Future Aircraft Stands

Conceptual Design

Action & Implementation Guidelines for Airports, Regulators, and Manufacturers

March 2025
ALIGHT Deliverable D5.3

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreeement No 957824.

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Summary

With a growing focus on reducing aviation's environmental impact, this study explores future aircraft stands in combination with cleaner energy, available energy technologies, smarter handling technologies and expected development in traffic. Conducted within the ALIGHT consortium, it draws from expertise across airports, manufacturers, and research institutions

Propelling towards a greener future

The aviation industry is a critical driver of global connectivity and economic growth, but it is also a significant contributor to greenhouse gas (GHG) emissions, accounting for approximately 2.5% of global CO_2 emissions, and around 3.5% of total anthropogenic climate impact when factoring in non-CO_2 effects such as contrails and nitrogen oxides (Source: Our World in Data, 2024). These emissions are projected to rise sharply due to increasing demand for air travel and freight, unless substantial mitigation measures are implemented. On a local level, air pollution of ultra-fine particles and noise from turbines are critical to bring down.

In recognition of these challenges, global efforts are underway to transition the aviation sector toward sustainability. The European Green Deal and policies, such as the Fit for 55 package, are driving stricter emission reduction targets and investments in zero-emission aircraft technologies. With the ambition of reaching net zero CO_2 emissions by 2050 from all flights within and departing from the EU, airlines, manufacturers, and governments worldwide are exploring electric, hydrogen as well as hybrid propulsion as transformative solutions. For these reasons, a focus on battery-electric and hydrogen propellants as well as autonomous operations for taxiing are considered for the aircraft stand of the future.

The future of a more sustainable aviation industry hinges on the development of infrastructure capable of supporting new technologies. Aircraft stands designed to accommodate electric and hydrogen-powered airplanes and specialised ground support equipment play a pivotal role in enabling the transition. These stands integrate facilities for rapid electric charging, hydrogen refuelling, and energy-efficient operations, reducing the carbon footprint of airport activities. As a core part of green aviation, such infrastructure helps to maximize environmental benefits, align the industry with global climate goals, and foster a more sustainable future for air transport.

Who is this document primarily for?

Regulators

Both national and international regulatory bodies play a vital role in setting appropriate standards and regulations to accelerate the green aviation transition.

Airports

Airports serve as hubs for the green aviation transition by enabling sustainable infrastructure, alternative fuels, and efficient ground operations.

Manufacturers

Manufacturers advance green aviation by innovating efficient aircraft, sustainable technologies, and low-emission ground equipment.

Key insights and findings

Electrification

- Short-haul battery electric flights are technically feasible in the near future. In 2050 it is assumed that all aircraft will have an on-board battery that will need recharging.
- Up to 3 MW MCS equipment and smart charging standards will be available from road transportation.
- Using mobile MCS combined with mobile battery banks offers flexible and scalable planning.
- Electric driveline for turbines may be more effective than fuel-burning turbines, enabling aircraft to fly on battery close to airports and move by electric power on ground.
- Pure-electric regional (<1500km) routes for narrow-body aircraft are expected to enter the market first, together with hybrid-electric regional flights.
- Pure-electric aircraft are limited to around 10% of total air traffic growth due to constraints in range related to battery weight, energy density, and energy-to-speed ratios.
- Longer haul flights will need a hybrid propulsion configuration even if battery density would triple.

Pushback & GSE

- Diesel-powered pushback tractors are among the top three GSE contributors to emissions and noise pollution in airports.
- Airports are already investing in transitioning to electric (and in some cases hydrogen) ground support equipment because of the immediate positive impact on emissions
- The business cases for electric GSE are positive, although they require substantial up-front investments.
- Significant investments in the airport electric grid is required over the coming years to accommodate electrification of many airport processes including GSE.
- Fully autonomous GSE solutions are still under development while partially autonomous / remote controlled solutions are on the market.

Hydrogen

- A few large aircraft manufacturers are committed to hydrogen strategies (e.g. Airbus, Rolls Royce, ZeroAvia).
- A phased introduction is expected for hydrogen with mobile gaseous bowsers servicing remote stands appearing in 2025-2030.
- Hybrid stands for gaseous hydrogen (GH2) and kerosene are expected to appear in 2030-2040.
- While GH2 systems are easier to implement initially, liquid hydrogen (LH2) provides the scalability needed for high volume and longer distances.
- Large-scale LH2 storage may appear in 2040 or later, although experts don't agree if intercontinental LH2 wide-body flights (>4000 km) will ultimately ever emerge.

Deployment

- Existing aircraft stands can be upgraded to support multiple propellants / future fuels.
- Upgrades of aircraft stand infrastructure require significant investments.
- Including aircraft stand operations into smart energy management and planning will be critical to optimise energy efficiency.
- Cyber security is critical before autonomous solutions can be scaled.
- Standards for autonomous systems, hydrogen refuelling, and electric charging are still evolving, creating uncertainties and delays.
- Shifting to more sustainable aviation is incremental, requiring careful planning to align infrastructure with technological maturity.
- While some have organised for innovation, the general innovation capability at some airports is relatively low.
- Adoption of new technology requires more collaboration between regulators, manufacturers, and airports.

Observations and insights

The current technology and regulatory landscape serves as a baseline to understand what is needed to future-proof aircraft stands

Electrification

The value and business case of electrification, for both aircraft and GSE is positive, since CO2 emissions are reduced, and operating and maintenance costs are significantly lower. Airports are already investing in transitioning to battery electric operations for most ground support equipment because of the immediate positive impact on emissions, which is substantial for this type of equipment. Similarly, GSE manufacturers have been growing the market share for electric equipment for more than two decades.

For electric aircraft, the underlying drivers are the same as for eGSE, although scaling barriers are quite different. The low battery energy density and energy-to-speed ratio are factors that limit flight range and capacity. Bigger planes require larger batteries, which will add extra weight to the plane. For these reasons, pure-electric flights are considered viable only for regional routes in Europe (approx. 10% of air traffic), while hybrid-electric aircraft will take the stage for continental (1500 km-4000 km) and intercontinental routes (Eurocontrol European Aviation Overview, 2023). Even so, significant advancements in battery technology will be necessary over the next 5–10 years for pure-electric aircraft to replace the existing fleet, as today's short-haul routes carry far more passengers than the first generation of electric aircraft can accommodate.

Electric aircraft require a lot of electric energy to be transferred onto the on-board batteries within short, standard turnaround times to be competitive, requiring robust charging solutions at power levels upwards of 2-3 MW to be available at the aircraft stand. The combined increase in energy demand across multiple charging points will therefore have a considerable impact on the broader power systems in and around airports.

From a grid perspective, airports are likely to face power capacity bottlenecks that impact infrastructure at other places than the aircraft stand, and energy optimisation such as flexible energy use and battery storage systems will be increasingly relevant.

Airports are already integrating real-time data from multiple sources into their ground control operations, and this will continue to support the optimisation of energy efficiency and safety of the charging logistics across the airport.

Regional electric flights are likely to be the first wave of the transition, and airports can already now implement charging solutions based on existing technologies

Hydrogen fuelling

As a potential future aircraft propellant, hydrogen holds the promise to replace Jet fuel on intercontinental flights. If hydrogen is generated using renewable sources, and can be distributed without leaks, the entire energy chain is essentially emission-free.

Industry experts are not in full agreement on the feasibility of large-scale hydrogen-based aviation before 2050. The technical challenges are rooted in the properties of hydrogen, which has a lower weight and higher volume than jet fuel, requiring a fundamentally different aircraft design. Changes in design include repositioning of the onboard fuel tanks from the wings to the fuselage and cryogenic insulation with new materials to keep the hydrogen below its boiling point at -253 °C and avoid evaporation.

A few large aircraft manufacturers are committed to hydrogen strategies with announced narrow-body, continental aircraft to enter the commercial market by 2035-45, and solutions to convert existing aircraft to fuel cells are also announced.

Safety challenges related to hydrogen fuelling at aircraft stands are well known in the industry and will impact the safety buffers and processes related to fuelling at aircraft stands. Although hydrogen is less flammable than Jet A fuel, it is much more volatile and requires very low energy to ignite - less than 0.02 mJ, which can be provided by static electricity. Some of the new safety measures will therefore involve advanced detection and containment systems.

This leads to an expectation that remote stands, rather than contact stands, will offer a better initial controlled environment for hydrogen fuelling, reducing safety risks compared to high-traffic areas, and allowing airports to make trials and tailor their stand designs to individual needs as they evolve in early stages of hydrogen aviation.

Liquid hydrogen has a leakage risk from cryogenic storage and distribution facilities, with 2050 leakage rate estimates ranging from 0.3% to 0.9% of the total liquid for refuelling station and up to 6% of the total liquid for above-ground storage (Source: Oxford Institute for Energy Studies, 2024).

Manufacturers like Airbus, ZeroAvia and Rolls Royce all invest in hydrogen propulsion and have extensive research and development programmes to bring continental aircraft into the market by 2035-2045.

Due to the fundamental challenges with liquid hydrogen and its impact on aircraft design, the initial growth is expected to be using gaseous hydrogen at 350-700 bar.

The first commercial planes are expected to be hybrid (hydrogen-electric or hydrogen-kerosene) because gaseous hydrogen by itself does not have the volumetric energy density necessary for aircraft to reach destinations above approximately 1000 km.

Due to these limitations, liquid hydrogen will be necessary to accommodate continental flights in the future.

Besides the loss itself, and associated safety concerns, free hydrogen molecules are considered harmful in the outer atmosphere since it breaks down ozone and prolongs the life of methane, both having impact on global warming. Real concerns are therefore rising that containment of hydrogen using new materials and storage placements will be essential to minimise leakage and boil-off, and regulation is expected to emerge in this area.

How to make it happen

Based on the expected development of alternative propulsion in commercial aviation, airports, manufacturers and regulators are urged to align their short-term actions to their long-term strategies.

Electric and hybrid-electric on regional routes up to 500 km & fully electric GSE.

2030

Hybrid stands as standard with hybrid-electric up to 1500 km & autonomous operations will mature for specific types of mobile GSE.

2040

Hydrogen and electric propulsion will expand for regional and continental flights, while liquid fuel / SAF remains dominant on intercontinental routes & autonomous GSE will be fully implemented.

2050

No-regrets moves

- Build (and upgrade to) remote, dedicated narrow-body electric aircraft stands, assess energy demand to ensure timely supply, invest in autonomous electrified GSE to enhance sustainability and efficiency, and implement cybersecurity.
- GSE and aircraft manufacturers are advised to prioritise electrification, automation, and standardised infrastructure development, while ensuring timely knowledge-sharing and collaboration with airports to enable efficient future operations.
- Introduce standards to support electric and hydrogen aircraft, upgrade infrastructure, ensure safe operations, adjust landing fees, promote innovation, encourage test environments, and engage with industry leaders on evolving needs.

Add to existing master plans today

- Plan for mobile aircraft recharging units, future hydrogen operations with safety measures, staff training, and a phased hydrogen infrastructure roll-out from mobile refuelers to large-scale LH2 by 2050.

Experiment today to create the future

- Create test beds and partner up to trial emerging technologies like e-planes, h-planes, and new propellants. Tracking advancements ensures future investments align with the most promising solutions for long-term readiness.

Context & background

The context and background chapter provides essential information about how this document is anchored within ALIGHT, the scope and methodology as well as an outline on the value drivers from a business perspective.

Introduction

The aircraft stand is a pivotal piece of infrastructure in the energy transition because it connects all the critical stakeholders who can act now - together - to bring change.

A call to action

Without aggressive decarbonisation efforts, the share of global emissions from aviation could rise dramatically. The aircraft stand is considered a key piece of infrastructure in the energy transition because it physically and operationally connects the major stakeholders: airports, airlines, aircraft manufacturers, GSE manufacturers, GSE handlers, and energy companies.

In the energy and aviation sectors, innovation levels have historically been lower compared to other industries due to high regulatory constraints, safety requirements, and reliance on well-established technologies. With pressures from climate change, rising sustainability demands and advances in alternative propulsion systems, the sectors must accelerate its pace of innovation significantly.

This guide aims to inspire airport stand designers and master planners to act on several levels to connect the present with the future:

- **No-regret moves**. What can be done *now* without significant risk of failed investments?
- **Add to existing plans today**. What budgets can be committed *now* within a 10-15 year timespan?
- **Experiment today to create the future**. What innovation initiatives can be taken *now* to de-risk longer-term investments?

The energy transition is inescapable, and businesses need to find ways to make the transition also profitable, and this is the logic upon which successful innovation strategies of airports will be built.

Scope

This guide has a specific focus on the aircraft stand, and is therefore concerned with its physical configuration, infrastructure, and enabling technologies. Effects on the surrounding airport infrastructure, and on the wider energy production, transmission, and distribution systems are only mentioned when aircraft stand design choices have specific consequences.

The energy sources in scope are primarily battery-electric and hydrogen as well as hybrid solutions, and to some extent sustainable aviation fuel (SAF). Aircraft flying on electric energy and/or hydrogen fuels are considered to be commercially viable at scale when they have passenger capacities of a narrow-body ICAO code B and C. As such, smaller aircraft are not expected to represent a significant proportion of commercial aviation and therefore specific stand designs for those aircraft are not included in this guide.

Creating long-term strategies is challenging for most organisations because the business environment is generally increasingly volatile. However, for airports in particular planning ahead has always had a relatively longer scope, which provides a genuine opportunity to innovate for both the short and the long term. In terms of timeframes, therefore, this guide covers the next 25 years.

The audience is primarily airport designers and planners, regulators, and manufactures of aircraft and ground support equipment. In terms of geography, the recommendations have a broad focus on European airports although the applicability is considered to be global. When useful, Copenhagen Airport has been used as a data source in examples.

The energy transition is inescapable, and businesses need to find ways to make the transition also profitable.

As part of the Horizon 2020 programme ALIGHT, one workstream focuses on the design and implementation of future aircraft stands to support the transition to sustainable propulsion and automation. This document provides practical recommendations for airports, aircraft and ground equipment manufacturers, and regulators.

Aircraft stand of the future

The primary focus in ALIGHT is on supply and infrastructure for sustainable and renewable aviation fuel, as well as renewable energy sources for ground activities. The aircraft stand of the future is a key enabler for both sustainable propulsion and renewable GSE. As such, this document focuses on the apron stands for aircraft classified as Code B and C under the ICAO Aerodrome Reference Code. Codes B and C were selected because those airplanes are most widespread in Europe. Broader infrastructure such as storage, distribution, and conversion of energy is handled in other tasks within the ALIGHT project and is not part of this guide.

This document has two main objectives. Firstly, the aim is to present several generic aircraft stand designs that can be realised in a specific airport aligned to the local master planning and gate strategies. The generic stands are visualised and explained in the following chapter on *Stand Designs*. Since no aircraft stand can operate without ground support, the chapter *Implications for ground support* focuses on the electrification and autonomous development of current and new GSE on the aircraft stand.

Secondly, the purpose is to provide guidelines on what the key stakeholders can do to accelerate the transition in relation to the aircraft stand. The chapter *How to Make it Happen* therefore includes a specific section per stakeholder on practical short-term, mid-term, and longer-term recommendations.

´This guide will act as a practical instrument to realise the stand of the future. It contributes to the ALIGHT replication toolbox with the ambition of reusing the approach and tools, especially in the final *How to Make it Happen* chapter, also for other areas within ALIGHT.

The production of this document was led by Copenhagen Airports as the Lighthouse and project manager under the ALIGHT task group 5.5 in collaboration with 16 partners from 9 different countries. The illustration below depicts the countries of all partners, including small, large and new European airports.

Illustration 1 – Map of ALIGHT partner locations

The main focus of the conceptual design for future aircraft stands is to provide a common point of view as well as practical recommendations for the key target groups.

Methodology

This guide is based on several building blocks consisting of concept designs for the aircraft stand of the future as well as studies on electricity, hydrogen and pushback.

Approach & building blocks

The point of departure took in the expected growth of new energy sources and alternative propellants driven by specific announcements from aircraft manufacturers.

The Conceptual Design of Future Aircraft Stands is built upon several supporting documents.

As demonstrated in the illustration to the right, studies on pushback, hydrogen and electricity were performed, and in addition, concepts of five aircraft stands were designed. These four building blocks are the basis for The Conceptual Design, and the guidelines include both short term actions which are backed up by insights from the studies but also offer a longer-term implementation approach which can help implementors to make decisions in the future.

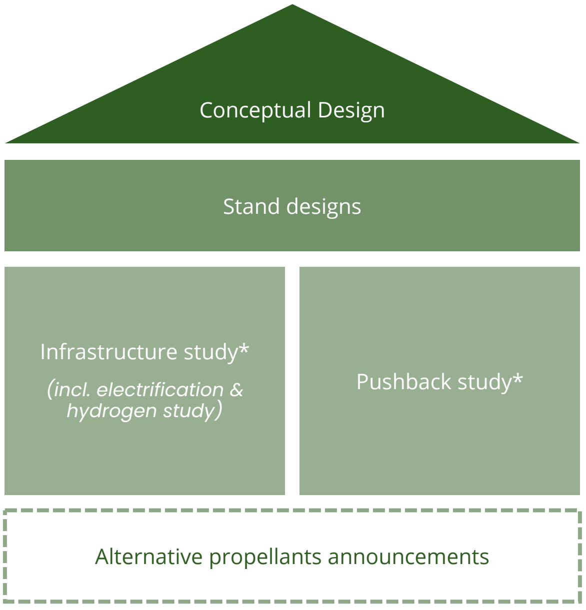


Illustration 2 – Methodology of Task 5.5 studies

For more details and insight in underlying subjects, please refer to the studies on infrastructure and pushback using the QR codes below, where background literature and references can also be found.

*) The full infrastructure study can be found here.

*) The full pushback study can be found here.

Forces shaping the future aircraft stand

Expectations to new types of propellants, driven by announced new types of aircraft, indicate potential future scenarios.

Aircraft manufacturers are increasingly announcing their plans to introduce new types of aircraft into the marketplace. Most of the announced aircraft flying on batteries or hydrogen are still quite small, seating less than 30 passengers with a flight range of up to 500 km, while a few recent announcements take a leap in both range and capacity.

Examples which drive this trend are the hydrogen-electric engines from ZeroAvia that can power aircraft for up to 80 passengers, the electric planes from Elysian that carry 90 passengers, and the Airbus ZEROe hydrogen turboprop and turbofan planes that extend the capacity to 200 people.

The aircraft stand designs in this guide are built on the fundamental presumption that larger, narrow-body aircraft will be necessary for commercial airlines to build a viable busines for passenger traffic using alternative propellants.

Electric aircraft are projected to have an upper limit and smallest range due to the battery weight and capacity, while hydrogen aircraft promises two or three times the performance. Sustainable aviation fuel will be the main type of propellant for larger, intercontinental routes because these aircraft will not be retired for many years to come.

Planned introductions 2027 – 2045

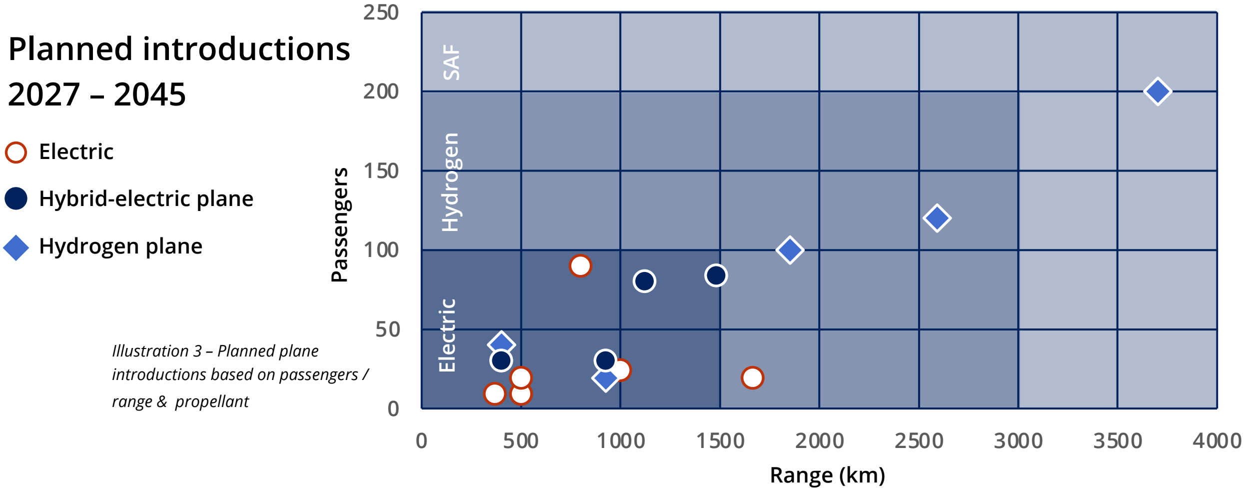


Illustration 3 – Planned plane introductions based on passengers / range & propellant

The early 2030s will be an inflection point for hydrogen- and battery-powered aviation (including hybrid electric models) as airlines will begin investing in new types of aircraft (Source: individual aircraft manufacturers' announcements)

Aircraft	Type	Capacity (pax)	Range (km)	Year
ZeroAvia ZA2000	Electric	80	1120	2027
Elysian E9X	Electric	90	800	2033
Heart Aerospace ES-30	Hybrid-Electric	30	800	2029
Maeve M80	Hybrid-Electric	84	1480	2030
Fokker 100	Hydrogen	120	2590	2035
Airbus ZEROe Turboprop	Hydrogen	200	1852	2035
Airbus ZEROe Turbofan	Hydrogen	200	3700	2040

Illustration 4 – Examples of announced electric & hydrogen aircraft

Impact lens

Introducing aircraft stands that accommodate electric and hydrogen planes offer profound sustainability benefits can be achieved - accelerating and scaling the transition.

Sustainability drivers

Greenhouse gas emissions. One of the most significant advantages is the reduction in greenhouse gas emissions. Hydrogen-powered aircraft, when using green hydrogen produced from renewable sources, generate no carbon dioxide emissions, making them a viable alternative to traditional fossil fuel-based aviation. Similarly, electric aircraft eliminate direct emissions altogether, particularly benefiting short-haul flights. On the ground, replacing conventional diesel-powered airport vehicles with electric, and where applicable hydrogen, ground support equipment drastically cuts airport-related emissions, contributing to cleaner air and a reduced carbon footprint.

Air quality. The transition to alternative propulsion improves air quality around airports and urban areas. Conventional jet fuel combustion releases nitrous oxide (NOx) and fine particulate matter, which contribute to respiratory issues and environmental pollution. By adopting electric and hydrogen-powered aircraft, these harmful emissions are minimized, ensuring healthier conditions for communities living near airports. This shift is particularly important as global air travel continues to grow, necessitating cleaner alternatives to sustain expansion without exacerbating environmental damage.

Decentralised energy production. Local energy systems can supply hydrogen and electricity, lowering the strain on the grid and on energy distribution.

Noise pollution. Electric propulsion systems operate with much lower noise levels than conventional jet engines, creating better working environments for staff, a quieter flying experience for passengers and reducing noise disturbances for airport-adjacent communities. Hydrogen-powered aircraft designed for sound optimization also offer quieter operations. Lower noise pollution improves quality of life for people working at the airport or living near airports and can ease restrictions on flight schedules imposed due to noise concerns.

Less reliance on fossil fuels. Currently, aviation relies heavily on petroleum-based fuels, making it vulnerable to price fluctuations and supply disruptions. By utilizing green hydrogen and renewable electricity, the industry can diversify its energy sources, making it more resilient. Additionally, as the cost of renewable energy continues to decline, operating electric and hydrogen-powered aircraft becomes more competitive in the long term.

Global positive impact on aviation. Switching to future stands now has the potential to dramatically lower aviation’s overall carbon footprint, bringing the industry closer to achieving international climate targets. By leading the way, airports can incentivise investments into electric and hydrogen aircraft design and implementation and create ripple effects throughout the industry.

Switching to sustainable aviation is what matters. Building aircraft stands to accommodate electric and hydrogen aircraft is the enabler.

Business lens

Complementing the sustainability impact, the business value drivers for airports when investing into aircraft stands supporting new propellants are strategic, commercial, operational, and relational.

Value drivers

Strategic positioning. Preparing for an inevitable shift towards sustainable aviation technologies positions the airport as a forward-looking hub, attracting customers focused on lowering their carbon footprint into long-term partnerships and strengthen the airport's position as a leader in sustainable aviation.

Commercial opportunities. Airlines with alternative energy aircraft in their fleet will naturally prefer airports with supporting facilities, boosting gate utilisation and passenger traffic. Likewise, since consumers are becoming increasingly environmentally conscious, aligning the airport's infrastructure with sustainable values will resonate with passengers willing to pay for green travel.

New business models. Airports can develop new business model built around hydrogen fuelling and electric charging, benefitting from lower energy cost as well as the energy flexibility they can provide at scale between production and consumption, offsetting fluctuations in energy prices and optimising for renewable sources.

Operational efficiency. By supporting a range of aircraft propulsion systems on the same aircraft stand, airports may improve the flexibility of stand usage. Moreover, electrification of ground support equipment represents a solid positive business case due to lower maintenance costs and longer life-span.

Community relations. Airports adopting sustainable practices, especially electrification of GSE and support for electric aircraft, can improve relations with local communities. Minimising noise pollution, carbon emissions, and air quality degradation is crucial for airports to reduce resistance to expansion projects and foster goodwill to reduce regulatory friction.

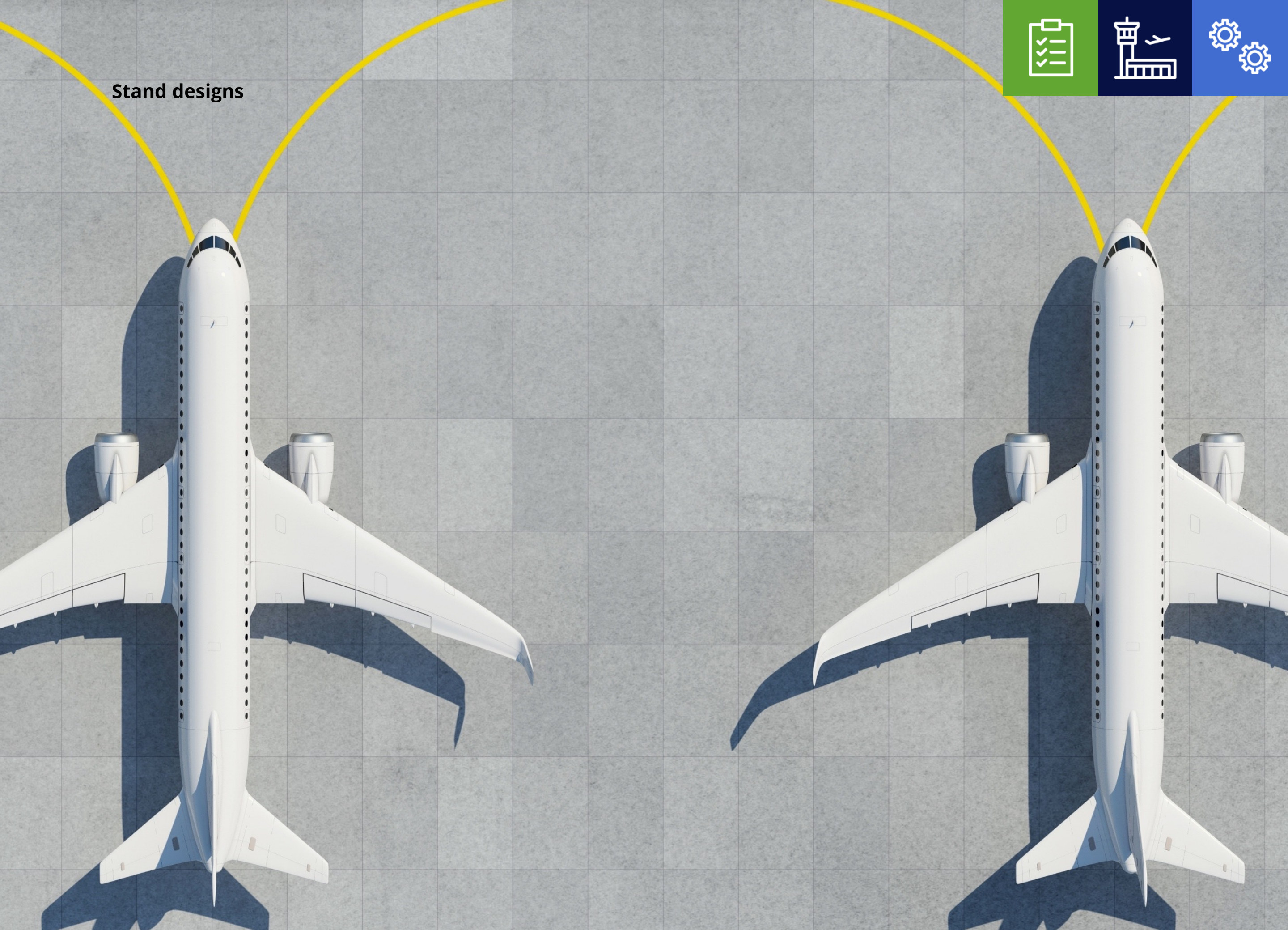
Technology leadership. Investments in emerging technologies can help position airports as centres of innovation excellence and collaboration networks within the aviation sector. Since the aircraft stand itself physically connects most critical stakeholders within the airport's business ecosystem, it is an excellent choice of focus to attract partners from the energy sector, airline manufacturers, ground support equipment manufacturers, as well as ground handlers, into innovation projects.

Future-proofing investments. Building scalable and adaptable infrastructure around the aircraft stand helps airports ensure that investments are resilient to changing technologies, market demands, and regulations. It minimises the risk of stranded assets and costly retrofits by aligning current developments with emerging trends. Commercial partners will indirectly benefit, because airports will be more responsive to change.

Airports have strategic and financial incentives to build green gates and future-proof their operations.

Stand designs

Inspiration to aircraft stand designers and airport planners: How to include infrastructure supporting new types of propellants and ground support equipment



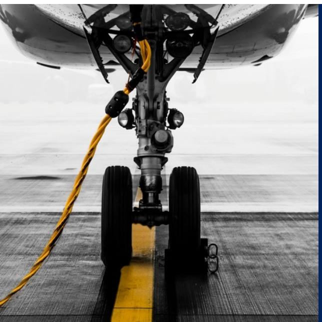
Future-proofing the aircraft stand

The aircraft stand designs presented aim to prepare airports for the integration of new, sustainable aviation technologies, specifically hydrogen-powered aircraft, electric aircraft, and electrified and autonomous ground support equipment.

The purpose of the designs is to help airport planners create flexible, scalable, and safe infrastructure that can accommodate emerging technologies while ensuring compatibility with current operations.

Multiple typologies of aircraft stands will ultimately materialise in airports to align with local master plans, green gate strategies, and legacy infrastructure. This guide makes few concrete assumptions about local variability and instead presents the maximum complexity of the aircraft stand of the future from which concrete implementations can be derived.

Three concrete implementations of future aircraft stands, notably the ones that will support the types of aircraft and propellants that are likely to emerge first, are presented as examples.



Future-proofing requires planning for multiple potential future scenarios, and demonstrating the necessary efforts help paving the way while encouraging stakeholders in the ecosystem to collaborate to lower the risk of going to the next levels of scale.

Future scenarios

Based on the expected emergence of electric and hydrogen propulsion in commercial aviation, airport planners can align their short - and long-term strategies.

Drivers of change

Investors are already making bets on sustainable aviation, and aircraft manufacturers are increasingly releasing their plans for building new products. As such, parts of the industry is already taking away risk in the transition.

The technologies are at most points mature – we know how to fly on batteries and hydrogen – so it is more a question of the markets to mature. In this equation it is worth mentioning that it is crucial in which speed airlines begin ordering new types of aircraft, because that is the main driver for rebuilding infrastructure at airports.

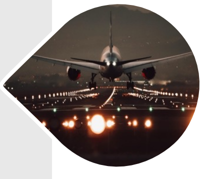
Regulation is likely to accelerate this development by altering taxes and subsidies. Some countries in the EU have already prohibited or restricted short-haul flights, and it is realistic to assume that sustainable aviation will be except from such legislation, incentivising airlines to invest in new types of planes.

Electric aviation is expected to expand in the coming years, but with a growth limit of around 10% of European traffic, corresponding to the regional routes. Hybrid-electric and hydrogen aircraft are likewise expected to emerge in the short- to medium term with a larger growth potential due to their longer ranges and passenger capacities. Hydrogen as a primary propellant for intercontinental routes is currently a speculative scenario.

Achieving Net Zero operations in 2050 requires a willingness to make bets along the way to the desired future scenario

Early adoption of sustainable solutions, primarily for regional routes. Hydrogen fuelling will begin with mobile gaseous units at remote stands. Electric and hybrid-electric aircraft will begin operating on regional routes up to 500 km. GSE will transition to electrified models.

2030



Liquid hydrogen storage and refuelling infrastructure will emerge at selected connected stands. Hybrid stands supporting electric, hydrogen, and SAF will become standard. Hybrid-electric up to 1,500 km will be the fastest growing routes.

Intercontinental flights will still rely mostly on kerosene and SAF, while hydrogen adoption for wide-body aircraft remains limited. Autonomous operations will mature for specific types of mobile GSE.

2040

Widespread adoption of hydrogen and electric propulsion for regional and continental flights. Large scale liquid hydrogen infrastructure supporting wide-body hybrid aircraft will appear at selected airports, but intercontinental routes are still dominated by an increasing amount of SAF.

Autonomous GSE will be fully implemented at automation level 3, and airports are integrated in terms of using real-time data for energy optimisation.

2050

Design fundamentals

As a baseline for aligning local aircraft stand planning with the recommendations in this guide, a set of fundamental assumptions is established.

Planning assumptions

Airports have different tailored design standards, compliance requirements, and operational procedures. Therefore, while the stand layouts presented here provide workable solutions, they will have to be tailored to suit each airport and aligned with stakeholders accordingly.

The generic stand designs provide an overview of the maximum complexity that can be descoped by taking away elements to simplify the designs for quicker and more suitable implementation. While the expectation to the kinds of propellants to support is central, planners are recommended to invest in supporting all propellants when converting existing stands to minimise the downtime.

Each stand is designed as a greenfield blueprint. In terms of assumptions, the generic stand designs address fixed equipment, mobile equipment, charging units for eGSE, hydrogen fuelling, ground power units (GPUs), and pre-conditioned air (PCA).

In terms of physical space, the designs are based on narrow-body ICAO code B/C aircraft, both turboprop and turbofan engine types, and the clearance and turning radii of new types of mobile GSE. As a general principle, the generic stand designs attempt to be as close as possible to existing aircraft stands, to minimise the disruption for airports and minimise the cost to begin the transition.

The overall planning assumptions across all five generic stand designs are:

1. Electric aircraft charging units are either fixed or mobile, and hydrogen refuelling units are mobile. Safety clearance requirements are to be determined for each airport, however, NFPA 415 rules should apply as a default, specifically 100 ft (30.5 m) between potential fuel spill points and passenger terminal glazing.

2. Aircraft Preconditioned Air (PCA) units for remote stands are provided as either a pop-up pit system or with mobile electric units using apron mounted power pillars to plug into during operation. These could be converted to an aerobridge in future if needed.

3. Ground Power Unit (GPU) for remote stands are fixed above ground units at the head of stand (with cable carrier/crocodile system). These could also be mobile units, dependent on feasibility/stand usage.

4. GPU and PCA for contact stands are provided on the aerobridges.

5. eGSE charging units at the head of stand would typically be 80 V type with single or dual port and should suit lithium, lead acid or other future battery types. Larger capacity chargers such as 400 V types would also be required in areas where large aircraft and associated equipment need the additional power, e.g., extra-large pushback tractors and pallet loaders.

Generic aircraft stand designs

A generic aircraft stand design provides an overview of the infrastructure and support equipment needed to service aircraft flying on any propellant.

Maximum complexity

The all-propellants remote stand is designed for all types of propellants including conventional Jet A/A-1, SAF, hydrogen aircraft shaped like E190, B737, A320, and A321 as a bussed operation, as well as future electric narrow body and large turboprop aircraft including Dash8 Q400 and ATR42/72.

The design for all propellants provides the totality of infrastructure and support equipment needed, and therefore maximum complexity. Specific infrastructure can be removed from the design as required to fit a particular gate strategy without breaking dependencies. This allows stand designers to consider as many details as possible.

The stand includes:

1. Co-located AVDGS (advanced visual docking guidance system) and Gate sign
2. GSE charging station and charging bay for battery fitted GSE vehicles
3. Provision for several mobile charging units. Location of aircraft connection point and charging unit position will vary across aircraft types.
4. Fuelling via the fuel hydrant system for Jet A/A1 or SAF can use a fuel dispenser vehicle rather than a fuel bowser. However, the layout also provides an increased wingtip separation to allow for large fuel bowsers (i.e. hydrogen or SAF)
5. Light mast
6. Ground mounted GPU with cable carrier system. The PCA is shown as mobile electric, using a power pillar to connect during operation.
7. A head of stand and rear of stand airside road for GSE and bussing operations (to allow for rear ground boarding) and GSE storage areas

Airports are likely to upgrade aircraft stands with as much expected infrastructure in a single construction project because of the cost of the downtime of the stand. However, some multiple-propellant stands will be built as greenfield projects, and in the short-term airports must be expected to build remote stands to support specific kinds of planes.

For this reason, this chapter details a remote stand for electric aircraft only, as well as both remote and contact stands for hybrid (electric-SAF and electric-hydrogen) aircraft.

Since there are no standards for the placement of charge points on electric planes, multiple fixed charge points should be installed on the stand.

Charging an electric plane requires a lot of energy to be transferred in a short period of time, and existing electricity infrastructure in airports may not be able to deliver that power to fixed charge points without significant upgrades. For this reason, a mobile or fixed battery to charge the plane is a flexible and scalable altertnative. The battery can itself recharge at a lower power levels and at off-peak times. A battery can have the capacity to charge one or two planes, and airports can dimension a fleet of mobile chargers based on how many aircraft are being serviced for increased flexibility. Special considerations in case of battery fires may require safety buffers or even firewalls to be put in place. These will depend on local fire regulations and are not shown in the visuals.

For hydrogen fuelling, the safety buffers are shown on the visuals as a 100 ft (32 m) distance from the fuelling point. Boarding a plane adjacent to a plane being fueled should be avoided, since it is within the clearance zone.

Service roads are included in the stand designs both in front of and behind the apron. However, at some airports, service roads behind the apron are deprecated.

All-propellant generic stands

The designs provides the totality of infrastructure and support equipment needed, from which elements can be deselected to fit a particular gate strategy.

Contact stand

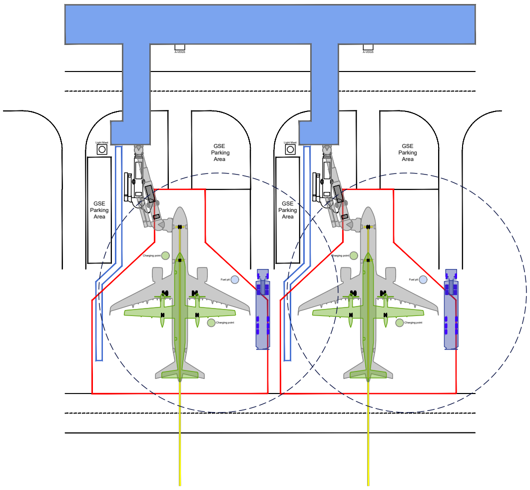


Illustration 5 – All-propellant contact stand

GSE charging station and charging bay for battery fitted GSE vehicles.

Fixed charge points and provision for a mobile electric charging unit.

Fuelling via the fuel hydrant system for jet A/A1 or SAF can use a fuel dispenser vehicle rather than a fuel bowser as well as an increased wingtip separation to allow for a large bowser (hydrogen or SAF). Safety buffers are shown in the dotted circles (100 ft/32 m).

A fixed link (with stair access to ground) and aerobridge (fitted with GPU and PCA.)

Remote stand

The remote generic stand design closely resembles the contact stand, with the aerobridge removed and GPU/PCA placed in the ground.

A head of stand and rear of stand airside road, allow for front and rear ground boarding.

On a remote stand, the distance between the stands can be increased to comply with safety standards and enable simultaneous fuelling and boarding of adjacent planes.

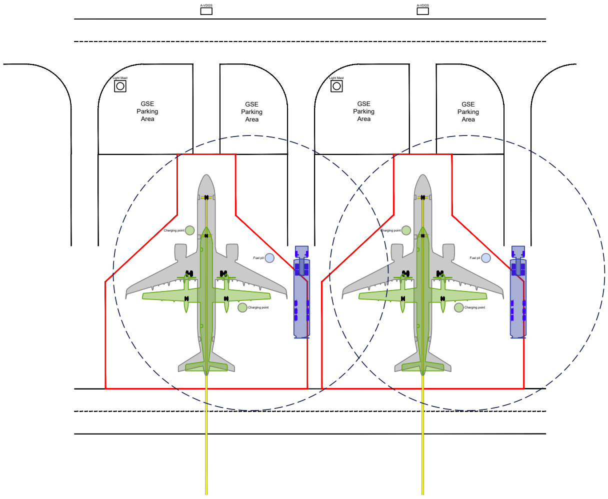


Illustration 6 – All-propellant remote stand

A shared vision for the design of future aircraft stand across airports in Europe will help accelerate the transition.

Remote, dedicated electric stand

Electric aircraft are expected to be among the first wave of sustainable aviation and the first to land in airports.

Implementation details

The stand offers multiple fixed charging points since the exact location of the charging point on the aircraft may vary. The energy demand may be higher than what can be supported by existing power distribution network, in which case a mobile charger based on batteries is preferred. A mobile charger also offers a high degree of flexibility regarding the uncertainty of location of charging points and design of future aircrafts.

The electric aircraft remote stand is designed primarily for future electric turboprop aircraft and can be extended to accommodate narrow-body aircraft. The design includes generic GSE charging stations for any battery fitted vehicles in the parking areas.

Passenger walkways are shown in blue. The stand entirely excludes fuel hydrants, and a GPU is also not required.

The energy demand of an electric aircraft stand depends on the aircrafts' battery capacities and number of aircraft turned around over time. A method for calculating the expected energy demand (details are given in the underlying infrastructure study) is based on the routes that are expected to be converted to electric flight and a conversion factor from jet fuel into electric energy.

Using these factors, the total energy demand for aircraft charging in the airport can be calculated and spread across several stands. It plays a critical role in planning future power supply and distribution using either fixed or mobile charging.

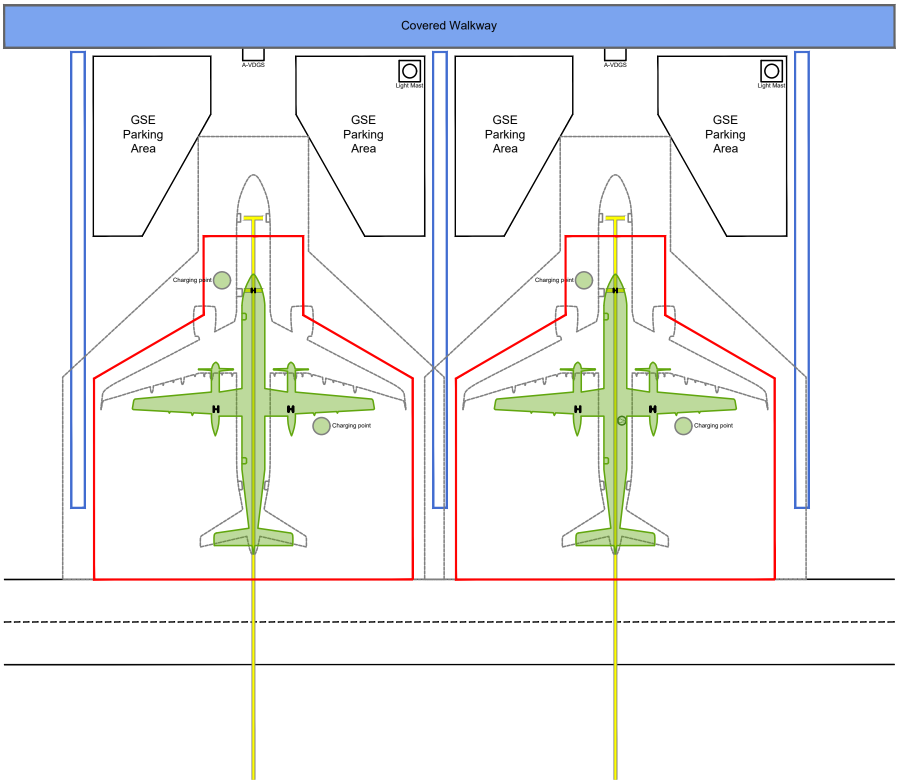


Illustration 7 – Remote, dedicated electric stand

Hybrid stands

Hybrid electric planes are expected to appear in the first wave of change in the early 2030's. These designs show concrete conversions of contact stands.

SAF/kerosene electric

This design shows a contact stand supporting turboprop and turbofan aircraft flying on battery electric and SAF/kerosene propellants. The airbridge contains PCA and stairs to the ground. There is provision to charge GSE in parking areas.

Passenger walkways are provided to allow for rear boarding. Back of apron service roads are shown although not all airports are using them.

Multiple charge points are provided to allow for different charging locations on the aircraft.

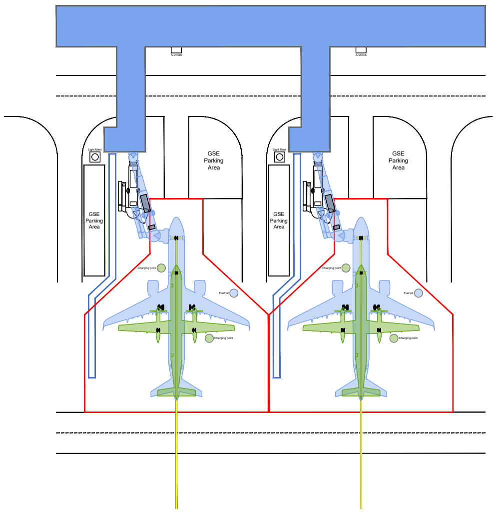


Illustration 8 – Hybrid SAF electric stand

Hydrogen electric

For hydrogen-electric hybrid aircraft service, this stand design resembles the SAF/kerosene electric design above, with the addition of safety buffers (dotted circles) and space for hydrogen fuelling bowsers.

Bowsers are assumed to be the the best choice for hydrogen fuelling for the foreseeable future, which in the scenarios presented in this guide is at least until 2040.

Simultaneous charging and fuelling is possible, however local regulations may apply to mitigate the risk of a battery hazard spreading to the highly flammable hydrogen.

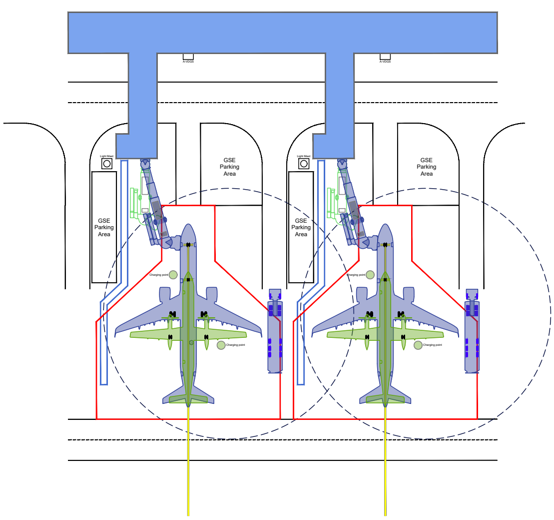


Illustration 9 – Hybrid hydrogen electric stand

Wide-body hydrogen MARS stand

Beyond the scenarios for the next 25 years is the prospect of long-range hydrogen-powered flight. While speculative, this may be the true aircraft stand of the future.

Imagining the future

A few fundamental barriers exist on the path to realising intercontinental flight with hydrogen-powered aircraft. It is uncertain if hydrogen can be produced using renewable sources at scale at competitive prices; safe distribution networks for LH2 will need to be designed and developed; there is scepticism with regards to large liquid hydrogen fuel cells; and there are concerns about the climate effects of leakage.

Besides these concerns, the dream of hydrogen long-range commercial flight will be realised in part by a connected aircraft stand that can service wide-body aircraft.

The wide-body (code E) hydrogen connected stand provides fuelling through large bowsers as well as hydrants in the ground. It is a multiple aircraft ramp system (MARS) configuration, and safety buffers are shown relative to the fuelling points for the different types of planes.

No infrastructure is planned into the design for electric charging or liquid fuel/SAF. PCA and GPU support are integrated into the airbridge.

Even though bowsers are shown in the design, and can be relied upon even in this scenario, the most robust solution is ultimately a liquid hydrogen piped distribution network.

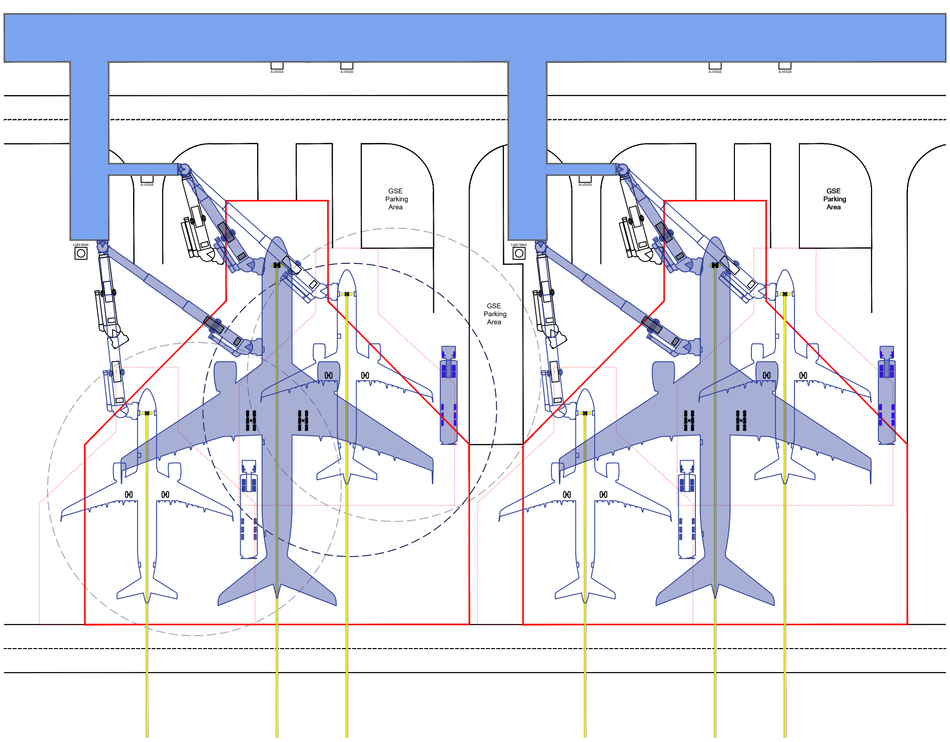


Illustration 10 – Wide-body hydrogen MARS stand

Implications for ground support

This chapter outlines the development of ground support equipment in terms of electrification, automation, cyber security, data integration as well as crucial infrastructure to accomodate emerging propellants.

Electrification

While the electrification of aircraft is more complex, electric infrastructure for GSE is already available today. Although up-front investments are required, there is a clear sustainable impact case, and also a positive the business case for eGSE.

Fully electric GSE in 2035

European airports and ground handlers are in full swing to reduce emissions from ground support equipment (GSE). For one the pressure is to reduce environmental impact, but more pressing is the reduction of exposure for employees on the apron to gaseous emissions and ultra fine particles.

Electrifying GSE has been ongoing for over a decade at several major European airports with GPUs, PCAs and most airside vehicles, including pushback tractors transitioning to electric powertrains.

This requires infrastructure upgrades and changes for charging and operational adjustment to account for the range and power supplied by these new powertrains and charging times. Getting enough power to the required locations for powering or charging all equipment will be a significant challenge for airports.

In the US, Sea-Tac Airport, Philadelphia International Airport and Dallas-Fort Worth International Airport lead the way on electrification.

In Europe, most large airports have published ambitions and timelines for electrifying their GSE fleets, including Amsterdam Airport Schiphol (Schiphol Group), Frankfurt Airport, Flughafen Wien, AENA (Spain), and more.

It is expected that, by 2030-2035, most airside GSE will have transitioned to fully electric, or hydrogen powered.

The following mobile equipment will benefit from decentral charging at contact or remote stands

- Tow trucks / push-back trucks / Electric Green Taxiing System
- Baggage transporters
- Baggage loaders
- Passenger stairs
- GPUs
- Refuelling trucks / hydrant dispensers

These types of GSE will have a higher utilisation over time because they can avoid returning to a home base only for charging.

From an energy flexibility perspective, the energy capacity of GSE batteries (and battery banks – mobile or stationary) represent a valuable energy buffer for the airport's electric energy distribution.

The business case for electric GSE is positive, although it requires up-front investments.

Autonomous ground equipment

The acceleration of automation advancements increases safety for ground handling personnel as well as increases operations efficiency on and beyond the aircraft stand.

Autonomous development

Autonomous ground handling vehicles, such as pushback tractors, will develop in phases, starting with semi-autonomous systems that assist human operators, advancing to full autonomy for routine tasks, and eventually integrating with other automated airport systems.

There are several key differences between ground handling vehicles and general autonomous vehicles such as passenger cars. GSE vehicles operate in a highly controlled environment (airport tarmacs), which makes automation easier due to fewer variables (defined traffic, predictable movements), as compared to autonomous vehicles that must navigate in highly dynamic and unpredictable environments (public roads), requiring more complex AI and decision-making systems.

Moreover, their safety systems can be highly tuned to the airport environment, with specific considerations for aircraft movement, ground crew, and other vehicles while autonomous vehicles need to account for pedestrians, cyclists, and other drivers, making safety systems more complex. Pushback tractors are also expected to benefit from advances in autonomous vehicle technology (sensors, AI algorithms), but will have a simpler path to full automation due to the controlled nature of airport operations.

Various car manufacturers have proposed different timelines for the levels of automation. The summarized timeline and description to the right details the automation of vehicles characterized by certain levels. As mentioned above, the timeline is expected to happen faster for autonomous GSE within airports due to the controlled nature of airport operations.

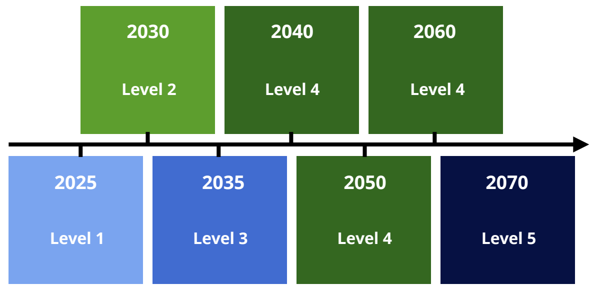


Illustration 11 – Autonomous development timeline

Level 1 automation: Steering or acceleration tasks are performed by the vehicle without human intervention

Level 2 automation: Advanced cruise control or original autopilot systems such that the vehicle can automatically take safety actions

Level 3 automation: Vehicle can take over "safety-critical functions" under certain traffic or environmental conditions.

Level 4 automation: Almost full automation except for unmapped areas or during severe weather conditions

Level 5 automation: Full automation in all conditions

The illustration shows the initial automation process of vehicles will go at a steady pace until it reaches level 2 to level 3 in 2040. Extending it further to level 4 and beyond would occur at a slower pace mainly because of the AI techniques being dependent on learning from existing data and images. Decision making for the unknown would remain more challenging. The automation of pushback tractors in airports will likely follow a gradual, phased evolution over several years, similar to how autonomous vehicle technology is being developed.

Cyber Security considerations

As for all supply systems, effective cybersecurity GSE involves secure communication, robust AI protection, real-time monitoring, and strong endpoint security.

Cyber Security is critical

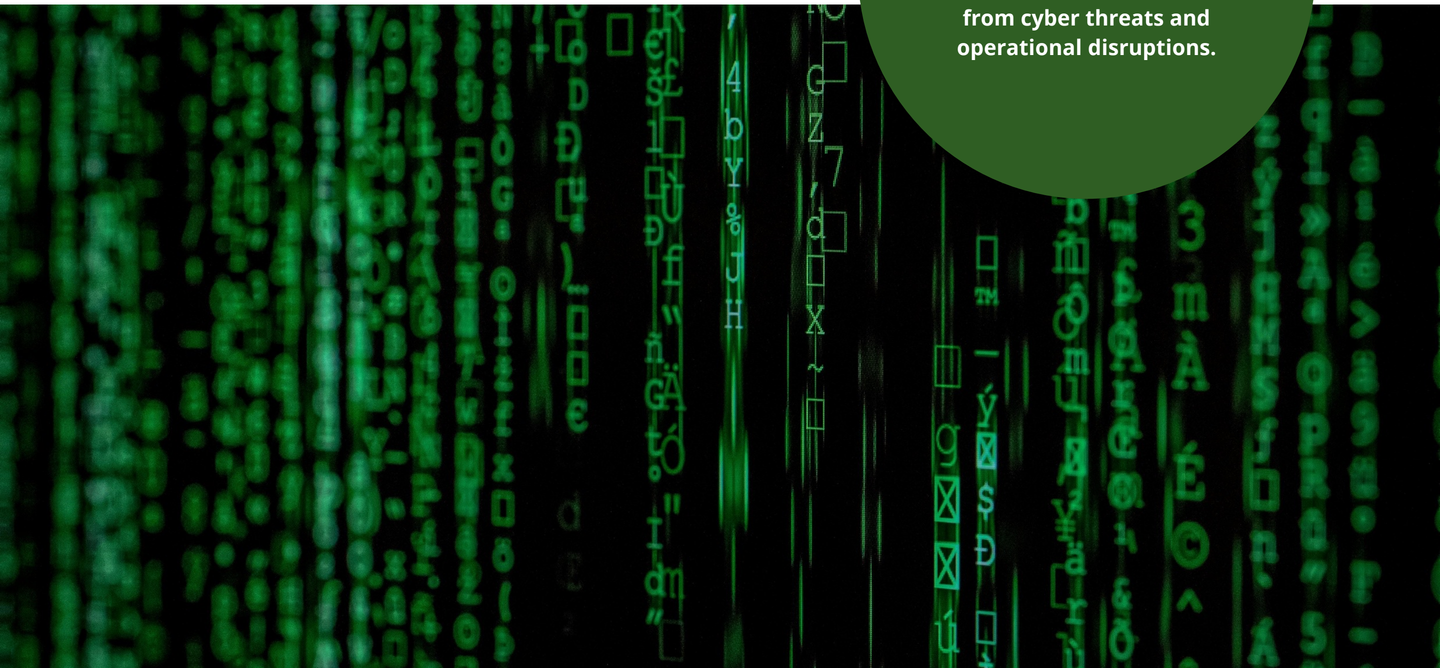
Cyber Security considerations for autonomous vehicles and GSE automation span several critical areas. First, vehicles are vulnerable to hacking, including remote access exploits, ransomware attacks, and breaches of personal or proprietary data. Communication systems, such as Vehicle-to-Everything (V2X) networks, face risks from signal jamming, spoofing, and misinformation that can disrupt operations.

Additionally, regular software updates are essential but pose risks like malicious updates or supply chain attacks, which can introduce vulnerabilities during manufacturing or development. Artificial intelligence systems in these vehicles are susceptible to adversarial attacks and biases, potentially compromising safety and functionality. Finally, regulatory challenges, such as the lack of standard cybersecurity protocols and complexities in assigning liability, exacerbate the risks of cyberattacks in these systems.

To address these concerns, cybersecurity for autonomous GSE must include measures like secure communication protocols with encryption and authentication, robust AI protection through adversarial testing and data validation, and real-time monitoring systems to detect anomalies and intrusions.

Strong endpoint security, such as hardware integrity checks and regular updates, coupled with network segmentation and supply chain security, ensures that critical systems remain insulated from threats. Disaster recovery plans, access control, and physical security measures further protect the systems, while fail-safe controls and redundant communication channels maintain safe operations even during cyberattacks.

Robust cybersecurity measures are essential to safeguard autonomous vehicles and GSE automation from cyber threats and operational disruptions.



Data integration and ecosystems

The successful deployment of electric and autonomous GSE depends on a coordinated approach that leverages advancements in technology, infrastructure, and regulation.

Seamless systems integration

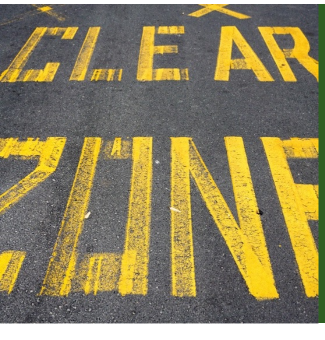
The transition to electric and autonomous GSE is a critical step towards sustainable and efficient airport operations. However, this shift introduces several technical, operational, and regulatory challenges that require enhanced collaboration among key stakeholders. Technological Integration must especially be coordinated in terms of 1) The charging & fuelling Infrastructure, 2) Autonomous navigation systems as well as 3) Data sharing and connectivity.

1) Airports will have to install sufficient charging stations for a growing electric GSE fleet, and systems will be required to optimize charging schedules and ensure that peak energy demand does not disrupt airport operations.

The transition to electric and autonomous GSE will impact various workflows, from baggage handling to aircraft refuelling. Airports and airlines must redesign ground operations to account for differences in charging times, vehicle speeds, and task automation.

Ground handling staff will need to undergo specialized training to operate and maintain electric and autonomous GSE. There may be a shift in roles as some manual tasks become automated, necessitating upskilling in areas like system monitoring and troubleshooting.

The lack of uniform standards for electric and autonomous GSE can hinder their widespread adoption.



With an increased level of technology, collaboration between airports, airlines, ground handlers, and equipment manufacturers and regulators will be crucial to ensure seamless systems integration of electric and autonomous GSE.

2) Autonomous GSE relies on precise navigation and communication systems to operate safely and efficiently in busy airport environments. Integration with airport management systems (AMS) and air traffic control (ATC) is crucial to prevent conflicts between autonomous vehicles and other ground movements.

3) A high level of data exchange between all stakeholders will be necessary for real-time monitoring and coordination. This includes sharing data on equipment status, task progress, and operational performance to optimize resource allocation and reduce delays.

Regulatory bodies must establish clear guidelines for the design, operation, and maintenance of these systems. Autonomous GSE must meet stringent safety standards to operate in dynamic and complex airport environments. This includes fail-safe mechanisms to prevent collisions and software redundancy to ensure reliability. In orde to enable the development and refinement of safe and efficient systems before broader implementation, it is crucial that testing beds for autonomous equipment at airports remain adequately but not overregulated to allow for flexible experimentation and innovation.

Charging & fuelling infrastructure

With electrification under way and hydrogen on the horizon, setting the right charge points and operations for maximised efficiency in place is crucial.

A paradigm shift

The increasing electrification of airports, including GSE, strains the existing electricity supplies at airports, especially the local distribution of electricity in combination with peak demands for direct use of electricity and charging of battery powered equipment.

To reduce strain on the electricity infrastructure, airports are looking to spread demand for use and charging throughout the operational schedule. Additionally, GSE vehicles such as pushback trucks and even more so sustainable taxiing vehicles, require multiple charging moments during the day to continue operations.

Opportunity charging during short stops or waiting periods at the apron might help spread charging demand throughout the day and increase operational time between required charging stops.

In the future, inductive charging in waiting areas or even on parking positions may increase the effectiveness of opportunity charging.

Mobile charging units will be crucial infrastructure for future electric airplanes, enabling flexible and efficient energy replenishment at airports and remote locations to support widespread electric aviation.

In order to accomodate the rising electricity needs, significant investments in electric grids for airports as well as the infrastructure and technology to locally generate, store and use electric energy are required.

The introduction of hydrogen fuelling bowsers at airports marks a transformative step in ground support operations. These mobile fuelling units enable rapid refuelling of hydrogen-powered GSE such as baggage tractors, cargo loaders, and tow vehicles as well as future hydrogen-powered airplanes. As hydrogen technology advances, there could be some overlap in infrastructure, but for now, separate bowsers for GSE compared to aircraft bowsers exist, tailored to specific fuelling needs which is essential to ensure safety, efficiency, and regulatory compliance.

Hydrogen fuelling will bring a paradigm shift in operations at aircraft stands, with a strong emphasis on safety, specialized infrastructure, and required training.

As airports increasingly adopt electric and hydrogen technology, ground operations will become quieter, cleaner, and more sustainable, supporting a broader transition to low-carbon aviation.

How to make it happen

This chapter highlights how airports, manufacturers, and regulators can act *today* by making specific decisions for immediate implementation, changing existing master plans *today*, and setting up innovation and collaboration programs *today*.

Short to medium term actions

Based on a more certain future until 2030-2040, there are several lower risk actions airports, manufacturers and regulators can take in the short- to medium-term.

No-regret moves

- The majority of the recommendations presented in this chapter are concrete implementation recommendations with a time horizon up to 2030. These are proposed actions that airports, regulators and manufacturers can do *now*, with a low risk of regret due to a high level of certainty.

2030

Add to plans today

- The second category of recommendations are medium term recommendations with a time horizon up to 2040. These are proposed actions that airports, regulators and manufacturers should add to their forward-looking masterplans, roadmaps and pathways for the upcoming 10-15 years to make the shift towards future aircraft stands happen.

2040

2050

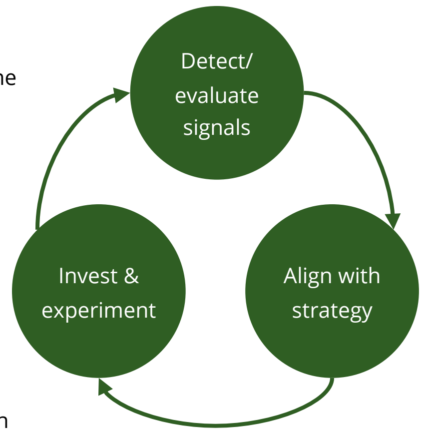
Long term collaboration and innovation

Airport planners can build innovation radars to listen to strong or weak signals that address technologies, market trends, and policy shifts to help de-risk decisions.

Experiment today to create the future

Beyond a 15-year horizon, solutions must be created through experimentation and collaborative innovation. Airports play a crucial role because they provide the physical assets to execute experiments in the real world.

The interplay between strategy and innovation is depicted in the feedback loop to the right. A systematic and data-driven approach to detecting early signals can inform strategy and, in turn, help decide where and how to invest in experiments to assess the feasibility and viability of new infrastructure.



Even though airports compete to attract airlines through competitive landing fees, hub status, and high-quality infrastructure, the benefits of working together to accelerate the transition to green gates outweigh the downsides.

Detecting signals from the future is a complementary approach to standardisation, as it listens to trends and behaviours from many different sources. Below is a list of examples to inspire airport planners to build an innovation radar to detect signals as early as possible to avoid deferring decisions.

Emergent trends and technologies (signals)	Decision trigger	Action
Battery energy density breakthrough	Energy density above 500 kWh/kg	Commit budgets to build connected electric stands
Electric aircraft market growth, including small aircraft	Fleet orders for regional aircraft surpass 500 units globally	Prioritise charging infrastructure and integrate grid capacity planning
Commercial hydrogen aircraft launch	The first hydrogen-powered aircraft begins commercial operations	Retrofit a small number of stands with hydrogen refuelling systems to test safety and efficiency
Passenger demand for green flights	Surveys show 50% of passengers are willing to pay extra for zero-emission flights	Market the airport as a green leader and expedite stand upgrades to attract eco-conscious airlines
Follow transnational regulators	Approved standards for hydrogen and electric flight	Adopt standards locally as quickly as possible

Illustration 11 – Tracking emerging technologies in an innovation radar

2030

2040

2050

Key recommendations for airports

No-regret moves

1. Build remote, dedicated aircraft stands to accomodate electric narrow-body aircraft
2. Calculate the energy demand for electric aircraft using the proposed methodology (infrastructure study)
3. Invest in eGSE, notably electrified, autonomous push-back tractors as well as charging capabilities
4. Develop & implement cyber-security measures, human oversight, and certifications
5. Work together with other regional airports to align the growth in charging capabilities

Add to plans today

1. Integrate the proposed solution of mobile aircraft recharging units into the existing plans
2. Allocate space for future hydrogen operations
3. Develop safety protocols for hydrogen detection and define safety zones
4. Build capabilities and define operational processes based on enabling technologies and new mix of propellants
5. Design for a phased roll-out of hydrogen infrastructure

Experiment today for the future

1. Monitor the evolution and experiment with emerging technologies

How airports can act now

By taking immediate no-regret actions, planning mid-term infrastructure upgrades, and actively testing emerging technologies, airports can lead the transformation towards a sustainable and future-ready aviation ecosystem.

No-regret moves

Build remote, dedicated aircraft stands for narrow-body aircraft. Airports should immediately designate specific areas for narrow-body aircraft stands to support the anticipated surge in regional electric flights. These stands will optimize infrastructure use and help airports lead the transition to sustainable aviation.

Calculate the energy demand for electric aircraft. Using the proposed methodology, airports must assess the electricity demand for charging electric aircraft accurately. This ensures that the necessary power infrastructure can be designed to support operations seamlessly as the electrification of aviation grows.

Invest in electrified, autonomous push-back tractors and other GSE. Replacing traditional ground support equipment with electric and autonomous alternatives reduces carbon emissions, air pollution and operational noise. This not only enhances sustainability but also streamlines airside efficiency, provides safety and health benefits for personnel and reduces ground traffic congestion. Base designs on existing automotive charging systems.

Develop & implement cybersecurity measures for airside autonomous operations. Airports should prioritize robust cybersecurity systems, alongside human oversight and certification, for autonomous operations. This approach ensures a safe, secure integration of new technologies into existing systems, safeguarding critical infrastructure.

The new approach is a balanced combination of following plans and responding to change

Add to plans & innovate

Integrate mobile aircraft recharging units into existing plans. Airports should include mobile aircraft recharging units in their master plans, ensuring adequate power supply and infrastructure is prepared. Securing space and grid capacity now will avoid costly retrofits and delays when these units become essential. Make autonomous charging possible and work with manufacturers to enable productization and upscaling.

Allocate space for future hydrogen operations. Designate areas for hydrogen operations with proper safety zones, technical corridors, and underground distribution tunnels. Bowser simulations for turning radii should guide layout planning to ensure efficient and safe refuelling processes.

Develop safety protocols for hydrogen detection. Establish robust safety protocols for detecting hydrogen leaks and defining safety zones around fuelling points and compression stations. These measures will mitigate risks and help airports comply with safety regulations.

Build capabilities and define operational processes for new technologies. Develop training programmes to upskill staff in power engineering, charging systems, and handling new propellants. These initiatives will ensure smooth operations and maintain high service standards as technologies evolve.

Design a phased roll-out of hydrogen infrastructure. Plan hydrogen infrastructure deployment in stages, beginning with mobile gaseous hydrogen refuelling by 2030. Introduce hybrid stands by 2040 and scale up to large-scale liquid hydrogen facilities by 2050 to accommodate growing demand sustainably.

Monitor the evolution of enabling technologies. Airports should create test beds to trial emerging technologies like e-planes, h-planes, and new propellants. Tracking advancements ensures future investments align with the most promising solutions for long-term readiness.

Key recommendations for manufacturers

No-regret moves

1. Follow standardisations and collaborate on defining certification requirements
2. Base designs on existing automotive charging systems
3. Integrate standards for certifications, safety systems, and maintenance tools into the aircraft design process
4. Prioritize the development/use of advanced batteries with a focus on both energy efficiency and fast charging times
5. Design aircraft that are compatible with already existing as well as emerging ground action equipment
5. Ensure that the location of the aircraft charge point allows for future autonomous operations by robots

How manufacturers can take action

Aircraft manufacturers must prioritise sustainability while making sure the critical interfaces to the future aircraft stand are observed.

Critical focus areas

Cooperation on standardisation. Achieving a sustainable aviation industry requires a unified approach to developing and implementing standards. Airports and manufacturers must collaborate to establish global standards for charging infrastructure and hydrogen handling. This includes engaging with aviation authorities to define certification requirements and ensuring these align with safety and efficiency goals. Additionally, airport operators should be involved from the onset to guarantee that infrastructure compatibility is maintained, both for current facilities and future expansions.

Integration with existing airport Infrastructure. In most cases, electric, hybrid, and hydrogen aircraft must be integrated into pre-existing airport environments. Therefore, aircraft manufacturers should prioritise the design of aircraft that are compatible with standardised charging and refuelling systems. Specifically, manufactures must be aligned with and follow the upcoming standards for charging and refuelling (EASA/SAE) to ease the compatibility at the airport. In addition to new propellants, the upcoming aircraft versions represent many other features that are important for ground handling activities at airports. These could be physical designs such as height, width, access doors, stairs and service gates, but could also be air-to-ground reporting systems, possible automated features or new digitalised solutions. Manufacturers and developers are recommended to include such aspects in dialogues with service providers and end users. Which topics this includes must be clarified and addressed in discussions between the manufacturer and relevant parties

Safety and regulation. The introduction of new propulsion technologies brings new safety challenges that require attention. It is essential for manufacturers to adopt existing standards, many of which exist for handling batteries and hydrogen. However, some will need to be established, such as battery analysis and H2 leakage monitoring.

Battery efficiency and accessibility. Manufacturers should prioritise the development of advanced batteries with a focus on both energy efficiency and fast charging times. Rapid charging is critical to minimise turn-around time and is a key factor for optimising operations at airports and for airlines. The more efficient, the more economically viable the operation becomes. Equally important is the strategic placement of batteries within the aircraft. Batteries should be designed for easy accessibility to enable swift replacements in the event of malfunctions and facilitate upgrades to newer, more efficient technologies as advancements emerge. Regular upgrades to cutting-edge batteries can enhance turn-around times, support longer flight ranges, and improve overall operational flexibility.

Ground handling compatibility. Manufacturers must make sure that the aircraft in as many other areas as possible are compatible with GSE standard equipment. This reduces the need for investment in new equipment for the airport. Design aircraft that support already existing ground action equipment. Which topics it covers must be clarified and addressed in discussions between producer and user.

The key words are integration and standards for interoperatiblity and safety.

Key recommendations for regulators

No-regret moves

1. Introduce regulatory frameworks for the certification and operation of electric and hydrogen aircraft for commercial use
2. Require new and converted aircraft stands to be adaptable as well as mandate and create incentives for charging and hydrogen refuelling at major airports
3. Develop strict health, safety, and fire protection standards for hydrogen refuelling and storage
4. Require training of all airport staff on general safety plans with regards to high-voltage systems and batteries
5. Require certification of all airport maintenance staff and emergency teams to safely handle hydrogen, batteries, and high-voltage systems
6. Adjust landing fees and incentivize electric aircraft adoption through tax exemptions
7. Encourage innovation by ensuring flexible regulations and promoting the adoption of effective standards across jurisdictions
8. Introduce special testing standards at airports to support experimentation with new technologies like autonomous equipment

Regulating to accelerate the transition

Standards and regulations currently lack completeness regarding interfaces for electric charging and hydrogen fuelling, and safety procedures have yet to be established.

Critical focus areas

Realising the aircraft stand of the future rests on sufficient regulation and standardisation. In general, the requirements will be based on already existing rules and regulations. Regulators are therefore urged to (1) duplicate adequate existing regulation from other industries (e.g., megawatt charging systems in land transport) and (2) minimise the distance between existing and new regulation impacting aircraft stands.

Supporting new aircraft types. Regulatory frameworks must be introduced for the certification and operation of electric and hydrogen aircraft for commercial use, allowing for mutual recognition of certifications across jurisdictions through bilateral agreements to reduce delays in market entry.

Upgrading infrastructure. Require new and converted aircraft stands to be adaptable, supporting Jet A1, hydrogen, and electric systems on the same platform, when possible, from 2030. Mandate, create incentives, and facilitate the deployment of charging stations and hydrogen refuelling facilities at major airports.

Establishing safety standards. Develop strict health, safety, and fire protection standards for hydrogen refuelling and storage, addressing risks like flammability and cryogenic temperatures. For electric systems, it is vital to establish standards for high-voltage battery handling, charging systems, and maintenance, including preventing and mitigating battery fires. The overall objective is to ensure that regulations for new aircraft stands allow the safe coexistence of hydrogen, electric, and traditional jet fuelling systems. Perhaps needless to state, standards for safe transportation, recycling, and disposal of batteries should also be covered.

Adapting landing fee structures. Current fee structures, which calculate charges based on maximum take-off weight (MTOW), disadvantage battery-electric aircraft due to their heavier battery systems. Regulators should introduce adjustments to subtract a portion of battery weight from MTOW and even exempt electric aircraft altogether from certain taxes to incentivise their adoption.

Training the workforce. Require training of airport personnel, emergency responders, and ground service teams in safe handling new technologies, including hydrogen, batteries, and high-voltage DC systems. Provide certification for fire services and maintenance crews to mitigate risks associated with hydrogen leaks and battery fires.

Promoting innovation. Regulators must ensure that the development and implementation of new standards do not slow down innovation in the industry. It is crucial to avoid overly restrictive regulation that could stifle experimentation and collaboration, and it is important to encourage jurisdictions to adopt and use another regulator's standards for certification if it improves the situation even though it is not sufficient.

Encouraging test environments. Provide airports with relaxed standards for experimentation with new technology, e.g., autonomous mobile equipment.

In general, regulators are encouraged to organise for engagement with commercial first movers in alternative propellants (aircraft manufacturers, airlines, and airports) to better understand their specific needs for regulation or deregulation as their products and services mature.

While regulation delivers essential knowledge to a smooth transition, it is important not to over-regulate to avoid stifling innovation.

Bridging ambition and action

Enabling a culture of innovation as well as increasing the visibility of the topic to involve the right people at the right time.

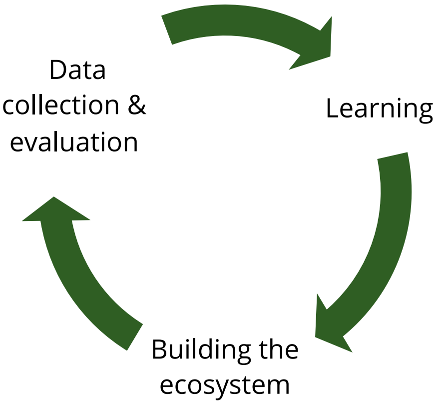
Fostering a culture of innovation

The vision of the future aircraft stand requires a practical approach to innovation that bridges ambition with actionable steps.

This three-block framework - learning, building the ecosystems, and data collection & evaluation – contains the activities and feedback mechanisms necessary to accelerate innovation. It is designed to drive collaboration, experimentation and continuous improvement, ensuring that the recommendations presented in this study are translated into actions among stakeholders.

In highly practiced environments such as aviation, knowledge is typically generated through analysis and research. The authors of this guide recommend that testing and experimentation of solutions can be a solid source of complementary data to existing analysis, and that stakeholders – primarily airports – collaborate to spread the risk and avoid working on similar solutions at the same time.

Sharing knowledge, building a network of first movers, and creating feedback loops through data driven insights will enable all stakeholders to raise their level of innovation.



Innovation is not only a process to match challenges with solutions, but first and foremost a human endeavour that can be foreign to people in expert roles participating in speculative projects. Therefore, leading the innovation effort involves the sensibility to create the psychological safe space for innovation teams and operations alike - this is the catalyst of thriving ecosystems of collaboration.

Turning the vision of the future aircraft stand into reality requires a practical approach to innovation that bridges ambition with actionable steps.

Data collection and knowledge sharing

Education

Building awareness and shared understanding.

Education is key to turning the future aircraft stand into a reality, as it ensures everyone involved understands their role in the shift toward sustainable aviation. Raising awareness about its significance and keeping internal and external stakeholders informed about advancements, regulations, and test findings helps build a shared perspective on the challenges and opportunities ahead. This can be achieved through tailored workshops, detailed reports, webinars, and public campaigns that resonate with different audiences across the ALIGHT consortium and working groups in EASA preparing future standards for electric and hydrogen aircraft. Fostering this shared understanding and ecosystem for exchanging ideas among decision-makers, design engineers, regulators, and manufacturers will equip them with the knowledge and confidence to act effectively.

Data collection and evaluation framework

Creating a feedback loop for informed decision making.

Another step is establishing a robust data collection and evaluation framework. Each experiment conducted within the ecosystem is an opportunity to build, measure, and learn. By systematically collecting data—such as operational efficiency, emissions reductions, and stakeholder satisfaction—ecosystem players can assess the impact of their efforts and refine their approaches. This feedback loop creates a dynamic cycle where insights from one phase inform the next, ensuring continuous improvement and scalability. Moreover, the data generated from these experiments supports internal decision-making and feeds back into the education block, enriching the knowledge base for all stakeholders. Over time, this iterative process builds a comprehensive body of evidence that supports informed decision-making and paves the way for widespread adoption of the future aircraft stand's recommendations.

Testing solutions together

Building internal and external ecosystems

Capitalising and expanding the effect of first-mover network.

Creating a thriving ecosystem of first movers is essential to accelerate the adoption and refinement of innovative solutions and their scalability. By bringing together airports, manufacturers, regulators, and other key players, this network forms a hub for experimentation, collaboration, and mutual learning.

Collaborators will be uniquely positioned to embrace the risks and rewards of testing new infrastructure and operational processes. Their willingness to innovate is the groundwork for developing operational practices and a culture prioritising agility and sustainability. Over time, this ecosystem should expand, creating a ripple effect that normalises the advancements across the industry. The proportional growth should enable a culture of innovation to become a natural part of operations in the industry.

A specific example of first movers could be aircraft manufacturers and their responsibility for sharing knowledge about critical interfaces. A swift knowledge sharing between airports and manufacturers gives airports sufficient time to plan for infrastructure changes. Currently, working groups established under EASA are creating procedures and guidelines for electric and hydrogen aircrafts to ensure these are in alignment with all stakeholders' findings.

Innovation management is a key enabler of the ecosystem. Practices such as prototyping, lean innovation methods, and design thinking form the backbone of the collaborative effort, complementing subject matter experts and specialists. Project management as well as rigorous innovation accounting are likewise essential to assess the value and impact of a large portfolio of initiatives.

For an airport, an innovation practice area with a skilled team and budgets for innovation projects is a prerequisite for engaging in collaborative, open projects. Airports are therefore encouraged to establish specialised innovation units who have the ability and mandate to involve the organisation and start new initiatives. This is an investment that is necessary to reach the sustainability targets and will also contribute to growing the business.

It is often said that the transition does not have a "technology fix", but instead that cross-national legislation will need to be significantly stricter. In the case of more sustainable aviation, however, regulation and standards will not bring about change quickly enough – the industry needs to come together across the entire value chain and support each other to mature the technologies through experimentation and bring them to scale. That is what a healthy ecosystem for innovation brings to the industry.

The transition requires subject matter experts, practitioners and deciders to bring their knowledge, and this is best achieved through collaboration.

Abbreviations & definitions

The following lists the abbreviations and terms defined in this document.

Abbreviations

AMS	Airport Management Systems
ATC	Air traffic control
AVDGS	Advanced Visual Docking Guidance System
E-planes	Electric planes
eGSE	Electric GSE
GH2	Gaseous hydrogen
GHG	Greenhouse gas
GPU	Ground Power Unit
GSE	Ground support equipment
H-planes	Hydrogen planes
Jet A fuel	Kerosene grade of fuel suitable for most turbine engined aircraft
LH2	Liquid hydrogen
MARS	Multiple Aircraft Ramp System
MW	Megawatt
PCA	Aircraft Preconditioned Air
SAF	Sustainable Aviation Fuel
V2X	Vehicle-to-Everything

Definitions

Regional routes/flights	<1500 km routes/flights
Continental routes/flights	1500 km – 4000 km routes/flights
Intercontinental routes/flights	>4000 km routes/flights

References

Background references are included in the underlying infrastructure and pushback study (more information on page 12). Additional references are added on the individual page in this document.

The following partners have contributed to this document.

Copenhagen Airports CPH

Aeroporti di Roma

Vilniaus oro uostas

Centralny Port Komunikacyjny

AIRBIZ

Lithuanian Airports VNO KUN PLQ

Danish Technological Institute

Hybrid Greentech Energy Storage Intelligence

Università degli Studi di Milano

Università di Parma

NISA Nordic Initiative for Sustainable Aviation

Olsen

Funded by the European Union

ALIGHT Sustainable Aviation

nlmtd create the future