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# BLUE SKIES, GREEN FUELS, BRIGHT FUTURE

A Roadmap to a Sustainable Future for Aviation

# 1. Introduction

Aviation technology is a modern marvel, connecting the world far faster than our ancestors ever dreamed of and helping to drive the globe's economic engine. However, the aviation sector is also one of the largest polluters and contributors to climate change, contributing 2.5 percent of carbon emissions, which could triple to 7.5% by 2050 [1]. In the future, sustainable alternatives will be necessary to drive down emissions and keep the sector going.

This paper analyzes the possible available technologies in 2050 to ensure a sustainable aviation future and proposes a hub airport design that accommodates all of these future designs. These include battery-electric aircraft and the utilization of sustainable fuels. It is shown that as much as 50% of future aircraft may be electrified, while most or all of the remainder could be fueled by sustainable fuels by 2050. All of these advancements will bring emissions down and bring the aviation sector closer to sustainability. The airport design overview features gate design, recharging and refueling infrastructure, and layout of the airport to take full advantage of these future advancements.

# 2. 2050 Aviation Landscape

The following is an analysis of the potential future aviation market of the 2050s. Potential future types of aircraft are broken down into two main groups: electrified aircraft and sustainable fuel aircraft. Electrified aircraft include Conventional Takeoff and Landing, Short Takeoff and Landing, and Vertical Takeoff and Landing aircraft (eCTOL, eSTOL, and eVTOL respectively). Sustainable fuel aircraft include hydrogen, ammonia, biofuels, conventional fuels, and novel aircraft configurations such as Blended Wing Body (BWB) craft.

## 2.1 Electric Aircraft

Electric aircraft are a possible alternative to jet fuel powered aircraft, although they suffer from short range and small size. This is due to the great difference in energy density between batteries and jet fuel. While batteries can hold only 250 watt-hours per kilogram, jet fuel can carry 12,000 [1]. Nonetheless, battery-electric aircraft are a great option for short-range due to their lack of carbon emissions. Within the next ten years, a typical battery-electric eCTOL plane are projected to have a range of approximately 500 miles and carry around ten passengers, based on predicted battery advancements. These planes should also be able to operate at around one-fifth the operating cost of current small aircraft [2]. While these numbers are aspirational, they are from a company currently developing an electric aircraft and are estimated for 2030. Therefore, this is likely actually a conservative estimate of performance in 2050. Several prototype electric aircraft have already flown, giving this technology a Technological Readiness Level (TRL) of 7, with 9 indicating full operational status.

Assuming the level of performance above, electric aircraft can be expected to dominate the short-range market. Their lower cost makes far more routes economically viable, allowing for access to airports currently defunct. According to Scientific American, "approximately half of all flights globally are less than 800 kilometers (500 miles), which is expected to be within the range of battery-powered aircraft by 2025.” [1] Again, this would be a conservative estimate of performance by 2050. Taking these numbers at face value, however, still gives a potential market share for electrified aircraft of 50%. Although these estimates may seem overly cautious, electrified aircraft are an entirely new technology and new airplanes will have to be constructed. There will also be strong economic incentives to use existing airliners, which cannot be converted into battery-powered planes due to their size. These aircraft will have to use sustainable fuels for operation. Due to all of these factors, this paper assumes electric airplanes will have a maximum range of around 500 miles by 2050, that they will be cheaper than other aircraft, and that half of air traffic will be electrified by 2050.

There are three main types of electric aircraft, as listed above: eCTOL, eSTOL, and eVTOL. By 2050, eCTOL planes would likely range from small aircraft carrying approximately ten passengers [2] to airliners carrying 100 [3]. The precise size of these aircraft is difficult to determine and not a main focus of this research; however, it is worth noting that there will likely be different sizes of eCTOL aircraft in regular use. eSTOL and eVTOL planes, which are also together referred to as Advanced Air Mobility (AAM), will likely be used for commuting and intracity travel, respectively [4]. eSTOL aircraft are designed to launch from a very short runway [5], requiring more infrastructure than eVTOLs but also having more efficiency and range. eVTOLs are the least efficient type of electric aircraft and likely will be the least used. eSTOLs are currently at around a TRL of 6, with eSTOLs at perhaps 5. However, extensive research is being done in this field and progress is being made quickly. This paper estimates that eCTOLs will comprise 30% of the 2050 market, with eSTOLs making up 15% and eVTOLs making up 5%. These numbers are due to the types of trips that the aircraft will serve: eVTOLs for local travel, eSTOLs for intercity, and eCTOLs for regional.

## 2.2 Sustainable Fuels

There are several types of sustainable fuels that could be in use by 2050 to power aircraft. These include hydrogen, ammonia, and sustainable aviation fuel (SAF). Each has their own set of advantages and disadvantages.

One option for sustainable fuel is hydrogen, either pressurized or liquified, which could be used in tandem with blended-wing body (BWB) aircraft. This paper assumes liquid hydrogen will be used. Hydrogen has even more energy density by weight than jet fuel, by a factor of around three, and thus has over 100 times the energy density by weight than a lithium-ion battery [6]. The main issues with hydrogen are its low volumetric density and the difficulty of sourcing it in a sustainable way. Currently, most hydrogen is produced by steam reforming, which uses fossil fuels and is not a sustainable process. However, there are ways to produce hydrogen cleanly, such as electrolysis, and it is likely these will have been improved substantially by 2050. Even once these problems are ameliorated, however, planes will still need specialized and larger tanks to hold hydrogen fuel. Liquid hydrogen (LH2) has an energy density by volume around a quarter that of jet fuel, meaning a liquid hydrogen tank would need to be four times as large [6].

As mentioned above, it is likely that BWB aircraft can utilize hydrogen fuels more effectively due to their high internal volume. LH2 itself has a TRL of 9, but BWBs are around a 3 or 4, although progress is being made. BWB aircraft combine the wing and body of the airplane, providing more efficiency and internal volume. This paper estimates approximately 20% of aircraft will utilize liquid hydrogen by 2050, and that most or all of these will be BWB aircraft.

A hydrogen carrier, such as ammonia, is also an option. According to Interesting Engineering, “Compared to hydrogen, ammonia is far easier and cheaper to transport and store, even though it can only carry roughly 20% of the energy that hydrogen does by weight. But on the flip side, it can carry roughly 70% more energy than liquid H2 in volume, according to the report. Typically, the problem of weight usually rules out ammonia when it comes to new aviation technologies.” [7] While the weight problem can be worked around, especially given that electric aircraft have far greater weight problems, ammonia also produces dangerous nitrous oxide emissions. Use of ammonia as fuel is also still at a TRL of perhaps 4. Therefore this paper estimates 10% of aircraft will be powered using ammonia by 2050.

Finally, there is sustainable aviation fuel (SAF). SAF covers everything from biofuels to synthetic jet fuel. “SAF is produced from sustainable resources such as waste oils from a biological origin, agri residues, or non-fossil CO2” [8]. It is estimated that there may be enough biomass sustainably produced per year in the US to make 50-60 billion gallons of biofuels [9]. This is about 2.7 times the current consumption rate of 18.27 billion gallons per year [10]. While the amount of fuel consumed per year will likely increase substantially by 2050, there is potential for a large part of the market to be fueled by SAF. However, SAF still produces carbon emissions, which may not be as desirable compared to zero-carbon options such as ammonia or liquid hydrogen. Most importantly for this paper, using SAF requires very little or no change in the operation of airplanes, so it requires no in-depth analysis. However, it is likely that in 2050 this will still be a common option, perhaps around 20% of the market.

There are also several new types of airplanes that might use sustainable fuels, such as blended wing body (BWB) and supersonic airplanes. As mentioned above, BWB planes are best used in conjunction with hydrogen. Some accommodations for these planes are described in the Airport Design section. Supersonic airplanes are not likely to require significantly different infrastructure on the ground than subsonic aircraft, and are thus not a focus of this paper. However, it is likely that supersonic aircraft will comprise a significant share of the 2050 market.

# 3. Airport Design

The airport, intended to be a hub airport, will consist of three main island linear terminals arranged perpendicular to the runways, and two U-shaped terminals. The island terminals will handle aircraft that are powered by sustainable fuels, including BWBs and supersonic aircraft, which will be accommodated at the central terminal. The U-shaped terminals will handle electric aircraft, including eCTOLs (Fig 1), eSTOLs, and eVTOLs (Fig 2) and will have direct connections with parking structures. The island terminals will be connected to each other and to the parking structures by both skybridges and an underground automated people mover (APM).

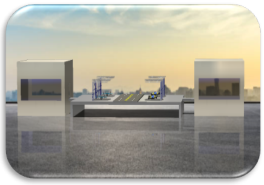

Fig 1: AAM Hub

Fig 2: eCTOLHub

The three types of terminal will have different infrastructure for different types of aircraft. The electric aircraft terminals will have charging infrastructure and special boarding procedures. Sustainable fuels, especially hydrogen, will require different storage techniques, and BWB aircraft will require a different gate configuration to accommodate a wider airplane and a higher number of passengers.

## 3.1 Electric Aircraft Terminals

Electric aircraft will be smaller and more suited for regional missions than other planes, and require different infrastructure. As such, this paper proposes having a separate terminal for them. Another reason for this is to keep them out of the path of the main runways, as these planes are so small they must be separated from larger aircraft and their landing vortices.

These terminals will have different infrastructure for different types of electric aircraft. It is assumed that eSTOL and eVTOL craft will land on the roof of each terminal at an AAM hub (Fig 1), as these aircraft are designed to land on city rooftops. eCTOL aircraft will dock at ground level, similar to conventional aircraft. All gates in the electric aircraft terminal will have charging infrastructure designed to recharge the planes as quickly as possible.

### 3.1.1 Aircraft Boarding

Most electric aircraft will be much smaller than an airliner, and even electric airliners, should they exist by 2050, will certainly be smaller than their conventional counterparts. As a result, this paper assumes that passengers will board electric aircraft directly, as the planes, especially eSTOL and eVTOL craft, would be too small and numerous to warrant a jetway.

Each type of electric aircraft would have a different docking procedure. eSTOL and eVTOL craft would land on a specially designated part of the rooftops of these terminals and then taxi under large awnings to protect passengers and planes from weather while they deplane and enplane. eSTOL planes are being designed to be able to land on runways as short as approximately 100 yards [10], while eVTOL planes could land at a standard helipad. The eCTOL planes would dock at ground level, and would move inside the terminal, which would have docking alcoves along the first floor (Fig 2). Passengers would board their planes directly inside these alcoves without the use of a jetway.

### 3.1.2 Charging Infrastructure

According to a report from the National Renewable Energy Laboratory, electric airplanes could be recharged in under half an hour using megawatt-scale charging [11]. According to the report, “Charging stations of this capacity will require solutions that consider the physical limitations of the charging infrastructure and energy storage device. These solutions may include parallel charging (i.e., charging from two separate battery banks), wireless charging (which poses an issue because of electromagnetic impacts on sensitive aviation and lightning arrest systems), and the use of nanoelectrofuel flow battery technology, where charging occurs by replacing battery fluids.” [11] All of these technologies are in varying stages of development and it can be expected that at least one will be mature enough (TRL 8 or 9) by 2050 to ensure rapid and constant charging of a sizable fleet of electric aircraft. This paper assumes charging infrastructure will be built into the electric aircraft docking areas, either on the roof or the docking alcoves on the ground floor, and that electric aircraft will be charged at the same time as passenger boarding.

## 3.2 Sustainable Fuel Aircraft Terminal(s)

Sustainable fuels will encompass three major types: hydrogen, ammonia, and sustainable aviation fuels (SAF). The latter two will require little specialized infrastructure, but hydrogen will require special accommodations. This paper assumes liquid hydrogen (LH2) is used, which requires cryogenic facilities similar to those at rocket launch sites. Use of pressurized hydrogen, either in place of or in tandem with LH2, would also require its own special infrastructure.

### 3.2.1 Fuel Infrastructure

Liquid Hydrogen (LH2) must be kept at a very low temperature to keep it in liquid form, approximately -253 degrees Celsius [12]. It is assumed that LH2 will be used due to it being the most compressed form of hydrogen and the least demanding in terms of volume. Liquid hydrogen tanks for aircraft are being designed with a vacuum layer and multi-layer insulation techniques to keep the hydrogen cold [12]. While these tanks are being designed for aircraft, it can be assumed that storage tanks at the airport itself will be very similar, albeit larger. LH2 will likely be stored in underground tanks near the sustainable fuel terminal. There will also be a need for special infrastructure such as pipes designed for cryogenic temperatures. It is also assumed that liquid hydrogen will be used in tandem with BWB aircraft due to their higher internal volume. While hydrogen fuel and BWB aircraft are not mutually inclusive, there is likely to be very significant overlap in their use.

### 3.2.2 Infrastructure for Other Fuels

Besides hydrogen, other sustainable fuel options include ammonia and sustainable aviation fuels (SAF), such as biofuels and synthetic jet fuel. There is extensive experience using ammonia in the fertilizer industry, and SAF is not likely to require any significant changes to pre-existing infrastructure in either the aircraft or the airport facilities. In addition, ammonia is being researched for many applications such as ships and other vehicles [7], and is likely to be in extensive use by 2050, allowing for easier implementation in the aviation sector. This paper assumes that no significant modifications to airports will be needed for SAF or ammonia.

Fig 3: BWB Hub

### 3.2.3 Blended Wing Body Accommodations

Blended Wing Body (BWB) aircraft will be wider and larger than conventional planes. BWB configuration is often considered for aircraft with over 400 passengers [13], and require modifications to the gate to allow for faster passenger deplanement (Fig 3). It is recommended that there be two jetways per airplane for faster boarding. BWB gates will also be wider than other gates and may have accommodations for passengers to board at the rear of the plane as well directly from the tarmac. This would be similar to the boarding procedures of an electric aircraft. Specialized equipment for BWB maintenance, fueling, and other services will be housed at the gates inside the terminal. Although BWB and hydrogen infrastructure are not mutually inclusive, it can be assumed that most or possibly all BWB gates will also have liquid hydrogen infrastructure as described in the above section.

## 3.3 Airport Layout

As mentioned above, the airport consists of five terminals, two for electric aircraft and three for sustainable fuels. The electric aircraft terminals are situated on either side of the airport grounds, with the three oval-shaped satellite sustainable fuel terminals between them. The runways are on either side of these five terminals, and it is assumed that a highway circles the entire airport to allow access from all directions. Check-in and security facilities are located in the electric aircraft terminals, and transportation to the central three terminals is served by a system of skybridges, underground tunnels, and an underground APM.

These design choices were made for several reasons. One was the design of Atlanta airport, which was considered one of the most efficient airports in the world for 14 consecutive years. Some reasons given for this efficiency are its terminals being perpendicular to the runways, its APM trains, and its massive underground walkways [14]. Other influences were the advantages of both linear terminals and satellite terminals. Linear terminals have short walking times and simple construction, while satellite terminals allow for efficient management of passengers and centralization of facilities and resources in the hub(s), such as security. Additionally, more satellite terminals can be added if needed, allowing an airport to adjust to changing demand [15]. Finally, the electric terminals are U-shaped due to the need for eSTOL runways on part of their roof. It is assumed that these runways should be oriented the same direction as the main runways but separated from them, so that smaller electric planes never interact with the downwash of larger airplanes. Meanwhile, the section for eCTOLs should be perpendicular to the runway for easier passenger access, leading to the U shape of the building.

### 3.3.1 Electric Taxiing System

Electric taxiing systems (ETS) allow airplanes to taxi without the use of their main engines, leading to some fuel savings and also making the runways safer for other vehicles. It is estimated that 65 gallons of fuel per plane, per flight can be saved with an ETS. In addition, an ETS can give a plane higher maneuverability on the runway [16]. This paper assumes that ETS will be nearly or totally ubiquitous by 2050, which will allow smaller aircraft like eCTOLs to interact safely with larger airplanes on the tarmac. This will also facilitate aircraft boarding of eCTOLs or BWBs on the tarmac, since there would not be as much disturbance from passing aircraft. Finally, this will facilitate the baggage transport system outlined in the next section.

### 3.3.2 Baggage Transport System

Baggage transport would be accomplished in much the same way as at current airports, with carts running baggage between planes on roads built directly into the tarmac and taxiing areas. However, there are several technologies that will make an impact on this aspect of airport design by 2050, including autonomous and electrified vehicles. It can be assumed that all baggage carts will be electrified by 2050, and also that the entire system will be automated or at least semi-automated. The aircraft themselves may be integrated with this system while on the ground, greatly reducing the risk of any collision. This will allow baggage to be transferred quickly between all flights or to baggage claim areas. Similar technology could be used to transfer passengers, such as a personal rapid transit system, but this paper assumes an automated people mover (APM) due to simplicity and a higher efficiency when transporting many people.

# 4. Conclusions

To create a sustainable future for aviation, new technologies will be required, and new airports will need to be designed to use those technologies to their full potential. This paper makes the following conclusions. First, future aviation will be split roughly equally between electric aircraft and aircraft utilizing sustainable fuel. Second, terminals in the future will be designed with one of these aircraft types in mind, due to their different infrastructure needs. Electric aircraft will be smaller and need new charging technologies, while sustainable aircraft will need special storage for their new carbon-free fuels.

This paper utilized a hub airport design to take advantage of as many of these new advances in aviation as possible. In the future, many airports will exclusively serve electric aircraft, and others may serve more conventional airplanes. The hub airport explained here is meant to be a microcosm of the future aviation market in general, however. These future airplanes will revolutionize the air industry and one day, hopefully by 2050, decarbonize it entirely. Ensuring that these airplanes are served in an efficient and effective manner is one important step toward a more sustainable aviation sector, and a more sustainable world.

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# Appendix B: Nomenclature

| | |
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| TRL | Technological Readiness Level |
| eCTOL | Electric Conventional Takeoff and Landing |
| eSTOL | Electric Short Takeoff and Landing |
| eVTOL | Electric Vertical Takeoff and Landing |
| AAM | Advanced Air Mobility |
| BWB | Blended Wing Body |
| LH2 | Liquid Hydrogen |
| SAF | Sustainable Aviation Fuel |
| APM | Automated People Mover |
| ETS | Electric Taxiing System |