A REVIEW OF SMART ENERGY PRACTICES AT AIRPORTS: CHALLENGES AND OPPORTUNITIES FOR SUSTAINABLE AVIATION

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ABSTRACT

Airports are intricate systems comprising buildings, parking lots and land infrastructure, each with unique characteristics that influence energy consumption patterns. On the airside, airfield lighting and radio navigation systems are the primary energy users, while on the landside, the terminal building stands out as a major energy consumer due to its role in passenger and cargo handling, and the extensive facilities it houses. Heating, Ventilation and Air Conditioning (HVAC), lighting, and Information and Communication Technology (ICT) systems are often the top energy consumers within airports, making it imperative to explore innovative strategies to reduce energy expenditure in these facilities. To address this challenge, airports are adopting smart energy solutions, involving electrification, ICT integration, and energy optimization. This paper reviews the current state and future prospects of these emerging trends, covering the following aspects. Regarding electrification, the paper discusses how airports are shifting to electrical power for ground support equipment, passenger vehicles, and terminal buildings, reducing their dependence on fossil fuels and improving their environmental performance. Focusing on ICT integration, the paper examines how airports are using advanced energy management systems, data analytics, and predictive modeling tools to monitor and optimize their energy consumption patterns, achieving significant energy savings, and operational efficiency. Finally for energy optimization, the paper explores how airports are implementing energy optimization measures, such as HVAC optimization and waste heat recovery, enhancing their overall sustainability and resilience.

The paper also analyzes the potential and challenges of using renewable energy sources at airports, such as solar and wind power, highlighting the technical, safety (e.g. glaring for photovoltaic panels or interference with communication and trajectories for wind generators) and regulatory issues that need to be addressed. The paper concludes with a vision of the future of smart energy at airports, emphasizing the role of innovation, collaboration, and stakeholder engagement in driving the transition to a more sustainable aviation sector.

1 INTRODUCTION

Aviation, encompassing both aircraft operations and airport infrastructure, is a significant energy consumer, contributing to approximately 2 % to 4 % of global greenhouse gas emissions (Afonso *et al.*, 2023). Decarbonizing this sector, which is often referred to as hard-to-abate, requires a comprehensive approach. Direct electrification for short-haul flights, utilizing electric aircraft engines, holds promise for reducing emissions in this segment of the aviation market. For long-haul flights, where electrification is not feasible, Sustainable Aviation Fuels (SAF), derived from renewable feedstocks, offer an alternative pathway (where liquid hydrogen holds potential for decarbonizing medium-haul flights).

The aviation sector is not limited to aircraft, but it also includes airport operations and passenger transportation to and from the airport. Airports, with their complex ecosystems of landside and airside facilities, contribute significantly to the energy demand of the aviation sector. Building air conditioning, followed by ground support equipment (GSE) operations and passenger vehicle transportation, are

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among the major contributions to the energy needs. The energy system of an airport can vary considerably depending on its size, location, and operational profile. In this context, smart airport concepts, leveraging advanced technologies such as Internet-of-Things sensors, data analytics, and Artificial Intelligence, are gaining traction to enhance operational efficiency, sustainability, and passenger experience (Rajapaksha and Jayasuriya, 2020). In addition, sector integration and ICT for energy management are crucial for optimizing energy consumption and environmental impact across the entire airport ecosystem. By embracing these strategies, the aviation industry can actually transition toward a more sustainable future.

A key for this transition is represented by the electrification of the demand currently met by fuels (e.g. building heating and ground vehicles) to let a higher amount of renewable energy be exploited. Renewable electricity generation can be done within or near the airport infrastructure, which is generally characterized by wide spaces. Since the electrical energy production from the sun and wind is not programmable, storage technologies are necessary to decouple production and consumption. The most profitable operation of these storage technologies in future energy systems can be enabled if smart management strategies are applied.

All these actions fall within the framework of smart energy. According to Lund *et al.* (2017) "smart energy" is used to describe an integrated and holistic approach to design sustainable energy systems that go beyond the concept of "smart grids" which focus primarily on the electricity sector. Smart energy encompasses multiple sectors including electricity, heating, cooling, industry, buildings, and transportation (Pandiyan *et al.*, 2023), allowing for the identification of more achievable and affordable solutions for renewable and sustainable energy. The concept of smart energy represents a shift in paradigms from single-sector thinking to a coherent understanding of how to benefit from the integration of all sectors and infrastructures with a multi-scale perspective (Zheng *et al*., 2024).

In this paper the relevant aspects of the transition toward more sustainable airports are summarized and analyzed in the light of the smart energy paradigm in order to provide a base of knowledge. In particular, Section 2 is devoted to the electrification of the end uses and the production of renewable electricity. The use of hydrogen for propulsion, its production and integration in the airport context are analyzed in Section 3. Smart management is assessed in Section 4. Finally, Section 5 summarizes the overall potentials and challenges, and reviews current research and innovation activities.

2 ELECTRIFICATION

Airports require large amounts of energy, especially electricity. Operationally, airports consist of two main areas: the landside and airside. The landside caters to the passenger, while the airside caters to the aircraft and their related operations. Airports generally exhibit stochastic, nonlinear, and dynamic energy consumption, which depend on various factors (Ortega Alba and Manana, 2016). A strategy for more sustainable airport operation is the electrification of the users currently fed by fossil fuels (e.g. buildings and vehicles) using renewable electrical energy to power them. Avoiding fuel combustion enables not only decarbonization but also improvement of local air quality.

2.1 Renewable energy generation

Renewable energy exploitation in airports for electrical energy generation can be based primarily on solar photovoltaic (PV) technologies and wind turbines. Both technologies need particular provisions for their implementation in or near the airport context.

Airport buildings are generally large, low-rise structures with minimal shading typically with rooftops, façades, and parking lots that can provide ample space for solar installations. Surrounding airport land is often impractical for other uses due to aviation regulations and noise from low-flying aircraft. Therefore, airport solar PV systems could effectively utilize space that would otherwise be underutilized. However, unlike traditional land-based solar PV plants, the siting of airport solar photovoltaic systems requires careful consideration of air navigation safety and airport operations (Sreenath *et al.,* 2020a). Anurag *et al.* (2019) reviewed and summarized the challenges and precautions that must be adhered to for the deployment of safe PV projects at airports, and outlined a general approach to their implementation. Sreenath *et al.* (2020b) assessed the risk of solar PV at airports and

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identified the potential hazards to aviation safety from these plants. The main challenges are related to the potential for glare interference with pilot vision, radar signal distortion, and airspace encroachment. Other possible risks are (i) bird strike resulting from birds using PV arrays for seeking shade and finding insects (even though DeVault *et al.* (2014) suggested that installing PV arrays could in fact decrease bird-strike risk compared to the grass or other natural land covers usually found in airports); (ii) detachment of solar PV system in strong winds; and (iii) electrical faults that may lead to electric shocks and possible fire outbreaks. Technical hurdles involve airport-specific weather and soil conditions, selecting appropriate PV technology, mitigating glare impact, choosing suitable sites, and integrating with the power grid. Therefore, careful planning, comprehensive glare assessment, and meticulous implementation are crucial for the success of these solar farms (Sreenath *et al.*, 2020a). Examples of PV installations in airports reported by Sreenath *et al.* (2020a) are: (i) the Indianapolis airport (Indiana, USA) solar farm with an installed capacity of 25 MW; (ii) the plant installed in Kuala Lumpur International Airport (Malaysia) of 19 MW; and (iii) the plants that sum 30 MW at Cochin International Airport (India).

According to Cuadra *et al.* (2019), airport zones, either at or even within their boundaries, present promising opportunities for wind energy generation, as they encompass wide, unpopulated, open spaces, minimize wind turbulence, and benefit from existing power grid connections. Despite the potential of airport zones for wind energy projects, the existence of aeronautical easements, i.e. areas where tall structures are prohibited, limits the feasibility of wind turbine installations. Easements are essential not only to prevent collisions between aircraft and wind turbines but also to mitigate other detrimental effects that could endanger air safety. These include turbulence that might hinder takeoff and landing operations, and complex electromagnetic scattering and interference with air traffic control systems. Nevertheless, Cuadra *et al.* (2019) listed airports that have evaluated wind energy exploitation: Dulles (Washington, USA), Clark County (Nevada, USA), Dekalb County (Indiana, USA), Rooks County Regional Airport (Kansas, USA), Burlington (Vermont, USA), Boston (Massachusetts, USA), Rome (Italy), East Midlands (UK) and Gran Canaria (Spain).

2.2 End uses electrification

Heat pumps are a viable option for the replacement of combustion-based technologies for heating buildings. Moreover, heat pumps, being reversible, can also provide cooling during the summer. They can reduce carbon emissions by leveraging both on their high efficiency and on the possibility of using renewable electricity. Heat pumps constitute an additional electrical load, but they present high flexibility when coupled with thermal energy storage or when demand side management strategies are implemented by modulating building temperatures (Fambri *et al*., 2023).

According to Ficca *et al.* (2023), in the next few decades, battery-powered aircraft are going to represent a significant share of the commuter segment and also play a role in the regional segment of the market. Aircraft electrification requires airports to deploy ultra-fast charging stations, similar to those used for electric vehicles. These stations, capable of fully charging an aircraft in 30 minutes, can be situated at gates or remote locations. To ensure sustainability, the electricity powering these stations should derive from renewable sources.

Ground support equipment plays a crucial role in facilitating efficient aircraft operations at airports. Several GSE types exist, but the most frequently utilized GSE include (Alruwaili and Cipcigan, 2022):

- Aircraft Push-Back Tractor: responsible for propelling airplanes away from gates and onto taxiways, particularly when aircraft are not under their own engine power.
- Baggage Tractor: used to move baggage carts or cargo containers between aircraft and airport facilities.
- Belt Loader: allowing loading and unloading of baggage and cargo from airplanes using a continuous conveyor belt.
- Container Loader: designated for handling containerized cargo, pallets, and other bulky payloads, ensuring their safe and secure transfer between aircraft and ground transportation.

Transitioning to low- or zero-emission GSE (e.g. electric- or hydrogen-fueled) and implementing supporting infrastructure represents a promising approach to mitigate airport-related greenhouse gas emissions. While standard electric vehicles primarily focus on power consumption during

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transportation, electric GSE must also account for energy utilization during service procedures. The operation of GSE at airports is primarily determined by flight schedules, which are pre-planned and predictable. This predictability eliminates the uncertainty associated with unexpected electric GSE departures and gives the opportunity to plan their charging (Zoutendijk and Mitici, 2024). It even enables smart charging or Vehicle-to-Grid applications (Alruwaili and Cipcigan, 2022). GSE can also be electrified indirectly, i.e. by producing hydrogen through renewable electrical energy and then using it in fuel-cell powered GSE (Degirmenci *et al.*, 2023a). For example, Berlin Brandenburg Airport (Germany), Montréal Pierre Elliott Trudeau International Airport (Canada), and Osaka Kansai International Airport (Japan) are testing hydrogen technologies (Baxter *et al.*, 2018).

Beyond airport vehicles, passenger vehicles must be considered. Airports, unlike other commercial or residential districts, serve as critical links between ground transportation and air travel. This unique characteristic requires a different approach to electric vehicle (EV) management in airport parking lots. Firstly, airports typically have designated areas for short-term and long-term EV parking. Long-term EV parking is typically utilized by passengers who book round-trip tickets and drive to the airport. These passengers often book their tickets in advance, allowing airport operators to anticipate parking demand based on flight schedules. Secondly, long-term EV parking spaces offer an opportunity to harness the energy storage capability of the vehicles. By aggregating the battery power of these parked EVs, airports can potentially utilize them as distributed energy storage (Guo *et al.*, 2023).

3 HYDROGEN

Sustainable fuels can be used to decarbonize aircraft that cannot be directly electrified. In the context of these fuels, liquid hydrogen could play a relevant role for the commuter segment feeding fuel-cells, for the regional segment for fuel cells and combustion engines, and for the narrowbody segment for combustion engines only (Ficca *et al.*, 2023).

When hydrogen-aircraft are used in a particular region, an airport could serve as a hydrogen hub within a wider hydrogen energy system around which multiple hydrogen users can cluster (Ochoa Robles *et al.*, 2019). The airport could act as a major consumer for which a dedicated hydrogen supply could be established. This could potentially lower supply costs for other hydrogen applications in the vicinity due to economy of scale. The role of the airport might overshadow all other hydrogen consumption from surrounding sectors, making the design of liquid hydrogen supply and refueling systems in the airports a unique aspect of the future hydrogen economy. It is important to investigate potential synergies or resource conflicts before implementing liquid hydrogen systems at airports, as other sectors might need a hydrogen supply infrastructure a decade earlier than larger commercial aircraft (Holtzen *et al.*, 2022). The cost of liquid hydrogen is influenced by the position of the hydrogen production and liquefaction plants (Holtzen *et al.*, 2023 and Taha *et al.*, 2024), which may be in different locations (i.e. by providing gaseous hydrogen to the liquefaction plant through pipelines).

Hydrogen is generated through an electrochemical process (i.e. electrolysis) that involves the division of water molecules into gaseous hydrogen and oxygen. This process takes place in an electrolyzer. Electrolyzers are primarily categorized by their operating temperature. Low temperature electrolyzers are alkaline and polymer electrolyte membranes (PEM), which operate at temperatures up to 90 °C. In contrast, high-temperature technologies that are still being developed are mainly the solid oxide electrolyte cell (SOEC), which can operate at temperatures ranging from 700 °C to 900 °C (Barbaresi *et al.*, 2022). As a rule of thumb, approximately 50 kWh of electrical energy are necessary to produce 1 kg of gaseous hydrogen (Otto *et al.*, 2022).

Established industrial processes for hydrogen liquefaction typically encompass two stages of refrigeration, each catering to distinct temperature ranges. Initially, the feed gas of hydrogen is precooled to an intermediate temperature of approximately 80 K using one or more aluminum brazed plate-fin heat exchangers. Liquid nitrogen is currently used for the precooling, then it evaporates and is wasted into the atmosphere. Subsequently, the precooled hydrogen undergoes further cooling and liquefaction via a closed-loop cryogenic refrigeration cycle. The cryogenic refrigeration cycle employed in these liquefaction processes is either a helium Brayton cycle or a hydrogen Claude cycle (Cardella *et al.*, 2017). In order to scale up to the production rate necessary for aviation, closed-loop refrigeration cycles are also proposed for the precooling step in order to reduce the specific energy consumption. The

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most promising seems to be the high-pressure hydrogen cycle with a mixed-refrigerant precooling cycle that allows a specific consumption of 6.2 kWh per kg of liquid hydrogen (Cardella *et al.*, 2017).

Both the production and liquefaction process need a consistent amount of electrical energy and both discharge a consistent amount of heat into the environment due to the irreversible phenomena that take place in electrolysis (about 13.5 kWh/kg according to Otto *et al.* (2022)), and due to heat rejection in the cooling cycles. In both cases heat is available at low temperatures, but with a heat pump it can be upgraded and distributed through district heating networks to end-users. Waste heat recovery enables more sustainable liquid hydrogen production both in terms of use of resources and production costs (IEA, 2023).

Many aspects are involved in the design of the liquid hydrogen supply chain for airports (Degirmenci *et al.*, 2023b), but from the smart energy perspective several reference points should be considered when selecting the position of the hydrogen production and liquefaction plants: (i) the renewable electrical energy production site; (ii) the airport and other hydrogen users; (iii) the transmission infrastructure for the gaseous hydrogen (i.e. the so-called "hydrogen backbone") from the production site to the liquefaction plant; and (iv) the final users for the heat (e.g. the airport).

Hydrogen is also a feedstock for the Power-to-Liquid process that produces a SAF in the form of liquid synthetic kerosene. The Power-to-Liquid process has three major components: (i) water electrolysis for hydrogen production; (ii) carbon capture to provide the carbon dioxide; and (iii) hydrocarbon synthesis (e.g. through the Fischer-Tropsch route or the methanol route) and upgrading (Schmidt *et al.*, 2018). Therefore, when dealing with such fuels, among the reference points that are listed above for liquid hydrogen, the carbon dioxide sources (e.g. waste incinerators, cement, and paper & wood industries) and existing refineries must be added in order to optimize the supply chain (Wassermann *et al.*, 2022).

4 MANAGEMENT

When dealing with electricity production from PV panels or wind turbines the airport energy system must face their non programmability. This means that energy management systems are fundamental in finding flexibility in the user side that is missing in the production side. Goh *et al.* (2024) proposed a new energy management strategy based on airport operational characteristics that fosters the decarbonization of the airport enabling the integration of wind, photovoltaic, and waste-to-energy generation. Flexibility can also be enabled by exploiting energy storage systems. They can be installed on purpose (e.g. batteries) but also available in the airport for other purposes (e.g. battery electric vehicles), as discussed in Section 2.2. Moreover, it is also possible to find virtual and distributed storage through the implementation of demand side management strategies or through airport participation in energy communities.

4.1 Storage

Microgrids, initially envisioned as compact energy grids catering to rural electrification, have expanded into complex distribution networks, finding extensive application in low-voltage residential and industrial settings. Their ability to seamlessly switch between grid-connected and islanded operations during faults or planned disconnections underscores their adaptability. Microgrids are recognized as a promising solution for incorporating high penetrations of distributed renewable energy sources into modern distribution networks, enhancing the flexibility, reliability, resilience, and energy security of local energy networks. Airports, like ports, act as hubs for multimodal transportation and diverse economic activities, enabling cross-sector coupling. Integrating microgrids into their energy systems can propel airports toward low-carbon operations or even carbon neutrality. However, research in this sector remains the least explored among transportation-related fields, with a limited number of journal articles exploring the electrification challenges faced by airports (Micallef *et al.*, 2023). Airport microgrids can benefit from the presence of battery energy storage systems (BESS) (Ollas *et al.*, 2023). Given the large size and complexity of an airport, multiple BESS can be installed and further benefits can arise from their coordination (Morstyn *et al.*, 2018). Moreover, BESS can also provide both long-term and short-term ancillary services (Prakash *et al.*, 2022).

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To address the growing impact of electric vehicles on the power grid, vehicle-to-grid (V2G) technology has emerged as a promising solution. V2G enables EVs to act as both energy consumers and suppliers, allowing them to charge during off-peak hours and discharge power back into the grid when demand surges. This bidirectional energy flow not only enhances grid stability but also empowers EV owners to become active prosumers, earning revenue from the energy stored in their idle vehicles. Liu *et al.* (2024) assessed a significant potential from ground electric vehicles in airports: the airside vehicles have the largest share, followed by the landside vehicles in the ground transportation center (i.e. passengers' cars, taxis, and shuttles) and the staff parking lots. To optimize V2G benefits, carefully controlled charging and discharging processes are crucial to minimize negative grid impacts. V2G stands out as a superior technology compared to conventional methods, as it effectively manages grid fluctuations by treating EVs as controllable loads. Moreover, V2G can also be a way to contribute to frequency regulation ancillary services (Alruwaili and Cipcigan, 2022). The advantage of doing this in airport is that the operation of the vehicles, and therefore their position, is more predictable: (i) the electric GSE charging and discharging sequence can be forecasted (Ajay *et al.*, 2023) being linked to the flight schedule; and (ii) the passengers who use long-term parking lots generally book parking in advance according to their flight plan. Guo *et al.* (2023) showed that the adoption of the V2G strategy in parking lots can improve the economic and operational performance of the airport grid. More specifically, V2G cases can reduce 12.9 % of OPEX compared to vehicles as simple loads. Alruwaili and Cipcigan (2022) showed instead that electric GSE can provide a significant profit by participating in frequency regulation ancillary service with the use of the V2G mode. To proceed in this direction, it will be essential to propose and test strategies to involve passengers owning EVs, as well as incentives to remunerate the potential exploitation of their batteries.

Guo *et al.* (2022) also proposed to use electric aircraft batteries as sources of flexibility during charging. Their new concept of Aviation-to-Grid flexibility utilizes an electric aircraft charging system with the battery swap method to provide grid frequency response services. They estimated annual revenues from this service that could cover 19.8 % to 30 % of energy consumption costs of electric aircraft charging in future airports.

4.2 HVAC smart management

Airport terminals are characterized by expansive and open spaces with non-uniform heat gains, often featuring wide glazing to harness natural light and enhance the aesthetic appeal of the facilities. HVAC systems consume substantial amounts of energy, accounting for up to 40 % of total airport electrical consumption. Most of this energy expenditure is attributed to air conditioning systems, while heating systems, with the exception of minor applications like hot water provision, can also nearly monopolize gas consumption at an airport (Kotopouleas and Nikolopoulou, 2018). While HVAC systems typically rank among the highest energy end-users alongside lighting, outdoor temperature and daylighting play a pivotal role in shaping energy demand patterns (Ortega Alba and Manana, 2016). Kotopouleas and Nikolopoulou (2018) delved into findings from extensive field investigations conducted in three airport terminal buildings in the United Kingdom. Indoor environmental conditions were monitored across seasons, and simultaneous structured interviews were conducted. The results substantiate that airport users exhibit remarkable thermal adaptability and extensive temperature comfort ranges, with averages of 6.1 °C in summer and 6.7 °C in winter. These insights underscore the possibility of energy conservation by optimizing indoor temperature settings.

Nevertheless, in the light of the shift toward heat pumps, this flexibility in temperature can also be exploited as heat (and therefore electrical) storage (Fambri *et al.*, 2023) by increasing building temperature when cheap or renewable electrical energy is available, and by letting the building cool down when expensive or fossil electrical energy would be used. Buildings have already been successfully exploited as thermal storage in the residential sector where a small deviation (i.e. ± 0.5 °C) is acceptable with respect to the comfort temperature (Kensby *et al.*, 2015). Since airport buildings are in general larger than residential buildings and occupants allow for a wider range of acceptable temperature, the potential for load shifting is higher.

In order to exploit this potential, smart control strategies must be implemented. Model Predictive Control (MPC) is gaining attention in the smart management of energy systems. MPC uses a model of

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the controlled system and an optimization algorithm to evaluate the most profitable control strategy. The optimization is done every time-step for a prediction horizon where the forecast of the external disturbances is known. Then, the control is actuated for the first time-step, and the optimization is repeated shifting the prediction horizon one time step forward (Saletti *et al.*, 2020). This strategy has been demonstrated in many tertiary contexts such as school complexes and university campuses (De Lorenzi *et al.*, 2020), hospitals (Gambarotta *et al.*, 2023), and airports (Yue *et al.*, 2023). In particular, Yue *et al.* (2023) presented a control retrofit strategy to improve the energy efficiency of existing building HVAC systems by incorporating data-driven MPC into the existing building automation systems. They also applied it to the existing HVAC system of an actual airport terminal. An average daily energy consumption reduction of 24.5 % and a discomfort time reduction from 70.2 % to 5.7 % on average were achieved following the control retrofit. Chinde and Woldekidan (2024) presented an MPC approach for scheduling chillers, pumps, and the thermal energy storage system of the energy system of a large airport. Simulation results showed that both energy and demand charge costs were reduced with MPC when compared to the baseline strategy. A field implementation was proposed as a user interface that can inform plant personnel of the MPC strategy while they are manually scheduling the plant operation and a 7 % saving was achieved.

As stated, MPC relies on the forecast of external disturbances that, when dealing with heating and cooling, are mainly external temperature and irradiance (Saletti *et al.*, 2020), but can also include other parameters, such as the number of occupants since they act as a source of heat and determine the request for fresh air. For this reason, models have been proposed for the forecast of passenger flows based on flight schedules (Lin *et al.*, 2023).

4.3 Energy communities

An energy community constitutes a structured assembly where small producers can consolidate their resources to establish a more substantial energy collective. This structure facilitates the redistribution of surplus energy among its members, thereby circumventing the complexities associated with grid negotiations and mitigating losses attributed to long-distance energy transportation. Moreover, it provides a streamlined platform for energy-related negotiations (de São José *et al.*, 2021).

Energy communities can assume a diverse array of functions within the dynamic electricity market. They can operate as both prosumers and distributors of renewable energy, enabling localized energy sharing and consumption (collective self-consumption) through community grids, effectively acting as local distribution system operators. This multi-faceted approach allows energy communities to bridge the gap between distributed energy resources and end-users, fostering a decentralized energy ecosystem and promoting collective self-consumption. They can optimize energy management and reduce reliance on traditional grid infrastructure, contributing to building up a more sustainable and resilient energy background (Hatziargyriou, 2023).

Airports can find flexibility and gain revenues also by promoting and participating in energy communities since they are used to manage their internal microgrid infrastructures, and they can see the community as an extension. In fact, microgrids serve as an enabling framework for energy communities, effectively facilitating the integration of renewable energy sources. Energy communities offer significant potential for energy transition, encompassing flexibility, interconnectedness, bidirectionality, and complementarity (Wu *et al.*, 2022).

5 ONGOING RESEARCH AND INNOVATION ACTIONS

Starting from the analyses reported above, Table 1 summarizes the potentials and challenges of implementing smart energy solutions in airports.

To demonstrate the feasibility to exploit these potentials and face these challenges the European Commission funded four projects in recent years under the Horizon 2020 program through two dedicated calls (i.e. Smart Airport call and Green Airport call): ALIGHT (alight-aviation.eu/), OLGA (www.olga-project.eu/), STARGATE (www.greendealstargate.eu/) and TULIPS (tulips-greenairports.eu/).

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The ALIGHT project started on November 1, 2020 and will last for 5 years. The partnership involves four airports: Copenhagen (Denmark), Rome (Italy), Vilnius (Lithuania), and that of Warsaw (Poland) which is under construction. The main activity in the smart energy framework deals with the experimentation of BESS in an airport environment in Copenhagen and its smart management also accounting for ancillary services. Moreover, the potential of smart charging and V2G in airports has been assessed (Barnekov Thingvad *et al.*, 2023).

The OLGA project (lasting 5 years from October 1, 2021) involves Paris Charles de Gaulle Airport in France, Zagreb Airport in Croatia, Milan-Malpensa in Italy, and Cluj in Romania. It focuses on the energy transition of GSE through their electrification or through the use of alternative fuels such as hydrogen, and the installation and optimization of charging infrastructures. Moreover, the project will demonstrate green hydrogen production and use in airports through the design and installation of a plant in Milan Airport.

The partnership of the STARGATE project (lasting 5 years from November 1, 2021) also aims at the electrification or hydrogen fueling of taxiing and ground handling. The activities are performed in the four participating airports: Brussels (Belgium), Athens (Greece), Budapest (Hungary) and Toulouse Blaignac (France).

Finally, the TULIPS project (lasting 4 years from January 1, 2022) involving Amsterdam Airport Schiphol (The Netherlands) as the lighthouse, and the airports in Oslo (Norway), Turin (Italy), and Larnaka (Cyprus) as followers, will implement improved airside electric vehicles including storage and direct PV charging, and integrated heat storage systems into the existing hotel infrastructure.

Table 1: Summary of potentials and challenges for smart energy in airports

Feature	Potentials	Challenges
PV panels	ample space for installations	hazards to aviation safety; site specific technical hurdles
Wind turbines	wide, unpopulated open spaces; minimized wind turbulence	aeronautical easements
Heat pumps	reversible operation; high efficiency; possible use of renewable electricity	additional electrical load
Electric aircraft	Aviation-to-Grid flexibility	ultra-fast charging
Electric GSE	predictable charging; smart charging; Vehicle-to-Grid	energy utilization for service
Passenger electric cars	parking booked in advance based on flight schedule; exploitable vehicle energy storage	infrastructure; regulation
Hydrogen	heat recovery	plant position logistics
Energy storage	long-term and short-term ancillary services	coordination
HVAC smart management	large buildings exploitable as thermal storage; wide range of acceptable temperature for load shifting	implementation; interface with current management systems
Energy communities	straightforward extension of airport microgrid	regulation

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6 CONCLUSIONS

This paper presented an overview of the current state, challenges, and main drivers for the implementation of the concept of smart airports in the context of energy transition, both airside and landside. Several recommendations and key guidelines can be drawn for the different airport areas, regarding electrification, fuels, and management.

Firstly, airports present a unique opportunity for the exploitation of renewable energy sources. Solar photovoltaic technology and wind turbines can be utilized for electrical energy generation. The ample space provided by airport buildings allows for extensive solar installations on rooftops, façades, and parking lots. However, careful siting of these systems is crucial to avoid interference with air navigation safety and airport operations.

Building on this, heat pumps offer a viable alternative to combustion-based technologies for heating and cooling buildings. Moreover, taking into account the human factor, airport users have shown adaptability to a wide range of temperatures. This flexibility can be leveraged to optimize indoor temperature settings and reduce energy consumption. Smart control strategies that take advantage of this flexibility can be implemented using Model Predictive Control.

The transition to electric ground support equipment can significantly mitigate airport-related greenhouse gas emissions. Furthermore, the energy storage capabilities of electric vehicles can be utilized through the effective management of electric vehicle parking by airport operators. The integration of microgrids into airport energy systems can enhance flexibility, reliability, and energy security. Battery Energy Storage Systems can further improve the performance of these microgrids. Vehicle-to-Grid technology and Aviation-to-Grid flexibility have the potential to reduce operational expenses and even generate revenue, covering a significant portion of the energy consumption costs of electric aircraft charging.

Nonetheless, energy communities, enabled by microgrids, offer significant potential for energy transition and can help airports reduce their carbon footprint. These communities are small-scale power grids that can operate independently of the main grid, further enhancing the sustainability of airport operations. This ties together the various strategies discussed, highlighting the interconnected nature of sustainable energy solutions in airport settings.

In addition to these strategies, liquid hydrogen has the potential to play a significant role in decarbonizing air travel. Airports could serve as hubs for hydrogen production and distribution. The production and liquefaction processes of hydrogen, which involve electrolysis and a two-stage refrigeration process, respectively, generate waste heat that can be harnessed for district heating. The location of these plants should be carefully considered to maximize energy efficiency and to reduce costs.

NOMENCLATURE

BESS	battery energy storage systems
EV	electric vehicle
GSE	ground support equipment
HVAC	heating, ventilation and air conditioning
ICT	information and communication technology
MPC	model predictive control
OPEX	operational expenditure
PEM	polymer electrolyte membranes
PV	photovoltaic
SAF	sustainable aviation fuel
SOEC	solid oxide electrolyte cell
V2G	vehicle-to-grid

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