2022 Gateways to Blue Skies: Airports of Tomorrow Competition

Bluebonnet Skies Team

Technical Paper by

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Table of Contents

INTRODUCTION

Carbon-neutrality in the aviation industry seems like a sky-high goal, but our Austin-based team is convinced it can be achieved by 2050, even with down-to-Earth assumptions. We analyzed fuel policies in many of the world's largest economies and future aviation technologies to design an airport for tomorrow's sustainable world. Our airport is located in nearby Houston, which has a large, dynamic aviation market serving international, domestic, and regional routes. Houston also has the added constraint of frequent flooding and hurricanes. Before diving into our airport design and the research behind our decisions, we would like to justify a couple of key choices for tomorrow's airport.

For the primary fuels for these projected aircraft of 2050, we selected Sustainable Aviation Fuel (SAF) and electrical batteries for their practical application. As SAF is currently in use, both governments and airlines have already designed policies and infrastructure around them. Moreover, SAF and battery-electric planes receive the most industry attention and investments. SAFs can be 100% carbon-neutral [1, 2], depending on how they are produced, and reduce contrails by 70%[3], significantly reducing the amount of heat trapped underneath an airplane's path. Battery-electric planes can be 100% carbon-neutral if they are charged from a sustainable source. Although hydrogen and ammonia have recently received a lot of media interest, we have determined these technologies will not be used in the aviation industry by 2050. These unattainable fuels have too many design concerns and unrealistic expectations due to the need for significant infrastructure overhauls that most airports could not support, sizable design challenges for current and future technologies, and lack of attention in the startup or established aviation world. For instance, Airbus recently stated they do not believe hydrogen-powered planes will be possible by 2050.[4]

Aircraft of the future will look similar to today with the addition of narrow supersonic aircraft, blended-wing body aircraft, and efficient small electric jets designed to carry heavy batteries. These new aircraft will impose challenges on today's infrastructure and were an important part of our investigation. Many airport terminals already have sunk costs within their construction and private developers prefer to utilize and adapt their existing facilities rather than completely discard them for a futuristic and financially unattainable airport. Accordingly, our futuristic airport design is financially viable and is based upon reducing energy consumption, generating extra on-site energy for electric planes and vehicles, and emphasizing flexibility to allow our airport to adapt to future changes in aviation.

OUR AIRPORT DESIGN

Our design rests on three pillars - flexibility, transition, and reliability. Flexibility allows our design to adapt to future technologies; transition makes our project trailblazing yet attainable airport that even dated airports can adopt; reliability means our airport has additional system redundancies, where if one system fails another system will automatically kick into action, without skipping a beat. In terms of power redundancy, the airport will be connected to the local municipal grid with the addition of onsite renewable energy generation to ensure renewables are the focus of energy consumption while assuring that the airport is not shut down due to unforeseen events that inhibit renewable energy generation. Mega batteries, added over time, will store energy generated on-site. However, because most of the airport's open spaces support taxiways and runways, which are encompassed by obstacle-free zones, only limited space beside the terminal structures and landside areas is set aside for sustainable energy generation. As a result, our design showcases a transparent solar-panel roof above the electric aircraft gate areas (Figure 4) and the installation of various vertical-axis wind turbines throughout the airport to exploit these under-utilized vertical spaces as seen in Houston Intercontinental terminal B (Figure 3).

The solar roof features semi permeable plastic next-generation solar panels modules, serving as a skylight by allowing light to pass through while collecting energy with solar cells. Our design draws inspiration from the Worldport terminal (Figure 2) from 1958, which allowed aircraft to park underneath an overhanging umbrella that offered a convenient way of boarding before jet bridges were invented. The airport will also receive several smaller wind turbines to capture energy from natural and airplane-produced winds. Houston's humid subtropical climate produces nearly 50 inches of rain annually. These high levels of precipitation mean the new wind turbines will be relied upon as the primary source for energy generation. Examples of potential future wind power technologies are Joe Doucet's wind turbine wall, EWICON bladeless turbines, Vortex Bladeless, Icewind's Freya, and the Halcium PowerPod, all of which are small enough to be out of the way of aircraft and visibility, have no moving parts or are covered, and can generate energy in unused areas of an airport, like beside hangars and on terminals facades. The batteries will charge electric aircraft and electric Ground Support Equipment (GSE) when they cannot be charged directly from energy generated on-site, due to low solar exposure or limited wind. Because electric GSEs can lose charge in cold weather, charging ports will be located underground at the gates to keep the gate area free and will be waterproofed to ensure they can withstand Houston flooding. The GSE will be automated, reducing their emissions by 5%5. Additionally, the batteries will allow electric aircraft to charge during a blackout. Energy generated on-site will allow airplanes to directly connect to electricity instead of using Auxiliary Power Units (APUs) or Ground Power Units (GPUs).

Electric planes are initially expected to take longer to charge than their turnaround time, so our design features a parking lot hard stand gates for charging electric aircraft and GSE with a similar rooftop. Airliners will schedule aircraft rotations so a different fully-charged aircraft is ready to depart with passengers when the plane that just landed would originally be needed. Passengers will disembark the aircraft at these covered gates and connect to the main terminal via a covered walkway. Electric "taxibot" pushback tugs like those at Amsterdam-Schiphol Airport will bring airplanes between the runway, the hard stands, the terminal, and back to the runway, reducing plane fuel and electricity consumption when taxiing between the runway and gate.

The roof has the added benefit of significantly shading the aircraft beneath it, reducing the energy needed to cool jet bridges and the aircraft plugged into the terminals. This plan will reduce the energy consumption of a gate's largest four energy consumers - cooling jet bridges, cooling the terminal, APUs/GPUs, and GSE - while generating electricity and increasing passenger comfort. Light will pass through the translucent solar pael roof, eliminating the need for lighting during the day and dealing with the heavy rains of Houston. This configuration is minimal, meaning it is easily dismantlable for the introduction of larger electric aircraft that would require a taller roof, following the flexibility theme for the airport.

Beneath the roof will be a similar gate layout to what we know today. Most planes will use SAF, which works smoothly with the same infrastructure as current jet A fuel, needing no additional infrastructure changes. Gates will have modular furniture and equipment to adapt to more aircraft types. Our main gate change is to use a pair of jet bridges to service blended-wing aircraft like the Flying V or X-48, streamlining boarding and disembarking. These aircraft will receive freight, baggage, food, and fuel from the back of the airplane to make space for the new jet bridge, significantly reducing turnaround time. When a blended-wing airplane is not at the gate, it can serve two small aircraft instead. Hence, one jet bridge at these gates will be redesigned to be more flexible to service planes that arrive at its left and right. Our design emphasizes flexibility by allowing the gate area to service small electric aircraft and also larger anticipated electric aircraft of the future. Regarding terminal operations, our terminals will mimic flagship airports in the world of sustainability, incorporating the highest LEED certifications and best energy-efficient HVAC systems, lighting, and insulation.

Finally, our airport will support electric vertical take-off (eVTOL) and landing aircraft. United Airlines, American Airlines, and Virgin Atlantic have announced orders for eVTOLs, which will be implemented in major hub airports to transport passengers from city cores to the airport. Additionally, our design features landing sites for eVTOLs, which are expected to require no more than three acres. Based on airport runway traffic patterns, such sites would be either on the airside area connected via people mover or on the landside area prominently on top of parking garages.

AIRPORT DESIGN JUSTIFICATIONS

Our airport design pays careful attention towards energy sources, aircraft design, and impacts upon passenger boarding. Fortunately, most aircraft flying to our 2050 airport will follow the same standardization of gate size configuration that has been followed since the 1950s, with the simple tube and wing aircraft design withstanding the test of time. Airplane families such as the Boeing 737, 787, 777, Airbus A350, and A320 will still be prominent in the aviation market by 2050 because electrification of high-capacity airplanes is not viable by such timelines. However, smaller regional electric and hybrid aircraft of two to twenty passengers will require charging systems and charging rotations at a “parking lot” to maximize efficiency.

Narrowbody and widebody aircraft in 2050 will use the current gate infrastructure with only minor adjustments. Future airline fleets will welcome the Boom Supersonic Overture, with the same wingspan as the ERJ-145; the KLM Tudelft Flying V, a hybrid wing-body aircraft, with the same wingspan as the Airbus A350; and the NASA X-48, with the same wingspan as the 767. Our flexible and modular gates will allow all of these aircraft to be served, supporting faster turnarounds as aforementioned for the electric aircraft and the hybrid wing-body aircraft.

Advancements in small aircraft have allowed for the electrification of redesigned small prop aircraft, such as Eviation’s Alice or Heart Aerospace’s ES-19, and have also allowed for old aircraft to be retrofitted, such as the Cessna Caravans and Twin Otters. However, retrofitting requires airports to adjust to these aircraft using airside assets. Historically, airport terminal design has been inflexible to changing aircraft capacity and has failed to be future-proof. According to Bloomberg City Lab, “terminals developed in lockstep with the aircraft they served, which have increased from a passenger capacity of about 100 in 1960 to more than eight times that amount in 2007’s”. Similarly, from 2030 to 2050, only small nine to nineteen passenger aircraft will be fully electric, and the size of such aircraft allows for more gate spaces to be added to the apron. For instance, the same distance of terminal length can fit three 737 MAX10s or six small electric aircraft. Our design emphasizes flexibility for the future by allowing our gate area to service small electric aircraft and future expected large electric aircraft.

We designed our airport's infrastructure around aircraft turnaround times and the expected ground capacity of aircraft. Electric aircraft require three hours of charging to fly their maximum range, nearly 4.5 times longer than a typical turnaround time. Although small planes like the Alice could fly an hour on 30 minutes of charging, which is on par with today’s turnaround schedule, some flight operations would require more charging, resulting in more planes parked than flying. Consequently, our airport will allow airlines to schedule aircraft rotations in the “parking lot.”

AIRLINE MARKETS

Airlines are switching to increased SAF usage, as seen in Table 1.1 and 1.2, due to international government mandates because it is more sustainable than Jet A fuel and can be implemented immediately. However, SAF is considerably more expensive than traditional fuel at nearly eight times[6] the price of Jet A fuel. This means that the price of flying will increase for consumers and indirect competition, like trains, buses, and driving, will see increased demand from competitive pricing. Because electric aircraft are independent of jet fuels, they are projected to be less expensive to run due to a cheaper fuel source, longer motor life spans, and reduced maintenance costs.

The US Department of Transportation (USDOT) subsidizes airlines to fly regional flights between medium-sized cities and small towns in the Essential Air Service program to guarantee a minimum number of flights to citizens in remote areas across the country. These reports provide valuable insights into airline revenues and expenses for regional routes because airlines rarely make income statements public, where electric planes can be the preferred option. In 2005, Cape Air flight 9K 1853, Boston to Rockland, ME, received a USDOT subsidy and released its operating costs of $3,350,746.00.[7] Implementing an electric aircraft on this route would increase the route’s profit by $927,947.50 because of reduced operating costs, increased ownership costs, and reduced maintenance costs, listed and justified in Table 2. As a result, many other smaller, regional routes will become far more profitable with the advancements of electric aircraft. This profit will only increase further due to rising fuel costs from incorporating SAF and recently shut down regional flights, like Houston to College Station, will again be profitable. Because airlines can be significantly more profitable on these routes with electric aircraft than with traditional jets, the US government will probably reduce these subsidies so that operating these routes with electric aircraft is as profitable as with traditional jets. As a result, these subsidies are expected to continue but be reduced, saving the US government around $87M, calculated in Table 3, when airliners switch to electric flights based on today’s technology. With a reduction of the subsidy to save the government money that no longer needs to be spent, traditional jets may not be financially feasible to run anymore. Electric aircraft’s cost savings will only increase further with the reduction of battery cost. Hence, many non-existent routes today will appear in the future and significantly boost regional travel. This is exciting news because all of these routes can be carbon-neutral if they are powered by a sustainable energy source.

SAFs are expensive. They have not fully taken off because they struggle with the green premium - the cyclical loop of a higher price of something sustainable, such as SAF, due to a lack of supply and logistics systems due to lower demand of the sustainable material because of its high price. Although the price of SAF is expected to decrease due to a reduction in the green premium, an increase in tax credits, advancements of SAF production technology, and widespread adoption of SAFs, electric aircraft will soon dominate the regional markets. Consequently, the airline market may shift away from the point-to-point model driven by advancements in smaller, more fuel-efficient long-range aircraft towards a hub and spoke model, where passengers connect between larger cities to fly to smaller airports. Consequently, our Houston airport will see an increase in regional flights compared to larger, international flights. Passengers flying in and out of smaller airports may pay less to take electric aircraft to nearby larger cities than to fly directly to farther away mid-size cities. For instance, currently, Houston directly connects to small cities like Knoxville TN, Savannah GA, Columbia SC, Grand Rapids MI, Des Moines IA, Kalispell MT, Palm Springs CA, and smaller ski towns in Colorado, among others. Some, if not many, of these flights would no longer be viable - passengers could pay less to fly between Houston and a nearby large city and then connect on a smaller electric or SAF-electric hybrid flight to their target destination city. This would result in larger SAF-fueled airplanes flying between cities on fewer domestic and international flights.

SUSTAINABLE AVIATION FUEL (SAF)

Foremost, it is exciting to note that SAF recently achieved the maximum technology readiness level (TRL) of 9[8]. This occurred on December 2, 2021[9] when a United Airlines B-737 MAX 8 (flight UA 4518) flew from Chicago's O'Hare to Washington D.C.'s Reagan National Airport with 100% SAF in one of its engines. Although federal regulation limits the maximum percentage of SAF in a flight to 50%, one of the two engines flew entirely on SAF, loopholing this rule and demonstrating pure SAF can power an aircraft engine. Outside of the US, Emirates is fueling one of its B-777-300ER with a pair of GE90 engines that are powered by 100% SAF[10] this year. However, due to government regulations and commitments from various airliners, shown in Tables 1.1 and 1.2, the green premium is expected to be reduced. Predominantly first-world, developed countries are listed in these tables because they are the only ones who can afford to bear the prices of the green premium while it remains. As demand for SAF increases, supply will follow, persuading current oil companies and SAF-specific companies, like SkyNRG, Neste, Gevo, and Northwest Advanced Biofuels, to start or increase current SAF production. Once the green premium disappears and SAF becomes competitive or even cheaper than Jet A fuel, many if not all airlines and countries may switch to exclusively SAF.

IATA, the International Air Transport Association, estimated only a 2% mix[11] of SAF into regular fuels would overcome the green premium. After this amount, costs would be reduced significantly enough[12] that demand would increase on its own, breaking the loop of the green premium. This 2% target was aimed to be reached by 2025, but projections show the world will only produce a guaranteed minimum of 85.7% of that 2%, calculated in Table 4, of this target. Regardless, the goal of 2% will be achieved by 2026 and production will take off.

There are currently seven ways to produce SAF, listed in Table 5, but only one, HEFA - Hydrotreated Esters and Fatty Acids - is currently commercially viable[13]. In the next 30 years, other methods may become commercially viable, other production methods may be found, or HEFA may be significantly scaled. Some SAF pathways even have net-negative[62] carbon footprints. More research, funding, and attention will be given to SAF production mechanisms following increasing commitments to SAF through government mandates and research and airliner commitments. For wide-scale adoption of SAF throughout US markets, the price of SAF needs to fall to near Jet A fuel or mandates must require 100% SAF by 2050. Regardless, due to increasing mandates of SAF, most if not all airplanes will have full SAF-processing engines by 2050 even if SAF costs more than Jet A fuel.

BATTERIES

Battery-powered aircraft at the airport can be utilized for regional flights where SAF or jet-fueled aircraft are not necessary, and possibly more costly. With regards to the consumer side, electric planes may be considered a more luxurious experience than commercial jet fuel planes. Battery-powered flights operate much quieter and feel much less crowded than commercial flights because they have less passenger capacity due to the battery's weight. There are many companies currently working on battery-powered aircraft technology, including companies like Eviation, MagniX, and Pipistrel. Israeli startup Eviation's nine-passenger electric commuter plane, Alice, costs $200 per flight hour to operate, while the same type of plane, a turboprop, powered by jet fuel costs $1,200-$2,000 per flight hour[14]. However, the most common plane for regional flights is a regular commercial jet fuel plane like the ERJ 145, which costs $3,763 per flight hour and can carry 50 passengers. Comparing the electric and jet fuel planes, the Alice costs about $22 per passenger per hour, and the ERJ 145 costs about $75 per passenger per hour, so the electric plane is still the more economical option.

The main challenge of electric aircraft is the weight of the battery needed to provide power, which is why most are smaller and can only go shorter distances. For example, Alice can fly up to 440 nautical miles. This can cover a flight from New York, NY, to Columbus, OH, or Houston, TX to Memphis, TN. According to data from the Department of Transportation, this could cover a significant number of flights. In 2018, 77% of flights in the US were domestic, roughly half of which were regional, so there is a high amount of potential for electric aircraft to be used for these types of flights[15]. In the Houston area, there are about 32 outgoing regional flights that could be replaced with today's fully electric aircraft, which can be seen in Figure 1. Based on the existing technology such as the Alice, this would require about 26240 kWh/day, costing $1960 per day, or about $61 per aircraft per flight. With higher capacity batteries the electricity cost will increase, but this is incredibly reasonable compared to Jet A fuel, which would cost about $6021 for the same flight distance and aircraft capacity. Another challenge is the turnaround time of electric aircraft. Swapping removable plane batteries is a possibility to optimize this process, but we opted to not include them in our design because they will be more expensive than adding charging stations.

Although current electric aircraft are only being developed for two-to-six, nine, and nineteen-seat planes, advancements in battery density and weight will make larger electric planes, or at least SAF-electric hybrid aircraft with higher flight duration feasible within the next 30 years. Right now, most electric aircraft use lithium-ion batteries certified for aircraft, which are similar but heavier than the lithium-ion batteries we are familiar with in our phones and computers today. A future contender to lithium-ion batteries is lithium-sulfur batteries, which can have an energy density up to ten times higher than lithium-ion batteries[16]. It is ahead of other battery technologies such as solid-state batteries or lithium-air batteries, with most at a (TRL) of 5[17]. A conceptual battery-powered aircraft designed by Bauhaus Luftfahrt, a German independent research institution, with a capacity of 189 passengers and a 900 nautical mile range is projected to be possible by 2035. The technology is predicted to be possible if current battery energy density innovations continue at the current rate[18]. This is exciting because it entails an exponential increase in flight capacity and doubles the current electric flight distance, which would make electric aircraft competitive with non-regional jet fuel airplanes. Eviation predicts it will be able to produce 20-40 passenger electric aircraft within 7-10 years, easily within the 2050 time period. Alice has already undergone engine testing and as of February 2022, is weeks away from a full flight test[19]. Also, electric taxiing technology is just around the corner according to IATA, with a TRL of 8. Batteries and electric propulsion systems may not be at TRL 9 yet, but startups like Eviation and MagniX are just a few years away from getting FAA approved, a key step to getting planes in the air. There are many companies actively working on making this technology a reality within a few years, and advances in battery energy density will accelerate this progress.

SAFETY OF SAF AND BATTERIES

Consumer and support staff safety is a focal point in our design. With the introduction of any new technology, it is necessary to analyze the risk and safety before large-scale use.

SAF

Thankfully, SAF fuel uses many of the same safety protocols as traditional Jet A fuel. Given that SAF and traditional jet fuel blends are considered as safe as conventional jet fuel for commercial flights by the American Society for Testing and Materials (ASTM), using SAF in planes is not expected to create any new complications with regards to aircraft safety[20]. However, for this to be true, SAF blends need to comply with ASTM standards which recommend using one of two methods to create the blends[1]. The first method is mixing pure SAF and pure Jet A fuel on-site at the airport. This is an unfavorable option, as airports would need to invest in new computer software able to frequently measure, monitor, and control the physical and chemical properties of the fuel. Airports with smaller budgets may find it difficult to correctly support this technology and its associated maintenance staff. The second method is purchasing from a third-party fuel refinery that manages the mixing of SAF and Jet A fuel. Because it is unlikely for fuel providers to accept SAF fuel or Jet A fuel refined by competitor companies, SAF blends would need to come from a single source rather than multiple sources. Although this is a small inconvenience, there are multiple companies already producing SAF blends. For example, SG Preston pledges to supply the green airline, JetBlue, with SAF blends supporting JetBlue's sustainability goals[21].

BATTERIES

As expected with quickly growing technologies, lithium-polymer battery efficiencies, safeties, and optimization continue to grow exponentially with research. There will most likely be unforeseen advancements in battery technology that may not be predicted with current and historical exponential growth rates. With that in mind, there are a couple of safety concerns associated with the use of battery-powered aircraft.

Among the problems specific to electric aircraft, there are two that stand out the most: battery energy uncertainty and thermal runaway[22]. Battery energy uncertainty refers to the idea that the exact amount of fuel in a battery is hard to precisely measure. Unlike liquid fuel, one cannot insert a rod into the fuel tank and see how much fuel is inside. For lithium-polymer batteries, their charge capacity is a function of their age, operating temperature, past charge, and usage history. However, this energy uncertainty is an easily preventable problem with many solutions. With improved battery monitoring and record-keeping paired with limiting usage time, the safety concerns associated with this problem are close to zero. Employing pushback tugs, capable of taxiing aircraft to the runway from the gate, will also preserve battery charge. Additionally, with over-designing batteries, therefore increasing their charge capacity, the risk of aircraft exceeding their battery capacity is also greatly reduced. Considering that we expect fixed-wing aircraft to continue being the most common aircraft in 2050, the chances of a fixed-wing aircraft exceeding the most power-demanding stage of flight, takeoff, are minor. The FAA's contingency fuel requirements call for aircraft to reserve 45 minutes of extra fuel in case of wind correction, missed approaches, and flight traffic delays. Applied to battery fuel consumption, pushback tugs and overdesigning batteries will help planes tackle this FAA requirement without sacrificing flight range and flight time. Overall, the energy uncertainty concern is a minor and easy to mitigate safety issue.

In comparison to other energy uncertainty concerns, thermal runaway is a risk equally hazardous but less easy to mitigate. Thermal runaway is when an internal short circuit causes battery cells to generate heat, potentially to the point of a fire. Having seen this as a risk for all lithium-polymer batteries, this should come as no surprise to the public, especially because of how the TSA, as well as mail delivery services, emphasize battery hazards. The difference between a tablet catching on fire and the battery of an aircraft is the size. Far more people are exposed to this potential danger than with just a phone or an EV. Although it may seem worrisome, preventative measures such as improving manufacturing and incorporating electrical protection will greatly reduce the probability of occurrence. Much like any other battery, the manufacturing and testing processes are improving every day and the risk of thermal runaway is being mitigated at the source. With incorporating electrical protection around the battery cells and regular battery monitoring, the risk of thermal runaway becomes less and less probable.

AIRPORT INFRASTRUCTURE (PRESENT AND FUTURE OPERATIONS)

Designing the airport of the future requires that we analyze the goals and trajectories of competitor airports. As aircraft technology evolves, so will the airport infrastructure to support innovations and technologies. Many international airports in the US are not only working to accommodate current SAF and electric demands but are also preparing for a zero-emissions future.

Today, the nation's largest airports are implementing a range of green initiatives -- a clear manifestation of consumers regarding sustainability as a high priority. Regarding the political landscape, a priority for the Biden Administration has been to give federal grants to airports electrifying their gate support and shuttle buses. Through the FAA's Zero-Emission Vehicles and Infrastructure Pilot Program[23], airports can tap into the $300 million budget earmarked for airport infrastructure by the Biden Administration[24]. Airports such as John Wayne Airport, Indianapolis International Airport, and Charlotte Douglas International Airport are all utilizing electric shuttle buses and investing in renewable infrastructure to support these electric vehicles on-site. For example, high-performance pushback tugs are being employed at Schiphol Airport to push aircraft as big as the 737 to the runway from the gate. These tugs, called taxibots, are capable of speeds up to 23 knots, compared to the 8-knot speed limit of regular tugs. At the forefront of airport technology, these newer tugs require no additional revision to FAA regulations as they comply with current the FAA's Guide to Ground Vehicle Operations[23]. An investment in electric pushback tugs can greatly reduce the takeoff fuel consumption of planes taxiing to and from the gate. In addition to federal grants, state departments have also awarded increasingly more grants to incentivize airlines to purchase charging stations and electric service vehicles at airports[21].

Not only are political incentives driving airports towards a SAF and electric-based future, but commercial pressure has increased as well. Regional airlines, focused on serving customers within a locality rather than across the nation, have publicly committed to implementing electric and hybrid aircraft into their fleet. Surf Air has partnered with Cessna to advance the use of hybrid planes as a step towards the company's transition to zero-emission flights in the future[25]. Companies like Cape Air, Cessna, Textron, and many others are joining Surf Air's shift towards zero-emission travel[26].

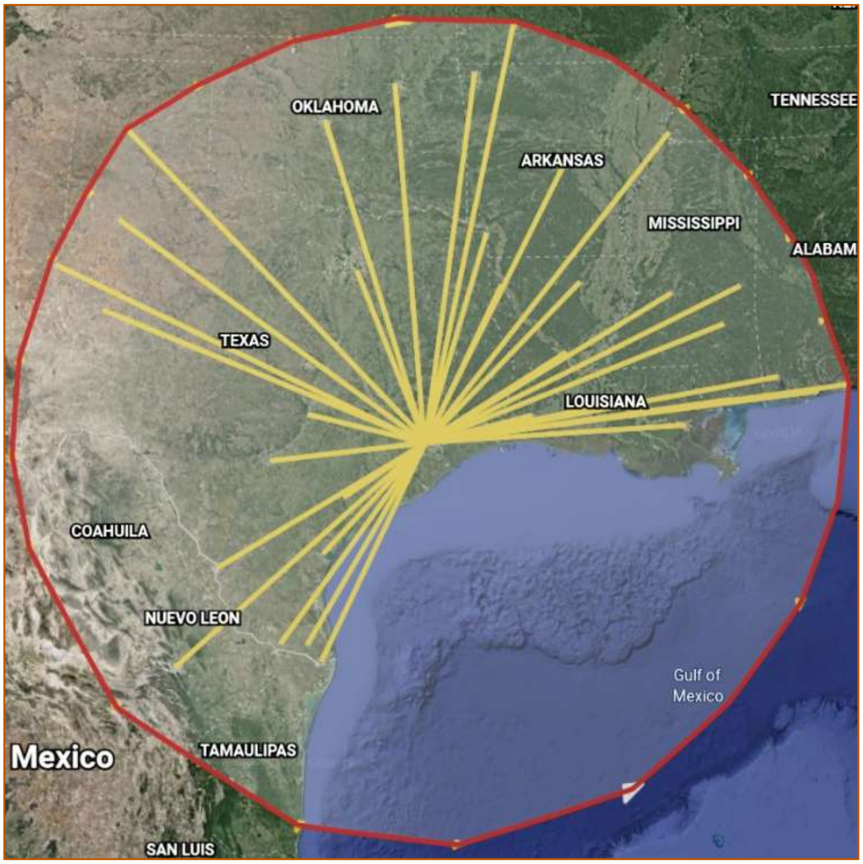
The demand for a zero-emission future has resonated with various airline companies and international airports alike. Major airports have committed to a green future and will allocate their budgets accordingly. With Indianapolis International Airport's largest solar farm at an airport in the world, Salt Lake City International Airport's on-site production of over 6% of their energy from renewable sources, Dallas Fort Worth International Airport's goal of Net Zero Carbon by 2030, and San Diego International Airport's regular sustainability reports [24], it is exciting to see that American airports have carved out a path towards a carbon-neutral future.

CONCLUSION

Governments and airlines across the world are adopting carbon-neutral policies in all industries. The aviation industry's large carbon footprint especially is catching the public's eyes due to its limited reduction in carbon emissions, making a transition towards carbon-neutral even more important. As a result, the use of SAF and battery electric planes will inevitably be ubiquitous by 2050, as sustainable fuels will be accessible, competitively priced, and integrated into the supply chain. Our 2050 airport provides the infrastructure required for airliners to make these changes through energy optimization at the gates, providing battery-electric aircraft with power, and reducing the fuel consumption of all airplanes. Our airport will support newer airline fleets with asset redesigns and reconfigurations to address the needs of blended-wing aircraft and increased electricity consumption. Our flexible airport design will allow it to take on market changes without outpacing its infrastructure capacity. Once these propositions are completed, this "electric age" will establish a carbon-neutral network that will enable the return of preexisting flights and the commencement of new routes in a more affordable medium without being carbon-positive.

Appendix

Figure 1 – Route Coverage with Radius of 440nm and Center at George Bush Intercontinental Airport



Yellow lines indicate flights leaving IAH airport that are under 440nm. These flights could be converted to electric flights using electric aircrafts like Alice.

Figure 2 – Pan Am Worldport

Figure 3 – George Bush Intercontinental Airport (IAH) Terminal B

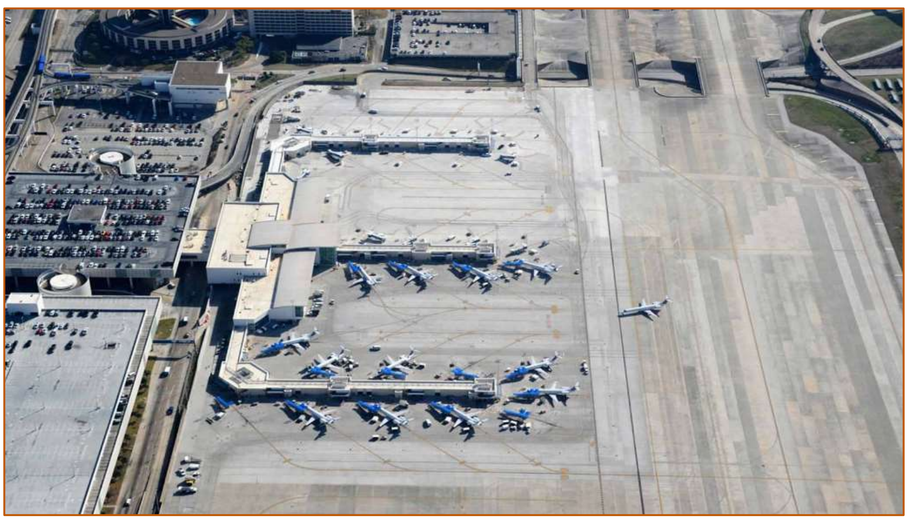


Figure 4 – Covered Gate Stand with Solar Panel

Table 1.1 - SAF Consumption Mandates by Region

	MANDATES (NON-INCLUSIVE)
EU[27]	5% by 2030; 32% by 2040; 63% by 2050
Norway[28]	0.5% by 2020; 30% by 2030
France[29]	1% mandate (current)
USA[30]	16% by 2030
UK[31]	10% total fuel production by 2030; 75% by 2050
Australia[32]	23.8M (USD) committed for SAF development and 10M gallon

Table 1.2 - SAF Consumption Commitments by Airliner

	COMMITMENTS (NON-INCLUSIVE)
KLM[29]	0.5% mandate on all flights out of Amsterdam, their largest hub (current)
Qantas[32]	30M lifted of fuel for flights from London
Air New Zealand[32]	10% SAF mandate by 2030
Cathy Pacific[33]	1.1M tons of SAF purchased over 10 years

Table 2 - Calculation for Savings of Cape Air Flight 9K 1853 (BOS to RKD)

Given	Operations Cost with Jet Fuel Engine: $3,350,746.00 Operations Cost* with electric motor aircraft: $2,422,798.50
Unknown	Reduction in operating costs from using an electric motor
Equation	Savings = Operating Costs 2 - Operating Costs1
Substitution	Savings = $3,350,746.00 - $2,422,798.50
Solution	**Savings = $927,947.50**

Note*	Operation Costs were determined by the following changes in the income statement of Flight 9K 1853[7]:
	• A ¾ reduction in fuel costs - based on the current price difference between electricity and Jet A Fuel (where the price of electricity is essentially negligible or at least a capital expense through capital investments of electricity generation, like Cape Air's installation of solar panels at their hubs)
	    o This is a reduction of $633,001.50 (from $844,002) from their annual operating expenses for this route
	• Maintenance costs would be significantly reduced because electric motors are far simpler than jet fuel engines
	    o Maintenance cost would be reduced from $927,502 by 90% to $92,750
	• A tripling of cost of ownership of aircraft (because electric aircraft will be more expensive than the well-known and mass produced Cessna 402 - the plane that would be replaced - as well as the reduction in value of the battery that will have to be replaced due to safety)
	    o Costs would increase from $269,903 to $809,709
	These changes result in a new operational cost of $2,422,798.50. It is important to note that this is based on current (2022) battery technology. In the last 10 years battery energy densities have almost tripled[35] and this trend can be expected for the future as more research and funding is put into batteries and we uncover more types of batteries and address problems with batteries, like stopping dendrite growth with advanced polymers and solid-state batteries. The changes in technology will only further reduce the operating costs of batteries as cost of ownership is reduced.

Table 3 - Calculation for Savings to the US Government from Subsidizing Small Routes (Essential Air Service Spending [EASS])

Given	The US government spent \$315,000,000 in 2021 from EASS. Savings from the Rockland flight were \$927,947.50 from an operational cost of \$3,350,746.00.[53]
Unknown	Number of future subsidies, based on 2022 technology*
Equation	$\frac{Savings}{Operational\ Cost} \times 100\% =$ Electric Aircraft Savings Percent (EASP) EASP × EASS spending = US government savings
Substitution	$\frac{\$927{,}947.50}{\$3{,}350{,}746.50} \times 100\% =$ EASP = 27.69%
Solution	27.69% × \$315,000,000 = **\$87,000,000**
Note*	As battery technology increases, the price of overall batteries in a plane will reduce, resulting in reduced operating costs and thus more profit. Hence, the US government will save more than the calculated \$87M annually.

Table 4 - Calculation for Projected Increase of SAF production

Given	Statista predicts 4,800,000[37] annual metric tonnes of SAF will be produced by 2025
Unknown	• Liters of SAF produced in 2025 • Percentage towards goal of 2%[2] SAF production (7Bn liters annually)
Equation	1 metric tonne of SAF is 1,250 liters
Substitution	$4{,}800{,}000\ metric\ tonnes \times \frac{1{,}250\ liters}{1\ metric\ tonne} =$ 6,000,000,000 Liters annually $\frac{6\ billion\ liters\ annually}{7\ billion\ liters\ annually} \times 100\% = 85.71\%$ towards goal
Solution	**6,000,000,000 Liters annually** **85.71% towards 2% SAF production by 2025**

Table 5 - Current Ways to Produce SAF[13]

Mechanisms	• Hydrotreated Esters and Fatty Acids (HEFA) • Fischer-Tropsch (FT) • Synthesized Iso-Paraffins (SIP) • Alcohol to Jet (AtJ) • Catalytic Hydrothermolysis (CHJ) • Hydroprocessed Hydrocarbons, Esters, and Fatty Acids (HC-HEFA) • Co-processing

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