TECHNICAL ASSESSMENT FOR AIRPLANE FUEL EFFICIENCY

BUSINESS

(FUEL CONSUMPTION, AIRCRAFT, WINGTIP DEVICES, RE-ENGINING)

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*Note: For some of the technical reports, the result section is not yet updated. Kindly refer to the model for the latest results.

DRAWDOWN

27 GATE 5 RD., SAUSALITO, CA 94965 INFO@DRAWDOWN.ORG WWW.DRAWDOWN.ORG

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EXECUTIVE SUMMARY

Project Drawdown defines the *airplanes* solution as: the increased use of technologies to reduce aircraft fuel burn. This solution replaces conventional aircraft with existing global fleet-wide fuel efficiency.

Air travel is estimated to cause approximately 2.42 percent of manmade carbon dioxide emissions in the world (BDL, 2014). However, its expansion is causing increasing alarm. Airplane fuel efficiency efforts aim to reduce fuel use per passenger-kilometer of air travel. Though freight-only aircraft fuel efficiency is not analyzed here, part of the impact on air freight fuel use is accounted for in the large fraction of total air freight that is carried in the belly of passenger aircraft.[1]

As there are numerous technologies and operational approaches for reducing airplane fuel use, only the most impactful technologies in use today to improve fuel efficiency were included in this study. Therefore, well-publicized but non-commercial technologies such as aviation biofuels were excluded.

Methodology

This analysis includes the newest, most fuel-efficient aircraft (called "intermediate generation"),[2] as well as the use of fuel efficiency retrofits to existing aircraft. Intermediate generation aircraft are expected to be 15-20 percent more fuel-efficient than earlier models, in part as a result of more fuel-efficient engines, new wingtip devices,[3] and light weighting approaches. Research suggests that the combination of these three technologies in a retrofit would amount to efficiency improvements comparable to a newer aircraft model. In this study, new and retrofitted aircraft are compared to conventional aircraft with the existing global fleet-wide fuel efficiency.

Total Addressable Market

The total addressable market for *airplanes* is measured in terms of total interurban passenger travel by air, projected for every year of analysis (2020-2050), in billion passenger-kilometers. Current adoption[4] was taken as the total passenger-kilometers provided by existing intermediate generation aircraft, in the single-aisle and twin-aisle categories.

Projected adoption of fuel-efficient aircraft was based on the expected production of intermediate generation aircraft, according to published delivery rates of major suppliers.[5] Delivery rates were assumed fixed for each aircraft type.

Adoption Scenarios

Impacts of increased adoption of *airplanes* from 2020-2050 were generated based on three growth scenarios, which were assessed in comparison to a *Reference* Scenario where the existing fraction of higher-efficiency aircraft remains constant.

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[1] According to Airbus, belly freight is about 52 percent of all air freight.
[2] Including the 787, 777X, and 737MAX family of Boeing, and the A320neo family, A330neo family, and A350XWB of Airbus.
[3] Also called "winglets" or "sharklets", these devices cannot be installed on all older aircraft due to lack of sufficient wing strength and other limitations.
[4] Current adoption is defined as the amount of functional demand supplied by the solution in the base year of study. This study uses 2014 as the base year due to the availability of global adoption data for all Project Drawdown solutions evaluated.
[5] Delivery of a single-aisle aircraft is assumed to provide 247 million passenger-kilometers, and a twin-aisle aircraft 840 million passenger-kilometers, of adoption.

- *Plausible* Scenario: Fuel burn is improved by 15 percent, Boeing and Airbus supply aircraft at their published rates, and aircraft older than 24 years are retired.
- *Drawdown* Scenario: Aircraft delivery rates and retirement remain the same as in the *Plausible* Scenario. However, a third supplier is included that produces new, comparable single-aisle aircraft by 2025 and twin-aisle aircraft by 2035.[6] Additionally, fifty aircraft are retrofitted annually.
- *Optimum* Scenario: This scenario differs from the *Drawdown* Scenario in only two key ways: 1) efficient aircraft are assumed to take more passengers (a higher load factor of 90 percent, compared to 80 percent in other scenarios); 2) fuel burn is reduced by 18.3 percent. Everything else remains the same as in the *Drawdown* Scenario, including the existence of an additional supplier.

Emissions Model

Emissions for each scenario were estimated using the fuel emissions factor taken from the Intergovernmental Panel on Climate Change (IPCC) guidelines, and applied to fuel consumption data from the International Council on Clean Transport (ICCT).

Financial Model

Costs of adopting the intermediate generation aircraft are reported as the additional cost compared to adopting aircraft with average fleet efficiency. For each intermediate generation aircraft, an equivalent conventional aircraft was priced and the price difference was derived.[7] The average difference for single-aisle aircraft was around US$11 million,[8] and that of twin-aisle was US$40 million.[9] Operating costs, which included only fuel costs (other costs were assumed equal in conventional and solution aircraft), were derived using historical data from the International Energy Agency (IEA).[10] The solution's operating costs were reduced by the efficiency improvements noted above.

Integration

To prevent double-counting, steps were taken to ensure that the total travel demand of all non-urban passenger Transport Sector solutions remained below the projected total non-urban travel demand.

Results

In the *Plausible* Scenario, a potential reduction of 5.05 gigatons of carbon dioxide-equivalent greenhouse gas was found from 2020-2050, which corresponds to a 63 percent adoption rate by 2050. Net costs over that time would be US$662 billion above the conventional approach. Efficiency improvements are estimated to bring operating savings of US$3.2 trillion, however. For the *Drawdown* Scenario, the emissions avoided amounted to 5.2 gigatons with 80 percent adoption; the *Optimum* Scenario would result in 6.5 gigatons of emissions reduced.

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[6] This additional manufacturer can represent any or all of numerous nascent options, such as COMAC of China or the UAC of Russia. It produces around 5 percent of all efficient aircraft annually.

[7] For instance, the Airbus A320neo was considered a more efficient replacement for the A320, and the Boeing 777X-9 was considered a replacement for the 777-300ER. These relationships were determined through web searches for each efficient model.

[8] All monetary values are presented in US2014$.

[9] It is assumed that this differential represents the retrofit costs for each aircraft type, and acknowledged that airlines often pay different prices than the list prices due to negotiations that occur with the manufacturers.

[10] Ten years (2008-2017) of fuel prices were averaged, and this fixed average was used for the future projections.

Discussion

The use of more efficient aircraft is desirable for airlines in times of higher fuel prices. It would have direct bottom-line impacts, as fuel often represents a third of operating costs. For much of 2016, however, fuel prices were low, and there is no assurance that prices will return to their previous levels of almost three times higher. Nevertheless, Project Drawdown's calculations indicate a large buffer in operating savings and marginal costs that make the investment in fuel-efficient aircraft financially viable for airlines at lower fuel prices. Using *Jet A* fuel prices of March, 2017, the operating savings are still high at US$1.2 trillion for the *Plausible* Scenario.

Limitations

There are limitations to this approach. For example, the potential of other technologies being implemented was excluded in this study.[11] Also, the *Reference* Scenario conservatively assumes fixed fleet efficiency. These limiting assumptions were made to show the impact of existing technologies on the airline industry. The results indicate that airlines have a role to play in the planet reaching the point of drawdown.

[11] The potential for open rotor engines could be large, but estimates seem to indicate availability in the 2030s onwards.

1 LITERATURE REVIEW

1.1 AIR-PASSENGER AND AIR-FREIGHT TRAFFIC IN THE WORLD

Commercial aviation has a reasonably brief history as a global transport mode. The first commercial trip by airplane was achieved in 1914, in Tampa, Florida. Percival Elliot Fansler, the businessman who promoted the journey wrote that ‘instead of playing around with jazz trips, we can start a real commercial line from somewhere to somewhere else’. (In Flight, 2014) The airboat that operated this voyage carried the pilot and only one passenger. The ticket was sold in auction in 10,000 USD in today´s money (In Flight, 2014). This event marked the moment when an aviation industry was visualized beyond the realm of daredevils and inventors, and it was turned into a proper form of transport. Since 1960, the traffic of passengers carried by aircraft grew at nearly 9% per year until 1997, when this trend slowed to 5% as the industry began to mature (IPCC, 1999).

Nowadays, the aviation industry is a rising source of environmental concern, at local, regional, and global levels. In the mobility sector, after road transport, the biggest contributor to climate change is aviation. Compared to motorcars, the energy consumption and CO2 emissions from the aviation industry are low. However, its rapid expansion is causing increasing alarm. According to Lee Chapman (2007) the effects of flying were overlooked in the Kyoto protocol of 1992. In the international treaty, no targets were established regarding the environmental impact of global aviation in greenhouse gas emissions other than CO2 from domestic flights (Chapman, 2007). The European Emissions Trading Scheme (EU ETS),the world’s first major carbon trading system was established in 2003, and also ignored the aviation sector, at least until 2012 when the sector was finally included, leading to extensive regional and international legal resistance from airlines and states (Gonçalves, 2013). Aviation was not formally addressed at the Paris Agreement of 2015 despite its broad and ambitious goals (Finamore & Lin, 2016). Global resistance to including aviation in the EU ETS stimulated discussion and eventually led to the creation of a global carbon trading system, CORSIA[12], which is to take effect in 2021, but only for international flight emissions above the 2020 level (ICCT, 2017). There will also be an adoption of more strict standards for aircraft design from 2020, but many existing in-production aircraft already meet the requirements (ICCT, 2016).

What is the state of operational approaches such as air traffic control in the world? What are the projections of airframe technologies and engine efficiency in the future? What are the targets regarding reductions in CO2 emissions from the aviation industry? The literature review analyzes the current state of airplane fuel efficiency around the world. This review is centered on the impact of growth in airfreight with respect to its CO2 footprint. It examines variables, examples, operational patterns, and technologies that shape the aviation industry globally.

[12] CORSIA: Carbon Offset and Reduction Scheme for International Aviation

The impact of fuel consumed by aviation depends largely on the length of flight. Nowadays, definitions of flight lengths in the world lack agreement. The United Kingdom Department for Environment, Food & Rural Affairs, and the Department of Energy and Climate Change have proposed three definitions of categories based on ranges of typical one-way flight distances: Domestic flight (Los Angeles to San Francisco), Short-haul international flight (Tokyo to Beijing), and Long-haul international flight (New York City to Sao Paulo). In geographically large countries such as China and United States, it may be pertinent to categorize some domestic flights as short haul.

In 2005 the global average flight length was 1,239 km (ICAO, 2006), and the average of 7 sources spanning 2006 to 2015 is 1,791km. The highest quantity of fuel during a flight is utilized during the ascent; therefore short-haul flights use more fuel per km compared to the consumption in longer flights (Chapman, 2007). As the flight time increases, large quantities of fuel are carried. Thus, the weight of the plane rises and burns more fuel (Chapman, 2007). The expanding numbers of the so-called 'budget' airlines (or Low Cost Carriers) provide services of short distances (IPCC, 2007). Although these airlines appear to focus on leisure-oriented routes, business travelers are using these services as well (Mason, 2000). Older, less fuel-efficient aircraft more commonly service these flights (IPCC, 2007).

Air travel is estimated to have caused about 2.42% of manmade CO2 emissions in 2011 (BDL, 2014), and is one of the fastest growing sources of emissions worldwide. This figure does not, however, include the potentially significant impact that non-CO2 emissions can have on the climate. In addition to CO2, nitrous oxides, sulphur oxides, water vapor and soot are emitted, all which have different impacts on the net radiative forcing[13] of aviation (including indirectly through interactions with ozone, methane, contrails[14] and clouds). The effects of these non-CO2 emissions are highly dependent on location, ambient temperature, altitude, time of year and concentrations of other gases in the atmosphere, and hence are very difficult to estimate for aviation. These effects have been estimated to have a total radiative forcing effect at least 90% higher than the effect of CO2 alone, in aggregate (Sensen et al, 2005).

Kerosene is the primary source of energy for civil aviation, and the dependence on fossil fuels is likely to persist in the coming decades (IPCC, 2007). Fuel efficiency is a major consideration for aircraft operators. From 2003 to 2016 fuel represented an average of 27% of total operating costs for airplanes (ICAO, 2016). A Boeing 747 plane from London to Singapore (long-haul) utilizes 1,500 barrels of oil each way, which is equal to 242,000 liters of fuel (In Flight, 2014). This means that an economy passenger consumes five barrels of oil each way, and a first class passenger would consume nine barrels (In Flight, 2014).

[13] Radiative forcing is a measure of the importance of a potential climate change mechanism. It expresses the perturbation or change to the energy balance of the Earth-atmosphere system in watts per square meter (Wm^{-2}). Positive values of radiative forcing imply a net warming, while negative values imply cooling.
[14] Contrail - condensation trail (i.e., white line-cloud often visible behind aircraft)

Table 1 Fuel Impact on operating cost (IATA, 2016)

Year	% of Operating Costs	Average Price per Barrel of Crude (US$)	Break-even Price per Barrel (US$)	Total Fuel Cost (US$ Billions)
2003	13.6%	28.8	23.7	44
2004	17.3%	38.3	34.7	65
2005	22.2%	54.5	52.0	91
2006	28.1%	65.1	68.1	127
2007	29.8%	73.0	81.7	146
2008	35.7%	99.0	83.4	204
2009	28.3%	62.0	59.1	134
2010	28.3%	79.4	89.8	152
2011	30.8%	111.2	116.1	191
2012	33.1%	111.8	117.1	228
2013	33.1%	108.8	114.8	230
2014	31.6%	99.9	107.3	226
2015	27.5%	53.9	72.0	181
2016 (Forecast)	19.7%	45.0	64.3	127

Air transport presents the highest growth amid all transport modes (Boeing, 2015). In 2013, nearly one-hundred years after the first commercial trip by airboat in Florida, 3.1 billion passenger tickets were sold across the world, compared to 642 million in 1980 (In Flight, 2014). The International Civil Aviation Organization (ICAO, 2006) suggests that aviation scheduled traffic, which is measured in revenue passenger-km, grew from 2001 to 2005 at an annual rate of 3.8%. According to the International Civil Aviation Organization (2012) domestic markets grew by 3.9 percent over 2011. This growth was mainly determined by demand for domestic air travel in the Latin America/Caribbean, Asia/Pacific, and the Middle East regions. Significant contributions to these regional results came from countries such as China, Australia, Indonesia, Mexico and Saudi Arabia and Japan.

Forecasts predict a global average annual passenger traffic growth of around 6%, with passenger traffic doubling in 15 years (Airbus, 2015). Freight traffic is expected to grow at a faster rate that passenger traffic over the next 25 years (Airbus, 2015; Boeing, 2016). According the German Aviation Association (BDL, 2014), a freighter uses less fuel per 100 kilometers than a passenger aircraft, mainly because its space can be managed more efficiently. A report from the International Air Transport Association (IATA) showed that demand, measured in freight tonne kilometers (FTKs), rose 6.1% from 2015 to 2016. The same report found that freight capacity, measured in available freight tonne kilometers (AFTKs), increased 4.7% in the same period.

Passenger Load Factor (PLF) and Freight Load Factor (FLF) are critical metrics in aviation. Airlines try to maximize these factors in order to take decisions about frequency, pricing, and capacity flights (MIT, 2016). Load factors are the proportion of airline output that is consumed. Load factor for a single flight are calculated by dividing the number of passengers by the number of seats, and the ratio is multiplied by 100 to obtain a percentage (MIT, 2016).

Table 2 Air Freight Market and Passenger Traffic Market in 2016. Freight Load Factor and Passenger Load Factor (IATA, 2016)

Region	Total freight traffic market shares by % of FTK (September)	Freight Load Factor (September)	Total passenger traffic market shares by % of RPK (January)	Passenger Load Factor (January)
Global	100%	43.7%	100%	78.8%
Asia Pacific	38.9%	54.7%	31.5%	78.5%
Europe	22.3%	44.9	26.7%	77.9%
North America	20.5%	33.9%	24.7%	80.7%
Middle East	14.0%	41%	9.4%	77.9%
Latin America	2.8%	37.9%	5.4%	82.8%
Africa	1.5%	23.8%	2.2%	71.3%

A significant percentage of air freight flows as 'belly' cargo in passenger airlines. Belly capacity is increasing faster than cargo traffic. The constant passenger traffic growth and the under-floor freight volume explain this trend (Airbus 2016). According to the report *Mapping Demand* (Airbus, 2016) in 2015 around 52% of all air freight traffic was carried in the baggage holds of passenger airplanes. It is expected that by 2035 the percentage will increase to 62%. In the United Kingdom context, from 2005 to 2006 the proportion of airfreight tonne-kms moved in the bellyholds of passenger aircraft averaged 95% (Chapman, 2007). However, cargo intensive flows and belly capacity availability are not necessarily suitable to routes such as trans-Pacific itineraries (IPCC, 2007). This situation motivates the implementation of dedicated freighter operations. The Intergovernmental Panel on Climate Change (2007) suggests that where passenger and freight movement is combined in the same airplane, establishing a fair allocation of CO_2 emissions between the two types of traffic is difficult.

In recent years, the aviation industry has experienced a substantial growth in dedicated express cargo services. Express carriers and e-commerce represent a strong growth scenario, predominantly in emerging economies. For instance, the express carrier market in China is thriving, with 50-70 aircraft flying today, compared with nearly 400 aircraft for express carriers on domestic operations in the United States (Airbus, 2016). In 2012 the top five airlines classified by total scheduled freight tonnes carried were: 1) Federal Express (6.9 million), 2) UPS Airlines (4.6 million), 3) Emirates (2.0 million), 4) Korean Air (1.5 million) and 5) Cathay Pacific Airways (1.4 million) (IATA, 2016).

There are, however, capacity constraints at many of the most heavily used airports. 39 out of 47 aviation mega cities (major airport cities) are schedule-constrained today (Airbus, 2015). Nevertheless, there are signs that airlines can re-configure their networks to avoid congestion and still expand services to meet growing demand (Evans, & Schäfer, 2014). There are also many airports in development to meet the expected expansion in global connectivity. China, for instance, is building 70 new airports, in addition to expanding 100 existing airports (In Flight, 2014).

1.2 AIRCRAFT: CURRENT STATE AND PROJECTIONS

The aviation industry is part of the world economic system. Nowadays two global manufacturers share the market in terms of units ordered: Airbus (58%) and Boeing (42%) (Airbus, 2015). According to Boeing (2015) in 2014 the passenger airplanes in the world were 19,880, and the freighter units in service were 1,720; thus, a total of 21,600 aircraft. Airbus (2016) reports that the fleet in 2016 of passenger aircraft is 18,019, with 1,564 freighter airplanes. According to these numbers the total market in 2016 has reached 19,583 units.

In 2035 it is expected a demand for 37,708 new passenger aircraft, while the prediction for freighter aircraft is to reach 2,111 new deliveries in the same year (Airbus, 2016). This prognostication for new deliveries is 39,819 in total. According to Boeing (2016) the future fleet in 2034 of passenger and freighter airplanes will be 40,630 and 2,930 respectively. This means 43,560 in service by 2034. The airplane market sector is defined by the seat capacity of passenger aircraft and in tonnes (capacity) for freighter. These definitions are important due to the relationship between the weight of airplanes and the consumption of fuel. What follows is a classification of airplanes that are defined by their seat and weight capacity (Boeing, 2016).

1) **SINGLE AISLE PASSENGER AIRPLANES** (up to 150 passengers): Examples, Boeing 737-100 through -500, and Airbus A318, A319, A320, A321
2) **SMALL WIDEBODY PASSENGER AIRPLANES** (200 to 340 seats): Examples, Airbus A300, A310, and Airbus A330-200, -300, -800, -900
3) **MEDIUM WIDEBODY PASSENGER AIRPLANES** (300 to 400 seats): Examples, Boeing 787-10, and Airbus A350-1000
4) **LARGE WIDEBODY PASSENGER AIRPLANES** (more than 400 seats): Examples, Boeing 747-100 through -400, and Airbus A380
5) **SMALL FREIGHTER** (Less than 45 tonnes): Examples, Boeing 737 and Boeing 707
6) **MEDIUM FREIGHTER** (40 to 80 tonnes): Examples, Airbus A300 and Boeing 787
7) **LARGE FREIGHTER** (more than 80 tonnes) Examples: Airbus A350 and Boeing 777

The Airbus Global Market Forecast (2015) suggests that single aisle aircraft is the sector that requires significant numbers of replacement, and despite the fact that single-aisle represent 71% of demand in terms of units, wide-bodies represent 55% of value. This market trend is considered in the configuration of the addressable market of the solution.

Table 3 Total Aircraft Market (Airbus, 2015)

Region	Start Fleet 2016	End Fleet 2035	20-year new deliveries	Converted	Remaining
Africa	656	1,450	1,000	68	382
Asia/Pacific	5,961	15,463	13,458	502	1,503
CIS	890	1,769	1,226	36	507
Europe	4,482	8,102	6,587	196	1,319
Latin America	1,373	3,036	2,567	55	414
Middle East	1,160	3,113	2,429	33	651
North America	5,060	6,886	5,807	345	734
World	**19,583**	**39,819**	**33,074**	**1,235**	**5,510**

Table 4 New deliveries prognostication 2016-2035 (Airbus, 2015)

Category	Africa	Asia/Pacific	CIS	Europe	Latin America	Middle East	North America	Total
Single Aisle	757	9,074	1,003	4,993	2,027	952	4,725	23,531
Medium	230	3,689	191	1,412	521	1,024	997	8,064
Very Large Aircraft	13	695	32	182	19	453	85	1,479
Total	**1,000**	**13,458**	**1,226**	**6,587**	**2,567**	**2,429**	**5,807**	**33,074**

As mentioned earlier, air travel is estimated to cause 2.42% of CO2 emissions in the world (BDL, 2014), and the dependence on fossil fuels is likely to continue in the future. The environmental impact of aviation demands innovative models for sustainable flying.

1.3 Fuel Efficiency Improvement Approaches

Among the contemporary approaches for improving fuel emissions efficiency (for both new and in-fleet aircraft) are, 1) the adoption of biofuels, 2) changed operations for control of aircraft movement (ascent and descent), 3) airframe improvements, and 4) engine configuration to reduce negative effects such as CO2 emissions and noise. There are many efforts to stimulate these innovations, none more known than the use of market-based measures such as the EU Emissions Trading Scheme and the CORSIA emissions trading scheme already mentioned. These carbon trading mechanisms seek to encourage greater emissions efficiency via the approaches detailed below.

1.3.1 Biofuels

Biofuels, or more generally sustainable aviation fuels, are bio-derived aviation fuels (coming from a wide range of biological sources). Biofuels are seen as the key to decarbonizing the aviation sector which has very specific fuel requirements due to the high energy density needs and the variety of environments experienced by flights. While the road transport sector has other non-liquid fuel options available such as electricity, aviation has no alternative at this stage (IATA. 2015). Examples of alternative biofuels currently under investigation are used cooking oil, Jatropha plant oil, Camelina plant oil, sugarcane, and Algae fuel processed through bioreactors (IATA, 2016). Additionally, wastes such as waste oils, forestry residue and municipal solid wastes are being studied as potential feedstocks owing to their superior ability to reduce lifecycle emissions (and their lack of competition with food sources) (Yilmaz & Atmanli, 2017).

One of the recommendations from the International Air Transport Association is to encourage jet fuel incentives equivalent with road biofuels. The panorama in some contexts is positive. Numerous worldwide activities are ongoing in attempts to expand alternative jet fuel use. Already 2,000 commercial flights in 2015 were flown on alternative fuels, and several major airlines, including United, Lufthansa and Cathay Pacific have multi-year agreements to use sustainable aviation fuel. Additionally, numerous multi-stakeholder groups as well as national roadmaps have been developed in the US, EU, Japan, UAE, Canada and Brazil to encourage sustainable aviation fuel use (US Department of Energy, 2017).

The introduction of biofuels could mitigate part of carbon emissions from aviation. However, the costs and emissions impacts are highly dependent on feedstock and processing and the availability of infrastructure (US Department of Energy, 2017; Hileman & Stratton, 2014). Alternative fuels for aircraft need to be compatible with aviation kerosene and to meet a comprehensive performance and safety specification. Some alternative fuels already meet this requirement. According to Chapman (2007) improving airframe and engine design to intensify fuel efficiency is a priority.

1.3.2 Aircraft operations

The operational system for aviation is mainly managed by air traffic management restrictions. According to the Intergovernmental Panel on Climate Change (2007), if aircraft were to operate for minimum fuel use, the following limitations would be modified: taxi-time would be reduced; aircraft would fly at their optimum cruising altitude for load and mission distances, and aircraft would fly minimum distance between departure and destination. In reality, there are many other restrictions and concerns that make aircraft deviate from the optimal trip profile.

We have seen that the highest quantity of fuel during a flight is utilized during the ascent and descent of airplanes. One adoption for operational systems is the Continuous Descent Approach (Optimized Profile Descent). It is a method of “late descent” developed in Germany that contributes to save kerosene and CO2 emissions. The method starts with calculations from the pilot on authorization by the controller after leaving cruise altitude. The higher the flight altitude, the less fuel the aircraft uses. Therefore, the plane remains at high altitudes for as long as possible before approaching the airport on a continuous descent. Simulated approaches for small aircraft at Munich Airport have demonstrated that it is possible to save up to 85 liters of fuel per flight (BDL, 2014).

Airlines can save fuel from continuous descent by determining the right fuel for ground-based traffic (BDL, 2014). Load planning is important. For instance, compared to a car (1.5 persons occupancy) with an average passenger load factor of 30% per cent and 50.7% for high-speed trains, the German aviation industry achieved in 2013 a passenger load factor of 81.3% on average. This number was higher than the global figure of 79.7% (BDL, 2014). Higher load factors result in lower fuel usage per traveler.

1.3.3 Airframe Improvements

Airframe Technologies such as Split Scimitar Winglets, sharklets or regular winglets improve the aerodynamics of aircraft by reducing drag. This technology can reduce fuel consumption by up to 6% compared to older regular wings. Newer wings however, such as those on the Boeing 787 and the Airbus A350 use raked wingtips, which have the same impact as winglets, but are a continuation of the main body of the wing.

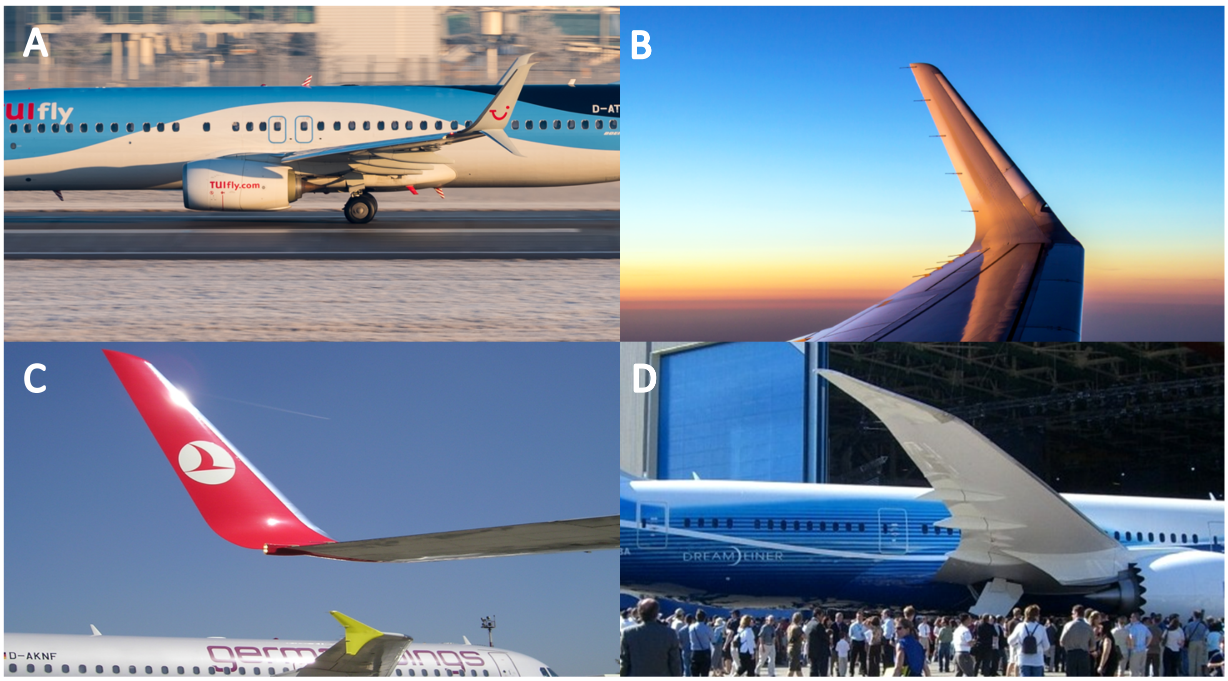

Figure 1 Examples of Wings with Aerodynamic Improvements: A. Split Scimitar Winglets, B. Sharklets, C. Winglets, D. Raked Wingtips. (Wikipedia)

Imitating the shark is part of new strategies to improve fuel efficiency. Lufthansa, and Airbus are currently studying the fluid dynamics of sharkskin mockups on aircraft. Their goal is to come up with an automated process of applying artificial sharkskin to the surfaces of an aircraft. This would reduce energy consumption by 1% (BDL, 2014). Additionally, using lighter materials, particularly composites, can dramatically reduce the amount of fuel needed for flight. Boeing and Airbus have increased their usage of composites in more recent aircraft from around 10% to 50% of the aircraft weight. Lower weight approaches in aircraft have been explored in the project “Clear-out”, every single MD-11F freighter in the Lufthansa Cargo fleet was removed of unnecessary weight. Each plane weighs around 35 kilos less at takeoff. In total, this measure reduced CO2 by around 250 tonnes at Lufthansa (BDL, 2014).

1.3.4 Engine Improvements

The main objectives of engine developments are to reduce weight, noise, emissions, and aerodynamic drag. Carbon fiber materials are very strong and are only half the density of steel. Rolls Royce is using this material in the development of its latest generation of engines. Each engine will weigh 700 kilograms less than previous designs (BDL, 2014). Engine developments require satisfying fuel efficiency and regulatory needs in terms of noise, NOx, particulate matter, and, as of 2016, carbon emissions. In addition, these changes should allow aircraft to remain commercially viable for 30 years or more (IPCC, 2007).

1.4 ADOPTION PATH

The adoption path is centered on exploring retrofitting options of older, less efficient airplanes with more efficient technologies. This approach is based on the report Technology Roadmap (IATA, 2013). It includes an analysis of 76 individual technologies that are designed to improve the fuel efficiency of an aircraft. The results are representative for diverse time horizons (retrofits of current in-service aircraft, new aircraft families before and after 2020, and upgrades of serial production types). From these seventy-six technologies, ten are suitable for retrofit programs. Nowadays blended winglet technology is one of the most visible fuel-saving, performance-enhancing technologies in the world (NASA, 2010). As seen in the section *Fuel Efficiency Improvement Approaches* blended winglets are arrow-shaped surfaces attached to the tip of each wing. The system enhances the overall efficiency of airplanes, saving fuel by reducing drag. This technology was chosen for exploring a global adoption for aircraft fuel efficiency.

Table 5 Technologies applied in aircraft retrofit program (IATA, 2013)

#	Group	Concept	Technology	Applicability to aircraft program	Fuel Reduction Benefits	Development Status *	Availability of technology (calculated)	Average Fuel Benefit
1	Aerodynamics	Advanced wingtip devices	wingtip fence	Retrofit	1 to 3%	9	2012	2%
2	Aerodynamics	Advanced wingtip devices	Blended winglet / Sharklets	Retrofit	3 to 6%	9	2012	4.50%
3	Aerodynamics	Advanced wingtip devices	Raked wingtip	Retrofit	3 to 6%	9	2012	4.50%
4	Aerodynamics	Drag Reduction Coatings	drag reduction coatings	Retrofit	< 1%	9	2012	0.50%
5	Aerodynamics	Drag Reduction Coatings	Turbulent flow drag Coatings (Riblets)	Retrofit	1%	8	2015	1%
6	Aerodynamics	Drag Reduction Coatings	Aircraft Graphic films	Retrofit	1%	9	2012	1%
7	Cabin	High power LED's for cabin lighting		Retrofit	< 0.5%	9	2012	0.25%
8	Cabin	Wireless/optical connections for Inflight-entertainment		Retrofit	< 0.5%	9	2012	0.25%
9	Cabin	Light weight cabin interiors		Retrofit	1 to 5%	9	2012	3%
10	System	Zonal dryer		Retrofit	< 1%	9	2012	0.50%

* - the Technology Readiness Level, 9 is the most mature level

The winglet concept has become a common retrofitting option for single aisle aircraft. The Airbus Global Market Forecast (2015) suggests that single aisle aircraft are the sector that requires significant numbers of replacement. This sector represents 71% of demand in terms of units (Airbus, 2015). The two families of aircraft that concentrate the global market of single aisle sector are Airbus 320 series, and Boeing 737 series.

Wingtip devices (Winglet as defined by Boeing and Sharklet as defined by Airbus) typically produces a 3- to 6-percent fuel savings, which is translated to thousands of gallons of fuel saved per plane, per year (NASA, 2010). According to Airbus (2015) over 4,000 A320 family in-service airplanes are eligible to be retrofitted with Sharklets. The rate for equipping older Airbus320 with wing-tip retrofit systems is 20 aircraft per month (FlightGlobal, 2014), which means that the annual rate is 240 aircraft retrofitted per year, at a 10-day period of installation. The manufacturer Aviation Partners Boeing has been retrofitting single aisles aircraft at a rate of 400 aircraft per year (NASA, 2010), with an average of 5 days for installation (APB, 2016). In 2015 Aviation Partners Boeing had installed over 6,100 in-service aircraft around the world. Most of these installations were performed in the Boeing 737 series (APB, 2016).

Table 6 Current adoption in single aisle aircraft (Airbus, 2015 and Boeing 2016)

Item	Number of aircraft	Billion Pass-km per year
Airbus 320 series in operation (2014)	6,982	1,735
Boeing 737 series in operation (2014)	7,826	1,944
Total single-aisle aircraft of Airbus (320 series) and Boeing (737 series) in 2014	14,808	3,679
Aircraft already adapted with Sharklet Systems in Airbus 320 series up to base year	2,982	741
Aircraft already adapted with Blended Winglet Systems in Boeing 737 series up to base year	5,978	1,485
Current adoption of Sharklet/Blended Winglet Systems in single aisle aircraft	**8,960**	**2,226**

The current solution relies on retrofitting existing single aisle aircraft with winglets as an adoption for reducing fuel consumption in commercial aviation. The numbers above mentioned are taken into account in our methodology. We also consider that other advanced wingtip devices will become standard on all future aircraft as indicated by the great attention paid in the airline industry to the Boeing 787 and Airbus A350 aircraft which have been heralded as the most advanced commercial aircraft due to, among other things, their improved wing design which include raked wingtips. Increased fuel prices in recent years have been a large incentive in the industry to install these devices considering that fuel costs approaches a third of all airlines costs. In 2016, international fuel prices dropped, so this might result in a reduction in adoption of retrofits, but the new wing designs are likely to become standard on new aircraft. The intense competition among airlines will continue to motivate improving their operating efficiency, and this may help maintain adoption of advanced wingtip devices. The following section will review the advantages and disadvantages of airplane fuel efficiency.

1.5 Advantages and disadvantages of Airplane Fuel Efficiency

Demand for air travel is only set to grow. As indicated earlier, year on year growth has been above 5% in passenger-km terms, and is driven by increased wealth, which is likely to continue in developing countries with huge populations. An advantage of airplane fuel efficiency is that it allows demand growth to continue while reducing the environmental impact (both climate and otherwise). Other solutions, such as telepresence and high speed rail encourage a reduction in air travel, but in many cases, when there is a premium on physical presence elsewhere, and travel is over long distances, there are few alternatives to air travel. It is also advantageous that some of the efficiency measures described result in lower costs for the airlines, and so there is a financial incentive for them to invest in more fuel efficient aircraft; this is good for business and good for the climate (except when fuel prices are so low and airlines have reduced incentives). It might also be the case that the strong aviation industry drive towards better biofuels can have an external effect in other sectors such as road transport.

Unfortunately there are some challenges to adoption of more efficient air travel systems. The measure with the greatest potential in the sector, biofuels, is not yet ready for broad adoption, may have a negative impact on food production, and may not results in a net zero lifecycle emissions[15] without much more research. Other measures such as airframe improvements often require taking aircraft out of service (where costs accumulate both for the retrofitting process and for the loss of revenue during retrofit period). Newer, more efficient aircraft take long to infiltrate established fleets since the lifetime of commercial aircraft is generally above 20 years. Establishing the acceptability of new measures is often slow due to the large number of players involved (e.g. airlines, airports, governments at all levels, research institutes, ground service providers, air traffic control, aircraft manufacturers, engine manufacturers, and multilateral organisations), and also because of the safety critical needs of commercial flights. Finally, as with many efficiency solutions, there is a risk of rebound demand cancelling out all gains in efficiency.

[15] Even if all fuels were biofuels, the CO2 cycle may be net zero, but the other emitted compounds could still cause warming due to their radiative forcing in the troposphere and stratosphere

2 METHODOLOGY

2.1 INTRODUCTION

All Project Drawdown solutions are modeled with an underlying functional unit that measures the fundamental value being provided to the public (and the Total Addressable Market, TAM and adoption), and with implementation units representing the actual product or service installed or purchased that would provide that value. Sometimes the implementation unit of the old conventional technology doesn't match perfectly with that of the solution, and in those cases, the model uses two different implementation units with annual and lifetime outputs adjusted appropriately. It would be expected that both implementation units provide the same type of functional unit however.

For this solution, like many transportation solutions, the functional unit is billion passenger-km[16], and the implementation unit is an average aircraft (either inefficient conventional or efficient solution aircraft)[17]. As both single aisle and twin aisle aircraft are included, relevant variables are weighted by the market shares of each aircraft class based on assumptions on passenger-km provided by each.

This solution is approached by analyzing adoption of either 1) retrofit systems for existing aircraft or 2) recent high efficient models. In order to know the average passenger-km per year per single aisle aircraft we need to estimate the distances and capacities of aircraft in terms of the following factors: 1) load factor, which is the proportion of airline output that is consumed 2) average fleet-wide working hours per day, 3) average time in hours for the aircraft to empty passengers, get cleaned and refueled, board new passengers and taxi to and from the runway, which is the time between consecutive flights, 4) average stage length in kilometers of the operating fleet (including typical rerouting), 5) average cruise speed, and 6) impact of operational delays (weather and unplanned maintenance).

Aircraft sizes were limited to single and small/medium twin aisle types. As seen earlier, the two families of aircraft that dominate the global market of single aisle sector are Airbus 320 and Boeing 737 families. Therefore, representative efficient single aisle aircraft were taken as the A320neo series, and the B737MAX series, the most efficient branch of each series. For the small/medium twin aisle, the representative efficient models are the Airbus 350, the Airbus 330neo, the Boeing 787 and Boeing 777X.

2.2 DATA SOURCES

Several sources were used for the most data-heavy aspects of the methodology, with an emphasis on the aircraft manufacturers: Boeing and Airbus. TAM data, aircraft class shares, and load factors

[16] A "passenger-km" is the functional unit of this and many passenger transport solutions, and equals one passenger transported 1 kilometer.

[17] The methodology calls for the averaging of variables for single aisle and twin-aisle aircraft, therefore every 4 aircraft equivalents would represent approximately 3 single aisle and 1 twin aisle aircraft.

estimates came from market data sources.[18] These market data were also used to weight certain variables that differed between single and twin aisle aircraft (such as seating capacity, range and speed). Similarly, aircraft production and delivery (historical and planned) as well as pricing data for each of the two major manufacturers came from the manufacturers' publications on efficient and other aircraft in the classes of this analysis.[19] Additional web searches supported data on production by aircraft family.

Aircraft vehicle data (such as capacity, speed, lifetime, and maintenance data, to be used for, inter alia, estimating annual work done and lifetime capacity) were obtained from industry sources.[20]

As fuel consumption is the focus of this analysis, several scientific sources were used to estimate the fuel consumption of older less efficient and newer aircraft.[21]

2.3 Adoption Scenarios

Two different types of adoption scenarios were developed: a Reference (REF) Case which was considered the baseline, where not much changes in the world, and a set of Project Drawdown Scenarios (PDS) with varying levels of ambitious adoption of the solution.

2.3.1 Reference Case / Current Adoption

For the Reference (REF), adoption is fixed at the current adoption[22] (in percent) of the market. That is, the current percent of total passenger-km provided by efficient aircraft remains constant throughout the study period to 2050. As the market grows, the total number of aircraft adopted grows equally to maintain the percent adoption at its starting value in 2014. It is acknowledged that this, in reality, may not be a "business as usual" considering changes taking place worldwide, but it allows measurement of the impact of recent and even more aggressive policies on greenhouse gas emissions.

2.3.2 PDS Scenarios

For this solution, it is recognized that the aircraft industry is production-constrained. Airbus and Boeing, the two dominant manufacturers of the vast majority of aircraft sold: single and twin aisle aircraft seating between 120 and 500 passengers are able to produce around 1600 aircraft annually cumulatively.[23] Yet they had, in June 2018, a 12,900-aircraft back log or over 8 years of production, and

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[18] Market data mostly came from: IEA (2016), ICCT (2012), IATA (2016b), Boeing (2015), Airbus (2015b) and calculations based on Swan & Adler (2006). Other supplementary sources also were used.

[19] Order and delivery data came from Airbus (2018), and Boeing (2018), aircraft pricing data came from Airbus (2017) and Boeing (2017).

[20] The most important aircraft data sources were Team Aero (2006, 2008a, 2008b, 2010)

[21] Fuel consumption sources were mainly published studies specifically of aircraft fuel consumption and the potential impact of new technologies and approaches, including: Schäfer et al (2016), Tecolote Research (2015), ICF International (2015), ICCT (2012) and Randt et al (2015)

[22] Current adoption is defined as the amount of functional demand supplied by the solution in the base year of study. This study uses 2014 as the base year due to the availability of global adoption data for all Project Drawdown solutions evaluated.

[23] There are other commercial aircraft manufacturers, but, except for Antonov of Ukraine, they generally make smaller aircraft: regional jets, smaller turbo propeller aircraft, business jets, or general aviation aircraft with 1 to 8 seats.

they each project a global demand for over 35,000 new aircraft between 2015 and 2034. This backlog is well known, and so might represent airlines planning far in advance to replace or expand their fleets. This however, coupled with recent actions taken by aircraft manufacturers in China and Russia, indicates that large aircraft manufacture is an attractive business. Incorporated into these scenarios therefore is entrance of a third manufacturer. Additionally, the total number of passengers flown in 2012 was already around 3 billion (ICAO, 2012), yet, compared to 2018, the total passenger-km flown globally is projected to at least double by 2050 (assuming heavy use of alternative methods like high speed rail or telepresence, without which might result in a 4-fold increase). One can therefore expect many new aircraft for fleet expansion.

The PDS scenarios were developed based on the combination of

- Assumptions of efficient aircraft orders and deliveries from Boeing and Airbus,
- Assumptions about a third manufacturer entering and producing comparable aircraft,
- Assumptions of retrofitting of less efficient in-fleet aircraft,
- Assumptions on the efficiency improvement from more efficient aircraft, and
- Assumptions on the global average load factor.

All three PDS scenarios share some common characteristics listed above. Efficient aircraft of Airbus and Boeing are assumed to continue at the maximum rates for each aircraft family identified in web searches even after all current orders for efficient aircraft were fulfilled. Since some orders remained on the order books for less efficient aircraft, these were assumed to be delivered completely within 8 years with a steady transition from more inefficient aircraft to more efficient aircraft. Efficient aircraft are delivered continuously at the maximum rates identified to 2050. Around 2025, a third manufacturer starts producing comparable single aisle aircraft first with production at low levels of around 2 per month, and then ramping up at a similar rate as Airbus in the 1990's. Ten years after that first single aisle delivery, an efficient twin aisle delivery starts with delivery rates again starting low and ramping up.

Other individual assumptions are combined in different ways in each of the PDS scenarios as detailed below.

2.3.2.1 Plausible Scenario

The Project Drawdown Plausible Scenario represents a reasonably aggressive adoption of a solution. With the common PDS characteristics listed above, new aircraft are assumed to provide a fuel consumption reduction equal to 1 standard deviation below the average of the 6 values collected from the literature (that is 13% fuel saving).

2.3.2.2 Drawdown Scenario

The Drawdown Scenario represents a set of modeling assumptions with the aim of achieving drawdown by 2050. For this solution, and with the common PDS characteristics listed above, there is an additional projection of 100 aircraft retrofitted annually[24], and both new and retrofitted aircraft achieving the maximum identified fuel reduction factor of the 6 sources included (18% fuel saving). Finally, the load factor of all solution aircraft is assumed to grow from the global average of 78% to 83% (approximately the US average).

2.3.2.3 Optimum Scenario

The Optimum Scenario is the highest projection that anyone might expect of the solution as defined by Project Drawdown, and may stretch the bounds of reasonableness to be close to technical, social and economic limits. For this solution, in addition to the common PDS assumptions above, there are an additional 1000 aircraft retrofitted annually, and all adopted aircraft are assumed to provide 20% fuel saving with 83% load factor.

2.4 Climate And Financial Impacts

2.4.1 Climate Inputs

The target of the solution is to reduce the fuel consumption of aircraft, and hence this is the basis of the main climate outputs reported. As discussed earlier, radiative forcing is the key effect of greenhouse gas emissions and other aviation outputs in the upper atmosphere. However measuring the actual radiative forcing is very challenging due to the dominance of local effects, temperature and altitude at time of emissions, season and other factors. As a result, only total greenhouse gas emissions avoided are presented in results, and this maintains consistency with the other solutions across Project Drawdown.

The variables used to calculate greenhouse gas emissions avoided are fuel consumed in liters per billion-passenger km of older inefficient and newer efficient aircraft. Fuel consumption for the older and newer aircraft is based on the average consumption across the world, and the reduction expected from the adoption of the solution technologies. This approach therefore takes into account the market weighting by aircraft type for the older aircraft. The type of fuel consumed for all aircraft is Jet A1, and the Fuel Emissions Factor is 2.5 kg CO2-eq per liter, calculated using data from the IPCC (2006).

2.4.2 Financial Inputs

The financial calculations examine the first cost in US$ per aircraft and the operating cost in US$ per billion-passenger km. For this, many inputs estimating annual output and lifetime output per plane, along with first and fuel costs (per aircraft and per functional unit respectively), were calculated. No other operating costs were considered since they were assumed to be the same for both the older and newer aircraft. A lifetime capacity of 9.7 or 9.95 billion-passenger km per aircraft (around 24 years) was calculated depending on the average aircraft load factor used. Fuel costs were based on average fuel

[24] Retrofits are assumed only possible on aircraft under 15 years old

consumption per billion passenger-km and the average cost of fuel over 2008-2017 according to the EIA data on refinery cost (EIA, 2018).

For each solution (efficient) aircraft, the conventional (inefficient) aircraft replaced was identified[25], and both aircraft were priced to obtain the price differential. The average values for single and twin aisle aircraft (US$11 million and US$40 million respectively) were weighted by the market shares of each class to identify a single combined value. This was assumed to be the price of the solution (either a retrofit, or the differential between an older and newer plane) with the conventional price set to zero. This is acceptable in the model since the results only depend on the differentials.

2.5 Assumptions

Many assumptions are made in any modeling exercise, here is no different. Listed below are the most important assumptions, and their justification.

Assumption 1: It is possible to match the improvements on an intermediate generation aircraft (over its predecessor) with a retrofit on that predecessor

- The improvement of recent aircraft models like the Airbus A350 and A320neo and the Boeing B737MAX and B777X are often additions of some of the same changes that are possible on older aircraft like better engines, wingtip devices, and lighter interior equipment. This assumption equalizes the decision to purchase a more efficient new aircraft over a less efficient new aircraft with the decision to retrofit a less efficient in-service aircraft over doing no retrofit. In both cases, the additional investment cost is assumed the same (the difference in list price between the more efficient and less efficient new aircrafts). It is acknowledged that in reality, there are some changes that will not be retrofitted onto old aircraft like extensive fuselage changes, and the retrofit costs are highly variable, and need to be added to the financial cost of taking aircraft out of service. These additional considerations have been ignored.

Assumption 2: Acceptable results can come even if the universe of aircraft considered is single aisle and small/medium twin aisle aircraft (that is, turbo-props, regional jets and very large aircraft are not considered), and data on these included classes is averaged.

- The vast majority of all commercial aircraft (passenger or freight) are single aisle (at 56% according to Cooper et al, 2017), then the small/medium twin aisle (these dominate the “wide-body” segment which is 20%). These do an even larger proportion of the work considering that medium twin aisle aircraft have ranges similar to the very large aircraft, and single aisle can take many more passengers than regional jets or turboprops. These two aircraft categories capture the bulk of aircraft investment and emissions.

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[25] The aircraft that replaces another in a fleet really depends on large variety of factors like whether an airline is willing to change manufacturers, whether the airline plans to alter their network or routes, and the level of discount that the airline receives. However to identify the cost differential of only the efficiency technologies of interest, the matching was done using web searches and information from the aircraft manufacturers themselves. The 737MAX clearly replaces the 737NG and previous 737 aircraft, but it’s less clear which aircraft a totally new series like the A350 replaces for instance. Research suggested the closest match in the Airbus family was the A340.

- The values for several variables of Single and Twin aisle aircraft were averaged according to the market-share weight of these two categories. This allows a balance of the accuracy of data for different aircraft classes with the ease with collecting data at more aggregated levels.

Assumption 3: Freight fleet is excluded from the analysis

- Most of fuel consumption in aviation comes from passenger commercial services, which carry 80% of airfreight as 'belly cargo'.

2.6 Integration

Across all Project Drawdown transportations solutions, the integration process is defined according to the combination of solutions included in each transport cluster. The clusters help allow a clearer identification of intra-solution links, and cross cluster-links. There are three main components of the transportation integration process within and across each cluster:

1. **Market/TAM/Adoption Consistency**: Ensuring that all solutions that are in the same market:
    a. use the same TAM data,
    b. use consistent market shares, and
    c. have projected adoptions that do not exceed the total projected demand
2. **Variable Consistency**: Ensuring that all variables that are used in several solutions have the same values.
3. **Grid Demand Changes**: Ensuring that the increased demand for grid electricity can be provided by the electricity generation sector.

This solution falls in the non-urban passenger transport cluster which includes High-speed Rail (HSR), Electric Vehicles, Car Fuel Efficiency (hybrids) and Telepresence.[26] For each of the three components above, the integration issues for Airplane Fuel Efficiency were:

1. **Market/TAM/Adoption Consistency:** It was assumed that increased adoption of both the High-speed Rail and Telepresence solutions would lead to decreased adoptions of air travel, and hence of efficient aircraft, but adoption of EV's and Hybrid Cars would reduce use of conventional cars. For air travel, the connection to alternative modes was automatically accounted for in the TAM sources collected as indicated by the decrease in total air travel projected in more climate-aggressive scenarios.
2. **Variable Consistency:** As air travel on inefficient aircraft was modeled as the "conventional technology" for Airplane Fuel Efficiency, High-speed Rail and Telepresence (albeit in different ways). Hence, the fuel consumption and jet fuel emissions factor inputs were consistent across all three models.
3. **Grid Demand Changes:** This was not relevant for this solution.

2.7 Limitations / Further Development

The exclusion of a number of competing technologies that offer higher fuel efficiency rates is a

[26] Telepresence is included in intercity passenger transport since it can have a direct effect on adoption of the other two solutions in the cluster.

limitation of this approach. As mentioned earlier, more than 70 individual technologies have been designed in the last few years with the aim of improving the fuel efficiency of aircraft. They are intended to provide high fuel savings on retrofits of current in-service aircraft, on new aircraft families before and after 2020, and on upgrades of serial production types. However, the current technology readiness level of most of these technologies is low, and the time horizon for their availability extends beyond 2025 (IATA, 2013), which means that they fail to meet Project Drawdown requirements of existence of a business case and scaling adoption. Additionally, a more granular approach of matching individual technologies with individual aircraft models to calculate individual fuel savings would have been more accurate, however the data requirements would have grown significantly and more assumptions would have been required.

Similarly, the adoption of biofuels was not included in this solution since in-use biofuels (first generation) are very likely to have major impacts on food security when adopted in large amounts, and second generation biofuels (which would use waste and other non-food feedstocks), do not yet have a business case and are not yet scaling. Biofuels overall however, are considered a key long tern solution to decarbonizing the aviation sector, which is seen as a difficult sector to decarbonize. For Project Drawdown however, this is considered a coming attraction.

The approach detailed in this document also omits the wider radiative forcing impacts of aircraft use in the upper atmosphere, which some sources suggest could quantify the impact of aviation at over twice what it would be if using carbon dioxide alone. The ability to estimate the actual radiative forcing of aviation at a granular level however is quite challenging due to the need to also gather information about local effects, and local weather among others. Integrating radiative forcing estimates with the other Project Drawdown solutions would also present a challenge.

Finally, this solution ignores freight-only aircraft, but as noted earlier, these represent a small portion of all aircraft, and the subsector is indirectly covered since most air freight passes through the passenger-aircraft anyway.

3 RESULTS

The model indicates a large increase in the number of passenger aircraft in the Plausible Scenario. *Table 7* and *Figure 2* summarize this growth. Adoption grows significantly in all scenarios, but in later years, the production constraints of the market become apparent in the Plausible and Drawdown Scenarios as a kink in the adoption plots even with the methodological assumption of a third major aircraft manufacturer. This indicates that the projection of air travel far in the future is dependent on a much faster rate of aircraft production than is currently available, or in the production of larger aircraft (such as more twin-aisle than single aisle aircraft).

The Optimum Scenario adoption is limited by a different constraint however. This scenario is based on a TAM than already assumes less air travel due to greater adoption of alternative technologies like High-speed Rail and Telepresence. Hence the kink in this adoption graph is due to a lower TAM. This is also evident in the results tables as fewer aircraft but higher percent adoption.

Table 7 Global Adoption. 2014 and 2050 for All scenarios

Result	2014	2050			
	(Estimate of reality)	REF Scenario	Plausible Scenario	Drawdown Scenario	Optimum Scenario
Total adoption in aircraft (implementation units)	1,250 aircraft equivalents[27]	5,250 aircraft equivalents	46,680 aircraft equivalents	48,380 aircraft equivalents	32,000 aircraft equivalents
Total adoption in fraction of TAM	8%	8%	75%	83%	100%

[27] Since the methodology calls for the weighted averaging of variables for single aisle and twin-aisle aircraft, every 4 aircraft equivalents is an indicative result representing approximately 3 single aisle and 1 twin aisle aircraft.

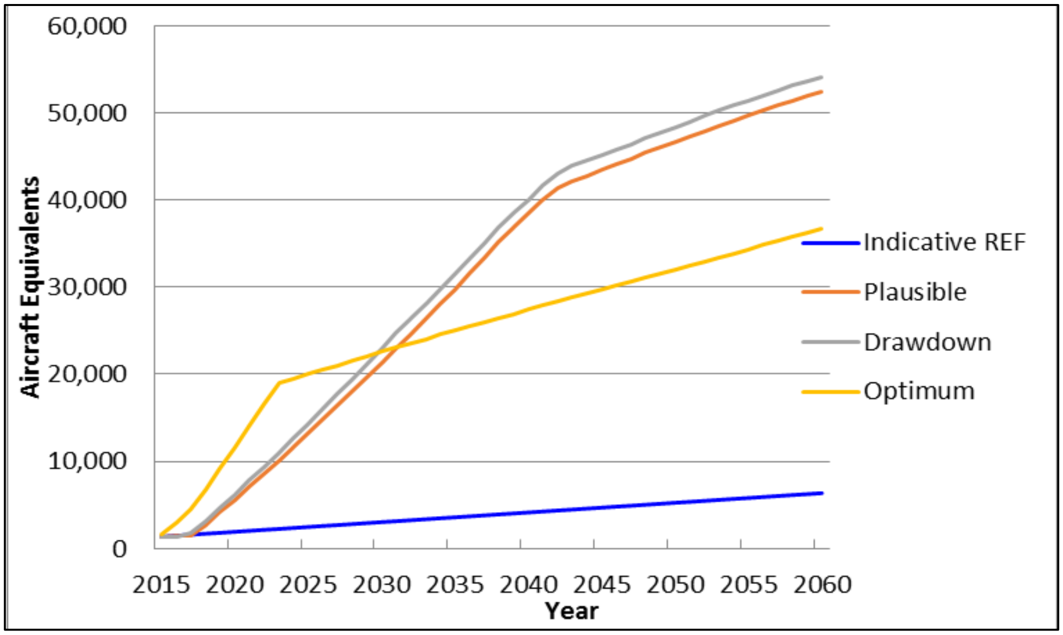

Figure 2 Adoption Growth of All Scenarios in Aircraft Equivalents

Table 8 Key Climate Outcomes

Result (Compared to REF)	2020-2050		
	Plausible Scenario	Drawdown Scenario	Optimum Scenario
Total Emissions Reduction (Gigatons of CO2-eq)	5.05	5.2	6.5

Table 9 Key Financial Outcomes

Result (Compared to REF)	2020-2050		
	Plausible Scenario	Drawdown Scenario	Optimum Scenario
Net First Cost (Billion USD)	914		
Operating Savings (Billion USD)	1,600		
Cash flow NPV of a Single Aircraft Equivalent (USD)	2,832,000		
Average Abatement Cost (USD/ton CO2-eq)	-6.81		

4 DISCUSSION

In terms of single aisle aircraft, 5,848 airplanes of this family required Sharklet/Blended winglet systems in 2014, while 8,960 in service aircraft were already converted by the base year. Therefore, the target was to estimate specific time horizons to convert 14,808 single aisle aircraft from Airbus and Boeing. The conversion rate from Boeing is 400 aircraft retrofitted per year, while the rate from Airbus is 240 aircraft per year. The PDS scenario applies the conversion rate of 640 aircraft modified per year, and additionally assumes that all **new** aircraft are by default, with wingtips. The key climate outcomes present a maximum annual emissions reduction of 0.04 Gt CO2/yr and a total emissions reduction of 0.62 Gt CO2 from 2020 to 2050 in the PDS scenario.

[illegible]. The adoption of biofuels, methods for control of aircraft movement such as ascent and descent), and engine configuration are options worth to explore in the future. The elements that require a more contextualized study in the future are the approache used to estimate the conversion rate for retrofitting single aisle aircraft, and the assumptions that in many cases passenger commercial services carry freight flows as 'belly cargo'. A significant database that differentiates emissions from belly cargo and passengers in commercial aircraft would increase the capacity to provide a more specific approach in a global scale.

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