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Developing a Comprehensive Framework for Assessing Airport Sustainability

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Abstract: The background of this research is the environmental sustainability assessments in the aviation ecosystem, particularly concerning airports, are getting significant attention from the industry, regulators, and researchers. A standardized and comprehensive approach is essential for uniformly addressing the global impacts of these assessments across the industry. The main objective of this study is to develop a unique framework that encompasses the requirements of aviation regulators as well as industry and academic metrics, aiming for a standardized approach to environmental sustainability assessments at airports. The methodology used the Sum of Ranking Method to evaluate each environmental indicator precisely. It was applied to five airports globally, providing a diverse testing ground to assess the proposed metrics' applicability and effectiveness and validate the framework. The results showed that applying the framework across these varied airport environments demonstrated its viability and effectiveness, indicating that it can be successfully applied to different airport realities. The conclusion shows that the developed framework can be successfully applied globally, suggesting that it can be a valid method for international adoption in environmental airport sustainability analysis, offering a standardized approach that could be accepted and utilized worldwide.

Keywords: airport; performance; environment; aviation; sustainability

1. Introduction

The importance of developing an assertive and comprehensive sustainability framework for the aviation ecosystem is on the agenda, and all of them must contribute. This study is associated with airport management, focusing on the interaction between airport performance and environmental sustainability. The research context highlights the growing approach to sustainability and the need to evaluate airports' environmental performance in the face of technological development and growing environmental concerns. Therefore, this study focuses on evaluating the environmental sustainability performance of airports with an emphasis on noise pollution, water waste and contamination, air pollution, and energy management [1].

The literature has already highlighted several environmental issues linked to airport operations, namely the impact of noise pollution on the local population in regions close to the airport, concerns about water scarcity and contamination, air pollution from emissions from aircraft and land vehicles, and the high energy consumption of airport facilities. The authors of [2–4] emphasised the importance of implementing measures to mitigate these environmental impacts, such as the development of noise management plans, water conservation strategies, and the use of sustainable energy sources.

Thus, a quantitative approach was implemented to evaluate the performance of airports in the environmental area, developing a framework that incorporates Key Performance Indicators (KPIs) obtained through literature reviews and sustainability reports. By assessing airport performance across multiple environmental dimensions, the developed framework seeks to provide insights into the effectiveness of current sustainability initiatives and identify areas for improvement [2,5,6].

The specific research problem addressed in this study is the need to evaluate airports' environmental performance using standardized performance indicators, considering noise pollution, water

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management, atmospheric emissions, and energy consumption. In doing so, this research simultaneously answers questions such as: How can standardised indicators improve the comparison and improvement of airport environmental performance? How do airports implement and measure their environmental sustainability practices?

The novelty of the proposed framework is substantiated under the same methodology for airport sustainability assessment of the main KPI identified by several authors, organizations, and airports. The developed framework concatenates all the major KPI for a unified and comprehensive evaluation under the same foundation. This makes it possible to identify the best practices and areas for improvement in various environmental domains.

The article is organized as follows: Chapter 2 consists of a Theoretical Assessment focusing on the four environmental areas: noise pollution, water waste and contamination, air pollution, and energy management as well as the Theoretical Framework Development. Chapter 3 presents the results and Chapter 4 discusses the results from the application of the framework to five airports. Finally, Chapter 5 offers conclusions and recommendations for future research and practices on airport sustainability.

2. Materials and Methods

2.1. Theoretical Assessment

According to the authors in [7], the topics of "water conservation and water quality", "Air quality", and "Energy Management" are integral to airports' environmental sustainability. In addition to these areas, airports such as Athens, Hong Kong, Sofia, Sydney, and Toronto also include noise pollution in their environmental performance reports, highlighting the comprehensive approach needed for effective environmental management.

Noise is present in any industry, and airports are no exception. However, when it is in excess or at high levels, it can become dangerous for the well-being of populations in the vicinity of airports. According to [8], noise pollution is any unwanted and disturbing sound that is higher than the comfort level of the human ear and negatively affects people and society. At airports, the main sources of noise pollution are [9–11]:

- The Use of reverse thrust: According to [9], this mechanism is used primarily in landings and rejected takeoffs (RTOs). This helps to decelerate the aircraft more effectively by redirecting the thrust forward. Despite enhancing the braking process and increasing overall safety during this critical flight phase, the noise produced also increases.
- Energy sources such as an Auxiliary Power Unit (APU) and a Ground Power Unit (GPU) are both generators. The first is incorporated into the aircraft, whereas the second is an external generator independent of the aircraft. The APU generates an average noise of 82.5 dBA, which can reach 100 dBA [10].
- Use of aircraft engines during taxi and takeoff. During a taxi, the engines operate mostly at idle power. During takeoff, the engine is the largest noise source [11], because its power can be used.

According to [12], in the European Union (EU) alone, more than 100 million people are exposed to dangerous levels of airport noise, which has consequences such as sleep deficits, hypertension, cardiovascular diseases, psychological disorders, and deterioration of cognitive systems. There is no method to reduce airport noise pollution; therefore, according to [13], a balanced approach must be adopted. This has been increasingly used by airports and focuses on four main points:

- Decreasing noise at the source.
- Land use planning and management.
- Operational procedures for noise reduction.
- Operational restrictions on air traffic.

The first focuses on the development of the main sources of noise such as aircraft engines. These are constantly developing, and aircraft manufacturers such as Airbus and Boeing systematically seek

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to develop more sustainable and less noisy engines. According to the authors in [14], Airbus developed a New Engine Option (NEO), which is approximately 50% less noisy than the Current Engine Option (CEO). Simultaneously, Boeing introduced MAX engines, which, among other new features, also presented a similar noise reduction compared to Next-Gen (NG) aircraft [15].

The second is an efficient way to ensure that activities carried out around airports are aviation compatible. The main objective of this study is to reduce the number of people affected by aircraft noise. According to [16], some of the main land use and planning standards are as follows:

- Locate new airports away from noise-sensitive areas.
- Defining zones around the airport with different noise levels, considering the population level and demographic forecasts, and establishing written criteria regarding the use of these zones per the ICAO standard.
- Ensure that written information about aircraft activities and their environmental impacts is available to communities near airports.

The third category represents several measures implemented to reduce noise during flight and on the ground. Some examples of Noise Abatement Procedures (NAPs) in flight are: Noise Abatement Departure Procedures (NADPs), Continuous Descent Approach (CDAs), and reverse thrust limitations. Some examples of NAP on the ground include limitations on APU use, engine testing restrictions, and the use of single-engine taxis [16].

The last point concerns how the air traffic controllers and airports manage their operations. According to [17], some examples are noise-preferred runways, arrivals, and airport curfews.

Water - Waste and Contamination in airport construction and operation are topics that deserve some attention because airports are places with a large movement of passengers, employees, and aircraft, which causes challenges concerning the responsible use of water and its contamination. Airports use large amounts of water for activities such as flushing toilets, preparing food, heating, ventilation, Heat-Ventilation and Air Conditioning (HVAC) systems, soil irrigation, and aircraft cleaning [7]. It is important to highlight that many of these activities do not require drinking water; however, they are still used to carrying them out in many airports.

Several common daily activities at airports can contaminate water reserves, reduce water quality in regions close to airports, and have toxic effects on marine life. Substances such as aircraft fuel, ethylene glycol, and ammonia used in airports, even in extremely small quantities, are carcinogenic and can be lethal to fauna and flora, consequently causing ecosystem disturbances [18]. The use of de-icing and anti-icing: The application of these fluids without adequate discharge control results in them being washed into the rainwater drainage system, which in turn can result in a reduction in water quality and a decrease in the amount of dissolved oxygen, making it impossible for some marine living beings to survive and present potential risks to human health [19].

When water demand exceeds its supply, water stress occurs, which can compromise the entire region around the airport [2]. This situation is common at airports in the Middle East, where most of the water comes from expensive desalination processes, but also at airports in large cities, such as Denver, Los Angeles, Madrid, Santiago, and New Delhi, where the water stress is greater than 80% [2]. Therefore, it is important to implement measures to reduce its use. These measures can be as simple as implementing low-flush toilets or more complex processes, such as rainwater collection systems [3].

It is also important that airports can predict natural phenomena such as floods, erosion, and drainage problems and design contingency plans as well as implement systems that allow the drainage and use of water before it transports contaminants present in the airport soil to other beds of water near the airport. The water used is normally classified as wastewater, which can be divided into greywater or blackwater [20]. The treatment and reuse of used water before it leaves airports is very important because it has the potential to contaminate the entire region in which it is located. Some airports reuse greywater for activities such as soil irrigation to reduce waste, as is the case at Hong Kong Airport [21].

Airport air pollution can be divided into [4]:

a) Pollution produced directly at airports;
b) Pollution produced on the outskirts of airports.

According to the authors in [22,23], the pollution produced directly at airports is due to normal aircraft operations (takeoffs, landings, taxis, etc.), diesel engines of airports handling vehicles, and fuel emissions during aircraft refueling. The main pollutants are Polycyclic Aromatic Hydrocarbons ($PAHs$), Sulfur Dioxide (SO_2), Nitrogen Oxides (NOx), Particulate Matter (PM), Volatile Organic Compounds ($VOCs$), Carbon Dioxide (CO_2) and Carbon Monoxide (CO) [24,25]. The pollution produced on the outskirts of airports is mainly due to road vehicles moving to and from airports which according to the authors in [22,26] represents the most non-aircraft-related airport pollution.

Reducing air pollution is a complex challenge; however, developing strategies that enable green transport and sustainable airport operations is becoming increasingly crucial as environmental concerns grow. According to [4], there are several ways to reduce air pollution at airports. These include the use of electric and hybrid ground vehicles, and ideally, an electric fleet of public transport that serves the airport, as is the case in Brisbane [22].

The use of single-engine taxi procedures in congested airports with long travel times between stands and runways can also reduce air pollution. According to authors in [27], single-engine taxi operations lasting more than 15 min resulted in reductions of 46%, 45%, 43%, and 44% in CO/NOx/SOx/HC emissions.

In addition to these two measures, it is important to use Sustainable Aviation Fuel (SAF), which will represent 65% of the contributions to achieving "NET Zero Carbon in 2050". This reduces CO_2 emissions by 80% [28].

Regarding energy management, airport terminals are some of the largest structures in the transport sector, and most operate 24 hours a day, meaning they have extremely high energy consumption. These terminals use fossil fuels and electricity to meet various operational requirements, such as regulating the temperature of facilities, lighting runways and buildings, fueling airport support vehicles, and Ground Support Equipment (GSE) [28].

According to [29], energy use in terminals represents more than 50% of all airport energy consumption, as they differ from other public buildings in terms of architecture, equipment, and use. Terminals are typically large buildings with several floors of retail stores and other forms of entertainment for passengers, which is why they require a large amount of energy to meet the comfort needs of their users in terms of temperature, humidity, and air quality. According to the authors in [30], HVAC systems account for the largest amount of energy use at airports. According to [6], a study of several Greek airports concluded that there is, in many cases, an inefficient use of these systems, where, for example, in summer, they cool the terminals too much. In winter, the opposite was true when unnecessary energy was used.

Many communities rely on natural gas, coal, and oil as their energy sources. Besides being responsible for greenhouse gas emissions, these are resources that our planet cannot produce at the rate that the population consumes, which leads to a gradual increase in their price or to the overexploitation of resources, which is not sustainable and irreversibly affects the planet. Therefore, it is necessary to explore viable alternatives. One is the use of renewable energy sources [6,30].

Another possible measure is optimizing HVAC systems. As the authors in [6] mentioned, many airports do not use these systems efficiently and must review their HVAC operation policy. Therefore, thermal satisfaction surveys could be conducted among terminal users, and the systems could be adjusted according to the preferences of most users, which would result in lower energy expenditure at these airports.

Comparing airports' environmental performance using a set of standardized indicators helps airport managers and stakeholders evaluate airport performance at a comparative level and by airport [31]. According to the authors in [32], environmental indicators related to airport operational activities must consider relevance, comparability, verifiability, clarity, and understandability. According

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to the same authors, the methodology for evaluating airport performance in environmental areas comprises several steps:

i) Data collection;
ii) Data analysis and conversion;
iii) Evaluation of information;
iv) Preparation of reports and communication.

A review of environmental and sustainability issues demonstrates that not only previous literature indicates, but also the aviation industry itself adopted four areas of environmental sustainability and its indicators as their sustainability metrics: noise pollution, waste and water contamination, air pollution, and energy management, as evidenced in their annual reports [24,33–41].

The proposed framework not only adopts industry indicators, but also those proposed by researchers. All these indicators lay the foundation of the proposed airport sustainability evaluation framework. The Framework indicators and their respective KPI are presented in Table 1.

Table 1. Framework Indicators and KPIs.

Environmental Area	References	KPI	KPI Number
Noise Pollution	[33,34,37]	Existence of a noise management plan	1
	[34,37,41]	The use of reverse thrust	2
	[33,40]	Engine run-up areas	3
	[34,42]	Airport curfew	4
	[33,37,41]	Specific arrival procedures for noise mitigation	5
	[33,38]	Number of noise complaints	6
	[33,34,37]	Number of noise complaints compared to the previous year	7
	[33,41]	Number of people affected by prolonged sound levels above 70 dBA	8
	[33,40]	Noise-preferred runways, nightly and aircraft model fees	9
	[33]	Importance given by the airport operator to noise pollution on a scale of 1 to 5	10
	[33]	Importance given by airport stakeholders to noise pollution on a scale of 1 to 5	11

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Table 1. *Cont.*

Environmental Area	References	KPI	KPI Number
Water-Waste and Contamination	[33,41]	Importance given by the airport operator to water management on a scale of 1 to 5	12
	[33,41]	Importance given by airport stakeholders to water management on a scale of 1 to 5	13
	[37,40]	Water consumption per movement compared to the previous year	14
	[37,40]	Water consumption per passenger compared to the previous year	15
	[33,41,43]	Water stress from main water sources used at the airport	16
	[40]	Passenger awareness programs	17
	[34,37,40]	% of wastewater treated as a function of total water used	18
	[34,37,41]	Water quality control on the surface of the airport	19
	[34,37,41]	Quality control of the airport's groundwater	20
Atmospheric Pollution	[33,41]	Importance given by the airport operator to air pollution on a scale of 1 to 5	21
	[33,41]	Importance given by airport stakeholders to air pollution on a scale of 1 to 5	22
	[37,38,40]	Ground vehicles fuel type	23
	[34,37,39]	Use of SAF	24
	[33,41]	Emission of greenhouse gases	25
	[24,33,41]	Emission of other polluting gases	26
	[37,38]	APU usage restrictions	27
	[33,38]	CO_2 emissions (Kg/PAX) compared to the previous year	28
	[33,38]	CO_2 emissions (Kg/Mov) compared to the previous year	29
	[38]	Implementation of single-engine taxi procedures	30

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Table 1. *Cont.*

Environmental Area	References	KPI	KPI Number
Energy Consumption	[33,41]	Importance given by the airport operator to energy management on a scale of 1 to 5	31
	[33,41]	Importance given by airport stakeholders to energy management on a scale of 1 to 5	32
	[33,34,37]	Energy reduction plan	33
	[38,40]	Use of renewable energies	34
	[38,41]	LED lighting systems	35
	[33,34,37]	Energy used per passenger compared to the previous year	36
	[33,34]	Energy used per movement compared to the previous year	37

2.2. Theoretical Framework Development

The Sum of Rankings Method (SRM) is a decision-making tool that works on a simple principle: ranking numerous parameters and summing the ranks to establish the most favorable alternative. The performance of each airport for each parameter was scored, and the scores were summed to yield an overall composite score. Using SRM may provide important insights into the environmental sustainability of airport operations.

From a complexity point of view, the SRM is very simple to implement because of its clear implementation methodology. This simplicity is crucial in data management and analysis, which is the large amount of data required to provide the right and necessary report regarding airports' environmental performance.

Furthermore, SRM can simultaneously host many sustainability indicators at the same time. The environmental impacts of airports are multifaceted, indicating that an inquiry into only one parameter will not yield satisfaction in the field. The SRM allows every indicator to be examined and ranked for ultimate assessment. Thus, this ensures that a more realistic view of airports' environmental sustainability performance is provided. Most importantly, the ranking order adopted by the SRM admits the variability that cannot be averted in the operations, size, and location of airports, which may impact the environment. Other methods could be biased towards airports with similar characteristics. Nevertheless, the SRM provides a framework in which all airports have the same level of chances to perform well in environmental sustainability, irrespective of their inherent factors. Moreover, this implies that the indicators and their weighting can be amended over time, and that these changes can reflect the changing nature of environmental issues and their scientific understanding. Therefore, this ensures that the SRM remains relevant and fits the purpose under dynamic environmental challenges. Finally, SRM is a very flexible tool because it can be easily adapted to new indicators.

The first step in implementing the SRM framework is to ensure that the data are in a suitable format, following Equation (1), where X is the indicator and x_{ij} Is the score of the $j-th$ airport in the $i-th$ environmental indicator.

$$X = \{x_{ij}\} \tag{1}$$

Following, and for each environmental indicator, each airport is ranked based on its performance score given by Equation (2):

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$$R_{ij} = \text{rank}\{x_{ij}; \text{desc}\} \tag{2}$$

Were R_{ij} is the rank of the $j-th$ airport for the $i-th$ indicator. The function $rank\ (x_{ij}; desc)$ assigns the highest score to rank 1, the second highest to rank 2, and so on, with higher scores considered better. These ties were assigned the same rank.

The summation of ranks for each airport across all indicators gives a composite score, reflecting an overall performance assessment following Equation (3).

$$S_j = \sum_{i=1}^{n} R_{ij} \tag{3}$$

Where S_j is the sum of the ranks for the $j-th$ airport, and n is the number of indicators.

The global ranking encompassing all the indicators across all the Environmental Areas, was obtained by ordering the composite scores S_j from the lowest to the highest. Lower scores indicate better overall performance owing to the ranking system design, where the best performance in each category receives the lowest rank number.

2.3. Framework Application

An environmental impact assessment framework was developed by combining measurable and quantitative indicators used by the academic literature, aviation organizations, and the aviation industry to carry out a more specific and independent assessment in various areas of airport sustainability analysis. The framework combines the 37 indicators listed in Table 1 and is evaluated under the evaluation scale given in Table A1 in Appendix A.

The 37 indicators were divided into four areas that raise the greatest environmental concern for airports:

i) Noise Pollution (11 indicators);
ii) Water - Waste Contamination (9 indicators);
iii) Atmospheric Pollution (10 indicators);
iv) Energy Management (7 indicators).

To evaluate the performance of airports, a 5-level Likert scale (1 to 5) was used, where each indicator was given a score based on its performance, with one being a very poor performance, two a poor performance, three an average performance, four a good performance, and five a very good performance. If there is no available information in the airport report for one or more indicators, it is considered 0.

The developed framework was subsequently validated by applying it to several international airports where the sustainability reports were available according to Table 2, applying the same indicator framework. For comparison, airports from different continents were included (America: Toronto; Asia: Hong Kong; Europe: Sofia; Oceania: Sydney). Athens was also included, so it would be possible to evaluate two airports from the same region to determine if there was any noticeable difference in their performance levels.

After the classification of each airport in each KPI, the airports were ranked using the SRM method. This ranks the airports according to the classification of each KPI.

Table 2. Detailed Airport Performance Under the Framework for each KPI.

Environmental Area	KPI Number	Value of performance at different airports				
		Sofia	Athens	Sydney	Hong Kong	Toronto
Noise Pollution	1	5	5	5	5	5
	2	2	3	5	1	3
	3	5	3	3	5	3
	4	1	1	5	1	1
	5	5	5	4	5	5
	6	4	3	5	5	1
	7	5	5	1	5	0
	8	5	0	0	0	1
	9	5	3	3	4	3
	10	3	0	0	0	0
	11	2	0	0	0	0
Water-Waste and Contamination	12	1	0	0	0	2
	13	1	0	0	0	2
	14	5	5	5	5	5
	15	5	5	5	5	5
	16	2	1	2	4	4
	17	1	1	1	3	1
	18	1	3	3	5	1
	19	1	5	5	5	5
	20	1	5	5	5	5
Atmospheric Pollution	21	3	0	0	0	3
	22	3	0	0	0	3
	23	3	4	3	5	3
	24	4	5	5	5	2
	25	5	5	5	5	5
	26	5	5	5	5	5
	27	2	5	3	3	3
	28	5	5	5	5	5
	29	5	5	5	5	5
	30	1	1	1	1	1
Energy Management	31	3	0	0	0	3
	32	2	0	0	0	4
	33	2	5	5	5	5
	34	2	4	4	4	2
	35	2	3	4	4	5
	36	5	5	5	5	5
	37	4	5	5	4	5

3. Results

Applying the SRM method to the KPI's from Table 1, and using the evaluation scale given in Table A1 in Appendix A, the studied airports have the classification given in Table 2.

When analyzing Table 2, it can also be seen that, concerning the Noise Pollution environmental area, for the total of 11 indicators evaluated at the five airports, 23 of the 55 performance values (41.8%) presented a good rating (value 4) or very good (value 5), 10 (18.2%) showed average performance (value 3), and another 10 (18.2%) showed below-average performance. It should be noted that the remaining 12 values (21.8%) correspond to indicators not reported by the airports. Considering the five studied airports, the indicators with the best performance were the "Existence of a Noise Management Plan" (KPI nº1) and "Specific Arrival Procedures for Noise Mitigation" (KPI nº5), because all airports have a plan for constant monitoring of noise and actions to control and reduce it and because in the large, most present Continuous Descent Approaches (CDA) with attention to noise caused in residential areas. The indicators with the worst performance (among those applicable to all) were "Airport Curfew" (KPI nº4) and "The Use of Reverse Thrust" (KPI nº2), which is because, in general, airports do not have restrictions on the use of reverse thrust, and only the Sydney airport limiting aircraft movements at night hours.

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Regarding the environmental area Water-Waste and Contamination, and for the total of 9 indicators evaluated at the 5 airports, 21 of the 45 performance values (46.7%) presented an above-average performance, 3 (6.7%) have an average performance, and 15 (33.3%) had poor or very poor performance. Considering the five studied airports, the indicators with the best performance were "Water Consumption per Movement Compared to the Previous Year" (KPI nº14) and "Water Consumption per Passenger Compared to the Previous Year" (KPI nº15) because all airports substantially reduced the consumption of water by 2022. The worst indicators (among those which all data was available) were "Passenger Awareness" (KPI nº17), "Water Stress of the Main Water Sources Used at the Airport" (KPI nº16), and "% of Wastewater Treated as a Function of the Total Water Used" (KPI nº18), this is because the only airport that carried out some passenger awareness campaigns to reduce the waste of water resources was Hong Kong. Most airports are located in areas of high water stress and treat less than 60% of the water used. Sofia and Toronto were treated with less than 20%.

Regarding the environmental area Atmospheric Pollution, and the 10 indicators evaluated at the five airports, 27 of the 50 performance values (54.0%) were above the average performance, 10 (20%) corresponded to the average performance, and 7 (14%) were weak and very weak. The remaining 6 (12%) corresponded to indicators not reported by the respective airports. Considering the five studied airports, there were four indicators where all airports achieved maximum performance (KPIs nº 25, 26, 28, 29) because they all control the emission of greenhouse gases and other polluting gases and, have a plan to reduce emissions in the long term. Furthermore, compared with 2021, all airports have reduced CO_2 emissions per passenger and movement. The indicators with the worst performance were the "Implementation of Single-Engine Taxi Procedures" (KPI nº30) and the "APU Usage Restrictions" (KPI nº27) because no airport suggests the use of just one engine before takeoff or after landing. In addition, on the overall basis of the five studied airports, there are few recommendations and restrictions regarding the usage of the APU.

For the last environmental area, Energy Management, and the total of the 7 indicators evaluated, 21 of the 35 performance values (60%) were good (value 4) and very good (value 5), three (8.6%) average performances were obtained, and five (14.3%) weak (value 2) and very weak (value 1) performances were obtained. The remaining six (17.1%) corresponded to indicators not reported by the studied airports. Considering the five studied airports, the two indicators with the best performance were the "Energy Used per Passenger in KwH Compared to the Previous Year" (KPI nº36) and the "Energy Used per Movement in KwH Compared to the Previous Year" (KPI nº37) because all airports managed to reduce energy consumption per passenger and movement significantly. The two indicators with the worst performance were the "Use of Renewable Energy" (KPI nº34) and the "Use of LED Lighting Systems" (KPI nº35).

The overhaul airport performance, considering all 37 indicators from the proposed framework, is given in Table 3 and indicates the results of the airports studied across all four environmental areas. Based on these results, it is possible to assess the following:

- Noise Pollution: Sofia has the best performance in Noise Pollution Enviromental Area Management, showing the lowest score, and hence, ranked best in this category. Both Toronto and Sydney, having the highest and second highest scores, respectively, indicate potential areas for significant improvement in noise pollution management at these two airports.
- Water - Waste and Contamination: Hong Kong and Toronto perform best in managing Water - Waste and contamination Environmental Area, as evidenced by their lowest scores. With the highest score, Sofia indicated the greatest room for improvement in this category.
- Atmospheric Pollution: Athens and Hong-Kong tie for the best performance in Atmospheric Pollution Environmental Area, as shown by the lowest scores. Although only slightly higher, Sofia ranks as having the most room for improvement in this category.
- Energy Consumption: Toronto has the best performance in the Energy Consumption Environmental Area, with only 10 points. On the other hand, Sofia has a much higher score than all the other airports, which means it lags well behind in energy management.

Table 3. Overhaul Airport Performance Under the Framework.

Environmental Area	Sofia	Athens	Sydney	Hong Kong	Toronto
Noise Pollution	17	24	2	21	28
Water-Waste and Contamination	25	19	17	13	13
Atmospheric Pollution	19	15	17	15	17
Energy Consumption	22	14	12	15	10
Overhaul Score	83	72	72	64	68

The Global Scores provide a summary metric derived from aggregating the ranked results across all environmental areas. The difference in global scores (from 64 to 83) suggests that airports have different environmental performance levels. Hong Kong is slightly ahead, showing a small, but potentially significant edge in environmental sustainability practices. Sofia still has room for environmental performance improvement. Comparing the two European airports, it is possible to verify a good competition by a difference of 11 in the framework score.

4. Discussion

The designed framework provides a dual-purpose tool for enhancing airport sustainability assessment. First, it establishes a standardized scoring metric that quantifies sustainability indicators across various airports. This metric facilitates a consistent and objective evaluation of the four key Environmental Areas identified by the academy, airports industry and aviation ecosystem stakeholders. The environmental areas of Noise Pollution, Water-Waste and Contamination, Atmospheric Pollution and Energy Management are crucial for evaluation under the same metric standards to obtain a comprehensive score.

Second, this framework supports the creation of a comparative ranking system. This ranking system enables stakeholders to benchmark and identify leading airports in terms of sustainability, fostering a competitive environment that encourages continuous improvement in sustainable practices. The integration of these elements within the framework not only aids in the holistic assessment of airport sustainability, but also promotes transparency and accountability in the management of airport operations.

The absence of airport information in some KPI's reveals a lack of uniformity in Sustainability performance reporting. Aviation Regulators must, not only enforce the practice to all airports have an annual Sustainability Report, but also create a uniform framework of required KPI's to be assessed and reported by the airports. This lays the foundation for a more transparent and assertive evaluation of airport sustainability metrics and performance.

5. Conclusions

It was possible to develop a comprehensive and complete environmental impact assessment framework that combines measurable and quantitative indicators used by previous literature, aviation organizations, and the industry to carry out a more specific independent and complete assessment in the various areas of sustainability. The developed framework integrated indicators in four distinct areas of sustainability: Noise Pollution, Water - Waste and Contamination, Atmospheric Pollution, and Energy Management. This framework was validated through its application to the airports of Athens, Hong Kong, Sofia, Sydney, and Toronto, showing that the developed framework can be applied

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to aviation industry standards. The framework application showed us that there is competition between the airports with some differences in performance, showing Hong Kong with the best performance but still with room for improvement and Sofia as the airport in need of better performance. Comparing airports in Europe, the performance is only slightly different, showing that Athens has a more environmentally sustainable performance than Sofia.

Moreover, sustainability is a very important topic that has consequences, if not addressed, including a decrease in public health, environmental degradation, and high economic costs for the current and future generations. Therefore, it is recommended that the aviation ecosystem and airports continue to develop and implement strategies that improve environmental sustainability, such as controlling noise and pollutant emissions, the quality and management of airport water usage, and the use of renewable energy.

Currently, the global community is confronted with significant environmental and sustainability challenges. Among all sectors, the aviation industry is particularly tasked with addressing these pressing issues. It is imperative that all stakeholders, including the academic community, actively engage in proposing and implementing novel technologies, methodologies, and frameworks to effectively mitigate, manage and eradicate environmental concerns.

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Abbreviations

The following abbreviations are used in this manuscript:

APU	Auxiliary Power Unit
CDA	Continuous Descent Approach
CEO	Current Engine Option
EU	European Union
GPU	Ground Power Unit
GSE	Ground Support Equipment
HVAC	Heat-Ventilation and Air Conditioning
KPI	Key Performance Indicators
NEO	New Engine Option)
NG	Next Generation
NADP	Noise Abatement Departure Procedures
NAP	Noise Abatement Procedures
PM	Particulate Matter
PAH	Polycyclic Aromatic Hydrocarbons
SAF	Sustainable Aviation Fuel
VOC	Volatile Organic Compounds

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Appendix A

Table A1. Sustainability Framework Evaluation Metrics

KPI Number	Performance/Classification Metric				
	1	**2**	**3**	**4**	**5**
1	There is no noise management plan	There is a noise management plan, and noise values are measured over periods longer than one year.	There is a noise management plan, which measures noise values over 6 months and one year.	There is a noise management plan, and noise values are measured over 1 and 6 months.	There is a noise management plan, and noise values are measured monthly.
2	There are no mandatory limitations or recommendations	There is no mandatory limitation, but there are nighttime recommendations	There are no limitations, but there are recommendations for the whole day	There are limitations at night and recommendations during the day	There are limitations throughout the day
3	There is no specific zone for engine run-up	There is a specific zone for engine run-up without time restrictions	There is a specific zone for engine run-up with time restrictions	There is a specific area for engine run-up with a sound barrier, without time restrictions	There is a specific engine run-up zone with a noise barrier, with time restrictions
4	There is no airport curfew	Curfew<2h	2h<curfew<4h	4h<curfew<5h	5h>curfew
5	The approximations do not take into account noise pollution, nor are CDAs	The approximations do not take noise pollution into account but are CDAs	The approaches do not take into account noise pollution, but at night, ATC provides radar vectors with distance to go in CDAs	The approximations are not CDAs but take noise pollution into account	The approximations take noise pollution into account and are CDAs
6	more than 100 complaints	50<complaints <100	25<complaints <50	0<complaints <25	0 complaints
7	Increased by more than 5%	Increased by up to 5%	Same as the previous year	Reduced up to 5%	Reduced more than 5%

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Table A1. *Cont.*

KPI Number	Performance/Classification Metric				
	1	**2**	**3**	**4**	**5**
8	more than 100 people affected	50<people affected<100	25<affected people<50	0<affected people<25	0 people affected
9	Noise does not influence the choice of lane in use, and there is no difference in rates depending on the time of day.	Noise has no influence on the choice of lane in use, but there is a difference in rates depending on the time of day.	Noise has no influence on the choice of lane in use, but there is no difference in rates depending on the time of day.	Noise influences the choice of lanes throughout the day, and there is a difference in rates depending on the time of day.	Noise influences the choice of runway throughout the day, and there are differences in rates depending on the time of day and type of aircraft.
10	1	2	3	4	5
11	1	2	3	4	5
12	1	2	3	4	5
13	1	2	3	4	5
14	increased by more than 5%	Increased by up to 5%	Same as the previous year	Reduced up to 5%	Reduced more than 5%
15	Increased by more than 5%	Increased by up to 5%	Same as the previous year	Reduced up to 5%	Reduced more than 5%
16	very high	high	Medium-high	Medium-low	low
17	No passenger awareness campaign was carried out for passengers	1 passenger awareness campaign was carried out for passengers in the last year	2 passenger awareness campaigns were carried out in the last year	3 passenger awareness campaigns were carried out in the last year	More than 3 passenger awareness campaigns were carried out in the last year
18	Treated water<20%	20%<Treated water<40%	40%<Treated water<60%	60%<Treated water<80%	80% or more Treated water
19	It was not reported, or there is no control	The last quality control was more than a year ago	Quality control is carried out annually	It is checked occasionally during the year	It is monitored regularly throughout the year
20	It was not reported, or there is no control	The last quality control was more than a year ago	Quality control is carried out annually	It is checked occasionally during the year	It is monitored regularly throughout the year
21	1	2	3	4	5
22	1	2	3	4	5
23	They are diesel-powered, and there is no plan to replace them	They are diesel-powered, and there is a plan to replace them in the future	They are powered by diesel, and there is a plan to replace them that is currently being implemented	The ground vehicle fleet is made up of hybrid and electric vehicles	The vehicles are electric
24	The airport does not have SAF or intends to start using it.	The airport intends to start using SAF within more than 2 years	The airport intends to start using SAF within 1 to 2 years	The airport intends to start offering SAF within less than a year	The airport offers SAF

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Table A1. *Cont.*

KPI Number	Performance/Classification Metric				
	1	**2**	**3**	**4**	**5**
25	The airport does not account for greenhouse gas emissions	The airport counts direct greenhouse gas emissions but does not have a plan to reduce them	The airport counts direct and indirect greenhouse gas emissions but does not have a plan to reduce them	The airport counts direct and indirect greenhouse gas emissions and is developing a plan to reduce them	The airport counts direct and indirect greenhouse gas emissions and is implementing a plan to reduce them
26	The airport does not count the emission of other polluting gases	The airport does not count emissions of other polluting gases but intends to start doing so	The airport counts emissions of other polluting gases but does not have a plan to reduce them	The airport counts emissions of other polluting gases and is developing a plan to reduce them	The airport counts emissions of other polluting gases and is implementing a plan to reduce them
27	There are no restrictions, and no GPU is provided	There are no restrictions, but GPU is provided	There are no restrictions, but GPU and air conditioning are provided	There are restrictions; GPU is provided, but not air conditioning.	There are restrictions, and GPU and air conditioning are provided
28	Increased by more than 5%	Increased by up to 5%	Same as the previous year	Reduced up to 5%	Reduced more than 5%
29	Increased by more than 5%	Increased by up to 5%	Same as the previous year	Reduced up to 5%	Reduced more than 5%
30	The airport does not encourage single-engine taxi procedures	The airport encourages single-engine taxi procedures only in taxis in	The airport encourages single-engine taxi procedures only in the taxi-out	The airport encourages single-engine taxi procedures, taxi in and taxi out when a long taxi time is expected	The airport encourages single-engine taxi procedures for taxi in and taxi out in all cases
31	1	2	3	4	5
32	1	2	3	4	5
33	The airport does not have an energy reduction plan	The airport has an energy reduction plan updated every 5 years or more	The airport has an energy reduction plan updated every (3-5) years	The airport has an energy reduction plan updated every (1-3) years	The airport has an energy reduction plan updated annually
34	The airport does not use renewable energy.	The airport does not use renewable energy but plans to use it.	The airport uses at least one type of renewable energy, representing less than 10% of total energy.	The airport uses at least one type of renewable energy, representing between 10 and 50% of total energy.	The airport uses at least one type of renewable energy, representing more than 50% of total energy.

Table A1. *Cont.*

KPI Number	Performance/Classification Metric				
	1	**2**	**3**	**4**	**5**
35	The airport does not use nor has any plans to use LED lamps	The airport does not use LED lamps but has plans to do so in the future	Less than 50% of lamps are LED	More than 50% of lamps are LED	All airport lamps are LED
36	Increased by more than 5%	Increased by up to 5%	Same as the previous year	Reduced up to 5%	Reduced more than 5%
37	Increased by more than 5%	Increased by up to 5%	Same as the previous year	Reduced up to 5%	Reduced more than 5%

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