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TOPICAL REVIEW

Airports and environmental sustainability: a comprehensive review

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Abstract

Over 2500 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).

List of acronyms

ACI Airport Council International
ACRP Airport Cooperative Research Program
APU auxiliary power unit
CO carbon monoxide
CO₂ carbon dioxide
EUI energy use intensity
GHG greenhouse gas
GPU ground power unit
GSE ground service equipment
HVAC heating, ventilation, air conditioning
IAQ indoor air quality
ISO International Organization for Standardization
LCA life-cycle assessment
LEED Leadership in Energy and Environmental Design
LTO landing and take-off
NOₓ nitrogen oxides
PKT passenger kilometer traveled
PM particulate matter
PV photovoltaic
SCM supplementary cementitious materials
SFO San Francisco International Airport

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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 2018). 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 (ASCE 2017, ACC 2020) 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 and 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 2019), but that estimate excludes the impacts from airport construction and operation. An analysis of 2019 data for San Francisco International Airport (SFO 2018, 2020) 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 (NOx), 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 and 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.

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 et al 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 and 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) refers
to this approach to sustainability as EONS (Martin-Nagle and Klauber 2015, Prather 2016). Common subcategories of EONS are shown in table 1. An important research dimension of the airport industry is the U.S. 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 (Brown 2012, Delaney and Thomson 2013, Lurie et al. 2014, Prather 2016, Malik 2017);
- feasibility of on-site energy provision (Lau et al. 2010, Barrett et al. 2014) and microgrids (Heard and Mannarino 2018);
- GHG emission reduction strategies (ACRP, FAA, Camp, Dresser, & McKee et al. 2011, Barrett 2019);
- air quality impacts (ACRP, FAA, CDM Federal Programs Corporation et al. 2012a, ACRP 2012b, Lobo et al. 2013, Kim et al. 2014, 2015)
- water efficiency (Krop et al. 2016) and stormwater management (Jolley et al. 2017);
- habitat management (Belant and Ayers 2014);
- sustainable ground transport (Kolpakov et al. 2018);
- sustainable construction practices (ACRP, FAA, Ricondo & Associates et al. 2011);
- waste management (Turner 2018);
- climate change adaptation of airports (Marchi 2015).

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; Kilkis and 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 (Chester and Horvath 2009) and data from operating airports (Chao et al. 2017; Kilkis and Kilkis 2016, Li and 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.

### 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 | • Air quality enhancement/climate change | • Socioeconomic benefits |
| • Accounting for life-cycle costs | • Energy conservation/renewable energy | • Noise abatement | • Community outreach & participation |
| | • Water quality protection & water conservation | • Land & natural resources management | |
| | • Land/property use | • Land/property use | |
| | • Pavement management | • Materials use & solid waste reduction/recycling | |
| | • Hazardous materials & waste management/reduction | • Hazardous materials & waste management/reduction | |
| | • Surface transportation management | • Buildings/facilities | |
| | • Buildings/facilities | | |
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                              |

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.

1.3. Overview of article
Section 2 presents the methodology for conducting the systematic review. Section 3 follows with a characterization, trend analysis, and synthesis of the reviewed literature, along with a review of the sustainability indicators used at a current SFO infrastructure project. Section 4 discusses the limitations and gaps of the existing literature, analyzes the efficacy of SFO’s sustainability assessment framework, and provides guidance for future research directions. Section 5 concludes with a summary of the overall work and a recommendation for practices that airports should implement in the short term.
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 |

2. Methods

2.1. Systematic literature review

2.1.1. Criteria for selecting research papers

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 (ACA 2020). Exact search terms for all criteria are provided in table A1 in appendix A (available online at https://stacks.iop.org/ERL/15/103007/mmedia). 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 takeoff (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 and 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. A bibliography for all articles included in this systematic review is provided in appendix A (table A3). Section 3 provides a trend analysis of the articles included in the systematic review.

3. Results

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

Figure 3. Cumulative articles by year (dotted line = moving average).

Figure 4. Cumulative articles by theme.
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.

3.1.1. Synthesis of research by category

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.

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 and 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 and 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 2018a, 2018c) is provided in table 4. An airport that implements a standardized energy management system is considered to be sustainable (Uysal and 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 and Bayraktar 2015).

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 (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 (Kilkis and Kilkis 2017, Suku-maran and 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 (Kilkis and 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 and Radcliffe 2018).

Modeling of a solar PV farm at a rural U.S. 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).

3.1.1.1.3. Energy-related emissions

Recommending 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 (ACRP, FAA, McKee, Dresser Camp, & Synergy Consulting Services 2011, Barrett 2019). GHG emissions from annual airport energy consumption are a typical sustainability evaluation metric (Monsalud et al 2015, Baxter et al 2018a, 2018c). 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) (ACRP, FAA, Camp, Dresser, & McKee et al 2011, Ozdemir and Filibeli...
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 and 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 (Kilkış 2014).

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.

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 (Meng et al 2009, Zhang et al 2013, Zhao et al 2014; Liu et al 2019). 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 (Kotopoulas and 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 and Rogers 2017).

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, Kim et al 2015). 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 (NO₂) 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 and Siskos 2011). One study linked IAQ at eight large Chinese airports with passenger satisfaction, finding that IAQ satisfaction is correlated with CO₂ concentration (Wang et al 2015).

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 (ACRP, 2012b, Lobo et al 2013). 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 U.S. 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

| Airport     | 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                                                                   |
| Copenhagen (CPH) | • 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                                                                        |
| Kansai (KIX) | • Use of fixed electrical ground                                                                         |
|             | • 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                                                                        |
|             | • 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                                                                        |
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 and Harrison 2014). Concentrations of CO$_2$, CO, PM, hydrocarbons, NO$_x$, 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 NO$_x$ from APUs and GSE are calculated for turnaround operations at major European airports (Padhra et al. 2016), and concentrations of NO$_x$ 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 NO$_x$ emissions from APU, GPU, and GSE operation (ACRP, 2012a, Yim et al. 2013, Winther et al. 2015, Padhra 2018, Preston et al. 2019). 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).

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.

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 (de Castro 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 (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 (Couto et al. 2013, 2015); seawater and grey-water use at an airport in Hong Kong (Leung et al. 2012). These studies assess the efficacy of alternative sources in terms of demand met.

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 (Presl 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).

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.

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; 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 and 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 and O’Keefe 2018).

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 (Liu and 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 (Wang and 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).

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 (Marchi 2015, Burbidge 2016, 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).

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.

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, Santero et al 2011, Miller et al 2016). 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 and 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 A4 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.

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 (Akyuez et al 2017, Kon and 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 (ACRP, FAA, Ricondo & Associates, R. &. Center for Transportation, C. for, & Ardmore Associates 2011). It is common practice, as mentioned in the ACRP literature, for airports to aim for green building certification from groups such as the U.S. 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 2020), with SFO’s Terminal 2 the first LEED Gold airport terminal in the U.S. (SFO 2011).

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 waste (Turner 2018). 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 2018b). 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).

3.1.1.6. Multidimensional studies
Sustainability, as expressed in ACRP reports (Brown 2012, Delaney and Thomson 2013, Lurie et al 2014, Prather 2016, Malik 2017), 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 enact 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 and Loo 2016). A composite ranking indicator is created by normalizing indicators across all categories to compare the environmental sustainability of multiple airports (S. Kilkis and 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 (Chester and Horvath 2009).

The multidimensional articles that include case study airports are listed in table 6, along with each airport’s location. All of 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 (Chester and 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).

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
### 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 <i>et al</i> (2019) | - Control emissions of NO\(_2\), SO\(_2\), CO, PM, VOCs, CO\(_2\) | - Create noise map & mitigation plan | - Control water consumption | - Integrate with public/private transport | - Treat hazardous waste from maintenance activities |
| | - Use ecological cars | - Take steps to isolate community buildings from noise pollution | - Reduce indoor/outdoor water consumption | - Select a site that meets aeronautical safety requirements | - Recycle waste |
| | - Offer infrastructure to support biofuels use | - Acoustic efficiency (number of people exposed per annual number of aircraft movements) | - Reduce water consumption in handling | - Measure soil quality | - Implement a construction/maintenance/demolition plan for infrastructure |
| | - Manage energy consumption | - Restrict engine testing during certain time periods | - Manage stormwater runoff | - Protect native flora & fauna | - Choose green building materials |
| | - Use renewable energy | - Monitor indoor air quality | - Treat wastewater | - Reduce light pollution | - Green building practices |
| | - Control air conditioning equipment for energy conservation | - Use efficient indoor lighting | - Reduce heat island effect | - Reduce heat island effect | - Practice ecological conservation |
| | - Use efficient indoor lighting | | - Design airside layout to minimize air-craft emissions | - Reduce parking footprint | - Use green building materials |
| | | | - Design airside layout to reduce noise impact | - Integrate infrastructure for public transport | - Engage in waste reduction, reuse, & recycling |
| | | | - Provide physical mitigation barriers between operating areas & surroundings | - Avoid destruction of sensitive habitats | - Use recycled materials |
| | | | - Reduce building-level energy consumption | - Avoid attracting certain species | - & rapidly renewable materials |
| | | | - Reduce outdoor energy consumption | - Design to reduce heat island effect | - Use materials with a high design service life |
| | | | - Use alternative & renewable energy | - Design to reduce light pollution | |
| | | | | - Design for storage & collection of recyclables | |

Lu <i>et al</i> (2018) | - Carbon emission reduction & energy conservation | - Prevention & monitoring of noise | - Install water-saving devices | - Practice ecological conservation | - Green building practices |

Chao <i>et al</i> (2017) | - Conserve energy in buildings | - Monitor noise | - Use water-saving devices | - Reduce parking footprint | - Design for deconstruction, reuse & recycling |

| | - Use ground power units over auxiliary power units | | - Use recycled water | - Integrate infrastructure for public transport | - Use recycled, bio-based, & rapidly renewable materials |
| | - Use low-emission vehicles | | - Recycle wastewater | - Avoid destruction of sensitive habitats | - Use materials with a high design service life |
| | - Use energy-savings control devices | | | - Avoid attracting certain species | |
| | - Use renewable energy | | | - Design to reduce heat island effect | |
| | - Monitor air quality | | | - Design to reduce light pollution | |
| | - Shorten runways to reduce queuing time | | | | |

Ferrulli (2016) | - Design airside layout to minimize aircraft emissions | - Landscape & design to reduce water use | - Reduce parking footprint | - Integrate infrastructure for public transport | - Design for deconstruction, reuse & recycling |
| | - Design infrastructure & buildings to minimize CO\(_2\) emissions | - Design for water efficient use | - Avoid destruction of sensitive habitats | - Use recycled, bio-based, & rapidly renewable materials | - Use materials with a high design service life |
| | - Reduce building-level energy consumption | - Design to maximize water harvesting, recycling, reuse | - Avoid attracting certain species | - Design to reduce heat island effect | - Design for storage & collection of recyclables |
| | - Reduce outdoor energy consumption | - Design to reduce stormwater quantity | - Design to reduce light pollution | - Design to reduce heat island effect | - Design for deconstruction, reuse & recycling |
| | - Use alternative & renewable energy | - Design to improve stormwater quality | - Integrate infrastructure for public transport | - Avoid destruction of sensitive habitats | - Use recycled, bio-based, & rapidly renewable materials |
| | | | - Avoid attracting certain species | - Design to reduce heat island effect | - Use materials with a high design service life |

| | - Use alternative & renewable energy | | - 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 | - Design for storage & collection of recyclables |
| Citation                      | Energy and atmosphere                                      | Comfort and health                          | Water and wastewater                  | Site and habitat                           | Materials and resources                    |
|-------------------------------|------------------------------------------------------------|---------------------------------------------|---------------------------------------|-------------------------------------------|---------------------------------------------|
| Kilkis and Kilkis (2016)      | • Energy Consumption (toe)                                 | • Noise abatement for decibels ≤ 60         | • Water withdrawal (m³)                | • Amount of conserved area (hectares)      | • ISO 14 001 Certification<sup>c</sup>      |
|                               | • Energy Consumed per Passenger (toe/passenger)            |                                             | • Percentage of utilized recycled water|                                            |                                             |
|                               | • ISO 50 001 Certification<sup>a</sup>                     |                                             |                                       |                                            |                                             |
|                               | • Implementation of energy-saving measures                  |                                             |                                       |                                            |                                             |
|                               | • Use of on-site energy                                     |                                             |                                       |                                            |                                             |
|                               | • CO₂ emissions (tonnes)                                    |                                             |                                       |                                            |                                             |
|                               | • CO₂ per passenger (tonnes/Passenger)                      |                                             |                                       |                                            |                                             |
|                               | • CO₂ emissions per unit energy (tonnes/toe)                |                                             |                                       |                                            |                                             |
|                               | • Recognition under ACI’s airport carbon accreditation<sup>b</sup> |                                             |                                       |                                            |                                             |
|                               | • Aiming for CO₂ Neutrality                                 |                                             |                                       |                                            |                                             |
|                               | • Concentration of PM<sub>10</sub> (µg/m³)                   |                                             |                                       |                                            |                                             |
|                               | • Use of low-emission ground vehicles                       |                                             |                                       |                                            |                                             |
| Li and Loo (2016)             | • Mass of CO₂, SO₂, NOₓ, PM, VOCs, HC, NH₃ per annual operations | • Level of Noise Pollution                  | • Amount of Water Pollution            | • Amount of Habitat Loss                   |                                             |
| Janic (2010)                 | • Energy efficiency (energy consumption per annual WLU<sup>d</sup>) | • 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 and Horvath (2009)    | • CO₂ emissions per passenger-kilometer-traveled (PKT)     | • CO₂ emissions per passenger-kilometer-traveled (PKT) | • Energy consumption per PKT           | • CO₂ emissions per passenger-kilometer-traveled (PKT) | • Energy consumption per PKT |
|                               | • CO₂ emissions per PKT                                     | • CO₂, SO₂, NOₓ per PKT                     |                                       | • CO₂, SO₂, NOₓ per PKT                   |                                             |

<sup>a</sup> ISO 50 001 Certification = International Standard Organization’s Energy Management System.

<sup>b</sup> Airport Carbon Accreditation = ACI certification that recognizes an airport’s efforts to manage CO₂ emissions.

<sup>c</sup> ISO 40 001 Certification = International Standard Organization’s Environmental Management System.

<sup>d</sup> WLU = Work Load Unit, a standardized metric for airport operations in terms of number of passengers processed or mass of freight handled.
Table 6. Case study airports/locations from multidimensional papers.

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

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 APU s, 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 U.S. airports. Sustainability indicators in the academic literature predominantly focus on energy consumption and GHG emissions. Sustainability is assessed with a number of 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.

3.2. 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.

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 2020b). 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 (SFO 2020, FAA 2020a). 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.).

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

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

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 B 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.

4. Discussion
4.1. Limitations and gaps of existing research
With few exceptions on airport energy (Kilkis and Kilkis 2017, Tagliaferri et al 2018), overall sustainability (Chester and Horvath 2009, 2012, 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 and 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. U.S. airport terminals are focused on food consumption; European/Asian airports serve as retail/recreational centers);
- 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;
- 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;
- 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;
• 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;
• Integration of actions in achieving societal sustainable development (economic, environmental, social) with airport, airline, air traffic control, and in general, civil aviation goals.

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 are 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.

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

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.

5. Conclusion

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 designation 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.

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).

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

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