University of Pennsylvania

Carbon Negative: A Modular Approach to Advancing Green Airport Infrastructure

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1. Overview:

The aviation industry has undergone several developments from its inception in 1903 to its transformation in security measures in the post-9/11 world. In the next 30 years, especially as regular travel operations resume post-pandemic, our research team anticipates a significant increase in the scope of the aviation sector and a sizable increase in the number of passengers relying on commercial aviation. As consumer and industry demands change, so will airport and airline offerings, which will revolutionize the way we view the critical environmental consequences of this industry.

Following the United Nations 17 Sustainable Development Goals (SDGs) the aviation industry has recently made major advances towards becoming more sustainable and efficient. From a commercial manufacturer point of view, this is evidenced by the rise of ultra-efficient long haul aircraft such as the 787 and A350, which offer 25-30% less fuel burn and CO2 emission per seat over earlier widebody airplanes[1]. These commercial and technological advancements have been accompanied by infrastructural efforts to make airports more environmentally and economically friendly, such as solar panel installations and green roofs. These advances have not only improved sustainability for airports and airline carriers, but they have also helped expand routes and connect developing countries, which have limited funding for airports, to global air transport networks. As a result, technological advancements that lead to increased airline sustainability are also heavily economically incentivized both for governments and commercial airline carriers.

Many experts and previous research have come to an agreement that airports' carbon footprints have the biggest impact on sustainability within the aviation sector.[2] Aviation accounts for an estimated 2.5% of global carbon emissions[3]. More specifically, the ten largest airports worldwide generate an estimated 127 million metric tons of carbon dioxide annually[4]. In fact, According to E Terrenoire et. al, carbon dioxide alone is expected to contribute to 36-51% of climate change caused by aviation in the short-term, and to have an even greater effect in the long term due to the gasses' long residence time in the atmosphere.[5]

As of today, airports and international organizations have set goals to achieve carbon neutrality by 2050, including 242 airports in the United States[6]. However, as of 2021, only four airports have met this objective, including Austin-Bergstrom International airport[7]. We believe that in the next 30 years, it will become necessary for all 242 airports to collectively produce and implement novel technologies in order to become carbon neutral.

In this report, we will assess various carbon mitigating technologies, including the rise of electric aircraft, the rise of electric support vehicles, and the use of advanced airport infrastructure, which will all collectively help airports work towards carbon neutrality objectives by 2050. For each of these

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[1] "A350 Less Weight. Less Fuel. More Sustainable.", *Airbus Aircraft*, https://aircraft.airbus.com/en/aircraft/a350/a350-less-weight-less-fuel-more-sustainable.

[2] D. W. Fahey, S. L. Baughcum, J. S. Fuglestvedt, M. Gupta, D. S. Lee, R. Sausen, and P. F. J. Van Velthoven, "White Paper on Climate Change Aviation Impacts on Climate: State of the Science", *ICAO Environmental Report*.

[3] Hannah Ritchie, "Climate change and flying: what share of global CO2 emissions come from aviation?", *Our World in Data*, October 22, 2020, https://ourworldindata.org/co2-emissions-from-aviation.

[4] Alex Leeds Matthews, "Airports in U.S., Europe and China Produce the Most Flight Carbon Emissions", *U.S. News*, November 2, 2021, https://www.usnews.com/news/best-countries/articles/2021-11-02/charting-the-airports-that-produce-the-most-carbon-emissions.

[5] E Terrenoire, D A. Hauglustaine, T Gasser, and O Penanhoat, "The contribution of carbon dioxide emissions from the aviation sector to future climate change", *Environmental Research Letters* 14, No. 8 (July 2019), https://doi.org/10.1088/1748-9326/ab3086.

[6] "The Net Zero Airport", *United Nations Climate Change,* November 26, 2021, https://unfccc.int/blog/the-net-zero-airport.

[7] "Austin-Bergstrom International Airport achieves carbon neutrality, one of four airports in North America", *Austin-Bergstrom International Airport*, December 6, 2021, https://www.austintexas.gov/news/austin-bergstrom-international-airport-achieves-carbon-neutrality-one-four-airports-north-america.

technologies, we will showcase its implementation, assess its impact on creating more sustainable airports, and address its feasibility for implementation by 2050.

2. Technological Solutions

Many aircraft manufacturers have investigated the use of alternative and more sustainable fuel sources, the most notable alternative fuel being electricity; this innovation has the potential to significantly decrease carbon emissions. We believe that the widespread use of electric and hybrid electric airplanes in the commercial aviation sector will significantly reduce net carbon emissions from airports. Likewise, the rise of commercial electric vehicles in recent years demonstrates the possible reliance on electric support vehicles that are used on the ground at airports. We believe that these will also constitute a large reduction in carbon emissions, especially as their use is compounded in airports across the world.

In addition, we anticipate that airports will employ the use of advanced infrastructure systems in order to mitigate unavoidable carbon emissions. For example, the use of direct air capture systems that can increase the air quality on both airports and surrounding grounds. In this paper, we will discuss these systems, and how they can be used to decrease net carbon emissions.

a. Electric Aircraft and Vehicles

Recent advances in aircraft technology have led to the electrification of aircraft components that are traditionally hydraulic or pneumatic. For example, the Boeing 787 and Airbus A380 have pioneered the use of electrical systems for critical flight functions such as actuation, wing ice protection, and fuel pumping systems, which have led to reductions in noise pollution and fuel consumption.[8] A 2015 study proposes a "More Electric Aircraft", which will make all existing systems (except for the engines) electrically powered. This includes cabin pressurization, which is currently pneumatically powered, fuel pumping, which is mechanically powered, and hydraulic components such as the flaps and landing gear.

However, by 2050, we predict a widespread use of electric-propulsion and hybrid-electric aircraft. Electric aircraft have already been in development for many years. One example is the 600 kg Li-ion powered aircraft capable of flying 160 kph that was proposed in 2013.[9] Since then, however, there have been significant advances. In 2021, Rolls-Royce successfully created and tested the "Spirit of Innovation", the fastest all-electric aircraft, which is capable of flying up to 555.9 kph.[10] Although many electric aircraft today have been developed for smaller-scale operations, aircraft manufacturers have proposed electric and hybrid-electric aircraft models to enter commercial service by 2050. An early model, the Wright Spirit (proposed to enter service in 2026), will have seating capacity of approximately 100 passengers, and will have enough range to fly 1-hour long flights (for example, the London to France route).[11] The International Civil Aviation Organization (ICAO) also anticipates that hybrid electric aircraft, capable of seating up to 130 passengers, will enter commercial service after 2030.[12] For example, the Boeing Sugar VOLT, proposed to enter service in 2040, will be able to seat 135 passengers and have a range of over 6000 km.[13]

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[8] P. Wheeler and S. Bozhko, "The More Electric Aircraft: Technology and challenges.," in *IEEE Electrification Magazine*, vol. 2, no. 4, pp. 6-12, Dec. 2014, doi: 10.1109/MELE.2014.2360720.

[9] D. Cervinka, I. Pazdera, P. Prochazka and B. Klima, "Battery for small electric airplane," *IECON 2013 - 39th Annual Conference of the IEEE Industrial Electronics Society*, 2013, pp. 4576-4579, doi: 10.1109/IECON.2013.6699873.

[10] "'Spirit of Innovation' Stakes Claim to Be the World's Fastest All-Electric Vehicle", *Rolls Royce*, November 19, 2021, https://www.rolls-royce.com/media/press-releases/2021/19-11-2021-spirit-of-innovation-stakes-claim-to-be-the-worlds-fastest-all-electric-vehicle.aspx.

[11] "Home: Wright Electric." *Wright Electric*, 2022. https://www.weflywright.com/.

[12] "Electric and Hybrid Aircraft Platform for Innovation (E-HAPI)", *Electric and Hybrid Aircraft Platform for Innovation (E-HAPI)*, https://www.icao.int/environmental-protection/Pages/electric-aircraft.aspx.

[13] "Large Commercial Aircraft: A Non Extensive List of Projects." *ICAO*, March 3, 2022, https://datastudio.google.com/embed/u/0/reporting/b11b0ed8-c723-4c79-a06d-74a437584ef3/page/p_wpfzvnx8lc.

The use of electric and hybrid-electric aircraft will lead to significant reductions in carbon emissions. Compared to airplanes powered by conventional fuel sources with similar seating capacity and range, electric aircraft could lead to a reduction in carbon emissions and hybrid electric aircraft will lead to an additional possible reduction. According to researchers at MIT, these improvements can lead to a 92% reduction in air pollution-related deaths caused by the aviation sector.[14]These electric aircraft may also replace or partially replace current airplane models that lead to the highest percentage of carbon emissions worldwide. According to data compiled by the International Council on Clean Transportation, Regional and Narrowbody airplanes, which seat between 75 and 200 passengers, were responsible for almost 60% of carbon emissions in the aviation sector.[15]

Airports can support the adoption of electric aircraft into commercial service by building and conducting research on electric charging stations to support electric aircraft. Electric charging infrastructure has seen preliminary usage in airports and testing as of today. For example, in October 2021, Swedish airport operator Swedavia opened 3 aircraft charging stations at a regional airport[16]. Trainelli et. al predicts that there will be two main types of charging stations: plug in stations and battery swapping stations. However, both types of stations experience unique barriers to smooth operations and quick turnaround time. Plug-in stations are currently infeasible for commercial airports due to their excessive charging times. Although battery swapping stations have the advantage of being able to charge batteries while they are not in use, numerous battery charging stations will be required to efficiently charge and prepare batteries for future flights.[17]

Several attempts have been made to tackle these challenges. For example, Guo et al. propose a model that can significantly increase the efficiency and economic feasibility of battery charging by compiling data on demand for electricity throughout the day.[18] However, additional research and investigations must be conducted before charging stations that are economically feasible for commercial airports can be built. Airports can help to achieve widespread installation of these charging stations by 2050 by installing and testing current charging station technologies, and conducting research studies on how to improve station price effectiveness and charging efficiency.

Airports also should prioritize a greater switch to electric ground transport and support vehicles. On its own, transportation is the fourth largest source of global carbon emissions at 14% of the total, and the technology already exists for airport transport vehicles to make a greater push towards going electric.[19] Currently, nearly all of the cargo tractors and belt loaders currently in use are gasoline or diesel powered and most often specifically chosen for the purposes of reliability and low maintenance. General Motors has announced an initiative to further develop conversion technology, which would allow for the retrofitted installation of an electric drivetrain into conventionally combustion engine-powered vehicles. Their announcement of a partnership with Textron Ground Support Equipment Inc. for the specific development of electric airport ground transportation bolsters the fact that electric-powered ground

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[14] Chu, Jennifer. "Concept for a Hybrid-Electric Plane May Reduce Aviation's Air Pollution Problem", *MIT News | Massachusetts Institute of Technology*, January 14, 2021, https://news.mit.edu/2021/hybrid-electric-plane-pollution-0114.

[15] B. Graver, D. Rutherord, S Zheng, "CO_2 Emissions From Commercial Aviation" *2020 International Council on Clean Transportation,* October 2020, https://theicct.org/sites/default/files/publications/CO2-commercial-aviation-oct2020.pdf.

[16] "Swedavia unveils electric aircraft charging stations at Visby Airport", *Airport Technology*, October 1, 2021, https://www.airport-technology.com/news/swedavia-electric-aircraft-charging-stations/.

[17] L. Trainelli, F. Salucci, C. E. D. Riboldi, A. Rolando, and F. Bigoni, "Optimal Sizing and Operation of Airport Infrastructures in Support of Electric-Powered Aviation", *Aerospace*, 8, No. 2 (January 2021), https://doi.org/10.3390/aerospace8020040.

[18] Z. Guo, X. Zhang, N. Balta-Ozkan, and P. Luk, "Aviation to Grid: Airport Charging Infrastructure for Electric Aircraft", *International Conference on Applied Energy 2020*, 10, no. 2, pp. 1-6 (December 2020), https://bura.brunel.ac.uk/handle/2438/23431.

[19] "Global Greenhouse Gas Emissions Data", *United States Environmental Protection Agency*, https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data.

support is feasible in the near future.[20] Utilizing General Motors' current incentive toward retrofitting of current support vehicles, a transition from the combustion-powered cargo and baggage tractors, belt loaders and tug equipment to electric drivetrains is almost immediately viable.

Airports must also be responsible for the installation of safety equipment and infrastructure for electric airplanes. As of February 2020, the FAA restricts the transport of Lithium-Ion (Li-Ion) Batteries on any commercial flight. Electric aircraft, which may rely on Li-Ion batteries as their primary power source, will therefore require additional safety precautions before they can enter into commercial service[21]. Gao et. al has shown in their study on flame retardant Li-ion battery storage systems that thermal runaway retardant (TRR) capsules can help protect Li-ion batteries from fire damage while still maintaining their electrochemical performance.[22] Such capsules have seen significant improvements over the past few years and have helped to greatly improve the safety of electric vehicles. Capsules can serve as protective equipment both for airport storage facilities and on-board the aircraft. Airports must also invest in airport crew training and equipment to effectively fight lithium fires on the ground. Since lithium fires are difficult to fight compared to conventional fires, airport firefighters must be trained to effectively respond to on-board lithium fires.[23]

b. <u>Airport Implementation of Exterior Direct Air Carbon Capture Systems</u>

By 2050, electric and hybrid vehicles will have not entirely phased out the existing fleet of conventional vehicles.[24] To best support green aviation technology of the future, airports must continue to offset the emissions of conventional airplanes. Direct air capture (DAC) is the name for technologies that extract CO2 directly from the atmosphere through a series of chemical processes and filters. DAC can function as both a carbon negative solution, when the captured CO2 is stored in underground geological formations, or carbon neutral solution when the CO2 is used for industrial, mechanical, or synthetic fuel purposes. In order for DAC to function as a carbon negative solution, it must minimize its CO2 output in the form of energy consumption so that the net offset is negative.

Optimizing that offset has proven to be one of the main challenges for engineers. To sequester enough carbon from the air, most DAC systems today use fans to draw in as much air as possible in order to maximize the CO2 concentration. As a result the fans draw energy from the grid and the system risks emitting more CO2 than it is sequestering. We propose that airports take advantage of their unique role as a large carbon emitting hub and implement DAC systems around the airport.

DAC falls under the category of Carbon Capture and Storage (CCS). CCS systems have existed for many years, but it has mainly been implemented in power plants where CO2 emissions are heavily concentrated, and the captured CO2 can be mechanically used, like recovering oil from the ground or pneumatically powering machines. DAC is a relatively new concept in climate technology. The first DAC plant began operating in 2015 through the company Carbon Engineering, and another large scale plant built by the company Climeworks began operating in 2017 and removes 4000 tons of CO2 per year. The

[20] Eisenstein, Paul A. "GM Wants to 'Electrify Everything.'" The Detroit Bureau, December 22, 2021. https://www.thedetroitbureau.com/2021/12/gm-wants-to-electrify-everything/.

[21] "Lithium Batteries in Baggage", *Federal Aviation Administration*, February 4, 2020, https://www.faa.gov/newsroom/lithium-batteries-baggage.

[22] Z. Gao, S. Rao, T. Zhang, F. Gao, Y. Xiao, L. Shali, X. Wang, Y. Zheng, Y. Chen, Y. Zong, W. Li, and Y. Chen, "Bioinspired Thermal Runaway Retardant Capsules for Improved Safety and Electrochemical Performance in Lithium-Ion Batteries", *Advanced Science*, 9, No. 5 (December 2021), https://dx.doi.org/10.1002%2Fadvs.202103796.

[23] Andrew Evers and Lora Kolodny, "Electric vehicle fires are rare, but hard to fight - here's why", *CNBC Climate*, January 29, 2022, https://www.cnbc.com/2022/01/29/electric-vehicle-fires-are-rare-but-hard-to-fight-heres-why.html.

[24] "Aircraft Technology Roadmap to 2050", *IATA*, 2019, https://www.iata.org/contentassets/8d19e716636a47c184e7221c77563c93/Technology-roadmap-2050.pdf,

cost of direct air capture, around $600 per ton, is currently too high to incentivize companies to scale.[25] The current technology readiness level of DAC systems is at 7 because the systems have already been tested. By 2050, DAC systems will be at level 9 with widespread use and scale.

By 2050, however, the cost per ton of sequestering carbon dioxide is expected to decrease dramatically. A study that reviewed relevant literature and current commercial trends projected that the cost of DAC could be reduced to $85 per ton of CO2. Combined with a renewable energy infrastructure, designing a large DAC system will be feasible by 2050.[26]

Looking at the United States as a possible need and use case study, airports are uniquely positioned to take advantage of DAC. According to an air travel study done by Upgraded Points, a consumer travel blog, 29.5 percent of U.S. cities with populations greater than 50,000 people are located within 25 miles of a large hub (defined as receiving 1% or more of annual enplanements within the United States.[27, 28] Furthermore, a CDC study, *Rural and Urban Differences in Air Quality, 2008–2012, and Community Drinking Water Quality, 2010–2015 — United States*, found that rural "counties experienced fewer unhealthy air-quality days than large central metropolitan counties, likely because of fewer air pollution sources in the non core counties."[29] Urban cities are on average closer to large hubs and have higher concentrations of air pollution. Large, concentrated, local populations could directly benefit from DAC being adopted by large hubs within the United States specifically.

The large hubs are also suited for the physical and electrical demands of DAC systems. Airports generally encompass large and flat lands with limited vertical obstructions and have large rooftop surfaces on airport infrastructure including terminals, parking garages, hangers, and transportation facilities. Airports are also heavily investing in their renewable energy capability, Denver International Airport is one such example, since 2008 the airport has added 56 acres of solar panel coverage, offsetting up to 11,465 metric tons of greenhouse-gas emissions yearly.[30] With more airports implementing renewable energy sources, DAC systems could possibly take advantage of carbon neutral energy to become carbon negative systems and have impacts beyond the airport.

The energy demands of a DAC system are dependent on factors such as the molar concentration of CO2 in the ambient air and how much the system is running. The amount of energy required for each ton of carbon sequestration decreases exponentially with an increase in molar concentration.[31] Referring to Appendix 3, ambient air sits on the top of the curve and as a result requires an immense amount of energy. DAC systems will not be able to substantially get around this challenge, however, DAC systems can utilize specific ambient conditions to their advantage. Outlined above, emissions from planes, cars, and the overall size of the airport contributes to high CO2 concentrations around an airport.

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[25] James Temple, "What It Will Take to Achieve Affordable Carbon Removal," MIT Technology Review (MIT Technology Review, June 25, 2021), https://www.technologyreview.com/2021/06/24/1027083/what-it-will-take-to-achieve-affordable-carbon-removal/#:~:text=In%202019%2C%20the%20Swiss%20direct,%24500%20to%20%24600%20per%20ton.

[26] Mahdi Fasihi, Olga Efimova, Christian Breyer, "Techno-economic assessment of CO2 direct air capture plants", Journal of Cleaner Production, Volume 224, 2019, Pages 957-980, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2019.03.086.

[27] Miller, Alex. "Airport Deserts - Exploring the Distance between Airports and the Cities They Serve [Data Study]." UpgradedPoints.com, April 26, 2021. https://upgradedpoints.com/travel/airports/airport-deserts-data-study/.

[28] "Airport Categories – Airports," Federal Aviation Administration, last modified October 28, 2021, accessed March 3, 2022, https://www.faa.gov/airports/planning_capacity/categories/ .

[29] Strosnider H, Kennedy C, Monti M, Yip F. Rural and Urban Differences in Air Quality, 2008–2012, and Community Drinking Water Quality, 2010–2015 — United States. MMWR Surveill Summ 2017;66(No. SS-13):1–10. DOI: http://dx.doi.org/10.15585/mmwr.ss6613a1

[30] "Energy Management: Denver International Airport," Energy Management | Denver International Airport, https://www.flydenver.com/about/administration/energy_management.

[31] Wilcox J. (2012) Introduction to Carbon Capture. In: Carbon Capture. Springer, New York, NY. https://doi.org/10.1007/978-1-4614-2215-0_1

A study measuring the emissions from Hartsfield Jackson Airport in Atlanta found that the CO2 concentration around an airport is much higher compared to locations farther away from the airport.[32] The study used the FAA standard Emissions and Dispersion Modeling System and the Here Sparse Matrix Operator Kernel Emission (SMOKE) system. Appendix 4 shows emissions as a mole fraction over the course of a day. The fraction peaks at .08 and averages around .05 as the day progresses. Comparing that to the figure provided by Wilcox, the CO2 concentration is similar to that of a natural gas combustion point source which requires an exponentially less amount of energy to remove. By positioning carbon capture systems at airports, the systems could be three times more efficient, making them an excellent option for supporting the transition to an electric fleet of aircraft.

Airports will employ modular carbon capture systems similar to those of Climeworks, a leader in the commercial DAC industry with the largest DAC system in operation. Climeworks's DAC system employs a technology called low temperature solid sorbent direct air capture.[33] Ambient air flows into the system and the CO2 chemically binds to a sorbent filter. Once the sorbent is saturated with CO2, air intake is cut off and a process called regeneration begins. During regeneration, the system is heated to 100C where the CO2 is purified. The compressed gas is then transferred through a network of pipelines where it is stored underground.

In terms of implementation, placement, and location of carbon capture systems on airport grounds, the research team looked to the Federal Aviation Administration's *Technical Guidance for Evaluating Selected Solar Technologies on Airports,* we propose both roof and ground mounted DAC systems. When exploring the viability of DAC systems, space is an important factor. Most airports have large unused spaces including noise buffers, areas near runways, and rooftops. Rural airports tend to have more possible citing locations, whereas urban airports may be limited to terminals, parking garages, and hangers. With either ground or rooftop mounted systems, existing aviation and airport activities must be evaluated. When designing and implementing DAC systems on airport ground it is important not to obstruct or impede on air navigation pursuant to 14 CFR Part 77 SAFE, EFFICIENT USE, AND PRESERVATION OF THE NAVIGABLE AIRSPACE, which is a governing doctrine for construction on airport grounds.[34]

Airport buildings (terminals) most often have flat rooms whereas hangers have angled roofs, both options provide many placement options for direct. Using FAA guidance outlined for mounting solar panels on airport roofs, a pre-mounting analysis of existing roof capacity is required to determine if the structure is efficient to hold the extra weight of a DAC, weights are dependent on the number of units, their size, and other equipment such as piping and mechanicals that are mounted directly on the units or are an another location.[35]

Installation of ground-mounted DAC systems, an example seen in Appendix 2, requires mostly flat terrain with reasonably unobstructed access and exposures. Given the weight of DAC systems and related components, such as CO2 storage tanks, power inverters, and other associated structures to house mechanicals, geotechnical analysis may be required to determine the long term soil stability. The lack of

[32] lper Unal, Yongtao Hu, Michael E. Chang, M. Talat Odman, Armistead G. Russell, "Airport related emissions and impacts on air quality: Application to the Atlanta International Airport", Atmospheric Environment, Volume 39, Issue 32, 2005, Pages 5787-5798, ISSN 1352-2310, https://doi.org/10.1016/j.atmosenv.2005.05.051.

[33] Fasihi et al. "Techno-economic assessment"

[34] 14 CFR Part 77

[35] U.S. Department of Transportation Federal Aviation Administration, "Technical Guidance for Evaluating Selected Solar Technologies on Airports", by Michael Lawrance, Magnotta Lawrance, and Patrick W, April 2018, accessed March 3, 2022, https://www.faa.gov/airports/environmental/policy_guidance/media/FAA-Airport-Solar-Guide-2018.pdf .

technical difficulty of both engineering and construction of ground systems may also contribute to lower project costs.[36]

DAC system designs should take into account site specific environmental factors, such as snow removal, hail storms, and high hurricane and tornado force wind loads. DAC systems should meet applicable building code standards and all DAC systems should be equipped with lightning protection measures.

Possible benefits to airports include achieving carbon neutral and or negative status, the ability to sell carbon allotments to airlines, companies, and other customers, as well as industrial or CO2 storage. Currently, DAC systems can cost in the hundreds of millions and the team recommends public / private partnerships. As DAC systems grow in popularity they will be coming to more and more areas, airports are in a key position to be able to incorporate them into their infrastructure and design(s).

3. Conclusion and Discussion

After extensively reviewing existing research regarding ways airports contribute to carbon emissions, types of carbon emissions, aviation infrastructure types, and technology readiness scores, our team chose three technology categories that will have promising impacts on the airports of tomorrow.

As battery technology improves and electric vehicles begin to match the efficiency and cost of conventional fossil fuels, electric vehicles will begin to swap out their counterparts, both on the ground and in the sky. This will require major infrastructural updates so airports can facilitate charging, battery maintenance, battery storage, and battery combustion.

Furthermore, instead of investing in passive infrastructure that reduces emissions and increases sustainability by choosing the greener option over another, airports can incorporate direct air capture systems to become active carbon negative organizations. Explored through a high level case study of large hub airports within the United States, carbon capture systems will have both positive economic and environmental ramifications for airports and their surrounding areas.

The design for the airports of tomorrow begins with an understanding and assessment of the technologies of today. The research team hopes that our novel, yet implementable solutions will help airports lead the way for a greener and cleaner future.

[36] U.S. Department of Transportation Federal Aviation Administration, *Technical Guidance*.

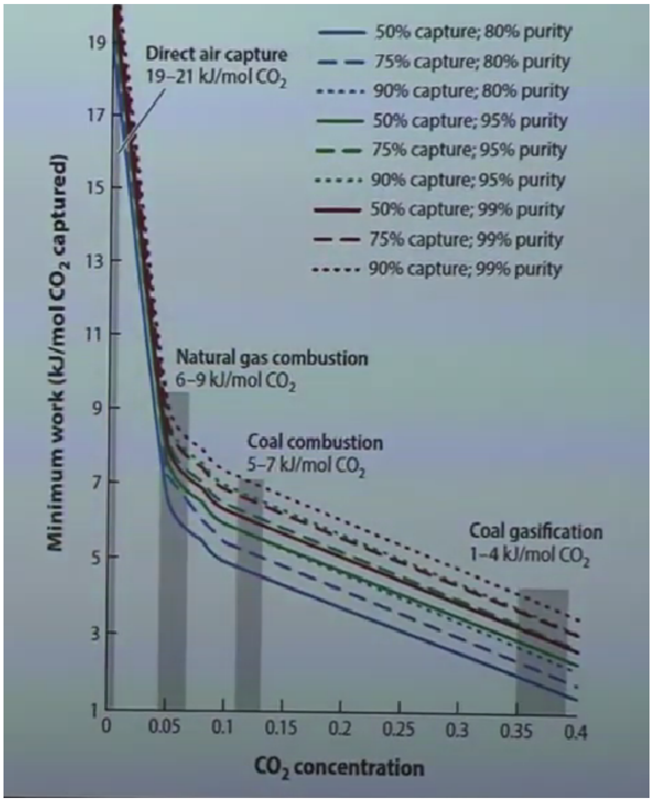
Appendix

Appendix 1 : An example of a roof mounted DAC on an airport terminal[37]

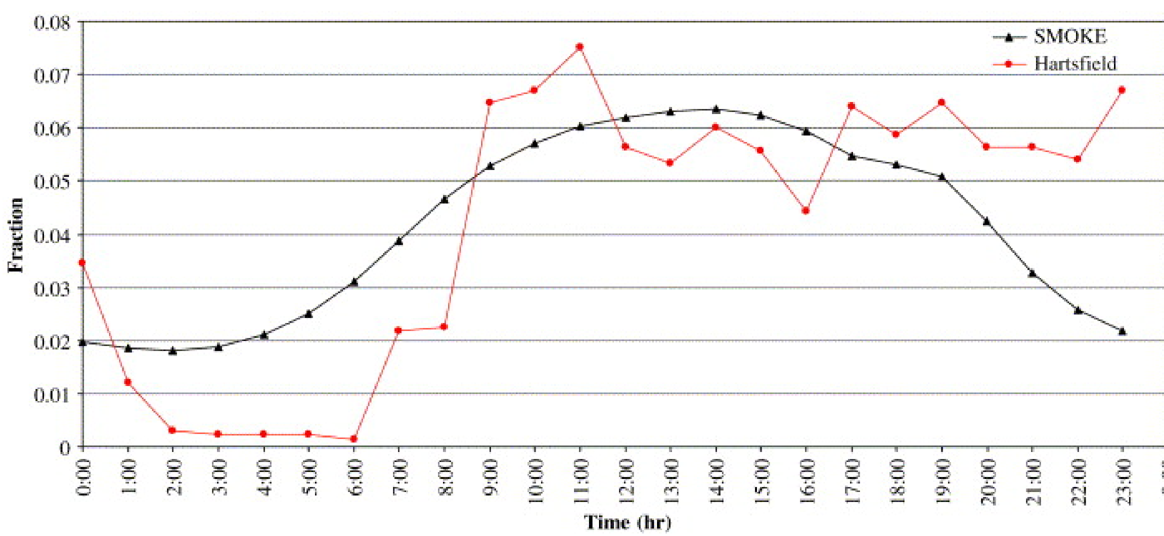
Appendix 2: An example of of a ground-mounted DAC system on an airport exterior[38]

[37] Image Created by Carbon Negative Team Member
[38] Ibid

Appendix 3: Minimum thermodynamic work as a function of CO2 concentration in the air[39]



Appendix 4: Diurnal emissions data for Hartsfield-Jackson airport (refer to the red line)[40]



[39] Jennifer Wilcox, "Professor Jennifer Wilcox on The Role of Carbon Capture toward Achieving our Climate Goals", (Class Lecture, Trinity Business School, September 19th, 2019)
[40] Unal et al., "Airport related emissions and impacts on air quality: Application to the Atlanta International Airport"