

# FLIGHT PATH

A Trajectory for U.S. Aviation to  
Meet Global Climate Goals



# **FLIGHT PATH: A TRAJECTORY FOR U.S. AVIATION TO MEET GLOBAL CLIMATE GOALS**

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# EXECUTIVE SUMMARY

At a time of climate emergency, the aviation industry's greenhouse gas emissions are skyrocketing, jeopardizing the international climate goal of limiting warming to 1.5 degrees Celsius to avoid increasingly devastating impacts around the planet. Aviation is rarely considered among top polluters. Yet if commercial aviation were considered a country, it would rank sixth between Japan and Germany in terms of carbon emissions.

The United States has an outsized responsibility to tackle airplanes' planet-warming pollution given that the U.S. aviation sector emits more than any other country, totaling a quarter of global passenger flight emissions. Despite this, in August 2020 the U.S. Environmental Protection Agency released a glaringly inadequate proposal to address aviation pollution — one that it acknowledged would do nothing to reduce emissions.

Our analysis quantifies the climate benefits of putting the U.S. aviation sector on a new path to decarbonize in the next 25 years through three technology-forcing strategies:

1. Fuel efficiency improvements of at least 3.5% annually starting in 2020;
2. Electrifying all short-haul flights by 2040;
3. Electrifying all long-haul flights by 2045.

We find that these measures are achievable and necessary to put the U.S. aviation sector on course to reduce emissions to near zero by 2040, as required to limit global warming to 1.5°C.

Without these measures, on the EPA's "business-as-usual" emissions trajectory, U.S. aviation will emit nearly 5 billion tons of CO<sub>2</sub> between 2020 and 2040, including nearly 250 million tons of CO<sub>2</sub> in 2040 alone.

By contrast, adopting measures to improve fuel efficiency by 3.5% annually and transitioning to an all-electric fleet could reduce U.S. aviation emissions by 1.5 billion tons of CO<sub>2</sub> between 2020 and 2040 — 32% less than business as usual. Allowing for partially electric aircraft (turboelectric or hybrid-electric), these measures would reduce U.S. aviation emissions to 64 million tons, or 75% less than business as usual in 2040, and to 27 million tons, or 90% less than business as usual, in 2045. With all-electric aircraft, the carbon savings are even greater: U.S. aviation emissions would be 80% less than business as usual in 2040 and near zero in 2045.

Electric commercial flight is on the horizon, even in the absence of the needed EPA regulation. Strong, technology forcing standards can speed the development and deployment of this important technology. According to NASA, with the right resources, turboelectric and hybrid-electric large aircraft could be tested by 2025 and enter service starting in 2035. Battery technology is advancing rapidly, making a fully electric aircraft viable in the same timeframe.

NASA's STARC-ABL turboelectric Plane Concept, courtesy NASA





An electric aviation fleet and the associated carbon savings is a reality that can be realized given the political will to do so.

Since U.S. aviation emissions should be as close to zero as possible by 2040, the U.S. should take additional measures to limit airplane emissions: promoting air travel alternatives, such as the full deployment of electric vehicles and high-speed rail; committing funds to developing countries to reduce their aviation emissions; and limiting flights, if necessary, to compensate for lack of progress decarbonizing the industry.

Importantly, these measures do not rely on dangerous carbon-offset schemes that violate human rights, cause environmental destruction and are not proven to curb emissions. Nor do they rely on biofuels, which are not carbon neutral or sustainable.

Due to the COVID-19 pandemic, air travel has seen a significant downturn that could persist for years to come. The pandemic has taken a tragic toll on America's health and the livelihoods of millions, and it underscores the urgent need for a positive transformation of the industry. A lengthy travel rebound period offers a chance to keep emissions from returning to 2019 levels and to jumpstart the strategies outlined. Strong, technology-forcing standards will drive the modernization and decarbonization of the aviation industry, providing good, family sustaining jobs in a changing economy weathering the climate crisis.

Our analysis shows that the United States can and must put aviation on a new course to align with international climate imperatives. The country must lead on strong fuel-efficiency improvements and a transition to all-electric aircraft, delivering on what science, equity and climate justice demand.

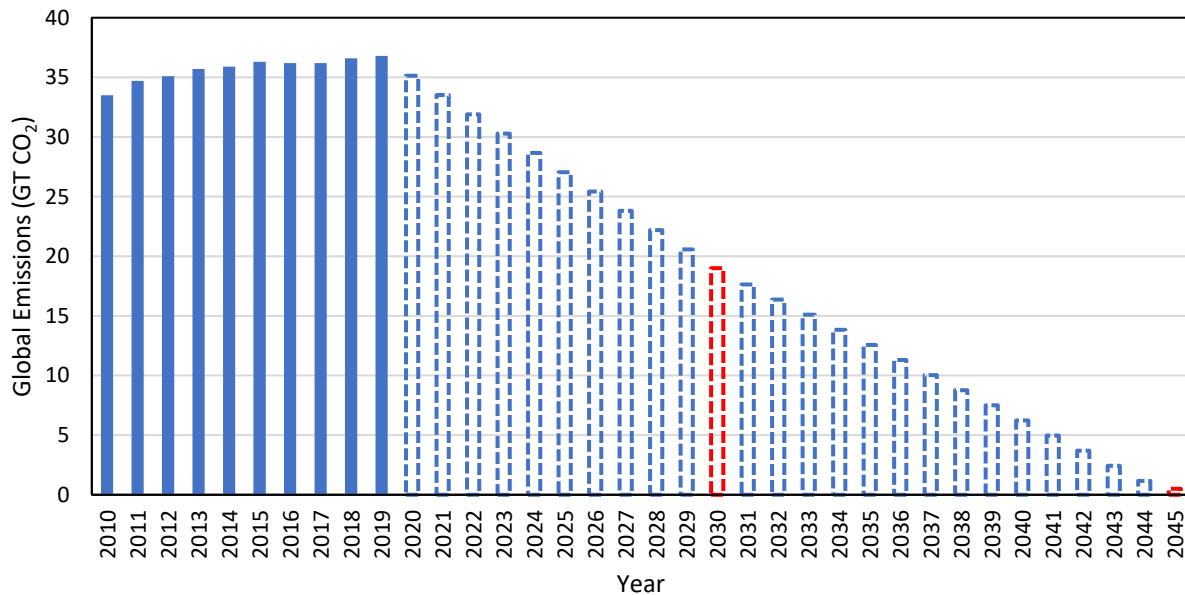


## THE CLIMATE CRISIS REQUIRES IMMEDIATE ACTION TO CURB U.S. AVIATION EMISSIONS

In August 2016 the U.S. Environmental Protection Agency concluded in its endangerment finding that planet-warming pollution from airplanes disrupts the climate and “endangers public health and welfare.”<sup>1</sup> Yet four years later, in August 2020, the agency published a long-overdue proposed rule to regulate greenhouse gas (GHG) emissions from aircraft that fails to reduce aircraft emissions or address the severity of the climate crisis. Instead, the rule mirrors weak standards adopted in 2017 by the International Civil Aviation Organization — a branch of the United Nations tasked with establishing international aircraft standards. ICAO standards do not reduce airplane pollution as required by the U.S. Clean Air Act. Given the United States’ outsized contribution to global aviation GHG emissions, the urgency of the climate crisis and the requirements of U.S. law, the EPA must curtail aviation emissions far beyond what ICAO standards will achieve.

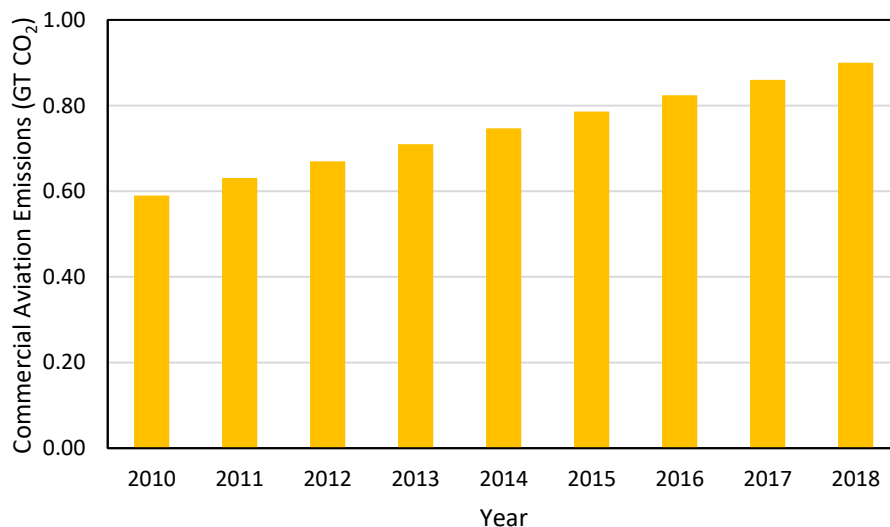
## A SIGNIFICANT CONTRIBUTOR TO CLIMATE CHANGE

Commercial aviation currently accounts for 2.6% of annual global carbon dioxide emissions from fossil fuel combustion,<sup>2</sup> which would place it sixth between Japan and Germany in emissions if aviation were a country.<sup>3</sup> If emissions are not curbed, between 2020 and 2050, aviation is projected to consume over a quarter of the budget for a 1.5 degree Celsius warming scenario.<sup>4</sup> Warming of greater than 1.5°C should be avoided to the fullest extent possible given the catastrophic climate harms that will result if such warming should occur. Considering that global anthropogenic CO<sub>2</sub> emissions must be halved by 2030 and reach near zero around 2045 to limit warming to 1.5°C (Figure 1),<sup>5</sup> the transportation sector, including aviation, will have to almost entirely decarbonize over the next 25 years. This will require deep emissions cuts, both internationally and domestically, for the United States.



**Figure 1:** Global CO<sub>2</sub> emissions from 2010 to 2045. Actual emissions are displayed for 2010 to 2019 (solid bars), whereas emissions from 2020 to 2045 are those expected assuming steady declines to meet a 2030 goal of emissions 45% below 2010 levels and a 2045 goal of near zero (dashed bars).<sup>6</sup>

Despite these imperatives, CO<sub>2</sub> emissions from global commercial aviation have increased 32% in the past five years (Figure 2).<sup>7</sup> To date no measures have been put in place to address aviation emissions with the stringency required to achieve urgent climate goals.



**Figure 2:** Global commercial aviation emissions from 2010 to 2018 (includes both passenger movement and freight transport).<sup>8</sup>

## **U.S. AVIATION A HUGE SOURCE OF GHG EMISSIONS**

U.S. aviation is one of the fastest-growing sources of GHG emissions. Flights departing from airports in the United States and its territories are responsible for almost a quarter of global passenger transport-related CO<sub>2</sub> emissions, two-thirds of which come from domestic flights.<sup>9</sup> Just in the United States, aviation makes up 12% of transportation emissions.<sup>10</sup> The U.S. aviation fleet achieved average annual fuel efficiency improvements of 1.3% between 2009 and 2020,<sup>11</sup> but these improvements have been offset by an increase in total fuel burn of 16% between 2009 and 2017.<sup>12</sup> Furthermore, the improvements fell short of the U.S. goal adopted from the International Air Transport Association (IATA) of 1.5% annual fuel efficiency improvements between 2009 and 2020.<sup>13</sup> In short, the United States is falling behind in making the necessary GHG reductions in aviation to avoid a 1.5°C warming future.<sup>14</sup>

## **THE U.S. SHOULD CUT AVIATION EMISSIONS TO NEAR ZERO IN 2040, STARTING IN 2020**

To avoid catastrophic climate harms, global greenhouse gas emissions must be halved by 2030 and eliminated altogether around 2050. However, the United States holds an outsized share of responsibility. It is the world's largest historic emitter of greenhouse gas pollution and is currently the world's second highest emitter on an annual basis.<sup>15</sup> It is also the wealthiest country, which through its exorbitant emissions is causing irreversible climate harms that are disproportionately felt by the most vulnerable global communities. Therefore, an earlier goal of reducing domestic emissions by 70% by 2030 and to near zero by 2040 is needed for it to align with what science, equity and climate justice demand.<sup>16</sup> As part of this effort, the United States must increase its efforts to reduce aviation emissions to near zero by 2040, starting in 2020.



Aircraft takeoff at SFO photo by dsleeter\_2000 CC BY-NC

## **U.S. MUST GO WELL BEYOND WEAK ICAO STANDARDS TO CURB EMISSIONS**

In 2017 ICAO adopted three “aspirational” goals to target global aviation emissions: an average 2% annual improvement in fuel efficiency through 2050, carbon-neutral growth from 2020, and a reduction of net aviation emissions by 50% by 2050 relative to 2005 levels.<sup>17</sup> To address these goals, it established a CO<sub>2</sub> performance standard that mandates reductions in CO<sub>2</sub> intensity from new aircraft. It will apply to new designs entering service from 2024 and all new commercial and business aircraft delivered starting in 2028. But the standard is so weak that, at best, it will serve only to prevent backsliding from previous improvements in fuel efficiency. The standard will require CO<sub>2</sub> reductions from new aircraft of just 4% over 12 years, which is less than market forces alone are predicted to achieve.<sup>18</sup> All U.S. regional carriers and 7 of 10 large carriers, accounting for 82% of 2017 aviation demand from U.S. airlines, would already meet the standard by 2028.<sup>19</sup> Two additional airlines, representing 17% of current demand, would comply with the standard with less than 2% additional fuel efficiency improvements. Thus, by all expectations, the standard will not require manufacturers to improve their aircraft efficiency when fully enforced in 2028. Yet the EPA is poised to adopt this standard, despite knowing that doing so will not result in any additional emissions reductions.

## **THE DOWNSIDE OF OFFSETS AND ALTERNATIVE FUELS**

ICAO has also proposed implementing a “basket of measures,” which includes improvements in operational efficiencies, advances in aircraft technology and standards, and the use of low-carbon fuels. Any emissions remaining are to be addressed by a market-based measure of carbon offsets called the Carbon Offsetting and Reduction Scheme for International Aviation (CORSA). ICAO’s 191 member states agreed to CORSA’s terms under which most air carriers will need to purchase carbon offsets for growth beyond 2019 levels of CO<sub>2</sub> emissions from international flights in order to have “carbon-neutral” growth from 2020.<sup>20</sup>

### **OFFSET SCHEMES: INEFFECTIVE AND HARMFUL**

However, the CORSA scheme will not effectively reduce greenhouse emissions by the amount promised and will likely provide no reductions at all. Researchers have found that most of the credits available today are for projects that would have gone forward by 2020 regardless of the offset program, meaning that there would be no additional benefit with CORSA’s implementation.<sup>21</sup> Also, because offsets are relatively cheap, making them especially appealing to industry, the aviation sector could possibly meet its entire emissions-reduction goal using offsets, without the technology and fuel efficiency innovations necessary for actual GHG reductions.

Beyond their lack of effectiveness, offset projects also lead to human rights violations in the global South. Research on offset projects has demonstrated that they violate the human rights of local communities and Indigenous peoples, often as a result of land grabs.<sup>22</sup> This shift of burden from countries in the global North to those in the South exacerbates the risks and injustices that communities already contending with hardship must bear. The United States should not rely on a system of offsets that violates human rights, causes environmental destruction and does not reduce emissions.

### **ALTERNATIVE FUELS: NOT CARBON-NEUTRAL OR SUSTAINABLE**

Furthermore, alternative fuels by and large have not proven to be carbon-neutral or sustainable. For instance, HEFA jet fuel, derived from oil and fat feedstocks, is approved for use in aircraft, but procuring the necessary feedstock is a challenge. When HEFA fuels are derived from palm feedstocks, the result can be an actual increase in overall emissions when accounting for external factors of production such as land-use change.<sup>23</sup> Similar to offsets, the impacts of such land-use change can put undue burden on already burdened countries and communities. Meanwhile, the other possible feedstock, waste fats, is often in short supply. Technologies do exist to convert more sustainable feedstocks to fuels, such as cellulosic biomass or municipal solid waste, but there are issues of advancing these technologies to the commercial scale.<sup>24</sup>

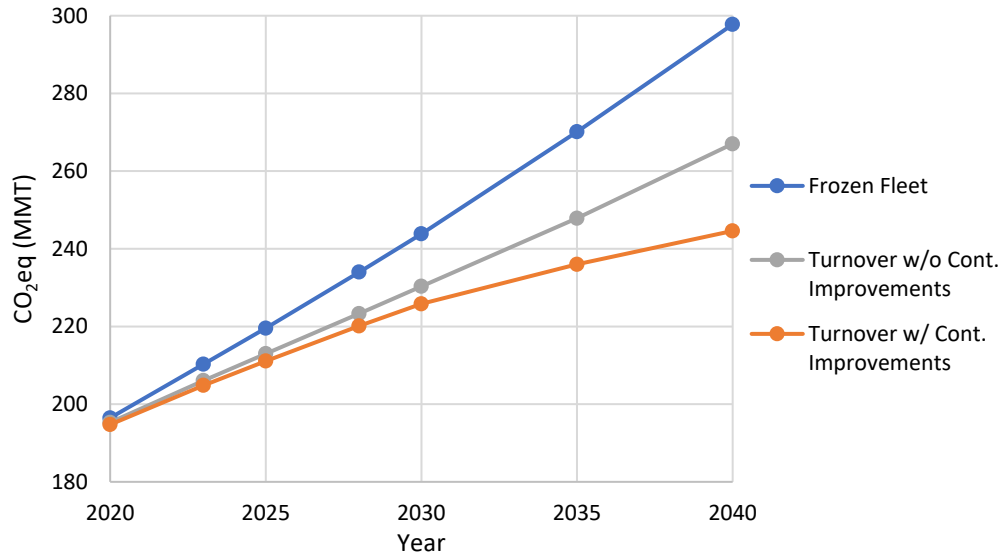
There are other alternatives, such as power-to-liquids fuels, hydrogen fuels and those reliant on the direct air capture of CO<sub>2</sub>, but these alternatives are generally either too early in development to be implemented cost-effectively,<sup>25</sup> or will reach commercial viability after substantial aviation emissions reductions need to be made. Thus the EPA should set stringent standards to regulate aviation emissions that are not reliant on ineffectual ICAO mechanisms. Relying on offsets and alternative fuels serves only to prolong unsustainable combustion-based air travel.

## **COMMITTING TO FUEL EFFICIENCY IMPROVEMENTS OF AT LEAST 3.5% ANNUALLY**

The EPA’s August 2020 proposal assumed a baseline “business-as-usual” 1% annual improvement in fuel efficiency, which is even less than the previous unaccomplished goal of 1.5% annual improvement adopted from IATA. However, a 3.5% improvement in annual fuel efficiency is achievable and necessary. In its *Draft Airplane Greenhouse Gas Standards Technical Support Document*,<sup>26</sup> the EPA presents expected U.S. aviation emissions for the years 2020 to 2040 under three scenarios: (1) emissions growing at the rate of passenger traffic growth assuming constant fleet fuel efficiency (frozen fleet, i.e., no fuel efficiency improvements or fleet evolution); (2) emissions where fleet fuel efficiency improves due to the introduction of newer aircraft, but the new airplanes entering the fleet are



assumed to be static and not improving between 2015 and 2040 (fleet turnover w/o constant improvement); and (3) emissions where the fleet fuel efficiency improves from the introduction of new airplanes and business-as-usual improvement of the new in-production airplanes (fleet turnover w/ continuous improvement) (Figure 3):



**Figure 3:** Commercial aviation emissions (million metric tons CO<sub>2</sub> (MMT)) assuming three different EPA scenarios: (1) A frozen fleet with 2.1% annual growth in commercial passenger traffic and therefore 2.1% annual growth in emissions; (2) A scenario of aircraft turnover but without aircraft improvements corresponding to 0.5% in annual fuel efficiency improvements, leaving average annual emissions to grow by 1.6%. (3) Business as usual (turnover w/ continuous improvement) with fuel efficiency improvements of approximately 1%, leaving average annual emissions to grow by 1.1%.

The frozen fleet scenario has 2.1% annual growth in emissions (due to 2.1% annual growth in passenger traffic) between 2020 and 2040, so at least 2.1% in annual fuel efficiency improvements would be required to offset this growth. Meanwhile, the business-as-usual (turnover w/ continuous improvement) scenario has 1.1% annual growth in emissions, which means it assumes only 1% annual fuel efficiency improvements (difference between frozen fleet and business-as-usual emissions).<sup>1</sup> The United States expects the proposed standard to achieve no more than the currently projected 1% annual fuel efficiency improvements, but it has the potential to do so much more.

### THREE PATHWAYS TO IMPROVED FUEL EFFICIENCY

According to the International Council on Clean Transportation, a declining fleet average standard, requiring airlines to reduce their emissions, could yield 2.5% annual fuel efficiency improvements.<sup>27</sup> In this scenario fuel efficiency improvements occur via three main pathways: (1) replacing older aircraft with newer, more fuel-efficient aircraft; (2) improving operations to carry more passengers and freight per flight and to fly more directly to destinations; and (3) finding optimal flight paths and avoiding congestion near airports using advanced air traffic management. Historically, replacing older aircraft has led to fuel burn reductions of 1.3% per year (since 1960), operational improvements have led to reductions of 0.5%, and advanced air-traffic management has led to reductions of 0.2%, producing total reductions of 2%. Thus, ICCT expects that an additional 0.5% in annual improvements above historical trends is achievable with a declining fleet average standard to reach 2.5%.

### SETTING TECHNOLOGY-FORCING STANDARDS

In setting standards the U.S. EPA should not limit itself to what has historically been achieved, or what is known to be achievable with current technology, but instead set *technology-forcing* standards. Although average fuel burn

<sup>1</sup> Fuel efficiency is in terms of revenue passenger miles per gallon (RPM/gallon) or similar. Likewise, growth in passenger traffic is in terms of revenue passenger miles (RPM).



reductions have been 1.3% per year since 1960, there have been decades where fuel burn reduction has been as high as 2.8% annually.<sup>28</sup> A comprehensive technology assessment also found that the rate of new aircraft fuel-burn improvement could be accelerated up to 2.2% annually through 2034 if cost-effective technologies were employed.<sup>29</sup> Meanwhile, though operational improvements and air-traffic management improvements typically provide fuel efficiency gains of around 0.5% and 0.2% per year, respectively, according to ICCT maximums of 1.3% and 0.6% have been observed, respectively.<sup>30</sup>

Moreover, the aviation sector had the short-term goal to improve fleet fuel efficiency by 1.5% annually from 2009 to 2020, with global airlines reportedly exceeding this standard with average annual improvement of 2.3%.<sup>31</sup> 2.5% is not much more ambitious than what has already been achieved by the aviation sector. Through maximizing gains from improving technology, improving operations, and improving air-traffic management, at least an additional 1% in annual fuel efficiency improvements would be possible above historical averages. Thus the United States should pursue a goal of at least 3.5% in annual fuel efficiency improvements by maximizing gains from retiring old aircraft and replacing them with newer more fuel-efficient aircraft, improving operations and managing air traffic. Since it produces more aviation emissions than any other country, it is only fair that its standard for emissions reductions not only supersedes historical trends, but also the ambitions of other nations and ICAO.

## **COVID-19 DOWNTURN REINFORCES NEED FOR STRONG, MODERNIZING STANDARDS**

In 2018 U.S. aviation CO<sub>2</sub> emissions from passenger transport totaled 182 million metric tons, with 126 million metric tons from domestic travel and 56 million metric tons from international travel of U.S. origin. This made up 24% of global passenger transport emissions.<sup>32</sup> Estimates for 2019 are expected to resemble those in 2018. However, due to COVID-19, it is now predicted that passenger traffic will be 60% lower in 2020, 40% lower in 2021, 10% lower in 2022, and 5% lower in 2023 than in 2019.<sup>33</sup> With a 60% decline in air traffic, 2020 could see emissions some 100 million metric tons below 2018 levels. Since air travel is unlikely to return to 2019 passenger volumes before 2024, the time between now and 2024 can serve as a buffer period during which to make improvements that equate to 3.5% or more in annual fuel efficiency gains.

In addition to the more than 210,000 lives lost and millions sickened in the United States alone, the pandemic has resulted in tens of thousands of lost jobs as air travel has plummeted. Ambitious standards can create good jobs in the aviation sector while also providing the necessary pollution reductions essential to human and environmental health. Now more than ever, we need strong, technology-forcing standards that will drive the modernization and decarbonization of the aviation industry, allowing it to survive and thrive in a carbon-constrained world.

## **ELECTRIFIED SHORT-HAUL FLIGHTS BY 2040**

In 2018 one-third of passenger CO<sub>2</sub> emissions occurred on short-haul flights of less than 1,500 km (810 nautical miles), one-third on medium-haul flights of between 1,500 km and 4,000 km (2,160 nautical miles), and one-third on long-haul flights greater than 4,000 km.<sup>34</sup> Assuming this breakdown is representative of future U.S. emissions trends, electrifying short haul flights by 2040 could reduce emissions by over 30%. Meanwhile a 2018 study found that, assuming strong progress in battery technology, electric aircraft could cover a 2,222 km (1,200 nautical mile) range, thus replacing more than 80% of global aircraft departures while reducing fuel use and direct CO<sub>2</sub> emissions by around 40%. This would depend on a battery with an energy density in excess of 800 Wh/kg (a topic discussed further below).<sup>35</sup>

## **BATTERY ADVANCES**

The transition from conventional aircraft to electric aircraft will overwhelmingly depend on advances in battery technology, where the current prevailing technology is the lithium-ion (Li-Ion) battery, as is used in electric cars. The best available Li-Ion battery cells currently have an energy density (energy per unit of mass) of 300 watt-

hour/kilogram of battery (Wh/kg). Given losses in efficiency when merging battery cells into battery packs, a battery pack with current technology for an aircraft would have an energy density of roughly 240 Wh/kg, which corresponds to only 2% of the energy density of jet fuel (about 12,000 Wh/kg).<sup>36</sup> Meanwhile, short-haul electric aircraft will require batteries with energy densities ranging from 750 to 2,000 Wh/kg, or 6 to 17% of jet fuel energy content.<sup>37</sup> However, an energy density of 750 to 2,000 Wh/kg should be attainable prior to 2040 given trends of advancement in battery technology.

It is predicted that energy density of Li-Ion batteries could increase to 400 to 450 Wh/kg in the 2022 to 2025 timeframe.<sup>38</sup> And there are two other promising technologies in the works that could go further. Lithium-sulfur (Li-S) batteries could reach commercial scale considering that they now have an energy density of over 350 Wh/kg and theoretically could achieve an energy density of greater than 2,000 Wh/kg. The technology is still too new to be sure, but it is envisioned that Li-S batteries could reach 500 to 650 Wh/kg energy density within 15 years (2035) and 800 to 950 Wh/kg in 30 years (2050).<sup>39</sup> Meanwhile lithium-air (Li-Air) batteries are anticipated to surpass both Li-Ion and Li-S technologies around 2030, according to a 2020 study. It is predicted that Li-Air batteries could achieve an energy density of 600 to 750 Wh/kg within 15 years (2035) and 1,200-1,400 Wh/kg within 30 years (2050).<sup>40</sup> A 2012 study was even more optimistic, predicting that Li-S batteries could have an energy density of 500 to 1,250 Wh/kg and Li-Air batteries an energy density of 800 to 1,750 Wh/kg by 2025.<sup>41</sup> With the impetus of an electrified short-haul aircraft mandate, this timeline could shift to meet a 2040 deadline, acknowledging that there are remaining challenges in making Li-S and Li-Air batteries ready for commercial aviation use.

For all-electric aircraft to compete with large airliners such as the Boeing 737 (which can carry around 200 passengers) on routes of more than 540 nautical miles, they will require a battery with an 800 Wh/kg energy density. This precludes all-electric aircraft from long-haul routes, such as from Los Angeles to New York, for the time being. However, according to the CEO of magniX, a leader in electric propulsion systems for aircraft, electric planes designed from scratch could achieve a range of about 432 nautical miles using today's batteries. With about 45% of flights under 432 nautical miles, according to magniX, even this achievement would go a long way toward curbing aviation CO<sub>2</sub> emissions.<sup>42</sup>

## ELECTRIC SHORT-HAUL FLIGHT FEASIBILITY

Numerous efforts are underway that reveal how short-haul electric commercial aircraft are feasible in the coming decades. According to one industry analysis, as of 2019, there are 215 electric aircraft projects in the works, with most being all-electric.<sup>43</sup> Urban air taxis dominate, constituting 45% of these projects, but there are also projects developing all-electric small commercial aircraft.

Heart Aerospace, for instance, which is based in Sweden, is designing an all-electric, 400 km (216 nautical miles) operating range, 19-passenger airliner named ES-19 that is expected to be certified for commercial operation by 2025.<sup>44</sup> The Israel-based company Eviation has a prototype called "Alice" designed to carry up to nine passengers and two pilots, with a range of 1,050 km (565 nautical miles).



Eviation "Alice" photo by Matti Blume CC BY-SA

The company is aiming for certification in 2022.<sup>45</sup> The British-based airline EasyJet is developing a 186-seater electric aircraft with U.S. startup Wright Electric that it hopes to test in 2023.<sup>46</sup> Airbus proposed a concept plane, called VoltAir, that would have approximately 33 seats and a range of 900 nautical miles and could enter service by 2035. Finally, the company Bauhaus Luftfahrt, based in Germany, proposed an all-electric aircraft concept called the Ce-Liner that would have 189 seats and a range of 900 nautical miles and could enter service by 2035, assuming the achievement of a 2000 Wh/kg battery.<sup>47</sup> These last two aircraft have not left the conceptualization stage, but such concepts indicate what could be achieved if the goal of electrifying all short-haul aircraft by 2040 were implemented.

Norway has set the international standard, announcing a target to electrify all short-haul flights by 2040.<sup>48</sup> And history was made in 2019 when the world's first fully electric commercial aircraft completed a test flight in Vancouver. The six-seater aircraft, a partnership between Harbour Air and magniX, signifies the start of Harbour Air's goal to electrify its fleet of more than 40 seaplanes in the coming years.<sup>49</sup> With some companies promising commercial short-haul, all-electric aircraft before 2030, and Norway committing to electrify all short-haul flights by 2040, the U.S. should likewise commit to 100% electric short-haul flights by 2040.

## **ELECTRIFIED LONG-HAUL FLIGHTS BY 2045**

A battery with the energy density sufficient to be competitive with current aircraft propulsion systems for regional and larger commercial flight could be available as early as 2030.<sup>50</sup> From there, to approach the necessary battery density to electrify long-haul flights by 2045, we will have to improve existing battery and aircraft technologies and perhaps embrace new ones. For instance, Li-S and Li-Air batteries are expected to have energy densities of 500-1,250 Wh/kg and 800-1,750 Wh/kg by 2025, respectively, but the energy densities theoretically possible for these battery types are much higher. The theoretical energy densities for Li-S and Li-Air batteries are 2,570 Wh/kg and 3500 Wh/kg, respectively, or about 22% and 30% of the energy density of jet fuel.<sup>51</sup> It is expected that, in order for aircraft to operate beyond distances of 1,200 nautical miles in a single-stage flight, a battery pack energy density of at least 1,600 Wh/kg would be required.<sup>52</sup> Going beyond Li-Ion batteries to other battery types such as Li-S and Li-Air will likely be key in realizing long-haul fully electric flights.

## **DESIGNING FOR LONG-HAUL ELECTRIC AIR TRAVEL**

It is important to note that batteries do not have to attain 100% of the energy density of jet fuel to be competitive. One reason is that electric propulsion will permit new aircraft designs. If new aircraft are designed around electric motors rather than relying on current aircraft shapes, then aircraft can be equipped with new features such as distributed motors and reduced drag to allow flight with less energy than is currently necessary.<sup>53</sup> Also, batteries are more than three times more efficient in energy delivery than internal combustion engines. While a battery pack with current technology has an energy density roughly 2% that of jet fuel,<sup>54</sup> when factoring in the efficiency difference, the energy density of batteries increases to roughly 7% that of jet fuel.<sup>55</sup>

Finally, flight range via electric propulsion could be extended by incorporating multistage flights with at least one intermediate stop. The downsides of this option are increased travel time, and potential limitations based on airport capacity and noise regulations.<sup>56</sup> However, in weighing the added inconvenience of multistage stops against the imperative to reduce aviation emissions and address climate change, multistage stops are a viable option.

## **PARTIALLY ELECTRIC AIRCRAFT LIKELY FOR LONG-HAUL FLIGHTS**

While we believe the perceived difficulties in fully electrifying long-haul flights could be overcome given sufficient effort, partially electric aircraft are another option that can be deployed between now and 2045. Partially electric aircraft include hybrid-electric and turboelectric aircraft. In turboelectric aircraft, gas turbines



drive electrical generators that power electric motors that generate propulsion. Hybrid-electric aircraft use high-capacity batteries to provide some or all propulsion during one or more phases of flight.

There are two partially electric aircraft concepts that show promise for enabling long-haul aviation before 2045. The first is the Boeing Sugar Volt, a hybrid-electric concept that could be ready as early as 2035. It would seat 154 passengers, travel 3,500 nautical miles (6,482 kilometers), and reduce fuel burn by 60% to 70%.<sup>57</sup> The second, the NASA N3-X, is a turboelectric concept. It would seat 300 passengers, travel 7,500 nautical miles (13,890 km), and reduce fuel burn by 70%.<sup>58</sup> Electric propulsion is only responsible for an approximate 20% reduction in fuel burn with the NASA N3-X; the remaining reductions come from a new airframe design (a hybrid-wing body concept where the wings and body blend together without an obvious division) and other technologies.<sup>59</sup> Thus the NASA N3-X exemplifies the importance of innovation in the complete design of future aircraft to bring about reductions in fuel burn.



N3-X Hybrid Wing Body Turboelectric Plane Concept, courtesy NASA

According to NASA, turboelectric and hybrid-electric large aircraft could be tested by 2025 and enter service starting in 2035 if resources are set toward this goal.<sup>60</sup> Therefore, viable pathways to fully electrifying air travel could reasonably include hybrid-electric and turboelectric aircraft. If resources are likewise set to the goal of producing fully electric aircraft, namely through advancing aircraft design and pushing battery energy densities toward their theoretical maximums, then an electrified long-haul fleet, allowing for partially-electric and fully-electric aircraft, could be realized by 2045.

## **REACHING NEAR-ZERO EMISSIONS BY 2040**

In order to align with a 1.5°C pathway, the United States must reduce its emissions to near zero by 2040.<sup>61</sup> As part of this effort, it must increase its efforts to reduce aviation emissions starting in 2020 in order to reach zero emissions in aviation. Reducing aviation emissions must include a major push for the electrification of both short-haul and long-haul air travel. As already noted, NASA believes that, provided the resources, turboelectric and hybrid-electric large aircraft could be ready by 2035. The EPA must set a standard that drives technology development and deployment. For the EPA to establish a standard that it knows will produce no additional emissions reductions is a failure that will lead to greater climate harms around the world. It simply will not do to establish a standard that the EPA knows will produce no additional emissions reductions. The EPA must instead establish a standard that requires annual emissions reductions through the retirement of old aircraft, operational and air traffic management improvements and the introduction of new aircraft that eventually constitute a 100% electric fleet.



## ANALYSIS:

# WITH AMBITIOUS BUT ACHIEVABLE GOALS, THE U.S. WOULD MAKE SIGNIFICANT STRIDES IN CURBING AVIATION EMISSIONS

The U.S. Clean Air Act requires the EPA to set a CO<sub>2</sub> emission standard that is much more stringent than the ICAO standard for both new and existing aircraft. The EPA's obligation to protect public health and welfare by reducing and preventing pollution demands a rule that will produce meaningful aviation emissions reductions. The United States should adopt a goal of at least 3.5% annual fuel efficiency improvement from 2020 through mid-century and incorporate the development and implementation of electric aircraft for both short- and long-haul flights.

## A MINIMUM 3.5% ANNUAL FUEL EFFICIENCY IMPROVEMENT

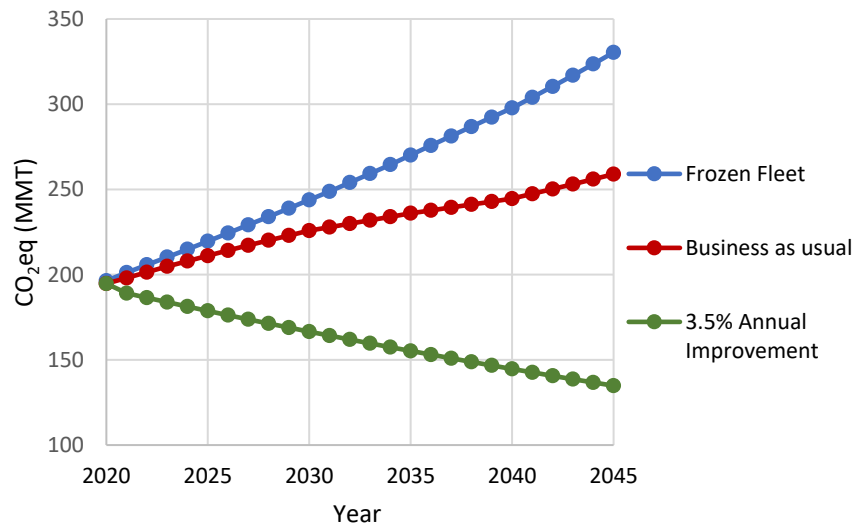
To calculate the impact of a 3.5% annual fuel efficiency improvement on aviation emissions, we did the following:

(1) We determined the annual and cumulative emissions that would occur if the United States maintained an annual fuel efficiency improvement of 3.5% from 2020 to 2045, yielding an annual decline in emissions of about 1.4% (1.4% being the difference between the 3.5% fuel efficiency improvement and the EPA estimate of passenger traffic growth of 2.1%). The goal should be to reach near-zero emissions by 2040, but we considered a timeline through 2045 since that is when we predict a 100% electric commercial aviation fleet would be feasible (including partially electric aircraft). Since the EPA only presented estimates of emissions for select years between 2020 and 2040, we used the trends in the EPA data to estimate emissions for the remaining years between 2020 and 2045.

(2) We used the EPA's estimate of 194.74 MMT CO<sub>2</sub>eq for commercial aviation emissions in 2020 as a starting value.<sup>62</sup> This business-as-usual estimate does not factor in the COVID-19 downturn in passenger traffic. We still used this non-COVID estimate as the basis of our analysis, which means that our estimates of annual and cumulative emissions serve as an upper bound that assumes a rebound in passenger traffic following the pandemic. However, our primary goal is to show the benefits of aggressive fuel efficiency improvements and aircraft electrification relative to business as usual, and this comparison is possible even while excluding the impacts of COVID-19 in our analysis.

(3) We compared the annual and cumulative emissions from a 3.5% annual fuel efficiency improvement scenario to the EPA scenarios of a frozen fleet with no improvements (2.1% annual emissions growth) and a fleet with business-as-usual improvements (1.1% annual emissions growth due to 1% in annual fuel efficiency improvements).

The comparison of our 3.5% annual improvement scenario to the two EPA scenarios is depicted in Figure 4 and summarized in Table 1:



**Figure 4:** Commercial aviation emissions (million metric tons CO<sub>2</sub>eq (MMT)) assuming three different scenarios: (1) A frozen fleet with 2.1% annual growth in commercial passenger traffic and therefore 2.1% annual growth in emissions; (2) Business as usual with fuel efficiency improvements of approximately 1%, leaving average annual emissions to grow by 1.1%; (3) Annual fuel efficiency improvements of 3.5%, leading to average annual emissions declines of 1.4%.

Emissions	Frozen Fleet	Business As Usual	3.5% Annual Improvement
Cumulative 2020-2040	5,149	4,684	3,565
Cumulative 2020-2045	6,735	5,949	4,269
2040	298	245	147
2045	330	259	137

**Table 1:** Commercial aviation emissions (million metric tons CO<sub>2</sub>eq (MMT)) assuming three different scenarios: (1) A frozen fleet with 2.1% annual growth in commercial passenger traffic and therefore 2.1% annual growth in emissions; (2) Business as usual with fuel efficiency improvements of approximately 1%, leaving average annual emissions to grow by 1.1%; (3) Annual fuel efficiency improvements of 3.5%, leading to average annual emissions declines of 1.4%. Shown are cumulative emissions 2020-2040 and 2020-2045 and the emissions in 2040 and 2045 alone.

Emphasizing the importance of continued fuel efficiency improvements, without any fuel efficiency improvements (a frozen fleet), cumulative emissions from aviation would be 5.1 GT CO<sub>2</sub>eq (GT: billion metric tons) between 2020 and 2040 and 6.7 GT CO<sub>2</sub>eq between 2020 and 2045. In contrast, with the U.S. business-as-usual scenario corresponding to 1% annual fuel efficiency improvements, cumulative emissions would be 4.7 and 5.9 GT CO<sub>2</sub>eq, respectively. Finally, if a mandate were put into place for 3.5% annual fuel efficiency improvements, the cumulative emissions would be 3.6 and 4.3 GT CO<sub>2</sub>eq, respectively, or a 24% and 28% drop from business as usual.

The savings are further highlighted when considering 2040 and 2045 emissions, as mid-century is a major benchmark against which we should measure emissions reduction progress. Emissions with a frozen fleet are 298 and 330 MMT CO<sub>2</sub>eq in 2040 and 2045, respectively. With the business-as-usual scenario, emissions in 2040 and 2045 drop to 245 and 259 MMT CO<sub>2</sub>eq, respectively, or by 18% and 22%. If a mandate were put into place for 3.5% annual fuel efficiency improvements, emissions in 2040 and 2045 would be 147 and 137 MMT CO<sub>2</sub>eq, or a 40% and 47% drop from business as usual.



While a 3.5% annual fuel efficiency improvement is a great improvement over the 1% expected from U.S. business as usual, reducing cumulative emissions by 24% between 2020 and 2040, this alone does not get aviation emissions to near zero by 2040. The country must expedite the development of electric aircraft for both short- and long-haul flights to bring emissions closer to zero by 2040, in line with what equity and climate science demand.

### **SCENARIO: ELECTRIFYING ALL SHORT-HAUL FLIGHTS BY 2040 PLUS 3.5% ANNUAL FUEL EFFICIENCY IMPROVEMENTS**

To determine the impact of electrifying all short-haul aircraft by 2040, we assumed the following:

(1) Short-haul flights, being those less than 1,500 km (810 nautical miles), would constitute one-third of commercial passenger CO<sub>2</sub> emissions in the absence of aircraft electrification.

(2) In a linear adoption scenario, there would be a 10-year ramp up in the years prior to 2040 in order to reach 100% electrified short-haul flights by 2040. This ramp-up was set at an idealized 10% annual increase in the proportion of all-electric short-haul aircraft between 2030 and 2040, with 10% of short-haul aircraft being all-electric in 2031 and 100% being all-electric in 2040. It is assumed that short-haul aircraft could be ready for incorporation into the larger aircraft fleet beginning in 2030. The FAA estimates a five- to nine-year certification process for new aircraft types and advances in battery technology and electric aircraft development suggest that such aircraft could be ready in the 2020s.

(3) With a 100% all-electric short-haul fleet in 2040, a full third of emissions that would otherwise occur based on fuel efficiency improvements and increases in passenger traffic would be removed in 2040, or one-third of the 147 MMT CO<sub>2</sub>eq estimated with 3.5% annual fuel efficiency improvement.

The calculation of the expected emissions in a given year between 2030 and 2045, given 3.5% annual fuel efficiency improvement and all-electric short-haul aircraft, is the following:

*Equation 1: Commercial passenger emissions (MMT CO<sub>2</sub>eq)*  
*= Base emissions - [(Base emissions) x (1/3) x (proportion short-haul electric aircraft)]*

- “Base emissions” are the emissions that occur with 3.5% annual fuel efficiency improvements in a given year starting in 2020 and no other mandates.
- The “1/3” multiplier is because short-haul aircraft represented one-third of passenger CO<sub>2</sub> emissions in 2018 and is assumed representative of the U.S. for future years.
- “Proportion short-haul electric aircraft” is the proportion of total short-haul passenger aircraft expected to be electric in a given year, starting with 10% in 2031 and ending with 100% in 2040 onwards.

With the above assumptions, introducing a 100% all-electric short-haul fleet mandate for 2040 in addition to 3.5% annual fuel efficiency improvements would yield cumulative emissions of about 3.3 and 3.8 GT CO<sub>2</sub>eq between 2020 and 2040 and 2020 to 2045, respectively. This corresponds to reductions in cumulative emissions relative to business as usual of 30% and 37%, respectively.

When considering 2040 and 2045 alone, the emissions are 98 and 91 MMT CO<sub>2</sub>eq, respectively, with reductions from business as usual of 60% and 65% (Table 2).

### **SCENARIO: ELECTRIFYING ALL FLIGHTS BY 2045 PLUS 3.5% ANNUAL FUEL EFFICIENCY IMPROVEMENTS**

To determine the impact of electrifying long-haul aircraft by 2045, we assumed the following:

(1) Long-haul flights for our purposes are those greater than 1,500 km (810 nautical miles) and as such constitute two-thirds of passenger CO<sub>2</sub> emissions in the absence of aircraft electrification.

(2) To be conservative, we assume that 100% long-haul electric aircraft in 2045 corresponds to 100% turboelectric or hybrid-electric (partially electric) aircraft capable of reducing fuel burn by 70% compared to conventional aircraft. In a linear adoption scenario, there would be a 10-year ramp up in the years prior in order to reach 100% electrified long-haul flights by 2045. This ramp-up was set at a 10% annual increase in the proportion of electric long-haul aircraft between 2035 and 2045, with 10% of long-haul aircraft being electric in 2036 and 100% being electric in 2045. It is assumed that partially electric aircraft could be ready for incorporation into the larger aircraft fleet beginning in 2035 given that the FAA estimates a five- to nine-year certification process for new aircraft types, and it is projected that such aircraft could be ready to enter the fleet in 2035 if there were an impetus to ready them.

(3) For comparison, we assume a scenario where 100% long-haul electric aircraft in 2045 means 100% all-electric aircraft, with all-electric aircraft constituting the ramp up to 2045 as well.

The calculation of the expected emissions of a given year between 2035 and 2045 given 3.5% annual fuel efficiency improvement and all-electric short-haul aircraft and partially electric long-haul aircraft is the following:

*Equation 2: Commercial passenger emissions (MMT CO<sub>2</sub>eq)*

*= (“Equation 1”) – [(Base emissions) \* (2/3) \* (proportion long-haul electric aircraft) \* (proportional fuel burn reduction)]*

- “Base emissions” are the emissions that occur with 3.5% annual fuel efficiency improvements starting in 2020 and no other mandates.
- The “2/3” multiplier is because long-haul aircraft represented two-thirds of passenger CO<sub>2</sub> emissions in 2018 and is assumed representative of the U.S. for future years.
- “Proportion long-haul electric aircraft” is the proportion of total long-haul passenger aircraft expected to be electric in a given year, starting with 10% in 2036 and ending with 100% in 2045.
- “Proportional fuel burn reduction” is the percent reduction in fuel burn of electric aircraft from conventional aircraft. In the case of partially electric aircraft, this is assumed to be 70%. In the case of all-electric aircraft, this would be 100%.

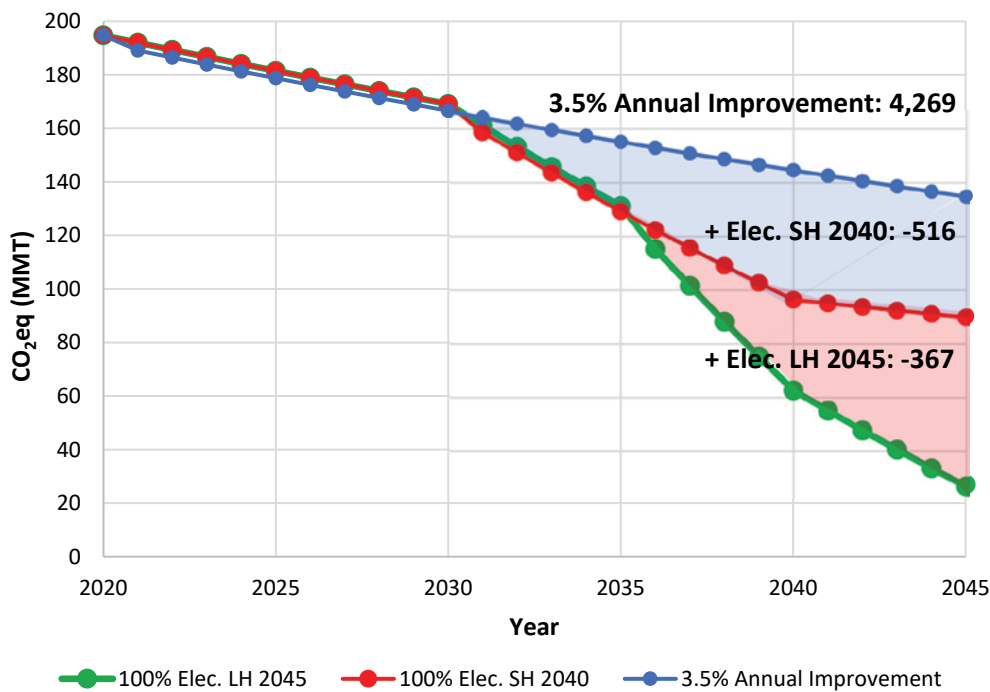
With the above assumptions, introducing a 100% electric long-haul fleet mandate for 2045 in addition to 3.5% annual fuel efficiency improvements starting in 2020 and 100% short-haul fleet by 2040 would yield cumulative emissions of about 3.2 and 3.4 GT CO<sub>2</sub>eq between 2020 and 2040 and 2020 and 2045, respectively (Figure 5). This corresponds to reductions in cumulative emissions relative to business as usual of 32% and 43%, respectively.

## PARTIALLY ELECTRIC VS. ALL-ELECTRIC LONG-HAUL AIRCRAFT

If, rather than allowing for partially electric aircraft, we incorporate only all-electric long-haul aircraft into the fleet, then the cumulative emissions are about 3.1 and 3.2 GT CO<sub>2</sub>eq, respectively, or 45 and 157 MMT CO<sub>2</sub>eq less than with partially electric aircraft (Table 2). When considering 2040 and 2045 emissions alone, partially electrifying all flights by 2045 in addition to 3.5% annual fuel efficiency improvements results in emissions that are 74% lower than business as usual in 2040 and 90% lower in 2045; completely electrifying all flights by 2045 results in emissions that are 80% and 100% lower in 2040 and 2045, respectively.

Emissions Type	BAU	3.5% Annual Improvement <sup>a</sup>	Plus Short-haul 2040 <sup>b</sup>	Plus Long-haul 2045 <sup>c</sup>
Cumulative 2020-2040	4,684	3,565	3,284	3,179 (3,134)
Cumulative 2020-2045	5,949	4,269	3,753	3,386 (3,229)
2040	245	147	98	64 (49)
2045	259	137	91	27 (0)

**Table 2:** U.S. commercial aviation emissions under business as usual (BAU) vs. 3.5% annual fuel efficiency improvements, 100% electric short-haul mandate by 2040, and 100% electric long-haul mandate by 2045. Emissions shown for (a) the case where 3.5% annual fuel efficiency improvements is implemented, (b) the case where 3.5% annual improvements and 100% short-haul aircraft by 2040 are implemented, and (c) the case 3.5% annual improvements and both 100% electric short-haul in 2040 and 100% electric long-haul in 2045 are implemented. In parenthesis are the predicted emissions if 100% electric long-haul means 100% all electric, whereas those outside of parenthesis correspond to 100% partially electric. Units are in million metric tons CO<sub>2</sub> (MMT CO<sub>2</sub>eq).



**Figure 5:** Aviation emissions trajectories resulting from (a) a 3.5% annual fuel efficiency improvement, (b) 100% all-electric short-haul by 2040, and (c) 100% partially electric long-haul by 2045. The “3.5% Annual Improvement” value displayed is the cumulative emissions from 2020 to 2045 assuming 3.5% annual fuel efficiency improvements. The “+Elec. SH 2040” value is the reduction in cumulative emissions from electrifying short-haul travel relative to 3.5% annual fuel efficiency improvements alone. The “+Elec. LH 2050” value is the additional reduction from electrifying long-haul travel (allowing for partially electric aircraft).

## EXPLORING ADDITIONAL MEASURES TO GET TO NEAR-ZERO EMISSIONS BY 2040

Even with the proposed mandates of 3.5% annual fuel efficiency improvements and electric air travel by 2040, U.S. commercial aviation would still emit 64 MMT CO<sub>2</sub>eq in 2040. While this is almost 75% less than the 2040 emissions under business as usual, there is still room to further reduce emissions and methods to do so should be explored. For instance, our proposal of 3.5% annual fuel efficiency improvements is based on going beyond what has historically been done and the need to set a goal that is technology-forcing. But the EPA should assess pathways for fuel efficiency improvements even greater than 3.5%. Furthermore, we propose pathways for the incorporation of electric aircraft starting in 2030 for short-haul flights and 2035 for long-haul flights. This technology should be incorporated into the fleet as it becomes available, prior to 2030 if possible. In our proposal for long-haul electric flight, we allow for hybrid-electric and turboelectric aircraft. But all-electric long-haul aircraft should ultimately be



prioritized. Even in our scenario of the introduction of long-haul electric flight beginning in 2035, the emissions in 2040 with all-electric long-haul aircraft are 23% less than with partially electric aircraft (49 MMT vs 64 MMT). Thus the ultimate goal should be long-haul all-electric flight, as this will maximize emissions reductions.

Our analysis also assumes that the power grid will transition to 100% renewable energy. With the near-term cost parity of clean energy, the remaining barrier to our renewable energy future is no longer economics and technology but political will.<sup>63</sup> In its efforts to decarbonize various sectors, the United States should commit to maximizing energy efficiency and ensuring 100% clean, renewable and zero-emission energy by 2030. This means phasing out all combustion-based power generation and biomass energy. To ensure the expediency and fairness of this transition, it should occur through restructuring and democratizing electricity systems so that the driver of the transition is community interests expressed via public ownership.<sup>64</sup>

Also, alternatives to air travel in general should be developed, such as the full deployment of electric passenger vehicles and high-speed rail. The United States is severely behind in this regard.<sup>65</sup> If, with all of these considerations, U.S. aviation is still unable to reach near-zero emissions by 2040, then the country should commit to limiting flights. It should also commit funds to developing countries to reduce their aviation emissions, a step warranted by the gravity of the climate crisis.

In sum the EPA should consider the measures proposed here — 3.5% annual fuel efficiency improvements starting in 2020, 100% electric short-haul flights by 2040, and 100% electric long-haul flights by 2045 — as goals to strive to *exceed*, rather than as an aspirational maximum.



## CONCLUSION:

### COMBINING 3.5% ANNUAL FUEL EFFICIENCY IMPROVEMENTS WITH ELECTRIC AIRCRAFT TARGETS IN 2040 AND 2045 WOULD HELP U.S. SATISFY MID-CENTURY CLIMATE GOALS

With 3.5% annual fuel efficiency improvements starting in 2020 and electric aircraft targets in 2040 and 2045, cumulative emissions would be 3.2 and 3.4 GT CO<sub>2</sub>eq by 2040 and 2045 respectively. This is in stark contrast to the business-as-usual scenario that the 2020 EPA proposal would perpetuate, and that would lead to almost twice the cumulative emissions.

By enacting a standard of 3.5% annual fuel efficiency improvements from 2020 onwards, the United States would go beyond ICAO's inadequate goal of carbon-neutral growth from 2020. 3.5% efficiency would yield carbon reductions, or carbon-negative growth from 2020, even if passenger traffic rates rebound. Relative to ICAO's goal of net aviation emissions 50% below 2005 levels by 2050, with electric aircraft mandates included, emissions would meet that target (2005 level: 132.7 MMT)<sup>66</sup> by as early as 2040, in time for the nation to contribute its equitable share to global emissions reductions.

To take responsibility for its role as the greatest cumulative emitter of greenhouse gas pollution, the United States must adopt aggressive standards to reduce its emissions in all sectors, including aviation. Merely adopting ICAO's CO<sub>2</sub> standard knowing that it will not yield any additional emissions savings does not satisfy this imperative. Only through exceeding the stringency of ICAO and embracing fuel efficiency improvements and an all-electric aviation future will the country align with a 1.5°C pathway and what science, equity and climate justice demand.

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<sup>13</sup> IATA, Fuel Efficiency (Accessed September 22, 2020), <https://www.iata.org/en/programs/ops-infra/fuel/fuel-efficiency/>.

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