project scale. There is a need for investigating the larger role that airports have in impacting the environment, especially in the context of achieving city- and regional-level environmental outcomes that lead most directly to higher environmental quality of people and ecosystems. This ties in with stakeholder involvement because for sustainability indicators including GHG emissions, an airport only claims responsibility for Scope 1 and Scope 2 emissions. Airports often exclude ownership of Scope 3 emissions (e.g., emissions from an airline's GSE, without which there are no airports). The outcome of an airport excluding ownership of Scope 3 emissions is twofold: (1) it is more difficult to manage Scope 3 emissions, and (2) it is difficult to understand an airport's total GHG impact at the city/regional/state/national level, which is important for meeting larger-scale climate performance targets. Therefore, a broader analysis of how different stakeholders should be included in addressing environmental sustainability efforts is necessary.

Society faces important challenges such as adapting to climate change, mitigating the spread of pandemic-causing diseases, and enhancing environmental quality of people and ecosystems. An airport's role in addressing these challenges is largely undefined, but sure to be a significant one. It is imperative that thorough research on an airport's role in managing these challenges gets organized.

2.5 Conclusions

A comprehensive, systematic review of 108 peer-reviewed articles and technical reports related to assessing and measuring aspects of airports' environmental sustainability has been conducted. Articles have been characterized according to the following categories: Energy and Atmosphere, Comfort and Health, Water and Wastewater, Site and Habitat, Materials and Resources, Multidimensional. Along with a systematic review of academic literature, a review has been undertaken of the application of an existing airport sustainability assessment framework for a case study airport, SFO.

A broad conclusion from the systematic review is that interest in airport environmental sustainability as a research topic is steadily increasing, but that there is ample need for more investigation. Prominent research themes within the scope of airport environmental sustainability include analyzing the environmental impacts (namely GHG emissions) from airfield pavements and energy management strategies for airport buildings, but not from other components of airports and for other environmental emissions and impacts. There is a dearth of research on the impacts of indoor air quality at airports. In the research community, there appears to be a lack of consensus about the scope of environmental impacts that should be included when evaluating the overall sustainability of airports. GHG emissions from energy consumption are one of the most commonly used metrics in research focused on overall airport sustainability.

Methods for evaluating environmental impacts vary. Systems like the World Resource Institute's Scope 1, 2, and 3 designations for GHG emissions and the LEED system for buildings are well-represented in airport-industry practice. The Scope designation primarily divides responsibility for mitigating emissions between airports and airlines, creating a gap whereby airports cannot directly control all emission sources. LEED is a minimum standard that is not sufficient for meeting quantified performance goals throughout the life cycle and supply chains of airports.

Moving forward, the increased use of assessment methodologies such as LCA will be useful in guiding decision makers and policy outcomes in a more robust, granular direction. In the academic literature, LCA is primarily used for evaluating the environmental impact of airfield pavement construction. However, LCA can and should be applied to evaluate all components of airport construction and operational activities and to guide decision-making as to what practices will yield optimal results. LCA is the only comprehensive, systematic methodology (defined in ISO 14040 and 14044) that estimates the entirety of life-cycle environmental impacts of a product, process, or service. This method is very useful for accounting for regional differences in impacts, for comparing among alternative strategies, and for identifying weak points or activities that result in the greatest environmental burdens. There are also economic and social aspects of LCA that are helpful for decision makers. One LCA approach, Economic Input-Output LCA, can be used to evaluate the resources, energy, and emissions resulting from economic activity throughout a product's supply chain (Hendrickson et al., 1998). There are efforts to use a life-cycle approach to focus on the social aspects of a product's impacts (Grubert, 2018). While addressing the economic and social impacts from airports is beyond the scope of this review, the economic and social implications of airports are likewise very important and demand thorough investigations and actions.

In conjunction with LCA, future research should apply analysis that connects environmental impacts with operational parameters for specific airport occupant groups (e.g., ground handlers), airport infrastructure (e.g., apron), and airport scale (e.g., small, medium, large hubs). Accounting for operational parameters at different scales will provide a better understanding of how environmental sustainability efforts impact different stakeholders and the airport's primary function (i.e., processing passengers and cargo).

A key aspect of addressing the environmental sustainability of airports is the involvement of different stakeholders. As identified in Figure 1, the airport is comprised of airside and landside components. Historically, these components have been managed by distinct stakeholders. Understanding the relationship among the airport components, their respective environmental impacts, and their ways of managing stakeholder groups is critical because it leads to identifying who must act to mitigate environmental impacts. Figure 7 depicts an annotated version of the airport system boundary with suggested best practices for major airport components. Based on the literature review and the application of the SFO case study, effective sustainability practices that airports can implement in the short term are: (1) supply electricity from renewable, low-carbon sources whether on-site or from local utilities; (2) electrify transportation vehicles (e.g., shuttles, maintenance trucks) within the airport system boundary; (3) electrify all gate and ground service equipment; (4) implement water conservation practices like installation of water-efficient faucets and toilets; (5) install energy-efficient fixtures like LED lighting in all airport infrastructure; (6) select durable interior building materials for improved maintainability and reduced waste production.

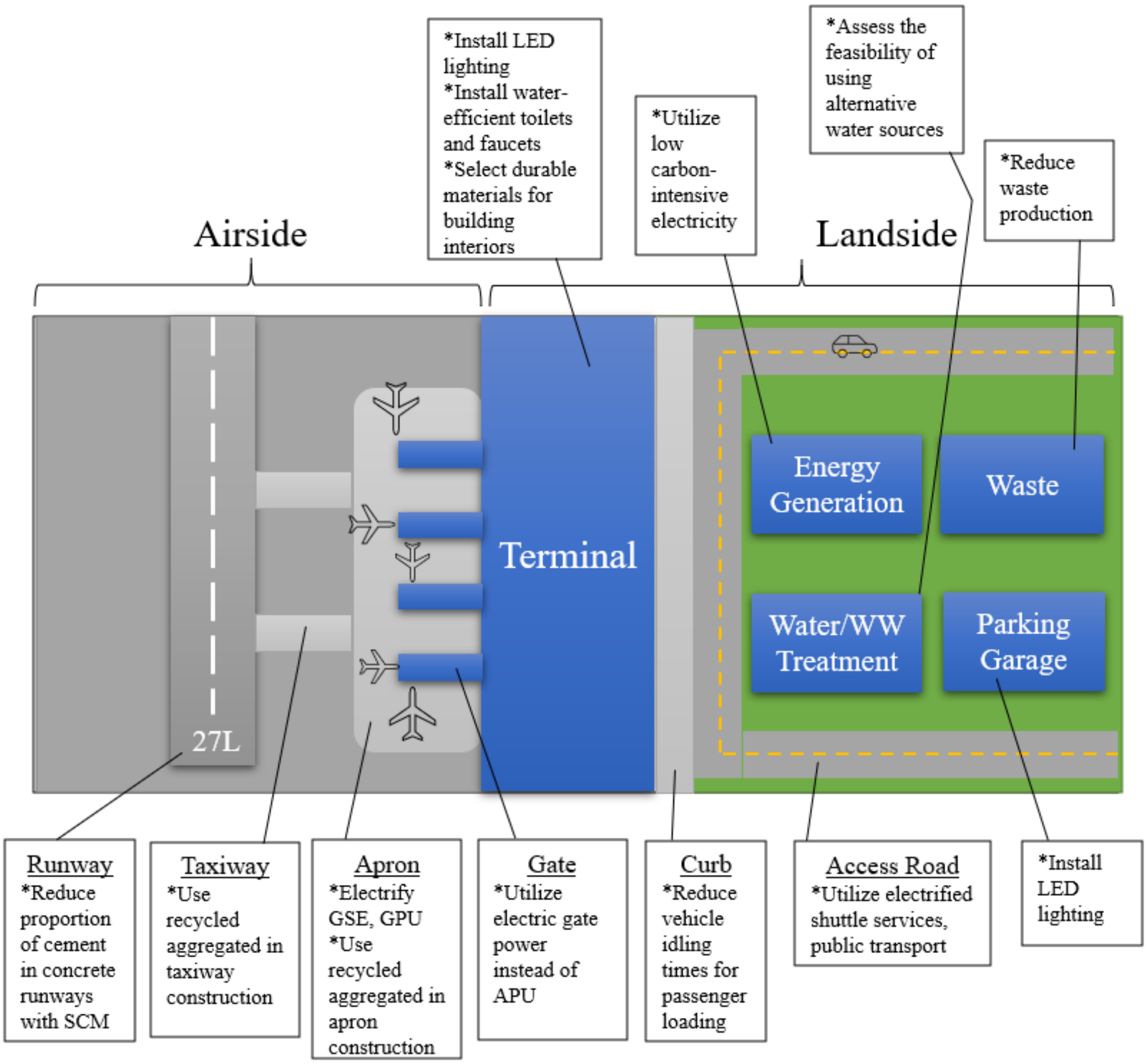


Figure 7. Suggested best practices for improving airport environmental sustainability.

These six suggested sustainability practices can result in prompt, substantive environmental benefits without significant tradeoffs. For example, relying on low-carbon electricity reduces GHG as well as other emissions. Electrifying ground service equipment and other airport vehicles results in reductions of air pollutants (NOx, PM) within the airport vicinity, which is a human health benefit. These practices are considered implementable in the 'short term' as opposed to longer-term projects such as changing the material composition of the airfield or installing on-site, decentralized wastewater treatment. These measures cover activities and operations that essentially occur at all airports, but to varying degrees of scale (e.g., all airports consume electricity). In that vein, ease of strategy implementation depends upon airport type, the resources (e.g., cost, accessibility, expertise) available to the airport for successful implementation and the controlling stakeholder. Further analysis of those distinctions is needed in future research.

One common tendency is for airports to adopt a perceived ‘best practice’ based upon another airport’s successful implementation. But progress is needed to ensure that every airport considers all relevant environmental sustainability indicators systematically to account for regional and supply-chain effects rather than simply follow others’ actions. This ties in with the further need to connect all relevant environmental impacts with local human health and ecosystem effects as communities living in proximity of airports bare a greater burden of airport operations. Future research should concentrate on the development of quantifiable indicators or performance metrics. Research and practice that increase stakeholder involvement, incorporates life-cycle assessment, and links environmental impacts with operational outcomes will help airports as well as the aviation industry to address their roles in major global challenges (e.g., climate change adaptation, mitigation of infectious diseases).

Chapter 3. Environmental and Economic Assessment of Airport Gate Electrification

The following chapter is adapted from Greer, F., Rakas, J. and Horvath, A., 2021. Reduce aviation's greenhouse gas emissions through immediately feasible and affordable gate electrification. Environmental Research Letters, 16(5), p.054039, with permission from Jasenka Rakas and Arpad Horvath. Copyright 2021, The Authors. Published by IOP Publishing Ltd.

Aircraft at airport gates require power and air conditioning, provided by fossil fuel-combusting equipment, to maintain functionality and thermal comfort. We estimate the life-cycle greenhousegas (GHG) emissions and economic implications from electrifying gate operations for 2,354 commercial-traffic airports in the world. Here we show that complete electrification could yield GHG reductions of 63%–97% per gate operation relative to current practice, with greater reductions correlated with low-carbon electricity. Economic payback periods average just 1–2 years. Shifting to complete gate electrification could save a high-traffic airport an average of $5–6 million in annual climate economic damages relative to estimates of current practice. 10–12million metric tons of annual GHG emissions are potentially saved if most airports in the world electrified gate operations, costing the 24 busiest global airports on average $25–30, United States airports $60–70, and non-United States airports $80–90 per metric ton of CO_2 mitigated, in some cases comparableto carbon-market prices. Environmental benefits depend primarily upon electricity sources and operational parameters such as aircraft fleet composition.

3.1 Introduction

The aviation industry is a critical component of the global transportation network, moving over 4.4 billion passengers in 2018 (IATA, 2019) and 221-billion-ton kilometers of freight (World Bank Group, 2020). The industry contributes 2%–3% of global anthropogenic greenhouse gas (GHG) emissions (Graver et al., 2019; ICAO, 2020a), but is expected to account for a larger share as other transportation and industrial sectors more easily decarbonize (Terrenoire et al., 2019). More effort is devoted to mapping the carbon impact from aircraft activities (e.g., take-off, cruising, and landing) than from airport operational activities (e.g., lighting terminal buildings and runways, servicing parked aircraft) (Monsalud et al., 2015). It is estimated that airports comprise only 5% of the aviation sector's total GHG emissions (Airport Carbon Accreditation, 2021), but that value is an underestimate because it does not consider the full scope of emissions from all operational activities, including regional and embodied impacts (Greer et al., 2020). Comprehensive environmental accounting of the aviation industry needs to consider GHG emissions from all airport operational activities as the industry explores opportunities to mitigate their climate change contributions more effectively.

During turnaround operations, when an aircraft is parked at a gate between flights, the aircraft requires electrical power and air conditioning to meet functional requirements (e.g., maintaining system functionality and thermal comfort for passengers). Typically, functional requirements are met by exclusively operating the aircraft's auxiliary power unit (APU) or by operating a combination of the APU and diesel-powered ground service equipment (GSE). The APU is a non-thrust engine located at the aircraft's rear and can provide both electrical power and air conditioning, while separate GSE units are necessary to supply additional power and air conditioning. The APU runs on jet fuel, a refined form of kerosene. Combustion of the APU's jet fuel and the GSE's diesel emits GHGs and air pollutants such as nitrogen oxides (NOx), particulate matter (PM), volatile organic compounds, and sulfur dioxides (Kinsey et al., 2012; Lobo et al., 2015; Mokalled et al., 2019; Padhra, 2018; Winther et al., 2015; Xu et al., 2020), which are detrimental to human health (Harrison et al., 2015; Yim et al., 2015). The addition of anthropogenic GHG emissions to the atmosphere leads to the increase of average global temperatures (Pachauri et al., 2014). Increased temperature anomalies are expected to cause, or are already causing, drastic changes in the climate system. Such changes result in impacts including increased frequency and intensity of droughts, wildfires, storm events/hurricanes, and coastal sea level rise, which all have long-ranging, negative consequences for everything living.

Instead of the APU and the GSE, parked aircraft can utilize electricity-powered gate equipment. When parked at the gate, the aircraft is supplied electricity from the airport's electrical grid through 400 Hz ground power cables. Thermal comfort is achieved by connecting hoses from a preconditioned air (PCA) unit to the aircraft. The 400 Hz and PCA systems are often attached underneath or adjacent to the passenger boarding bridge (PBB). The PBB is the fully enclosed gateway that connects passengers from the terminal gate to the parked aircraft (Figure B1 in Appendix B. Recent analysis indicates that gate electrification reduces ambient concentrations of NOx and PM on the airport apron, which is important for mitigating human population exposures (Benosa et al., 2018; Fleuti, 2018; Preston et al., 2019). It has been qualitatively suggested that using 400 Hz and PCA units also helps reduce fuel costs for airlines (Program, Administration, & Associates, 2012). Gate electrification has been identified as an important GHG reduction strategy for airports (S. Barrett, 2019), but currently there is no estimate for the scope of its reduction potential.

While GHG emissions have been inventoried for other airport activities such as the landing and take- off cycle of aircraft (Dissanayaka et al., 2020), there are no existing studies that quantify the GHG emissions, let alone use life-cycle assessment (LCA) to inventory the potential emission reductions from gate electrification across multiple aircraft types, airports, ambient air temperature conditions, or electricity supply mixes. LCA is a standardized methodology, formally outlined in International Organization for Standardization (ISO) 14040, for estimating the environmental impacts throughout a product, project, or service's life-cycle phases (i.e., raw material extraction, processing and manufacturing, transportation and logistics, operations, maintenance, and end of life) (ISO, 2006). LCA is recognized as a robust methodology for holistic decision-making and has been previously used in estimating GHG emissions associated with airport infrastructure such as airfield pavements (H. Wang et al., 2016; Yang & Al-Qadi,

2017) and in inventorying GHG and criteria air pollutants from infrastructure, fuels, supply chains, and flight operations for an average airport (M. V. Chester & Horvath, 2009).

We use flight records and site-specific electricity and air temperature data to quantify the GHG and economic implications, and climate economic damages associated with a range of gate electrification scenarios for the top 24 busiest airports in the world. These 24 airports account for a quarter of global annual traffic (ACI, 2020). We then extend our environmental analysis, with less specific data, to estimate life-cycle GHG emissions from gate electrification for the 2,354 airports responsible for the majority of commercial traffic. We investigate how GHG emission savings from gate electrification compare for airports with differing electricity supply mixes and air temperatures. To provide a perspective on the relative emissions impact from gate electrification, we compare the life-cycle GHG emissions from an average flight to an average gate operation. In assessing the economic impacts of installing and using gate electrification equipment, we calculate the payback period and levelized annual costs at each case study airport. Addition- ally, the climate economic damages associated with gate electrification for both an average gate operation and for all annual operations at each case study airport are quantified. We demonstrate the cumulative GHG emissions reduction potential for a range of gate electrification scenarios for small, medium, and large airports in Africa, Asia, Europe, Latin America, North America, the Middle East, Russia, and the Southwest Pacific. Finally, we estimate the cost per metric ton of mitigated GHG emissions for the 24 case study airports, as well as for the 2354 airports in the global dataset.

3.2 Methods

We use measured data and literature sources to calculate the life-cycle GHG emissions, payback periods, levelized annual costs, and climate damages for annual turnaround operations at the busiest 24 international airports, which span North America, Europe, and Asia. Specific airport names and locations are provided in Table B1 of Appendix B. The 24 airports all serve major domestic and international markets and are responsible for approximately 25% of all commercial flights by aircraft movements. We extend our analysis using fewer specific data to estimate cumulative life-cycle GHG emissions from the 2354 airports that serve all commercial aviation traffic (see section B5 in Appendix B).

Five scenarios (Table 7) are evaluated to determine the range of effects from utilizing the gate equipment. Local characteristics for each airport (i.e., aircraft fleet mix, number and type of flight operations, electricity supply, heating/cooling requirements) are considered so that results are site-specific. Scenarios 1 and 3a/3b represent upper and lower bounds, respectively, on potential GHG emissions from parked gate operations. The scenarios referred to as ‘2a’ and ‘2b’ are an average representation of current practice at a typical commercial traffic airport, taken from a year’s worth of measured data. Scenarios 2a and 2b are representative of the minimum and maximum amount of emissions associated with current practice because of their use of electric and diesel-powered PCA units, respectively. While there is no available comprehensive assessment of the utilization of electric versus diesel-powered PCA, it is likely that actual usage falls somewhere between the rates outlined in scenarios 2a and 2b. The analyzed scenarios, while not an exact depiction of all possible configurations of gate electrification, are emblematic of the conceivable scope of GHG emissions.

Table 7. Descriptions of operational scenarios for analysis.

Scenario	Description	Characterization
1	APU is used for 100% of each turnaround operation	Worst Case
2a	400Hz and electric PCA are used for 70% of each turnaround operation APU is used for 30% of each turnaround operation	Current Situation
2b	400Hz and diesel PCA are used for 70% of each turnaround operation APU is used for 30% of each turnaround operation	Current Situation
3a	400Hz and electric PCA are used for 100% of each turnaround operation	Best Case
3b	400Hz and diesel PCA are used for 100% of each turnaround operation	Best Case

3.2.1 Life-cycle GHG emissions

A life-cycle approach is used to estimate GHG emissions for turnaround operations (i.e., providing electrical power and heating/cooling to parked aircraft) for each scenario. The scope of the LCA is listed in Table 8. End of life impacts are not considered in the analysis.

Table 8. Scope of LCA.

	System			
	APU	400Hz Ground Power	Electric PCA	Diesel PCA
Infrastructure		• Unit manufacturing	• Unit manufacturing	• Unit manufacturing
Operation	• Power • Heating • Cooling	• Power	• Heating • Cooling	• Heating • Cooling
Fuels	• Jet fuel refining and production	• Infrastructure for electricity production • Electricity generation	• Infrastructure for electricity production • Electricity generation	• Diesel fuel refining and production

The life-cycle GHG emissions per turnaround operation are dependent upon multiple factors, including the type of aircraft at the gate, the duration of the aircraft's stay at the gate, the source of electricity utilized by the airport, the air temperature profile of the airport, the gate configuration of the airport, and most significantly, the type of equipment supplying electricity and air conditioning to the parked aircraft. The type of equipment used in supplying electricity and air conditioning is a function of the operational scenario (e.g., scenario 2a). Equation 1 is used to calculate the per-gate-operation life- cycle GHG emissions for scenario 2a (all remaining scenarios are presented in section B.2.1 in Appendix B). Table 9 defines the variables and their corresponding units for Equation 1. The amount of heating and cooling that is provided by the APU and/or the PCA in all scenarios depends upon the air temperature profile of the specific airport. The air temperature profile is determined using monthly average temperatures, which while not temporally refined, are in keeping with previous methodological approaches (Program, Administration, & Associates, 2012).

$$E_i = \Big[D_{TA} \times \Big(Cold\,\% \times FR_{APU,H/C} + Neutral\,\% \times FR_{APU,P} + Hot\,\% \times FR_{APU,\frac{H}{C}}\Big) \times EF_{Jet\ Fuel} \times UR_{APU}\Big] + [D_{TA} \times PR_{400Hz} \times EF_{Elec} \times UR_{400Hz}] + \big[D_{TA} \times (Cold\,\% \times PR_{ePCA,H} + Hot\,\% \times PR_{ePCA,C}) \times EF_{Elec} \times UR_{ePCA}\big] + [EC_{PBB} \times EF_{Elec}] + E_{M,400Hz} + E_{M,ePCA} + E_{M,PBB} \quad \text{[Eq. 1]}$$

Table 9. Scenario 2a equation variables and definitions.

Variable	Definition	Units
E_i	Life-cycle GHG emissions per gate operation *i*	kg CO_2 (eq)op^{-1}
D_{TA}	Turnaround duration of specific operation	h
Cold %	Airport-specific annual share of cold conditions, inclusive between 0 and 1	Unitless
Neutral %	Airport-specific annual share of neutral conditions, inclusive between 0 and 1	Unitless
Hot%	Airport-specific annual share of hot conditions, inclusive between 0 and 1	Unitless
$FR_{APU, H/C}$	Fuel rate for APU heating/cooling conditions, dependent upon wingspan class	L h^{-1}
$FR_{APU, P}$	Fuel rate for APU providing power, dependent upon wingspan class	L h^{-1}
$EF_{Jet Fuel}$	Life-cycle emission factor for jet fuel	kg CO_2 (eq)L^{-1}
UR_{APU}	Utilization rate of APU, dependent upon wingspan class	Unitless
PR_{400Hz}	Power rating of 400 Hz, dependent upon wingspan class	kW
UR_{400Hz}	Utilization rate of 400 Hz, dependent upon wingspan class	Unitless
$PR_{ePCA, H}$	Power rating electric PCA heating conditions, dependent upon wingspan class	kW
$PR_{ePCA, C}$	Power rating electric PCA cooling conditions, dependent upon wingspan class	kW
UR_{ePCA}	Utilization rate of electric PCA, dependent upon wingspan class	Unitless
EC_{PBB}	Electricity consumption of PBB per operation	kWh op^{-1}
EF_{Elec}	Life-cycle emission factor for electricity, airport-specific	kg CO_2 (eq)kWh^{-1}
$E_{M, 400Hz}$	Manufacturing emission factor for 400Hz, airport-specific	kg CO_2 (eq)op^{-1}
$E_{M, ePCA}$	Manufacturing emission factor for electric PCA, airport-specific	kg CO_2 (eq)op^{-1}
$E_{M, PBB}$	Manufacturing emission factor for PBB, airport-specific	kg CO_2 (eq)op^{-1}

Figure 8 provides a schematic diagram that details the types and sources of data used for estimating turnaround durations as well as carbon intensities for the 400 Hz unit and the PBB (with schematics for the other equipment presented in section B2.1. in Appendix B). The figure outlines the sources of data (‘Database’ section), the distinct parameters used in calculations (‘Data’ section), and the outcomes from the calculations (‘Results’ section).

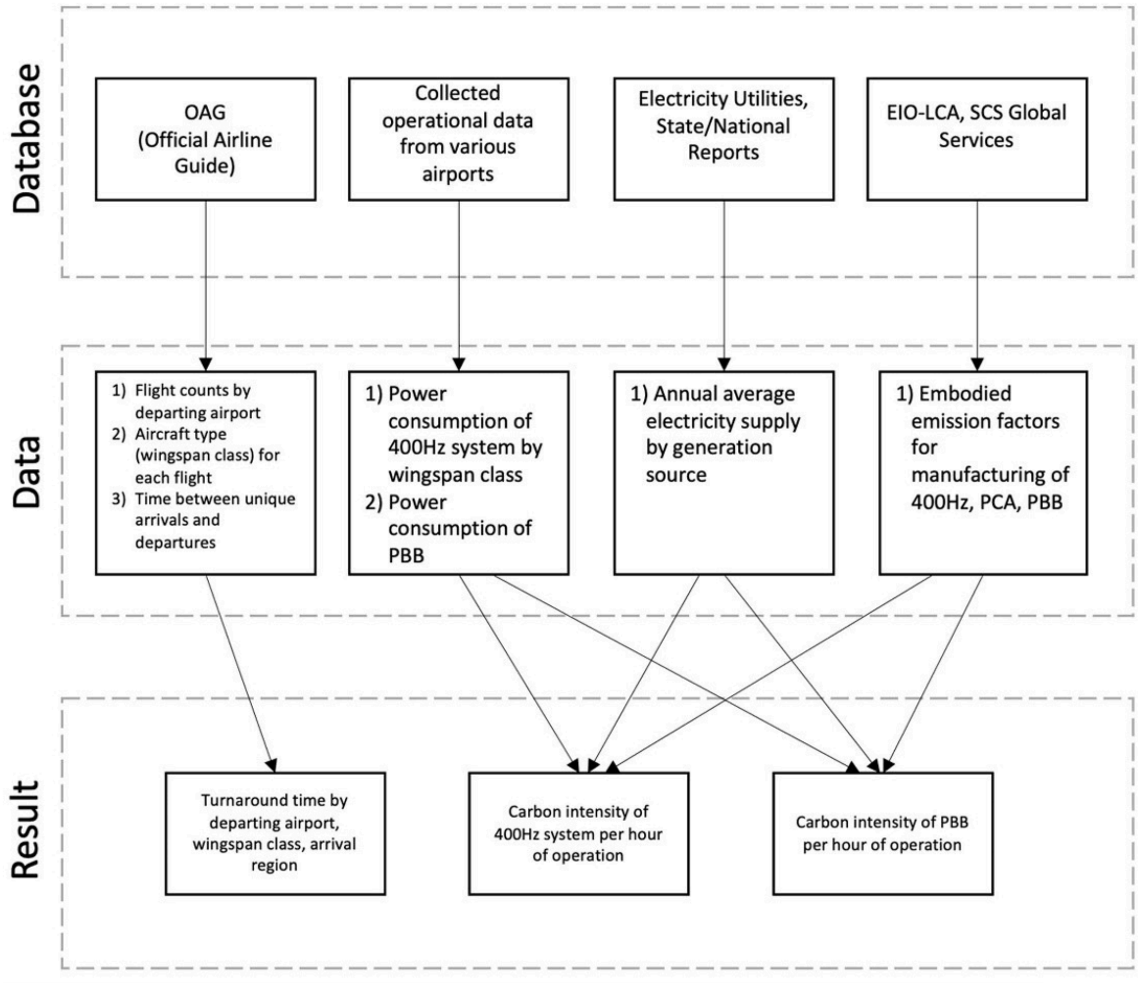


Figure 8. Depiction of data used for estimating GHG emissions from 400Hz and PBB per gate operation.

Data from a flight record database are used to estimate turnaround durations for each of the 24 case study airports (L. Perry, personal communication, 22 June 2020). Using the flight record database, we develop an inventory of flight counts by departing airport and by aircraft type, which is also known as wingspan class, for the 2019 calendar year (section B2.2.1.1. in Appendix B). Using data on a representative day from July 2019, we then use unique arrival and departure times by aircraft to estimate mean, minimum, and maximum turnaround durations for each airport (section B2.2.1.2. in Appendix B). July is selected because it is one of the busiest air travel months; thus, a range of aircraft types and trip types are reflected in the turnaround durations. We then merge these two datasets to arrive at an approximate operational matrix of turnaround durations for each airport (section B2.2.1.3 in Appendix B). The turnaround matrix is then finally ‘cleaned’ to limit the duration of turnaround operations when it is unlikely that the aircraft would require power and air conditioning (e.g., when an aircraft is parked overnight).

The carbon intensity of each equipment piece is a function of how much energy each equipment type consumes per wingspan class, the type of energy each equipment consumes, and the equipment’s manufacturing impact. Energy consumption data for each equipment type is compiled from measured data and literature sources (section B2.2.2. in Appendix B). As the

APU and both electric and diesel PCA units provide heating and cooling, we developed the ambient air temperature profile for each case study airport to determine the amount of time that heating and cooling conditions are activated (Table B19 in Appendix B).

The APU combusts jet fuel, the 400 Hz and electric PCA units consume electricity, and the diesel PCA unit combusts diesel fuel. Emission factors for electricity are location-dependent due to the differing power generation mixes supplied to each airport. As explained in section B2.2.3. of Appendix B, electricity emission factors for each airport are calculated by multiplying the annual average power generation mix of the airport's local electric utility by fuel-specific life-cycle emission factors (Horvath & Stokes, 2011a). Although regional differences exist in processing and refining, the emission factors for jet fuel and diesel fuel are assumed to be the same regardless of location (Table B18 in Appendix B). Figure 9 shows the life-cycle GHG emission factor for the electricity consumed at each airport. A relatively high emission factor indicates that the electricity for a specified airport is generated using a greater percentage of fossil fuels. For example, roughly 70% of the electricity at Beijing Capital International Airport (PEK) is sourced from coal, while nearly 100% of the electricity consumed at San Francisco International Airport (SFO) is sourced from hydroelectric power plants. The lower electricity emission factors for airports such as Dallas Fort Worth International Airport (DFW) and London Heathrow Airport (LHR) are due to their commitments to purchasing renewable sources of electricity, despite fossil fuels dominating their regions' average electricity supplies (DFW, 2021; LHR, 2020).

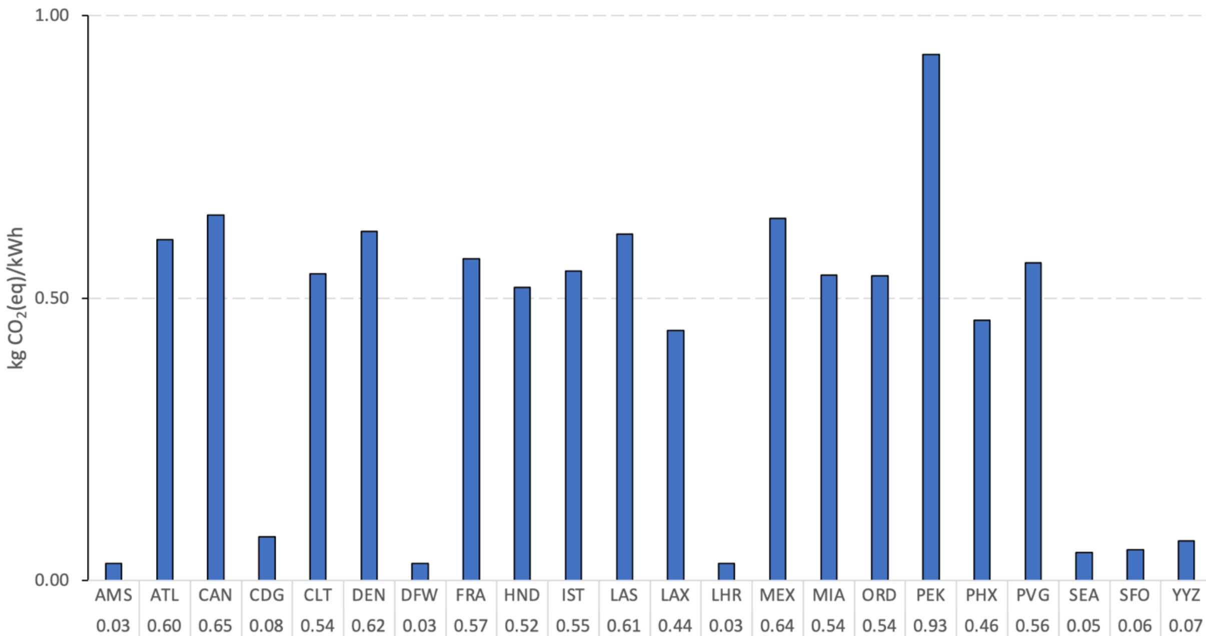


Figure 9. Life cycle GHG emission factors for electricity supply for each of the 24 airports responsible for 25% of annual global commercial aviation traffic. Airport codes are: AMS (Amsterdam, NL); ATL (Atlanta, GA); CAN (Guangzhou, CN); CDG (Paris, FR); CLT (Charlotte, NC); DEN (Denver, CO); DFW (Dallas, TX); EWR (Newark, NJ); FRA (Frankfurt, DE); HND (Tokyo, JP); IST (Istanbul, TR); JFK (Queens, NY); LAS (Las Vegas, NV); LAX (Los Angeles, CA); LHR (London, GB); MEX (Mexico City, MX); MIA (Miami, FL); ORD (Chicago, IL); PEK (Beijing, CN); PHX (Phoenix, AZ); PVG (Shanghai, CN); SEA (Seattle, WA); SFO (San Francisco, CA); YYZ (Toronto, CAN)

Impacts from the manufacturing of the 400Hz and PCA units are approximated using aggregate data from the Economic Input–Output Life Cycle Assessment (EIO–LCA) model (Matthews, 2021) as explicit data for estimating these components are currently unavailable. We use data from a representative PBB to estimate the life-cycle GHG emissions associated with its manufacturing (SCS Global Services, 2019). Since we do not have exact information regarding gate configurations at each airport, we make some assumptions. All gates at each case study airport are assumed to be used on an annual basis and each gate is equipped with one PBB, one PCA unit, and one 400 Hz unit. We assume that all equipment will have a lifespan of 20 years. Further data and assumptions for the manufacturing impact of equipment are provided in section B2.2.2.3 in Appendix B.

The utilization rate for each equipment type is unique for each operational scenario (section B2.2.2.1. in Appendix B). The utilization rates for Scenario 1 and Scenarios 3a/3b are maximum bounds for the APU and 400 Hz/PCA units, respectively. The utilization rates for Scenarios 2a and 2b are representative of current practice at major international airports and come from measured data from airport gates.

3.2.2 Payback period and levelized annual costs

The economic issues of upgrading an airport's gate electrification equipment, or any airport infrastructure upgrade/renovation, are complex. Although there might be different investment relationships, an airport typically purchases and installs the equipment, but an airline might reap the benefit of that investment in terms of savings in fuel costs. An analysis of different investment relationships is outside the scope of this study. We make a simplifying assumption and lump both airport operators and airlines together, and assume these stakeholders jointly make the investment and accrue resulting benefits. The payback period indicates how long it takes for an initial investment to be recouped from savings in annual operation and maintenance costs. We estimate the payback period to determine the economic benefit of switching to electrified gate operations from APU operation entirely (i.e., switching away from scenario 1). The payback period is evaluated for each scenario for each case study. Equation 2 is used in estimating the payback period (Rubin & Davidson, 2001)

$$n_{pb} = \frac{log\left[1 - \left[\left(\frac{\Delta P}{\Delta U}\right) \times i\right]\right]^{-1}}{\log(1+i)} \quad \text{[Eq. 2]}$$

Where n_{pb} is the payback period, in number of years;
ΔP is the cost of the initial capital investment, in USD
ΔU is the annual savings that occur as a result of making the investment, in USD
i is the discount rate, assumed to be 6%.

Capital investment costs are the direct monetary costs associated with equipping each gate in the case study airport with 400 Hz and PCA units. Annual savings are calculated by determining how much money is saved from shifting away from 100% utilization of jet fuel (i.e., scenario 1). Annual savings depend upon the utilization rates of each equipment type outlined in the hypothetical operational scenarios.

We calculate the levelized annual costs in constant, 2019 United States dollars (USD) in order to compare the economic benefits from switching between scenarios 2a and 2b and between scenarios 3a and 3b. Levelized annual costs are useful in determining the cheaper option between alternatives, especially when the capital investment for the two options is the same. The key difference between scenarios 2a and 2b and between scenarios 3a and 3b is the type of PCA unit (i.e., electric versus diesel). Levelized annual costs are calculated using Equation 3 (Rubin & Davidson, 2001)

$$AC_{Total} = AC_{Oper} + AC_{Main} + \left[P \times \left(\frac{i}{1-(1+i)^{-n}}\right)\right] \quad \text{[Eq. 3]}$$

Where AC_{Total} is total levelized annual cost for a scenario, in USD
AC_{Oper} is the annual operating cost of the scenario, in USD
AC_{Main} is the annual maintenance cost associated with the scenario, in USD
P is the capital investment cost, or purchase price, in USD
I is the discount rate, assumed to be 6%
n is the total number of operating years, assumed to be 20 years

Capital costs for gate electrification depend upon the size of aircraft (i.e., the wingspan class) that a gate is equipped to handle. Therefore, it is critical to know the total number of gate types at each airport. As most airports do not publicly document this data, estimates are determined from a combination of airport-specific resources such as annual financial reports and terminal maps. Gate type allocations are proportional to each airport's aircraft fleet mix. All economic data (e.g., jet fuel and diesel fuel costs, electricity prices) and further assumptions are outlined in section B3 of Appendix B.

3.2.3 Climate economic damages

We calculate the climate economic damages for each airport's turnaround operations. Climate damages indicate the economic harm that will result from climate change impacts such as rising sea levels and wildfires. We estimate climate economic damages by multiplying the mass of GHG emissions from a turnaround operation by the social cost of carbon (SCC). The SCC is a valuation metric that estimates the economic value of the harm caused by emitting one additional metric ton of carbon dioxide to the atmosphere (Nordhaus, 2017). The SCC is used to demonstrate the full cost of an entity's GHG emissions and to provide an economic incentive for polluters to reduce their emissions (i.e., a polluter would want to reduce its emissions so that it would not have to pay a regulatory agency or government for non-compliance). Damages per gate operation are calculated using Equation 4:

$$D_i = E_i \times SCC_{2019} \qquad \text{[Eq. 4]}$$

Where D_i are the damages per gate operation i, in USD
E_i are the total of emissions per gate operation i, in metric tons
SCC_{2019} is the social cost of carbon for 2019, in USD/metric ton

We adjust the 2015 SCC that uses a 3% discount rate (Interagency Working Group, 2016). We first linearly interpolate between the 2015 and 2020 SCC to determine the 2019 SCC. We then transform the 2019 SCC from 2007 dollars to constant, 2019 dollars. Equation 5 is used to determine the 2019 SCC

$$SCC_{2019} = \left[SCC_{2015} + (Y_{2019} - Y_{2015})\left(\frac{SCC_{2020} - SCC_{2015}}{Y_{2020} - Y_{2015}}\right)\right](CF_{2007\rightarrow 2019}) \qquad \text{[Eq. 5]}$$

Where SCC_{2019} is the calculated social cost of carbon for 2019, in USD per tonne
SCC_{2015} is the social cost of carbon for 2015 when using a 3% discount, \$36 USD/tonne
SCC_{2020} is the social cost of carbon for 2020 when using a 3% discount rate, \$42 USD/tonne
Y_i is the year of interest;
$CF_{2007\square 2019}$ is the conversion factor for adjusting 2007 dollars to 2019 dollars

The adjusted SCC2019 used in the analysis is valued at \$52 per metric ton of GHG emissions. The SCC is highly sensitive to the discount rate used in its valuation (Pizer et al., 2014). However, since this analysis does not evaluate climate economic damages for future emissions (i.e., our period of study is the calendar year 2019), we believe that the SCC calculated using Equation 5 offers a suitable estimation. The methods used in determining the SCC for 2019 are provided in section B4 of Appendix B. Cumulative annual climate damages per airport are estimated by multiplying the per-gate-operation damages by the total number of gate operations. Further assumptions are outlined in section B4 of Appendix B.

3.2.4 Global analysis

We extend the environmental analysis with less precise data to estimate the annual life-cycle GHG emissions from fuel consumption (i.e., electricity, jet fuel, diesel fuel) for the top 2,354 commercial traffic airports in the world. These 2,354 airports account for the majority of all commercial air traffic. Results from the global analysis offer an estimate of the scale at which gate electrification can reduce GHG emissions. We do not follow the precision of the analysis used for the 24 case study airports. The fidelity of the global analysis is sufficient to reach definitive conclusions.

Using departure data (which are a proxy for number of turnaround operations) from the calendar year 2019, we first group airports into three size categories. Small airports have between 1,000 and 10,000 annual turnaround operations, medium airports have between 10,001 and 100,000 annual turnaround operations, and large airports have more than 100,001 annual turnaround operations. Typically, airport size classifications are characterized by number of annual passengers or share of total passenger traffic (FAA, 2020; OAG, 2020). The number of annual passengers is not strictly correlated with aircraft movements, but there is overlap between the two classification schemes. For example, SFO is considered a 'large' airport according to both annual passenger numbers and annual aircraft movements.

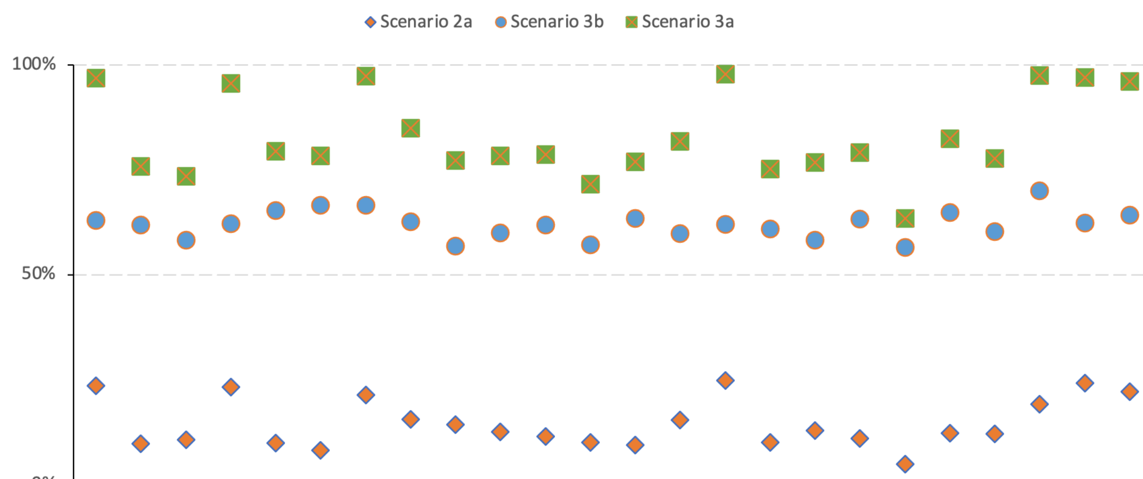
We do not have the same level of granularity for turnaround durations or flight data (i.e., the number of flights by wingspan class) as we do for the original 24 case study airports. We calculate the average of the mean, minimum, and maximum turnaround durations for each of the case study airports and assume that these turnaround durations are applicable to all of the 'Large Airports' in the extension analysis. Scaling factors of 25% and 50% are applied to 'Large Airports' turnaround durations to estimate turnaround durations for the 'Medium Airports' and 'Small Airports', respectively. Scaling factors are necessary to apply. Smaller airports have different traffic patterns (e.g., not as many long-haul international flights) than the airports in the 'Large Airport' category and as such will tend to have shorter turnaround durations.

We calculate life-cycle GHG emissions per gate operation for each of the five operational scenarios. Cumulative emissions for each airport are found by multiplying the emissions impact per gate operation by the airport's total number of operations. Cumulative annual emissions are grouped by operational scenario, airport size, and airport region. We do not account for PBB operating emissions or infrastructure emissions in the extension analysis due to the potential for greater uncertainty. Estimating these emission sources requires knowing the exact number and type of gates at each airport. The life-cycle emission factors for electricity supplies are estimated according to the same methodology previously outlined, albeit they are estimated at the region level (e.g., North America, Asia) and not airport/city level. Further data and assumptions are documented in section B5 of Appendix B.

3.3 Results

3.3.1 Environmental results for case study airports

The results point to a clear conclusion: gate electrification would yield large reductions in GHG emissions, especially compared to aircraft turnaround operations that are powered by the APU. While not demonstrating an exact depiction of current practice of gate electrification, the results indicate the likely range of GHG reduction potential. Figure 10 shows the average percentage reductions in GHG emissions for a range of operational scenarios (scenarios 2a and scenarios 3a/b) relative to the upper-bound of current practice, scenario 2b, which utilizes the APU and diesel-powered PCA. Total emissions per average gate operation depend upon multiple factors, including the type and duration of each equipment's use, the source of electricity, and the airport's aircraft fleet composition and frequency of flights. For the complete electrification scenario (scenario 3a), GHG emissions per gate operation are reduced at least by 63% for each of the case study airports. In particular, the airports that have the cleanest electricity supplies (i.e., AMS, CDG, DFW, LHR, SEA, SFO, YYZ) exhibit the greatest reductions in GHG emissions for a gate operation. A carbon-intensive electricity mix (e.g., more than 70% of PEK airport's electricity is sourced from coal) yields a smaller GHG percentage reduction for each scenario, irrespective of the other parameters of gate operation.

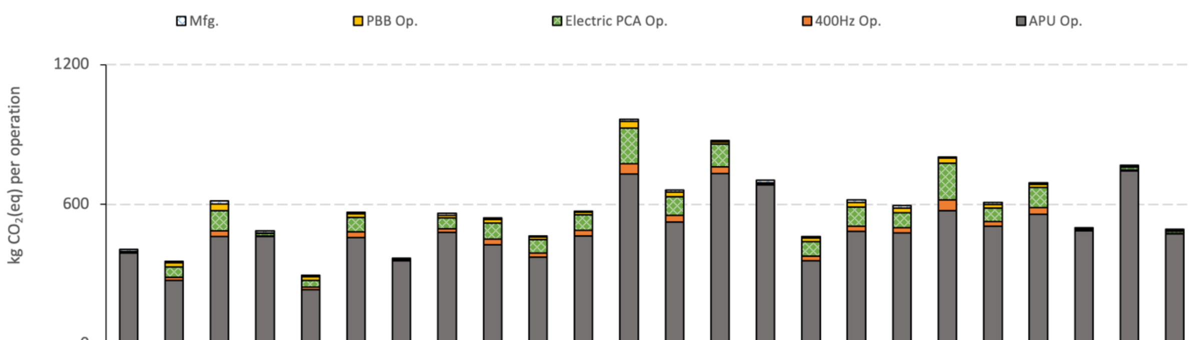


	AMS	ATL	CAN	CDG	CLT	DEN	DFW	EWR	FRA	HND	IST	JFK	LAS	LAX	LHR	MEX	MIA	ORD	PEK	PHX	PVG	SEA	SFO	YYZ
Scenario 2a	24%	10%	11%	23%	10%	8%	21%	16%	14%	13%	12%	10%	9%	15%	25%	10%	13%	11%	5%	12%	12%	19%	24%	22%
Scenario 3b	63%	62%	58%	62%	65%	67%	66%	63%	57%	60%	62%	57%	63%	60%	62%	61%	58%	63%	56%	65%	60%	70%	62%	64%
Scenario 3a	97%	76%	73%	96%	79%	78%	97%	85%	77%	78%	79%	72%	77%	82%	98%	75%	77%	79%	63%	82%	78%	97%	97%	96%

Figure 10. Reductions in life-cycle GHG emissions per average gate operation for each case study airport, relative to Scenario 2b (30% APU utilization per operation, diesel-powered PCA).Scenarios 2a/2b utilize the APU 30% of the time per operation. Scenarios 3a/3b do not rely on the APU. Scenarios 2a/3a utilize the electric PCA for meeting thermal comfort requirement. Scenarios 2b/3b utilize a diesel-powered PCA for meeting thermal comfort. Mitigation potential increases for scenarios where electricity is used for most or for the entirety of the gate operation. Higher mitigation potential is correlated with airports supplied with relatively low-carbon electricity. Airport acronyms are found in Figure 9.

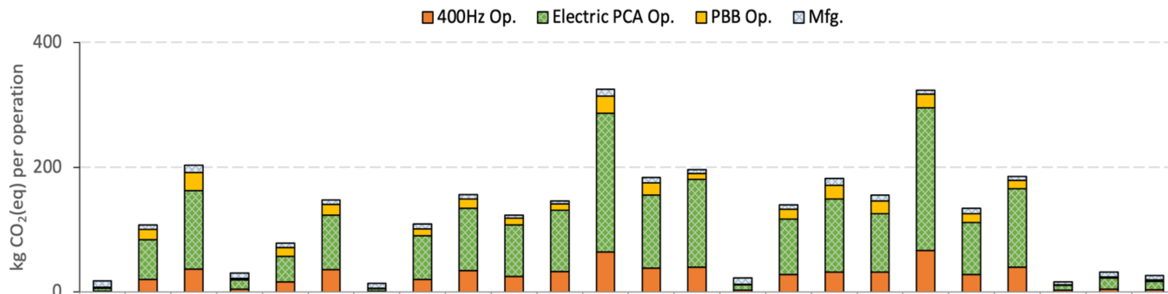
Figure 11 indicates the breakdown of GHG emissions by life-cycle component for scenario 2a when the 400Hz cable and the electric PCA are utilized for approximately 70% of an average gate operation. Breakdowns by life-cycle component for the remaining scenarios are provided in

Figures B5 through B7 in section B2.3 in Appendix B. Operating emissions from the APU dominate. Across all airports, emissions from equipment manufacturing are not as dominant on a per-gate-operation basis. The relative total emissions per gate operation across each airport do not necessarily matter in terms of understanding the efficacy of gate electrification in mitigating GHG emissions. That is, it does not matter that SFO's gate emissions for Scenario 2a are greater than CLT's gate emissions because one airport might service different aircraft types and trip lengths. It is significant that when airports have low-carbon electricity supplies, GHG emissions from using equipment that exclusively rely on electricity are minimally represented in the total. This point is further emphasized in Figure 12, which shows the breakdown by operating and manufacturing emissions for scenario 3a when 100% gate electrification occurs for each turnaround operation. The results in Figure 12 suggest that complete electrification coupled with low-carbon electricity supplies can diminish the climate impact from extensive turnaround operations. That is, the gate emissions from a relatively longer turnaround operation in an airport with a clean electricity mix will likely be less than those of a shorter operation at an airport with a dirtier mix.



	AMS	ATL	CAN	CDG	CLT	DEN	DFW	EWR	FRA	HND	IST	JFK	LAS	LAX	LHR	MEX	MIA	ORD	PEK	PHX	PVG	SEA	SFO	YYZ
Mfg.	10	7	12	9	7	7	8	8	7	5	5	11	9	6	10	7	11	10	6	8	6	4	8	7
PBB Op.	1	16	29	3	15	17	1	11	15	10	10	28	20	9	1	16	22	20	22	14	13	1	2	2
Electric PCA Op.	3	44	87	10	28	61	3	48	69	57	68	154	81	97	6	61	81	65	158	58	87	6	13	9
400Hz Op.	1	14	26	3	11	25	1	14	24	17	23	45	27	28	2	20	22	23	46	20	28	2	3	3
APU Op.	391	274	461	462	234	458	357	480	428	375	465	730	525	733	684	358	484	478	573	508	558	487	744	472

Figure 11. Sample breakdown of GHG emissions per average gate operation by life-cycle stage for Scenario 2a. Total emissions per gate operation depend upon the utilization of each equipment type, the electricity supply, and the airport's aircraft fleet composition and frequency of flights. Emissions from operating the APU dominate the share of total emissions.



	AMS	ATL	CAN	CDG	CLT	DEN	DFW	EWR	FRA	HND	IST	JFK	LAS	LAX	LHR	MEX	MIA	ORD	PEK	PHX	PVG	SEA	SFO	YYZ
Mfg.	10	7	12	9	7	7	8	8	7	5	5	11	9	6	10	7	11	10	6	8	6	4	8	7
PBB Op.	1	16	29	3	15	17	1	11	15	10	10	28	20	9	1	16	22	20	22	14	13	1	2	2
Electric PCA Op.	5	63	125	14	40	87	4	70	99	82	98	222	116	140	9	88	117	93	229	83	126	8	18	14
400Hz Op.	1	21	37	5	16	36	1	20	34	25	33	64	39	40	3	28	32	32	66	28	40	3	5	4

Figure 12. Sample breakdown of GHG emissions per average gate operation by life-cycle stage for Scenario 3a. (100% gate electrification). For airports with low-carbon electricity supplies (e.g., AMS, DFW, LHR, SEA, SFO, YYZ), the share of emissions from the electricity-operated equipment is minimized. Emissions from the electric-powered PCA dominate the total share of emissions.

3.3.2 Effect of ambient air temperature on GHG emissions

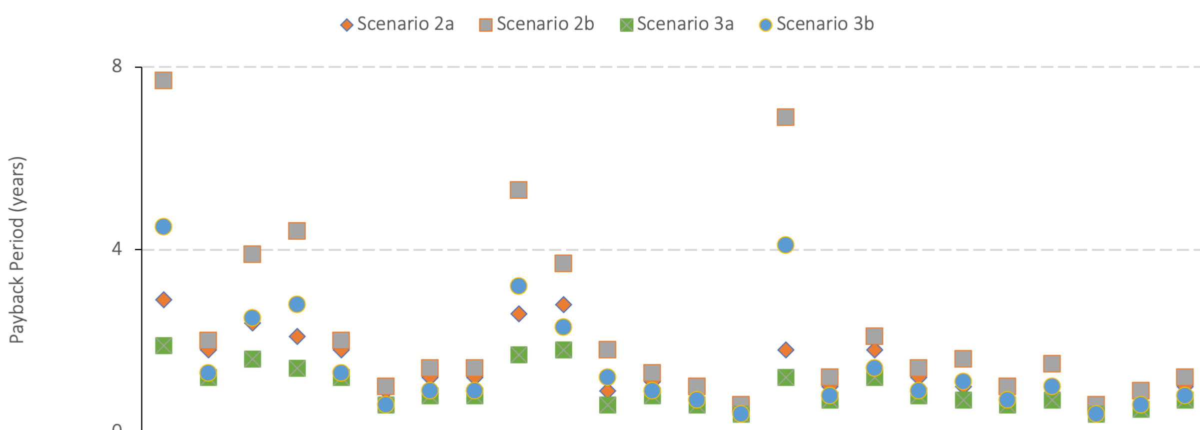
Between the 400 Hz unit and the PCA unit, the PCA dominates the share of GHG emissions per gate operation. What role does ambient air temperature play in increasing the GHG impacts from PCA utilization? The temperatures that trigger heating and cooling activation are close (e.g., less than 7.2 ◦C for heating and greater than 10 ◦C for cooling). According to these temperature bounds, seven of the case study airports (CAN, LAS, LAX, MEX, MIA, PHX, SFO) operate under 100% ‘hot weather’ conditions where the PCA is activated for cooling for every gate operation. In hot weather, the PCA units consume energy at a higher rate because it takes more work to cool down air than it does to heat it up. A sensitivity analysis demonstrates that the electricity mix plays a more significant role than ambient air temperature in the total GHG emissions per gate operation (section B6 in Appendix B).

3.3.3 Significance of gate electrification relative to aviation activities

We use the average gate operation emissions for a domestic flight between SFO and LAX airports and compare them to previous data on the life-cycle emissions from a flight operation between SFO and LAX airports (M. Chester & Horvath, 2012). Total emissions for a flight between Point A and Point B are equal to the sum of gate-operation emissions and flight-operation emissions. When the APU is used for the entire aircraft turnaround duration, gate operation emissions account for 25% of total operation emissions. For a completely electrified turnaround operation, gate operation emissions comprise a mere 0.3% of total Point A to Point B emissions. In this specific example of a typical short-haul flight, GHG emissions from gate operations are significant, particularly for operational scenarios where the APU is utilized. Further research relating life-cycle GHG emissions from flights to life-cycle GHG emissions from gate (and other airport) operations would be necessary to determine their comparative impacts and find ways of reducing emissions.

3.3.4 Economic results for case study airports

The payback periods for each operational scenario for the 24 case study airports are shown in Figure 13. A shorter payback period means that the investor earns a quicker return on their investment. Scenario 2b (partial gate electrification with diesel-powered PCA units) results in the longest payback period among the four operational scenarios. For locations where diesel fuel costs are relatively high, which is true for many European airports due to higher taxes (US DOE, 2021), the payback periods for Scenario 2b are considerably longer than for the other scenarios. In locations with relatively cheap fuel, as is the case for most North American airports, there is little difference in payback period among the four scenarios. Across all airport locations, Scenario 3a yields the shortest payback period. Complete gate electrification is the best investment according to the payback period metric.



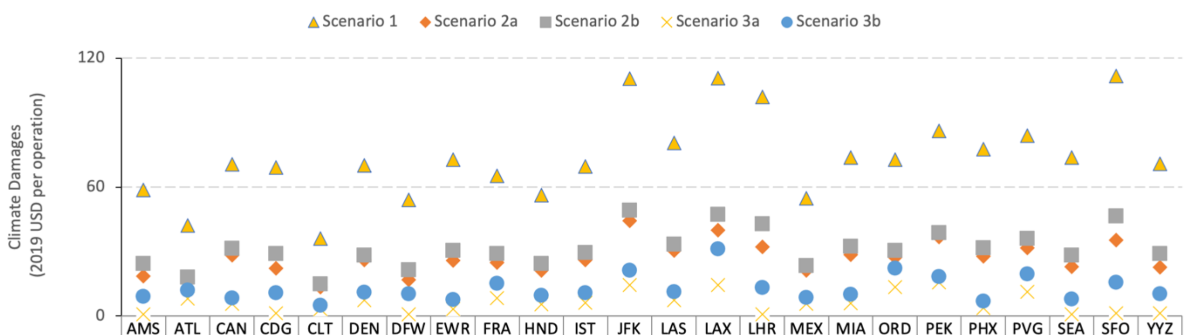
	AMS	ATL	CAN	CDG	CLT	DEN	DFW	EWR	FRA	HND	IST	JFK	LAS	LAX	LHR	MEX	MIA	ORD	PEK	PHX	PVG	SEA	SFO	YYZ
Scenario 2a	2.9	1.8	2.4	2.1	1.8	0.9	1.2	1.2	2.6	2.8	0.9	1.1	0.9	0.5	1.8	1	1.8	1.2	1	0.9	1	0.5	0.8	1
Scenario 2b	7.7	2	3.9	4.4	2	1	1.4	1.4	5.3	3.7	1.8	1.3	1	0.6	6.9	1.2	2.1	1.4	1.6	1	1.5	0.6	0.9	1.2
Scenario 3a	1.9	1.2	1.6	1.4	1.2	0.6	0.8	0.8	1.7	1.8	0.6	0.8	0.6	0.4	1.2	0.7	1.2	0.8	0.7	0.6	0.7	0.4	0.5	0.7
Scenario 3b	4.5	1.3	2.5	2.8	1.3	0.6	0.9	0.9	3.2	2.3	1.2	0.9	0.7	0.4	4.1	0.8	1.4	0.9	1.1	0.7	1	0.4	0.6	0.8

Figure 13. Payback period (in years) for each case study airport implementing the necessary infrastructure to switch from Scenario 1. The payback period ranges from less than 1 year to under 2 years for most of the airports. Greater variability in payback period is apparent for many of the European airports where fuel costs are higher relative to fuel costs for North America and Asia.

Results for average annual savings and levelized annual costs, both in constant, 2019 United States dollars ($), are provided in Tables S27 and S28 in Appendix B. Over the 20-year lifespan of the gate electrification equipment, airport stakeholders (i.e., airlines, airport operators) would be expected to pay around $14 million in levelized annual costs for scenario 3a, compared to $24 million for Scenario 3b, $28 million for scenario 2a, and $35 million for scenario 2b. Compared to the estimated state of current practice (i.e., scenarios 2a and 2b), scenario 3a has the lowest levelized annual costs and the greatest annual savings.

3.3.5 Climate economic damages for case study Airports

The average climate economic damages per gate operation are shown in Figure 14. Implementing scenario 3a (100% gate electrification) results in the lowest climate economic damages across all 24 airports, regardless of the airport's electricity supply or aircraft fleet composition. In locations with electricity supplied from low-carbon sources, 100% gate electrification results in quite low climate economic damages. More variability in climate economic damages among the airports is exhibited for Scenario 1 than for the other four operational scenarios. That variability is caused by factors such as the aircraft fleet mix, the total number of flights, and the duration for which an aircraft is parked at a gate. The reduced variability in damages across the busiest 24 global airports for the other scenarios suggests that implementing gate electrification dampens the effects from factors such as fleet mix and turnaround duration. The total annual damages from global warming potential of GHG emissions for each scenario for the 24 airports are provided in Table B29 in Appendix B. Average annual damages per airport for scenario 3a are $1.4 million compared to $2.9 million for scenario 3b, $6.2 million for scenario 2a, $7.2 million for Scenario 2b, and $17 million for scenario 1. Relative to scenarios 2a and 2b, which stand as an approximate range for current practice, the average annual avoided damages from complete electrification at an airport is between $5 million and $6 million. It is not unreasonable to expect similar annual climate economic damages for other major international airports not included in the case study analysis.



	AMS	ATL	CAN	CDG	CLT	DEN	DFW	EWR	FRA	HND	IST	JFK	LAS	LAX	LHR	MEX	MIA	ORD	PEK	PHX	PVG	SEA	SFO	YYZ
Scenario 1	59	42	71	69	36	70	54	73	65	56	70	110	81	111	102	55	74	73	86	78	84	74	112	71
Scenario 2a	19	16	28	22	14	26	17	26	25	21	26	44	30	40	32	21	28	27	37	28	32	23	35	23
Scenario 2b	24	18	31	29	15	28	22	30	29	24	29	49	33	47	43	23	32	31	39	32	36	28	46	29
Scenario 3a	1	8	6	1	3	7	1	3	8	5	6	15	7	14	1	6	6	13	16	4	11	1	1	1
Scenario 3b	9	12	8	11	5	11	10	8	15	9	11	21	11	31	13	9	10	22	18	7	20	8	16	10

Figure 14. Climate economic damages per average gate operation for 24 case study airports. Damages are the lowest for Scenario 3a (complete electrification) and airports with relatively low-carbon electricity supplies. Damages from Scenario 1 (complete APU utilization) are more variable across the 24 airports, compared to damages from the other scenarios. This suggests that electrification dampens impacts from unique airport characteristics such as aircraft fleet composition, total number of flights, and turnaround duration.

3.3.6 Uncertainty assessment

The uncertainty of the data we use for the environmental, economic, and climate damage analyses are evaluated using the pedigree matrix approach. Pedigree matrices are used in LCA studies to assess the uncertainty of data (Ciroth et al., 2016). Uncertainty is scored according to how reliable and complete the data are, how old the data are, what locations the data reflect, and whether the data apply specifically for the entity, process, or material being studied.

We evaluate the uncertainty in electricity and air temperature data. We explore the uncertainty related to the flight operational data, the cost data for electricity, fuel, and equipment, and the jet/diesel fuel emission factor data. We also estimate the quality of the power consumption and manufacturing data for the 400 Hz, PCA, APU, and PBB equipment. Section B7 in Appendix B shows the pedigree matrices for each of the evaluated data categories.

We find from the results of the pedigree matrix that the uncertainty associated with the electricity, air temperature, flight operational data, and power consumption data is low. The uncertainty of the jet/diesel fuel emission factors and cost used in the analysis is moderately low. The uncertainty of the PBB manufacturing data is low, while the uncertainty for the 400 Hz and PCA manufacturing data is moderate. Overall, the results indicate that uncertainty associated with the data is relatively low. The results of the study represent a reasonable assessment of the lifecycle GHG, economic, and climate damage impacts from gate electrification at commercial airports.

3.3.7 Global GHG emissions reduction potential

When extending the analysis to account for the 2,354 airports that are responsible for the majority of global commercial traffic, the results confirm that the greatest cumulative reductions in life-cycle GHG emissions occur with scenario 3a. Figure 15 shows, by scenario, airport size, and region, the annual mean, minimum, and maximum GHG emissions. The share of emissions by airport size is approximately the same for each scenario. Large Airports are responsible for approximately 49% of annual GHG emissions from gate operations. Medium Airports account for around 41% of total GHG emissions, and Small Airports are responsible for roughly 10% of annual GHG emissions. Large and Medium Airports in Asia, Europe, and North America have the largest annual emissions. Asia and North America dominate in the Small Airports category. In general, the majority of GHG emissions are attributable to airports in Asia, North America, and Europe, highlighting the importance of greening the electricity supplies in those regions in order to increase the mitigation potential of gate electrification. Electrifying all turnaround operations for the 2,354 commercial airports in the world would save, relative to the estimation of current practice (i.e., Scenarios 2a and 2b), on average between 10 and 12 million metric tons of GHG emissions annually. To provide some perspective, these savings are conservatively 1% of global aviation emissions (Graver et al., 2019) and 3% of California’s annual anthropogenic GHG emissions (CARB, 2021). Given the relative GHG contributions of other economic activities (e.g., the cement industry), the carbon contribution from parked aircraft operations is not insignificant.

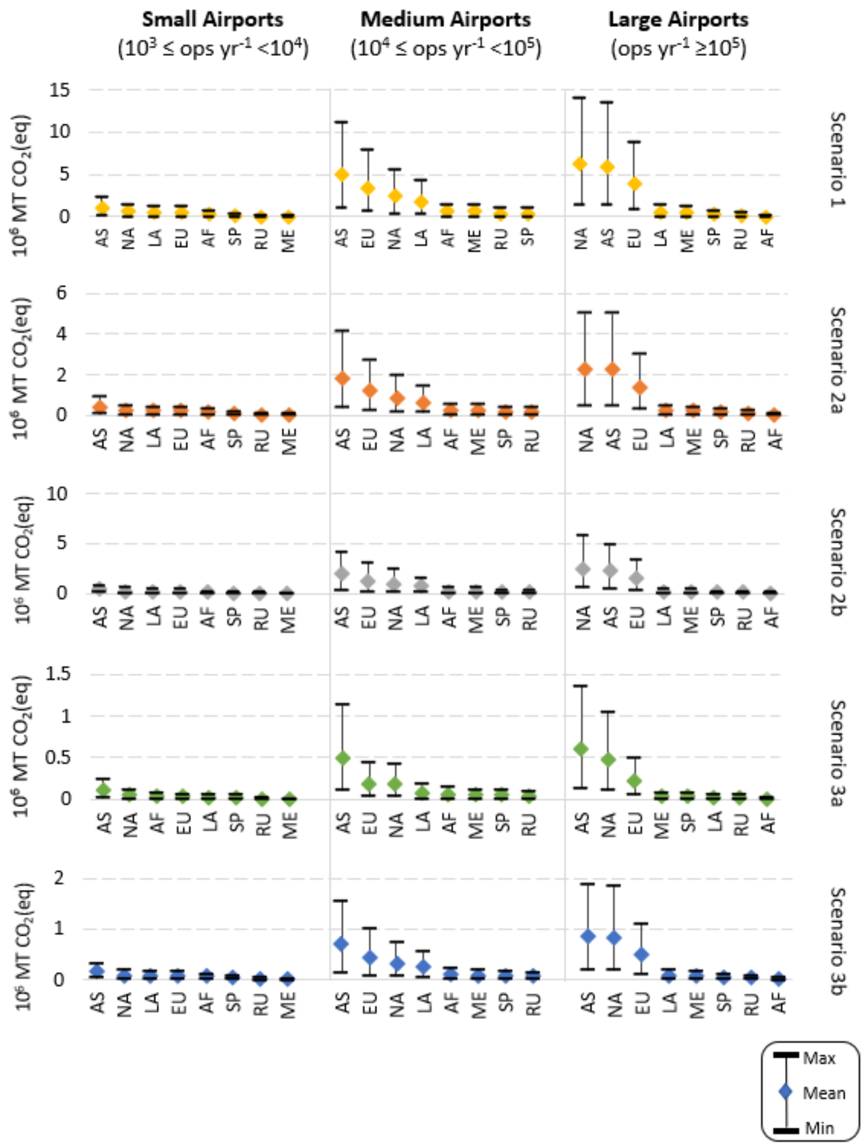


Figure 15. Annual life-cycle GHG emissions by scenario, airport size, and region. Regions: AF = Africa; AS = Asia; EU = Europe; LA = Latin America; NA = North America; ME = Middle East; RU = Russia; SP = Southwest Pacific. "Ops" refers to the number of turnaround (or gate) operations that occur on an annual basis. In general, the majority of GHG emissions are attributable to airports in Asia, North America, and Europe, highlighting the importance of greening the electricity supplies in those regions in order to increase the mitigation potential of gate electrification.

3.4 Discussion

Electrifying aircraft turnaround operations results in reductions in life-cycle GHG emissions, levelized annual costs, and monetized climate damages at commercial airports worldwide. Complete electrification (i.e., scenario 3a) yields the greatest reductions even across differing geographic regions and airport sizes. It represents a feasible, deployable, and affordable opportunity for significant GHG emissions reductions. Although not considered in the context of this analysis, there should be a concerted research effort to investigate practical questions associated with using gate electrification equipment and how this might impact emissions. For example, how might pilot or ground crew and maintenance procedures impact equipment utilization? How might emissions be impacted with different system configurations such as centralized boilers and chillers?

Under complete electrification, for the 24 case study airports, the annualized capital cost per metric ton of GHG emissions removed is between \$25 and \$30 with no discernible difference between United States and non-United States airports (see section B8 in Appendix B). For the 2,354-airport dataset (which uses fewer specific data than the 24 case study airports; see section B5 in Appendix B), it would cost \$2 billion to electrify gates at all United States airports and \$8 billion at all other airports. As a mitigation opportunity, the annualized capital cost per metric ton of GHG emissions removed ranges between \$60 and \$70 for United States airports and between \$80 and \$90 for all other airports. These estimated costs per mitigated emissions can be compared to current, local carbon-market prices in Shanghai (\$6 per metric ton), California (\$16 per metric ton), Canada (\$23 per metric ton) and Sweden (\$126 per metric ton) (World Bank Group, 2019). Furthermore, these mitigation costs are relative to scenarios 2a/2b where gate electrification equipment is on average used for 70% of every parked gate operation. When considering that capital costs will be recuperated within a couple of years, gate electrification is a prudent mitigation opportunity.

While other transportation sectors could decarbonize mainly through electrification, it will be difficult for the aviation sector (airlines) to reduce emissions because of the challenges associated with electrifying aircraft, especially large ones. Challenges with completely electrifying commercial aircraft fleet, particularly aircraft used in long-haul flights, stem from current limitations in battery capacity (Baumeister et al., 2020) as large power amounts are required for the landing and take-off phases of flight (Epstein & O'Flarity, 2019). The aviation industry needs to act to reduce its GHG emissions. Impacts from increased anthropogenic GHG emissions have dire consequences. The effects from droughts, wildfires, hurricanes, and sea level rise will lead to physical property damage to both infrastructure and natural ecosystems. Additional effects from climate change, which will be distributed unevenly across populations, include increased water scarcity, food insecurity, heat stress events, and economic vulnerability (Pachauri et al., 2014). By consistently integrating gate electrification at all commercial airports, the aviation industry can actively mitigate future deleterious effects from climate change.

3.5 Conclusions

Gate electrification, in addition to reducing GHG emissions, improves air quality on the airport apron. Reduced exposure to air pollutants such as PM is a human health benefit for passengers, airport employees, and communities living within proximity of an airport. However, in locations where electricity is supplied by fossil fuel sources, such as coal, and where demand for air conditioning is high, the air quality burden stemming from gate turnaround operations is just shifted to communities living near electric power plants. Exploring that scenario is beyond the scope of this research, but it demonstrates the need to apply systems-level thinking to ensure that policies intended to improve one infrastructure system do not have unintended consequences for another.

Chapter 4. Airport Terminal Environmental Support Tool (ATEST) Development

4.1 Introduction

The Airport Terminal Environmental Support Tool (ATEST) is a scalable, customizable decision-support tool. It is based entirely in Excel, relies on user input on building size and material composition, source of energy provision and amount of energy consumed, indoor and outdoor water consumption, and landfilled, recycled, and composted solid waste generation to calculate annualized life-cycle greenhouse gas (GHG) and criteria air pollutant (CAP) emissions, operational costs, and monetized climate damages from the construction and operation of airport terminals and ancillary structures for resiliency. Climate change and human health indicators from annual emissions are estimated using impact factors from EPA's Tool for Reduction and Assessment of Chemicals (TRACI). Users can select mitigation strategies from four modules within ATEST (Building Materials, Operational Energy, Water and Wastewater, Solid Waste) to determine which strategies yield the greatest reductions in emissions, costs, and monetized damages.

ATEST is intended for airport planning, environmental management, and sustainability teams to explore mitigation and adaptation strategies at the planning stages of projects. ATEST can also be used by policy makers, researchers, and other stakeholders to understand the larger role that airport terminals and ancillary structures play in the environmental impact of the aviation industry.

ATEST can be used to answer the following example questions:

- What are baseline annualized GHG and CAP emissions associated with constructing and operating an entire terminal or an addition/renovation of a terminal?
- What are baseline and mitigated emissions for each module in ATEST?
- How do emissions relate to climate change and human health indicators using TRACI impact factors?

- What are baseline operational costs and climate damages, and how do they change after mitigation? Which strategies yield the greatest reductions in operational costs and monetized climate damages?
- What are future impacts relative to the current baseline, considering changing conditions such as renewable portfolio standards (RPS) or mandated waste goals?

The remainder of the chapter details the development and structure of ATEST in the Methods section, explores how data uncertainty is managed and documents limitations with the design of ATEST in the Discussion section, and concludes with the benefits of the tool in the Conclusion section.

4.2 Methods

ATEST relies upon user input, default and custom values, and look-up tables to estimate life-cycle GHG and CAP emissions, operational costs, monetized climate change damages, and climate change and human health indicators associated with four main modules: (1) Building Materials; (2) Operational Energy; (3) Water and Wastewater; and (4) Solid Waste Management. Each module receives user input to calculate that module's baseline footprint. Users also select from a variety of mitigation strategies (listed in Chapter 5). Baseline footprints and potential reductions in emissions and costs are provided on each module's results page. Figure 16 depicts the main factors accounted for within each module.

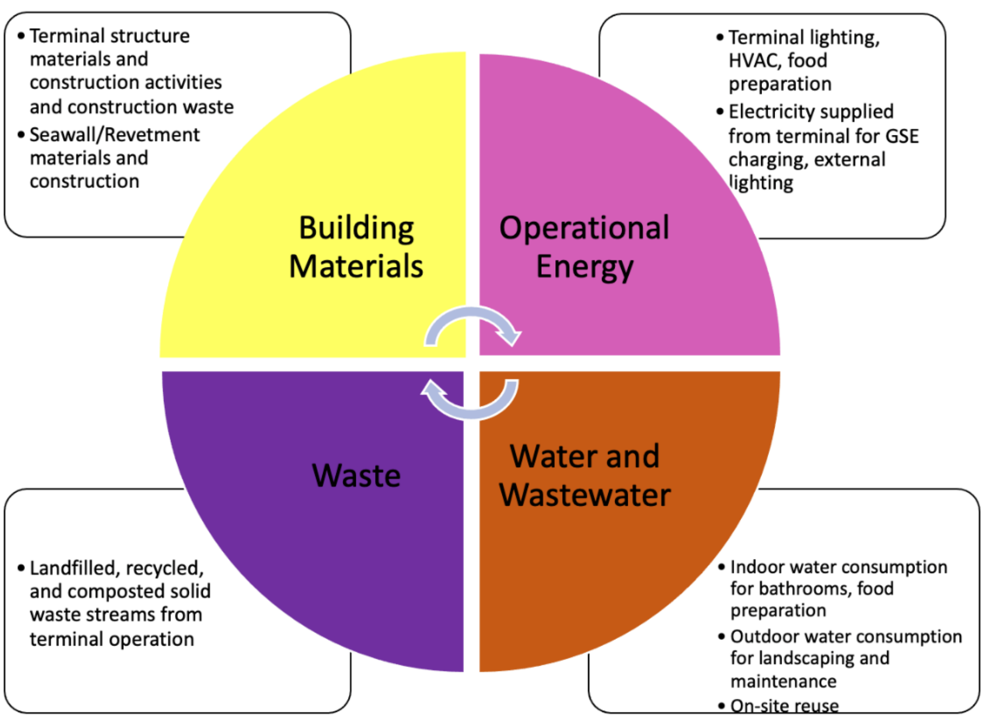


Figure 16. Scope of each module within ATEST.

The user inputs for general information and for each module are depicted in Figure 17.

Figure 17. Primary user input for general airport information and for each module. Additional user input related to default and custom selections is not depicted.

ATEST is comprised of six main components as shown in Figure 18. Additional sheets, that are by default hidden in ATEST, are explained in Appendix C.

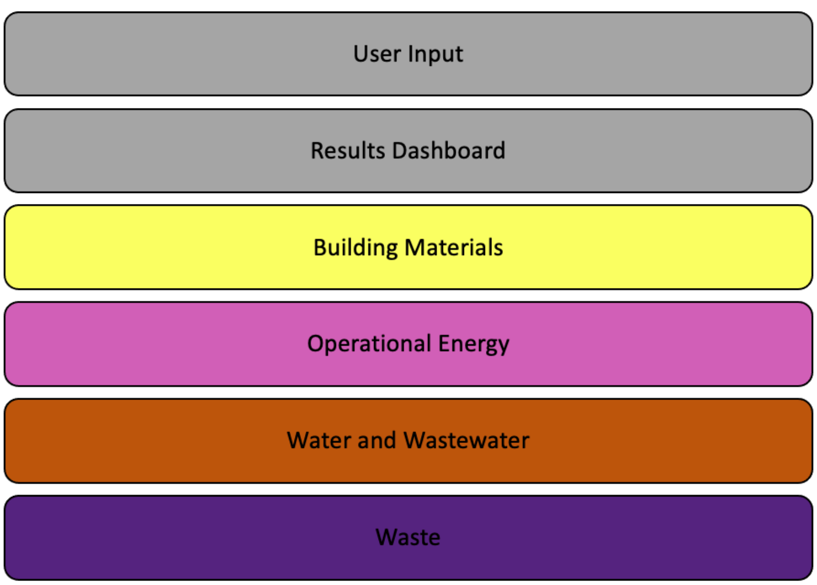


Figure 18. Major components in ATEST.

Users enter general information about the airport terminal, enter data to calculate the baseline annual emissions, operational costs, and damages for each module, and select mitigation strategies on the 'User Input' sheet. Figure 19 depicts a portion of the 'User Input' sheet.

Airport Terminal Environmental Support Tool (ATEST)

User instructions: Fill out information under the first column. Select strategies for each Module under the second column. To clear all entries, select "Reset Inputs".

Reset Inputs

Airport Terminal Information	
STEP 1: Enter General Development Information	
State	Please Select
County	Please Select
City	Please Select
Number of Daily Passengers	Please Enter
Number of Annual Aircraft Movements	Please Enter
STEP 2a: Select electricity mix method. The "eGRID" option utilizes state-level generation data from 2018. The "Custom" option allows for users to input a utility or site-specific generation mix on hidden *"Electricity Data"* sheet in cells *B65:L65*.	
Electricity Mix	Please Select
STEP 2b: If "NETL Electricity LCI" option is selected, download Excel-based Grid Mix Explorer, Version 4.2.	
STEP 2c: On the "consumption_mix" sheet in NETL Electricity LCI Grid Mix Explorer, enter airport's zip code into Region and BA Lookup button to determine the resepective FERC and Balancing Authority regions. Select Impact Category of interest (Global Warming Potential OR Particulate Matter Formation Potential). Enter value from "Total" column in cells *C15:C16*.	
Global Warming Potential [kg CO_2(eq) per MWh delivered]	Please Enter
Particulate Matter Formation Potential [kg $PM_{2.5}$(eq) per MWh delivered]	Please Enter
STEP 3: Select either "Default" or "Custom" from the drop-down menu in cell *C17*. If "Default" is selected, the adjusted 2020 Social Cost of Carbon value with a 3% discount rate will be used to estimate climate economic damages. If "Custom is selected enter the Social Cost of Carbon in USD per metric ton of CO_2(eq) in cell *C18*.	Please Select
Custom Social Cost of Carbon [USD per ton CO_2(eq) emitted]	Please Enter

Figure 19. Example of 'User Input' screen.

The 'Data' sheet, shown in Figure 20, incorporates values collected from the 'User Input' sheet and calculates the annual baseline resource use associated with constructing and operating the terminal/structure. The 'Calculation' sheet, depicted in Figure 21, quantifies baseline emissions, operational costs, and damages from baseline resource use. Reductions in resource use, emissions, operational costs, and damages, which depend upon the user-selected mitigation strategies, are also calculated. Figure 22 shows an example output on the 'Results' sheet. Each module displays tables and charts to show how mitigation strategies compare to baseline conditions. On the 'Results' sheet users can select from drop-down menus, colored in light yellow, to see specific pollutant emission reductions by strategy (e.g., efficient toilets) and category of strategy (e.g., indoor water conservation). Users can also choose to see charts for both global warming potential (GWP) and particulate matter formation potential, as well as for operational costs and climate damages.

1. User Selections	
State	Please Select
County	Please Select
Represenative City	No selection made
Landscaping Type	No selection made

2. Indoor Water Baseline		
Location	Source	Volume (m^3/year)
Restrooms	Toilets	0.00E+00
	Urinals	0.00E+00
	Restroom Faucets	0.00E+00
	Restroom Subtotal	0.00E+00
Food Concessions	Kitchen Faucets	0.00E+00
	Pre-rinse spray valves	0.00E+00
	Dishwashers	0.00E+00
	Ice machines	0.00E+00
	Food Concessions Subtotal	0.00E+00

Figure 20. Example screen from Water Module 'Data' sheet.

2. Baseline Water Volume (Indoor)	
Baseline Indoor Water Volume for Selected State and County (m^3/yr)	0.00E+00

3. Indoor Water Conservation Strategies					
Toilet		Urinal		Bathroom Faucet Aerator	
Selected Toilet Type	No	Selected Urinal	No	Selected Bathroom Faucet Type	No
New Toilet Volume (m^3/yr)	No Change	New Urinal Volume (m^3/yr)	No Change	New Bathroom Faucet Aerator Volume (m^3/yr)	No Change
Toilet Volume Reduction (m^3/yr)	0.00E+00	Urinal Volume Reduction (m^3/yr)	0.00E+00	Bathroom Faucet Volume Reduction (m^3/yr)	0.00E+00

4. Baseline Water Volume (Outdoor)	
Baseline Outdoor Landscaping Water Volume for Selected State and County (m3/yr)	0.00E+00

Figure 21. Example screen from Water Module 'Calc' sheet.

2. Strategy Emission Reductions by Component					
	Baseline	Typical Materials	Achievable Materials	Reduced C&D Waste	All Strategies
Component	Units (tons CO2e)	Units (tons CO2e)	Units (tons CO2e)	Units (tons CO2e)	Units (tons CO2e)
Materials	8.92E+04	0.00E+00	4.50E+04	0.00E+00	4.50E+04
Construction	8.25E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Construction & Demolition Waste	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Total	1.72E+05	0.00E+00	4.50E+04	0.00E+00	4.50E+04

All Strategies

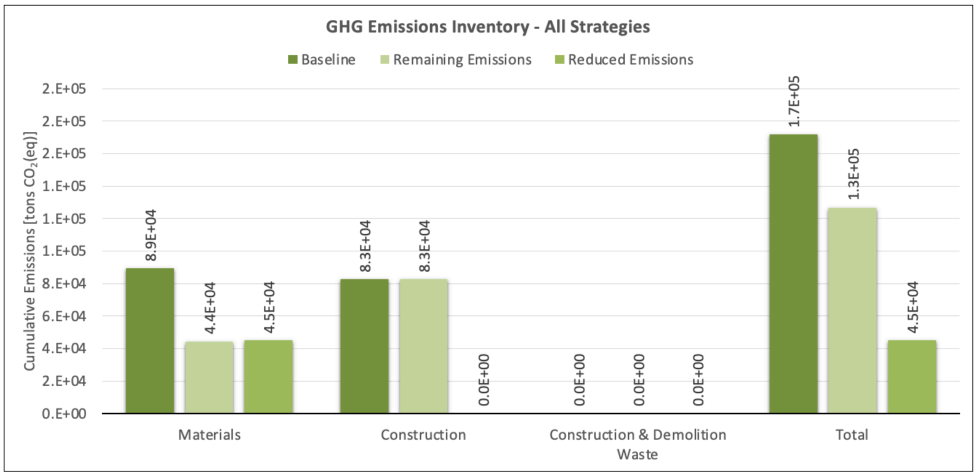


Figure 22. Example screen from Building Materials Module 'Results' sheet.

The 'Results Dashboard' displays baseline and mitigation impacts for all modules. Users select among three options to display normalized results on an annualized cumulative, per passenger, or per aircraft movement basis (shown in Figures 23 through 25).

1. Baseline Impacts by Terminal Module				
Global Warming Potential				
	Building	Energy	Water	Waste
Emissions per year	5.72E+03	1.68E+04	1.63E+01	2.48E+01
Emissions per pax	2.65E+00	7.79E+00	7.52E-03	1.15E-02
Emissions per aircraft movement	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Particulate Matter Formation Potential				
Emissions per year	4.35E+00	5.48E+00	7.72E-03	1.24E-04
Emissions per pax	2.01E-03	2.53E-03	3.57E-06	5.74E-08
Emissions per aircraft movement	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Notes: Assumes that airport operates for 365 days a year

Emissions per year

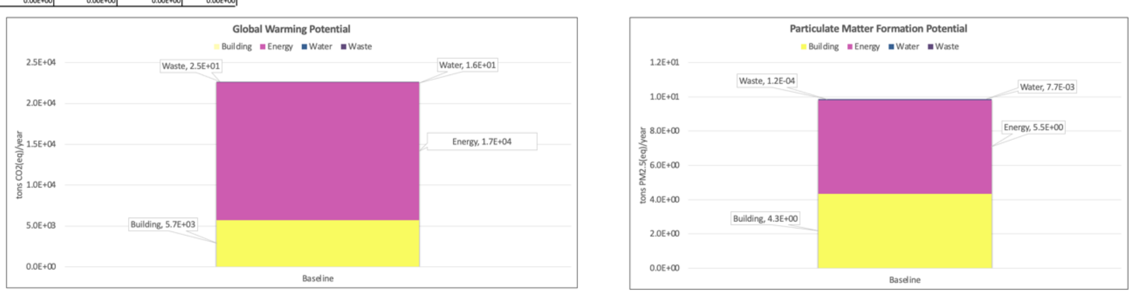


Figure 23. Example of baseline impacts by terminal module shown in 'Results Dashboard' sheet.

2. Impact Assessment by Strategy Types

Global Warming Potential

	Baseline	All Strategies - WSR	All Strategies - WSSR	All Strategies - WSSC	All Strategies - WSD	Materials	Construction	Construction & Demolition Waste	Energy Efficiency	Energy Source
Emissions per year	2.2599E+04	1.0130E+04	1.0143E+04	1.0143E+04	1.0143E+04	2.1099E+04	2.2599E+04	2.2599E+04	2.2599E+04	1.1651E+04
Emissions per pax	1.05E+01	4.68E+00	4.69E+00	4.69E+00	4.69E+00	9.76E+00	1.05E+01	1.05E+01	1.05E+01	5.39E+00
Emissions per aircraft movement	2.26E+02	1.01E+02	1.01E+02	1.01E+02	1.01E+02	2.11E+02	2.26E+02	2.26E+02	2.26E+02	1.17E+02
Particulate Matter Formation Potential										
Emissions per year	9.83E+00	4.53E+00	4.53E+00	4.53E+00	4.53E+00	9.83E+00	9.83E+00	9.83E+00	9.83E+00	4.54E+00
Emissions per pax	4.55E-03	2.10E-03	2.10E-03	2.10E-03	2.10E-03	4.55E-03	4.55E-03	4.55E-03	4.55E-03	2.10E-03
Emissions per aircraft movement	9.83E-02	4.53E-02	4.53E-02	4.53E-02	4.53E-02	9.83E-02	9.83E-02	9.83E-02	9.83E-02	4.54E-02

Emissions per year

NOTE: 1) Number labels = percentage decrease in emissions relative to baseline 2) All Strategies = savings from implementing all strategies 3) Waste stream strategies by category are not additive

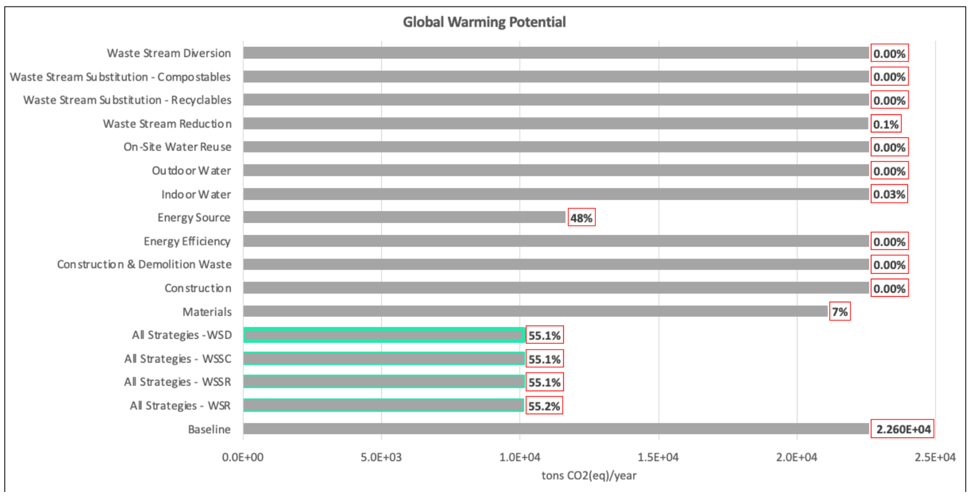


Figure 24. Example of impact assessment charts on ‘Results Dashboard’ sheet.

3. Economic Assessment by Strategy Types

Cost Type	Baseline	All Strategies - WSR	All Strategies - WSSR	All Strategies - WSSC	All Strategies - WSD	Materials	Construction	Construction & Demolition Waste	Energy Efficiency	Energy Source
Operational Costs										
Cost per year	$6,049,635.20	$6,043,040.49	$6,043,611.69	$6,043,611.69	$6,043,611.69	$6,049,635.20	$6,049,635.20	$6,049,635.20	$6,049,635.20	$6,049
Cost per pax	$2.80	$2.79	$2.80	$2.80	$2.80	$2.80	$2.80	$2.80	$2.80	
Cost per aircraft movement	$60.50	$60.43	$60.44	$60.44	$60.44	$60.50	$60.50	$60.50	$60.50	
Climate Damages										
Damages per year	$949,173.61	$425,467.73	$426,004.77	$426,004.77	$426,004.77	$885,320.64	$949,173.61	$949,173.61	$949,173.61	$489
Damages per pax	$0.44	$0.20	$0.20	$0.20	$0.20	$0.41	$0.44	$0.44	$0.44	
Damagers per aircraft movement	$9.49	$4.25	$4.26	$4.26	$4.26	$8.85	$9.49	$9.49	$9.49	

Cost per year

Damages per year

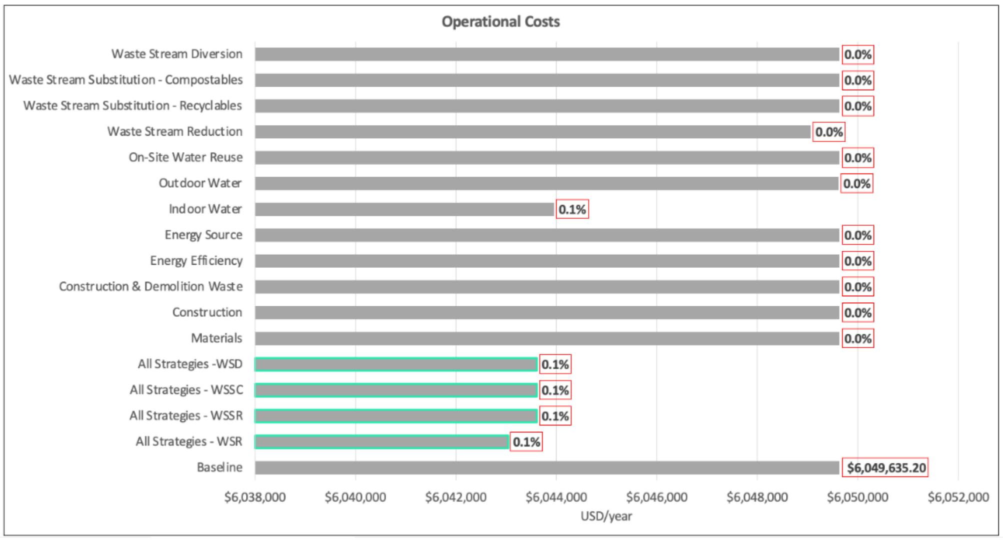


Figure 25. Example of economic impact assessment charts for 'Results Dashboard' sheet.

The following four sections (*Building/Structure Materials Module*, *Operational Energy Module*, *Water and Wastewater Module*, *Waste Module*) describe how emission factors, baseline resource uses and impacts, and mitigation emissions are calculated. Operational costs and monetized climate damage calculations are explained in the *Economic Assessment* section.

4.2.1 Building/Structure Materials Module

4.2.1.1 Emission Factors

We use GHG emission factors for materials and construction activities. We use a FAA report on presumed to conform terminal upgrade projects to estimate CAP emissions from terminal construction.

4.2.1.1.1 Materials

Users have the option of selecting between default and custom GHG emission factors from EC3. EC3 is a web-based tool that aggregates industry environmental product declarations (EPDs) for various building materials. Users can access custom emission factors by making an account at https://www.buildingtransparency.org/ and selecting regional and state options for each material. Default emission factors, which are further characterized as 'Baseline (High)', 'Typical (Median)', and 'Achievable (Low)', are listed in Table 10.

Table 10. Material GHG emission factors used in Building Materials module.

Category	Subtype	Unit	Achievable kg CO_2 (eq)/unit	Typical kg CO_2 (eq)/unit
CONCRETE			**Achievable kg CO_2 (eq)/unit**	**Typical kg CO_2 (eq)/unit**
Ready Mixed Concrete	0-2500 psi (0-17.2 MPa)	m^3	190	266
Ready Mixed Concrete	2501-3000 psi (17.2-20.7 MPa)	m^3	210	291
Ready Mixed Concrete	3001-4000 psi (20.7-27.6 MPa)	m^3	260	343
Ready Mixed Concrete	4001-5000 psi (27.6-34.5 MPa)	m^3	320	406
Ready Mixed Concrete	5001-6000 psi (34.5-41.4 MPa)	m^3	330	429
Ready Mixed Concrete	6001-8000 psi (41.3-55.1 MPa)	m^3	380	498
Ready Mixed Concrete	>8001 psi (>55.1 MPa)	m^3	411	535
STEEL			**Achievable kg CO_2 (eq)/unit**	**Typical kg CO_2 (eq)/unit**
Rebar		kg	0.8	0.98
Structural Steel	Hollow Sections	kg	1.5	2.39
Structural Steel	Hot-Rolled Sections	kg	0.8	1.16
Cold Formed Steel	Framing	kg	1.5	2.28
Prefabricated Assemblies	Open-web steel joists	kg	0.7	1.38
WOOD & COMPOSITES			**Achievable kg CO_2 (eq)/unit**	**Typical kg CO_2 (eq)/unit**
Dimension Lumber	Wood framing	m^3	50	63
Sheathing Panels	Plywood & OSB Sheathing	m^3	200	230
Sheathing Panels	Glass Mat Gypsum Sheathing	1000 m^2	2600	4170
Prefabricated Wood Products	Wood I-joists	m	1.0	1.97
Composite Lumber	LSL/LVL/PSL	m^3	230	361
Mass Timber	GLT/CLT/DLT/NLT	m^3	104	137
INSULATION			**Achievable kg CO_2 (eq)/unit**	**Typical kg CO_2 (eq)/unit**
Insulation by form	Board	m^2-Rsi	2	10
Insulation by form	Blanket	m^2-Rsi	0.5	3
Insulation by form	Foamed-in-Place	m^2-Rsi	2.33	9
Insulation by form	Blown	m^2-Rsi	1	2
FINISHES			**Achievable kg CO_2 (eq)/unit**	**Typical kg CO_2 (eq)/unit**
Gypsum Board		1000 m^2	2500	2980
Acoustical Ceiling Tiles		m^2	6	11
Resilient Flooring		m^2	6	13
Carpet		m^2	6	11
BULK MATERIALS			**Achievable kg CO_2 (eq)/unit**	**Typical kg CO_2 (eq)/unit**
Flat Glass		kg	1.2	1.4

4.2.1.1.2 Construction

The GHG emission factor for construction is the average of calculated emission factors from a review of building construction LCA studies (Säynäjoki et al., 2017). The review documented the normalized GHG emission factors, in kg CO_2 (eq) per square meter, that previous researchers had calculated for construction of residential, commercial, and institutional buildings located in a variety of countries. The average of these factors is 0.5 tons CO_2 (eq) per square meter.

CAP emissions from construction are approximated using a FAA report on presumed to conform terminal upgrade projects (FAA, 2007). CAP emission thresholds are the maximum mass of emissions that could be emitted depending upon the classification of the region in which the airport is located. If the airport is in a nonattainment region, the emission limit for the specified classification characterization (e.g., serious, severe) and pollutant are used in ATEST calculations. If the airport is in a region designated as being in maintenance or attainment, marginal emission limits are used. See Table 11.

Table 11. CAP emission limits for predetermined terminal construction projects (SOURCE: FAA)

Nonattainment Classification Characteristics and Pollutant				Emission Limits (ton/Year)
Ozone		Serious	NO_x	50
Ozone		Serious	VOC	50
Ozone		Severe	NO_x	25
Ozone		Severe	VOC	25
Ozone		Extreme	NO_x	10
Ozone		Extreme	VOC	10
Ozone	Inside OTR	Marginal	NO_x	100
Ozone	Inside OTR	Marginal	VOC	50
Ozone	Outside OTR	Marginal	NO_x	100
Ozone	Outside OTR	Marginal	VOC	100
			CO	100
			SO_2	100
			NO_2	100
		Moderate	PM_{10}	100
		Serious	PM_{10}	70
			$PM_{2.5}$	100
Marginal/Attainment Classification Characteristics and Pollutant				**Emission Limits (Tons/Year)**
Ozone			NO_x	100
Ozone	Inside OTR	Marginal	VOC	50
Ozone	Outside OTR	Marginal	VOC	100
			CO	100
			SO_2	100
			NO_2	100
			PM_{10}	100
			$PM_{2.5}$	100

4.2.1.1.3 Construction and Demolition Waste

GHG emission factors for construction and demolition waste are compiled from EPA's Waste Reduction Model (WARM) for various materials. Emission factors depend on the waste management option used. The waste management options considered for construction and demolition waste are landfilling and recycling. See Table 12.

Table 12. Construction and demolition waste emission factors.

Material	Landfilling (ton CO_2 (eq)/short ton of material)	Recycling (ton CO_2 (eq)/short ton of material)
Asphalt Concrete	0.02	-0.08
Carpet	0.02	-2.38
Concrete	0.02	-0.01
Drywall	-0.06	0.03
Fiberglass Insulation	0.02	N/A
Structural Steel	0.02	-1.93
Vinyl Flooring	0.02	N/A
Wood Products (Dimensional Lumber)	-0.92	-2.66

4.2.1.2 Baseline Material Amounts and Emissions

To estimate the emissions impact from building the airport terminal, the user must know approximate quantities of the materials used to construct the terminal. If available, users can estimate quantities of materials using construction documents or 3D modeling software. For the purposes of testing ATEST, we use a building materials database (De Wolf, 2017) to estimate structural material quantities for case study airports. We use a factor developed for German commercial and residential buildings to estimate the amount of glass (Ortlepp et al., 2016, 2018). We assume that the insulation, gypsum board, carpet, and resilient flooring used in the case study airports is approximately 75% of each airport's gross terminal area. See Table 13. Each materials quantity factor is multiplied by the terminal gross area to estimate total material quantities.

Table 13. Material estimation factors.

Concrete (kg/m^2)	**Rebar (kg/m^2)**	**Structural Steel (kg/m^2)**	**Insulation Board (m^2)**	**Gypsum Board (1000 m^2)**	**Carpet (m^2)**	**Resilient Flooring (m^2)**	**Glass (kg/m^2)**
995	21	66	75% of gross terminal area	75% of gross terminal area	75% of gross terminal area	75% of gross terminal area	2.57

Baseline GHG emissions are the sum of emissions from materials, construction activities, and construction and demolition waste (Equation 6).

Baseline GHG Emissions [tons CO_2 (eq)] [Eq. 6]
$$= (\text{Material Quantity Factor} * \text{Gross Terminal Area} \times EF_{\text{Material, Baseline}}) + (\text{Gross Terminal Area} * EF_{\text{Const, GHG}}) + (\text{Material Quantity} * EF_{\text{C\&D}})$$

Baseline CAP emissions are the threshold limit for a specific pollutant for the county in which the airport is located.

4.2.1.3 Emission Reductions

There are two mitigation strategies considered for the Building Materials module in ATEST. Users can select either 'Typical Materials' or 'Achievable Materials' for lower carbon building materials. Users can also select whether they want to divert 75% of construction and demolition waste from a landfill to a recycling facility. We assume that without mitigation, 100% of construction and demolition waste is always disposed of in a landfill.

4.2.1.3.1 Material Substitution

Emission reductions from switching to lower carbon materials are calculated using Equation 7**:**

Emission reductions [tons CO_2 (eq)] [Eq. 7]
$$= \text{Materials Quantities} * (EF_{\text{Material, Baseline}} - EF_{\text{Material, Typical/Achievable}})$$

4.2.1.3.2 Construction and Demolition Waste Diversion

Emission reductions from diverting 75% of construction and demolition waste are calculated using Equation 8**:**

Emission reductions [tons CO_2 (eq)] [Eq. 8]
= (Waste Material Quantities * $EF_{Landfill, Materials}$)
– [(Waste Material Quantities * 25% * $EF_{Landfill, Materials}$)
+ (Waste Material Quantities * 75% * $EF_{Recycle, Materials}$)]

4.2.2 Energy Module

4.2.2.1 Emission Factors

4.2.2.1.1 Electricity

There are two methods for calculating electricity emission factors in ATEST. The first method allows users to select between their state's average mix from the 2018 version of the EPA's Emissions & Generation Resource Integrated Database (eGRID) or their utility's custom mix (US EPA, 2020).

The emission factors for either the eGRID or Custom mixes are calculated using Equation 9:

EF_{Elec} [tons CO_2 (eq)/kWh]
= (% Coal * EF_{Coal})
+ (% Oil * EF_{Oil})
+ (% Natural Gas * $EF_{Natural\ Gas}$)
+ (% Nuclear * $EF_{Nuclear}$)
+ (% Hydro * EF_{Hydro}) [Eq. 9]
+ (% Biomass * $EF_{Biomass}$)
+ (% Wind * EF_{Wind})
+ (% Solar * EF_{Solar})
+ (% Geothermal * $EF_{Geothermal}$)
+ (% Other * $EF_{Average, All}$)

Fuel specific life-cycle emission factors used in the first method, which are listed in Table 14, come from a previous report (Horvath & Stokes, 2011a).

Table 14. Fuel-specific life-cycle emission factors used in calculating electricity emissions.

Fuel Source	Coal	Oil	Natural Gas	Nuclear	Hydro	Biomass	Wind	Solar	Geothermal
g CO_2 (eq)/kWh	1059	957	696	17	55	56	31	64	28
g NO_x/kWh	0.37	0.92	0.36	0.0065	0.019	1.4	0.019	6.5	0.19
g PM/kWh	0.016	0.022	0.37	0	0.0057	0.34	0.0095	0.07	0
g SO_x/kWh	1.4	0.24	2	0.022	0.004	0.11	0.043	0.18	0.062
g VOC/kWh	3.2	0.13	0.069	0.0045	0.004	0.15	0.012	0.09	0.035
g CO/kWh	0.12	0.24	0.55	0	0.067	0.083	0.097	0.11	0.21

The second method for calculating electricity emission factors relies on a life-cycle tool developed by the DOE's National Energy Technology Laboratory (NETL) (Skone, n.d.). The NETL Grid Mix Explorer version 4.2 calculates life-cycle emission factors for each Federal Energy Regulatory Commission (FERC) regions, balancing authority, and customized mix. The NETL emission factors are based on electricity consumption for each specified region or balancing authority. Consumption data can be more accurate than generation data, as the former accounts for imports and exports of electricity. The NETL emission factors are estimated for greenhouse gases (mass of CO_2 (eq) per kWh consumed) and fine particulate matter (mass of $PM_{2.5}$ (eq) per kWh consumed).

To use the NETL emission factors, users must download the Grid Mix Explorer tool developed by NETL.

In the "consumption_mix" sheet in the NETL Electricity LCI Grid Mix Explorer, users can enter their airport's zip code to look up their respective FERC and balancing authority regions. Alternatively, users can enter custom data about their utility. Users can then enter the values for Global Warming Potential (kg CO_2 (eq) per MWh delivered) and Particulate Matter Formation Potential (kg $PM_{2.5}$ (eq) per MWh delivered) from the "Total" column in the "consumption_mix" sheet.

4.2.2.1.2 Natural Gas

Life-cycle building sector NG emission factor comes from a report (NREL, 2021) that utilizes stationary emission factors from California's Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies (GREET) model. The emissions intensity from combusting natural gas does not vary regionally. We assume that any emissions related to processing natural gas are the same, regardless of region. We use the total emission factor listed in Table 15. It should be noted that we assume CAP emissions related to processing natural gas are negligible.

Table 15. Life-cycle emission factors for stationary combustion of natural gas (NREL 2019).

Combustion (g CO_2 (eq)/therm)	Processing (g CO_2 (eq)/therm)	Total (g CO_2 (eq)/therm)
5953	1687	7640

4.2.2.2 Baseline Energy Consumption and Emissions

There are two methods for estimating baseline energy consumption associated with terminal operation. All calculation methods are modeled after ACRP's *Methodology to Develop the*

Airport Terminal Building Energy Use Intensity (ATB-EUI) Benchmarking Tool (Transportation Research Board, 2016b).

The first method uses utility bill data and allows users to choose between two default options. Default Option 1 estimates baseline emissions from annual electricity consumption, in kWh, and natural gas consumption, in therms using Equation 10:

$$\text{Baseline Emissions [tons X/year]} = (\text{Total Electricity Consumption} * EF_{Elec,\,i}) + (\text{Total Natural Gas Consumption} * EF_{NG}) \quad \text{[Eq. 10]}$$

Users should select Default Option 2 if heating and cooling for the terminal is provided by an on-site plant. Users must input total electricity used for lighting and equipment systems, in kWh, any natural gas utilized for non-heating purposes in therms, and energy used for chilled and heated water in kBTUs. Baseline emissions for energy consumption under Default Option 2 are calculated using Equation 11:

$$\text{Baseline Emissions [tons X/year]} = (\text{Total Electricity}_{Lighting/Equipment} * EF_{Elec,\,i}) + (\text{Total Natural Gas}_{Non\text{-}Heating} * EF_{NG}) + (\text{Total Energy}_{Chilled\ \&\ Heated\ Water} * EF_{Elec,\,i} * 1\ \text{kWh}/3.412\ \text{kBTUs}) \quad \text{[Eq. 11]}$$

The second method used for calculating energy, referred to as the Custom Option, calculates energy consumption as the sum of energy used for specific zones (Table 16) and airport terminal systems (Table 17). Note that the floor zone energy intensities are customizable such that users can enter their own values or distribution of values. Zone energy is found by multiplying the gross area of a specific zone by its corresponding energy use intensity (EUI). The system energy, which is the sum of energy used for equipment and external lighting, is calculated according to Equations 12 and 13:

$$\text{System Energy}_{Equipment}\ \text{[kWh/year]} = [(\text{Power}_{Active}\ (\text{kW}) * \text{Operation Hours}_{Active}\ (\text{hrs/day}) * \text{Operation Days (days/year)}) + (\text{Power}_{Standby}\ (\text{kW}) * \text{Operation Hours}_{Standby}\ (\text{hrs/day}) * \text{Operation Days (days/year)})] * \text{Number of units} \quad \text{[Eq. 12]}$$

$$\text{System Energy}_{External\ lighting}\ \text{[kWh/year]} = \text{Lighting Power Density (kW/m}^2) * \text{Illuminated Area (m}^2) * 12\ \text{hrs/day} * 365\ \text{days/year} \quad \text{[Eq. 13]}$$

Table 16. Floor zones and energy intensities per zone (ACRP 2016).

	Zone	EUI per Zone (kBTUs/m^2-yr)
1	Concession - Food	2780.3
2	Concession - Retail	795.5
3	Office	1000.0
4	Transient Space	1010.7
5	Ticketing Check-In	1010.7
6	Departures Hold Room	1010.7
7	Departure/Border Security	1246.5
8	Outbound/Inbound Baggage Handling	1010.7
9	Arrivals/Baggage Claim	1010.7
10	Service (Mechanical/Electrical/Server)	1769.6

Table 17. Airport terminal systems included in analysis (ACRP 2016).

System
People Movers
Escalators
Elevators
Baggage Handling Systems
GSE - De-icing Cart
GSE - Ramping Cart
GSE - Jet Engine Airstart Cart
GSE - Portable Ground Power
GSE - Aircraft Tug
GSE Total
External Lighting - Covered Area
External Lighting - Uncovered Area

Since the Custom Option converts cumulative energy consumption to kBTUs, we assume that 75% of the energy used for the terminal zones is electricity and 25% is for natural gas. All system energy is provided by electricity. This default assumption can be changed to reflect differing climate zone energy needs

Baseline emissions for energy consumption under the Custom Option are calculated using Equation 14:

Baseline emissions [tons X/year] [Eq. 14]
= (Terminal zone energy (kBTUs) * 75% * (1 kWh/3.412 kBTUs) * $EF_{Elec,\,i}$)
+ (Terminal zone energy (kBTUs) * 25% * (1 therm/100 kBTUs) * EF_{NG})
+ (Terminal systems energy (kWh) * $EF_{Elec,\,i}$)

4.2.2.3 Emission Reduction

4.2.2.3.1 Green electricity source

Since we do not know how electricity and natural gas are specifically used in ‘Default Option 1’ and ‘Default Option 2’, the only emission reduction strategy that we can apply if either of those methods is selected is ‘switching to green electricity source’. ‘Switching to green electricity source’ applies if either Default options or the Custom option is selected. Emission reductions for switching to a green electricity source, either 100% wind or 100% solar, are calculated in Equation 15:

Emission reductions [tons X/year] [Eq. 15]
= Baseline emissions
- (Adjusted annual electricity consumption * $EF_{Elec,\ Wind/Solar}$)

If energy efficiency strategies are selected, the annual electricity consumption will reflect these changes.

4.2.2.3.2 Energy efficiency

Emission reductions from implementing energy efficient escalators, elevators, and people movers, which only apply if the Custom Option is selected, are calculated using Equation 16:

Emission reductions [tons X/year] [Eq. 16]
= Baseline Escalators, Elevators, People Movers Energy Consumption * 15% * $EF_{Elec,\ i}$

It is assumed that the efficient escalations, elevators, and people movers are 15% more efficient than baseline equipment. The efficiency value is customizable.

Emission reductions from implementing energy efficient baggage handling systems, which are assumed to be 50% more efficient than baseline conditions, are calculated using Equation 17:

Emission reductions [tons X/year] [Eq. 17]
= Baseline Baggage Handling Energy Consumption * 50% * $EF_{Elec,\ i}$

Emission reductions from implementing energy efficient external lighting systems are calculated using Equation 18:

Emission reductions [tons X/year] [Eq. 18]
= (Baseline Lighting Power Density – 1.1 W/m^2)
* (1 kW/1000W) * Lighting Area * 12 hrs/day * 365 days/year * $EF_{Elec,\ i}$

Per ASHRAE design guidelines for efficient commercial structures, an efficient lighting power density is 1.1 Watts per square meter of lighting area. It should be noted that the efficient lighting standards apply to: (1) lighting that is sourced from terminal electricity and (2) lighting that does not support aircraft operations on the taxi or runway.

4.2.3 Water Module

4.2.3.1 Emission Factors

Emission factors for water supply and wastewater production are determined by multiplying the airport's electricity emission factor for a specific pollutant (e.g., CO_2 (eq)/kWh, NO_x/kWh) by the energy intensities for water and wastewater, which relate how much electricity is needed to treat and convey one cubic meter of water or wastewater. We use nationally averaged energy intensities for water and wastewater (Table 18). Energy intensity values from rainwater harvesting and greywater reuse are from a review of previous literature (Table 19).

4.2.3.1.1 Water and Wastewater

Table 18. Water and wastewater emission factors (Chini & Stillwell, 2018).

Water (kWh/m^3)	Wastewater (kWh/m^3)
0.34	0.43

4.2.3.1.2 On-Site Reuse

Table 19. On-site reuse emission factors

Rainwater Harvesting (kWh/m^3)	Greywater (kWh/m^3)
4	2

As with other default values used within ATEST, users can customize the energy intensity values to a static number or distribution of numbers.

4.2.3.2 Baseline Water and Wastewater Volumes and Emissions

Indoor baseline and outdoor maintenance water volumes are calculated using methodologies developed in ACRP's *Water Efficiency Management Strategies for Airports* (Krop et al., 2016).

Indoor water sources included in volume calculations include water used for toilets, urinals, restroom faucets, kitchen faucets, pre-rinse spray valves, dishwashers, ice machines, cooling towers, and boilers. The baseline indoor water volume is the sum of Equations 19 through 27**:**

$$\text{Volume}_{\text{Toilets}}\ [\text{m}^3/\text{year}] = 1.6\ \text{gal/flush} * (0.625\ \text{flushes/pax*day}) * \text{pax/day} * 365\ \text{days/year} * 1\ \text{m}^3/264\ \text{gal} \quad \text{[Eq. 19]}$$

$$\text{Volume}_{\text{Urinals}}\ [\text{m}^3/\text{year}] = 1.0\ \text{gal/flush} * (0.375\ \text{flushes/pax*day}) * \text{pax/day} * 365\ \text{days/year} * 1\ \text{m}^3/264\ \text{gal} \quad \text{[Eq. 20]}$$

$$\text{Volume}_{\text{Faucets, Restroom}}\ [\text{m}^3/\text{year}] = 1\ \text{gal/min} * (0.16667\ \text{min/pax*day}) * \text{pax/day} * 365\ \text{days/year} * 1\ \text{m}^3/264\ \text{gal} \quad \text{[Eq. 21]}$$

$Volume_{Faucets, Kitchen}$ [m^3/year]
= 1 gal/min * (1 min/meal*day) * meal/day * 365 days/year * 1 m^3/264 gal [Eq. 22]

$Volume_{Pre\text{-}rinse\ spray\ valves}$[$m^3$/year]
= 2 gal/min * (0.02 min/meal*day) * meal/day * 365 days/year * 1 m^3/264 gal [Eq. 23]

$Volume_{Dishwashers}$[m^3/year]
= 2.5 gal/rack * (0.05 rack/meal*day) * meal/day * 365 days/year * 1 m^3/264 gal [Eq. 24]

$Volume_{Ice\ Machines}$[m^3/year]
= 0.25 gal/lb * (0.5 lb/meal*day) * meal/day * 365 days/year * 1 m^3/264 gal [Eq. 25]

$Volume_{Cooling\ Towers}$[m^3/year]
= ($Volume_{Windage}$+ $Volume_{Evaporation}$+ $Volume_{Blowdown}$) * 365 days/year * 1 m^3/264 gal

Where:
$Volume_{Windage}$
= Cooling Area (m^2) * (10.7639 ft^2/m^2) * (ton cooling/500 ft^2) * (3 gal/ton*min) * Drift Rate (0.1%) * 1440 Btu/lb [Eq. 26]

$Volume_{Evaporation}$
= Cooling Area (m^2) * (10.7639 ft^2/m^2) * (ton cooling/500 ft^2) * (3 gal/ton*min) * 8.34 lb/gal * 1440 Btu/lb * (10/1000/8.34 lb/gal)

$Volume_{Blowdown}$
= [($Volume_{Windage}$ * (# $Cycles_{Baseline}$ – 1)) - $Volume_{Evaporation}$]/ (1 - (# $Cycles_{Baseline}$))

$Volume_{Boilers}$[m^3/year]
= # Boilers * (100 gal/boiler*day) * 365 days/year * 1 m^3/264 gal [Eq. 27]

Sources included in outdoor water volume calculations include water used for landscaping, pavement cleaning, and vehicle washing. The baseline outdoor water volume is the sum of Equations 28 through 30:

$Volume_{Landscaping}$[m^3/year]
= Irrigation Factor (m^3/m^2*year) * Landscape Area (m^2) / Irrigation Efficiency (65%) [Eq. 28]

$Volume_{Pavement\ Cleaning}$ [m^3/year]
= 10 gal/day*pax * (0.001 uses/day) * pax/day * 365 days/year * 1 m^3/264 gal [Eq. 29]

$Volume_{Vehicle\ Washing}$ [m^3/year]
= 80 gal/day*pax * (0.0002 uses/day) * pax/day * 365 days/year * 1 m^3/264 gal [Eq. 30]

Users can select between rainwater collected from precipitation events and greywater collected restroom faucets. Each source can either be used to supply water for toilet and urinal function or for landscaping needs. The available on-site water volumes are calculated using Equations 31 and 32:

$$Volume_{Rainwater}\ [m^3/year] = Precipitation\ (m/year) * Catchment\ Area\ (m^2) * Collection\ Efficiency\ (90\%) \quad [Eq.\ 31]$$

$$Volume_{Greywater}\ [m^3/year] = Volume_{Faucets,\ Restroom} \quad [Eq.\ 32]$$

Baseline emissions from water consumption and wastewater production are calculated using Equation 33:

$$Baseline\ emissions\ [tons\ X/year] = (Water\ Volume_{Baseline,\ Indoor} + Water\ Volume_{Baseline,\ Outdoor\ Maintenance\ \&\ Landscaping} * EF_{Water,\ j}) + (Water\ Volume_{Baseline,\ Indoor} + Water\ Volume_{Baseline,\ Outdoor\ Maintenance} * EF_{WWater,\ j}) \quad [Eq.\ 33]$$

4.2.3.3 Emission Reductions

Emission reductions from implementing any indoor water conservation strategy are calculated with Equation 34:

4.2.3.3.1 Emission Reductions for Indoor Strategies

$$Emission\ reductions\ [tons\ X/year] = (Water\ Volume_{Baseline,\ Indoor} - Water\ Volume_{Reduced,\ Indoor}) * (EF_{Water,\ j} + EF_{WWater,\ j}) \quad [Eq.\ 34]$$

Emission reductions from implementing any outdoor landscaping water conservation strategy are calculated with Equation 35:

4.2.3.3.2 Emission Reductions for Outdoor Landscaping Strategies

$$Emission\ reductions\ [tons\ X/year] = (Water\ Volume_{Baseline,\ Landscaping} - Water\ Volume_{Reduced,\ Landscaping}) * EF_{Water,\ j}$$

Where:

IF EFFICIENT LANDSCAPING selected:
= minimum irrigation factor for selected city [Eq. 35]

IF EFFICIENT IRRIGATION selected:
= 50% reduction in outdoor landscaping water demand

IF EFFICIENT LANDSCAPING AND EFFICIENT IRRIGATION selected:

= minimum irrigation factor for selected city and 50% reduction in outdoor landscaping water demand

Emission reductions from implementing any outdoor maintenance water conservation strategy are calculated with Equation 36:

4.2.3.3.3 Emission Reductions for Outdoor Maintenance Strategies

$$\text{Emission reductions [tons X/year]} = (\text{Water Volume}_{\text{Baseline, Outdoor Maintenance}} - \text{Water Volume}_{\text{Reduced, Outdoor Maintenance}}) * (EF_{\text{Water, j}} + EF_{\text{WWater, j}}) \quad \text{[Eq. 36]}$$

Emission reductions from implementing any on-site water reuse strategy are calculated using Equations 37 through 40:

4.2.3.3.4 Emission Reductions for Rainwater Harvesting – Irrigation

$$\text{Emission reductions [tons X/year]} = (\text{Water Volume}_{\text{Adjusted, Outdoor Landscaping}} * EF_{\text{Water, j}}) - [(\text{Volume}_{\text{Rainwater}} * EI_{\text{RWH}} * EF_{\text{Elec, i}}) + (\text{Volume}_{\text{Rainwater, Remaining}} * EF_{\text{WWater, j}}) - (\text{Volume}_{\text{Rainwater 4 Irrigation}} * EF_{\text{Elec, i}})] \quad \text{[Eq. 37]}$$

4.2.3.3.5 Emission Reductions for Rainwater Harvesting – Toilets/Urinals

$$\text{Emission reductions [tons X/year]} = \text{Water Volume}_{\text{Adjusted, Toilets/Urinals}} * (EF_{\text{Water, j}} + EF_{\text{WWater, j}}) - [(\text{Volume}_{\text{Rainwater}} * EI_{\text{RWH}} * EF_{\text{Elec, i}}) + (\text{Volume}_{\text{Rainwater, Remaining}} * EF_{\text{WWater, j}}) - (\text{Volume}_{\text{Rainwater 4 Toilets/Urinals}} * (EF_{\text{Water, j}} + EF_{\text{WWater, j}}))] \quad \text{[Eq. 38]}$$

4.2.3.3.6 Emission Reductions for Greywater – Irrigation

$$\text{Emission reductions [tons X/year]} = (\text{Water Volume}_{\text{Adjusted, Outdoor Landscaping}} * EF_{\text{Water, j}}) - [(\text{Volume}_{\text{Greywater}} * EI_{\text{Greywater}} * EF_{\text{Elec, i}}) + (\text{Volume}_{\text{Greywater, Remaining}} * EF_{\text{WWater, j}}) - (\text{Volume}_{\text{Greywater 4 Irrigation}} * EF_{\text{Elec, i}})] \quad \text{[Eq. 39]}$$

4.2.3.3.7 Emission Reductions for Greywater – Toilets/Urinals

$$\text{Emission reductions [tons X/year]} = \text{Water Volume}_{\text{Adjusted, Toilets/Urinals}} * (EF_{\text{Water, j}} + EF_{\text{WWater, j}}) - [(\text{Volume}_{\text{Greywater}} * EI_{\text{Greywater}} * EF_{\text{Elec, i}}) + (\text{Volume}_{\text{Greywater, Remaining}} * EF_{\text{WWater, j}}) - (\text{Volume}_{\text{Greywater 4 Toilets/Urinals}} * (EF_{\text{Water, j}} + EF_{\text{WWater, j}}))] \quad \text{[Eq. 40]}$$

It should be emphasized that ATEST prevents the double counting of emissions savings from interdependent strategies. For example, if both efficient toilets/urinals and on-site reuse for toilets/urinals are selected, each savings calculation considers newly adjusted water volumes.

4.2.4 Waste Module

4.2.4.1 Emission Factors

Waste Module emission factors are estimated using EPA's Waste Reduction Module (WARM). WARM calculates GHG emission and energy factors for various waste management strategies for different types of waste. Emission factors for landfilling recyclables and for recycling are weighted averages of material-specific emission factors (e.g., how many GHGs are emitted from landfilling one ton of corrugated cardboard) and the amount of the recyclable material within the airport's waste stream. ATEST users can select between default or custom options to determine how the recyclables in their waste stream impact emission factors. The default option, in Table 20, shows the composition of specific recyclables. These values come from a waste audit of EWR Airport. If users select the custom option, they can change the default composition values.

Table 20. Default recyclable material composition.

Material	**% of Material in Waste Stream - DEFAULT**
Aluminum Cans	1.2%
Steel Cans	0.6%
PET	4.6%
HDPE	0.7%
Glass	3.1%
Corrugated cardboard	*2.0%*
Magazines/3rd class mail	0.0%
Newspaper	0.0%
Office paper	0.0%
Telephone books	0.0%
Mixed Paper	9.1%
Mixed Plastics	5.2%

CAP emission factors for the Waste Module stream are approximated using energy factors developed for EPA's WARM. WARM's energy factors classify, for each materials type and waste management practice, how much process and transportation energy are consumed per ton of material. We convert the process energy, which is in units of mmBtu per ton of material, with the simplifying assumption that all process energy is sourced from electricity (Equation 41).

$$EF_{CAP,\ Process} = \text{Process Energy Factor } (10^6 \text{ Btu/ton waste}) * (1 \text{ kWh}/3412.14 \text{ Btu}) * EF_{Elec,\ i} \quad \text{[Eq. 41]}$$

We assume that all transportation energy is sourced by diesel-powered trucks. We use life-cycle diesel fuel emission factors from EPA's GREET to convert transportation energy to an equivalent CAP emission factor (Equation 42).

$$EF_{CAP,\ Trans} = \text{Trans Energy Factor } (10^6 \text{ Btu/ton waste}) * EF_{Truck,\ Diesel} \qquad \text{[Eq. 42]}$$

The total CAP emission factor for a specific material type and waste management strategy is calculated using Equation 43:

$$EF_{CAP,\ Total} = EF_{CAP,\ Process} + EF_{CAP,\ Trans} \qquad \text{[Eq. 43]}$$

A complete calculation of CAP emission factors is included the sheet called "WARM – NonGHG" in ATEST.

4.2.4.1.1 Landfilling

Landfilling GHG and CAP emission factors for specific waste streams are listed in Table 21.

Table 21. Landfilling GHG and CAP emission factors

	Food Stream	**Landscape Stream**	**Non-Recoverable Stream**	**Recycling Stream-DEFAULT**	**Recycling Stream - CUSTOM**
Raw Landfill Emission Factor (ton CO_2 (eq)/short ton of feedstock)	5.00E-01	-2.00E-01	2.00E-02	N/A	N/A
Weighted Average Landfill Emission Factor (ton CO_2 (eq)/ton waste)	5.51E-01	-2.20E-01	2.20E-02	2.02E-02	0.00E+00
Weighted Average Landfilling Emission Factor (ton VOC/ton waste)	1.20E-05	1.22E-05	1.24E-05	2.44E-06	0.00E+00
Weighted Average Landfilling Emission Factor (ton CO/ton waste)	2.31E-04	2.34E-04	2.37E-04	5.85E-04	0.00E+00
Weighted Average Landfilling Emission Factor (ton NO_x/ton waste)	1.06E-05	1.47E-05	1.79E-05	2.38E-06	0.00E+00
Weighted Average Landfilling Emission Factor (ton PM_{10}/ton waste)	1.85E-06	2.16E-06	2.40E-06	2.91E-07	0.00E+00
Weighted Average Landfilling Emission Factor (ton $PM_{2.5}$/ton waste)	6.29E-07	9.36E-07	1.18E-06	1.44E-07	0.00E+00
Weighted Average Landfilling Emission Factor (ton SO_x/ton waste)	1.90E-06	2.17E-06	2.40E-06	2.90E-07	0.00E+00

4.2.4.1.2 Composting

Composting GHG and CAP emission factors for specific waste streams are listed in Table 22.

Table 22. Composting GHG and CAP emission factors.

	Food Stream	Landscape Stream
Raw Composting Emission Factor (ton CO_2 (eq)/short ton of feedstock)	-0.12	-0.05
Weighted Average Composting Emission Factor (ton CO_2 (eq)/ton waste)	-1.3E-01	-5.5E-02
Raw Energy Factor (mmBTU/ton of composted material)	0.73	0.26
Weighted Average Composting Emission Factor (ton VOC/ton waste)	3.4E-05	1.2E-05
Weighted Average Composting Emission Factor (ton CO/ton waste)	6.4E-04	2.3E-04
Weighted Average Composting Emission Factor (ton NO_x/ton waste)	4.8E-05	1.7E-05
Weighted Average Composting Emission Factor (ton PM_{10}/ton waste)	6.5E-06	2.3E-06
Weighted Average Composting Emission Factor (ton $PM_{2.5}$/ton waste)	3.2E-06	1.1E-06
Weighted Average Composting Emission Factor (ton SO_x/ton waste)	6.5E-06	2.3E-06

4.2.4.1.3 Recycling

Recycling GHG and CAP emission factors for specific waste streams are listed in Table 23.

Table 23. Recycling emission factors.

	Recycling Stream - DEFAULT	Recycling Stream - CUSTOM
Raw Recycling Emission Factor (ton CO_2 (eq)/short ton of feedstock)	N/A	N/A
Weighted Average Recycling Emission Factor (ton CO_2 (eq)/ton waste)	-7.15E-01	0.00E+00
Weighted Average Recycling Emission Factor (ton VOC/ton waste)	-1.85E-05	0.00E+00
Weighted Average Recycling Emission Factor (ton CO/ton waste)	-2.91E-04	0.00E+00
Weighted Average Recycling Emission Factor (ton NO_x/ton waste)	-2.13E-04	0.00E+00
Weighted Average Recycling Emission Factor (ton PM_{10}/ton waste)	-1.67E-05	0.00E+00
Weighted Average Recycling Emission Factor (ton $PM_{2.5}$/ton waste)	-1.60E-05	0.00E+00
Weighted Average Recycling Emission Factor (ton SO_x/ton waste)	-1.52E-05	0.00E+00

4.2.4.2 Baseline Solid Waste Stream Volumes and Emissions

Equation 44 is used to calculate the baseline solid waste stream (SWS) volume:

$$SWS_{Baseline}\,[\text{tons waste/year}] = Volume_{Non\text{-}Recoverables} + Volume_{Recyclables} + Volume_{Compostables} \quad \text{[Eq. 44]}$$

Where:

$$Volume_{Recyclables} = Volume_{Recyclables,\ Landfilled} + Volume_{Recyclables,\ Recycled}$$

$$Volume_{Compostables} = Volume_{Compostables,\ Landfilled} + Volume_{Compostables,\ Composted}$$

Baseline emissions from the SWS volume are calculated with Equation 45**:**

$$\begin{aligned}
\text{Baseline emissions [tons X/year]} &= (Volume_{Recyclables,\ Landfilled} * EF_{Recyclables,\ Landfilled}) \\
&+ (Volume_{Recyclables,\ Recycled} * EF_{Recyclables,\ Recycled}) \\
&+ (Volume_{Non\text{-}Recoverables} * EF_{Non\text{-}Recoverables,\ Landfilled}) \\
&+ (Volume_{Food\ Compostables,\ Landfilled} * EF_{Food\ Compostables,\ Landfilled}) \\
&+ (Volume_{Landscape\ Compostables,\ Landfilled} * EF_{Landscape\ Compostables,\ Landfilled}) \\
&+ (Volume_{Food\ Compostables,\ Composted} * EF_{Food\ Compostables,\ Composted}) \\
&+ (Volume_{Landscape\ Compostables,\ Composted}) * EF_{Landscape\ Compostables,\ Composted})
\end{aligned} \quad \text{[Eq. 45]}$$

4.2.4.3 Emission Reductions

4.2.4.3.1 Waste Reduction Strategies

Emission reductions for waste management strategies that focus on solid waste reductions are calculated in are calculated in Equations 46 and 47. Users can either reduce food waste within the terminal or reduce non-recoverable waste within the terminal.

4.2.4.3.1.1 Reduce food waste within terminal by 20%

$$\begin{aligned}
\text{Emission reductions [tons X/year]} &= (Volume_{Food\ Compostables,\ Landfilled\ (New)} * EF_{Food\ Compostables,\ Landfilled}) \\
&+ (Volume_{Food\ Compostables,\ Composted\ (New)} * EF_{Food\ Compostables,\ Composted})
\end{aligned} \quad \text{[Eq. 46]}$$

Where:

$$Volume_{Food\ Compostables,\ Landfilled\ (New)} = Volume_{Food\ Compostables,\ Landfilled} * 20\%$$

$$Volume_{Food\ Compostables,\ Composted\ (New)} = Volume_{Food\ Compostables,\ Composted} * 20\%$$

4.2.4.3.1.2 Reduce non-recoverables waste within terminal by 20%

$$\text{Emission reductions [tons X/year]} = (Volume_{Non\text{-}Recoverables,\ Landfilled\ (New)} * EF_{Non\text{-}Recoverables,\ Landfilled}) \quad \text{[Eq. 47]}$$

Where:
$Volume_{Non\text{-}Recoverables,\ Landfilled\ (New)} = Volume_{Non\text{-}Recoverables,\ Landfilled} * 20\%$

4.2.4.3.2 Waste Substitution Strategies

Users can select to substitute non-recoverable materials with recyclables, as calculated in Equation 48, or to substitute non-compostable materials with compostables entering the food waste stream (Equation 49).

4.2.4.3.2.1 Substitute 10% of non-recoverable materials with recyclables

$$Emission\ reductions\ [tons\ X/year] = Volume_{Non\text{-}Recoverables,\ Landfilled\ (New)} * (EF_{Non\text{-}Recoverables,\ Landfilled} - EF_{Recyclables,\ Recycled}) \quad [Eq.\ 48]$$

Where:
$Volume_{Non\text{-}Recoverables,\ Landfilled\ (New)} = Volume_{Non\text{-}Recoverables,\ Landfilled} * 10\%$

4.2.4.3.2.2 Substitute 5% of non-compostable materials with compostables

$$Emission\ reductions\ [tons\ X/year] = Volume_{Non\text{-}Recoverables,\ Landfilled\ (New)} * (EF_{Non\text{-}Recoverables,\ Landfilled} - EF_{Compostables,\ Composted}) \quad [Eq.\ 49]$$

Where:
$Volume_{Non\text{-}Recoverables,\ Landfilled\ (New)} = Volume_{Non\text{-}Recoverables,\ Landfilled} * 5\%$

4.2.4.3.3 Waste Diversion Strategies

Users can select to divert 100% recyclables from the terminal (Equation 50), compost 100% of landscape waste on-site (Equation 51), or compost 100% of food waste (Equation 52).

4.2.4.3.3.1 Divert 100% of recyclables from terminal

$$Emission\ reductions\ [tons\ X/year] = Volume_{Recyclables,\ Recycled\ (New)} * (EF_{Recyclables,\ Landfilled} - EF_{Recyclables,\ Recycled}) \quad [Eq.\ 50]$$

Where:
$Volume_{Recyclables,\ Recycled\ (New)} = Volume_{Recyclables,\ Landfilled}$

4.2.4.3.3.2 Compost 100% of landscape waste on-site

$$Emission\ reductions\ [tons\ X/year] = Volume_{Landscape\ Compostables,\ Composted\ (New)} * (EF_{Landscape\ Compostables,\ Landfilled} - EF_{Landscape\ Compostables,\ Composted}) \quad [Eq.\ 51]$$

Where:
$\text{Volume}_{\text{Landscape Compostables, Composted (New)}} = \text{Volume}_{\text{Landscape Compostables, Landfilled}}$

4.2.4.3.3.3 Compost 100% of food waste

Emission reductions [tons X/year]
$= \text{Volume}_{\text{Food Compostables, Composted (New)}}$
$* (\text{EF}_{\text{Food Compostables, Landfilled}} - \text{EF}_{\text{Food Compostables, Composted}})$ [Eq. 52]

Where:
$\text{Volume}_{\text{Food Compostables, Composted (New)}} = \text{Volume}_{\text{Food Compostables, Landfilled}}$

4.2.5 Economic Assessments

4.2.5.1 Operational Costs

On the ‘User Input’ sheet, users enter their unit cost rates for purchasing electricity (USD/kWh), natural gas (USD/therm), and water (USD/m^3). They enter the unit cost rate for producing wastewater (USD/m^3). They also enter landfilling tipping fees (USD/ton), recycling cost rates (USD/ton), and composting cost rates (USD/ton).

Baseline operational costs for each module are calculated according to Equation 53:

Baseline costs [USD/year]
= Baseline Resource Amount (X/year) * Unit Cost (USD/X) [Eq. 53]

Operational cost reductions are calculated according to Equation 54:

Cost reductions [USD/year]
= [Baseline Resource Amount (X/year) - Reduced Resource Amount (X/year)] [Eq. 54]
* Unit Cost (USD/X)

4.2.5.2 Monetized Climate Damages

Users can select between either a default or custom method for calculating the monetized climate damages on the “User Input” sheet. The default method adjusts the Social Cost of Carbon (SCC) to year 2019 by linearly interpolating between the 2015 and 2020 SCCs with a 3% discount rate that were developed by the Interagency Working Group (National Academies of Sciences, 2017). The custom method allows users to enter their own, internally developed SCC in the “User Input” sheet.

4.3 Discussion

An application of ATEST for multiple airports is provided in Chapter 5 of the dissertation. Further discussion is included in Chapter 5.

4.3.1 Uncertainty Assessment

4.3.1.1 Uncertainty in Life-Cycle Assessment

ATEST is an integrated, deterministic model. It combines existing modeling frameworks developed by the ACRP, EPA, and DOE, built-in assumptions, and user input, and it outputs point values. It is important to adequately address inherent uncertainty and variability in how we construct a deterministic LCA model, use the model to analyze specific problems, and collect and interpret results from the model. Users should have confidence in the LCA approach and in the accuracy of the model results. To improve confidence in results, we must address the uncertainty associated with data, scenario decisions, and model choices in a systematic manner.

4.3.1.2 Types and Sources of Uncertainty

If we are uncertain about our results, we are unsure about how accurate the results are in depicting the truth. Types of uncertainty in LCA can be categorized into three areas: (1) parameter or input data; (2) decisions about the context of the system/boundary analysis; and (3) the mathematical relationships used to construct the model (Lloyd & Ries, 2007). Uncertainty arises from errors in measure of data, subjective judgment about measuring data, errors in attempting to quantify qualitative data, scenarios, or relationships, subjectivity in values or models derived by experts, and approximation of data values or model relationships (Lloyd & Ries, 2007). Characterizing the type of uncertainty can help us in determining which methods are most appropriate and useful in mitigating uncertainty. It is necessary to distinguish between uncertainty and variability. Uncertainty largely stems from a lack of complete information. Variability in some data and model outcomes is often inherent due to specific temporal, spatial, or technological factors. Inherent variability in input data can lead to uncertainty.

4.3.1.3 Methods for Addressing Uncertainty in LCA

Given the inherent complexity of some models, an effective approach for minimizing uncertainty is to focus efforts on the parameters, choices, and mathematical relationships that have the largest influence (Björklund, 2002).

Methods for addressing uncertainty include stochastic and scenario modeling, such as Monte Carlo simulation or global sensitivity analyses. A lot of computational effort can be required to perform Monte Carlo simulations (Bojacá & Schrevens, 2010; Heijungs, 2020). Information on ranges or distributions of values for parameters are necessary for performing Monte Carlo simulation and global sensitivity analyses (Qin et al., 2020). If such information is unavailable or difficult to come by, or if the computational effort is too great, one method for addressing parameter uncertainty that can be used is the semi-quantitative pedigree matrix. The pedigree matrix method was developed in the 1990s and modeled off the Numeral Unit Spread

Assessment Pedigree (NUSAP) framework, a multidimensional uncertainty assessment system (Muller et al., 2016; Qin et al., 2020) The pedigree matrix approach is aimed at improving the quality of data used in LCAs. With the pedigree matrix method, a probability distribution is assigned to data quality indicators. These indicators include the data's reliability, completeness, temporal and geographical correlations, and technological correlations.

The pedigree matrix method is employed in ecoinvent's LCI database (Muller et al., 2016), which can be used with proprietary LCA software and is compliant with ISO 14040 and 14044, the standards for conducting LCAs. Data inaccuracy and lack of comprehensive, or representative, data are the two types of parameter uncertainty that are modeled in ecoinvent's LCI database. While a weakness of the pedigree matrix is the inherent subjectivity of the expert's scoring of data (Qin et al., 2020), it can provide some measure of user confidence when stochastic modeling is not conducted.

4.3.1.4 Uncertainty in ATEST and Opportunities for Model Validation

ATEST is an integrated model, incorporating methodological frameworks and data from ACRP, the EPA, DOE, and other government and academic sources. Although a relatively simple model, there is uncertainty associated with the default assumptions and data used in ATEST. The uncertainty of the data used in ATEST is assessed using the pedigree matrix method, which is commonly used in LCA studies. We use the publicly available ecoinvent framework for scoring data (Ciroth et al., 2016). Uncertainty of the data is scored according to the data's reliability, completeness, temporal correlation, geographical correlation, and further technological correlation. The geometric standard deviation represents the spread of uncertainty for each indicator's score (which has a log-normal distribution). Data with low uncertainty will have scores of 1.00. Low uncertainty scores in factors such as data age, completeness, and specificity indicate that results are reasonably reliable. Uncertainty scoring for major data sets used in ATEST are included in tables (outlined in bold) in Appendix C.

Although designed to output a point value for results, users can validate ATEST results in several ways. Users can conduct multiple runs of ATEST using known upper and lower bounds for input values. Additionally, users can change values designated as default or assumption with their own custom data. Where applicable, users can validate model results by comparing ATEST output to previous data (e.g., GHG emission inventory, monthly utility reports).

4.3.2 Limitations

ATEST offers a preliminary assessment of which strategy or suite of strategies are most impactful at mitigating an airport terminal's impacts to climate change and human health, compared to baseline, unmitigated conditions. We do not advocate that this tool be used in lieu of existing environmental impact reporting and planning that, in the case of United States airports, is required by federal law when embarking on new projects. Additionally, use of ATEST does not supplant exposure and risk assessment practices that airports might need to conduct as part of investigation requirements for proposed projects. Additional limitations of ATEST are discussed in Chapter 5.

4.4 Conclusions

ATEST is a novel decision-support tool, entirely encapsulated within Excel, that stakeholders can use to assess life-cycle GHG and CAP emissions, climate change and human health indicators, operational costs, and monetized climate damages associated with the construction and operation of airport terminals and ancillary structures.

ATEST should be considered a complement to existing assessment methods practiced by airport stakeholders by:

- Supporting project planners/collaborators at design and pre-construction stages when (1) the scope of a project is not yet fully defined and (2) it is easier to compare among potential mitigation strategies;

- Efficiently incorporating regional variation and supply chain effects to demonstrate that what is considered sustainable and ideal for one airport might not necessarily be effectual or worthwhile for another airport; and

- Combining multiple pieces of information, including emissions inventories, climate change and human health indicators, operational costs, and monetized damages, so that decision makers can choose projects and strategies more holistically, emphasizing values such as sustainability and resiliency

Chapter 5. ATEST Application

The following chapter has been for publication in the Transportation Research Record from Greer, F., Horvath, A. and Rakas, J., 2021. Life-Cycle Approach to Healthy Airport Terminal Buildings: A Spatial-Temporal Analysis of Mitigation Strategies for Addressing the Pollutants that Affect Climate Change and Human Health.

We explore the potential environmental and human health impacts associated with constructing and operating terminal buildings for commercial airports in the United States. The primary research objectives are to quantify baseline and mitigated greenhouse gas (GHG) and criteria air pollutant (CAP) emissions, operational costs, and monetized climate change damages for terminal building construction and materials, annual operational energy consumption, annual water consumption and wastewater generation, and annual waste production. An Excel-based decision-support tool, Airport Terminal Environmental Support Tool (ATEST), is created to allow airport stakeholders to conduct preliminary assessment of baseline and mitigated impacts. Emissions are quantified using a life-cycle approach that accounts for cradle-to-grave effects. Climate change and human health impacts are characterized using EPA's Tool for Reduction and Assessment of Chemical (TRACI) impact factors. ATEST is applied to multiple case study airports (RNO, PIT, EWR, SEA, SFO, ATL) to demonstrate its scalability and capability to assess varying spatial factors. Across all airports, electricity mix is a significant factor in determining GHG emissions, and construction is important for CAP emissions. A sensitivity analysis of the SFO case study reveals that the electricity mix, amount of electricity consumed in the airport terminal, terminal gross area, and the amount of compostables in the waste stream have the most impact on increasing annual GHG emissions. ATEST represents a crucial first step of help for airport stakeholders to make decisions that will lead to healthier, more sustainable airport terminals.

5.1 Introduction

Aviation facilities and infrastructure, such as communication, navigation, and surveillance systems, air traffic control towers, runways, and airport terminals, support the movement of billions of passengers and tens of millions of tons of freight each year (ICAO, 2020b). Terminal buildings are an integral element of the airport system boundary, processing passengers from the landside to the airside, and vice versa. The terminal also serves as a critical revenue source, with in-terminal concessions accounting for between 7.1 and 10.6% of total operating revenue and between 12.2 and 24.7% of an airport's non-aeronautical revenue in 2019 (FAA, 2021b). Even with uncertainty in how COVID-19 will continue to affect the aviation industry, assessments indicate that terminals will still require upgrades to meet changing aircraft and capacity needs (ASCE, 2021). Upgrades are also necessary for improving passenger experiences, complying with environmental regulations, and reducing the exposure of infectious diseases such as COVID-19. Changes to terminal infrastructure should incorporate the healthy building concept, which emphasizes that buildings should be sustainable for both the environment and for people.

Construction, operation, and renovation of terminal buildings consumes resources and releases of pollutants to air, water, and soil. The release of greenhouse gas (GHG) emissions contributes to climate change. Given the relative speed with which some other sectors are expected to decarbonize (e.g., electricity generation, on-road vehicles), the aviation industry will be a significant source of GHG emissions into the 21st century (Terrenoire et al., 2019). In addition to mitigating aircraft emissions, reducing an airport's facility-related emissions will help meet the governmental GHG emission reduction targets aimed at minimizing climate-related impacts such as sea level rise, devastating storms and wildfires, and population displacements are minimized. Emissions of criteria air pollutants (CAPs), particularly fine particulate matter ($PM_{2.5}$), are associated with negative human health consequences, including lung and cardiovascular disease, for people working in and living near airports. In the United States, mitigating air pollution exposure is paramount to support compliance with National Ambient Air Quality Standards (NAAQS) for CAPs and to ensure that historically underserved communities are not disproportionately burdened by airport construction and operation.

Airports are committed to reducing pollution, whether due to federal, state, or local regulations, market forces, or perceived customer satisfaction. Frameworks at the individual airport level aim to minimize emissions from construction and operational activities. For example, San Francisco International Airport (SFO) created planning, design, and construction guidelines to provide contractors with expected and expanded requirements when building sustainable airport facilities (SFO, 2015). Similar guidelines are implemented at Los Angeles International Airport (LAX), with an additional policy requiring new terminals to reach a certain level of Leadership in Energy and Environmental Design (LEED) certification (LAWA, 2021). Best practices and support tools developed by the ACRP rate the most sustainable strategies at an airport (Lurie et al., 2014), identify potential operational GHG mitigation opportunities (S. Barrett, 2019; Program et al., 2011; Transportation Research Board, 2016a), and develop pathways for minimizing air pollution and other negative impacts on the surrounding environment (Transportation Research Board, 2020; Transportation Research Board & National Academies of Sciences, 2019, 2020). Other ACRP efforts include frameworks for accounting for and managing airport construction emissions (Kim et al., 2014; Transportation Research Board, 2011) and for overall airport air quality (Transportation Research Board, 2012; Transportation Research Board & National Academies of Sciences, 2018). Airport Council International's Airport Carbon and Emissions Reporting Tool (ACERT) offers airport managers a free Excel-based tool for creating an inventory of airport operational GHG emissions (ACI, 2021). There are fewer studies that incorporate life-cycle methodologies to estimate GHG and CAP emissions. Life-cycle studies directly related to airport terminals include efforts to estimate the appropriate wall thickness dimensions to optimize performance while limiting GHG emissions (Akyüz et al., 2017; Kon &

Caner, 2019) and similarly identify optimal floor construction materials (Petersen & Solberg, 2003).

A review of recent academic and industry literature supports the need for more holistic decision-making for airport infrastructure, as there is a lack of exploration of the significance of embodied and supply-chain impacts on overall emissions (Greer et al., 2020). Specifically, there is a gap in quantifying life-cycle impacts from construction and operation of airport infrastructure, such as terminals, and in mapping how those impacts vary regionally.

The primary objective of this study is to create a customizable, scalable decision-support tool to aid airport stakeholders in: (1) Determining the baseline life-cycle GHG and CAP emissions associated with terminal building construction and materials, annual operational energy consumption, annual water consumption and wastewater production, and annual waste production; (2) Identifying the emission reductions and operating costs and damages associated with selecting mitigation strategies in each category; and (3) Understanding how location and temporal factors influence baseline (current conditions without any mitigation), and strategic (applied mitigation) outcomes. The decision-support tool is tested on diverse case study airports in the United States to investigate the efficacy of strategies based upon location factors. The case study airports include Reno/Tahoe International (RNO), Pittsburgh International (PIT), Newark Liberty International (EWR), Seattle-Tacoma International (SEA), SFO, and Hartsfield-Jackson Atlanta International (ATL). They represent a mix of small, medium, and large hubs across the country, and demonstrate the scalability of the tool.

A significant outcome of this study is the creation of a novel decision-support tool. Table 24 provides an overview of previous decision-support tools created for airport stakeholders. None integrate life-cycle methods, economic costs, and spatial and temporal factors to assess the emissions footprint of terminal buildings. No existing tool for airports connects emissions to climate change and human health impacts or assesses how mitigation strategies affect operational costs and monetized damages.

Table 24. Overview of decision-support/modeling tools for airports

Tool	Who Makes It?	What Does It Model?
Airport Construction Emissions Inventory Tool (ACEIT)	ACRP	Estimates: GHG and CAP emissions from construction activities and equipment
Airport Carbon and Emissions Reporting Tool (ACERT)	ACI	Inventories: Scope 1, 2, & 3 GHG emissions from airports
Aircraft Ground Energy System-Simulator (AGES-S)	ACI	Estimates: GHG emissions and financial savings associated with switching from APU to 400 Hz and Pre-Conditioned Air (PCA)
Airport Greenhouse Gas Emission Assessment & Reduction (AirportGEAR)	ACRP	Analyzes: GHG reduction strategies according to 11 criteria among 3 categories: (1) Financial; (2) Implementation; (3) Potential environment impacts
Evaluation Process and Cost-Benefit Tool (EP&CBT)	ACRP	Evaluates: Life-cycle costs of O&M impacts of implementing sustainability practices for the following categories: water conservation, energy conservation, waste management, materials, alternative fuels

The expected benefit from the tool is improved decision-making processes for airport operators, sustainability teams, and environmental management teams to be used at planning and operating stages of projects. Importantly, the tool provides focus on potentially consequential emissions phases, including construction and supply chains. The tool can be used to determine, among the four categories (building construction/materials, operational energy, water/wastewater, waste management), which category is the most impactful from an emissions or cost perspective for a specific airport. Stakeholders can utilize the tool to assess environmental and human health impacts from construction of brand-new terminals and from both renovations and additions to existing terminals. Given the variability in airport locations, sizes, and budgets, and appreciation for difficulties in enacting sustainable policies (Martin-Nagle & Klauber, 2015; Prather, 2016), the tool serves as a first step for stakeholders to assess strategies that can contribute beneficial climate change and human health outcomes.

The remaining sections of this study include Methods, Results, Discussion, and Conclusions. The Methods section outlines the analytical models used in estimating impacts as well as the framework for the decision-support tool. The Results section presents the application of the decision-support tool to case study airports. The Discussion sections explores the relevance of the tool and limitations of the study. Final implications and areas for future research are discussed in the Conclusions section.

5.2 Methods

5.2.1 Case Study Airports

The airports selected as case studies (Table 25) are a range of small, medium, and large hub airports with varying flight types (e.g., international, destination, regional) across the United States. Each airport is currently constructing or planning to embark on terminal projects. As each airport has a distinct electricity supply, the case studies demonstrate the efficacy of different strategies by region. Annual enplanement data reflects levels from 2019, to avoid unrepresentative data arising from COVID-19 (FAA, 2021d) in 2020.

Table 25. Case study Airports

Airport Name (ICAO Code)	Location	Annual Enplanements (CY 2019)	Hub Designation	Energy Supply
Reno/Tahoe International (RNO)	Reno, NV	2,162,250	Small	NV Energy
Pittsburgh International (PIT)	Pittsburgh, PA	4,715,947	Medium	On-site microgrid
Newark Liberty International (EWR)	Newark, NJ	23,160,763	Large	PSE&G
Seattle-Tacoma International (SEA)	Seattle, WA	25,001,762	Large	Bonneville Power Admin.
San Francisco International (SFO)	Burlingame, CA	27,779,230	Large	SFPUC
Hartsfield-Jackson Atlanta International (ATL)	Atlanta, GA	53,505,795	Large	Georgia Power

5.2.2 Data Collection

All data used in developing the decision-support tool, including input data for case study airports, have been collected from individual airports and government, academic, and industry sources. Data used as inputs for each module in the tool (e.g., annual electricity usage, composition of waste streams in the terminal) are sourced from a combination of individual airport sustainability and annual operating reports and electronic communication with airports. A questionnaire requesting specific input data for the tool was developed and sent to several airports. The questionnaire is included in Appendix C.

Emission factor data have been collected from government, academic, and industry sources. The source of emission factors depends upon the system of interest. For example, GHG emission factor data for building materials comes from the Embodied Carbon in Construction Calculator (EC3), an online tool that aggregates industry-reported environmental product declarations for concrete, structural steel, wood and composites, insulation, finishes, and bulk materials such as glass (Carlisle et al., 2021). Multiple emission factors for the same system of interest are compiled, if applicable, to improve the uncertainty of results. Within the tool, users have the option of selecting between two methods for calculating electricity emissions. The two methods, which can be used to analyze utility-specific, state-level, and regional electricity supplies, calculate electricity emissions from emission factors from an academic report (Horvath & Stokes, 2011b) and from a tool developed by the United States Department of Energy (DOE) (Skone, n.d.).

Construction cost data, which account for materials, equipment, and labor, come from RS Means, an aggregated construction cost database. City-level location factors are applied to adjust the nationally averaged costs. Energy, water, and waste utility rates for each case study airport are input by airport stakeholders to estimate changes in annual operating costs after implementing mitigation measures. Climate damages are estimated using the social cost of carbon (SCC) metric, adjusted to 2019 (National Academies of Sciences, 2017).

5.2.3 Life-cycle Assessment

Baseline and mitigation strategy emissions are calculated following a life-cycle approach. Life-cycle assessment (LCA) is a method used for estimating the life-cycle, or cradle-to-grave, environmental impacts associated with a product, process, or project. Impacts are determined by cataloging the inputs (i.e., energy, water, air, materials) and the outputs (i.e., emissions, wastes) associated with each life-cycle stage. Typically, life-cycle stages considered range from raw material extraction/processing, construction/manufacturing, transportation/logistics, operation/maintenance, to end of life. LCA is formally outlined as a standardized methodology in ISO 14040 as a four-step process (ISO, 2006). The four steps include: (1) defining the goal and scope of the study; (2) inventorying relevant environmental impacts; (3) performing an impact assessment; (4) interpreting results. An inventory and partial impact assessment are conducted for this study.

There are two general models used to calculate the life-cycle inventory (LCI), process-based and economic input-output (EIO-LCA). The scope of a process-based LCI model includes as many relevant processes as possible for a system boundary of interest. Process-based LCI models are detail-rich, but an important limitation is the subjectivity of the system boundary of analysis. It can be difficult to capture all conceivably relevant processes as well as the interdependencies, or circularities, between certain processes. EIO-LCA combines EIO tables, which are matrices that relate interdependent relationships among sectors of the economy, with environmental data matrices to compute the environmental impacts (e.g., GHG emissions) associated with a specified amount of economic activity in a distinct economic sector (Hendrickson et al., 1998). The advantage of EIO-LCA is that its system boundary encompasses the entire United States economy, and it captures the impacts from supply chains, which are difficult to account for with process-based LCI models (M. Bilec et al., 2006). Constraints associated with the EIO-LCA model are that data are aggregated at the national economic sector level making it impossible to analyze specific products, regional differences, and process improvements. Additionally, the data are United States centric, which can limit its use for analysis of non-United States products.

Combining the best attributes of process-based LCI and EIO-LCA results in a hybrid approach that captures relevant specific processes as well as supply chain and upstream impacts. This research relies on a hybrid method, according to the scope outlined in Table 26. Some system elements are excluded (e.g., infrastructure for water and wastewater treatment plants) due to data unavailability.

Table 26. Scope of LCA by emissions type and tool module

		Modules			
		Building Materials	**Operational Energy**	**Water and Wastewater**	**Waste**
Emissions	**GHG**	• Construction • Material production	• Infrastructure for electricity generation and distribution, natural gas production • Electricity, natural gas consumption	• Infrastructure for electricity • Electricity generation for water consumption, wastewater treatment	• Raw material extraction/ processing • Manufacturing of virgin material • Transportation • Disposal • Energy recovery
	CAP	• Construction	• Infrastructure for electricity • Electricity generation	• Infrastructure for electricity • Electricity generation for water consumption, wastewater treatment	• Raw material extraction/ processing • Manufacturing of virgin material • Transportation • Disposal • Energy Recovery

A partial life-cycle impact assessment (LCIA) is conducted to explore what impact a LCI has on specific environmental and human systems. An LCIA can be used to answer questions such as how emissions from a project may affect climate change, water quality, or human health. The EPA's Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI 2.1) is used to characterize LCI emissions into impact categories (J. Bare, 2011; Ryberg et al., 2014). We use the 100-year global warming potential (GWP) to estimate carbon dioxide-equivalent (CO_2e) emissions for the GHGs that contribute to climate change and the particulate matter (PM) formation potential for pollutants that affect human health (Appendix C). We perform a partial LCIA because we do not connect the impact factors to their end-point categories. In a complete LCIA, GWP might be connected to a change in global mean temperature increase and PM formation potential might be linked to increased number of mortalities and/or disease. Although decision makers might find end-point indicators potentially more relevant, there are documented uncertainties in how the results from impact factors, such as GWP, are transformed to end-point categories, such as global mean temperature increases (J. C. Bare et al., 2000). The results from impact factors can still be an effective point for decision-making and are the accepted units in federally developed LCA tools (Skone, n.d.).

5.2.4 Tool Development

The decision-support tool named Airport Terminal Environmental Support Tool (ATEST), is an Excel-based tool comprised of four modules. Users enter general characteristics about an airport terminal, such as state, county, and city location, gross terminal area, and annual number of enplanements and aircraft movements. Users enter relevant data for each of the four modules and select which mitigation strategies they want to implement. Data, calculations, and results are displayed in separate sheets for each module. An additional results dashboard displays results for all modules in one sheet. Mitigation strategies for each module are listed in Table 27. Emissions levels after mitigation are estimated by subtracting emissions savings for a strategy from each module's baseline emissions. Detailed explanations for each tool module are provided in Appendix C.

Table 27. Mitigation strategies for each module in ATEST

	Mitigation Strategies	
Building Materials	Material Selection • Moderate carbon building materials • Lowest carbon building materials	Construction Activities • Recycle construction and demolition waste (divert 75%)
Operational Energy	Energy Efficiency • Efficient escalators, elevators, people movers (15% reduction) • Efficient baggage handling systems (50% reduction) • Install LEDs for external lighting in parking lots/non-aircraft areas	Alternative Energy Sourcing • Green power purchasing agreement with utility (100% solar or 100% wind)
Water and Wastewater	Indoor Water Conservation • Low-flow bathroom faucets • High-efficiency toilets and urinals • Efficient pre-rinse spray valves • Efficient dishwashers • Low-flow kitchen faucets • Efficient ice machines • Efficient cooling towers • Efficient boilers	Outdoor Water Conservation • Efficient pavement cleaning • Efficient vehicle washing • Efficient landscaping • Efficient irrigation
Waste	Waste Stream Reduction • Reduce food waste within terminal (20% reduction) • Reduce non-recoverable usage within terminal (20% reduction)	Waste Stream Substitution • Substitute non-recoverable materials with recyclables (10% substitution) • Substitute non-compostable materials with compostables (5% substitution)

5.2.4.1 Building Materials

The Building Materials module estimates emissions from construction activities and materials used in the terminal structure. Materials considered include ready-mixed concrete, steel rebar, structural steel, prefabricated steel assemblies (open-web steel joists), wood and composites, insulation, gypsum board, ceiling tiles, resilient flooring (e.g., vinyl or plastic composite flooring), carpet, and flat glass. GHG emissions from building materials, also known as the material's embodied carbon, are calculated by multiplying material quantities by their respective emission factors from EC3. Users can estimate material quantities using construction documents or 3D building information modeling (BIM) software. For our sample results, we estimate material quantities using approximate estimates developed for a building materials database (De Wolf, 2017). An emission factor based on a review of building construction LCAs (Säynäjoki et al., 2017) is multiplied by gross terminal area to estimate GHG emissions from construction activities (e.g., excavation, pouring concrete).

CAP emissions from construction are approximated using a threshold method developed by the FAA (FAA, 2007) to support compliance with the Clean Air Act General Conformity Rule. The method identifies examples of terminal upgrade projects that can be presumed to conform with the applicable plans adopted and implemented by regulators to improve air quality in areas that do not meet NAAQS (e.g., nonattainment and maintenance areas). EPA designates areas as attainment if ambient concentrations meet the NAAQS (US EPA, 2014). An area that does not meet the NAAQS is considered to be in nonattainment. Areas that are previously designated as nonattainment but then meet the NAAQS are classified as being in maintenance. For specific terminal gross areas, the FAA established allowable emission limits for each CAP and for ozone precursors, such as volatile organic compounds (VOCs) and oxides of nitrogen (NO_x). Emission limits depend upon the airport's geographic area and EPA's classification of the attainment status of the area for specific pollutants. As an example, an airport project to build approximately 70,000 square meters of terminal in a geographic area classified as "Serious" nonattainment for ozone could be presumed to conform if the net increase in emissions from construction and operation of the project would result in less than 50 tons/year of VOCs or NOx, the CAPs that are precursors to ozone formation. In ATEST, when users enter their state, county, and city, look-up tables are used to identify whether the project is in an area designated as nonattainment, maintenance, or attainment for a specific pollutant. Depending on the area's attainment status and the specified gross terminal area, allowable CAP emissions can be identified for projects that would presumably conform.

5.2.4.2 Operational Energy

The Operational Energy module calculates GHG and CAP emissions from the annual electricity and natural gas consumed in the terminal. Users have the option of selecting a "Default" or "Custom" option to calculate baseline emissions. If "Default" is selected, baseline emissions are estimated using utility bill consumption data for electricity and natural gas. The "Default" option can account for heating and cooling if they are provided by an on-site thermal plant for the terminal. If the "Default" option is selected, users are only able to choose the alternative energy sourcing mitigation strategy as ATEST does not disaggregate utility bill input data.

The "Custom" option calculates a baseline electricity and natural gas consumption using methodology developed by ACRP (Transportation Research Board, 2016b). Total energy consumption is calculated as the sum of energy used to heat, cool, ventilate, and light terminal building zones (e.g., concessions, ticketing, security), to power discrete terminal building systems (e.g., escalators, baggage handling systems), and to charge electric ground service equipment (GSE). The ACRP method calculates terminal building zone energy in units of kBTUs. To convert to units of kWh and therms, respectively, we assume in this study that electricity accounts for 75% of terminal building zone energy consumption and natural gas for 25%. The percentage assumptions can be manually changed within ATEST by users to reflect variations in natural gas usage by climate region.

Operational energy GHG and CAP emissions are calculated using Equation 55:

$$E_{Energy} = \left(Electricity\ Use \times EF_{Elec,ij}\right) + \left(Natural\ Gas\ Use \times EF_{NG}\right) \qquad \text{[Eq. 55]}$$

Where E_{Energy} are emissions attributable to annual energy consumption in the terminal, $EF_{Elec,\ ij}$ is a location (*i*) and pollutant-specific (*j*) life-cycle electricity emission factor, and EF_{NG} is the life-cycle emission factor for stationary combustion of natural gas.

5.2.4.3 Water Consumption and Wastewater Generation

Baseline emissions from water consumption and wastewater generation are calculated using methods developed by ACRP (Krop et al., 2016). Indoor water consumption for end uses such as toilets, faucets, and food preparation are a function of daily passenger counts within the terminal. Outdoor water consumption depends upon climate zone and landscaping type; a method developed by the DOE uses a proxy city to approximate outdoor water needs by plant type (US DOE, 2010). Users choose from one of thirty-six representative cities from ten different climate zones to determine the yearly outdoor water budget. For all indoor water consumption, GHG and CAP emissions are determined using Equation 56:

$$E_{Indoor} = \left(Indoor\ Use \times EF_{Water,j}\right) + \left(Indoor\ Use \times EF_{WWater,j}\right) \qquad \text{[Eq. 56]}$$

Where E_{Indoor} are emissions attributable to annual indoor water consumption in the terminal, $EF_{Water,\ j}$ is a pollutant-specific (*j*) life-cycle water emission factor and $EF_{WWater,\ j}$ is the pollutant-specific (*j*) life-cycle wastewater emission factor. Emissions from outdoor water consumption are calculated in a similar manner, except that it is assumed that consumed outdoor water does not enter the sewer system and will not be treated at a wastewater treatment plant. Water and wastewater emission factors are calculated using energy intensities of 0.34 kWh per m^3 of treated water and 0.43 kWh per m^3 of treated wastewater (Chini & Stillwell, 2018). These energy intensities, which are nationally averaged values, are likely a conservative estimate as studies have values ranging from 0.3 - 5 kWh per m^3 (Stokes & Horvath, 2009, 2010; Stokes-Draut et al., 2017). Energy intensities vary by water supply source, level of treatment, treatment technology, and location so users can change these default values as deemed appropriate.

Savings from indoor and outdoor water mitigation strategies (Table 27) are cumulative. Users are limited in selecting one of four on-site reuse options. Harvested rainwater from a rooftop collection system or greywater sourced from terminal bathroom faucets can supply either irrigation or toilet/urinal needs. Savings from an on-site reuse strategy reflect any changes in indoor or outdoor water needs. For example, an efficient bathroom faucet would result in a reduced volume of available greywater, potentially limiting the emissions savings from that strategy. Equations for calculating baseline emissions and emissions savings from on-site reuse are provided in Appendix C (Appendix C, Section C4.2.).

5.2.4.4 Waste Management

Users enter details about the composition of the solid waste stream and the volumes of material disposed to landfills and diverted to recycling and composting facilities to estimate emissions associated with terminal waste. There is a "Default" and "Custom" method for calculating emissions. The "Default" method assumes a composition of specific recyclable materials within the solid waste stream from a previous audit report of a terminal's solid waste stream (Transportation Research Board, 2018a, 2018b). The "Custom" option allows for an airport to enter its specific solid waste composition, accounting for recyclables including aluminum, plastics, glass, cardboard, and paper. We utilize GHG emission factors from the EPA's Waste Reduction Module (WARM) v.15 (US EPA, 2016). WARM calculates life-cycle GHG emissions for waste management practices (e.g., recycling, composting, landfilling) of recyclable, organic, and non-recoverable materials. We develop CAP emission factors using energy factors in WARM v.15 by making some simplifying assumptions about energy used for transportation and for electricity (see Appendix C, Section C5.1). GHG and CAP emissions associated with the terminal's solid waste stream are calculated using Equation 57:

$$E_{Waste} = \left(Landfill\ Volume \times EF_{Landfill,kj}\right) + \left(Recycle\ Volume \times EF_{Recycle,kj}\right) + \left(Compost\ Volume \times EF_{Compost,kj}\right) \quad \text{[Eq. 57]}$$

Where E_{Waste} are emissions attributable to annual solid waste consumption in the terminal, $EF_{Landfill,\ kj}$ is a material (k) and pollutant-specific (j) life-cycle landfilling emission factor, $EF_{Recycle,\ kj}$ is a material (k) and pollutant-specific (j) life-cycle recycling emission factor, and $EF_{Compost,\ kj}$ is a material (k) and pollutant-specific (j) life-cycle composting emission factor.

Waste management strategies across each category (i.e., Reduction, Substitution, Diversion) are interdependent. Since strategies are interdependent, selecting a waste stream reduction strategy will change the amount of solid waste that could be diverted or substituted, which would affect emission savings potential. Savings from waste mitigation strategies are not additive across strategy category in the current version of ATEST. Therefore, ATEST users are only able to evaluate the savings from implementing one waste mitigation strategy over the other.

5.2.5 Economic Impacts

Operational costs are estimated for the energy, water, and waste modules by multiplying user-input utility costs by respective amounts of electricity, natural gas, water, wastewater, and solid waste. Changes in operational costs are calculated as the difference between baseline and mitigation operating costs. Climate damages, which place an economic value on the harm caused by climate change (e.g., increased intensity and frequency of wildfires), are evaluated using Equation 58:

$$D_m = E_m \times SCC_{2019} \quad \text{[Eq. 58]}$$

Where D_m are the damages, in USD, from the emissions (E_m) from a module (m). SCC_{2019} is the social cost of carbon adjusted to constant 2019 USD. The SCC can be modified as either “Default”, which uses an adjusted 2015 SCC and 3% discount rate from the Interagency Working Group (29), or as “Custom”. The SCC monetizes the harm of emitting one additional ton of GHG emissions to the atmosphere (Nordhaus, 2017). The metric provides airport stakeholders with a more complete understanding of the negative externalities, or total costs to society, caused by terminal construction and operation.

5.2.6 ATEST Application

Decision makers can use ATEST to develop preliminary answers to questions such as:

- What are baseline GHG and CAP emissions associated with constructing and operating an entire terminal or an addition/renovation?
- What are baseline and mitigated emissions for each module in ATEST?
- How do emissions relate to climate change and human health impacts using TRACI impact factors?
- What are baseline operational costs and climate damages, and how do they change after mitigation? Which strategies yield the greatest reductions in operational costs and monetized climate damages?
- What are future impacts relative to the current baseline, considering changing conditions such as implementation of renewable portfolio standards (RPS) or mandated waste recovery goals?

5.3 Results

We present multiple applications of ATEST for each module and for various airports. We demonstrate reductions from each module’s mitigation strategies relative to baseline conditions for one case study airport (RNO). Input data and assumptions for each application are provided in Appendix C. For each module, users can see baseline, reduced, and remaining emissions and costs associated with selecting each mitigation strategy or combination of strategies. Example output is shown in Appendix C.

Figure 26 shows normalized results for GWP, PM formation, and monetized climate damages associated with terminal building energy use. We compare changes, normalized to annual number of passengers (pax), associated with switching from each airport's current electricity mix to electricity either 100% sourced from wind or 100% from solar. We then investigate changes when comparing to a future electricity mix, as designated by each state's renewable portfolio standard or RPS (Barbose, 2021). The RPS for Nevada mandates 50% renewables by 2030 and for Pennsylvania 18% by 2021. No RPS results are analyzed for SFO as their electricity mix already exceeds the state mandate of 60% renewable by 2030. According to Figure 24, 100% wind results in better emissions and damages outcomes for all airports except for PM formation from SFO's energy use. SFO's electricity source is almost entirely hydroelectric power, so PM formation from manufacturing of wind turbines or solar photovoltaic systems will exceed baseline emissions. For RNO and PIT, which have fossil fuel-dominant electricity mixes, mitigation is modest when implementing their respective RPS scenarios. It should be noted that Figure 26 is not demonstrating that one airport is more sustainable, or "healthy", than the other. Rather, Figure 26 highlights that an airport's impacts vary based on many spatial, temporal, logistical, and physical factors, demonstrating that a "one size fits all" approach to mitigation is likely insufficient for achieving meaningful, targeted mitigation goals.

Figure 26. Results from application of Operational Energy Module

Figure 27 presents normalized GWP from annual water consumption and wastewater generation at RNO, PIT, and SFO. Each bar represents annualized emissions if all mitigation strategies in each strategy category are implemented. For example, if "No on-site reuse" is selected, then the "Indoor" bar accounts for emissions from mitigated indoor water use and from baseline outdoor water use. The "All Sources" bar accounts for emission changes from all mitigation strategies in every strategy category. Results are run for each of five on-site reuse scenarios. Percentage changes in Figure 27 are relative to the "Baseline, No on-site reuse" scenario. As water and wastewater energy intensity, irrigation amount, and plant type are held constant across each airport in this hypothetical example, it appears that emission reductions in the water module depend upon spatial characteristics such as climate zone and electricity mix. Optimum strategies differ by airport location. For RNO and PIT airports, under the default assumptions explained in Appendix C, indoor mitigation strategies with no on-site reuse consistently yield significant reductions in emissions and monetized climate damages except when all mitigation strategies and greywater (GW) reuse for toilets and urinals are selected. For SFO, rainwater harvesting or grey water reuse for toilets, coupled with indoor and outdoor mitigation, yield greater GHG reductions compared to just indoor and outdoor mitigation. On-site reuse for irrigation yields emissions increases under the inputs and assumptions. Although not analyzed here, it is important to explore how impacts might change when combining reuse sources and when selecting between on-site reuse or centralized reclaimed water from utilities.

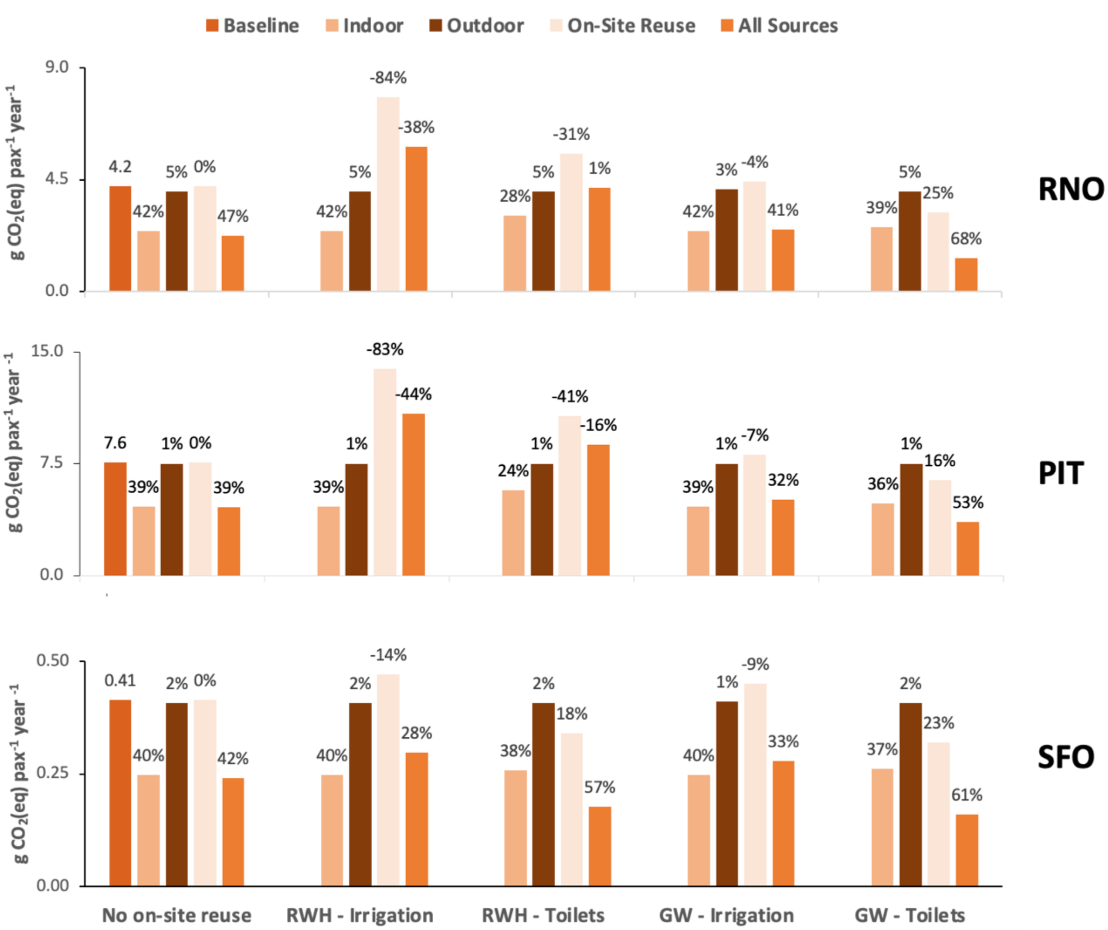


Figure 27. Annualized GWP for water mitigation strategies. Results are run for each of five on-site reuse scenarios.

Each bar indicates results for the specified reuse scenario, assuming all strategies in a mitigation category are implemented. Percentage changes are relative to the "Baseline, No on-site reuse" scenario.

Annual emissions and operational costs from waste management strategies are depicted in Figure 28. Emissions are dependent upon the quantity and composition of the solid waste stream. Data from each analyzed airport indicates that compostables represent a critical component of terminal waste production. Compostables and recyclables tend to have negative life-cycle emission factors, so an airport with a higher composition of compostables and recyclables might result in limited baseline emissions (e.g., RNO). For EWR, SEA, and ATL, waste stream reduction and waste stream diversion yield the greatest reductions in emissions. Diverting 100% of compostable food waste and 100% of recyclables would result in complete emission reductions relative to baseline conditions. Operational costs vary by airport location due to changes in tipping, recycling, and composting fees.

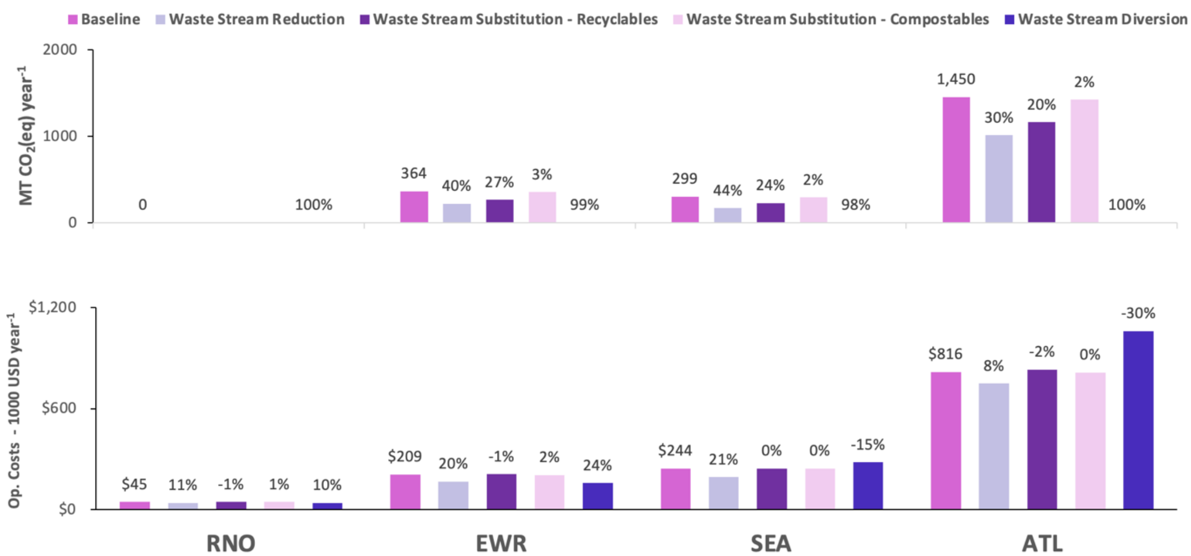


Figure 28. Annualized GWP and Operational Costs for Waste Module

Figures 29 shows baseline GWP and PM formation results for RNO Airport for all four modules. Impacts from energy consumption dominate for both climate change and human health, but embodied emissions from building construction are important for PM formation. Note that cumulative embodied emissions from building materials and construction (which are displayed within the Building Materials module in ATEST) have been annualized according to the airport terminal's service life, which is assumed to be for 30 years in this example. Based on RNO's terminal gross area of 27,542 m^2, if the terminal were to be constructed today the tool provides an indication that the project would conform with all applicable plans to meet NAAQS, with the exception of emissions of NO_x, because the area has a "marginal" nonattainment classification for ozone. Note that Figure 29 relates all CAP emissions to fine particulate matter formation using the TRACI impact factors. Results within the Building Materials module also display the normalized human health indicator (i.e., fine particulate matter formation) as well as the emission thresholds for each CAP for the user-inputted airport location.

Within ATEST, users have the option of changing the service life of the terminal, allowing for analysis about temporal impacts from building materials and construction. Previous work has demonstrated that construction and materials emissions that occur in one discrete instance can potentially be greater than operational emissions, especially if the building's design is energy efficient.

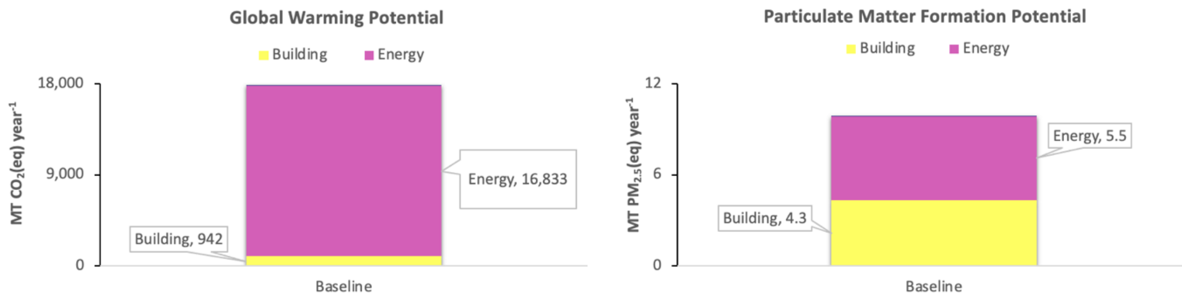


Figure 29. Global Warming Potential and Particulate Matter Formation Potential for RNO Airport case study.

In Figure 30, we show emission changes relative to the baseline GWP for RNO Airport if all strategies in each category are implemented except for strategies in "Construction", "Construction & Demolition Waste", "Energy Efficiency", "Waste Stream Diversion", and "Waste Stream Substitution". As mentioned in the methods section, emission reductions from strategies in each waste category are not additive. Therefore, we examine emission reductions for scenarios where only one category of mitigation strategies is selected by the user (e.g., "All Strategies – Waste Stream Reduction). In this hypothetical example for RNO, switching from the airport's current electricity source to 100% wind will yield the greatest climate change benefits. Airports with cleaner electricity mixes, such as SFO, might explore investigating mitigation strategies other than energy source (Figure 31).

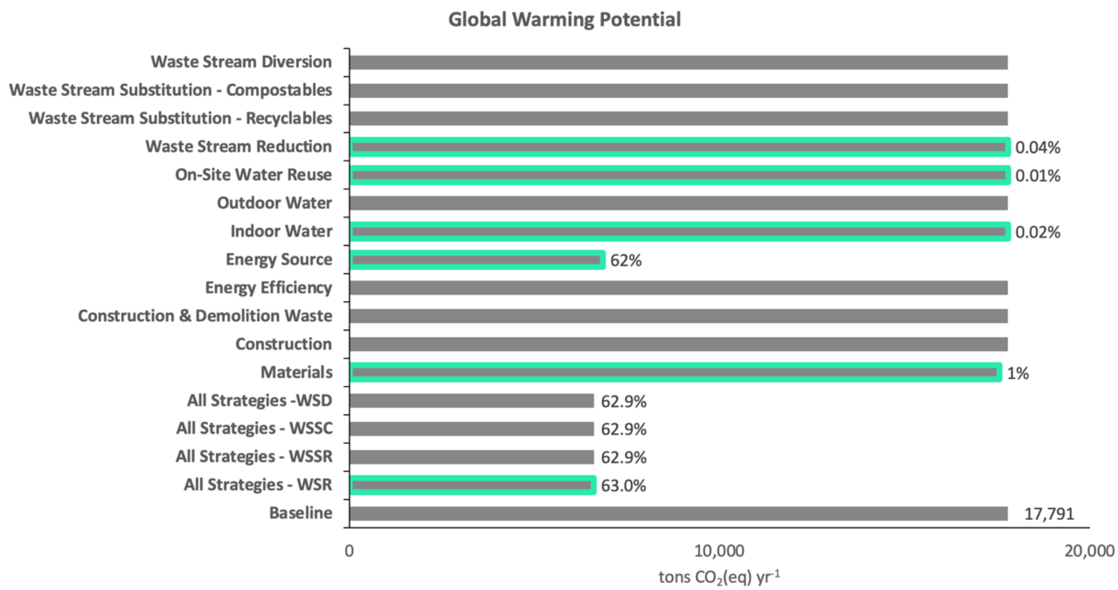


Figure 30. Global Warming Potential for mitigation strategies for RNO Airport. Bars with green outline indicate that a strategy category leads to emission reductions. Note that all four "All Strategies" bars appear, even though "Waste Stream Reduction" is the only waste mitigation category considered in this example.

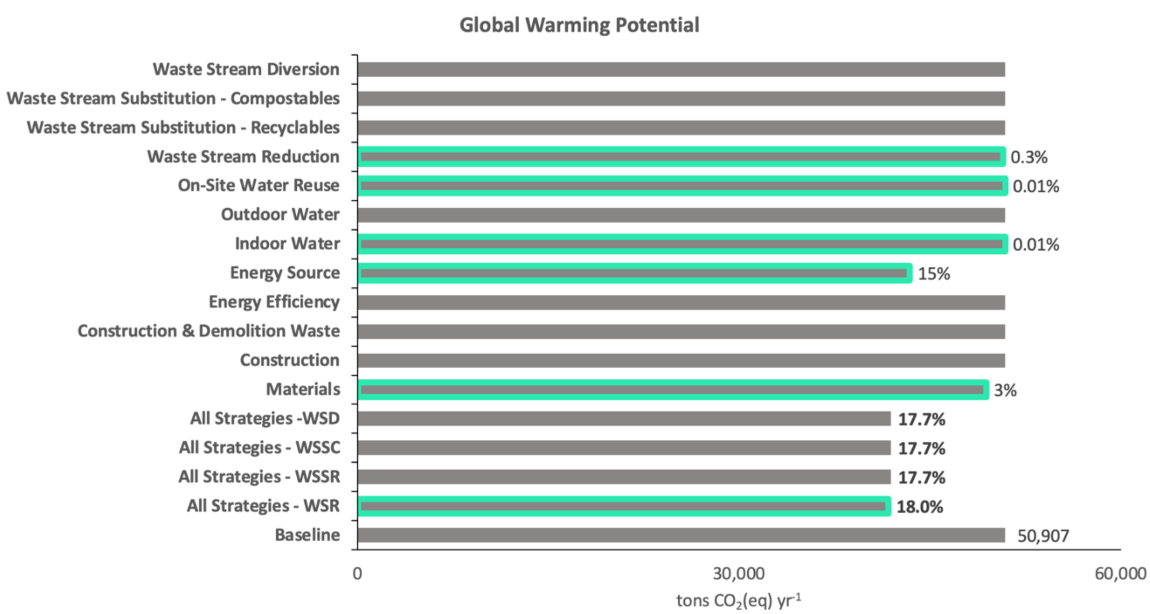
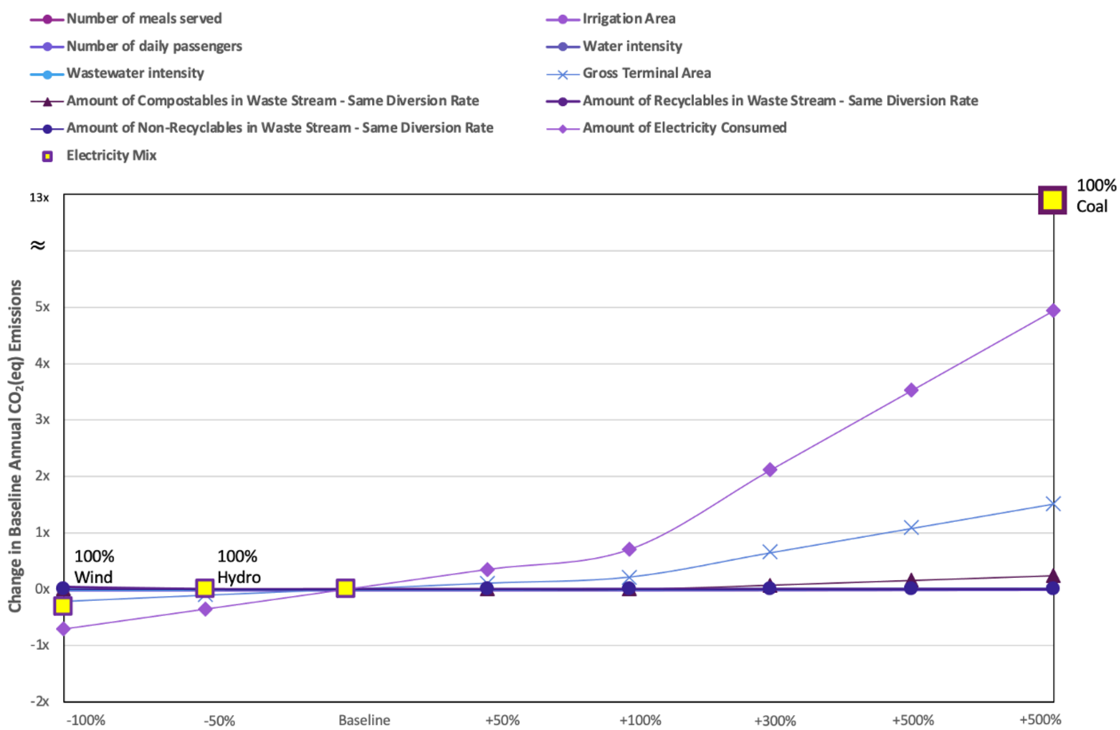


Figure 31. Global Warming Potential for mitigation strategies for SFO Airport

5.4 Discussion

As demonstrated in the sample results, which rely on actual data collected from the case study airports, mitigation benefits are influenced by airport location, module, strategy type, and impact category. A sensitivity analysis of the SFO case study reveals which parameters have the greatest impact on changing overall GHG emission results (Figure 32). Select model parameters are changed relative to their baseline conditions, while all remaining parameters are left unchanged. The data table depicts the exact percentage change for an input parameter for a specified change.

For example, decreasing the number of daily passengers by 50% relative to the baseline number of passengers results in an 0.01% decrease in annual GHG emissions. Figure 32 indicates that the electricity mix, amount of electricity consumed in the airport terminal, terminal gross area, and amount of compostables in the waste stream have the most impact on increasing annual GWP for SFO. The electricity mix, demarcated with a yellow square outlined in purple, is especially sensitive to SFO's overall baseline GWP. SFO's baseline electricity mix is essentially entirely sourced by hydroelectric power (all case study electricity mixes are provided in Appendix C). It should be emphasized that these critical factors are applicable to SFO; sensitivity analyses would need to be conducted for each airport to determine the most significant input parameters. Additional analyses should explore the sensitivity of mitigation strategies to specific parameters.



Number of meals served	0%	0%	0%	0%	0.01%	0.02%	0.03%	0.04%
Irrigation Area	0%	0%	0%	0%	0%	0%	0%	0%
Number of daily passengers	-0.03%	-0.01%	0%	0.02%	0.03%	0.1%	0.1%	0.2%
Water intensity	-0.02%	-0.01%	0%	0.04%	0.3%	0.5%	0.8%	1.1%
Wastewater intensity	-0.02%	-0.01%	0%	0.03%	0.3%	0.5%	0.8%	1.1%
Gross Terminal Area	-22%	-11%	0%	11%	22%	65%	108%	151%
Amount of Compostables in Waste Stream - Same Diversion Rate	0%	0%	0%	0%	0%	8%	16%	24%
Amount of Recyclables in Waste Stream - Same Diversion Rate	4%	0%	0%	0%	0%	0%	0%	0%
Amount of Non-Recyclables in Waste Stream - Same Diversion Rate	0%	0%	0%	0%	0%	0%	0%	0%
Amount of Electricity Consumed	-71%	-35%	0%	35%	71%	212%	353%	494%
Electricity Mix	-31%	0%	0%	-	-	-	-	1286%

Figure 32. Sensitivity of GWP to changing model parameters for SFO Airport. An electricity mix powered entirely by coal would increase SFO's baseline emissions by 1300%. Electricity mix, electricity amount, and gross terminal area have the largest impact on overall emissions in the SFO case study.

ATEST results can be validated in multiple ways. Results are qualitatively validated by comparing model output to previous literature and reports and by using the pedigree matrix approach to assess the uncertainty of underlying data. For example, CAP emissions from building construction in the RNO and SFO results are on the same order of magnitude for similarly sized buildings (M. M. Bilec et al., 2010). While not completely exact, as ATEST calculates emissions using a life-cycle approach, users can compare model output to their airport's Scope 1 and Scope 2 GHG emissions to determine if model results are of the same magnitude. Users can further validate results by running ATEST using upper and lower bounds for various input parameters and changing default assumptions to reflect custom information.

Pedigree matrices are used to analyze the data uncertainty in LCA studies (Ciroth et al., 2016; Miller, 2021). Low uncertainty scores in factors such as data age, completeness, and specificity indicate that results are reasonably reliable. Pedigree matrices (in Appendix C) are evaluated for electricity, natural gas, water/wastewater, waste, building size/composition, and construction emission data used in ATEST. Uncertainty is relatively low for the energy, water/wastewater, and waste data used in ATEST. There is moderate uncertainty for the building size/composition and construction emission data used in ATEST due to the age of the data. Overall, all data used are reliable.

5.4.1 Limitations

5.4.1.1 Bottom-Up Approach

A limitation of ATEST is centered on the bottom-up approach used in its development. While an improvement on previous efforts that use a per square meter approach to estimate environmental impacts from terminal infrastructure (M. V. Chester & Horvath, 2009), the bottom-up approach has some disadvantages. Since ATEST is entirely encapsulated within Excel and relies on limited inputs from users, we are limited in the types of calculations that can be run, which constrains the emission sources we analyze and mitigation strategies we investigate. The bottom-up approach is likely most impactful on the Building Materials module, which has cascading impacts on the Operational Energy module. As an example, we do not investigate any building design strategies (e.g., building orientation or window-to-wall ratio) as they require sophisticated energy simulation software. Due to potential limitations in data input by the users, we use proxy emission factors to estimate construction emissions. A more complete approach for estimating emissions would be to use a bill of materials and construction schedule from a terminal project.

5.4.1.2 Economic Assessment

Operational costs are calculated on a unit basis and do not account for additional factors such as demand or service charges incurred from utilities. Annualized investment and maintenance costs would provide airport stakeholders with a more complete economic impact analysis of distinct mitigation options.

5.4.1.3 Temporal Assessment

Emission results and life-cycle impacts are calculated on an annualized basis, which is useful for comparing progress to previous years and for meeting annual targets/reduction goals. However, as evident by events such as the global COVID-19 pandemic, real-time conditions can have an instantaneous impact on the environment and human health. ATEST cannot estimate the real-time impacts from indoor air quality within a terminal caused by the spread of infectious diseases or from off-gassing of interior finishes. Quantifying these impacts is a critical component for making terminals as healthy as possible.

5.5 Conclusions

We developed a novel decision-support tool for airport stakeholders to analyze the baseline and mitigated GHG and CAP emissions associated with constructing and operating terminals. The tool, known as ATEST, quantifies life-cycle GHG and CAP emissions, operational costs, and monetized climate damages for four modules: (1) Building Materials; (2) Operational Energy; (3) Water and Wastewater; and (4) Waste. Using RNO, PIT, EWR, SEA, SFO, and ATL as case study airports, we explore how emissions and economic impacts change for different mitigation strategies due to varying operational parameters, energy supplies, climate zones, and regulatory mandates. According to our sample application of ATEST, the electricity mix is one of the dominant factors in changing emissions. The construction phase of a terminal is important from a human health perspective as most of the fine particulate matter emissions are attributable to the Building Materials module.

Future research to improve the modeling within ATEST should account for additional life-cycle economic costs and environmental phases, particularly the investment costs and manufacturing requirements from mitigation strategies. For example, choosing to implement an on-site greywater collection and treatment system would result in additional emissions from construction and in upfront capital costs. Monetized damages can be expanded to include economic harm to human health caused by airport terminal construction and operation. It should be investigated how ATEST can be incorporated with existing tools that stakeholders are familiar with, including ACERT and the Airport Construction Emissions Inventory Tool (ACEIT). With the addition of country-specific look-up tables and changes to default settings, ATEST can perform analysis on airports located outside of the United States. An ultimate research goal is to explore how ATEST can be modified to select an optimal portfolio of strategies given a performance objective and constraints such as operating/investment budgets.

ATEST can be used by airport operators, sustainability teams, and environmental management teams at the planning and operating stages of projects to assess the emissions footprint of terminal buildings. The tool can be used to provide a preliminary indication of which module (building, energy, water, waste) is most important for specific emissions and for operational costs. Such a tool is critical for airports that might have conflicting environmental priorities. ATEST represents a first step for airport stakeholders to evaluate options to mitigate the climate change and human health impacts from constructing and operating terminals.

Chapter 6. Conclusions

The overarching goal of this dissertation is to explore holistically and systematically how to reduce the emissions intensity from the construction and operation of airport infrastructure in an efficient manner. Chapter 2 provides a detailed literature review of how academics and practitioners define airport environmental sustainability, according to commonly used metrics and assessment methods. An existing assessment framework, developed by San Francisco International Airport, is evaluated for its efficacy in yielding performance objectives. Chapter 3 examines the scope of potential GHG and cost savings from electrifying gate operations for all commercial airports. Gate electrification represents a cost-effective strategy for the reduction of millions of metric tons of GHG emissions. Chapters 4 and 5 present the development and application of a novel decision-support tool for preliminarily assessing GHG and CAP emissions, operational costs, monetized damages, and climate change and human health indicators associated with the construction and operation of airport terminals and ancillary structures.

6.1 Research Questions and Answers

1. **What does it mean for an airport to be sustainable?**

The question is answered through the review of literature presented in Chapter 2. An airport is sustainable if its environmental footprint is assessed and mitigation strategies are implemented using a systematic, evidence-based, quantitative framework that relies upon incorporating the following key factors:

- Life-cycle methods, which capture the cradle-to-grave impacts from raw material extraction, manufacturing, processing, constructing, transportation, operation and maintenance, and end of life actions in the analysis;

- Regional variation of model inputs and interpretation of model results;

- Environmental impacts with operational parameters for specific airport occupant groups (e.g., ground support equipment handlers), infrastructure components (e.g., terminals, runways), and airport scales (e.g., large hubs, general aviation);

- Stakeholder involvement from all relevant actors so that responsible parties must act to manage and mitigate their impacts; and

- Multiple, quantifiable evaluation criteria (environmental, economic, and social costs) for decision-making to connect the impacts from airport construction and operation to measurable outcomes for climate change, local human health, and ecosystem vitality.

2. **What are feasible, readily deployable, and cost-effective strategies an airport should implement to reduce its energy consumption, GHG and CAP emissions, economic costs, monetized damages, indicators of poor human health?**

Feasible, readily deployable, and cost-effective strategies are identified in the case studies presented in Chapters 3 (Gate Electrification) and 5 (Airport Terminal). Strategies focused on electrification, coupled with low-carbon electricity supplies are critical. Energy efficiency measures are also important, but the scale of their mitigation potential is less for airports with low-carbon energy supplies.

3. **How should strategies be implemented when goals or environmental priorities might be in conflict?**

Conflicting goals or environmental priorities might exist because of feedback loops (e.g., a terminal's HVAC system intended to filter the air could be more energy-intensive), regulatory climate (e.g., regulations prioritizing climate change mitigation over indoor air pollution exposure), or concerns about resiliency (e.g., an airport might install an on-site natural gas power plant to guard against grid interruptions). The question is answered with the ATEST decision-support framework outlined in Chapter 4 and applied in Chapter 5. Multiple environmental, economic, and social evaluation criteria should be used when making decisions about which strategies to implement. The use of climate change and human health indicators, such as TRACI's impact factors, can aid stakeholders in connecting and comparing emissions inventories to impacts.

4. **How do these strategies get practically implemented? Which strategies are most important depending upon a range of criteria, such as meeting policy objectives or reducing inequity?**

The first question is answered explicitly in Chapter 2, which in addition to a review of academic literature and industry practices, investigates the feasibility of an existing airport's sustainability assessment framework in delivering performance objectives. Strategies are implemented using strict contract language between owners (airports) and contractors that mandates the implementation of sustainable practices (e.g., use of low-carbon building materials). The second question is answered with the two case studies presented in Chapters 3 and 5. What is considered the most important depends upon stakeholder objectives. Using quantifiable indicators in ATEST can aid stakeholders in strategy selection.

5. **What are current constraints in how some environmental impacts, particularly GHG emissions, are managed?**

The question is answered in Chapter 2. Airport practitioners tend to favor adopting "suggested best practices" to improve the sustainability of their airport. Another common industry practice, whether due to local regulations (e.g., San Francisco) or market forces, is to rely upon frameworks such as LEED for buildings or the Scope designation for GHG emissions. While a starting off point for directing attention to environmental impacts from airport construction and operation, these frameworks are relatively limited in that they do not consider the full scope and quantitative scale of embodied impacts or supply chain effects.

6.2 Research Findings

6.2.1 Finding #1 – Electrification

Electrification, or converting practices or technologies from fossil fuel-combusting energy sources to electricity, is a critical mitigation strategy. As explained in Chapter 3, even in situations where electricity is sourced from fossil fuel-heavy mixes, significant GHG mitigation benefits are attained. Exposure to harmful pollutants such as fine particulate matter are reduced, potentially improving health outcomes for workers and those living within the vicinity of airports. These two factors provide evidence that policy makers should urgently heed; stricter and faster enforcement of policies aimed at electrifying airport GSE and operations is necessary. For example, the California Air Resources Board promotes the implementation of zero-emission GSE. Regulation is warranted.

The economics of electrification make sense for multiple reasons. Specifically, capital investments for gate electrification can be recovered within a short amount of time. Millions in monetized damages can be saved by emitters. It is foreseeable in the future that major emitters, such as airports, might be compelled to pay a carbon tax on their emissions. Additionally, there is increasing uncertainty in the resilience of energy generated from fossil sources. In the United States in particular, the regions that produce petroleum-based energy are becoming increasingly susceptible to supply-interrupting events such as extreme temperature swings, storms, and hurricanes.

From a global perspective, stakeholders should consider electrifying airport operations in regions where air travel demand is expected to grow and where adoption of gate and GSE electrification is low.

6.2.2 Finding #2 – Regional Variation, Embodied Impacts, and Application of LCA

Recognizing the importance of regional variation in the efficacy of mitigation strategies and the scope of embodied impacts is critical for understanding the true scope of an airport's environmental footprint. To the extent that airports already account for localized parameters in their environmental assessments for proposed projects, they should be broadened to include LCA. Incorporating life-cycle methods into assessing the efficiency of potential mitigation approaches is especially important for airports that already utilize clean sources of energy provision. For such an airport, mitigation that focuses on energy efficiency potentially does not provide as great a savings as efforts focused on sustainable building design and construction choices.

6.2.3 Finding #3 – Increased and Improved Collaboration

Increased and improved collaboration among stakeholders, such as airport owners and airlines/tenants, can support efforts to reduce the airport's overall impact on the environment and surrounding communities. Ownership and operation of airport infrastructure can be complicated. Actions for simplifying and improving relationships among airport stakeholders include:

- Increased interactions at beginning stages of airport projects or when new strategies are going to be implemented such that they work effectively and efficiently by the people who will be directly involved with the completed project. For example, while not explored in this dissertation, operational conflicts might exist between airline pilots and ground support crew when trying to successfully electrify a gate operation.

- Increased integration of city/state/national-level regulations into airport infrastructure planning, design, construction, operation, and end of life decisions. In the United States, while the life-cycle design of airfield pavements is managed at the federal level, a similar approach for terminals, landside buildings, air traffic control and surveillance structures, and resiliency/adaptation infrastructure (e.g., seawalls) is lacking. Airports might consider building upon existing frameworks such as San Francisco International's sustainable planning, design, and construction guidelines for airport buildings, but as mentioned in Chapter 2, ensure that strict contract requirements are enforced.

6.2.4 Finding #4 – Understanding Priorities

Airports have multiple safety, operational, health, and environmental priorities that they must address. We stress that improving the way that environmental priorities are assessed can be accomplished by incorporating LCA and the use of high-quality data. Data tracking and monitoring is improving at airports, but a wider range of potential sources should be monitored.

6.2.5 Finding #5 – Improving Existing Approaches to Airport Sustainability

If airports are actively trying to minimize their environmental impacts, they might rely upon accreditation frameworks such as LEED or ACI's Airport Carbon Accreditation, or planning frameworks that are developed using local regulations and building codes (e.g., SFO's planning framework). These frameworks represent a minimum standard that, on their own, might not be efficient at achieving targeted environmental and human health performance outcomes or at providing a comprehensive assessment of an airport's true impacts. With the presentation of two interrelated projects, we demonstrate how to effectively incorporate holistic and systematic assessment methods with multiple evaluation criteria so that stakeholders can preliminarily assess and incorporate mitigation opportunities.

6.3 Contributions to Knowledge

Contributions to both theoretical and practical bodies of knowledge include:

- Providing a systematic life-cycle environmental assessment of components of the airport infrastructure system that is: (1) often neglected in environmental accounting of the aviation industry; (2) critical for meeting GHG emissions goals of the aviation industry; (3) important for curtailing potentially adverse human health outcomes for those living and working within proximity of airports.

    - The scope of GHG emission savings from gate electrification at all commercial airports in the world is documented in Chapter 3. Under a worst-case scenario where all gate operations are powered by fossil fuel-combusting equipment, complete gate electrification could save upwards of 34 million metric tons of GHG emissions from a year of operations, compared to a scenario with limited gate electrification implementation.

    - We use life-cycle methodologies to assess the scope of GHG and CAP emissions from the construction and operation of airport terminals and ancillary structures in Chapters 4 and 5, demonstrating how footprints and mitigation strategies can vary by airport hub type, size, and location. Airport terminals and ancillary structures will be renovated and expanded to meet changes in capacity needs and building code requirements. A tool that documents current GHG and CAP footprints and identifies possible options for mitigating emissions will be useful for an airport's capital investment planning, environmental management, and sustainability teams during the planning and design phases for projects.

- Offering insight into how environmental impacts vary for different regions and different airport scales (e.g., small, medium, large airports). In practice, as identified in Chapter 2, airports might consider adopting a perceived "best practice" after another airport's successful implementation. Additionally, an airport's environmental planning team might not possess adequate resources for conducting a detailed preliminary assessment of the scale of impacts from different project options. A rigorous appraisal of "best practices" includes incorporating how regional variations (e.g., in energy supplies, climate conditions, supply chains) affect an airport's overall environmental footprint and opportunities for pursuing efficient mitigation strategies. Understanding the scope of impacts for airports of different scale is also useful from a policy perspective because it helps identify potential areas for targeted intervention. For example, is it more important to direct resources towards medium hub airports, which outnumber large hub airports?

- Creating a novel decision-support tool (ATEST) for airport capital investment, sustainability, planning, and management teams, as well as for other industry professionals, regulators, or researchers, to investigate and assess the environmental footprint of terminal buildings and ancillary structures and decide, based upon multiple environmental and economic criteria, which strategies they should implement to yield improved outcomes. No such tool currently exists that uses multiple environmental and economic evaluation criteria or life-cycle methodologies to assess the impact from airport terminals and structures. ATEST is also the first tool that performs a partial environmental impact assessment so that an inventory of emissions can be connected to climate change and human health indicators. Project planners and regulators can use the climate change and human health indicators to gain improved insight into how different design choices and mitigation strategies can potentially lead to improved climate change and health outcomes.

- Most previous LCA studies on airport components typically only consider GHG emissions. While it is important to consider GHG emissions, especially in the context of meeting legislative requirements (e.g., Assembly Bill 32 in California) or obtaining funding grants from the FAA, it is just as important to consider the local impacts of a strategy. Considering local impacts, such as air quality, is important for assessing the potential health impacts on local populations. An inventory of CAPs is the first step in determining the exposure concentrations and, ultimately, intake amounts for specific populations. Such information can help airports and regulatory agencies identify specific strategies to put in place to mitigate human exposure.

- Understanding the relationships among the airport components, their respective environmental impacts, and the managing stakeholder groups is critical because it leads to identifying which groups must act to mitigate environmental impacts. The gate electrification study, conducted in Chapter 3, provides supporting evidence that collaboration among airport operators, airlines, and ground crews can lead to improved environmental outcomes.

6.4 Future Work

This dissertation is a starting point for understanding and mitigating the impact that airports have on the environment and on people. Future research priorities are focused on several key areas, including finetuning decision-making tools for assessing individual airports and eventually expanding analysis to include evaluating a region's airports or a network of airports.

6.4.1 Improving ATEST for Future Decision-Making

Continuing revision of the decision-support tool ATEST will be focused on addressing the limitations discussed in Chapter 5. Future anticipated revisions include:

- Improving the fidelity of construction activity data and building material specifications and quantities;

- Incorporating more temporal aspects into results analysis and depiction to demonstrate how emissions change over a specified number of years;

- Including capital investment costs and financial decision analysis that reflect the level of analysis that practitioners are familiar with (e.g., benefit-cost ratios, payback periods, internal rates of return on investments); and

- Integrating optimization techniques so that users can select a suite of mitigation strategies that meet their specified performance objectives and constraints.

6.4.2 Exposure Impacts from Airport Construction and Operation

Intake of fine $PM_{2.5}$ can lead to negative human health consequences for people with chronic exposure. One's likelihood of exposure to fine $PM_{2.5}$ from airport construction and operation depends upon socioeconomic factors. To ensure the equitable minimization of harm caused by pollution from airports, a vital next step will be to map exposure concentrations and intake, or the inhaled mass of an air pollutant, from construction and operation of airfield pavements, terminals, and aircraft and equipment operation on the airfield and within the vicinity of the airport for different racial and socioeconomic demographics to provide concrete evidence for mitigation policies and future regulatory efforts.

6.4.3 Suite of Decision-Support Tools

Future work will also focus on expanding decision-support tools for additional components of the airport system boundary. Eventually, a tool similar to ATEST will be developed to quantify life-cycle emissions from the construction and operation of airfields, air traffic support structures and facilities, landside operations, and resilience infrastructure. Such a tool will provide stakeholders with a comprehensive understanding of an airport's entire scope of impacts in one tool.

6.4.4 Implications of Airports as Sustainable, Multimodal Transportation Hubs

Airports are vital components of a vast and complicated global transportation network. Future work will explore how airports, especially regarding logistics and shipping of goods, can operate efficiently while minimizing negative environmental and human health consequences. Such analysis will focus on evaluating multiple airports at various scales of operation, including at the regional and network level.

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Appendix A. Addendum to Chapter 2

This appendix contains the supporting information for Chapter 2: Literature Review of Airports and Environmental Sustainability. References for all sections appear at the end of Appendix A.

- Section A1 includes the search terms and criteria used in the systematic literature review.

- Section A2 includes an overview of assessment metrics and methods for sustainable airfield pavements, as appropriate for the "Materials and Resources" category of the airport environmental sustainability framework defined in Chapter 2.

- Section A2 includes the methodology used in assessing the SFO case study framework.

A1. Literature Review Search Terms and Criteria

Table A1. Search terms for systematic review.

Search Terms
airport AND
• sustainability OR sustainable development OR environmental sustainability OR environmental impact • LCA OR life cycle assessment OR life-cycle assessment • energy OR energy management OR renewable energy • greenhouse gas OR GHG emission(s) • Scope 1 OR Scope 2 OR Scope 3 • building comfort OR ventilation OR HVAC OR thermal control OR daylighting • indoor air quality OR outdoor air quality OR air quality • ground service equipment OR GSE • auxiliary power unit OR APU • ground power unit OR GPU OR ground handling • parked aircraft • water conservation • alternative water sources • water quality • wastewater treatment OR wastewater • habitat OR site • electric vehicles OR EV • public transportation OR public transport OR private transportation OR private transport • climate change adaptation OR climate change resilience • construction OR construction materials OR building materials • airfield OR runway OR apron • terminal • waste management OR recycling

Table A2. Inclusion criteria for screening articles.

Article Inclusion Criteria
• Peer-reviewed journal articles and technical reports • Relevant to at least one of the 5 sustainabilitycategories • Not focused on sustainable aircraft, aircraft fuels, oraircraft operations • *Written in English • *Published between 2009 and 2019 • *Not part of a book

A2. Assessment Methods/Metrics for Sustainable Airfield Pavements

Table A3. Overview of assessment methods/metrics for sustainable airfield pavements in "Materials and Resources" category.

Citation	Airfield Component	Sustainable Feature	Assessment Method	Assessment Metric
Said & Al-Qadi, 2019	Runway, all layers	None	LCA (Raw Materials, Construction)	• Energy consumption per unit area • CO2 emissions per unit area
Yang Al-Qadi, 2017	Runway, all layers	None	LCA (Raw Materials, Construction)	• Primary energy consumption • Cumulative CO2 emissions
Magnoni et al., 2016	Taxiway, all layers	Use of recycled aggregate	LCA (Raw Materials, Construction)	• Cumulative CO2 emissions
Shen et al., 2016	Apron	Alternative Heating System	LCA (Operation)	• Cumulative CO2 emissions
Wang et al., 2016	Runway, surface layer	None	LCA (Raw Materials, Construction, Maintenance)	• Primary energy consumption • Cumulative CO2 emissions
Guercio & McCarthy, 2015	Taxiways & Aprons, all layers	*Warm Mix Asphalt *Use of recycled aggregate	LCA (Raw Materials)	• Cumulative CO2 emissions
Jamshidi et al., 2015	Runway, all layers	Use of waste product in pavement	Carbon Footprint	• Fuel consumption • Cumulative CO2 emissions
Giustozzi et al., 2012	Runway, sub-base & foundation layers	Use of recycled aggregate	LCA (Raw Materials, Construction)	• CO2 emissions per unit area
Stempihar et al., 2012	Runway, surface layer	Use of fibers in pavement	Carbon Footprint	• CO2 emissions per unit length
Pittenger, 2011	Runway, surface layer	Sustainable Maintenance Treatments	Resource Footprint	• Cumulative mass of raw material

A3. Methodology for Assessing SFO Framework

SFO Energy Use Intensity (EUI)

The EUI data was supplied by SFO. The EUI reflects the total amount of site energy used (i.e., electricity and natural gas) for SFO buildings. See Table A4 for the average SFO EUI and the projectedEUI for the new Terminal 1.

Table A4. EUI data for SFO.

Building	Energy Use Intensity (kBTU/sf/year)
SFO Average	179
Projected Improvements forTerminal 1	77

SFO Utility Consumption Data

Data on monthly electricity and natural gas consumption at SFO was used to calculate the average share of each energy type. Consumption data was collected from an open data repository for San Francisco (DataSF, 2020). Electricity and natural gas data reflect both commission (i.e., airport- owned) and tenant consumption. For both electricity and natural gas, monthly consumption data was averaged for the entire year for the years 2013 through 2018. Consumption data was converted to a similar unit (kBTU) and then the percentage share of each energy type was estimated. The average ofthe six years' worth of data was taken to estimate the share of each in SFO's building energy use intensity. It is assumed that the six-year average provides a reasonable estimation of the breakdown between building site electricity and natural gas usage (i.e., site demand). See Table A5.

Table A5. Annual percentage share of electricity and natural gas consumption at SFO from 2013-2018.

Year	Electricity	Natural Gas
2013	74.42%	25.58%
2014	77.40%	22.60%
2015	76.22%	23.78%
2016	75.19%	24.81%
2017	74.89%	25.11%
2018	74.64%	25.36%
6-year average	75.46%	24.54%

Emission Factors for Electricity and Natural Gas

Electricity

SFO's electricity is supplied from San Francisco Public Utility Commission's (SFPUC's) Hetch Hetchy Hydroelectric System (SFO, 2020). The life-cycle emission factor for SFPUC's electricity is estimated at 0.083 kilograms of CO2 equivalents per kWh of electricity supplied (Kavvada et al., 2016).

Natural Gas

The direct combustion-related CO2 emission factor for natural gas is assumed to be 5307 grams per therm (EIA, 2020). The United States national average emission factor for upstream processes (i.e., production, gathering and boosting, processing, transmission, storage, pipeline, distribution) is estimated to be 19.9 grams of CO2 equivalents per MJ of natural gas (Littlefield et al., 2019). The direct combustion and upstream processing emission factors are converted to similar units and added for a total life-cycle natural gas emission factor.

GHG Use Intensity Calculation

The CO_2 emissions associated with consuming energy on-site per area of airport building (i.e., the GHG use intensity) is calculated according to Equation 1:

$$(1)\quad GHG\ Use\ Intensity = Share_{Elec} * Building\ EUI * EF_{Elec} + Share_{NG} * Building\ EUI * EF_{NG}$$

Where: $Share_{Elec}$ is the average percentage share of electricity usage within airport buildings
EF_{Elec} is the life-cycle CO2 emission factor for electricity
$Share_{NG}$ is the average percentage share of natural gas usage within airport buildings
EF_{NG} is the life-cycle CO2 emission factor for natural gas

References

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Appendix B. Addendum to Chapter 3

This appendix contains the supporting information for Chapter 3: Environmental and Economic Assessment of Airport Gate Electrification. References for all sections appear at the end of Appendix B.

- Section B1 provides an overview of the scope of the analysis for Chapter 3.
- Section B2 includes additional information regarding the methodology and scenario descriptions used in the environmental analysis.
- Section B3 expands upon the economic analysis methods and provides additional results on payback periods and levelized annual costs for various gate electrification scenarios.
- Section B4 includes an overview of the methodology in calculating monetized climate damages and provides results for the 24 case study airports.
- Section B5 includes a methodological overview of the global analysis used in estimating emissions from all commercial airports.
- Section B6 provides an explanation of the methods used in conducting various sensitivity analyses of the environmental results.
- Section B7 includes the results from the uncertainty assessment for all data used in the analysis.
- Section B8 details the methods used in assessing the cost per mitigated emissions for gate electrification.

B1. Scope of Study

Figure B1 shows a schematic of how electrical power and air conditioning are delivered to a parked aircraft during turnaround operations. The parked aircraft is connected to the passenger boarding bridge (PBB), which is used as a walkway for passengers to and from the aircraft to the terminal gate. The 400Hz unit and preconditioned air (PCA) unit are often located very close to the PBB, either directly attached to its underside or mounted on the ground adjacent to it. The 400Hz and PCA rely upon electricity drawn from the airport's power grid. If the airport does not generate its own power onsite, their electricity is supplied from an electricity utility.

Figure B1: Schematic of 400Hz and electric PCA configuration for parked aircraft.

Table B1 lists the twenty-four case study airports included in this analysis. These airports rank among the top thirty airports in the world in terms of annual aircraft movements for the calendar year 2019. The case study airports provide both domestic and international commercial service and carry comparable fleet mixes (i.e., each airport utilizes similar aircraft subtypes).

Table B1. Case study airports.

Airport Code	Airport Name	Location
AMS	Amsterdam Airport Schiphol	Amsterdam, the Netherlands
ATL	Hartsfield-Jackson Atlanta International Airport	Atlanta, Georgia, USA
CAN	Guangzhou Baiyun International Airport	Guangdong Province, China
CDG	Charles de Gaulle Airport	Paris, France
CLT	Charlotte Douglas International Airport	Charlotte, North Carolina, USA
DEN	Denver International Airport	Denver, Colorado, USA
DFW	Dallas/Fort Worth International Airport	Dallas, Texas, USA
EWR	Newark Liberty International Airport	Newark, New Jersey, USA
FRA	Frankfurt Airport	Frankfurt, Germany
HND	Tokyo International Airport	Tokyo, Japan
IST	Istanbul Airport	Istanbul, Turkey
JFK	John F. Kennedy International Airport	Queens, New York, USA
LAS	McCarran International Airport	Las Vegas, Nevada, USA
LAX	Los Angeles International Airport	Los Angeles, California, USA
LHR	London Heathrow Airport	London, United Kingdom
MEX	Mexico City International Airport	Mexico City, Mexico
MIA	Miami International Airport	Miami, Florida, USA
ORD	Chicago O'Hare International Airport	Chicago, Illinois, USA
PEK	Beijing Capital International Airport	Beijing, China
PHX	Phoenix Sky Harbor International Airport	Phoenix, Arizona, USA
PVG	Shanghai Pudong International Airport	Shanghai, China
SEA	Seattle-Tacoma International Airport	Seattle, Washington, USA
SFO	San Francisco International Airport	Unincorporated San Mateo County, California, USA
YYZ	Toronto Pearson International Airport	Toronto, Canada

B2. Environmental Analysis

B2.1. Methodology and Scenario Descriptions

The life-cycle GHG emissions per gate operation are dependent upon multiple factors including the type of aircraft at the gate, the duration of the stay at the gate, the source of electricity utilized by the airport, the weather profile of the airport, the gate configuration of the airport, and most significantly, the type of equipment supplying electricity and air conditioning to the parked aircraft. Figures B2(a) through B2(c) provide schematic diagrams that detail the type and source of data used for estimating the carbon intensity for the 400Hz unit, the passenger boarding bridge (PBB), the electric and diesel-powered preconditioned air (PCA) units, and the aircraft's auxiliary power unit (APU), respectively.

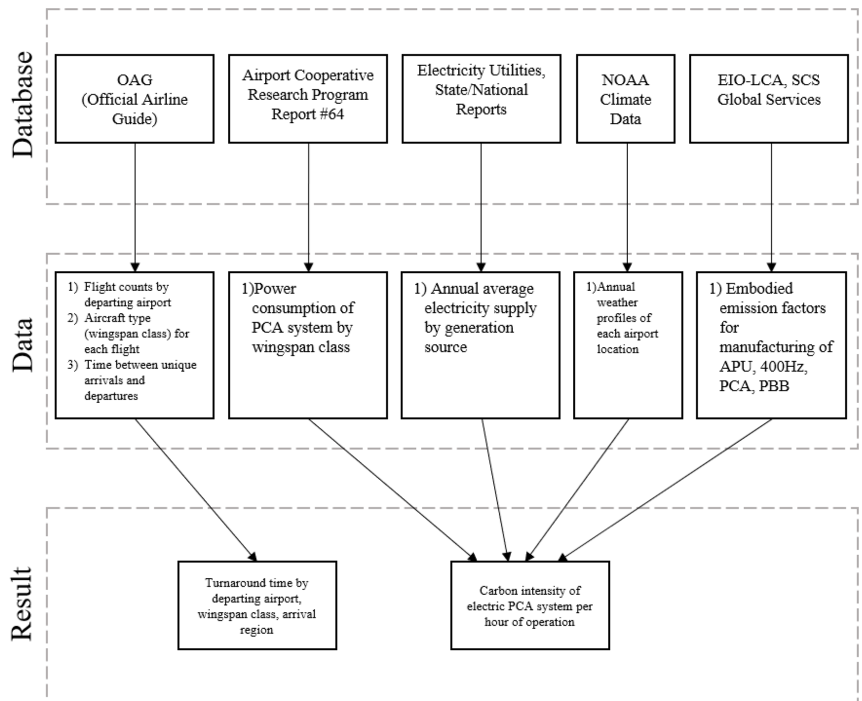

Figure B2(a): Diagram for estimating GHG emissions from electric PCA per gate operation.

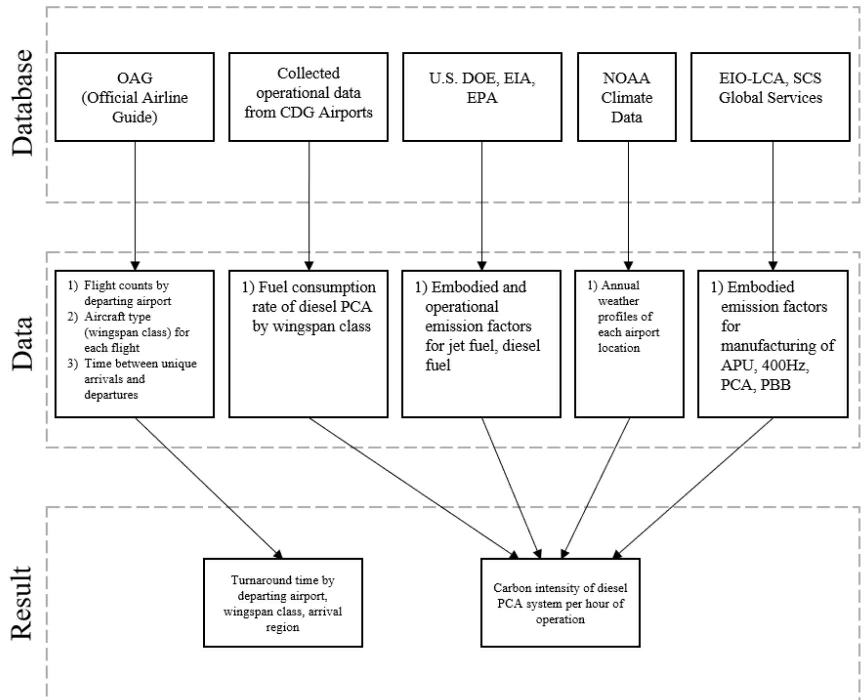

Figure B2(b): Diagram for estimating GHG emissions from diesel PCA per gate operation.

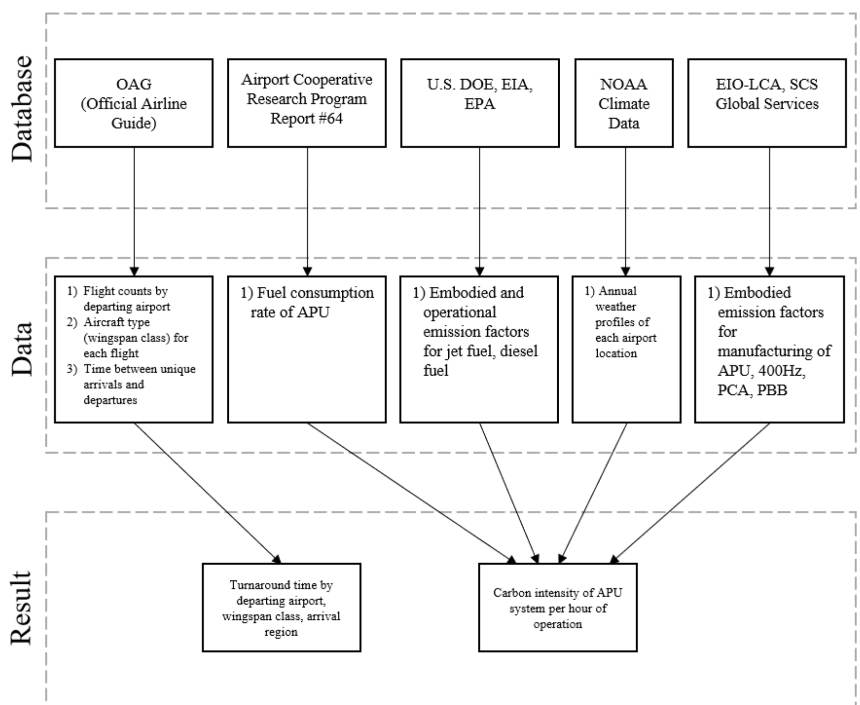

Figure B2(c): Diagram for estimating GHG emissions from the APU per gate operation.

To explore the range of results from utilizing different combinations of the power-supplying and air conditioning equipment, we define five operational scenarios as described in the main text.

For each scenario, life-cycle GHG emissions are calculated per gate operation. The following subsections outline sample equations and parameters used in making these gate operation calculations.

B2.1.1. Scenario 1

Equation B1 is used to calculate the per gate operation life-cycle GHG emissions for Scenario 1. Table B2 defines the variables and their corresponding units for Equation B1.

$$E_i = \left[D_{TA} \times \left(Cold\,\% \times FR_{APU,H/C} + Neutral\,\% \times FR_{APU,P} + Hot\,\% \times FR_{APU,H/C}\right) \times EF_{Jet\,Fuel} \times UR_{APU}\right] + \left[EC_{PBB} \times EF_{Elec}\right] + E_{M,PBB} \quad \text{[Eq. B1]}$$

Table B2. Scenario 1 equation variables and definitions.

Variable	Definition	Units
Ei	Life-cycle GHG emissions per gate operation *i*	kg CO_2 (eq)op^{-1}
D_{TA}	Turnaround duration of specific operation	hr
Cold %	Airport-specific annual share of cold conditions, inclusive between 0 and 1	unitless
Neutral %	Airport-specific annual share of neutral conditions, inclusive between 0 and 1	unitless
Hot %	Airport-specific annual share of hot conditions, inclusive between 0 and 1	unitless
$FR_{APU,\,H/C}$	Fuel rate for APU heating/cooling conditions, dependent upon wingspan class	Lhr^{-1}
$FR_{APU,\,P}$	Fuel rate for APU providing power, dependent upon wingspan class	Lhr^{-1}
$EF_{Jet\,Fuel}$	Life-cycle emission factor for jet fuel	kg CO_2 (eq)L^{-1}
UR_{APU}	Utilization rate of APU, assumed to be 1	unitless
EC_{PBB}	Electricity consumption of PBB per operation	kWh op^{-1}
EF_{Elec}	Life-cycle emission factor for electricity, airport-specific	kg CO_2 (eq)kWh^{-1}
$E_{M,\,PBB}$	Manufacturing emission factor for PBB, airport-specific	kg CO_2 (eq)op^{-1}

B2.1.2. Scenario 2a

Equation B2 is used to calculate the per gate operation life-cycle GHG emissions for Scenario 2a. Table B3 defines the variables and their corresponding units for Equation B2.

$$E_i = \left[D_{TA} \times \left(Cold\,\% \times FR_{APU,H/C} + Neutral\,\% \times FR_{APU,P} + Hot\,\% \times FR_{APU,\frac{H}{C}}\right) \times EF_{Jet\,Fuel} \times UR_{APU}\right] + \left[D_{TA} \times PR_{400Hz} \times EF_{Elec} \times UR_{400Hz}\right] + \left[D_{TA} \times \left(Cold\,\% \times PR_{ePCA,H} + Hot\,\% \times PR_{ePCA,C}\right) \times EF_{Elec} \times UR_{ePCA}\right] + \left[EC_{PBB} \times EF_{Elec}\right] + E_{M,400Hz} + E_{M,ePCA} + E_{M,PBB} \quad \text{[Eq. B2]}$$

Table B3. Scenario 2a equation variables and definitions.

Variable	Definition	Units
E_i	Life-cycle GHG emissions per gate operation *i*	kg CO_2 (eq)op^{-1}
D_{TA}	Turnaround duration of specific operation	hr
Cold %	Airport-specific annual share of cold conditions, inclusive between 0 and 1	unitless
Neutral %	Airport-specific annual share of neutral conditions, inclusive between 0 and 1	unitless
Hot %	Airport-specific annual share of hot conditions, inclusive between 0 and 1	unitless
$FR_{APU, H/C}$	Fuel rate for APU heating/cooling conditions, dependent upon wingspan class	Lhr^{-1}
$FR_{APU, P}$	Fuel rate for APU providing power, dependent upon wingspan class	Lhr^{-1}
$EF_{Jet\ Fuel}$	Life-cycle emission factor for jet fuel	kg CO_2 (eq)L^{-1}
UR_{APU}	Utilization rate of APU, dependent upon wingspan class	unitless
PR_{400Hz}	Power rating of 400Hz, dependent upon wingspan class	kW
UR_{400Hz}	Utilization rate of 400Hz, dependent upon wingspan class	unitless
$PR_{ePCA, H}$	Power rating electric PCA heating conditions, dependent upon wingspan class	kW
$PR_{ePCA, C}$	Power rating electric PCA cooling conditions, dependent upon wingspan class	kW
UR_{ePCA}	Utilization rate of electric PCA, dependent upon wingspan class	unitless
EC_{PBB}	Electricity consumption of PBB per operation	kWh op^{-1}
EF_{Elec}	Life-cycle emission factor for electricity, airport-specific	kg CO_2 (eq)kWh^{-1}
$E_{M, 400Hz}$	Manufacturing emission factor for 400Hz, airport-specific	kg CO_2 (eq)op^{-1}
$E_{M, ePCA}$	Manufacturing emission factor for electric PCA, airport-specific	kg CO_2 (eq)op^{-1}
$E_{M, PBB}$	Manufacturing emission factor for PBB, airport-specific	kg CO_2 (eq)op^{-1}

B2.1.3. Scenario 2b

Equation B3 is used to calculate the per gate operation life-cycle GHG emissions for Scenario 2b. Table B4 defines the variables and their corresponding units for Equation B3.

$$E_i = \Big[D_{TA} \times \Big(Cold\ \% \times FR_{APU,H/C} + Neutral\ \% \times FR_{APU,P} + Hot\ \% \times FR_{APU,\frac{H}{C}}\Big) \times EF_{Jet\ Fuel} \times UR_{APU}\Big] + [D_{TA} \times PR_{400Hz} \times EF_{Elec} \times UR_{400Hz}] + \big[D_{TA} \times \big(Cold\ \% \times PR_{dPCA,H} + Hot\ \% \times PR_{dPCA,C}\big) \times EF_{Diesel\ Fuel} \times UR_{dPCA}\big] + [EC_{PBB} \times EF_{Elec}] + E_{M,400Hz} + E_{M,dPCA} + E_{M,PBB} \quad \text{[Eq. B3]}$$

Table B4. Scenario 2b equation variables and definitions.

Variable	Definition	Units
E_i	Life-cycle GHG emissions per gate operation *i*	kg CO_2 (eq)op^{-1}
D_{TA}	Turnaround duration of specific operation	hr
Cold %	Airport-specific annual share of cold conditions, inclusive between 0 and 1	unitless
Neutral %	Airport-specific annual share of neutral conditions, inclusive between 0 and 1	unitless
Hot %	Airport-specific annual share of hot conditions, inclusive between 0 and 1	unitless
$FR_{APU, H/C}$	Fuel rate for APU heating/cooling conditions, dependent upon wingspan class	Lhr^{-1}
$FR_{APU, P}$	Fuel rate for APU providing power, dependent upon wingspan class	Lhr^{-1}
$EF_{Jet Fuel}$	Life-cycle emission factor for jet fuel	kg CO_2 (eq)L^{-1}
$EF_{Diesel Fuel}$	Life-cycle emission factor for diesel fuel	kg CO_2 (eq)L^{-1}
UR_{APU}	Utilization rate of APU, dependent upon wingspan class	unitless
PR_{400Hz}	Power rating of 400Hz, dependent upon wingspan class	kW
UR_{400Hz}	Utilization rate of 400Hz, dependent upon wingspan class	unitless
$FR_{dPCA, H}$	Fuel rate for diesel PCA heating conditions, dependent upon wingspan class	Lhr^{-1}
$FR_{dPCA, C}$	Fuel rate for diesel PCA cooling conditions, dependent upon wingspan class	Lhr^{-1}
UR_{dPCA}	Utilization rate of diesel PCA, dependent upon wingspan class	unitless
EC_{PBB}	Electricity consumption of PBB per operation	kWh op^{-1}
EF_{Elec}	Life-cycle emission factor for electricity, airport-specific	kg CO_2 (eq)kWh^{-1}
$E_{M, 400Hz}$	Manufacturing emission factor for 400Hz, airport-specific	kg CO_2 (eq)op^{-1}
$E_{M, dPCA}$	Manufacturing emission factor for diesel PCA, airport-specific	kg CO_2 (eq)op^{-1}
$E_{M, PBB}$	Manufacturing emission factor for PBB, airport-specific	kg CO_2 (eq)op^{-1}

B2.1.4. Scenario 3a

Equation B4 is used to calculate the per gate operation life-cycle GHG emissions for Scenario 3a. Table B5 defines the variables and their corresponding units for Equation B4.

$$E_i = [D_{TA} \times PR_{400Hz} \times EF_{Elec} \times UR_{400Hz}] + \left[D_{TA} \times \left(Cold\ \% \times PR_{ePCA,H} + Hot\ \% \times PR_{ePCA,C}\right) \times EF_{Elec} \times UR_{ePCA}\right] + [EC_{PBB} \times EF_{Elec}] + E_{M,400Hz} + E_{M,ePCA} + E_{M,PBB} \quad \text{[Eq. B4]}$$

Table B5. Scenario 2a equation variables and definitions.

Variable	Definition	Units
E_i	Life-cycle GHG emissions per gate operation *i*	kg CO_2 (eq)op^{-1}
D_{TA}	Turnaround duration of specific operation	hr
Cold %	Airport-specific annual share of cold conditions, inclusive between 0 and 1	unitless
Neutral %	Airport-specific annual share of neutral conditions, inclusive between 0 and 1	unitless
Hot %	Airport-specific annual share of hot conditions, inclusive between 0 and 1	unitless
PR_{400Hz}	Power rating of 400Hz, dependent upon wingspan class	kW
UR_{400Hz}	Utilization rate of 400Hz, assumed to be 1	unitless
$PR_{ePCA, H}$	Power rating electric PCA heating conditions, dependent upon wingspan class	kW
$PR_{ePCA, C}$	Power rating electric PCA cooling conditions, dependent upon wingspan class	kW
UR_{ePCA}	Utilization rate of electric PCA, assumed to be 1	unitless
EC_{PBB}	Electricity consumption of PBB per operation	kWh op^{-1}
EF_{Elec}	Life-cycle emission factor for electricity, airport-specific	kg CO_2 (eq)kWh^{-1}
$E_{M, 400Hz}$	Manufacturing emission factor for 400Hz, airport-specific	kg CO_2 (eq)op^{-1}
$E_{M, ePCA}$	Manufacturing emission factor for electric PCA, airport-specific	kg CO_2 (eq)op^{-1}
$E_{M, PBB}$	Manufacturing emission factor for PBB, airport-specific	kg CO_2 (eq)op^{-1}

B2.1.5. Scenario 3b

Equation B5 is used to calculate the per gate operation life-cycle GHG emissions for Scenario 3b. Table B6 defines the variables and their corresponding units for Equation B5.

$$\begin{aligned} E_i = {} & [D_{TA} \times PR_{400Hz} \times EF_{Elec} \times UR_{400Hz}] \\ & + \left[D_{TA} \times \left(Cold\ \% \times PR_{dPCA,H} + Hot\ \% \times PR_{dPCA,C}\right) \right. \\ & \qquad \left. \times EF_{Diesel\ Fuel} \times UR_{dPCA}\right] \\ & + [EC_{PBB} \times EF_{Elec}] \\ & + E_{M,400Hz} + E_{M,dPCA} + E_{M,PBB} \end{aligned} \qquad \text{[Eq. B5]}$$

Table B6: Scenario 3b equation variables and definitions.

Variable	Definition	Units
E_i	Life-cycle GHG emissions per gate operation *i*	kg CO_2 (eq)op^{-1}
D_{TA}	Turnaround duration of specific operation	hr
Cold %	Airport-specific annual share of cold conditions, inclusive between 0 and 1	unitless
Neutral %	Airport-specific annual share of neutral conditions, inclusive between 0 and 1	unitless
Hot %	Airport-specific annual share of hot conditions, inclusive between 0 and 1	unitless
$EF_{Diesel\ Fuel}$	Life-cycle emission factor for diesel fuel	kg CO_2 (eq)L^{-1}
PR_{400Hz}	Power rating of 400Hz, dependent upon wingspan class	kW
UR_{400Hz}	Utilization rate of 400Hz, dependent upon wingspan class	unitless
$FR_{dPCA,\ H}$	Fuel rate for diesel PCA heating conditions, dependent upon wingspan class	Lhr^{-1}
$FR_{dPCA,\ C}$	Fuel rate for diesel PCA cooling conditions, dependent upon wingspan class	Lhr^{-1}
UR_{dPCA}	Utilization rate of diesel PCA, dependent upon wingspan class	unitless
EC_{PBB}	Electricity consumption of PBB per operation	kWh op^{-1}
EF_{Elec}	Life-cycle emission factor for electricity, airport-specific	kg CO_2 (eq)kWh^{-1}
$E_{M,\ 400Hz}$	Manufacturing emission factor for 400Hz, airport-specific	kg CO_2 (eq)op^{-1}
$E_{M,\ dPCA}$	Manufacturing emission factor for diesel PCA, airport-specific	kg CO_2 (eq)op^{-1}
$E_{M,\ PBB}$	Manufacturing emission factor for PBB, airport-specific	kg CO_2 (eq)op^{-1}

B2.2. Data

B2.2.1. Gate Operations

B2.2.1.1. Flight counts by wingspan class and arrival region

Operation data for the case study airports is provided from an online database that tracks every commercial flight to and from every airport in the world (Perry, 2020). A gate operation occurs between a unique flight arrival and departure pair. For each case study airport, we assume that the annual number of departures is the annual number of gate operations. Annual departures are subdivided by specific aircraft model. The flight record data groups flight frequency by arrival region so for each case study airport, there is a record of the number of flights by specific aircraft model to each arrival region. Each aircraft model is further characterized by wingspan class, which is designated by the International Civil Aviation Organization (ICAO) aerodrome reference code (ICAO, 2004). The ICAO aerodrome reference code is very similar to the Federal Aviation Administration (FAA) Airplane Design Group designation (FAA, 2014, p. 2). These designations are used to determine whether an aircraft is allowed to land on a particular airport's runway. Table B7 lists the wingspan criteria and example aircraft models for the ICAO and FAA designations. Wingspan class is a proxy for the type of flight trip. Local charter flights would likely use a Wingspan Class "A" or "B" aircraft. Regional commercial flights and intra-continental flights would use Wingspan Class "C" and "D" aircraft. Most Class "C" and "D" aircraft can also be characterized as narrow-bodies (i.e., a single-aisle aircraft). Wingspan Class "E" and "F" aircraft are used for long-haul international flights. These are typically referred to as wide bodies (e.g., two aisles). For each airport, we compile a matrix of flight departures by wingspan class (Table B8).

Table B7. Aircraft Wingspan Designation.

ICAO Aerodrome Reference Code	FAA Airplane Design Group	Wingspan Criteria	Example Aircraft Model
A	I	< 15 m	Cessna Light Aircraft (Single Turboprop)
B	II	15 m ≤ x < 24 m	Embraer RJ145
C	III	24 m ≤ x < 36 m	Airbus 318, Boeing 737-300
D	IV	36 m ≤ x < 52 m	Boeing 757-300
E	V	52 m ≤ x < 65 m	Airbus A330, Boeing 777-300
F	VI	65 m ≤ x < 80 m	Airbus 380

Table B8. Flight counts by airport and wingspan class.

Airport Code	Wingspan Class	Ops by Airport	Percentage of Fleet Mix
AMS	C	199474	83.8%
	D	4283	1.8%
	E	33490	14.1%
	F	808	0.3%
ATL	C	343491	87.6%
	D	39519	10.1%
	E	8645	2.2%
	F	572	0.1%

Airport Code	Wingspan Class	Ops by Airport	Percentage of Fleet Mix
CAN	C	195340	82.1%
	D	1010	0.4%
	E	39718	16.7%
	F	1856	0.8%
CDG	C	175262	75.5%
	D	3944	1.7%
	E	47092	20.3%
	F	5824	2.5%
CLT	C	202897	98.0%
	D	734	0.4%
	E	3435	1.7%
DEN	C	215904	95.6%
	D	5520	2.4%
	E	4461	2.0%
	F	1	0.0%
DFW	C	298696	93.8%
	D	5751	1.8%
	E	13841	4.3%
	F	318	0.1%
EWR	C	168691	82.0%
	D	21013	10.2%
	E	15781	7.7%
	F	353	0.2%
FRA	C	194725	80.4%
	D	7485	3.1%
	E	30084	12.4%
	F	9799	4.0%
HND	C	114076	50.1%
	D	37258	16.4%
	E	76085	33.4%
	F	362	0.2%
IST	C	160816	75.7%
	D	2255	1.1%
	E	49506	23.3%
	F	1	0.0%
JFK	C	142634	68.9%
	D	18360	8.9%
	E	42127	20.4%
	F	3870	1.9%
LAS	C	176405	96.4%
	D	3628	2.0%
	E	3051	1.7%
LAX	C	233640	79.3%
	D	20180	6.9%
	E	36779	12.5%
	F	3987	1.4%
LHR	C	146586	61.3%
	D	5677	2.4%
	E	78623	32.9%
	F	8131	3.4%
MEX	C	200478	95.0%
	D	1637	0.8%

Airport Code	Wingspan Class	Ops by Airport	Percentage of Fleet Mix
	E	8141	3.9%
	F	719	0.3%
MIA	C	120889	81.0%
	D	11695	7.8%
	E	15986	10.7%
	F	616	0.4%
ORD	C	247745	89.0%
	D	9566	3.4%
	E	20292	7.3%
	F	760	0.3%
PEK	C	184544	63.0%
	D	2371	0.8%
	E	103349	35.3%
	F	2518	0.9%
PHX	C	169824	96.8%
	D	4130	2.4%
	E	1499	0.9%
PVG	C	173599	74.0%
	D	1332	0.6%
	E	57897	24.7%
	F	1786	0.8%
SEA	C	199990	92.9%
	D	8725	4.1%
	E	6567	3.1%
SFO	C	149860	77.3%
	D	15057	7.8%
	E	27922	14.4%
	F	1149	0.6%
YYZ	C	155959	81.8%
	D	11499	6.0%
	E	23037	12.1%
	F	260	0.1%

B2.2.1.2. Turnaround data from July 2019 by airport

Turnaround time, in number of hours, is calculated from a single day's worth of data for the case study airports (Perry, 2020). The representative date is July 15, 2019. The months of July and August are typically the highest traffic months for airports, and so a representative July date provides a robust distribution of different arrival and departure operations with distinct aircraft types. Turnaround times are calculated as the difference between an arrival time and departure time for a unique flight operation (i.e., the amount of time an aircraft is parked at a gate). To reflect actual usage of 400Hz, APU, and PCA units for gate operations more accurately, maximum turnaround times are limited to six hours. The six-hour limit was observed from a sample of measured 400Hz usage data for one of the case study airports (CDG Airport). Figure B3 shows the distribution of observed turnaround durations for all twenty-four airports. Approximately 90% of all observations are less than 6 hours. Average, minimum, and maximum turnaround times, by wingspan class and arrival region are finally estimated with the 6-hour maximum imposed.

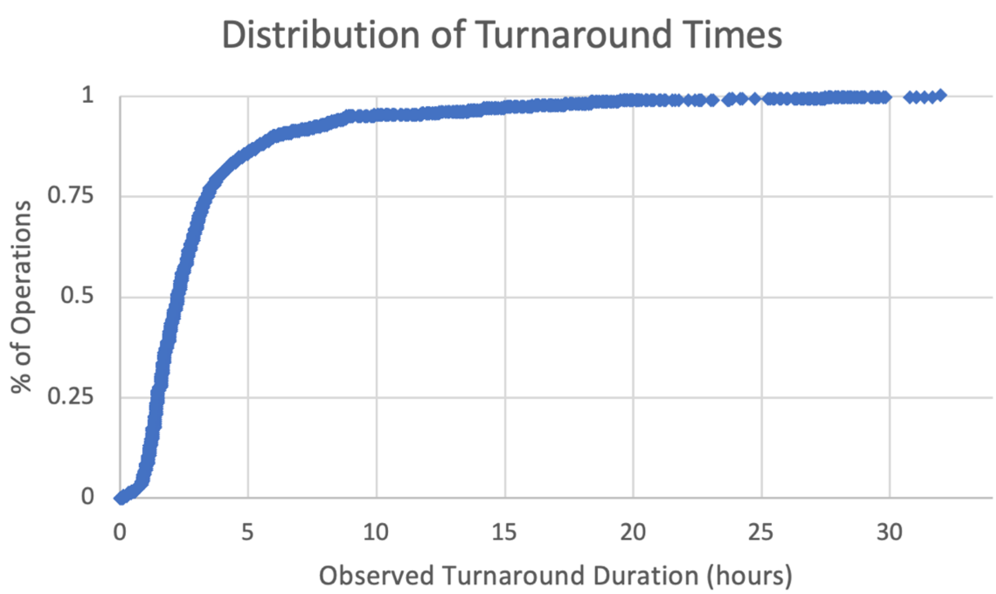

Figure B3. Cumulative distribution of observed turnaround times for all airports. A maximum turnaround time of 6 hours is imposed on gate operations exceeding the 6-hour limit.

B2.2.1.3. Gate Operations Matrix

The turnaround times, with the imposed maximum time limit, are matched with the flight departure matrix described in Section B2.2.1.1. Table B9 shows a sample of the final gate operations matrix. The complete gate operations matrix is used to estimate life-cycle GHG emissions, economic costs, and monetized damages by departure airport and by each gate operation.

Table B9. Sample portion of gate operations matrix.

Departure Airport Code	Arrival Region Name	Wingspan Class	Total Gate Operations by Wingspan Class	Mean Turnaround [hr]	Min Turnaround [hr]	Max Turnaround [hr]
AMS	Africa	C	2903	2.75	2.083333	4.5
AMS	Asia	C	209	6	6	6
AMS	Europe	C	194142	1.664938	0	5.083333
AMS	Middle East	C	2220	5.616667	5.5	5.916667
ATL	Latin America	C	17627	2.494445	1.05	4.683333
ATL	North America	C	325864	1.485989	0	2.8
CAN	Asia	C	195338	2.483143	0.916667	6
CAN	Middle East	C	2	3.833333	3.833333	3.833333
CDG	Africa	C	12225	1.753788	1.25	4.416667
CDG	Asia	C	73	6	6	6
CDG	Europe	C	159744	1.831947	0.083333	6
CDG	Middle East	C	3185	5.557692	5.25	6
CDG	North America	C	35	2.5	2.5	2.5

B2.2.2. Equipment

B2.2.2.1. Utilization Rate of Equipment

The utilization rate indicates the portion of each gate operation for which each equipment is running. The utilization rate of equipment is tied to the operational scenarios. For all operational scenarios, it is assumed that the PBB is always utilized 100% for each gate operation. In Scenario 1, we assume the utilization rate of the APU to be 100 percent; no external gate equipment is utilized. In Scenarios 3a and 3b, we assume 100 percent utilization rate of the 400Hz unit and PCA unit. The utilization rates of equipment for Scenarios 2a and 2b come from measured data. We use a sample of measured data from CDG airport to estimate the utilization rate of the APU engine, 400Hz unit, and PCA unit by wingspan class.

The CDG dataset contains a sample of 25,000 gate operations for the calendar year 2018. For each gate operation, the cumulative time of APU usage and 400Hz/PCA usage is measured. The utilization rate for each piece of gate equipment is the ratio of the specific equipment's usage time relative to the duration of the entire gate operation. The utilization rates in operational Scenarios 2a and 2b (Table B10) represent the measured data from CDG airport.

Table B10. Utilization rate of equipment by wingspan class and operational scenario.

Scenario 1: Worst Case			
Wingspan Class	**APU Utilization Rate**	**400Hz Utilization Rate**	**PCA Utilization Rate**
C	1	0	0
D	1	0	0
E	1	0	0
F	1	0	0
Scenario 2a and 2b: Current Situation			
Wingspan Class	**APU Utilization Rate**	**400Hz Utilization Rate**	**PCA Utilization Rate**
C	0.31	0.69	0.69
D	0.3	0.7	0.7
E	0.31	0.69	0.69
F	0.28	0.72	0.72
Scenario 3a and 3b: Best Case			
Wingspan Class	**APU Utilization Rate**	**400Hz Utilization Rate**	**PCA Utilization Rate**
C	0	1	1
D	0	1	1
E	0	1	1
F	0	1	1

B2.2.2.2. Power and Fuel Consumption Characteristics of Equipment

Power and fuel consumption data are determined from both measured data and literature sources. From the CDG dataset, we estimate the average power rating of the 400Hz unit by wingspan class (Table B11). Power consumption increases by wingspan class (i.e., larger aircraft will draw more power than smaller aircraft). The power consumption data for the electric PCA is from a recent National Academies of Science report from the Airport Cooperative Research Program (ACRP) ACRP report (ACRP et al., 2012). We use a sample of measured power consumption data from SFO from the calendar year 2019 to estimate the average power rating of a standard PBB. We assume that the PBB is used for each gate operation and that the PBB can accommodate all wingspan classes. In this analysis, we do not account for the ramping up and down of the PBB. That is, we do not consider the energy used to turn on/off the PBB and to have the PBB on but not servicing a specific aircraft.

Table B12 provides the fuel usage data for the diesel PCA and the APU equipment. The fuel consumption data for the APU is from the recent ACRP report (ACRP et al., 2012). Fuel consumption data for the diesel PCA is provided from contacts at CDG airport. Unlike with the 400Hz unit, which just delivers electrical power, the rate at which power/fuel is consumed by the PCA units and the APU depends upon the mode of the equipment. The APU consumes more fuel during heating and cooling operations than when it is exclusively providing electricity. The PCA units consume more power/fuel for cooling operations than for heating operations.

Table B11. Equipment power usage characteristics by Wingspan Class.

Wingspan Class	400Hz Power Rating (kW)	ePCA Cooling (kW)	ePCA Heating (kW)
C	17	49	47
D	26	130	98
E	34	153	114
F	66	153	114

Table B12. Equipment fuel usage characteristics by Wingspan Class.

Wingspan Class	Diesel PCA Cooling (L/hr)	Diesel PCA Heating (L/hr)	APU Heating/Cooling (L/hr)	APU Power Supply (L/hr)
C	17	16	148	94
D	37	28	233	148
E	54	40	273	157
F	107	80	273	157

We use samples of measured power consumption data from SFO and measured electricity consumption data from Boston Logan International Airport (BOS) from the calendar year 2019 to estimate the average electricity consumption of a standard PBB (Civic and Lurie, 2021; Nagengast, 2020). We assume that the PBB is used for each gate operation and that the PBB can accommodate all wingspan classes. In this analysis, we do not account for the ramping up and down of the PBB. That is, we do not consider the energy used to turn on/off the PBB and to have the PBB on but not servicing a specific aircraft. Figure B4 shows the power consumption data for one gate at SFO. The SFO data is converted from power to electricity consumption by multiplying each incremental power rating by the time step of fifteen minutes. Data from BOS is already in units of electricity consumption.

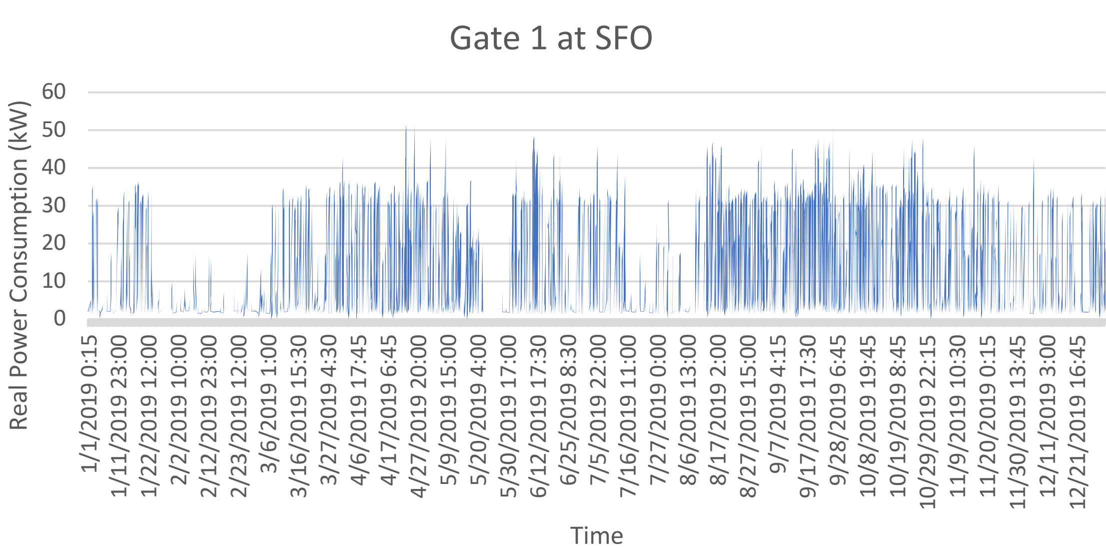

Figure B4. Sample of power consumption data for passenger boarding bridge at SFO for calendar year 2019.

We then compiled the average of seven samples of yearly electricity consumption from gates at SFO and BOS airports (Table B13).

Table B13. Sample of PBB electricity consumption for calendar year 2019.

	BOS	SFO
	PBB Electricity Consumption (kWh/yr)	PBB Electricity Consumption (kWh/yr)
Gate 1	13,098	58,718
Gate 2	14,774	155,272
Gate 3	12,970	106,031
Gate 4	20,138	N/A

Using this average electricity consumption for one gate (approximately 54,000 kWh per year), we estimate the electricity consumption from all gates at each case study airport and then apportion that electricity consumption based on the annual number of turnaround operations.

B2.2.2.3. Manufacturing of Equipment

We attempted to find previous studies that discussed the environmental impacts from manufacturing, PCA, 400Hz, and PBB units. Except for the PBB (SCS Global Services, 2020), we use proxy data (Carnegie Mellon University, 2020) to estimate the GHG emissions associated with manufacturing the 400Hz and PCA units.

Assumptions for estimating GHG emissions using EIO-LCA are that the 400Hz and PCA units each cost $250,000 USD. These unit costs are based upon current manufacturing estimates for each unit. Table B14 lists the embodied emission factors for each system unit.

Table B14. Manufacturing GHG data per system unit.

Unit	Value	Source
PCA unit	145 metric tons CO_2 (eq) per unit	EIO-LCA (Sector: HVAC and commercial refrigeration equipment manufacturing - Air conditioning, refrigeration, and warm air)
400Hz unit	94.9 metric tons CO_2 (eq) per unit	EIO-LCA (Sector: Other electrical equipment and component manufacturing - All other miscellaneous electrical equipment)
PBB	1500 kg CO_2 (eq) per lineal ft	Environmental Product Declaration

Since we do not have exact data from the case study airports regarding their total number of gates and whether each gate is fully equipped, we make the following assumptions:

- All gates at each case study airport are used on an annual basis and each gate is equipped with one passenger boarding bridge, one PCA unit, and one 400Hz unit;
- All units {400Hz, PCA, PBB} last for 20 years
- Each PBB is assumed to be 35 feet long (approximately 11 meters), which is in keeping with FAA regulations (FAA, 2012, p. 2)
- No emissions from maintenance or repairs

Equation B6 outlines how manufacturing emissions for each unit in the set {PCA, PBB} are apportioned to each airport for each gate operation.

$$E_{M,i} = \frac{\left[N_{Gates} \times \frac{GHG_M}{unit}\right]}{\left[\left(N_{Ops} \times yr^{-1}\right) \times LS_{unit}\right]} \qquad \text{[Eq. B6]}$$

where $E_{M,i}$ is the manufacturing emissions apportioned to each gate operation;
N_{gates} is the total number of gates per airport;
GHG_M are the GHG emissions from manufacturing the unit;
N_{Ops} is the total number of annual operations per airport;
LS_{unit} is the assumed lifespan of the unit in years

Equation B7 is used to apportion the manufacturing emissions for the PBB to each airport's gate operation.

$$E_{M,i} = \frac{\left[N_{Gates} \times \frac{GHG_M}{lineal\ ft} \times L_{PBB}\right]}{\left[\left(N_{Ops} \times yr^{-1}\right) \times LS_{unit}\right]} \qquad \text{[Eq. B7]}$$

where $E_{M,i}$ is the manufacturing emissions apportioned to each gate operation;
N_{gates} is the total number of gates per airport;
GHG_M are the GHG emissions from manufacturing the unit;
L_{PBB} is the total lineal length of the passenger boarding bridge in feet;
N_{Ops} is the total number of annual operations per airport;
LS_{unit} is the assumed lifespan of the unit in years

B2.2.3. Electricity

Electricity supplies are location-dependent and contingent upon factors such as resource availability, legislative requirements, and contract agreements. The first step in estimating the life-cycle GHG emissions from an airport's electricity consumption is to identify the specific electricity supplier, or utility. Each airport's utility is determined by reading annual reports and direct personal communication with airport representatives (see Table B15). If an airport's specific utility cannot be determined, we assume that the airport's electricity mix is like the regional or national electricity mix. In the case of many of the international airports (e.g., IST, MEX), the utility is often nationally run. Table B15 indicates the level of specificity of each airport's electricity supplier used in this analysis. The life-cycle GHG emissions for each kWh of electricity generated is calculated by multiplying the share of each mix's fuel (Table B16) by each specific fuel's life-cycle emission factor (Table B17). The emission factors in Table B17 (Horvath and Stokes, 2011) encompass upstream and operational impacts for each fuel type (e.g., the GHG emission from manufacturing solar PV cells).

Table B15. Electricity supplier for each airport.

Dep Airport Code	Utility/Regional/National/Other	Reference
AMS	Other: Unspecified wind farms	(Royal Schiphol Group, 2020)
ATL	Utility: Georgia Power	(Georgia Power, 2020)
CAN	Other: Research Study	(Shen et al., 2019)
CDG	National: Réseau de Transport d'Électricité	(Groupe ADP, 2020; RTE France, 2019)
CLT	Utility: Duke Energy	(Duke Energy, 2020)
DEN	Utility: XCEL	(XCel Energy, 2020)
DFW	Other: Unspecified wind farms	(DFW, 2019)
EWR	Utility: Public Service Electric Group	(PSEG, 2020)
FRA	Regional: Regionalverband FrankfurtRheinMsain	(AG Energiebilanzen, 2020; Fraport, 2020; Regionalverband FrankfurtRheinMain, 2020)
HND	Utility: Tokyo Electric Power Company	(TEPCO, 2020)
IST	National: Electricity Generation Company (Elektrik Üretim Anonim Şirketi)	(Electricity Generation Company (EUAS), 2020)
JFK	Other: On-site generation	(PANYNJ, 2020)
LAS	Utility: Nevada Power Company	(NVEnergy, 2020)
LAX	Utility: Los Angeles Department of Water and Power	(CEC, 2020a)
LHR	Other: Unspecified wind farms	(LHR, 2020)
MEX	National: Comision Federal de Electricidad	(Secretaria de Energia, 2019)
MIA	Utility: Florida Power and Light Company	(FPL, 2020)
ORD	Utility: Commonwealth Edison	(ComEd, 2019)
PEK	Other: Research Study	(Shen et al., 2019)
PHX	Utility: Arizona Public Services	(PWCC, 2020)
PVG	Other: Research Study	(Shen et al., 2019)
SEA	Utility: Bonneville Power Administration	(BPA, 2020)
SFO	Utility: San Francisco Public Utilities Commission	(CEC, 2020b)
YYZ	Utility: Toronto Hydro	(Toronto Hydro, 2020)

Table B16. Average annual electricity mix profiles by airport.

Airport Code	Coal	Natural Gas	Oil	Nuclear	Hydro	Biomass	Solar	Wind	Geothermal	Other
AMS	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	0.0%	0.0%
ATL	25.0%	46.0%	0.0%	22.0%	2.0%	0.0%	1.5%	1.5%	0.0%	2.0%
CAN	55.8%	5.6%	0.0%	8.8%	29.0%	0.0%	0.0%	0.8%	0.0%	0.0%
CDG	1.1%	5.7%	0.4%	71.7%	12.5%	1.8%	1.9%	5.1%	0.0%	0.0%
CLT	27.0%	36.0%	0.0%	35.0%	1.0%	0.0%	1.0%	0.0%	0.0%	0.0%
DEN	33.0%	37.0%	0.0%	0.0%	0.3%	0.3%	4.0%	25.0%	0.3%	0.0%
DFW	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	0.0%	0.0%
EWR	10.0%	33.0%	0.7%	55.0%	0.7%	0.0%	0.7%	0.0%	0.0%	0.0%
FRA	28.0%	14.9%	0.8%	12.3%	3.3%	8.2%	7.8%	20.6%	0.03%	4.20%
HND	5.0%	46.0%	14.0%	20.0%	16.0%	0.0%	0.0%	0.0%	0.0%	0.0%
IST	36.6%	18.4%	1.0%	0.0%	29.4%	1.6%	3.1%	7.2%	3.0%	0.0%
JFK	0.0%	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
LAS	7.5%	75.4%	0.0%	0.3%	2.4%	0.4%	5.6%	1.8%	6.6%	0.2%
LAX	18.0%	30.0%	0.0%	10.0%	5.0%	0.0%	13.0%	11.0%	7.0%	6.0%
LHR	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	0.0%	0.0%
MEX	22.4%	55.9%	0.7%	4.3%	10.2%	0.2%	0.7%	3.9%	1.7%	0.0%

Airport Code	Coal	Natural Gas	Oil	Nuclear	Hydro	Biomass	Solar	Wind	Geothermal	Other
MIA	2.0%	74.0%	0.0%	22.0%	0.0%	0.0%	2.0%	0.0%	0.0%	0.0%
ORD	32.0%	27.0%	0.0%	36.0%	1.0%	0.0%	0.0%	3.0%	0.0%	1.0%
PEK	72.4%	23.5%	0.0%	0.0%	0.7%	0.0%	0.0%	3.4%	0.0%	0.0%
PHX	22.7%	25.5%	0.0%	31.2%	0.0%	0.2%	4.7%	2.5%	0.1%	13.2%
PVG	39.3%	18.0%	0.0%	5.1%	36.9%	0.0%	0.0%	0.7%	0.0%	0.0%
SEA	0.0%	0.0%	0.0%	11.5%	83.2%	0.0%	0.0%	0.6%	0.0%	4.8%
SFO	0.0%	0.0%	0.0%	0.0%	99.0%	0.0%	1.0%	0.0%	0.0%	0.0%
YYZ	0.0%	6.1%	0.0%	58.2%	24.0%	0.5%	2.4%	8.2%	0.0%	0.6%

Table B17. Life-cycle emission factors by fuel source. Source: Horvath and Stokes 2011.

Fuel Source	Life-Cycle Emission Factor [kg CO_2 (eq) kWh^{-1}]
Coal	1.059
Natural Gas	0.696
Oil	0.957
Nuclear	0.017
Hydro	0.055
Biomass	0.056
Solar	0.064
Wind	0.031
Geothermal	0.028

B2.2.4. Jet and Diesel Fuel

Jet fuel is consumed whenever the APU is operating, and diesel fuel is consumed whenever the diesel PCA is operating. We consider both the upstream (i.e., refining, production) and the operational GHG emissions associated with consuming jet and diesel fuel. Table B18 lists the upstream and operational emission factors, which are calculated from government and literature sources (EIA, 2016; EPA, 2014; Speth et al., 2016; Wang et al., 2016). The operational emissions, which are determined by the energy density and composition of each fuel type, do not change based upon airport location. We assume that regional differences in how the fuel types are refined and produced can be ignored. The total emission factor for each fuel type is the sum of the upstream and operational emission factors.

Table B18. Jet fuel and diesel fuel emission factors.

	Jet Fuel [kg CO_2(eq) L^{-1}]	Diesel Fuel [kg CO_2(eq) L^{-1}]
Upstream	0.64	0.57
Operational	2.58	2.7
Total	3.22	3.27

B2.2.5. Ambient Air Temperature Profiles

The ambient air temperature profile for each case study airport is needed to determine the amount of time that heating and cooling conditions get activated. Following standards set by the FAA, heating conditions are activated for temperatures less than 7.2 degrees Celsius and cooling conditions are activated for temperatures greater than 10 degrees Celsius (ACRP et al., 2012). Neutral conditions, which occur for a temperature range between 7.2 and 10 degrees Celsius, indicate that no heating or cooling is required. For each airport location, the average number of days of the year that fall into each category (i.e., Cold, Neutral, Hot) are determined using average monthly air temperature data from 2017 to 2019 (NOAA, 2020). Average annual air temperature conditions are indicated in Table B19.

Table B19. Average annual air temperature conditions by case study airport.

Airport	Cold Conditions	Neutral Conditions	Hot Conditions
AMS	41.0%	0.0%	59.0%
ATL	8.5%	8.5%	83.0%
CAN	0.0%	0.0%	100.0%
CDG	24.7%	16.7%	58.6%
CLT	8.0%	17.0%	75.0%
DEN	41.0%	17.0%	42.0%
DFW	0.0%	8.0%	92.0%
EWR	41.0%	0.0%	59.0%
FRA	32.9%	8.5%	58.6%
HND	16.2%	17.0%	66.9%
IST	16.2%	17.0%	66.9%
JFK	41.0%	0.0%	59.0%
LAS	0.0%	0.0%	100.0%
LAX	0.0%	0.0%	100.0%
LHR	24.7%	16.7%	58.6%
MEX	0.0%	0.0%	100.0%
MIA	0.0%	0.0%	100.0%
ORD	41.4%	8.2%	50.4%
PEK	41.1%	0.0%	58.6%
PHX	0.0%	0.0%	100.0%
PVG	24.7%	8.8%	66.9%
SEA	24.7%	16.7%	59.0%
SFO	0.0%	0.0%	100.0%
YYZ	49.6%	0.0%	50.4%

B2.3. Results

Figures B5 through B7 show the breakdown of life-cycle GHG emissions per gate operation and by scenario. Operating emissions account for the largest share of GHG emissions.

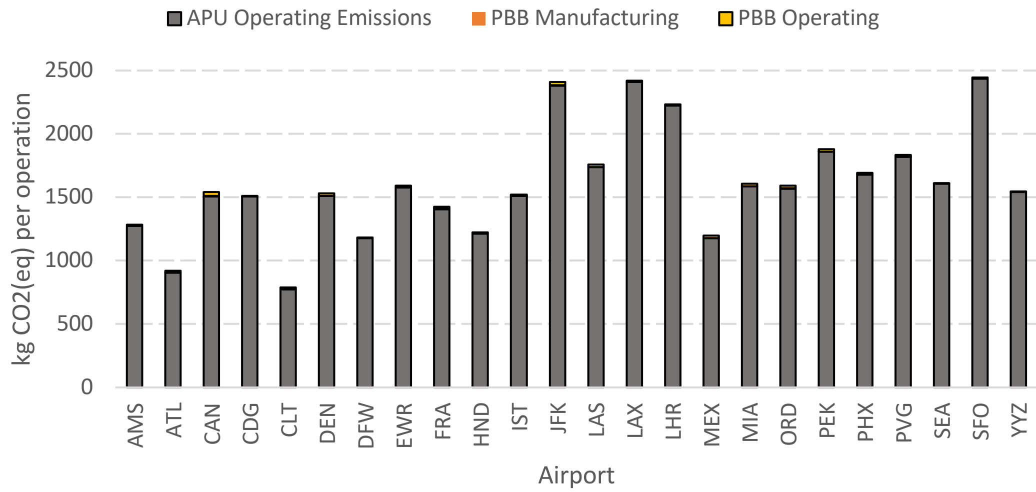

Figure B5. Breakdown of life-cycle emissions per gate operation for Scenario 1.

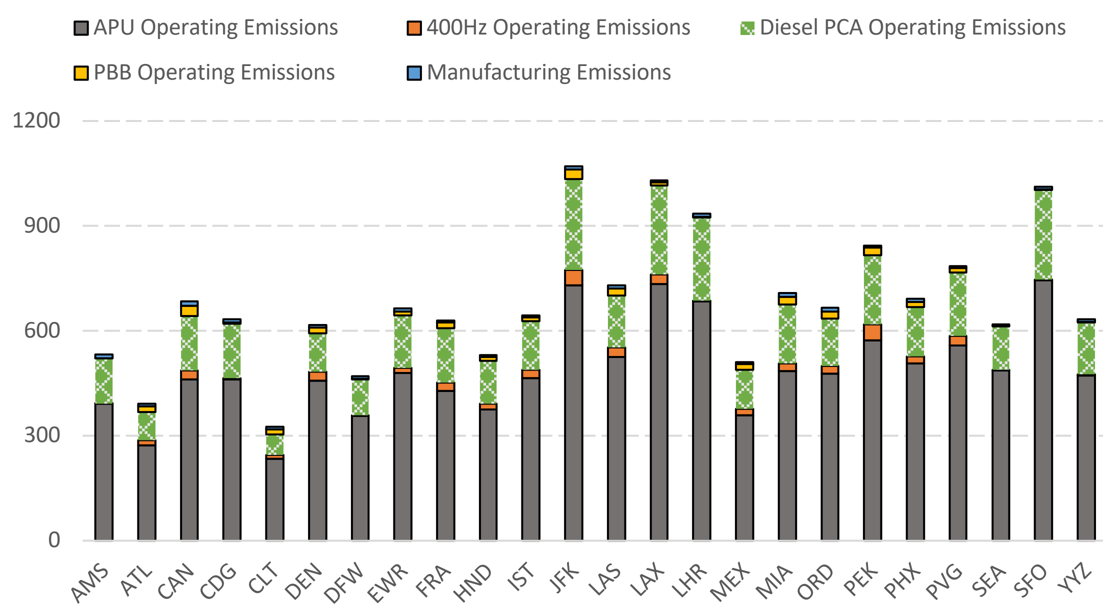

Figure B6. Breakdown of life-cycle emissions per gate operation for Scenario 2b.

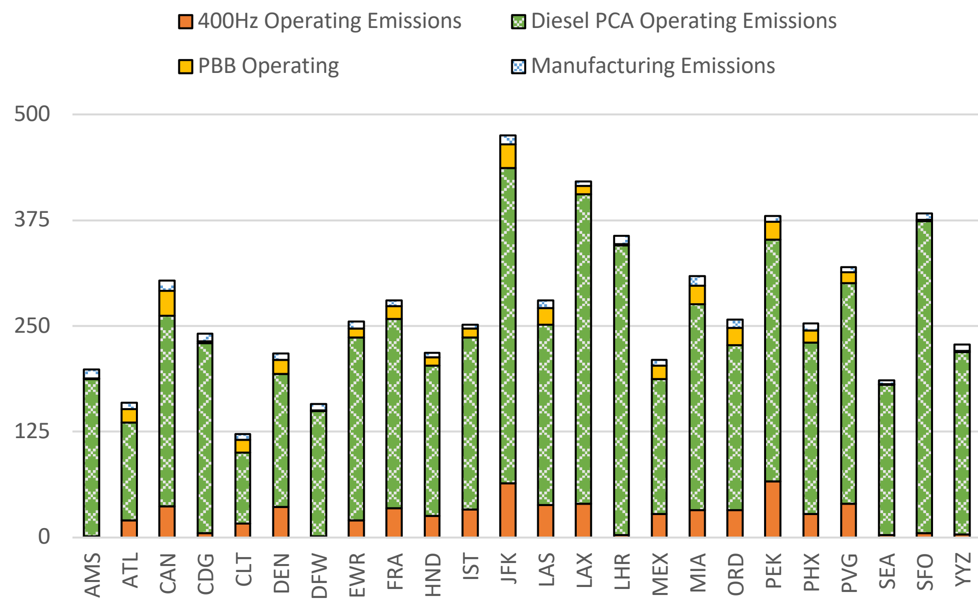

Figure B7. Breakdown of life-cycle emissions per gate operation for Scenario 3b.

B3. Economic Analysis

B3.1. Payback Period Methodology

The payback period is a metric is used to characterize the profitably of an investment project. For this analysis, the payback period is investigated for switching from exclusive APU usage in the worst-case Scenario 1 to each of the four alternative operational scenarios. Equation S8 is used to calculate payback period.

$$n_{pb} = \frac{log\left[1 - \left[\left(\frac{\Delta P}{\Delta U}\right) \times i\right]\right]^{-1}}{\log(1+i)}$$ [Eq. B8]

Where n_{pb} is the payback period in number of years;
ΔP is the cost of the initial capital investment;
ΔU is the annual savings that occur as a result of making the investment;
i is the discount rate, assumed to be 6%

The capital investment, ΔP, is always equal to purchase and installation costs for the 400Hz and PCA units on each gate at each case study airport. Capital costs for gate electrification depend upon the size of aircraft (i.e., the wingspan class) that a gate is equipped to handle. Therefore, it is critical to know the total number of gate types at each airport. Gate configurations for each of the case study airports are indicated in Section B3.3. in Appendix B.

Annual savings are calculated by determining how much money is saved from shifting away from 100 percent utilization of jet fuel (i.e., Scenario 1) and from current practice (Scenarios 2a and 2b). Annual savings depend upon the utilization rates of each equipment type outlined in the hypothetical operational scenarios. We provide sample equations for estimating the annual savings at a case study airport based upon each operational scenario.

The discount rate is a measure of how important future economic amounts are to the investor (e.g., the airport) at present day. We assume a 6% discount rate, which is typical for payback period calculations.

B3.1.1. Scenario 2a Annual Savings

Equation B9 is used to calculate the annual savings an airport incurs after implementing Scenario 2a. Equation variables are explained in Table B20.

$$\Delta U = \left(A_{JF,1} \times OC_{JF}\right) - \left[\left(A_{Elec,2a} \times OC_{Elec}\right) + \left(A_{JF,2a} \times OC_{JF}\right)\right] - MC_{400Hz,ePCA} - MC_{APU}$$ [Eq. B9]

Table B20. Scenario 2a annual savings variables and definitions.

Variable	Definition	Units
$A_{JF,1}$	Annual amount of jet fuel consumed in Scenario 1	liters
$A_{Elec,2a}$	Annual amount of electricity consumed in Scenario 2a	kWh
$A_{JF,2a}$	Annual amount of jet fuel consumed in Scenario 2a	liters
OC_{JF}	Airport-specific operating unit cost for jet fuel	USD liters^{-1}
OC_{Elec}	Airport-specific operating unit cost for electricity	USD kWh^{-1}
$MC_{400Hz,ePCA}$	Airport-specific annual maintenance costs for 400Hz and electric PCA	USD
MC_{APU}	Airport-specific annual maintenance costs for APU	USD

B3.1.2. Scenario 2b Annual Savings

Equation B10 is used to calculate the annual savings an airport incurs after implementing Scenario 2b. Equation variables are explained in Table B21.

$$\Delta U = \left(A_{JF,1} \times OC_{JF}\right) - \left[\left(A_{Elec,2b} \times OC_{Elec}\right) + \left(A_{JF,2b} \times OC_{JF}\right) + \left(A_{DF,2b} \times OC_{DF}\right)\right] - MC_{400Hz,dPCA} - MC_{APU} \quad \text{[Eq. B10]}$$

Table B21. Scenario 2b annual savings variables and definitions.

Variable	Definition	Units
$A_{JF,1}$	Annual amount of jet fuel consumed in Scenario 1	liters
$A_{Elec,2b}$	Annual amount of electricity consumed in Scenario 2b	kWh
$A_{JF,2b}$	Annual amount of jet fuel consumed in Scenario 2b	liters
$A_{DF,2b}$	Annual amount of diesel fuel consumed in Scenario 2b	liters
OC_{JF}	Airport-specific operating unit cost for jet fuel	USD liters^{-1}
OC_{Elec}	Airport-specific operating unit cost for electricity	USD kWh^{-1}
OC_{DF}	Airport-specific operating unit cost for diesel fuel	USD liters^{-1}
$MC_{400Hz,dPCA}$	Airport-specific annual maintenance costs for 400Hz and diesel PCA	USD
MC_{APU}	Airport-specific annual maintenance costs for APU	USD

B3.1.3. Scenario 3a Annual Savings

Equation B11 is used to calculate the annual savings an airport incurs after implementing Scenario 3a. Equation variables are explained in Table B22.

$$\Delta U = \left(A_{JF,1} \times OC_{JF}\right) - \left[\left(A_{Elec,3a} \times OC_{Elec}\right)\right] - MC_{400Hz,ePCA} \quad \text{[Eq. B11]}$$

Table B22. Scenario 3a annual savings variables and definitions.

Variable	Definition	Units
$A_{JF,1}$	Annual amount of jet fuel consumed in Scenario 1	liters
$A_{Elec,3a}$	Annual amount of electricity consumed in Scenario 3a	kWh
OC_{JF}	Airport-specific operating unit cost for jet fuel	USD $liters^{-1}$
OC_{Elec}	Airport-specific operating unit cost for electricity	USD kWh^{-1}
$MC_{400Hz,ePCA}$	Airport-specific annual maintenance costs for 400Hz and electric PCA	USD

B3.1.4. Scenario 3b Annual Savings

Equation B12 is used to calculate the annual savings an airport incurs after implementing Scenario 3b. Equation variables are explained in Table B23.

$$\Delta U = \left(A_{JF,1} \times OC_{JF}\right) - \left[\left(A_{Elec,3b} \times OC_{Elec}\right) + \left(A_{DF,3b} \times OC_{DF}\right)\right] - MC_{400Hz,dPCA} \quad \text{[Eq. B12]}$$

Table B23. Scenario 3b annual savings variables and definitions.

Variable	Definition	Units
$A_{JF,1}$	Annual amount of jet fuel consumed in Scenario 1	liters
$A_{Elec,3b}$	Annual amount of electricity consumed in Scenario 2b	kWh
$A_{DF,3b}$	Annual amount of diesel fuel consumed in Scenario 2b	liters
OC_{Elec}	Airport-specific operating unit cost for electricity	USD kWh^{-1}
OC_{DF}	Airport-specific operating unit cost for diesel fuel	USD $liters^{-1}$
$MC_{400Hz,dPCA}$	Airport-specific annual maintenance costs for 400Hz and diesel PCA	USD

B3.2. Levelized Annual Costs Methodology

We calculate the levelized annual costs among Scenarios 2a, 2b, 3a, 3b to determine which scenario is the most economical (i.e., the cheapest strategy) for each airport to implement. The generalized formula for calculating levelized annual costs is provided in Equation B13:

$$AC_{Total} = AC_{+AC_{Main}+\left[P\times\left(\frac{i}{1-(1+i)^{-n}}\right)\right]} \quad \text{[Eq. B13]}$$

Where AC_{Total} is total levelized annual cost for a scenario;
AC_{Oper} is the annual operating cost of the scenario;
AC_{Main} is the annual maintenance cost associated with the scenario;
P is the capital investment cost, or purchase price, associated with installing 400Hz and PCA units at the case study airport;
i is the discount rate, assumed to be 6%
n is the total number of operating years, assumed to be 20 years

For a given case study airport, the annual operating costs depend upon how much electricity, jet fuel, and diesel fuel are consumed according to each operational scenario. Annual maintenance costs for the 400Hz and electric/diesel PCA units, which are airport-specific, are derived from literature sources (ACRP et al., 2012). The assumption for the total number of operating years is in keeping with manufacturing estimates for equipment.

S3.3. Data

Table B24 lists the fuel cost rates for electricity, jet fuel, and diesel fuel at each of the case study airports. Electricity prices are national averages for each airport's country (IEA, 2020a). Jet fuel prices are regional estimates for Asia, Europe, and North America (EIA, 2020; IATA, 2020). Diesel fuel prices are national averages for each airport's country (World Bank Group, 2020a). While the cost rates in Table B24 do not represent the exact costs that airlines at airports would pay to use these fuels, we believe that the price data offers adequate granularity to come to conclusions about which operational scenarios are relatively better for each airport's economic bottom line.

Table B24. Electricity, jet fuel, and diesel fuel cost rates by airport.

Airport Code	Electricity (USD/kWh)	Jet Fuel (USD/L)	Diesel Fuel (USD/L)
AMS	0.211	0.4	1.608
ATL	0.129	0.53	0.78
CAN	0.081	0.38	0.972
CDG	0.202	0.4	1.44
CLT	0.129	0.53	0.78
DEN	0.129	0.53	0.78
DFW	0.129	0.53	0.78
EWR	0.129	0.53	0.78
FRA	0.353	0.4	1.44
HND	0.239	0.38	1.056
IST	0.104	0.4	1.476
JFK	0.129	0.53	0.78
LAS	0.129	0.53	0.78
LAX	0.129	0.53	0.78
LHR	0.229	0.4	1.788
MEX	0.063	0.53	0.864
MIA	0.129	0.53	0.78
ORD	0.129	0.53	0.78
PEK	0.081	0.38	0.972
PHX	0.129	0.53	0.78
PVG	0.081	0.38	0.972
SEA	0.129	0.53	0.78
SFO	0.129	0.53	0.78
YYZ	0.113	0.53	0.876

Table B25 indicates the capital and maintenance costs for each equipment type. The costs of purchasing and installing a 400Hz unit and PCA unit increase by wingspan class. Capital and maintenance costs for the 400Hz and PCA units are adapted from the literature(ACRP et al., 2012). We assume an annual maintenance cost for the APU. The assumed APU maintenance cost is comparable with an airport's annual 400Hz and PCA maintenance.

Table B25. Capital costs and annual maintenance costs (in 2019 USD) by wingspan class. Adapted from (ACRP et al., 2012)

Wingspan Class	400Hz and PCA Capital ($/gate)	400Hz and PCA Annual Maintenance ($/gate)	APU Annual Maintenance ($/airport)
C	$ 230,667.00	$ 6705.00	$ 1,000,000.00
D	$ 387,700.00	$ 6705.00	$ 1,000,000.00
E/F	$ 888,500.00	$ 6705.00	$ 1,000,000.00

Table B26 lists the estimated total number of gates by gate type for each of the case study airports. As most airports do not publicly document this data, estimates are determined from a combination of airport-specific resources such as annual financial reports and terminal maps. Gate type allocations are proportional to each airport's aircraft fleet mix. Wingspan class C aircraft make up the largest share of each airport's aircraft fleet and so it is likely that greatest share of gate types will be for wingspan class C aircraft. A complete list of sources for gate number allocation is provided in the references.

Table B26. Gate counts by wingspan class for each airport.

Dep Airport Code	Number of C Gates	Number of D Gates	Number of E/F Gates
AMS	138	24	3
ATL	152	32	8
CAN	161	34	1
CDG	105	32	2
CLT	99	2	1
DEN	106	3	2
DFW	154	7	3
EWR	94	12	9
FRA	93	19	4
HND	42	27	14
IST	54	16	1
JFK	104	34	13
LAS	105	2	2
LAX	91	16	8
LHR	100	59	4
MEX	92	4	1
MIA	45	65	0
ORD	171	20	0
PEK	79	45	1
PHX	97	2	1
PVG	73	24	1
SEA	60	3	2
SFO	52	43	6
YYZ	61	31	0

B3.4. Results

Table B27 shows the average annual savings for Scenarios 3a and 3b relative to Scenarios 2a and 2b, respectively. Tables B28(a) and B28(b) highlights the average annual savings and levelized annual costs, both in 10 million USD, for each operational scenario for the 24 case study airports. For all case study airports, Scenario 3a has the lowest levelized annual costs and the greatest annual savings among the four operational scenarios.

Table B27. Average annual savings (in 10 million USD) relative to Scenarios 2a/2b for Scenario 3a and 3b. Negative savings occur when switching from non-diesel PCA (Scenario 2a) to diesel-powered PCA (Scenario 3b) for select airport locations.

Airport Code	Scenario 3a Annual Savings Relative to Scenario 2a	Scenario 3a Annual Savings Relative to Scenario 2b	Scenario 3b Annual Savings Relative to Scenario 2a	Scenario 3b Annual Savings Relative to Scenario 2b
AMS	0.8	1.8	-0.5	0.4
ATL	1.6	1.9	1.0	1.4
CAN	1.1	2.0	-0.1	0.8
CDG	1.0	2.0	-0.5	0.5
CLT	0.7	0.9	0.5	0.6
DEN	1.5	1.8	1.1	1.4
DFW	1.7	2.1	1.1	1.5
EWR	1.4	1.8	0.9	1.3
FRA	0.7	1.3	-0.2	0.4
HND	0.7	1.0	0.2	0.5
IST	1.1	2.1	-0.5	0.6
JFK	2.1	2.8	1.2	1.8
LAS	1.4	1.7	0.9	1.3
LAX	3.1	4.0	1.7	2.7
LHR	1.4	3.5	-1.6	0.5
MEX	1.2	1.7	0.5	1.0
MIA	1.0	1.3	0.6	0.9
ORD	1.9	2.4	1.3	1.7
PEK	1.7	3.1	-0.2	1.2
PHX	1.3	1.6	0.9	1.2
PVG	1.4	2.3	0.0	0.9
SEA	1.5	1.9	1.1	1.4
SFO	2.0	2.6	1.2	1.8
YYZ	1.3	1.8	0.6	1.1

Table B28(a). Average annual savings (in 10 million USD) relative to Scenario 1 and levelized annual costs (in 10 million USD) for each operational scenario.

Airport Code	Scenario 2a Annual Savings	Annualized Costs for Scenario 2a	Scenario 2b Annual Savings	Annualized Costs for Scenario 2b
AMS	1.7	2.7	0.7	3.6
ATL	3.3	3.1	3.0	3.5
CAN	2.4	2.4	1.5	3.2
CDG	2.0	2.8	1.0	3.8
CLT	1.5	1.4	1.3	1.6
DEN	3.3	2.6	3.0	2.9
DFW	3.6	3.1	3.2	3.5
EWR	3.1	2.7	2.7	3.0
FRA	1.4	3.4	0.7	4.0
HND	1.3	2.3	1.0	2.6
IST	2.2	1.9	1.2	3.0
JFK	4.7	4.0	4.0	4.7
LAS	3.1	2.5	2.7	2.8
LAX	6.9	5.2	5.9	6.1
LHR	2.9	4.3	0.9	6.3
MEX	2.5	1.8	2.0	2.3
MIA	2.1	2.1	1.8	2.4
ORD	4.2	3.5	3.7	4.0
PEK	3.7	3.1	2.4	4.4
PHX	2.8	2.3	2.5	2.6
PVG	2.9	2.4	2.0	3.3
SEA	3.4	2.5	3.1	2.8
SFO	4.5	3.6	3.9	4.2
YYZ	2.8	2.3	2.3	2.8

Table B28(b). Average annual savings (in 10 million USD) relative to Scenario 1 and levelized annual costs (in 10 million USD) for each operational scenario.

Airport Code	Scenario 3a Annual Savings	Annualized Costs for Scenario 3a	Scenario 3b Annual Savings	Annualized Costs for Scenario 3b
AMS	2.5	1.8	1.1	3.2
ATL	4.9	1.5	4.3	2.1
CAN	3.5	1.2	2.3	2.5
CDG	3.0	1.8	1.5	3.3
CLT	2.2	0.7	2.0	0.9
DEN	4.9	1.1	4.4	1.5
DFW	5.2	1.4	4.6	2.0
EWR	4.5	1.2	4.0	1.8
FRA	2.0	2.7	1.1	3.6
HND	2.0	1.7	1.5	2.1
IST	3.3	0.9	1.7	2.4
JFK	6.8	1.8	5.8	2.8
LAS	4.5	1.1	4.0	1.6
LAX	9.9	2.1	8.6	3.5
LHR	4.3	2.9	1.4	5.8
MEX	3.7	0.6	3.0	1.4
MIA	3.2	1.1	2.7	1.5
ORD	6.1	1.6	5.5	2.3
PEK	5.5	1.3	3.6	3.2
PHX	4.1	1.0	3.7	1.4
PVG	4.3	1.0	2.9	2.4
SEA	4.9	1.0	4.5	1.4
SFO	6.5	1.6	5.6	2.5
YYZ	4.1	1.0	3.4	1.7

B4. Climate Damages

B4.1. Methodology

Climate economic damages are estimated by multiplying emissions from a gate operation by the Social Cost of Carbon (SCC). We adjust the 2015 SCC that uses a 3% discount rate (Interagency Working Group, 2016). We first linearly interpolate between the 2015 and 2020 SCC to determine the 2019 SCC. We then transform the 2019 SCC from 2007 dollars to constant, 2019 dollars. Equation B14 is used to determine the 2019 SCC.

$$SCC_{2019} = \left[SCC_{2015} + (Y_{2019} - Y_{2015})\left(\frac{SCC_{2020} - SCC_{2015}}{Y_{2020} - Y_{2015}}\right)\right](CF_{2007\rightarrow 2019}) \quad \text{[Eq. B14]}$$

Where SCC_{2019} is the calculated social cost of carbon for 2019, in USD per tonne;
SCC_{2015} is the social cost of carbon for 2015 when using a 3% discount, $36 USD/tonne;
SCC_{2020} is the social cost of carbon for 2020 when using a 3% discount rate, $42 USD/tonne;
Y_i is the year of interest;
$CF_{2007\rightarrow 2019}$ is the conversion factor for adjusting 2007 dollars to 2019 dollars

The adjusted SCC_{2019} used in the analysis is valued at 52 USD per metric tonne of GHG emissions. The SCC is highly sensitive to the discount rate used in its valuation (Pizer et al., 2014). However, since this analysis does not evaluate climate economic damages for future emissions (i.e., our period of study is the calendar year 2019), we believe that the SCC calculated using Equation B14 offers a suitable estimation.

B4.2. Results

Table B29 provides the cumulative annual climate damages by scenario for each case study airport.

Table B29. Cumulative annual climate damages (in 10 million USD) by scenario.

Airport Code	Scenario 1	Scenario 2a	Scenario 2b	Scenario 3a	Scenario 3b
AMS	1.4	0.44	0.58	0.019	0.22
ATL	1.7	0.64	0.70	0.19	0.29
CAN	1.7	0.67	0.74	0.22	0.33
CDG	1.6	0.52	0.67	0.033	0.26
CLT	0.74	0.28	0.31	0.074	0.12
DEN	1.6	0.59	0.64	0.15	0.22
DFW	1.7	0.54	0.69	0.020	0.23
EWR	1.5	0.53	0.63	0.10	0.24
FRA	1.6	0.60	0.70	0.17	0.31
HND	1.3	0.48	0.55	0.13	0.23
IST	1.5	0.55	0.63	0.14	0.24
JFK	2.3	0.9	1.0	0.31	0.45
LAS	1.5	0.55	0.61	0.15	0.23
LAX	3.3	1.2	1.4	0.26	0.57
LHR	2.4	0.77	1.02	0.025	0.39
MEX	1.2	0.45	0.49	0.13	0.20
MIA	1.1	0.42	0.48	0.12	0.21
ORD	2.0	0.76	0.85	0.20	0.33
PEK	2.5	1.1	1.1	0.43	0.51
PHX	1.4	0.49	0.56	0.11	0.20
PVG	2.0	0.74	0.84	0.20	0.34
SEA	1.6	0.49	0.61	0.016	0.18
SFO	2.1	0.68	0.89	0.028	0.34
YYZ	1.3	0.43	0.55	0.023	0.20

B5. Global Environmental Analysis

We extend the environmental analysis to estimate the annual life-cycle GHG emissions from fuel use (i.e., electricity, jet fuel, diesel fuel) for the top 2,354 commercial traffic airports in the world. These 2354 airports account for essentially 100% of all commercial traffic. Results from this extension analysis offer an estimate of the scale at which gate electrification can reduce GHG emissions.

B5.1. Methodology Overview

Using departure data (which are a proxy for number of turnaround operations) from the calendar year 2019 (Perry, 2020), we first group airports into three size categories. Small airports have between 1,000 and 10,000 annual turnaround operations, medium airports have between 10,001 and 100,000 annual turnaround operations, and large airports have more than 100,001 annual turnaround operations. Figure B8 shows the number of airports that fall into each size category. Airports in each size category are further grouped by their region (Table B30).

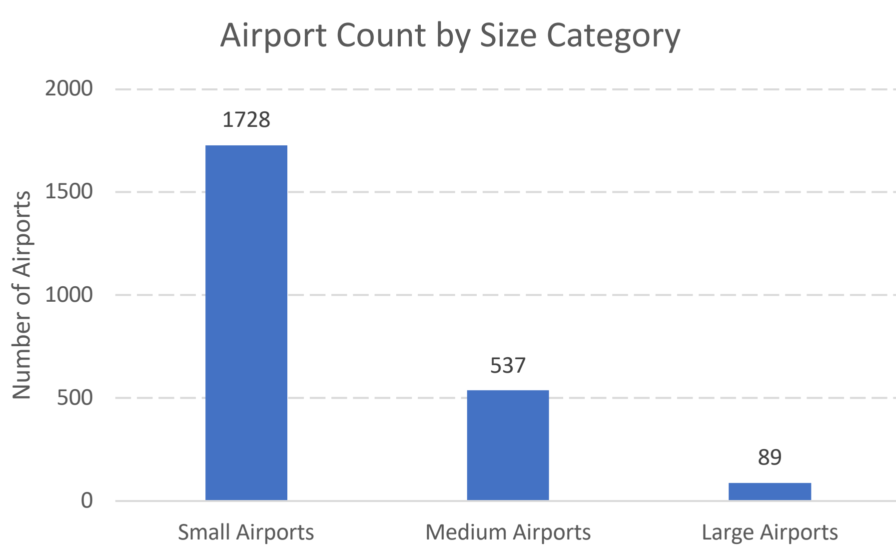

Figure B8. Number of airports included in each size category.

Table B30. Airport totals by region and size.

Region	Size	Total
Africa	Large	1
	Medium	30
	Small	159
Asia	Large	28
	Medium	158
	Small	440
Europe	Large	22
	Medium	127
	Small	260
Latin America	Large	3
	Medium	70
	Small	238
Middle East	Large	3
	Medium	18
	Small	44
North America	Large	29
	Medium	100
	Small	420
Russia	Large	1
	Medium	19
	Small	56
Southwest Pacific	Large	2
	Medium	15
	Small	111

We do not have the same level of granularity for turnaround durations or flight data (i.e., the number of flights by wingspan class) as we do for the original 24 case study airports. We calculate the average of the mean, minimum, and maximum turnaround durations for each of the case study airports and assume that these turnaround durations are applicable to all the “Large Airports” in the extension analysis. Scaling factors of 25 and 50 percent are applied to “Large Airports” turnaround durations to estimate turnaround durations for the “Medium Airports” and “Small Airports”, respectively. Scaling factors are necessary to apply. Smaller airports have different traffic patterns (e.g., not as many long-haul international flights) than the airports in the “Large Airport” category and as such, will tend to have shorter turnaround durations. We assume that each turnaround operation occurs with a Wingspan Class C aircraft. Table B31 provides the turnaround durations used in the extension analysis.

Table B31. Estimated mean, minimum, and maximum turnaround durations for large, medium, small airports.

Size	Mean Turnaround Duration [hr]	Minimum Turnaround Duration [hr]	Maximum Turnaround Duration [hr]
Large	2.7	0.6	6.0
Medium	2.0	0.4	4.5
Small	1.4	0.3	3.0

Similar to the methodologies explained in Sections B2.1.1. through B2.1.5, we calculate life-cycle GHG emissions per gate operation for each of the five operational scenarios. Cumulative emissions for each airport are found by multiplying the emissions impact per gate operation by the airport's total number of operations. Cumulative annual emissions are grouped by operational scenario, airport size, and airport region. We do not account for infrastructure emissions in the extension analysis due to the potential for great uncertainty (e.g., estimating manufacturing emissions requires knowing number of gates at each airport).

Electricity generation data (IEA, 2020b) for each region is listed in Table B32. The life-cycle emission factors for electricity are estimated according to the same methodology outlined in Section B2.2.3. The final life-cycle electricity emission factor for each region is provided in Table B33.

Table B32. Average annual electricity mix profiles by region.

Region	Coal	Natural Gas	Oil	Nuclear	Hydro	Biomass	Solar	Wind	Geothermal	Other
Africa	31%	40%	8%	1%	16%	0%	1%	2%	1%	0%
Asia	59%	12%	1%	5%	14%	2%	2%	4%	0%	0%
Europe	21%	20%	1%	22%	16%	4%	3%	10%	0%	2%
Latin America	5%	19%	8%	2%	55%	6%	1%	5%	0%	0%
North America	25%	33%	2%	18%	14%	1%	2%	6%	0%	0%
Middle East	0%	72%	25%	1%	2%	0%	0%	0%	0%	0%
Southwest Pacific	51%	19%	2%	0%	13%	1%	5%	6%	3%	0%
Russia	16%	47%	1%	18%	17%	0%	0%	0%	0%	0%

Table B33. Life-cycle electricity emission factors by region.

Region	Final EF (kg CO2eq/kWh)
Africa	0.695
Asia	0.739
Europe	0.402
Latin America	0.294
North America	0.523
Middle East	0.745
Southwest Pacific	0.699
Russia	0.520

As explained in Section B2.1, emissions from usage of the APU and PCA unit depend upon the ambient air temperatures at each airport. We use the average monthly air temperature data from 1991 to 2016 (World Bank Group, 2020b) to estimate the share of cold, neutral, and hot conditions for each region. Average monthly temperature data by region is shown in Table B34, while the share of cold, neutral, and hot conditions is indicated in Table B35.

Table B34: Annual monthly temperatures (C°) by region for the period 1991-2016.

Region	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec
Africa	21.36	22.76	24.42	25.63	26.22	26.07	25.69	25.83	26.09	25.56	23.57	21.7
Asia	-13.82	-11.45	-4.7	3.67	10.72	16.45	18.89	16.97	11.73	3.9	-5.69	-11.85
Europe	-1.96	-1.38	2.13	6.7	11.57	15.42	17.97	17.34	13.06	7.88	2.98	-0.75
Latin America	23.01	22.96	22.75	22.08	20.95	20.13	19.85	20.76	21.73	22.53	22.61	22.83
Middle East	11.8	13.74	17.27	22.18	26.74	30.03	31.07	30.74	27.96	23.42	17.53	13.29
North America	-17.35	-16.52	-13.42	-6.11	1.97	8.66	11.91	10.31	4.82	-2.54	-10.2	-15.4
Russia	-13.82	-11.45	-4.7	3.67	10.72	16.45	18.89	16.97	11.73	3.9	-5.69	-11.85
Southwest Pacific	27.74	27.06	25.2	22.08	18.24	15.4	14.67	16.27	19.62	22.72	25.11	26.64

Table B35. Average annual weather profile by region.

Region	Cold Conditions (%)	Neutral Conditions (%)	Hot Conditions (%)
Africa	0%	0%	100%
Asia	58%	0%	42%
Europe	50%	2%	42%
Latin America	0%	0%	100%
Middle East	0%	0%	100%
North America	75%	2%	6%
Russia	58%	0%	42%
Southwest Pacific	0%	0%	100%

B6. Sensitivity Analysis

We perform a parametric sensitivity analysis to investigate the roles that differing electricity supplies and ambient air temperatures play in changing GHG emissions per gate operation. We examine a hypothetical turnaround operation for a Wingspan Class C aircraft under Scenario 3a operating conditions using data from CAN airport.

To explore the effects of a changing electricity supply, we vary the carbon intensity of CAN airport's electricity supply in ten percent increments and use Equation B4 from Section B2.1.4. to calculate average GHG emissions per gate operation (see Table B36). All other parameters, including air temperature conditions are held constant.

Table B36. Average gate emissions with changing electricity supply.

Iteration	Average Turnaround [hr]	Electricity Emission Factor [kg CO_2(eq)/kWh)]	Cold	Neutral	Hot	Gate Emissions [kg CO_2(eq)/op]	400Hz [kg CO_2(eq)/op]	PCA [kg CO_2(eq)/op]
1	2	0.65	0%	0%	100%	85.9	22.4	63.5
2	2	0.71	0%	0%	100%	94.5	24.7	69.8
3	2	0.78	0%	0%	100%	103.9	27.1	76.8
4	2	0.86	0%	0%	100%	114.3	29.9	84.5
5	2	0.95	0%	0%	100%	125.8	32.8	92.9
6	2	1.04	0%	0%	100%	138.3	36.1	102.2
7	2	1.15	0%	0%	100%	152.2	39.7	112.4
8	2	1.26	0%	0%	100%	167.4	43.7	123.7
9	2	1.39	0%	0%	100%	184.1	48.1	136.0
10	2	1.53	0%	0%	100%	202.5	52.9	149.6
11	2	1.68	0%	0%	100%	222.8	58.2	164.6

The effects are ambient air conditions are investigated by changing the percentages of cold, neutral, and hot conditions and then by using Equation B4 to calculate average GHG emissions per gate operation (Table B37). All other parameters are held constant.

Table B37. Average gate emissions with changing air temperature conditions.

Iteration	Average Turnaround [hr]	Electricity Emission Factor [kg CO_2(eq)/kWh)]	Cold	Neutral	Hot	Gate Emissions [kg CO_2(eq)/op]	400Hz [kg CO_2(eq)/op]	PCA [kg CO_2(eq)/op]
1	2	0.65	100%	0%	0%	83.3	22.4	60.9
2	2	0.65	90%	0%	10%	83.6	22.4	61.1
3	2	0.65	80%	0%	20%	83.8	22.4	61.4
4	2	0.65	70%	0%	30%	84.1	22.4	61.7
5	2	0.65	60%	0%	40%	84.3	22.4	61.9
6	2	0.65	50%	0%	50%	84.6	22.4	62.2
7	2	0.65	40%	0%	60%	84.9	22.4	62.4
8	2	0.65	30%	0%	70%	85.1	22.4	62.7
9	2	0.65	20%	0%	80%	85.4	22.4	62.9
10	2	0.65	10%	0%	90%	85.6	22.4	63.2
11	2	0.65	0%	0%	100%	85.9	22.4	63.5

Figure B9 shows that an incremental change in the carbon intensity of the electricity mix yields a faster rate of change in overall GHG emissions relative to an incremental change in ambient air temperature conditions.

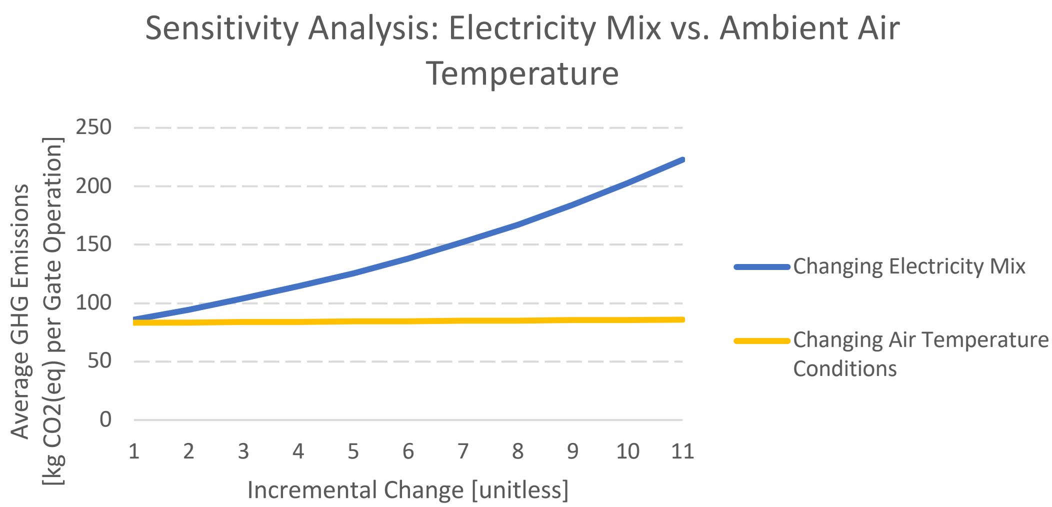

Figure B9. Sensitivity analysis on impact of electricity mix and ambient air temperature on GHG emissions per gate operation.

S7. Uncertainty Assessment

We qualify the uncertainty of the data used in our analysis using pedigree matrices, a common uncertainty assessment methodology used in LCA studies (Ciroth et al., 2016; Igos et al., 2019; Qin et al., 2020). We model the pedigree matrices after the framework established in ecoinvent. Data quality are scored across five indicators. A log-normal distribution is applied to each indicator's score, with the geometric standard deviation representing the spread of each log-normal distribution. When the geometric standard distribution is equal to 1.00, there is very low uncertainty (i.e., uncertainty can be assumed to be essentially zero). The numbers in Tables B38 through B48 are the geometric standard deviation for each data quality indicator. Higher quality data will have more scores of 1.00.

Table B38. Pedigree matrix for electricity data used for 24 case study airports.

	Indicator	Score				
		1 (Low uncertainty)	2 (Moderately low uncertainty)	3 (Moderate uncertainty)	4 (Moderately high uncertainty)	**5** (High uncertainty)
1	Reliability	Verified data based on measurements 1.00	Verified data partly based on assumptions ***or*** non-verified data based on measurements 1.05	Non-verified data partly based on qualified estimates 1.10	Qualified estimate (e.g., by industrial expert) 1.20	Non-qualified estimate 1.50
2	Completeness	Representative data from all sites relevant for the market considered, over an adequate period to even out normal fluctuations 1.00	Representative data from >50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations 1.02	Representative data from only some sites (<<50%) relevant for the market considered ***or*** >50% of sites but from shorter periods 1.05	Representative data from only one site relevant for the market considered ***or*** some sites but from shorter periods 1.10	Representativeness unknown or data from a small number of sites ***and*** from shorter periods 1.20
3	Temporal correlation	Less than 3 years of difference to the time period of the dataset 1.00	Less than 6 years of difference to the time period of the dataset 1.03	Less than 10 years of difference to the time period of the dataset 1.10	Less than 15 years of difference to the time period of the dataset 1.20	Age of data unknown or more than 15 years of difference to the time period of the dataset 1.50
4	Geographical correlation	Data from area under study 1.00	Average data from larger area in which the area under study is included 1.01	Data from area with similar production conditions 1.02	Data from area with slightly similar production conditions 1.05	Data from unknown ***or*** distinctly different area (North America instead of Middle East, OECD-Europe instead of Russia) 1.10
5	Further technological correlation	Data from enterprises, processes, and materials under study 1.00	Data from processes and materials under study (i.e., identical technology) but from different enterprises 1.10	Data from processes and materials under study but from different technology 1.20	Data on related processes or materials 1.50	Data on related processes on laboratory scale ***or*** from different technology 2.00

Table B39. Pedigree matrix for electricity data used for global analysis of 2,354 airports.

	Indicator	Score				
		1 (Low uncertainty)	2 (Moderately low uncertainty)	3 (Moderate uncertainty)	4 (Moderately high uncertainty)	**5** (High uncertainty)
1	Reliability	Verified data based on measurements 1.00	Verified data partly based on assumptions ***or*** non-verified data based on measurements 1.05	Non-verified data partly based on qualified estimates 1.10	Qualified estimate (e.g., by industrial expert) 1.20	Non-qualified estimate 1.50
2	Completeness	Representative data from all sites relevant for the market considered, over an adequate period to even out normal fluctuations 1.00	Representative data from >50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations 1.02	Representative data from only some sites (<<50%) relevant for the market considered ***or*** >50% of sites but from shorter periods 1.05	Representative data from only one site relevant for the market considered ***or*** some sites but from shorter periods 1.10	Representativeness unknown or data from a small number of sites ***and*** from shorter periods 1.20
3	Temporal correlation	Less than 3 years of difference to the time period of the dataset 1.00	Less than 6 years of difference to the time period of the dataset 1.03	Less than 10 years of difference to the time period of the dataset 1.10	Less than 15 years of difference to the time period of the dataset 1.20	Age of data unknown or more than 15 years of difference to the time period of the dataset 1.50
4	Geographical correlation	Data from area under study 1.00	Average data from larger area in which the area under study is included 1.01	Data from area with similar production conditions 1.02	Data from area with slightly similar production conditions 1.05	Data from unknown ***or*** distinctly different area (North America instead of Middle East, OECD-Europe instead of Russia) 1.10
5	Further technological correlation	Data from enterprises, processes, and materials under study 1.00	Data from processes and materials under study (i.e., identical technology) but from different enterprises 1.10	Data from processes and materials under study but from different technology 1.20	Data on related processes or materials 1.50	Data on related processes on laboratory scale ***or*** from different technology 2.00

Table B40. Pedigree matrix for jet and diesel fuel emission factors.

	Indicator	Score				
		1 (Low uncertainty)	2 (Moderately low uncertainty)	3 (Moderate uncertainty)	4 (Moderately high uncertainty)	**5** (High uncertainty)
1	Reliability	Verified data based on measurements 1.00	Verified data partly based on assumptions ***or*** non-verified data based on measurements 1.05	Non-verified data partly based on qualified estimates 1.10	Qualified estimate (e.g., by industrial expert) 1.20	Non-qualified estimate 1.50
2	Completeness	Representative data from all sites relevant for the market considered, over an adequate period to even out normal fluctuations 1.00	Representative data from >50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations 1.02	Representative data from only some sites (<<50%) relevant for the market considered ***or*** >50% of sites but from shorter periods 1.05	Representative data from only one site relevant for the market considered ***or*** some sites but from shorter periods 1.10	Representativeness unknown or data from a small number of sites ***and*** from shorter periods 1.20
3	Temporal correlation	Less than 3 years of difference to the time period of the dataset 1.00	Less than 6 years of difference to the time period of the dataset 1.03	Less than 10 years of difference to the time period of the dataset 1.10	Less than 15 years of difference to the time period of the dataset 1.20	Age of data unknown or more than 15 years of difference to the time period of the dataset 1.50
4	Geographical correlation	Data from area under study 1.00	Average data from larger area in which the area under study is included 1.01	Data from area with similar production conditions 1.02	Data from area with slightly similar production conditions 1.05	Data from unknown ***or*** distinctly different area (North America instead of Middle East, OECD-Europe instead of Russia) 1.10
5	Further technological correlation	Data from enterprises, processes, and materials under study 1.00	Data from processes and materials under study (i.e., identical technology) but from different enterprises 1.10	Data from processes and materials under study but from different technology 1.20	Data on related processes or materials 1.50	Data on related processes on laboratory scale ***or*** from different technology 2.00

Table B41. Flight data for 24 case study airports and for 2,354 airports in global analysis.

	Indicator	Score				
		1 (Low uncertainty)	2 (Moderately low uncertainty)	3 (Moderate uncertainty)	4 (Moderately high uncertainty)	**5** (High uncertainty)
1	Reliability	Verified data based on measurements 1.00	Verified data partly based on assumptions ***or*** non-verified data based on measurements 1.05	Non-verified data partly based on qualified estimates 1.10	Qualified estimate (e.g., by industrial expert) 1.20	Non-qualified estimate 1.50
2	Completeness	Representative data from all sites relevant for the market considered, over an adequate period to even out normal fluctuations 1.00	Representative data from >50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations 1.02	Representative data from only some sites (<<50%) relevant for the market considered ***or*** >50% of sites but from shorter periods 1.05	Representative data from only one site relevant for the market considered ***or*** some sites but from shorter periods 1.10	Representativeness unknown or data from a small number of sites ***and*** from shorter periods 1.20
3	Temporal correlation	Less than 3 years of difference to the time period of the dataset 1.00	Less than 6 years of difference to the time period of the dataset 1.03	Less than 10 years of difference to the time period of the dataset 1.10	Less than 15 years of difference to the time period of the dataset 1.20	Age of data unknown or more than 15 years of difference to the time period of the dataset 1.50
4	Geographical correlation	Data from area under study 1.00	Average data from larger area in which the area under study is included 1.01	Data from area with similar production conditions 1.02	Data from area with slightly similar production conditions 1.05	Data from unknown ***or*** distinctly different area (North America instead of Middle East, OECD-Europe instead of Russia) 1.10
5	Further technological correlation	Data from enterprises, processes, and materials under study 1.00	Data from processes and materials under study (i.e., identical technology) but from different enterprises 1.10	Data from processes and materials under study but from different technology 1.20	Data on related processes or materials 1.50	Data on related processes on laboratory scale ***or*** from different technology 2.00

Table B42. Air temperature data for 24 case study airports.

	Indicator	Score				
		1 (Low uncertainty)	2 (Moderately low uncertainty)	3 (Moderate uncertainty)	4 (Moderately high uncertainty)	**5** (High uncertainty)
1	Reliability	Verified data based on measurements 1.00	Verified data partly based on assumptions ***or*** non-verified data based on measurements 1.05	Non-verified data partly based on qualified estimates 1.10	Qualified estimate (e.g., by industrial expert) 1.20	Non-qualified estimate 1.50
2	Completeness	Representative data from all sites relevant for the market considered, over an adequate period to even out normal fluctuations 1.00	Representative data from >50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations 1.02	Representative data from only some sites (<<50%) relevant for the market considered ***or*** >50% of sites but from shorter periods 1.05	Representative data from only one site relevant for the market considered ***or*** some sites but from shorter periods 1.10	Representativeness unknown or data from a small number of sites ***and*** from shorter periods 1.20
3	Temporal correlation	Less than 3 years of difference to the time period of the dataset 1.00	Less than 6 years of difference to the time period of the dataset 1.03	Less than 10 years of difference to the time period of the dataset 1.10	Less than 15 years of difference to the time period of the dataset 1.20	Age of data unknown or more than 15 years of difference to the time period of the dataset 1.50
4	Geographical correlation	Data from area under study 1.00	Average data from larger area in which the area under study is included 1.01	Data from area with similar production conditions 1.02	Data from area with slightly similar production conditions 1.05	Data from unknown ***or*** distinctly different area (North America instead of Middle East, OECD-Europe instead of Russia) 1.10
5	Further technological correlation	Data from enterprises, processes, and materials under study 1.00	Data from processes and materials under study (i.e., identical technology) but from different enterprises 1.10	Data from processes and materials under study but from different technology 1.20	Data on related processes or materials 1.50	Data on related processes on laboratory scale ***or*** from different technology 2.00

Table B43. Air temperature data for regions used in global analysis.

	Indicator	Score				
		1 (Low uncertainty)	2 (Moderately low uncertainty)	3 (Moderate uncertainty)	4 (Moderately high uncertainty)	**5** (High uncertainty)
1	Reliability	Verified data based on measurements 1.00	Verified data partly based on assumptions ***or*** non-verified data based on measurements 1.05	Non-verified data partly based on qualified estimates 1.10	Qualified estimate (e.g., by industrial expert) 1.20	Non-qualified estimate 1.50
2	Completeness	Representative data from all sites relevant for the market considered, over an adequate period to even out normal fluctuations 1.00	Representative data from >50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations 1.02	Representative data from only some sites (<<50%) relevant for the market considered ***or*** >50% of sites but from shorter periods 1.05	Representative data from only one site relevant for the market considered ***or*** some sites but from shorter periods 1.10	Representativeness unknown or data from a small number of sites ***and*** from shorter periods 1.20
3	Temporal correlation	Less than 3 years of difference to the time period of the dataset 1.00	Less than 6 years of difference to the time period of the dataset 1.03	Less than 10 years of difference to the time period of the dataset 1.10	Less than 15 years of difference to the time period of the dataset 1.20	Age of data unknown or more than 15 years of difference to the time period of the dataset 1.50
4	Geographical correlation	Data from area under study 1.00	Average data from larger area in which the area under study is included 1.01	Data from area with similar production conditions 1.02	Data from area with slightly similar production conditions 1.05	Data from unknown ***or*** distinctly different area (North America instead of Middle East, OECD-Europe instead of Russia) 1.10
5	Further technological correlation	Data from enterprises, processes, and materials under study 1.00	Data from processes and materials under study (i.e., identical technology) but from different enterprises 1.10	Data from processes and materials under study but from different technology 1.20	Data on related processes or materials 1.50	Data on related processes on laboratory scale ***or*** from different technology 2.00

Table B44. Pedigree matrix for power consumption data for 400Hz, PCA, APU, PBB Equipment

	Indicator	Score				
		1 (Low uncertainty)	2 (Moderately low uncertainty)	3 (Moderate uncertainty)	4 (Moderately high uncertainty)	**5** (High uncertainty)
1	Reliability	Verified data based on measurements 1.00	Verified data partly based on assumptions ***or*** non-verified data based on measurements 1.05	Non-verified data partly based on qualified estimates 1.10	Qualified estimate (e.g., by industrial expert) 1.20	Non-qualified estimate 1.50
2	Completeness	Representative data from all sites relevant for the market considered, over an adequate period to even out normal fluctuations 1.00	Representative data from >50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations 1.02	Representative data from only some sites (<<50%) relevant for the market considered ***or*** >50% of sites but from shorter periods 1.05	Representative data from only one site relevant for the market considered ***or*** some sites but from shorter periods 1.10	Representativeness unknown or data from a small number of sites ***and*** from shorter periods 1.20
3	Temporal correlation	Less than 3 years of difference to the time period of the dataset 1.00	Less than 6 years of difference to the time period of the dataset 1.03	Less than 10 years of difference to the time period of the dataset 1.10	Less than 15 years of difference to the time period of the dataset 1.20	Age of data unknown or more than 15 years of difference to the time period of the dataset 1.50
4	Geographical correlation	Data from area under study 1.00	Average data from larger area in which the area under study is included 1.01	Data from area with similar production conditions 1.02	Data from area with slightly similar production conditions 1.05	Data from unknown ***or*** distinctly different area (North America instead of Middle East, OECD-Europe instead of Russia) 1.10
5	Further technological correlation	Data from enterprises, processes, and materials under study 1.00	Data from processes and materials under study (i.e., identical technology) but from different enterprises 1.10	Data from processes and materials under study but from different technology 1.20	Data on related processes or materials 1.50	Data on related processes on laboratory scale ***or*** from different technology 2.00

Table B45. Pedigree matrix for Manufacturing Passenger Boarding Bridge Equipment.

	Indicator	Score				
		1 (Low uncertainty)	2 (Moderately low uncertainty)	3 (Moderate uncertainty)	4 (Moderately high uncertainty)	**5** (High uncertainty)
1	Reliability	Verified data based on measurements 1.00	Verified data partly based on assumptions ***or*** non-verified data based on measurements 1.05	Non-verified data partly based on qualified estimates 1.10	Qualified estimate (e.g., by industrial expert) 1.20	Non-qualified estimate 1.50
2	Completeness	Representative data from all sites relevant for the market considered, over an adequate period to even out normal fluctuations 1.00	Representative data from >50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations 1.02	Representative data from only some sites (<<50%) relevant for the market considered ***or*** >50% of sites but from shorter periods 1.05	Representative data from only one site relevant for the market considered ***or*** some sites but from shorter periods 1.10	Representativeness unknown or data from a small number of sites ***and*** from shorter periods 1.20
3	Temporal correlation	Less than 3 years of difference to the time period of the dataset 1.00	Less than 6 years of difference to the time period of the dataset 1.03	Less than 10 years of difference to the time period of the dataset 1.10	Less than 15 years of difference to the time period of the dataset 1.20	Age of data unknown or more than 15 years of difference to the time period of the dataset 1.50
4	Geographical correlation	Data from area under study 1.00	Average data from larger area in which the area under study is included 1.01	Data from area with similar production conditions 1.02	Data from area with slightly similar production conditions 1.05	Data from unknown ***or*** distinctly different area (North America instead of Middle East, OECD-Europe instead of Russia) 1.10
5	Further technological correlation	Data from enterprises, processes, and materials under study 1.00	Data from processes and materials under study (i.e., identical technology) but from different enterprises 1.10	Data from processes and materials under study but from different technology 1.20	Data on related processes or materials 1.50	Data on related processes on laboratory scale ***or*** from different technology 2.00

Table B46. Pedigree matrix for Manufacturing 400Hz and PCA equipment.

	Indicator	Score				
		1 (Low uncertainty)	2 (Moderately low uncertainty)	3 (Moderate uncertainty)	4 (Moderately high uncertainty)	**5** (High uncertainty)
1	Reliability	Verified data based on measurements 1.00	Verified data partly based on assumptions ***or*** non-verified data based on measurements 1.05	Non-verified data partly based on qualified estimates 1.10	Qualified estimate (e.g., by industrial expert) 1.20	Non-qualified estimate 1.50
2	Completeness	Representative data from all sites relevant for the market considered, over an adequate period to even out normal fluctuations 1.00	Representative data from >50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations 1.02	Representative data from only some sites (<<50%) relevant for the market considered ***or*** >50% of sites but from shorter periods 1.05	Representative data from only one site relevant for the market considered ***or*** some sites but from shorter periods 1.10	Representativeness unknown or data from a small number of sites ***and*** from shorter periods 1.20
3	Temporal correlation	Less than 3 years of difference to the time period of the dataset 1.00	Less than 6 years of difference to the time period of the dataset 1.03	Less than 10 years of difference to the time period of the dataset 1.10	Less than 15 years of difference to the time period of the dataset 1.20	Age of data unknown or more than 15 years of difference to the time period of the dataset 1.50
4	Geographical correlation	Data from area under study 1.00	Average data from larger area in which the area under study is included 1.01	Data from area with similar production conditions 1.02	Data from area with slightly similar production conditions 1.05	Data from unknown ***or*** distinctly different area (North America instead of Middle East, OECD-Europe instead of Russia) 1.10
5	Further technological correlation	Data from enterprises, processes, and materials under study 1.00	Data from processes and materials under study (i.e., identical technology) but from different enterprises 1.10	Data from processes and materials under study but from different technology 1.20	Data on related processes or materials 1.50	Data on related processes on laboratory scale ***or*** from different technology 2.00

Table B47. Pedigree matrix for electricity and fuel cost data.

	Indicator	Score				
		1 (Low uncertainty)	2 (Moderately low uncertainty)	3 (Moderate uncertainty)	4 (Moderately high uncertainty)	**5** (High uncertainty)
1	Reliability	Verified data based on measurements 1.00	Verified data partly based on assumptions ***or*** non-verified data based on measurements 1.05	Non-verified data partly based on qualified estimates 1.10	Qualified estimate (e.g., by industrial expert) 1.20	Non-qualified estimate 1.50
2	Completeness	Representative data from all sites relevant for the market considered, over an adequate period to even out normal fluctuations 1.00	Representative data from >50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations 1.02	Representative data from only some sites (<<50%) relevant for the market considered ***or*** >50% of sites but from shorter periods 1.05	Representative data from only one site relevant for the market considered ***or*** some sites but from shorter periods 1.10	Representativeness unknown or data from a small number of sites ***and*** from shorter periods 1.20
3	Temporal correlation	Less than 3 years of difference to the time period of the dataset 1.00	Less than 6 years of difference to the time period of the dataset 1.03	Less than 10 years of difference to the time period of the dataset 1.10	Less than 15 years of difference to the time period of the dataset 1.20	Age of data unknown or more than 15 years of difference to the time period of the dataset 1.50
4	Geographical correlation	Data from area under study 1.00	Average data from larger area in which the area under study is included 1.01	Data from area with similar production conditions 1.02	Data from area with slightly similar production conditions 1.05	Data from unknown ***or*** distinctly different area (North America instead of Middle East, OECD-Europe instead of Russia) 1.10
5	Further technological correlation	Data from enterprises, processes, and materials under study 1.00	Data from processes and materials under study (i.e., identical technology) but from different enterprises 1.10	Data from processes and materials under study but from different technology 1.20	Data on related processes or materials 1.50	Data on related processes on laboratory scale ***or*** from different technology 2.00

Table B48. Pedigree matrix for capital and maintenance costs for equipment.

	Indicator	Score				
		1 (Low uncertainty)	2 (Moderately low uncertainty)	3 (Moderate uncertainty)	4 (Moderately high uncertainty)	**5** (High uncertainty)
1	Reliability	Verified data based on measurements 1.00	Verified data partly based on assumptions ***or*** non-verified data based on measurements 1.05	Non-verified data partly based on qualified estimates 1.10	Qualified estimate (e.g., by industrial expert) 1.20	Non-qualified estimate 1.50
2	Completeness	Representative data from all sites relevant for the market considered, over an adequate period to even out normal fluctuations 1.00	Representative data from >50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations 1.02	Representative data from only some sites (<<50%) relevant for the market considered ***or*** >50% of sites but from shorter periods 1.05	Representative data from only one site relevant for the market considered ***or*** some sites but from shorter periods 1.10	Representativeness unknown or data from a small number of sites ***and*** from shorter periods 1.20
3	Temporal correlation	Less than 3 years of difference to the time period of the dataset 1.00	Less than 6 years of difference to the time period of the dataset 1.03	Less than 10 years of difference to the time period of the dataset 1.10	Less than 15 years of difference to the time period of the dataset 1.20	Age of data unknown or more than 15 years of difference to the time period of the dataset 1.50
4	Geographical correlation	Data from area under study 1.00	Average data from larger area in which the area under study is included 1.01	Data from area with similar production conditions 1.02	Data from area with slightly similar production conditions 1.05	Data from unknown ***or*** distinctly different area (North America instead of Middle East, OECD-Europe instead of Russia) 1.10
5	Further technological correlation	Data from enterprises, processes, and materials under study 1.00	Data from processes and materials under study (i.e., identical technology) but from different enterprises 1.10	Data from processes and materials under study but from different technology 1.20	Data on related processes or materials 1.50	Data on related processes on laboratory scale ***or*** from different technology 2.00

B8. Cost Per Unit Mitigation Potential

We estimate the annualized capital cost per metric ton of mitigation for complete gate electrification (Scenario 3a) first for the 24 case study airports and then for the 2,354 airports included in the global analysis. The capital cost for both sets of airports is found by multiplying the number of gates at each airport by the cost to purchase and install the 400Hz and PCA units for each gate. Capital costs for each gate type are provided in Table B25. The number and type of gates for the 24 case study airports is previously provided in Table B26. For the 2,354 airports, we make a simplifying assumption about the number of gates at each airport. We assume that Large Airports have 100 gates, Medium Airports have 30 gates, and Small Airports have 10 gates. We transform the capital costs for each airport into annualized capital costs using Equation B15:

$$Annualized\ Capital\ Cost = P\left[\frac{i}{1-(1+i)^{-n}}\right] \quad \text{[Eq. B15]}$$

Where P is the capital cost of all the gates at the airport;
i is the discount rate, assumed to be 6%;
n is the number of years the equipment are utilized, assumed to be 20 years

The annualized capital cost per mitigation potential is then calculated using Equation B16:

$$Cost\ Per\ Mitigation = \frac{AC_{Airport,i}}{E_{Airport,Sc.2a/2b} - E_{Airport,Sc.3a}} \quad \text{[Eq. B16]}$$

Where $AC_{Airport,i}$ is the annualized capital cost for airport “i”;
$E_{Airport,Sc.1}$ are the annual emissions for airport “i” under Scenario 2a or 2b conditions;
$E_{Airport,Sc.3a}$ are the annual emissions for airport “i” under Scenario 3a conditions

Results for the 24 case study airports are presented in Table B49. Values range from a minimum of 11.30 USD per metric ton for SEA airport and a maximum of 48.95 USD per metric ton for ATL airport. The average for the 24 case study airports ranges between 25 and 30 USD per metric ton of mitigated CO_2 equivalents. Results for the 2,354 airports are provided in Table B50. The average for United States airports in the dataset (430 airports) ranges between 62.94 and 72.04 USD per metric ton of mitigated CO_2 equivalents and non-United States airports (1,924 airports) ranges between 77.28 and 87.97per metric ton of mitigated CO_2 equivalents.

Table B49. Annualized capital cost for Scenario 3a per metric ton of mitigated carbon for the 24 case study airports relative to Scenario 2a and 2b.

Airport Code	Annualized Capital Cost Per Mitigation [USD/MT CO_2(eq)] Relative to Scenario 2a	Annualized Capital Cost Per Mitigation [USD/MT CO_2(eq)] Relative to Scenario 2b
AMS	$41.25	$31.23
ATL	$48.95	$42.70
CAN	$45.67	$39.07
CDG	$31.74	$24.04
CLT	$47.84	$41.93
DEN	$25.16	$22.54
DFW	$31.50	$24.57
EWR	$32.14	$26.25
FRA	$30.23	$24.66
HND	$36.64	$30.73
IST	$18.93	$16.15
JFK	$31.99	$27.50
LAS	$26.74	$23.45
LAX	$15.00	$12.19
LHR	$26.53	$19.80
MEX	$30.31	$26.28
MIA	$47.65	$39.69
ORD	$33.67	$29.00
PEK	$22.66	$20.95
PHX	$25.21	$21.45
PVG	$19.83	$16.74
SEA	$14.05	$11.30
SFO	$20.94	$15.74
YYZ	$25.79	$19.85

Table B50. Annualized capital cost per metric ton of mitigated carbon for airports in the global analysis.

Airport Location	Annualized Capital Cost per Mitigation Potential [USD/metric ton CO2(eq)] Relative to Scenario 2a	Annualized Capital Cost per Mitigation Potential [USD/metric ton CO2(eq)] Relative to Scenario 2b
United States	$72.04	$62.94
Outside of United States	$87.97	$77.28

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Appendix C. Addendum to Chapter 5

This appendix contains the supporting information for Chapter 5: ATEST Application. References for all sections appear at the end of Appendix C.

- Section C1 contains the results of the uncertainty assessment for ATEST model parameters.
- Section C2 includes frequently used acronyms pertaining to ATEST.
- Section C3 provides definitions for acronyms used in equations in ATEST.
- Section C4 lists the hidden sheets included in ATEST and provides explanations and additional data for each hidden sheet.
- Section C5 includes the inputs used to develop results for the case study airports.
- Section C6 includes the questionnaire sent to various airports in April 2021.

C1. Uncertainty assessment results

Table C1. Uncertainty assessment for electricity data used in ATEST

	Indicator	Score			
		1 (Low uncertainty)	2 (Moderately low uncertainty)	3 (Moderate uncertainty)	4 (Moderately high uncertainty)
1	Reliability	Verified data based on measurements 1.00	Verified data partly based on assumptions ***or*** non-verified data based on measurements 1.05	Non-verified data partly based on qualified estimates 1.10	Qualified estimate (e.g., by industrial expert) 1.20
2	Completeness	Representative data from all sites relevant for the market considered, over an adequate period to even out normal fluctuations 1.00	Representative data from >50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations 1.02	Representative data from only some sites (<<50%) relevant for the market considered ***or*** >50% of sites but from shorter periods 1.05	Representative data from only one site relevant for the market considered ***or*** some sites but from shorter periods 1.10
3	Temporal correlation	Less than 3 years of difference to the time period of the dataset 1.00	Less than 6 years of difference to the time period of the dataset 1.03	Less than 10 years of difference to the time period of the dataset 1.10	Less than 15 years of difference to the time period of the dataset 1.20
4	Geographical correlation	Data from area under study 1.00	Average data from larger area in which the area under study is included 1.01	Data from area with similar production conditions 1.02	Data from area with slightly similar production conditions 1.05
5	Further technological correlation	Data from enterprises, processes, and materials under study 1.00	Data from processes and materials under study (i.e., identical technology) but from different enterprises 1.10	Data from processes and materials under study but from different technology 1.20	Data on related processes or materials 1.50

Table C2. Uncertainty assessment for natural gas data used in ATEST

	Indicator	Score			
		1 (Low uncertainty)	2 (Moderately low uncertainty)	3 (Moderate uncertainty)	4 (Moderately high uncertainty)
1	Reliability	Verified data based on measurements 1.00	Verified data partly based on assumptions ***or*** non-verified data based on measurements 1.05	Non-verified data partly based on qualified estimates 1.10	Qualified estimate (e.g., by industrial expert) 1.20
2	Completeness	Representative data from all sites relevant for the market considered, over an adequate period to even out normal fluctuations 1.00	Representative data from >50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations 1.02	Representative data from only some sites (<<50%) relevant for the market considered ***or*** >50% of sites but from shorter periods 1.05	Representative data from only one site relevant for the market considered ***or*** some sites but from shorter periods 1.10
3	Temporal correlation	Less than 3 years of difference to the time period of the dataset 1.00	Less than 6 years of difference to the time period of the dataset 1.03	Less than 10 years of difference to the time period of the dataset 1.10	Less than 15 years of difference to the time period of the dataset 1.20
4	Geographical correlation	Data from area under study 1.00	Average data from larger area in which the area under study is included 1.01	Data from area with similar production conditions 1.02	Data from area with slightly similar production conditions 1.05
5	Further technological correlation	Data from enterprises, processes, and materials under study 1.00	Data from processes and materials under study (i.e., identical technology) but from different enterprises 1.10	Data from processes and materials under study but from different technology 1.20	Data on related processes or materials 1.50

Table C3. Uncertainty assessment for water/wastewater data used in ATEST

	Indicator	Score			
		1 (Low uncertainty)	2 (Moderately low uncertainty)	3 (Moderate uncertainty)	4 (Moderately high uncertainty)
1	Reliability	Verified data based on measurements 1.00	Verified data partly based on assumptions ***or*** non-verified data based on measurements 1.05	Non-verified data partly based on qualified estimates 1.10	Qualified estimate (e.g., by industrial expert) 1.20
2	Completeness	Representative data from all sites relevant for the market considered, over an adequate period to even out normal fluctuations 1.00	Representative data from >50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations 1.02	Representative data from only some sites (<<50%) relevant for the market considered ***or*** >50% of sites but from shorter periods 1.05	Representative data from only one site relevant for the market considered ***or*** some sites but from shorter periods 1.10
3	Temporal correlation	Less than 3 years of difference to the time period of the dataset 1.00	Less than 6 years of difference to the time period of the dataset 1.03	Less than 10 years of difference to the time period of the dataset 1.10	Less than 15 years of difference to the time period of the dataset 1.20
4	Geographical correlation	Data from area under study 1.00	Average data from larger area in which the area under study is included 1.01	Data from area with similar production conditions 1.02	Data from area with slightly similar production conditions 1.05
5	Further technological correlation	Data from enterprises, processes, and materials under study 1.00	Data from processes and materials under study (i.e., identical technology) but from different enterprises 1.10	Data from processes and materials under study but from different technology 1.20	Data on related processes or materials 1.50

Table C4. Uncertainty assessment for waste data used in ATEST

	Indicator	Score			
		1 (Low uncertainty)	2 (Moderately low uncertainty)	3 (Moderate uncertainty)	4 (Moderately high uncertainty)
1	Reliability	Verified data based on measurements 1.00	Verified data partly based on assumptions ***or*** non-verified data based on measurements 1.05	Non-verified data partly based on qualified estimates 1.10	Qualified estimate (e.g., by industrial expert) 1.20
2	Completeness	Representative data from all sites relevant for the market considered, over an adequate period to even out normal fluctuations 1.00	Representative data from >50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations 1.02	Representative data from only some sites (<<50%) relevant for the market considered ***or*** >50% of sites but from shorter periods 1.05	Representative data from only one site relevant for the market considered ***or*** some sites but from shorter periods 1.10
3	Temporal correlation	Less than 3 years of difference to the time period of the dataset 1.00	Less than 6 years of difference to the time period of the dataset 1.03	Less than 10 years of difference to the time period of the dataset 1.10	Less than 15 years of difference to the time period of the dataset 1.20
4	Geographical correlation	Data from area under study 1.00	Average data from larger area in which the area under study is included 1.01	Data from area with similar production conditions 1.02	Data from area with slightly similar production conditions 1.05
5	Further technological correlation	Data from enterprises, processes, and materials under study 1.00	Data from processes and materials under study (i.e., identical technology) but from different enterprises 1.10	Data from processes and materials under study but from different technology 1.20	Data on related processes or materials 1.50

Table C5. Uncertainty assessment for building size and material composition data used in case-studies

	Indicator	Score			
		1 (Low uncertainty)	2 (Moderately low uncertainty)	3 (Moderate uncertainty)	4 (Moderately high uncertainty)
1	Reliability	Verified data based on measurements 1.00	Verified data partly based on assumptions ***or*** non-verified data based on measurements 1.05	Non-verified data partly based on qualified estimates 1.10	Qualified estimate (e.g., by industrial expert) 1.20
2	Completeness	Representative data from all sites relevant for the market considered, over an adequate period to even out normal fluctuations 1.00	Representative data from >50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations 1.02	Representative data from only some sites (<<50%) relevant for the market considered ***or*** >50% of sites but from shorter periods 1.05	Representative data from only one site relevant for the market considered ***or*** some sites but from shorter periods 1.10
3	Temporal correlation	Less than 3 years of difference to the time period of the dataset 1.00	Less than 6 years of difference to the time period of the dataset 1.03	Less than 10 years of difference to the time period of the dataset 1.10	Less than 15 years of difference to the time period of the dataset 1.20
4	Geographical correlation	Data from area under study 1.00	Average data from larger area in which the area under study is included 1.01	Data from area with similar production conditions 1.02	Data from area with slightly similar production conditions 1.05
5	Further technological correlation	Data from enterprises, processes, and materials under study 1.00	Data from processes and materials under study (i.e., identical technology) but from different enterprises 1.10	Data from processes and materials under study but from different technology 1.20	Data on related processes or materials 1.50

Table C6. Uncertainty assessment of construction emission data used in ATEST

	Indicator	Score			
		1 (Low uncertainty)	2 (Moderately low uncertainty)	3 (Moderate uncertainty)	4 (Moderately high uncertainty)
1	Reliability	Verified data based on measurements 1.00	Verified data partly based on assumptions ***or*** non-verified data based on measurements 1.05	Non-verified data partly based on qualified estimates 1.10	Qualified estimate (e.g., by industrial expert) 1.20
2	Completeness	Representative data from all sites relevant for the market considered, over an adequate period to even out normal fluctuations 1.00	Representative data from >50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations 1.02	Representative data from only some sites (<<50%) relevant for the market considered ***or*** >50% of sites but from shorter periods 1.05	Representative data from only one site relevant for the market considered ***or*** some sites but from shorter periods 1.10
3	Temporal correlation	Less than 3 years of difference to the time period of the dataset 1.00	Less than 6 years of difference to the time period of the dataset 1.03	Less than 10 years of difference to the time period of the dataset 1.10	Less than 15 years of difference to the time period of the dataset 1.20
4	Geographical correlation	Data from area under study 1.00	Average data from larger area in which the area under study is included 1.01	Data from area with similar production conditions 1.02	Data from area with slightly similar production conditions 1.05
5	Further technological correlation	Data from enterprises, processes, and materials under study 1.00	Data from processes and materials under study (i.e., identical technology) but from different enterprises 1.10	Data from processes and materials under study but from different technology 1.20	Data on related processes or materials 1.50

C2. Frequently Used Acronyms

Table C7. Frequently used acronyms

Acronym	**Description**
ATEST	Airport Terminal Environmental Support Tool
BTU	British thermal unit
CAP	Criteria air pollutant
CO	Carbon Monoxide
CO_2 (eq)	Carbon dioxide equivalents
DOE	Department of Energy
EF	Emission factor
EI	Energy intensity
EPA	Environmental Protection Agency
EUI	Energy Use Intensity
GHG	Greenhouse gas
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies
GWP	Global Warming Potential
LCA	Life-cycle Assessment
LCI	Life-cycle Inventory
LCIA	Life-cycle Impact Assessment
NAAQS	National Ambient Air Quality Standards
NETL	National Energy Technology Laboratory
NO_x	Nitrogen oxides
PM	Particulate matter
$PM_{2.5}$	Fine particulate matter
$PM_{2.5}$ (eq)	Particulate matter formation potential
SCC	Social Cost of Carbon
SO_2	Sulfur dioxide
TRACI	Tool for Reduction and Assessment of Chemicals
VOC	Volatile organic compound
WARM	Waste Reduction Model

C3. Equation Acronyms

Table C8. Equation acronyms and descriptions

Acronym	Description
$EF_{Biomass}$	Electricity emission factor for biomass
$EF_{C\&D}$	GHG emission factor for construction and demolition waste materials
$EF_{CAP, Process}$	CAP emission factor for process energy used in waste management strategies
$EF_{CAP, Total}$	CAP emission factor used in waste management strategies
$EF_{CAP, Trans}$	CAP emission factor for transportation energy used in waste management strategies
EF_{Coal}	Electricity emission factor for coal
$EF_{Const, GHG}$	GHG emission factor for construction
$EF_{Elec, i}$	Electricity emission factor for a FERC/state/balancing authority/utility by GHG or CAP
$EF_{Elec, Wind/Solar}$	Electricity emission factor for 100% wind or 100% solar by GHG or CAP
$EF_{Food\ Compostables, Composted}$	Emission factor for composting food compostables
$EF_{Food\ Compostables, Landfilled}$	Emission factor for landfilling food compostables
$EF_{Geothermal}$	Electricity emission factor for geothermal
EF_{Hydro}	Electricity emission factor for hydroelectric
$EF_{Landfill, Materials}$	GHG emission factor for landfilling construction and demolition waste
$EF_{Landscape\ Compostables, Composted}$	Emission factor for composting landscape compostables
$EF_{Landscape\ Compostables, Landfilled}$	Emission factor for landfilling landscape compostables
$EF_{Material, Baseline}$	Baseline GHG emission factor for each building material type
$EF_{Material, Typical/Achievable}$	Typical/achievable GHG emission factor for each building material type
$EF_{Natural\ Gas}$	Electricity emission factor for natural gas
EF_{NG}	Stationary combustion GHG emission factor for building-sector natural gas
$EF_{Non\text{-}Recoverables, Landfilled}$	Emission factor for landfilling non-recoverables
$EF_{Nuclear}$	Electricity emission factor for nuclear
EF_{Oil}	Electricity emission factor for fuel oil
$EF_{Recyclables, Landfilled}$	Emission factor for landfilling recyclables
$EF_{Recyclables, Recycled}$	Emission factor for recycling recyclables
$EF_{Recycle, Materials}$	GHG emission factor for recycling construction and demolition waste
EF_{Solar}	Electricity emission factor for solar
$EF_{Truck, Diesel}$	CAP emission factor for diesel-powered truck
$EF_{Water, j}$	Water emission factor by GHG or CAP
EF_{Wind}	Electricity emission factor for wind
$EF_{WWater, j}$	Wastewater emission factor by GHG or CAP
$EI_{Greywater}$	Energy intensity of greywater system
EI_{RWH}	Energy intensity of rainwater harvesting system

C4. Hidden Sheets in ATEST

"User Interface Data (1)"
The "User Interface Data (1)" sheet contains look-up tables for every county for all 50 states.

"User Interface Data (2)"
The "User Interface Data (2)" sheet contains look-up tables for cities by county for all 50 states. Not all cities for a respective county are included. Cities for every small, medium, and large hub airport are included in the look-up tables.

"User Interface Data (3)"
The "User Interface Data (3)" sheet contains all the text used in drop-down menus.

"User Interface Data (4)"
The "User Interface Data (4)" sheet contains the nonattainment classification by pollutant for all relevant counties in all 50 states. This data is used when determining whether a terminal upgrade project would conform with NAAQS for an airport's location. Nonattainment classification is current as May 31, 2021.
https://www3.epa.gov/airquality/greenbook/ancl.html

"TRACI"
The "TRACI" sheet contains GWP and particulate matter formation potential impact factors for GHG and CAP emissions. These impact factors are used when completing the partial life-cycle impact assessment (LCIA), where emissions quantified in the inventory stage of the life-cycle assessment (LCA) are characterized according to impact category.

GWP is calculated according to Equation C1:

$$\text{GWP [tons } CO_2 \text{ (eq)/year]} = \text{mass } CO_2 \text{ (eq)/year} * ((1.0 \times 10^{0} \text{ ton } CO_2 \text{ (eq)/ton } CO_2 \text{ (eq)}) \quad \text{[Eq. C1]}$$

Particulate matter formation potential is calculated according to Equation C2:

$$\begin{aligned}
&\text{Particulate matter formation potential [ton } PM_{2.5} \text{ (eq)/year]} \\
&= \text{mass } NO_2 \text{ /year} * ((7.22 \times 10^{-3} \text{ ton } PM_{2.5} \text{ (eq)/ton } NO_2) \\
&+ \text{mass } NO_x \text{ /year} * ((7.22 \times 10^{-3} \text{ ton } PM_{2.5} \text{ (eq)/ton } NO_x) \\
&+ \text{mass CO /year} * ((3.56 \times 10^{-4} \text{ ton } PM_{2.5} \text{ (eq)/ton CO}) \quad \text{[Eq. C2]} \\
&+ \text{mass } SO_2 \text{ /year} * ((6.11 \times 10^{-2} \text{ ton } PM_{2.5} \text{ (eq)/ton } SO_2) \\
&+ \text{mass } PM_{10} \text{ /year} * ((2.28 \times 10^{-1} \text{ ton } PM_{2.5} \text{ (eq)/ton } PM_{10}) \\
&+ \text{mass } PM_{2.5} \text{ /year} * ((1.00 \times 10^{0} \text{ ton } PM_{2.5} \text{ (eq)/ton } PM_{2.5})
\end{aligned}$$

"Location_Cost_Factors"
The "Location_Cost_Factors" sheet contains the construction cost location index for cities where all major small, medium, and large hub commercial airports are located. The city cost index (CCI) adjusts costs to reflect the differences in construction markets relative to the national average. We use the 2019 CCIs from RSMeans, a construction cost database, to estimate the cumulative construction costs from a terminal project (RSMeans, 2021). We assume, based on

conversations with airport officials, an average terminal construction cost of 850 USD per square foot. Total construction costs are calculated with Equation C3:

$$\text{Total Construction Costs [USD]} = \text{CCI (\%)} * \$850/ft^2 * 1\ ft^2/0.092903\ m^2 * \text{Gross Terminal Area } (m^2) \quad \text{[Eq. C3]}$$

"Electricity Data"
The "Electricity Data" sheet contains electricity life-cycle emission factors by fuel source, the average electricity grid mixes, from eGRID2018, for all 50 states, and the option for users to enter a custom electricity grid mix.

"Electricity Calc"
The "Electricity Calc" sheet calculates, based upon user selection, the electricity emission factors for each pollutant.

"Precipitation_Lists"
The "Precipitation_Lists" sheet contains annual median precipitation data by counties within the United States. The precipitation data is the median of ten years' worth of data, from 2010 to 2019 (NOAA, 2021).

"Irrigation – Lists"
The "Irrigation – Lists" sheet contains look-up data for users to select when calculating the outdoor water requirements.

"Irrigation – Annual Factors"
The "Irrigation – Annual Factors" sheet contains look-up data by climate zone and landscaping type for each of the proxy cities used in estimating annual irrigation requirements. The representative cities and their climate zones are included in Table C9. Landscaping types are listed in Table C10. These descriptions come from a DOE report on unmetered irrigation watering (18).

Table C9. Representative cities for estimating landscaping water requirements

Climate Zone	**City**
Alpine	Bozeman, MT
Alpine	Laramie, WY
Alpine	Santa Fe, NM
Desert	Bakersfield, CA
Desert	Las Vegas, NV
Desert	Phoenix, AZ
Desert	Reno, NV
Humid Continental - Cool Summer	Bangor, ME
Humid Continental - Cool Summer	Milwaukee, WI
Humid Continental - Cool Summer	Minneapolis, MN
Humid Continental - Warm Summer	Boston, MA
Humid Continental - Warm Summer	Cincinnati, OH
Humid Continental - Warm Summer	Kansas City, MO
Humid Continental - Warm Summer	Omaha, NE
Humid Continental - Warm Summer	Philadelphia, PA
Humid Southern	Atlanta, GA
Humid Southern	Houston, TX
Humid Southern	Memphis, TN
Humid Southern	New Orleans, LA
Humid Southern	San Antonio, TX
Humid Southern	Raleigh, NC
Humid Southern	Washington, DC
Marine - West Coast	Olympia, WA
Marine - West Coast	Portland, OR
Marine - West Coast	Seattle, WA
Mediterranean	Los Angeles, CA
Mediterranean	Sacramento, CA
Mediterranean	San Francisco, CA
Semi-arid	Amarillo, TX
Semi-arid	Boise, ID
Semi-arid	Denver, CO
Semi-arid	Rapid City, SD
Semi-arid	Salt Lake City, UT
Subarctic	Anchorage, AK
Tropical	Honolulu, HI
Tropical	Miami, FL

Table C10. Landscaping types and descriptions

Landscaping Types	Description/Examples
Turfgrass - Cool Season	Annual bluegrass, annual ryegrass, colonial bentgrass, creeping bentgrass, hard fescue, highland bentgrass, Kentucky bluegrass, meadow fescue, perennial ryegrass, red fescue, rough-stalked, tall fescue
Turfgrass - Warm Season	Bermuda grass, buffalo grass, kikuyugrass, seashore paspalum, St. Augustinegrass, zoysiagrass
Landscaped - L LD P	Low water requirements, low density, protected microclimate
Landscaped - L AD O	Low water requirements, average density, open microclimate
Landscaped - L HD IE	Low water requirements, high density, intense exposure
Landscaped - M LD P	Medium water requirements, low density, protected microclimate
Landscaped - M AD O	Medium water requirements, average density, open microclimate
Landscaped - M HD IE	Medium water requirements, high density, intense exposure
Landscaped - H LD P	High water requirements, low density, protected microclimate
Landscaped - H AD O	High water requirements, average density, open microclimate
Landscaped - H HD IE	High water requirements, high density, intense exposure

"WARM – NonGHG"

The "Warm – NonGHG" sheet contains the process and transportation energy factors and CAP emission factors for different waste management strategies and material types.

C5. Case Study Inputs

Case Study #1: Operational Energy Module

The Operational Energy Module is tested on three airports (RNO, PIT, SFO). Data inputs for Case study #1 are listed in Tables C11 and C12. Since we do not investigate the custom energy method, the only mitigation strategy we assess is purchase of green electricity.

Table C11. Data input for Operational Energy Module case study

Airport	**State**	**County**	**City**	**Pax (2019)**	**Annual Electricity Consumption (kWh)**	**Annual Natural Gas Consumption (therms)**
RNO	NV	Washoe	Reno	2,162,250	18,845,497	693,827
PIT	PA	Allegheny	Pittsburgh	4,715,947	48,429,964	13,040
SFO	CA	San Mateo	Burlingame	27,779,230	311,219,440	3,621,795

Table C12. Data inputs for case study #1

Airport	**Electricity Mix Method**	**Energy Calculation Method**	**Electricity Rate ($/kWh)**	**Natural Gas Rate ($/therm)**	**SCC Method**	**SCC**	**RPS**
RNO	Custom	Default Option 1	$0.0634	$0.4178	Custom	52 in 2019 dollars	50% by 2030
PIT	Custom	Default Option 1	$ 0.05081	$0.6200	Custom	52 in 2019 dollars	18% by 2021
SFO	Custom	Default Option 1	$0.1003	$0.9074	Custom	52 in 2019 dollars	60% by 2030

Electricity mixes for each airport are listed in Table C13. These mixes reflect each utility's 2019 fuel mixes. When assessing RPS scenarios for PIT and NG, we assume that all fossil fuel sources become natural gas by the RPS date and any remaining gaps in renewables are filled equally by wind and solar.

Table C13. Electricity mixes for RNO, PIT, and SFO Airports

Airport	**SFO**	**PIT**	**RNO**
Utility	SFPUC	On-site natural gas	NV Energy
Coal	0.00%	0.00%	7.53%
Oil	0.00%	0.00%	0.00%
Natural Gas	0.00%	100.00%	75.36%
Nuclear	0.00%	0.00%	0.30%
Hydro	99.00%	0.00%	2.44%
Biomass	0.00%	0.00%	0.34%
Wind	0.00%	0.00%	1.81%
Solar	1.00%	0.00%	5.62%
Geothermal	0.00%	0.00%	6.58%
Other	0.00%	0.00%	0.02%
Total	100.00%	100.00%	100.00%

References

Electricity Mixes:

https://www.energy.ca.gov/sites/default/files/2020-01/2018_PCL_SFPUC.pdf

https://es.nvenergy.com/publish/content/dam/nvenergy/bill_inserts/2019/12_dec/power-content-insert-south-2019-10_1_31.pdf

Costs:

https://www.sfwater.org/modules/showdocument.aspx?documentid=7743

https://www.eia.gov/electricity/state/pennsylvania/

https://www.nvenergy.com/publish/content/dam/nvenergy/brochures_arch/about-nvenergy/rates-regulatory/sppgas_rateschedule.pdf

https://www.eia.gov/dnav/ng/ng_pri_sum_dcu_nus_a.htm

Renewable Portfolio Standards:

https://eta-publications.lbl.gov/sites/default/files/rps_status_update-2021_early_release.pdf

Annual Pax:

https://www.faa.gov/airports/planning_capacity/passenger_allcargo_stats/passenger/media/cy19-commercial-service-enplanements.pdf

Case study #2: Water and Wastewater Module

The Water and Wastewater Module is tested on three airports (RNO, PIT, SFO). Data inputs for Case study #2 are listed in Tables C14 and C15. Note that the landscaping and roof areas in Table 22 are assumed values, based upon available space at those airports. We assume that 25% of daily passengers will purchase a meal from within the terminal. We assume that RNO, PIT, and SFO provide 25,000 m^2, 100,000 m^2, and 100,000 m^2 of cooling, respectively. Assumptions are colored in light red. We select all mitigation strategies. For landscaping, we select "Efficiency Landscaping and Irrigation".

Table C14. Data input for Water and Wastewater Module in case study

Airport	**State**	**County**	**City**	**Pax (2019)**	**Average Daily Pax (2019)**	**Electricity Mix Method**	**Energy Calculation Method**
RNO	NV	Washoe	Reno	2,162,250	5,924	Custom	Default Option 1
PIT	PA	Allegheny	Pittsburgh	4,715,947	12,920	Custom	Default Option 1
SFO	CA	San Mateo	Burlingame	27,779,230	76,107	Custom	Default Option 1

Table C15. Additional data inputs for RNO, PIT, and SFO airports

Airport	**Water Rate ($/m^3^)**	**Wastewater Rate ($/m^3^)**	**SCC Method**	**SCC**	**Landscaping Area (m^2^)**	**Number of daily meals served**	**Roof Area (m^2^)**
RNO	$0.80	$1.23	Custom	52 in 2019 dollars	2,000	1,481	10,000
PIT	$3.15	$1.78	Custom	52 in 2019 dollars	2,000	3,230	10,000
SFO	$3.28	$3.70	Custom	52 in 2019 dollars	2,000	19,027	10,000

<u>References</u>

Costs:
https://tmwa.com/wp-content/uploads/2021/06/2021-06-01_TMWA_Rate_Schedule.01.pdf#page=6

https://www.cityofelreno.com/sites/elreno2/uploads/documents/Resolution_20_017___Water_Rates.pdf

https://www.pgh2o.com/residential-commercial-customers/rates

https://sfwater.org/modules/showdocument.aspx?documentid=7743

Case Study #3: Waste Module

The Waste Module is tested on four airports (RNO, EWR, SEA, ATL). Data inputs for Case Study #3 are listed in Tables C16 through C18. Assumed values in Tables C17 and C18 are colored light red. We assess all mitigation strategies.

Table C16. Data inputs for Waste Module case study

Airport	**State**	**County**	**City**	**Electricity Mix Method**	**SCC Method**	**SCC**	**Pax (2019)**
RNO	NV	Washoe	Reno	Custom	Custom	52 in 2019 dollars	2,162,250
EWR	NJ	Essex	Newark	Custom	Custom	52 in 2019 dollars	23,160,763
SEA	WA	King	Seattle	Custom	Custom	52 in 2019 dollars	25,001,762
ATL	GA	Clayton	Atlanta	Custom	Custom	52 in 2019 dollars	53,505,795

Table C17. Additional data inputs for RNO, EWR, SEA, and ATL airports

Airport	Total Landfilled (tons)	Landfilled - non-recoverable (tons)	Landfilled – recyclable (tons)	Landfilled – compostable (tons)	Total Recycled (tons)	Total Composted (tons)	Composition Composts - Landscape	Composition of Composts - Food
RNO	740	202	254	284	70	0	50%	50%
EWR	3041.9	1355.1	433.7	1253.1	511.1	0	100%	0%
SEA	3,223.03	980	598.8	1,644.23	399.2	336.77	25%	75%
ATL	14,250	2,992.5	6,127.5	5,130	750	0	25%	75%

Table C18. Cost data for Waste Module case study

Airport	Tipping Fee ($/ton)	Recycling Fee ($/ton)	Composting Fee ($/ton)
RNO	$74.20	$100.00	$35.00
EWR	$81.91	$100.00	$35.00
SEA	$89.08	$100.00	$108.00
ATL	$48.77	$100.00	$35.00

Electricity mixes for each airport are listed in **Table C19**.

Table C19. Electricity mixes for SEA, ATL, and EWR airports

Airport	**SEA**	**ATL**	**EWR**
Utility	Bonneville Power Administration	Georgia Power	PSE&G
Coal	0.00%	25.00%	10.00%
Oil	0.00%	0.00%	0.70%
Natural Gas	0.00%	46.00%	33.00%
Nuclear	11.50%	22.00%	55.00%
Hydro	83.20%	2.00%	0.70%
Biomass	0.00%	0.00%	0.00%
Wind	0.60%	1.50%	0.00%
Solar	0.00%	1.50%	0.70%
Geothermal	0.00%	0.00%	0.00%
Other	4.80%	2.00%	0.00%
Total	100.00%	100.00%	100.00%

References

Electricity:

https://www.bpa.gov/p/Generation/Fuel-Mix/FuelMix/BPA-Official-Fuel-Mix-2019.pdf

http://www.georgiapower.com/company/about-us/facts-and-financials.html

https://s24.q4cdn.com/601515617/files/doc_downloads/2020/02/FACTBOOK-19-BOD-and-EOG-update.pdf

Waste Amounts and Compositions:

http://onlinepubs.trb.org/onlinepubs/webinars/190205.pdf

https://www.portseattle.org/sites/default/files/2018-05/TM-No-08-Environmental-Effects-Overview.pdf

http://onlinepubs.trb.org/onlinepubs/acrp/synthesis92/A20_ACRP11-03TopicS02-18WasteManagementFINALAppendix20SEACaseExample20180418.pdf

https://www.atlantaga.gov/Home/ShowDocument?id=17150

http://onlinepubs.trb.org/onlinepubs/acrp/synthesis92/A18_ACRP11-03TopicS02-18WasteManagementFINALAppendix18RNOCaseExample20180418.pdf

Costs:

https://erefdn.org/wp-content/uploads/woocommerce_uploads/2017/12/MSWLF-Tipping-Fees-2019-FINAL-revised-revised-1-gcml72.pdf

Case Study #4: Building Materials Module and All Modules

The Building Materials Module is tested on two airports (RNO, SFO). Results from the Building Materials Module are then compared to results from all modules for RNO and SFO Airports. Data inputs for Case Study #4 are listed in Tables C20 and C21. We select the "Achievable" low carbon building materials mitigation strategy. We do not consider construction and demolition waste for Case Study #4. We assume a concrete density of 2,400 kg per cubic meter of concrete.

Table C20. Data input for Building Materials Module for case study

Airport	**State**	**County**	**City**	**Electricity Mix Method**	**SCC Method**	**SCC**	**Pax (2019)**	**Expected Service Life (years)**
RNO	NV	Washoe	Reno	Custom	Custom	52 in 2019 dollars	2,162,250	30
SFO	CA	San Mateo	Burlingame	Custom	Custom	52 in 2019 dollars	27,779,230	30

Table C21. Terminal size and material quantities for case study

Airport	**Terminal Size (m^2)**	**Amount of Concrete (m^3)**	**Concrete Strength (psi)**	**Amount of Steel (kg)**	**Amount of Rebar (kg)**	**Insulation - Board (m^2)**	**Gypsum Board (1000 m^2)**	**Carpet (m^2)**	**Resilient Flooring (m^2)**	**Glass (kg)**
RNO	27,542	11,418	5000 - 6000	1,817,772	578,382	20,657	21	20,657	20,657	70,783
SFO	165,000	68,406.25	5000 - 6000	10,890,000	3,465,000	123,750.00	124	123,750.00	123,750.00	424,050

Additional waste data for SFO Airport is provided in Table C22. Energy and water data for RNO and SFO are provided in the previous case study descriptions.

Table C22. Waste amount and composition data for SFO

Airport	Total Landfilled	Landfilled - non-recoverable	Landfilled - recyclable	Landfilled - compostable	Total Recycled	Total Composted	Composition of Composts - Landscape	Composition of Composts - Food
SFO	4730	567.6	331.1	3,831.3	3,135	3,135	25%	75%

References

Terminal Sizes:

https://data.sfgov.org/w/yuvm-3ujh/ikek-yizv?cur=6TvOjXJxrRs&from=root

https://www.renoairport.com/sites/default/files/PDFs/Other/Reduced_RNO%20MP_Inventory_Draft0618.pdf

SFO Waste Amounts and Composition:

https://www.flysfo.com/sites/default/files/media/sfo/community-environment/13259_Zero_Waste_Roadmap.pdf

C6. Airport Questionnaire
The following questionnaire was sent to a handful of commercial airports in April 2021. PIT Airport and the PANYNJ responded to some of the questions.

General Airport Information:

What is the name of the airport's electricity utility?

If electricity is not supplied from a utility, what is the source of the airport's electricity?

What are the names of the airport's water and wastewater utilities, if known?

What is the average number of daily passengers processed through a specific terminal? What is the average number of annual passengers?

Note: All following questions refer to a specific terminal.

Water/Wastewater Questions:

If known, how many gallons of water are consumed per annum?

What is the average number of meals served in the terminal on a daily basis?

What is the approximate area of the terminal for which cooling is supplied?

If applicable, how many boilers serve the terminal?

If there is landscaping associated with the terminal, what is the general type of landscaping (e.g., turf grass, landscaped)?

Waste Management Questions:

What are the approximate annual amounts of solid waste from the terminal, in tons per year, that are sent to a landfill, recycling facility, and/or composting facility?

Of the solid waste sent to a landfill, what is its general composition? For example, how many tons are non-recoverable materials, how many tons are recyclable, how many tons are compostable?

What is the general composition of the compostable material? What percentage of the compostable material is food waste and what percentage of the compostable material is landscape waste?

Energy Management Questions:

What is the annual electricity consumption of the terminal, in kWh? What is the annual natural gas consumption of the terminal, in therms?

If heating and cooling energy for the terminal is provided by an on-site thermal plant, please list the approximate annual consumptions:

Annual Energy Usage from Chilled Water (kBTUs):
Annual Energy Usage from Heating Hot Water (kBTUs):
Annual Electricity Consumption in Terminal - Lighting, Equipment (kWh):
Annual Natural Gas Consumption in Terminal - Non-heating (therms):

What are the approximate areas, in m^2 or ft^2, of the following zones within the terminal?

Concession – Food:
Concession – Retail:
Office:
Transient Space:
Ticketing Check-In:
Departures Hold Room:
Departure/Border Security:
Outbound/Inbound Baggage Handling:
Arrivals/Baggage Claim:
Service (Mechanical/Electrical/Server):

If the following equipment utilizes electricity supplied by the terminal, please indicate each equipment's power rating (kW), approximate number of operation hours per day, number of days of operation per year, and total number of units.

<u>People Movers</u>
*Power (kW):
*Average Operation Hours in active mode (hrs/day):
*Operation Days (days/yr):
*Number of Units:

<u>Escalators</u>
*Power (kW):
*Average Operation Hours in active mode (hrs/day):
*Operation Days (days/yr):
*Number of Units:

Elevators
*Power (kW):
*Average Operation Hours in active mode (hrs/day):
*Operation Days (days/yr):
*Number of Units:

Baggage Handling Systems
*Power (kW):
*Average Operation Hours in active mode (hrs/day):
*Operation Days (days/yr):
*Number of Units:

De-Icing Cart Charging System
*Power (kW):
*Average Operation Hours in active mode (hrs/day):
*Operation Days (days/yr):
*Number of Units:

Ramping Cart Charging System
*Power (kW):
*Average Operation Hours in active mode (hrs/day):
*Operation Days (days/yr):
*Number of Units:

Jet Engine Airstart Cart Charging System
*Power (kW):
*Average Operation Hours in active mode (hrs/day):
*Operation Days (days/yr):
*Number of Units:

Portable Ground Power
*Power (kW):
*Average Operation Hours in active mode (hrs/day):
*Operation Days (days/yr):
*Number of Units:

Aircraft Tug Charging System
*Power (kW):
*Average Operation Hours in active mode (hrs/day):
*Operation Days (days/yr):
*Number of Units:

Does the terminal supply electricity for gate electrification operations (e.g., 400Hz ground power, pre-conditioned air)? If so, what is the system configuration for pre-conditioned air (e.g., point-of-use or central chillers and boilers)?

Does the terminal supply electricity for external and/or parking lighting? If so, what are the approximate covered and uncovered illuminated areas? What are the lighting power densities for these illuminated areas in Watts per m^2?

Materials/Structure Questions:
What is the structural system for the terminal (e.g., steel frame, reinforced concrete)?

If known, what are the approximate volumes of the following materials used in the construction of the terminal?

Concrete:
Reinforcement steel:
Structural steel:
Wood products (dimensional lumber):
Glass:
Carpeting:
Vinyl flooring:
Drywall
Fiberglass insulation: