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Research Paper

A strategic PESTEL-based analysis of renewable energy integration in airports

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Abstract. In an era where the climate crisis is a major issue and net-zero commitments have become binding, the use of renewable energy in airports has become a key factor for the sustainable competitiveness and operational resilience of businesses. While the existing literature primarily focuses on the technical and financial feasibility of renewable energy, there is a significant gap in holistic strategic studies evaluating its integration into aviation infrastructure. To address this gap, this study aims to provide a multi-dimensional strategic assessment of renewable energy integration in airports, aligned with the "net-zero by 2050" targets. Methodologically, this study adopts a qualitative conceptual review approach. Academic literature published between 2015 and 2025, along with institutional reports from international aviation authorities (e.g., ICAO, ACI), was systematically reviewed and analyzed. The findings are evaluated under a PESTEL analysis framework that systematically examines external environmental determinants. The analyses show that the Paris Agreement and regional regulations have accelerated investments, but high initial investment and supply chain risks, despite decreasing technology costs, create economic barriers to the use of renewable energy in airports. Aviation-specific safety factors and regulatory constraints, such as glare risk and radar and communication effects, are particularly pronounced in photovoltaic applications. Smart grid and energy storage solutions enhance operational resilience, social acceptance, and environmental benefits by strengthening uninterrupted energy supply. This study contributes to the aviation management literature by shifting the discussion from solely the dimension of technology adoption to a comprehensive strategic governance model, and by offering airport companies a PESTEL-based framework for multidimensional risk and opportunity management.

Keywords: Airport sustainability, renewable energy integration, green aviation, airport energy management, strategic PESTEL analysis.

Araştırma Makalesi

Havaalanlarında yenilenebilir enerji entegrasyonuna ilişkin stratejik PESTEL temelli bir analiz

Öz. İklim krizinin büyük bir sorun olarak değerlendirildiği ve net sıfır taahhütlerinin bağlayıcı hale geldiği bir dönemde, havaalanlarında yenilenebilir enerji kullanımı, işletmelerin sürdürülebilir rekabet gücü ve operasyonel dayanıklılığı için kilit bir faktör haline gelmiştir. Mevcut literatür öncelikle yenilenebilir enerjinin teknik ve finansal fizibilitesine odaklanırken havacılık altyapısına entegrasyonunu değerlendiren bütünsel stratejik çalışmalarda önemli bir boşluk bulunmaktadır. Bu boşluğu gidermek için, bu çalışma, "2050 yılına kadar net sıfır" hedefleriyle uyumlu olarak, havaalanlarında yenilenebilir enerji entegrasyonunun çok boyutlu stratejik bir değerlendirmesini sağlamayı amaçlamaktadır. Metodolojik olarak, bu çalışma nitel bir kavramsal inceleme yaklaşımı benimsemektedir. 2015 ile 2025 yılları arasında yayınlanan akademik literatür ve uluslararası havacılık otoritelerinin (örneğin, ICAO, ACI) kurumsal raporları sistematik olarak incelenmiş ve analiz edilmiştir. Bulgular, dış çevresel belirleyicileri sistematik olarak inceleyen bir PESTEL analizi çerçevesi altında değerlendirilmiştir. Bulgular, Paris Anlaşması ve bölgesel düzenlemelerin yatırımları hızlandırdığını, ancak azalan teknoloji maliyetlerine rağmen yüksek başlangıç yatırımı ve tedarik zinciri risklerinin, havaalanlarında yenilenebilir enerji kullanımına ekonomik engeller oluşturduğunu göstermektedir. Parlama riski, radar ve iletişim etkileri gibi havacılığa özgü güvenlik faktörleri ve düzenleyici kısıtlamalar, özellikle fotovoltaik uygulamalarda belirgindir. Akıllı şebeke ve enerji depolama çözümleri, kesintisiz enerji tedarikini güçlendirerek operasyonel dayanıklılığı, sosyal kabulü ve çevresel faydaları artırır. Bu çalışma, tartışmayı yalnızca teknoloji benimseme boyutundan kapsamlı bir stratejik yönetim modeline kaydırarak ve havaalanı şirketlerine çok boyutlu risk ve fırsat yönetimi için PESTEL tabanlı bir çerçeve sunarak havacılık yönetimi literatürüne katkıda bulunmaktadır.

Anahtar Kelimeler: Havalimanı sürdürülebilirliği, yenilenebilir enerji entegrasyonu, yeşil havacılık, havalimanı enerji yönetimi, stratejik PESTEL analizi.

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1. INTRODUCTION

Sustainability is an integrated value creation process that reduces risks, increases stakeholder value, ensures resource efficiency, and strengthens resilience by securing long-term competitive advantage from a strategic management perspective. The concept of sustainability is defined as a social goal established for people to live together on Earth for many years, and the meanings of this term vary according to the literature, context, and time. The concept of sustainability is evaluated in terms of its social, economic, and environmental sub-dimensions and refers to the balanced management of all systems while meeting today's needs without compromising the ability of future generations to meet their own needs (United Nations, 2025).

Today, the idea of sustainability at airports means all systematic activities carried out to reduce the impacts on the environment, build economic resilience, and enhance social well-being during the operation of an airport. There are three basic dimensions to the sustainability of an airport, namely, environmental sustainability, economic sustainability, and social sustainability, and the integration of these three dimensions into strategic management processes should be ensured (Graham, 2020).

All the activities aimed at reducing the environmental impacts that result from the operation of the airport fall under the concept of environmental sustainability. Environmental sustainability in the operation of the airport is realized through the efficient and effective use of renewable sources of energy, reduction of carbon emissions, and management of water and wastes (Thangavel & Sridevi, 2016). For example, Oslo Airport has reduced its carbon footprint in the context of environmental sustainability by expanding the usage of geothermal energy in the terminal building (Nordic Office of Architecture, 2017).

The meaning of the concept of economic sustainability lies in the ability of airports to sustain their financial stability and long-term competitive advantage. Therefore, airports are expected to enhance their efficiency and develop new sources of revenue in the context of economic sustainability. For example, Singapore Changi Airport diversified its revenue base by investing in the commercial area within the airport terminal building, which has made a major contribution to its economic sustainability (Changi Airport Group, 2019).

The meaning of the term social sustainability can be defined as the responsibility to provide services to the community, considering the social impacts for airport employees, passengers, and the community living around the airport. The social sustainability aspect includes different social factors such as accessibility, occupational health and safety, community engagement, and stakeholder participation (Foot & Ross, 2017). London Heathrow Airport has set a pioneering example for social sustainability for airports across Europe by launching employment schemes for the community living around the airport (Heathrow Airport Limited, 2017).

Airports today can be defined as a specialized area which is the focal point of the aviation industry, where all aviation business and transactions are conducted and where all flight operations start and end. Today, the definition of a modern airport can be given as intermodal transportation hubs which generate a physical, social, and economic environment intended to safely and efficiently transfer passengers and cargo between air transportation and other modes of transportation and to serve the needs of all stakeholders (Şengür, 2021).

Today, airports consume significant amounts of energy due to their 24/7 operational activities. In line with the global goals of the Paris Agreement, signed to achieve global sustainability, and the long-term global goal adopted by the International Civil Aviation Organization (ICAO) for net-zero carbon emissions by 2050, airports and their operators must follow a strategic roadmap on energy consumption and carbon management (International Civil Aviation Organization, 2022). Within this scope, airports that continue their operations using their own resources for renewable energy production and energy issues have been adopted as strategic objectives. For example, the Airport Council International (ACI) Europe's Net Carbon Zero target and Airport Carbon Accreditation (ACA) program outline strategic roadmaps that will enable airport operators to reduce carbon emissions and promote green energy infrastructure and investments and energy efficiency in line with sustainability goals (Airport Council International, 2023). The use of green energy at airports can make significant contributions to the environmental dimension of sustainability by reducing carbon emissions and environmental impacts, and subsequently to the economic dimension of sustainability by lowering energy costs in the long term.

The Sustainable Development Goals (SDGs) established by the United Nations to achieve global sustainability, specifically SDG-7 (affordable and clean energy) and SDG-13 (climate action), aim to promote the use of sustainable green energy and combat climate change. Today, the use of renewable energy in airports reduces carbon footprints by meeting critical energy needs and contributes to Sustainable Development Goal-7. Additionally, establishing and

utilizing renewable energy infrastructure at airports will contribute to Sustainable Development Goal-13, which addresses combating global warming and climate change.

Renewable energy sources commonly used at airports include solar photovoltaic systems located on terminal roofs, parking lots, and flat land; geothermal energy systems for heating and cooling; wind energy systems powered by common airport winds; and biogas and biomass conversion plants in remote locations (El Zein, Karimipanah, & Ameen, 2025). Energy generated from renewable energy sources is used primarily in the airport's main and backup power systems, with excess energy being transferred to the city's energy systems or stored.

International airports around the world that use renewable energy sources are shown on the map below in Figure 1.

Figure 1. International Airports Using Renewable Energy Sources

The aim of this study is to evaluate the use of renewable energy at airports and the applications implemented within this scope in a multidimensional manner through a PESTEL analysis, within the framework of sustainability and from a strategic perspective. PESTEL analysis is described in literature as a detailed screening model including *(P)* political, *(E)* economic, *(S)* social, *(T)* technological, *(E)* environmental, and *(L)* legal dimensions, created to examine external factors systematically and strategically. Despite the growing literature on airport sustainability, current studies primarily focus on the technical feasibility and financial viability of specific renewable energy projects. Consequently, there is a significant research gap in the literature regarding holistic strategic frameworks to guide this multidimensional transition. To address this gap, the main objective of this study is to evaluate renewable energy integration in airports not merely as a technical and economic issue, but within the framework of a comprehensive strategic transformation process using the PESTEL framework. Accordingly, the study seeks to answer the following research question:

RQ1: What are the key external macro-environmental factors (Political, Economic, Social, Technological, Environmental, Legal) influencing the integration of renewable energy in airports?

Within this scope, a comprehensive strategic PESTEL study was conducted by examining current literature and reports from international aviation authorities. This study offers both theoretical and practical contributions. Theoretically, it contributes to the literature by examining the issue of renewable energy in airports within a strategic and holistic framework. Practically, it provides a multi-dimensional PESTEL-based framework for effective risk and

opportunity management in the transition process of airport operators to renewable energy and net-zero operations.

2. LITERATURE REVIEW

When examining studies published over the past decade on the use of renewable energy at airports, it has been determined that the literature is organized under five main headings: technical and performance, governance and policy, safety and security, infrastructure and storage, and general evaluation.

Technical and performance focused studies have focused on the installation, positioning, and technical improvements of renewable energy sources within airports, as well as performance measurements. Sukumaran & Sudhakar (2017) simulated the technical aspects of the solar power plant located within Cochin International Airport in India, conducted performance analyses, and stated that there was a significant reduction in the airport's carbon footprint. Birhanu, Kitterod, Krogstad, & Kvaerno (2015) analyzed the simulation and energy performance impacts of the installation and storage of thermal energy systems at Oslo Gardermoen Airport. Yousuf, Saleem, & Umair (2024) evaluated the feasibility of photovoltaic solar power plants at major airports in Pakistan using the "7E" framework (energy, exergy, economic, environmental, energo-environmental, emissions, efficiency) and made performance-oriented assessments. Jiang, et al. (2021) comprehensively assessed the technical potential and economic feasibility by evaluating the suitability of the existing infrastructure of 239 airports in China for solar energy systems. While these technical studies successfully demonstrate the physical feasibility and performance of renewable energy systems, they often overlook certain macro-environmental constraints such as regulatory changes or social acceptance.

Governance and policy-oriented studies have emphasized various processes concerning the use of renewable energy in airports. Kim (2020) studied the investment decision on solar energy systems in airports, local policies, and assessments of public-private partnerships on renewable energy investments through data collected from 488 airports in the US and extensive interviews with four airport managers. Another study by Mańkowska, Tłoczyński, Wach-Kloskowska, and Bulczak (2023) discussed various factors affecting environmentally friendly practices in managing airports in Poland and evaluated the impact of managerial practices on renewable energy investments and sustainability. In addition, another study by Dissanayaka, Ryley, Spasojevic, and Caldere (2024) discussed environmental policies and reports of major airports in Australia and conducted extensive research to propose a transition management strategy according to the "airports net zero 2050" goal. Parhamfar (2024) emphasized that sustainability performance of renewable energy technologies improves considerably if evaluated through an integrated framework that includes various aspects like technical infrastructure, corporate governance, and accreditation processes. Miller & Rutledge (2025) highlight the strategic importance of roadmaps and Federal Aviation Administration (FAA)-funded resources for reducing dependence on the conventional power grid and aligning with net-zero targets at airports in the United States and offer various policy recommendations.

Airport studies on safety and security aspects of renewable energy use focus on the safety factor, which is the most crucial element in civil aviation, and provide various risk assessments and recommendations. Sreenath, Sudhakar, Yusop, Cuce, & Solomin (2020) examined the impact of photovoltaic installations on flight safety and safety classifications by investigating the glare risk of solar energy systems used at airports and stated that the location selection, geometric design, and materials of the system installation must be optimized together. Kim, Lee, Lee, & Song (2022) evaluated the energy production potential and safety/operational risks for photovoltaic power plant installation at nine airports in South Korea, investigating the scale of production achievable with acceptable risk. The study states that safety and security risks in renewable energy systems at airports can be managed through design optimization. However, these studies primarily frame security as a technical and isolated barrier, failing to specify how its limitations interact with economic feasibility and legal obligations in strategic macro-environmental decision-making.

Airport studies focusing on energy infrastructure and storage in renewable energy use emphasize the critical infrastructure characteristics of airports and the need for rapid scaling of storage and grid integration. Tang, Liu, Shen, & Zeng (2022) developed a scheduling strategy based on heterogeneous energy storage at the airport microgrid level for a green airport, thereby separating energy storage types and proposing a carbon- and cost-effective solution. Li, Zhang, and Zhang (2025) conducted a study on the use of electric and hydrogen-based aircraft and ground equipment by designing a common microgrid architecture that simultaneously manages electricity, heat, and hydrogen

flows in airport operations related to renewable energy, and emphasized that the combined use of electricity, heat, and hydrogen energy sources is quite important in the transition phases to carbon neutral processes in airports.

Studies that provide a general assessment of the use of renewable energy in airports emphasize the necessity of using renewable energy sources effectively and efficiently and the practices that should be implemented in the aviation sector. El Zein, Karimipanah, and Ameen (2025) used a literature review method to examine the role of airports in carbon reduction in the context of renewable energy and sustainability and noted that academic literature focuses more superficially on Sustainable Aviation Fuel (SAF) solutions. Couto & Baltazar (2025) examined airport renewable energy and sustainability issues using a systematic literature review method in their study and stated that studies conducted on sustainability did not sufficiently address all dimensions of sustainability. In this context, it has been determined that the individual dimensions of the literature have been examined in depth and divided into sections, but a comprehensive strategic evaluation has not been conducted.

Research in literature largely focuses on empirical, micro-level technical and financial assessments or fragmented policy discussions, leaving a significant gap in holistic and macro-level strategic planning. To close this critical gap, this study conceptually positions the adoption of renewable energy as a multi-dimensional strategic transformation and synthesizes the fragmented technical, governance, and security constraints identified in the literature within a framework based on PESTEL analysis.

3. METHOD, ANALYSIS, AND FINDINGS

This study adopts a qualitative conceptual review design to evaluate the integration of renewable energy in airports from a multidimensional perspective. To ensure methodological transparency, literature and international aviation authorities' reports were systematically collected, reviewed, and analyzed before applying the PESTEL analytical framework in the research.

A structured literature search was conducted using the Web of Science (WoS) and Scopus databases to comprehensively review the literature on airport and energy sustainability. The search was limited to publications between 2015 and 2025 to observe the latest technological developments and policy changes following the Paris Agreement. The core search string included combinations of the following keywords: ("airport" OR "aviation") AND ("renewable energy" OR "solar" OR "green energy" OR "net-zero") AND ("sustainability" OR "strategic management" OR "PESTEL"). In addition to academic databases, institutional reports from global civil aviation authorities, particularly the International Civil Aviation Organization (ICAO) and the International Airports Council (ACI), were manually obtained to examine sector-specific regulatory and policy practices. Strict inclusion and exclusion criteria were applied to ensure the relevance and quality of the selected documents, as shown in Table 1.

Table 1. Inclusion and Exclusion Criteria within the Study

Criteria	Inclusion	Exclusion
Publication Type	Peer-reviewed journal articles, institutional reports (ICAO, ACI)	Non-peer-reviewed articles, books, theses, blogs
Language	English	Non-English publications
Timeframe	2015-2025	Pre-2015 publications
Thematic Focus	Strategic management, sustainability, renewable energy integration at airports	Purely technical and engineering studies with no strategic or management context

After selecting the relevant literature, a thematic coding procedure was applied. The data obtained within the scope of the study were not only summarized but also systematically categorized within six predetermined macro-environmental dimensions using the PESTEL framework.

3.1. Political Dimension

The use and growth of renewable energy at airports are significantly influenced by political factors. Airport renewable energy investments can be shaped by long-term investment decisions made by regional organizations like the European Union, local government decisions and political practices, and international aviation authorities like ICAO and ACI. For instance, the European Union's "Fit for 55" investment package seeks to reduce carbon

emissions in the aviation industry by 55% by 2030 by expanding airport infrastructure and utilizing renewable energy sources (European Commission, 2023). In this context, there are regional differences in practices. While airports in Europe are primarily guided by binding climate directives and significant carbon reduction subsidies, airports in developing regions generally evaluate renewable energy policies within the framework of energy security and economic stability.

The CORSIA (International Aviation Carbon Offsetting and Reduction Programme) of ICAO includes decisions that make the reduction of carbon emissions in the aviation industry an international political necessity (International Civil Aviation Organization, 2022). In addition, other agreements such as the Paris Climate Agreement and the European Green Deal either directly or indirectly support the aviation industry in using renewable energy. Moreover, other tax incentives and projects widely provided by local authorities for solar (photovoltaic) systems, wind turbines, or biomass power plants are a great opportunity for airport investment decisions.

In Türkiye, the "Green Airport" project conducted under the General Directorate of Civil Aviation promotes energy efficiency and the use of renewable resources as certification requirements, and this has come to the fore as a political tool for Türkiye's airports (Sivil Havacılık Genel Müdürlüğü, 2022).

On the other hand, corporate accreditation programs such as Airport Carbon Accreditation (ACA) are accelerating the pace of renewable energy projects at airports and helping organizations implement policies on a more comprehensive scale. In addition to all this, some local governments, due to geopolitical uncertainties, consider airports to be critical infrastructure facilities and support them as independent elements from the national grid to ensure energy security and make them self-sufficient in terms of energy.

3.2. Economic Dimension

When considering the economic aspect of renewable energy use in airports within the framework of sustainability, the most principal factor is high initial costs. Within this framework, businesses focus on the financial sustainability of the project. Renewable energy investments in airport land have quite high initial costs when factors such as project feasibility, construction of infrastructure facilities, and system integration are considered. However, following a solid and planned investment roadmap can provide long-term operating cost and various marginal cost reductions, operational efficiency, and economic predictability despite the high initial costs.

The Cochin International Airport in India, cited as a global example, is the first airport powered entirely by solar energy. The renewable energy infrastructure investments at the airport have now paid for themselves, and the airport even generates significant revenue by selling the surplus energy back to the grid (Sukumaran & Sudhakar, 2017). This case is a significant example of how airports located in regions with high solar radiation can transform energy from an operational cost into a net revenue generating source.

In addition, rapidly increasing technological advancements have significantly reduced the installation costs of solar and wind energy infrastructure facilities and shortened the investment payback period for renewable energy infrastructure facilities. According to data from the International Renewable Energy Agency (IRENA), the global weighted average Levelized Cost of Electricity (LCOE) for solar (PV) energy fell by approximately 85% between 2010 and 2022, fundamentally changing the economic feasibility of airport solar energy (International Energy Agency, 2024). In this regard, the airport operators have been able to make clear decisions owing to the reduced uncertainty associated with financial investment decisions. Moreover, some local authorities, especially those found in European countries, assist the airport operators financially through the reduction of carbon emissions through various incentives.

On the other hand, fuel price volatility in today's energy market represents a risk to budget planning in airports. The use of renewable energy sources in airports makes a significant contribution to ensuring economic sustainability and developing a stable budget in terms of fuel prices. In addition, airports that use renewable energy sources can have access to various economic benefits through easier access to low-interest financing sources on a global scale. Reports from the International Energy Agency (IEA) and the International Renewable Energy Agency (IRENA) indicate that investments in renewable energy infrastructure and facilities at airports, as well as production and storage costs, are beginning to decrease thanks to current technological advancements. However, they also note that challenges persist in grid integration, permitting and connection processes, and supply chain risks (International Energy Agency, 2024). From a strategic perspective, it can be concluded that economic feasibility is no longer solely

dependent on technology costs but is also vulnerable to external supply chain disruptions and local infrastructure capacities.

3.3. Social Dimension

The use of renewable energy at airports is supported by social awareness and passenger expectations. For example, the rapidly growing environmental awareness in Europe is leading passengers to prefer more environmentally friendly airports and airlines for their travels. On the other hand, airports that do not support environmentally friendly activities are also heavily criticized. An empirical study conducted on Polish airports determined that factors such as airports' level of commitment to environmentally friendly practices and traffic volume significantly differentiate the perceived sets of obstacles/incentives. In other words, it was determined that the level of social acceptance resulting from environmentally friendly practices affects airport usage at the passenger level (Mańkowska, Tłoczyński, Wach-Kloskowska , & Bulczak , 2023). This finding demonstrates that environmentally conscious passenger behavior has an impact on market competition, showing that social acceptance directly translates into economic resilience.

The widespread use of renewable energy at airports can be accelerated by evaluating this step within the framework of corporate social responsibility. Corporate Social Responsibility, defined as businesses not only pursuing profit-oriented activities but also operating sustainably by taking responsibility for the community, environment, and other stakeholders they are part of, is considered to have a significant catalytic effect on promoting the use of renewable energy at airports (Cowper-Smith & Grosbois, 2011).

Additionally, at some airports, operational and support vehicles powered by renewable energy can operate with less noise, which can increase social acceptance for those living in and around the airport.

In addition to all this, the installation, maintenance, and operation of renewable energy systems and facilities at airports and surrounding facilities create green industry activities that represent sectors that continue their operational activities in line with environmental protection and sustainability goals, and in this context, they can make important contributions to social employment opportunities.

3.4. Technological Dimension

Within the framework of sustainability at airports, the use of renewable energy is considered the greatest facilitator and accelerator in all aspects of technology installation, integration, maintenance, and operation processes. The technological readiness level of solar energy systems, which are renewable energy sources at airports, is at a mature stage, and this situation creates an opportunity for widespread use at all airports around the world in the future.

Solar and wind energy from renewable energy sources are not continuous, but this situation has been overcome with technological developments. Thanks to artificial intelligence-supported smart battery storage infrastructure systems to be established in the airport's surrounding area, energy obtained from renewable energy sources has become manageable through smart grid systems. It has become possible to meet the airport's 24/7 uninterrupted energy needs and transfer excess energy to city infrastructure grids through technological elements (Alharasees, Kale, Rohacs, & Rohacs, 2024). For example, the integration of lithium-ion battery energy storage systems (BESS), whose global costs have fallen by over 80% in the last decade, has proven to play a significant role in bridging the gap between renewable energy generation and critical airport operations.

Additionally, problems arising from renewable energy infrastructure investments at airports and surrounding areas have been resolved quickly and safely, an indispensable element of the aviation sector, thanks to technological advances. The risk of glare, which is a negative effect of solar panels built for solar energy from renewable energy sources that can obstruct pilots' vision, has been minimized thanks to anti-reflective coating technologies, a product of R&D studies conducted in this context, ensuring the sustainability of environmentally friendly investments without compromising safety. For example, Edmonton International Airport in Canada is building the world's largest airport solar farms, and modern technology is being used to prevent interference with radar and communication signals and glare, ensuring the effective use of renewable energy sources without compromising flight safety. (Edmonton International Airport, 2020). Strategically, technological progress acts as a bridge over strict legal and security restrictions, facilitating the removal of legal obstacles to the use of renewable energy in airports.

In addition, since ground handling vehicles, aircraft ground power units, and other electric operational equipment used in various airports today can operate using electric power, the need for the use of renewable energy in airports has increased.

3.5. Environmental Dimension

Within the framework of sustainability at airports, the environmental aspect of renewable energy use is considered one of the fundamental dimensions of the sustainability framework. As part of environmental sustainability, the use of renewable energy at airports reduces carbon emissions and ensures the protection of the ecosystem in the airport and surrounding areas.

The development of large-scale infrastructure projects at an airport can have a negative effect on the local biodiversity of soil flora and fauna. This negative effect can be avoided by developing and analyzing comprehensive environmental impact reports before making investments in renewable energy infrastructure projects at airports, which will allow airports to gain a long-term strategic competitive advantage by safeguarding the entire ecosystem. Moreover, the shade created by solar panels used in renewable energy infrastructure projects at airports reduces the heat island effect created by covering large areas of airports with concrete.

The Seychelles and Galapagos Airports can be cited as examples of the effective and efficient use of renewable energy sources without harming the environment. These airports operate in ecologically sensitive regions and aim to protect endemic life by meeting their energy needs from renewable sources such as solar and wind energy, instead of generators or other non-renewable energy sources (International Civil Aviation Organization, 2016).

In addition to all this, the use of renewable energy at airports improves air quality in and around the airport, reduces noise pollution, and thus has a positive impact on human psychology.

When these factors are synthesized, it can be stated that the environmental benefits of renewable energy are not isolated, but also directly contribute to the social dimension by improving relations with society and are related to the political dimension by fulfilling international net-zero commitments.

3.6. Legal Dimension

The aviation industry operates under very strict regulations, and renewable energy investment projects are shaped within this strict regulatory framework. International and national regulatory bodies and organizations determine the legal scope and framework for renewable energy applications in the aviation sector. For instance, Annex 14 establishes international standards for airport design and operation based on airport sources and specifies the minimum requirements that businesses must comply with. (International Civil Aviation Organization, 2022).

The construction of energy production facilities for renewable energy use at airports must comply with airport mania plans as a legal requirement. In other words, renewable energy facilities to be constructed at airports and surrounding areas must not compromise flight safety and its elements. For example, a wind turbine is constructed in such a way that it does not exceed a certain height around the airport. Furthermore, it is a legal requirement to obtain Environmental Impact Assessment reports for renewable energy infrastructure facilities that will operate within the airport and to proceed with construction in accordance with airport master plans.

The legal aspects of renewable energy at airports around the world can be illustrated by the technical guidelines of the US Federal Aviation Administration (FAA). The Federal Aviation Administration requires that a solar glare hazard analysis (Solar Glare Hazard Analysis Tool - SGHAT) be conducted for solar panels to be installed at airports and surrounding areas. Projects that fail this analysis cannot obtain legal approval, and renewable energy investments cannot be made at airports. (Federal Aviation Administration, 2013). From a strategic perspective, the legal dimension acts as the ultimate operational gatekeeper.

Table 2 summarizes, within an analytical framework, the key macro-environmental factors (PESTEL) driving renewable energy integration at airports and the strategic implications of these factors for airport operators.

Table 2. Analytical Summary of PESTEL Findings and Strategic Implications

PESTEL Dimension	Key Analytical Factors	Strategic Implications for Airport Operators
Political	"Fit for 55", CORSIA program, local tax incentives, geopolitical energy security.	Acts as a primary strategic catalyst and subsidies mitigate initial capital costs, de-risking long-term investments.
Economic	High initial costs vs. 85% drop in PV/BESS costs, fuel price volatility.	Shifts renewable energy to a revenue generator and is highly sensitive to supply chain and global risks.
Social	Eco-conscious passenger behavior, CSR, green employment.	Social acceptance influences market competition and compels businesses to adopt corporate social responsibility strategies.
Technological	Smart grid integration, BESS, anti-reflective coatings for solar panels.	Serves as the fundamental bridge overcoming strict aviation safety constraints (e.g., radar interference, glare).
Environmental	Carbon offsetting, biodiversity protection, mitigating heat island effects.	Feeds directly into social community relations and satisfies international political net-zero mandates.
Legal	ICAO regulations, Annex 14 compliance, airport mania plans.	Legal compliance directly dictates technological choices and inflates costs.

4. DISCUSSION AND RECOMMENDATIONS

This study examines the use of renewable energy at airports within the PESTEL framework, broadening the discussion, which in the literature is shaped around technical performance, site selection, or feasibility calculations, to evaluate it within a broader framework that includes the sustainability dimension. The findings of this study suggest that the use of renewable energy in airports is not merely a technical infrastructure problem, but a multi-dimensional transformation element that must be addressed within the framework of political governance, economic resilience, social acceptance, technological transformation, environmental management, and strict regulatory rules. This study significantly contributes to the aviation management and sustainability literature by shifting the focus of airport renewable energy studies to a holistic strategic governance model. By systematically applying the PESTEL framework to airport renewable energy integration, the study offers a multi-dimensional perspective. Concepts previously considered fragmented, such as legal safety constraints, social acceptance, and political imperatives, are synthesized to comprehensively assess how macro-environmental factors determine the success of renewable energy transitions.

In the context of the political dimension that is being evaluated in the current study, the international policy instruments such as the Paris Agreement, the European Green Deal, and the ICAO CORSIA program include elements that make the transition to renewable energy a mandatory action and accelerate the transition for airport operators. At the same time, the national/local political incentive mechanisms, especially in Europe, are considered a factor in the expansion of the application of renewable energy for airports. The results regarding the economic dimensions that are evaluated in the current study indicate that the high initial costs are a major barrier in the integration of renewable energy for airports. At the same time, the reduced costs for technology and the various financing tools that are available in the market, such as green bonds, are making the application of renewable energy a common practice in the field. In that context, the results obtained in the current study are in accordance with the results obtained in the economic feasibility studies that are presented in the literature, such as the cases of the Cochin and Oslo International Airports.

The findings of the study show that when the social, technological, and environmental factors assessed in the context of the study are examined together, the application of renewable energy sources at airports is also associated with a wide-ranging social transformation factor, from passenger demand to improved noise and air quality. By considering the safety and security standards, such as the glare hazard of solar panels and their impact on radar and communication systems, the findings of the study indicate the importance of airside design optimization. This

indicates that the aviation industry maintains the continuity of operations within a strict legal framework, and that safety and security factors are essential elements in the investment process.

In light of the findings evaluated in this study, policy frameworks promoting the use of renewable energy in airports should be integrated with energy supply security, critical infrastructure resilience, and regional development goals; the importance of green airport certifications, such as the Airport Carbon Accreditation (ACA) program, should be fully understood by management and integrated with sectoral practices; and international mechanisms should be developed to encourage and facilitate the use of renewable energy in airports.

In today's competitive world, it is essential to address airport renewable energy projects as corporate transformation projects. In this regard, all international and national airports need to prepare a roadmap that includes their respective renewable energy infrastructure projects based on aviation net-zero carbon emission targets. It is also essential that this roadmap facilitates the usage of renewable energy at airports with a risk and opportunity analysis based on PESTEL dimensions and sustainability through analysis based on various factors like compliance, safety, integration, and financial feasibility. Furthermore, while revising airport master plans, renewable energy infrastructure needs to be integrated as a basic element of airport infrastructure like runways and terminals, as opposed to being integrated as another element within airport infrastructure.

From a practical perspective, this research makes concrete strategic implications and clearly states that renewable energy investments for airport managers and operators can no longer be evaluated solely on the basis of financial Return on Investment (ROI) or technical feasibility, other macroeconomic framework factors also play a significant role.

5. CONCLUSION

This study aims to assess the utilization of renewable energy sources within airports from a multi-dimensional perspective, following the 2050 aviation industry's goal of achieving net zero carbon emissions, and PESTEL analysis. Contrary to most of the existing economic and technical analyses of the subject within literature, the subject of the utilization of green energy within airports has been assessed by the current study from a strategic perspective, with the subject being analyzed with a sustainability perspective, and with comprehensive assessments within the sub-dimensions of PESTEL analysis. The findings of the current study indicate that the utilization of renewable energy within airports needs to be assessed from a multi-dimensional strategic transformation perspective, including the political, economic, and social dimensions of the subject.

The analyses conducted in this study indicate that international rules and regulations at the political level, as well as national incentive mechanisms, are highly significant factors influencing the investment decisions of airport operators. Economically, although the initial investment costs of renewable energy technologies are high, declining technology costs and long-term energy supply security decisions make these investments financially sustainable. One of the most important outcomes of the study is seen at the intersection of technological and legal dimensions, and the design of solar power plants in a way that does not compromise flight safety and the relevant authority approval processes are considered the most decisive factors for feasibility phases of renewable energy projects. Moreover, it has been intended on the use of renewable energy increases social acceptance of airports and provides several environmental benefits, such as noise reduction. From the legal perspective addressed in the study, it is stated that the aviation sector is one of the sectors with the strictest legal regulations in the world and that renewable energy investment projects must be evaluated within the framework of these strict rules.

Despite its strong conceptual contributions, this study has some methodological limitations. First, as a qualitative conceptual review, this research relies heavily on secondary data, literature, and institutional reports. Furthermore, the rapidly evolving nature of renewable energy technologies and global climate policies means that some current technological barriers or economic cost structures may become obsolete soon. Future research is recommended to support the theoretical framework presented in this study with numerical data and numerical analysis methods specific to airports in different geographical regions, thereby providing decision-makers with more concrete application models. In the future, airports, which are going to be at the heart of the major transportation networks in the world, will transform from energy-consuming infrastructures into energy hubs that are capable of efficiently and effectively generating and managing their own energy. This will not only minimize the environmental impacts of aviation but also maximize its social impacts and economic sustainability.

ETHICAL STATEMENT & GENERAL STATEMENTS

It was declared by the author(s) that the tools and methods used in the study do not require the permission of the Ethics Committee. This article meets the standards of research and publication ethics.

ARTIFICIAL INTELLIGENCE USE DISCLOSURE

During the preparation of this manuscript, [name of AI tool] was used solely to improve grammar, spelling, punctuation, and/or linguistic fluency. AI was not used to generate the scientific content of the study. All AI-assisted suggestions were reviewed and verified by the author(s).

AUTHORS' CONTRIBUTIONS

All authors have read and approved the final manuscript.

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COMPETING INTERESTS

The authors declare that they have no competing interests.

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