This work was sponsored by the Federal Aviation Administration and conducted through the Airport Cooperative Research Program (ACRP), which is administered by the Transportation Research Board of the National Academies of Sciences, Engineering, and Medicine. It is a product of ACRP Project 03-51, “Electric Aircraft on the Horizon -- An Airport Planning Perspective”.

APPENDIX A

Market Assessment: Other Segments of Electric Aircraft Value Chain

In evaluating the potential size of the electric aircraft market, the market can be split into four primary segments representing the major market participants: manufacturers, operators, maintenance providers, and charging infrastructure developers.

A.1 Electric Aircraft Original Equipment Manufacturers

Manufacturers for native and converted electric aircraft are the first step in the market value chain for electric aircraft, dealing directly with both flight service providers (FSPs) and private customers. Cumulatively, aircraft sales and conversions represent the largest total portion of the U.S. electric aircraft market, with an estimated value of $387 million in 2025, increasing to $570 million by 2030. This market's size and distribution are determined by four primary factors: aircraft unit price, aircraft adoption rate, conversion price, and aircraft conversion rate.

Aircraft Unit Price

Across the five use cases, the biggest sensitivity to aircraft unit price is the volume procured during the 2025 to 2030 period. As manufacturers secure larger orders, they can spread the high fixed costs of development across the fleet. With increasing volume, buyers may expect a unit price decline. Original equipment manufacturers (OEMs) must carefully balance aircraft price curves with volume to generate a healthy return on investment—a rule hewed closely to successful commercial aviation launches.

- **The baseline** scenario holds that, while several leading manufacturers (e.g., Pipistrel) begin producing electric aircraft, most do not commit to full-scale production. In this scenario, operational savings to flight services providers remain modest, which limits their order size. In turn, manufacturers sell a lower number of orders at a higher unit price.
- **In a bullish world**, manufacturers can lean into electric aircraft production as fleet operating costs fall, fulfilling a positive economics flywheel that drives adoption across the board. In this scenario, unit aircraft prices may reach parity with comparable conventional aircraft, while presenting significant year-on-year operational savings. As a result, fleet operators with aging tenure are more likely to replace comparable conventional aircraft with electric models.
- **However, in a downside scenario**, electric aircraft are manufactured primarily by small companies at a small volume—as fleet operators recognize only thin operational savings

per unit. As a result, electric aircraft unit prices are at a material premium to comparable conventional aircraft, further limiting their appeal to buyers.

Electric Aircraft Sales Volume

As economics—primarily unit price and operational savings—and electrical-charging capabilities turn increasingly favorable for electric aircraft in this period, electric aircraft will account for a larger share of new aircraft purchases.

- **On the upside**, sales volume is taken as the sales of an aircraft company, Cirrus, upon first entering the established general aviation aircraft market with their first fully certified aircraft, having previously sold kit aircraft. Their success and rapid production growth serve as a good fit across use cases for a bullish estimation. Introduction over the first 6 years is used as a reliable proxy.
- **In the baseline** scenario, due to the assumed higher purchase price of electric aircraft over conventional, the adoption rate drops by 50 percent from the upside.
- **In a bearish world**, where electric aircraft prices are fully double the price of comparable conventional aircraft, a further 50 percent reduction in adoption is expected from the baseline. The turboprop airliner use case represents an exception to this assumption. In the downside scenario, the introduction of these aircraft types is not expected before 2030 due to technology and certification development delays.

Conversion Cost

Similar to the market for new electric aircraft, the conversion market is largely driven by the fleet operator’s willingness to pay. Conversion costs will encompass the hardware, software, and labor required, as well as costs associated with re-certification of an aircraft post-conversion. Current industry thinking estimates electric conversion costs as a percentage of aircraft unit price across the aircraft platforms in the use cases presented in this report.

- **In the baseline**, current industry projections for electric conversion costs 30 percent of new purchase prices.
- **The upside** scenario assumes motor, battery, and control electronics have developed at a more rapid pace, with conversion costs dropping correspondingly. This reduction is passed on to aircraft operators, and conversion costs drop to 20 percent of the price of a new aircraft.
- **In a bearish world**, significant delays and development cost overruns result in much higher conversion costs. This is a contributing factor to a conversion market failing to emerge.

Conversion Rate

In addition to the estimated price of conversion, the rate at which fleet operators choose to convert their aircraft is impacted by fleet age (cohort mix) and predicted remaining service life. Adoption rates assume that operators are more likely to invest in conversion on younger aircraft with more service life remaining.

- **In the baseline scenario**, conversion costs decline and operational savings increase. This results in fleet operators beginning to convert their fleets to electric models. Of aircraft with more than 10 years of useful life remaining, only four percent are converted to electric propulsion. For aircraft with between 5 and 10 years of life, this number reduces to two percent converted, while aircraft with less than 5 years remaining are not converted.
- **In the bull scenario**, technological advances lead to a significant drop in conversion price from the baseline, and conversion rates increase to five, three, and one percent for each respective category.
- **In a bearish world**, high conversion costs and higher than expected electric aircraft operating costs result in a conversion market not emerging.

Market Size in 2025: Discussion

The aircraft sales and conversion market distribution between use cases can be seen in Tables A1 and A2. General aviation makes up the largest portion of the market in the 2025 use cases, followed by commuter aircraft, pilot training, and then light air cargo in turn. Turboprop airliner makes up the smallest cumulative market portion across the 2025 adoption scenario because, on the downside and baseline, neither the sales nor conversion markets emerge.

Table A1. Electric aircraft sales market ($ million).

	2025			2030		
Use case	**Downside**	**Baseline**	**Upside**	**Downside**	**Baseline**	**Upside**
Turboprop Airliner	0.0	0.0	0.0	0.0	82.0	119.9
Commuter Aircraft	0.0	20.3	40.6	20.2	93.7	168.5
Light Air Cargo	0.0	0.0	0.6	0.0	11.2	21.3
Flight Training	0.0	15.3	28.5	14.1	19.0	36.0
General Aviation	4.0	51.1	103.9	88.8	134.4	256.5

Table A2. Aircraft conversion market ($ million).

	2025			2030		
Use case	**Downside**	**Baseline**	**Upside**	**Downside**	**Baseline**	**Upside**
Turboprop Airliner	0.0	0.0	31.3	0.0	23.0	36.8
Commuter Aircraft	0.0	43.1	54.2	0.0	67.3	76.8
Light Air Cargo	0.0	7.1	14.1	0.0	10.3	15.6
Flight Training	0.0	9.3	25.9	0.0	13.7	35.5
General Aviation	0.0	170.5	289.8	0.0	186.9	316.8

General aviation represents the largest portion of both the sales and conversion markets in 2025. On the downside, sales represent $4 million while a conversion market does not emerge. In the baseline scenario, sales and conversion represent $51 million and $170 million, respectively, while on the upside, these numbers are $103 million and $289 million. the significantly larger market size for aircraft conversion is due to the large potential customer base of 100,000+ active general aviation aircraft.

The commuter aircraft sales market will likely not emerge by 2025 in the downside likely due to the slow initial adoption expected of a newly emerged technology. The baseline and upside represent $20 million and $40 million, respectively. The commuter aircraft conversion market is projected to be larger than the sales market due to the cost, savings of conversion, and the relatively high average remaining service life of commuter aircraft—roughly 63 percent are estimated to have 10 or more years remaining.

The flight training market sales and conversion markets are projected to be of similar size in 2025. Neither will emerge in the base case, while the baseline market will be $15 million for sales and $9 million for conversion, and the upside will be $28 million and $25 million, respectively.

The light air cargo sales market, similar to the turboprop airliner use case, does not emerge in the 2025 downside and baseline scenarios, while the upside scenario represents only $0.6 million. In these scenarios, the value stream is driven entirely by aircraft conversions. This is estimated to be $7.1 million in the baseline and $14 million in the upside. The driving nature of the conversions market is due to the significant cost savings of conversions over new purchases and the desire of fleet operators to maximize the value of currently operating aircraft.

Market Size in 2030: Discussion

As of 2030, general aviation remains the largest portion of the electric aircraft sales and conversion markets. The sales market will rapidly grow in the downside use case, as more electric aircraft platforms are certified. The baseline and upside scenarios will more than double to represent $134 million in the baseline and $256 million in the upside. The aircraft conversion market growth is comparatively small between 2025 and 2030 as conversion rates are expected to be fairly constant while future conventional aircraft purchases will increase the potential customer base.

The commuter aircraft sales market is projected to grow by more than a factor of four between 2025 and 2030 to represent $20 million in the downside, $93 million in the baseline, and $168 million in the upside. Conversely, the conversion market for commuter aircraft will experience a more sedate growth, increasing by only modestly to $67 million in the baseline and $76 million in the upside. this will largely be due to expected steady conversion rates and growth of the conventional fleet.

The turboprop airliner sales market will emerge by 2030, growing to $82 million in the baseline and $120 million in the upside, as hybrid-electric technologies are fully introduced, and regional carriers identify their potential as revenue enhancers. The baseline aircraft conversion market for turboprop airliners will also emerge by 2030, after technologies are developed and certified, representing $23 million. The upside conversion market exhibits only modest growth between 2025 and 2030 due to the small size of the active turboprop fleets, the limited projected growth, and the high average aircraft age.

The flight training sales and conversion market is projected to see only moderate growth between 2025 and 2030, with sales increasing to $14 million, $19 million, and $36 million in the downside, baseline, and upside scenarios and the conversion market growing to $15 million and $35 million in the baseline and upside. The mild growth rate of the aircraft conversion market, as in other use cases, will be driven by steady conversion rates and the future growth of conventional trainer fleets.

As of 2025, light aircraft will make up the smallest portion of the electric aircraft sales and conversion markets. A sales market will emerge by 2030 in the baseline scenario, growing to represent $11 million. The upside scenario will experience significant growth. However, the 2030 value will remain small relative to other use cases at $21.3 million. The conversion portion of the light air cargo market will experience only minor growth between 2025 and 2030 to represent $10 million and $15 million in the baseline and upside scenarios, respectively. This will likely be due to relatively steady conversion rates as less than half of the active fleet is estimated to have more than 10 years of service life remaining.

A.2 **Electric Flight Service Providers**

FSPs play a crucial role in facing the passenger, and, except for the general aviation use case, they are fleet operators who procure directly from OEMs. In contrast, general aviation platforms are targeted at private ownership, with charter operators folded into the commuter aircraft use case. Electric aircraft may present fleet operators with opportunities to increase the profitability of both low traffic and high traffic routes through reduced operating costs.

The market for FSPs is estimated to have an aggregate value of $24 million in 2025, increasing to $147 million in 2030 in the baseline case. The market size is primarily influenced by three variables: willingness to pay among passengers or consumers, average flight hours per electric aircraft, and seat and payload utilization on average trips.

Service Price

Customer willingness to pay is a decisive swing variable. FSPs, like airlines, directly face consumers in a competitive and likely crowded, commoditized space. Ticket and cargo fares are often the driving decision factor as consumers choose among airlines, routes, and trips. In commercial aviation, a host of digital price tools and apps have created cost transparency, further placing pricing power in the hands of the passenger. Electric FSPs will confront the same landscape:

- **While turboprop airliners** will enjoy a lower cost of ownership from electrified aircraft, the upside scenario estimates that only 11 percent of the fleet will be converted in this period. As a result, operators may not need to pass on the savings to passengers, and we expect the Federal Aviation Administration (FAA) predictions of modest ticket price increases to apply to the electric turboprop use case in the 2025 to 2030 period. Based on FAA projections, the average revenue per passenger seat mile will be 11.5 cents in 2025 and increase to 12.5 cents in 2030.

- **Commuter aircraft** ticket prices in a bearish world assume no appreciable impact from the electrification of aircraft and will remain flat at current rates estimated to be around $120 per leg based on a survey of commuter and air taxi rates. The baseline assumes that wider implementation of electric aircraft and operational cost savings are passed along to the customer resulting in an estimated 12 percent reduction in ticket prices to an average of $106. The bullish scenario assumes further savings pass through, producing a 23 percent decrease to an average price of $92 per leg.

- **Light air cargo** rates per pound are expected to vary largely due to reductions in fuel surcharges, estimated at $0.50 per pound, as fleets partially electrify. Downside rates of $1.16 per pound are based on average prices across several small air cargo firms and assume no reduction in fuel surcharges. The baseline presents a world in which the introduction of a small number of electric aircraft into cargo fleets leads to a 25 percent decrease in fuel surcharges lowering prices to $1.04 per pound on average. The bull case assumes that increasingly, but not yet fully, electric air cargo fleets will lead to a larger 50 percent drop in fuel surcharges leading to a per pound cargo price of $0.91.
- **Flight training** prices per hour are based on aircraft operating costs and fleet overhead costs with a markup, along with instructor hourly rate. Across the adoption scenarios, instructor prices are assumed to be fixed at $50 per hour, while hour aircraft rental costs will vary based on reduced operating costs and savings passed through to the customer. In a bearish world, the average hourly aircraft price will remain flat as operational cost savings will not be sufficient to pass through to the customer. Prices will average at $120 per hour based on a survey of flight schools. The baseline scenario assumes a savings pass-through of 50 percent as pilot schools look to increase public interest leading to an average cost of $100 per hour. The upside scenario takes this trend further with a 75 percent pass-through resulting in average costs of $90 per hour.

Aircraft Annual Flight Hours

The profitability of FSPs is driven by utilization to cover the high fixed costs of procuring the fleet. Increasing flight hours with electric aircraft, either due to higher demand or by using electric aircraft on higher traffic routes, will reduce operating costs and increase profit over comparable conventional aircraft.

- **Turboprop airliner** annual flight hours will be significantly higher than the other use cases. The downside case assumes a current fleet-wide average of 2,600 hours per year based on the average for current airline platforms. In the baseline, this increases to 3,400 as lower operating costs drive airlines to use electric aircraft on busier routes. In a bullish scenario, average utilization further increases to around 4,300 hours.
- **Commuter aircraft** platform flight hours from a bearish world view will average 370 flight hours per year based on current statistics. The baseline scenario assumes that increased demand brought about by cost efficiencies passed through to the consumer will increase average flight hours to 434 per year. In the upside scenario, this increase is extended to 498 flight hours per year.
- **Light air cargo** annual flight hours will remain constant at 370 flight hours per year across all three scenarios. This assumes that market demand is fairly inelastic, and any increased demand will be reflected in increased load utilization.
- **Flight Training** aircraft flight hours are a function of the number of pilots actively training. The downside assumes that aircraft utilization remains at current levels of 390 flight hours per year. The baseline assumes that operational cost savings and resulting price reductions will attract additional students at a rate that addresses 10 percent of the current pilot

shortage (a deficiency of around 7,000 pilots per year), resulting in average flight hours increasing to 414. In a bullish world view, the addressed percentage increases to 30 percent, and average flight hours increase to 460.

Aircraft Load Factor

Applying the concept of utilization from annual flight hours down to the individual aircraft, ensuring a high seat utilization rate (or load factor) is the last major lever for FSPs to manage. Load factors are largely a factor of consumer demand. However, fleet operators may choose to shift electric aircraft to routes with high load factors to maximize revenue while minimizing operating costs.

- **Turboprop airliner** operators will seek to schedule hybrid-electric aircraft for high load routes, as the lower operating costs will increase revenue over conventionally powered aircraft. The downside scenario assumes that, with no difference in maintenance, repair, and overhaul (MRO) costs, hybrid-electric aircraft load factors will remain at the current average of 80 percent. In baseline, decreased operating costs will lead to average load factor increasing to 85 percent, and a bullish scenario results in a load factor of 90 percent.
- **Commuter aircraft** platform load factors will be impacted by decreasing ticket prices and through the group of rideshare services such as Hitch, which help fleet operators fill empty seats. A bearish scenario assumes no change from the current average of 45 percent for non-scheduled flights. As lower operating costs allow services to reduced prices, load factors will increase to 51 percent in the baseline and 58 percent in the upside.
- **Light air cargo** markets are assumed to be relatively inelastic, and changes in load factors are driven by changes in per pound price. The downside scenario assumes no change in freight prices; thus, aircraft load factor will remain at the current average of 30 percent. As prices lower, the increase in load factor is estimated using the elasticity of air cargo based on crude oil prices. The baseline assumes an average load factor of 32 percent, while a bullish scenario predicts 33 percent.

Market Size in 2025: Discussion

As Table A3 shows, in 2025, a flight service downside market does not emerge in any use case due to delays in electric aircraft certification. Across the baseline and upside scenarios, flight training flight services are anticipated to make up the largest portion of the market, followed by commuter aircraft, turboprop airliner, and light air cargo.

Table A3. Flight services market ($ million).

	2025			**2030**		
Use case	**Downside**	**Baseline**	**Upside**	**Downside**	**Baseline**	**Upside**
Turboprop Airliner	0.0	0.0	33.2	0.0	100.6	551.2
Commuter Aircraft	0.0	10.9	18.5	2.8	49.9	86.6
Light Air Cargo	0.0	4.4	6.9	0.0	26.1	49.9
Flight Training	0.0	13.8	33.4	7.8	62.3	160.7

Electric flight training flight services represent $14 million in the baseline and $33 million in the upside. This market size is due to the decreased cost of pre-flight hours that fleet operators may offer to attract higher enrollments and address the growing shortage of pilots. Price decreases are enabled by the savings in variable costs that electric aircraft offer over conventionally powered trainer platforms.

Commuter aircraft represents the second largest part of the market with a potential size of $11 million in the baseline and $18 million in the upside. This initial market is likely to be based primarily on small initial fleets used on existing routes. The profit-enhancing potential of electric aircraft has not yet been fully realized.

The flight service market for turboprop airliners does not emerge in 2025 for the downside or baseline scenarios due to delays in aircraft technology and an unfavorable certification climate. On the upside, estimated at $33 million, electric turboprop airline platforms are only initially introduced and flying limited routes.

The smallest market portion is represented by the light air cargo use case representing $4 million in the baseline and $7 million in the upside. The initial adoption of electric aircraft in this use case, similar to turboprop airliners, will be limited to a few routes where installation of supporting infrastructure makes financial sense. Utilization will likely remain similar to conventionally powered aircraft across the adoption scenarios.

Market Size in 2030: Discussion

In 2030, turboprop airliners now represent the largest portion of the market at $100 million in the baseline and $551 million in the upside. This rapid increase will be driven by operators moving to leverage the cost savings presented by electric aircraft. Seeking to maximize profits, FSPs maximize electric aircraft utilization and load factor by placing them on routes with consistently high passenger traffic.

Flight training service providers see a significant, though less drastic, growth representing $7.8 million in the downside, $62.3 million in the baseline, and $160.7 million in the upside. This growth will be a result of increasingly electric trainer fleets reducing operator overhead costs, allowing savings to be passed on to consumers, reducing pilot training costs. Lowered barriers to entry into the pilot profession will drive an uptick in pilot school enrollment.

Commuter aircraft will see slightly more subdued growth between 2025 and 2030 as market sizes increase to $2.8 million on the downside, $50 million in the baseline, and $86 million on the upside. Lower operating costs may allow FSPs to reduce prices to the point where commuter aircraft become a viable competitor with ground transportation. This has the potential to create an uptick in demand driven by the attraction of increased speed, comfort, and ease of travel at a similar price point. Additionally, as in the turboprop airliner use case, operators will see to maximize their profits by placing electric aircraft on highly trafficked routes.

Light air cargo again represents the smallest portion of the total market in 2030. A downside market fails to emerge for light air cargo because delayed technology development leads to no conversion market emerging, delayed implementation of larger electric cargo aircraft, and lower than expected cost savings. This results in fleet operators choosing not to invest in new electric aircraft. In the other use cases, growth between 2025 and 2030 is significant, with the 2030 market representing $26 million in the baseline and $50 million in the upside. This growth may be attributed to an increased number of electrified flight routes and destinations, increased cargo load utilization, and an uptick in demand driven by passing on operating costs to the consumer.

A.3 Maintenance, Repair, and Overhaul

Electric aircraft will require unique MRO requirements to the increased reliance on complex electronics and software in areas such as battery and motor management. As a core benefit of electrification, the significant reduction in moving parts will lead to a lower cost footprint, requiring a less frequent overhaul and minimizing lifetime part replacement requirements. The early years' net effect is a niche MRO market, marked by capabilities and expertise targeted specifically at electric aviation and smaller initial size. Airport practitioners seeking a better understanding of this emerging market can focus on two primary variables.

Benchmarked Maintenance, Repair, and Overhaul Cost Estimates

The MRO market for each use case is grounded on benchmarked engine and airframe maintenance hourly costs of comparable legacy aircraft. This estimate keeps maintenance costs associated with aircraft components such as landing gear, airframe, and avionics consistent across conventional and electric aircraft of similar size. The majority of savings will be associated with the propulsion system.

- **Turboprop airliners** powered by conventional means will have an average MRO cost per flight hour of around $1,000 (based on the comparably sized ATR 42 and 72).
- **Commuter aircraft**, due to a much smaller size and less complexity, have significantly lower MRO costs per hour, assuming an average of $300.
- **Light air cargo** has a similar average to MRO cost as commuter aircraft. Although the larger aircraft size typically requires an average of $340 per flight hour.
- **Flight Trainings** have the lowest hourly MRO of the use cases. Currently, comparable aircraft indicate an hourly cost of $26, benefiting primarily from smaller and less complex aircraft with easy-to-maintain piston engines.
- **General aviation** aircraft typically have lower MRO costs than light air and commuter aircraft platforms due to smaller size and easy-to-maintain design. The average cost across the comparable aircraft (such as Cessna 182, Cirrus SR-22, and Diamond DA-62) is approximately $40 per hour.

Cost Savings of Hybrid and Fully Electric Aircraft

Reduction in maintenance and operating costs is the key driving factor in electric aircraft adoption. The model reflects the wide spectrum of industry estimates in cost savings across the bullish, baseline, and bearish scenarios (Table A4).

- **Turboprop airliners**, during the time period examined, will likely use hybrid-electric rather than fully electric propulsion. Thus, expected cost savings will be less significant than fully electric systems. The model defines the downside as a world in which there are no MRO cost savings compared to conventionally powered platforms. In contrast, the baseline envisions an ecosystem where MRO costs are down 20 percent, rising to 30 percent in a bullish scenario.

- **In the runup to 2030, commuter aircraft, light air cargo, flight training, and general aviation** use cases deviate from turboprop in their significantly greater likelihood to use fully electric propulsion systems. As a result, more significant MRO savings are expected: up to 20 percent in a downside case, rising to 35 percent in the baseline, and 50 percent in a more bullish outcome.

Table A4. Maintenance, repair, and overhaul market size ($ million).

	2025			**2030**		
Use case	**Downside**	**Baseline**	**Upside**	**Downside**	**Baseline**	**Upside**
Turboprop Airliner	0.0	0.0	16.4	0.0	72.9	268.0
Commuter Aircraft	0.0	3.6	4.9	0.9	18.5	25.4
Light Air Cargo	0.0	0.5	0.7	0.0	3.4	5.7
Flight Training	0.0	2.0	4.3	1.3	8.7	19.2
General Aviation	**0.1**	**2.7**	**4.4**	**2.1**	**14.8**	**23.8**

Market Size in 2025: Discussion

In 2025, the overall MRO market size for electric aviation is expected to be relatively small. Although emerging only in the upside, turboprop airliner platforms will account for the largest portion of the market, followed by commuter aircraft, general aviation, flight training, and light air cargo.

A turboprop airliner MRO market is expected to only emerge in the upside case in 2025. This is due to potential delays in technology development and the emergence of favorable certification policy. The upside scenario value of $16 million is due to the expectation that maintenance costs for aircraft in this class will be much more expensive than in the other use cases. Additional, hybrid-electric aircraft are expected to present lower operational savings potential than fully electric aircraft.

Commuter aircraft represents the second-largest portion of the electric MRO market in 2025 at $3.6 million in the baseline and $5 million in the upside. Aircraft in this category are predicted to have much lower MRO costs compared to turboprop airliner platforms, and as potential operational savings increase, more fleet operators will begin investing.

Pilot training and general aviation make up similarly size portions of the electric aviation MRO market, between $2 million and $3 million in the baseline and around $4 million in the upside. Aircraft MRO costs are predicted to be fairly similar between these use cases, with general aviation being the more expensive. The high number of annual flight hours expected drives the MRO market size for the flight training use case, while aircraft volume is the driver for general aviation.

The smallest portion of the market is represented by light air cargo. Although MRO costs will likely be similar to commuter aircraft platforms, the number of active electric light air cargo vehicles is estimated to be far lower; thus the market remains nascent across the scenarios representing only $0.5 million and $0.7 million in the baseline and upside scenarios.

Market Size in 2030: Discussion

In 2030, turboprop airliner represents the overwhelming majority of the electric MRO market, having experienced an increase by nearly a factor of 15. In both the baseline and upside scenarios, fleet operators identify the potential cost savings presented by electric aviation over conventional platforms and take steps to maximize aircraft utilization among the growing fleet. This drives the significant growth in market size between 2025 and 2030.

The general aviation use case MRO market size has grown significantly to the point where, in 2030, it represents a similar potion of the market as the commuter aircraft use case. These use cases have experienced growth between five- and seven-fold during the 2025 to 2030 period. As with many portions of the electric general aviation value chain, the fleet size is the primary driver of market growth, and, by 2030, higher numbers of general aviation aircraft owners have seen the savings potential of electric aircraft through new purchase or conversion. Conversely, while experiencing some growth in overall electric fleet size, the primary driver of the commuter aircraft use case is operators maximizing the utilization of their electric platforms.

The flight training use case experiences between four- and five-fold growth between 2025 and 2030. Driving this increase is the projected increase in annual flight hours across electric pilot training fleets. The lower average MRO costs per flight hour allow fleet operators to pass savings on to their customers and lower the per hour cost of flight training. This results in increased enrollment because the cost is a major barrier to many interested pilot training candidates.

Light air cargo, while experiencing growth by up to a factor of seven, continues to represent the smallest portion of the MRO market in 2030. As this market is relatively inelastic to service price, savings in MRO will likely not result in the increase in flight hours seen in turboprop airline and commuter aircraft. Thus, the increase in MRO market will be largely driven by the increase in electric aircraft fleet size through sales and conversions as operators see the potential for increased profits.

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APPENDIX B

Market Assessment: Model Assumptions

B.1 Model Assumptions: OEM Market Size

Due to the variability of available data, the original equipment manufacturer (OEM) section of the model follows slightly different structures for each of the five use cases. The assumption set for this section of the model is the same across use cases, while the values associated with those assumptions vary. These assumptions include electric aircraft production as a percent of total aircraft production, electric aircraft price as a percentage of comparable conventional aircraft price, aircraft conversion rate, and conversion cost.

OEM Market Size: Turboprop Airliner

Conventional Turboprop Airliner Market Size

This section begins by calculating the forecast growth rate of conventional aircraft deliveries. The growth rate is estimated in three steps:

- **Step 1**: Identifying the expected total turboprop airliner sales in the years 2018 to 2037 from the autothermal reforming (ATR) Turboprop Market Forecast 2018 to 2037.
- **Step 2**: Determining the combined 2017 North American aircraft sales from ATR and Bombardier and assuming they represent the majority of the North American turboprop airliner market.
- **Step 3**: Estimating 2037 sales and calculating the compound annual growth rate (CAGR) such that total deliveries in 2018-2037 match the ATR projection.

This growth rate is then used to calculate projected annual North American deliveries for each example aircraft for 2025 to 2030 using the following steps:

- **Step 1**: Forecasting ATR’s North American sales by applying the calculated CAGR to ATR sales data from 2017.
- **Step 2**: Projecting sales for ATR-42 and ATR-72 by assuming a split of one-third and two-thirds, respectively, based on the projected split in total deliveries between 40 to 60 seats (ATR-42) and 61 to 90 seat (ATR-72) platforms from the ATR Turboprop Market Forecast.

To estimate the total turboprop airliner delivery market size, the percent of total sales volume represented by the example ATR aircraft must be approximated in the following two steps:

- **Step1**: Identifying the global number of outstanding orders for turboprop airliners of more than 40 seats from an Embry-Riddle Market Analysis.
- **Step 2**: Dividing the total number of outstanding orders by those of the example aircraft to determine the percentage of outstanding orders represented by example aircraft.

Calculated next are the projected conventional turboprop airliner aircraft delivery market sizes for 2025 to 2030, using annual delivery numbers and the estimated percent of the market made up by the example aircraft. Five steps are required:

- **Step 1**: Identifying published purchase pricing, for example, aircraft.
- **Step 2**: Identifying expected price inflation rate predictions from the Federal Reserve.
- **Step 3**: Calculating inflated aircraft prices for 2025 to 2030.
- **Step 4**: Multiplying the projected example aircraft sales numbers by the estimated aircraft costs and summing.
- **Step 5**: Calculating the total projected turboprop airliner sales market by dividing example aircraft deliveries by the estimated percent of the total sales volume represented by the example aircraft.

Hybrid-electric Turboprop Airliner Market Size

The next calculation estimates the sales per year of hybrid-electric versions of the example turboprop airliner aircraft from 2025 to 2030.

- **Step 1**: Identifying the estimated percent of the turboprop airliner sale market represented by hybrid-electric aircraft sales for each year (*Upside: Starting at one percent increasing annually to 26 percent over 5 years, Baseline: Starting at one percent increasing annually to 13 percent over 5 years, Downside: No hybrid-electric production*).
- **Step 2**: Calculating the number of hybrid-electric versions of example aircraft sold by multiplying forecast conventional example aircraft sales per year, from above, by the hybrid-electric sales percentage.

The market value of sales of hybrid-electric versions of the example aircraft is then calculated utilizing the estimated number of hybrid-electric aircraft produced.

- **Step 1**: Utilizing the previously identified purchasing price for the example aircraft.
- **Step 2**: Estimating hybrid-electric aircraft price by multiplying the purchase price by the appropriate hybrid-electric aircraft price modifier (*Upside: 100 percent, Baseline: 108 percent, Downside: 115 percent*).
- **Step 3**: Adjusting the calculated hybrid-electric aircraft purchase price to account for projected price inflation.
- **Step 4**: Calculating the market value by multiplying the adjusted hybrid-electric aircraft price by the projected number of hybrid-electric aircraft produced.

The projected market size for sales of hybrid-electric versions of the example aircraft is then adjusted to estimate the total market for hybrid-electric turboprop airliner aircraft.

- **Step 1**: Identifying the percent of the total sales volume represented by the hybrid-electric aircraft.
- **Step 2**: Estimating the total hybrid-electric turboprop airliner market by dividing the value of produced hybrid-electric versions of the example aircraft by the estimated percentage of total sales volume represented by the example aircraft.

Turboprop Airliner Hybrid-electric Conversion Market Size

To calculate a potential market size for the conversion of existing aircraft to hybrid-electric, the model first estimates the projected growth rate of the active turboprop airliner fleet. This is done in the following steps:

- **Step 1**: Identifying the estimated size of the North American turboprop airliner fleet in 2017 and 2037 based on the ATR Turboprop Market Forecast.
- **Step 2**: Calculating the CAGR using the estimated 2017 and 2037 turboprop airliner fleet sizes.

Using the calculated fleet growth rate, an estimate for the number of active conventional example aircraft during the 2025 to 2030 period is determined through the following steps.

- **Step 1**: Determining the number of currently active example aircraft in North America through the FAA’s aircraft registry database.
- **Step 2**: Utilizing the estimated annual fleet growth rate to calculate the number of active example aircraft during the 2025 to2030 time period and summing.

The next step is to determine what percent of the active North American Turboprop Airliner fleet is represented by the example aircraft. This is approximated through the following two steps:

- **Step1**: Identifying the global number of active turboprop airliners of more than 40 seats from an Embry-Riddle Market Analysis.
- **Step 2**: Dividing the number of active example turboprop airliner aircraft by the total number of active turboprop airliner platforms.

The rate of conversion of current aircraft to hybrid-electric propulsion is based on an estimate of the effective remaining lifespan distribution of active turboprop airliner aircraft. This is first calculated for the active example aircraft using data from the FAA’s aircraft registry database in the following steps:

- **Step 1**: Identifying the appropriate estimation for average aircraft lifespan from a 2018 International Air Transport Association (IATA) aircraft decommissioning study.
- **Step 2**: Calculating the age of active aircraft by subtracting the manufacturing year from 2019.

- **Step 3**: Estimating the remaining effective service life by subtracting aircraft age from the average life span.
- **Step 4**: Categorizing aircraft by remaining lifespan, grouping into aircraft with “10 years or more,” “5 to 10 years,” and “5 years or less.”
- **Step 5**: Producing a percentage distribution of example aircraft age by dividing the category sizes by the total number of active example aircraft.

Based on this “remaining service life distribution,” the number of active example aircraft converted each year is calculated through the following steps:

- **Step 1**: Multiplying the number of active example aircraft by the “remaining service life distribution” to estimate the number of aircraft in each category.
- **Step 2**: Multiplying the number of example aircraft in each service life category by the estimated annual conversion percentage by category (*Upside: 5, 3, and 1 percent; Baseline: 4, 2, and 0 percent; Downside: 0, 0, and 0 percent*).

To reach a market value for the conversion of existing aircraft to hybrid-electric propulsion, the estimated cost of conversion for the 2025 to 2030 time period must be first determined following these steps:

- **Step 1**: Identifying the appropriate conversion cost, as a percentage of the price of a new conventional aircraft, based on industry views (*Upside: 25 percent, Baseline: 30 percent, Downside: 40 percent*).
- **Step 2**: Calculating the estimated conversion cost by multiplying conventional aircraft cost by the estimated conversion cost percentage.
- **Step 3**: Adjusting projected costs for inflation, utilizing the forecast rate of price inflation.

With an estimated price for converting existing example aircraft to hybrid-electric, a total aircraft conversion market size can be calculated.

- **Step 1**: Multiplying the number of example aircraft converted to hybrid-electric by the projected conversion cost.
- **Step 2**: Calculating total aircraft conversion market size by dividing the example aircraft market size by the estimated percent of the active turboprop airliner fleet represented by the example aircraft.

OEM Market Size: Commuter Air

Conventional Commuter Aircraft Market Size

This section begins by calculating the forecast growth rate of conventional commuter aircraft deliveries. The growth rate is estimated in five steps:

- **Step 1**: Identifying the total number of small turboprop and piston aircraft deliveries in North America from 2012 to 2018.

- **Step 2**: Calculating the estimated percent of total small turboprop and piston aircraft utilized for commercial Part 135 operations from the FAA General Aviation and Part 135 Activity Survey.
- **Step 3**: Assuming that 70 percent of Part 135 aircraft are used for passenger carrying.
- **Step 4**: Calculating the estimated number of small turboprop and piston aircraft delivered for commuter aircraft operations by multiplying the total North American deliveries by the percent used for Part 135 and the percent used for passenger carrying.
- **Step 5**: Calculating the estimated CAGR between 2012 and 2018 from the calculated aircraft delivery numbers.

This growth rate is then used to calculate projected annual North American deliveries for each example aircraft for 2025 to 2030 using the following steps:

- **Step 1**: Determining the number of example aircraft delivered globally in 2018 from the General Aviation Manufacturer's Association (GAMA) 2018 year-end shipment and billing report.
- **Step 2**: Identifying what percent of global deliveries in 2018 were represented by North America from the GAMA report.
- **Step 3**: Estimating the number of example aircraft delivered for commuter aircraft operations in North America by multiplying the total example aircraft deliveries by the percent delivered in North America, by the percent used for commercial operations, by the percent used for commuter aircraft.

To estimate the total commuter aircraft delivery market size, the percent of total sales volume represented by the example aircraft must be approximated in the following three steps:

- **Step 1**: Identifying the global number of small turboprop and piston aircraft delivered in 2018 from the GAMA report.
- **Step 2**: Adjusting this number to estimate the number of aircraft delivered for commuter aircraft use as above.
- **Step 3**: Dividing the estimated number of example aircraft delivered in 2018 by the total number of commuter aircraft platforms delivered.

Calculated next are the projected conventional commuter aircraft delivery market sizes for 2025 to 2030, using annual delivery numbers and the estimated percent of the market made up by the example aircraft. Five steps are required:

- **Step 1**: Identifying published purchase pricing, for example, aircraft.
- **Step 2**: Identifying expected price inflation rate predictions from the Federal Reserve.
- **Step 3**: Calculating inflated aircraft prices for 2025 to 2030.
- **Step 4**: Multiplying the projected example aircraft sales numbers by the estimated aircraft costs and summing.

- **Step 5**: Calculating the total projected commuter aircraft sales market by dividing example aircraft deliveries by the estimated percent of the total sales volume represented by the example aircraft.

Electric Commuter Aircraft Market Size

The next calculation estimates the sales per year of electric versions of the example aircraft from 2025 to 2030.

- **Step 1**: Identifying the estimated percent of the commuter aircraft sales market represented by electric aircraft sales for each year (*Upside: Starting at one percent then increasing annually to 26 percent over 5 years; Baseline: Starting at one percent then increasing annually to 13 percent over 5 years; Downside: Starting at zero percent then increasing annually to seven percent over 5 years*).
- **Step 2**: Calculate the number of electric versions of example aircraft sold by multiplying forecast conventional example aircraft sales per year, from above, by the electric sales percentage.

The market value of sales of electric versions of the example aircraft is then calculated using the estimated number of electric aircraft produced.

- **Step 1**: Using the previously identified purchasing price for the example aircraft.
- **Step 2**: Estimating electric aircraft price by multiplying the purchase price by the appropriate electric aircraft price modifier (*Upside: 100 percent, Baseline: 108 percent, Downside: 115 percent*).
- **Step 3**: Adjusting the calculated electric aircraft purchase price to account for projected price inflation.
- **Step 4**: Calculating the market value by multiplying adjusted electric aircraft price by the projected number of example electric aircraft produced.

The projected market size for sales of electric versions of the example aircraft is then adjusted to estimate the total market for electric commuter aircraft.

- **Step 1**: Identifying the percent of the total sales volume represented by electric aircraft.
- **Step 2**: Estimating the total electric commuter aircraft market by dividing the value of produced electric versions of the example aircraft by the estimated percentage of total sales volume represented by the example aircraft.

Commuter Aircraft Electric Conversion Market Size

To calculate a potential market size for the conversion of existing aircraft to electric propulsion, the model first calculates an estimate for the number of active conventional example aircraft during the 2025 to 2030 period through the following steps.

- **Step 1**: Approximating commuter aircraft fleet growth rate with the Part 135 turboprop fleet growth rate from 2019 to 2029 taken from the FAA’s Aerospace Forecast 2019-2039.

- **Step 2**: Determining the number of currently active example aircraft in North America through the FAA's aircraft registry database.
- **Step 3**: Adjusting the number of example aircraft to estimate the number of active example aircraft utilized for passenger carrying by multiplying by the percent assumed to be used for commercial operations and the percent assumed to be used for passenger carrying.
- **Step 4**: Using the estimated annual fleet growth rate to calculate the number of active example aircraft during the 2025 to 2030 time period and summing.

The next step is to determine what percent of the active North American commuter aircraft fleet is represented by the example aircraft. This is approximated through the following three steps:

- **Step 1**: Estimating the total number of Part 135 aircraft from the FAA General Aviation and Part 135 Activity Survey.
- **Step 2**: Adjusting the total fleet numbers to reflect an estimate for active commuter aircraft by multiplying by the percent of Part 135 aircraft used for passenger carrying.
- **Step 3**: Dividing the estimated number of active example commuter aircraft by the estimated total number of active commuter aircraft.

The rate of conversion of current aircraft to electric propulsion is based on an estimate of the effective remaining lifespan distribution of active commuter aircraft. This is first calculated for the active example aircraft using data from the FAA's aircraft registry database in the following steps:

- **Step 1**: Identifying the appropriate estimation for average aircraft lifespan from a 2018 IATA aircraft decommissioning study.
- **Step 2**: Calculating the age of active aircraft by subtracting the manufacturing year from 2019.
- **Step 3**: Estimating the remaining effective service life by subtracting aircraft age from the average life span.
- **Step 4**: Categorizing aircraft by remaining lifespan, grouping into aircraft with "10 years or more," "5 to 10 years," and "5 years or less."
- **Step 5**: Producing a percentage distribution of example aircraft age by dividing the category sizes by the total number of active example aircraft.

Based on this "remaining service life distribution," the number of active example aircraft converted each year is calculated through the following steps:

- **Step 1**: Multiplying the number of active example aircraft by the "remaining service life distribution" to estimate the number of aircraft in each category.
- **Step 2**: Multiplying the number of example aircraft in each service life category by the estimated annual conversion percentage by category (*Upside: 5, 3, and 1 percent; Baseline: 4, 2, and 0 percent; Downside: 0, 0, and 0 percent*).

To reach a market value for the conversion of existing aircraft to electric propulsion, the estimated cost of conversion for the 2025 to 2030 time period must be first determined following these steps:

- **Step 1**: Identifying the appropriate conversion cost, as a percentage of the price of a new conventional aircraft, based on industry views (*Upside: 25 percent, Baseline: 30 percent, Downside: 40 percent*).
- **Step 2**: Calculating the estimated conversion cost by multiplying conventional aircraft cost by the estimated conversion cost percentage.
- **Step 3**: Adjusting projected costs for inflation, using the forecast rate of price inflation.

With an estimated price for converting existing example aircraft to electric, a total aircraft conversion market size can be calculated.

- **Step 1**: Multiplying the number of example aircraft converted to electric by the projected conversion cost.
- **Step 2**: Calculating total aircraft conversion market size by dividing the example aircraft market size by the estimated percent of the active commuter aircraft fleet represented by the example aircraft.

OEM Market Size: Light Air Cargo

Conventional Light Air Cargo Aircraft Market Size

This section begins by calculating the forecast growth rate of conventional light air cargo aircraft deliveries. The growth rate is estimated in five steps:

- **Step 1**: Identifying the total number of small turboprop and piston aircraft deliveries in North America from 2012 to 2018.
- **Step 2**: Calculating the estimated percent of total small turboprop and piston aircraft utilized for commercial Part 135 operations from the FAA General Aviation and Part 135 Activity Survey.
- **Step 3**: Assuming that 30 percent of Part 135 aircraft are used for cargo carrying.
- **Step 4**: Calculating the estimated number of small turboprop and piston aircraft delivered for light air cargo operations by multiplying the total North American deliveries by the percent used for Part 135 and the percent used for cargo carrying.
- **Step 5**: Calculating the estimated CAGR between 2012 and 2018 from the calculated aircraft delivery numbers.

This growth rate is then used to calculate projected annual North American deliveries for each example aircraft for 2025 to 2030 using the following steps:

- **Step 1**: Determining the number of example aircraft delivered globally in 2018 from the GAMA 2018 year-end shipment and billing report.

- **Step 2**: Identifying what percent of global deliveries in 2018 were represented by North America from the GAMA report.
- **Step 3**: Estimating the number of example aircraft delivered for light air cargo operations in North America by multiplying the total example aircraft deliveries by the percent delivered in North America, by the percent used for commercial operations, by the percent used for light air cargo.

To estimate the total light air cargo delivery market size, the percent of total sales volume represented by the example aircraft must be approximated in the following three steps:

- **Step 1**: Identifying the global number of small turboprop and piston aircraft delivered in 2018 from the GAMA report.
- **Step 2**: Adjusting this number to estimate the number of aircraft delivered for light air cargo use as above.
- **Step 3**: Dividing the estimated number of example aircraft delivered in 2018 by the total number of light air cargo platforms delivered.

Calculated next are the projected conventional light air cargo aircraft delivery market sizes for 2025 to 2030, utilizing annual delivery numbers and the estimated percent of the market made up by the example aircraft. Five steps are required:

- **Step 1**: Identifying published purchase pricing, for example, aircraft.
- **Step 2**: Identifying expected price inflation rate predictions from the Federal Reserve.
- **Step 3**: Calculating inflated aircraft prices for 2025 to 2030.
- **Step 4**: Multiplying the projected example aircraft sales numbers by the estimated aircraft costs and summing.
- **Step 5**: Calculating the total projected light air cargo aircraft sales market by dividing example aircraft deliveries by the estimated percent of the total sales volume represented by the example aircraft.

Electric Light Air Cargo Aircraft Market Size

The next calculation estimates the sales per year of electric versions of the example aircraft from 2025 to 2030.

- **Step 1**: Identifying the estimated percent of the light air cargo sales market represented by electric aircraft sales for each year (*Upside: Starting at one percent then increasing annually to 26 percent over 5 years; Baseline: Starting at one percent then increasing annually to 13 percent over 5 years; Downside: Starting at zero percent increasing annually to seven percent over 5 years*).
- **Step 2**: Calculate the number of electric versions of example aircraft sold by multiplying forecast conventional example aircraft sales per year, from above, by the electric sales percentage.

The market value of sales of electric versions of the example aircraft is then calculated using the estimated number of electric aircraft produced.

- **Step 1**: Using the previously identified purchasing price for the example aircraft.
- **Step 2**: Estimating electric aircraft price by multiplying the purchase price by the appropriate electric aircraft price modifier (*Upside: 100 percent, Baseline: 108 percent, Downside: 115 percent*).
- **Step 3**: Adjusting the calculated electric aircraft purchase price to account for projected price inflation.
- **Step 4**: Calculating the market value by multiplying adjusted electric aircraft price by the projected number of example electric aircraft produced.

The projected market size for sales of electric versions of the example aircraft is then adjusted to estimate the total market for electric light air cargo aircraft.

- **Step 1**: Identifying the percent of the total sales volume represented by electric aircraft.
- **Step 2**: Estimating the total electric light air cargo market by dividing the dollar value of produced electric versions of the example aircraft by the estimated percentage of total sales volume represented by the example aircraft.

Light Air Cargo Electric Conversion Market Size

To calculate a potential market size for the conversion of existing aircraft to electric propulsion, the model first calculates an estimate for the number of active conventional example aircraft during the 2025 to 2030 period through the following steps.

- **Step 1**: Approximating light air cargo fleet growth rate with the Part 135 turboprop fleet growth rate from 2019 to 2029 taken from the FAA's Aerospace Forecast 2019 to 2039.
- **Step 2**: Determining the number of currently active example aircraft in North America through the FAA's aircraft registry database.
- **Step 3**: Adjusting the number of example aircraft to estimate the number of active example aircraft used for cargo carrying by multiplying by the percent assumed to be used for commercial operations and the percent assumed to be used for light air cargo.
- **Step 4**: Utilizing the estimated annual fleet growth rate to calculate the number of active example aircraft during the 2025 to 2030 time period and summing.

The next step is to determine what percent of the active North American light air cargo fleet is represented by the example aircraft. This is approximated through the following three steps:

- **Step 1**: Estimating the total number of Part 135 aircraft from the FAA General Aviation and Part 135 Activity Survey.
- **Step 2**: Adjusting the total fleet numbers to reflect an estimate for active light air cargo aircraft by multiplying by the percent of Part 135 aircraft used for cargo carrying.

- **Step 3**: Dividing the estimated number of active example aircraft used for light air cargo by the total number of aircraft estimated to be utilized for light air cargo.

The rate of conversion of current aircraft to electric propulsion is based on an estimate of the effective remaining lifespan distribution of active light air cargo aircraft. This is first calculated for the active example aircraft using data from the FAA’s aircraft registry database in the following steps:

- **Step 1**: Identifying the appropriate estimation for average aircraft lifespan from a 2018 IATA aircraft decommissioning study.
- **Step 2**: Calculating the age of active aircraft by subtracting the manufacturing year from 2019.
- **Step 3**: Estimating the remaining effective service life by subtracting aircraft age from the average life span.
- **Step 4**: Categorizing aircraft by remaining lifespan, grouping into aircraft with “10 years or more,” “5 to 10 years,” and “5 years or less.”
- **Step 5**: Producing a percentage distribution of example aircraft age by dividing the category sizes by the total number of active example aircraft.

Based on this “remaining service life distribution,” the number of active example aircraft converted each year is calculated through the following steps:

- **Step 1**: Multiplying the number of active examples of the aircraft, by the “remaining service life distribution” to estimate the number of aircraft in each category.
- **Step 2**: Multiplying the number of example aircraft in each service life category by the estimated annual conversion percentage by category (*Upside: 5, 3, and 1 percent; Baseline: 4, 2, and 0 percent; Downside: 0, 0, and 0 percent*).

To reach a market value for the conversion of existing aircraft to electric propulsion, the estimated cost of conversion for the 2025 to 2030 time period must be first determined following these steps:

- **Step 1**: Identifying the appropriate conversion cost, as a percentage of the price of a new conventional aircraft, based on industry views (*Upside: 25 percent, Baseline: 30 percent, Downside: 40 percent*).
- **Step 2**: Calculating the estimated conversion cost by multiplying conventional aircraft cost by the estimated conversion cost percentage.
- **Step 3**: Adjusting projected costs for inflation, using the forecast rate of price inflation.

With an estimated price for converting existing example aircraft to electric, a total aircraft conversion market size can be calculated.

- **Step 1**: Multiplying the number of example aircraft converted to electric by the projected conversion cost.

- **Step 2**: Calculating total aircraft conversion market size by dividing the example aircraft market size by the estimated percent of the active light air cargo fleet represented by the example aircraft.

OEM Market Size: Flight Training

Conventional Flight Training Aircraft Market Size

This section begins by calculating the forecast growth rate of conventional flight training aircraft deliveries. The growth rate is estimated in four steps:

- **Step 1**: Identifying the total number of piston aircraft deliveries in North America from 2012 to 2018.
- **Step 2**: Calculating the estimated percent of total piston aircraft used for pilot training operations from the FAA General Aviation and Part 135 Activity Survey.
- **Step 3**: Calculating the estimated number of piston aircraft delivered for pilot training operations by multiplying the total North American piston aircraft deliveries by the percent used pilot training.
- **Step 4**: Calculating the estimated CAGR between 2012 and 2018 from the calculated aircraft delivery numbers.

This growth rate is then used to calculate projected annual North American deliveries for each example aircraft for 2025 to 2030 using the following steps:

- **Step 1**: Determining the number of example aircraft delivered globally in 2018 from the GAMA 2018 year-end shipment and billing report.
- **Step 2**: Identifying what percent of global deliveries in 2018 were represented by North America from the GAMA report.
- **Step 3**: Estimating the number of example aircraft delivered for pilot training operations in North America by multiplying the total example aircraft deliveries by the percent delivered in North America, by the percent used for pilot training.

To estimate the total flight training delivery market size, the percent of total sales volume represented by the example aircraft must be approximated in the following three steps:

- **Step 1**: Identifying the global number of piston aircraft delivered in 2018 from the GAMA report.
- **Step 2**: Adjusting this number to estimate the number of aircraft delivered for pilot training use as above.
- **Step 3**: Dividing the estimated number of example aircraft delivered in 2018 by the total number of pilot training platforms delivered.

Calculated next are the projected conventional pilot training aircraft delivery market sizes for 2025 to 2030, using annual delivery numbers and the estimated percent of the market made up by the example aircraft. Five steps are required:

- **Step 1**: Identifying published purchase pricing, for example, aircraft.
- **Step 2**: Identifying expected price inflation rate predictions from the Federal Reserve.
- **Step 3**: Calculating inflated aircraft prices for 2025 to 2030.
- **Step 4**: Multiplying the projected example aircraft sales numbers by the estimated aircraft costs and summing.
- **Step 5**: Calculating the total projected flight training sales market by dividing example aircraft deliveries by the estimated percent of the total sales volume represented by the example aircraft.

Electric Flight Training Aircraft Market Size

The next calculation estimates the sales per year of electric versions of the example aircraft from 2025 to 2030.

- **Step 1**: Identifying the estimated percent of the pilot training sales market represented by electric aircraft sales for each year (*Upside: Starting at one percent then increasing annually to 26 percent over 5 years; Baseline: Starting at one percent then increasing annually to 13 percent over 5 years; Downside: Starting at zero percent then increasing annually to seven percent over 5 years*).
- **Step 2**: Calculate the number of electric versions of example aircraft sold by multiplying forecast conventional example aircraft sales per year, from above, by the electric sales percentage.

The market value of sales of electric versions of the example aircraft is then calculated using the estimated number of electric aircraft produced.

- **Step 1**: Using the previously identified purchasing price for the example aircraft.
- **Step 2**: Estimating electric aircraft price by multiplying the purchase price by the appropriate electric aircraft price modifier (*Upside: 100 percent, Baseline: 108 percent, Downside: 115 percent*).
- **Step 3**: Adjusting the calculated electric aircraft purchase price to account for projected price inflation.
- **Step 4**: Calculating the market value by multiplying adjusted electric aircraft price by the projected number of example electric aircraft produced.

The projected market size for sales of electric versions of the example aircraft is then adjusted to estimate the total market for electric flight training aircraft.

- **Step 1**: Identifying the percent of the total sales volume represented by electric aircraft.
- **Step 2**: Estimating the total electric flight training market by dividing the dollar value of produced electric versions of example aircraft by the estimated percentage of total sales volume represented by the example aircraft.

Flight Training Electric Conversion Market Size

To calculate a potential market size for the conversion of existing aircraft to electric propulsion, the model first calculates an estimate for the number of active conventional example aircraft during the 2025 to 2030 period through the following steps.

- **Step 1**: Calculating CAGR for the flight training fleet using the annual number of active flight training aircraft from the FAA General Aviation and Part 135 Activity Survey.
- **Step 2**: Determining the number of currently active example aircraft in North America through the FAA's aircraft registry database.
- **Step 3**: Adjusting the number of example aircraft to estimate the number of active example aircraft used pilot training by multiplying by the estimated percent of total piston aircraft used for pilot training.
- **Step 4**: Using the estimated annual fleet growth rate to calculate the number of active example aircraft during the 2025 to 2030 time period and summing.

The next step is to determine what percent of the active North American flight training fleet is represented by the example aircraft. This is approximated through the following three steps:

- **Step 1**: Estimating the total number of pilot training aircraft from the FAA General Aviation and Part 135 Activity Survey.
- **Step 2**: Dividing the estimated number of example aircraft used for the flight training, by the total number of active flight training aircraft.

The rate of conversion of current aircraft to electric propulsion is based on an estimate of the effective remaining lifespan distribution of active pilot training aircraft. This is first calculated for the active example aircraft using data from the FAA's aircraft registry database in the following steps:

- **Step 1**: Identifying the appropriate estimation for average aircraft lifespan from a 2018 IATA aircraft decommissioning study.
- **Step 2**: Calculating the age of active aircraft by subtracting the manufacturing year from 2019.
- **Step 3**: Estimating the remaining effective service life by subtracting aircraft age from the average life span.
- **Step 4**: Categorizing aircraft by remaining lifespan, grouping into aircraft with "10 years or more," "5 to 10 years," and "5 years or less."
- **Step 5**: Producing a percentage distribution of example aircraft age by dividing the category sizes by the total number of active example aircraft.

Based on this "remaining service life distribution," the number of active example aircraft converted each year is calculated through the following steps:

- **Step 1**: Multiplying the number of active example aircraft by the “remaining service life distribution” to estimate the number of aircraft in each category.
- **Step 2**: Multiplying the number of example aircraft in each service life category by the estimated annual conversion percentage by category (*Upside: 5, 3, and 1percent; Baseline: 4, 2, and 0 percent; Downside: 0, 0, and 0 percent*).

To reach a market value for the conversion of existing aircraft to electric propulsion, the estimated cost of conversion for the 2025 to 2030 time period must be first determined following these steps:

- **Step 1**: Identifying the appropriate conversion cost, as a percentage of the price of a new conventional aircraft, based on industry views (*Upside: 25 percent, Baseline: 30 percent, Downside: 40 percent*).
- **Step 2**: Calculating the estimated conversion cost by multiplying conventional aircraft cost by the estimated conversion cost percentage.
- **Step 3**: Adjusting projected costs for inflation, using the forecast rate of price inflation.

With an estimated price for converting existing example aircraft to electric, a total aircraft conversion market size can be calculated.

- **Step 1**: Multiplying the number of example aircraft converted to electric by the projected conversion cost.
- **Step 2**: Calculating total aircraft conversion market size by dividing the example aircraft market size by the estimated percent of the active flight training fleet represented by the example aircraft.

OEM Market Size: Personal-Use General Aviation

Conventional General Aviation Aircraft Market Size

This section begins by calculating the forecast growth rate of conventional general aviation aircraft deliveries. The growth rate is estimated in five steps:

- **Step 1**: Identifying the total number of piston aircraft deliveries in North America from 2012 to 2018.
- **Step 2**: Calculating the estimated percent of total piston aircraft used for personal use of general aviation operations from the FAA General Aviation and Part 135 Activity Survey.
- **Step 3**: Calculating the estimated number of piston aircraft delivered for personal-use general aviation operations by multiplying the total North American piston aircraft deliveries by the percent used personal-use general aviation.
- **Step 5**: Calculating the estimated CAGR between 2012 and 2018 from the calculated aircraft delivery numbers.

This growth rate is then used to calculate projected annual North American deliveries for each example aircraft for 2025 to 2030 using the following steps:

- **Step 1**: Determining the number of example aircraft delivered globally in 2018 from the GAMA 2018 year-end shipment and billing report.
- **Step 2**: Identifying what percent of global deliveries in 2018 were represented by North America from the GAMA report.
- **Step 3**: Estimating the number of example aircraft delivered for personal-use general aviation operations in North America by multiplying the total example aircraft deliveries by the percent delivered in North America, by the percent used for personal-use general aviation.

To estimate the total personal-use general aviation delivery market size, the percent of total sales volume represented by the example aircraft must be approximated in the following three steps:

- **Step 1**: Identifying the global number of piston aircraft delivered in 2018 from the GAMA report.
- **Step 2**: Adjusting this number to estimate the number of aircraft delivered for personal-use general aviation use as above.
- **Step 3**: Dividing the estimated number of example aircraft delivered in 2018 by the total number of personal-use general aviation platforms delivered.

Calculated next are the projected conventional personal-use general aviation aircraft delivery market sizes for 2025 to 2030, using annual delivery numbers and the estimated percent of the market made up by the example aircraft. Five steps are required:

- **Step 1**: Identifying published purchase pricing, for example, aircraft.
- **Step 2**: Identifying expected price inflation rate predictions from the Federal Reserve.
- **Step 3**: Calculating inflated aircraft prices for 2025 to 2030.
- **Step 4**: Multiplying the projected example aircraft sales numbers by the estimated aircraft costs and summing.
- **Step 5**: Calculating the total projected personal-use general aviation sales market by dividing example aircraft deliveries by the estimated percent of the total sales volume represented by the example aircraft.

Electric Personal-Use General Aviation Aircraft Market Size

The next calculation estimates the sales per year of electric versions of the example aircraft from 2025 to 2030.

- **Step 1**: Identifying the estimated percent of the personal-use general aviation sales market represented by electric aircraft sales for each year (*Upside: Starting at one percent then increasing annually to 26 percent over 5 years; Baseline: Starting at one percent then increasing annually to 13 percent over 5 years; Downside: Starting at zero percent then increasing annually to seven percent over 5 years*).

- **Step 2**: Calculate the number of electric versions of example aircraft sold by multiplying forecast conventional example aircraft sales per year, from above, by the electric sales percentage.

The market value of sales of electric versions of the example aircraft is then calculated using the estimated number of electric aircraft produced.

- **Step 1**: Utilizing the previously identified purchasing price for the example aircraft.
- **Step 2**: Estimating electric aircraft price by multiplying the purchase price by the appropriate electric aircraft price modifier *(Upside: 100 percent, Baseline: 108 percent, Downside: 115 percent*).
- **Step 3**: Adjusting the calculated electric aircraft purchase price to account for projected price inflation.
- **Step 4**: Calculating the market value by multiplying adjusted electric aircraft price by the projected number of example electric aircraft produced.

The projected market size for sales of electric versions of the example aircraft is then adjusted to estimate the total market for electric personal-use general aviation aircraft.

- **Step 1**: Identifying the percent of the total sales volume represented by electric aircraft.
- **Step 2**: Estimating the total electric personal-use general aviation market by dividing the dollar value of produced electric versions of example aircraft by the estimated percentage of total sales volume represented by the example aircraft.

Personal-Use General Aviation Electric Conversion Market Size

To calculate a potential market size for the conversion of existing aircraft to electric propulsion, the model first calculates an estimate for the number of active conventional example aircraft during the 2025 to 2030 period through the following steps.

- **Step 1**: Calculating CAGR for the personal-use general aviation fleet using the annual number of active personal-use general aviation aircraft from the FAA General Aviation and Part 135 Activity Survey.
- **Step 2**: Determining the number of currently active example aircraft in North America through the FAA’s aircraft registry database.
- **Step 3**: Adjusting the number of example aircraft to estimate the number of active example aircraft used personal-use general aviation by multiplying by the estimated percent of total piston aircraft used for personal-use general aviation.
- **Step 4**: Using the estimated annual fleet growth rate to calculate the number of active example aircraft during the 2025 to 2030 time period and summing.

The next step is to determine what percent of the active North American personal-use general aviation fleet is represented by the example aircraft. This is approximated through the following two steps:

- **Step 1**: Estimating the total number of personal-use general aviation aircraft from the FAA General Aviation and Part 135 Activity Survey.
- **Step 2**: Dividing the estimated number of example aircraft used for personal-use general aviation by the total number of active personal-use general aviation aircraft.

The rate of conversion of current aircraft to electric propulsion is based on an estimate of the effective remaining lifespan distribution of active personal-use general aviation aircraft. This is first calculated for the active example aircraft using data from the FAA’s aircraft registry database in the following steps:

- **Step 1**: Identifying the appropriate estimation for average aircraft lifespan from a 2018 IATA aircraft decommissioning study.
- **Step 2**: Calculating the age of active aircraft by subtracting the manufacturing year from 2019.
- **Step 3**: Estimating the remaining effective service life by subtracting aircraft age from the average life span.
- **Step 4**: Categorizing aircraft by remaining lifespan, grouping into aircraft with “10 years or more,” “5 to 10 years,” and “5 years or less.”
- **Step 5**: Producing a percentage distribution of example aircraft age by dividing the category sizes by the total number of active example aircraft.

Based on this “remaining service life distribution,” the number of active example aircraft converted each year is calculated through the following steps:

- **Step 1**: Multiplying the number of active example aircraft by the “remaining service life distribution” to estimate the number of aircraft in each category.
- **Step 2**: Multiplying the number of example aircraft in each service life category by the estimated annual conversion percentage by category (*Upside: 5, 3, and 1 percent; Baseline: 4, 2, and 0 percent; Downside: 0, 0, and 0 percent*).

To reach a market value for the conversion of existing aircraft to electric propulsion, the estimated cost of conversion for the 2025 to 2030 time period must be first determined following these steps:

- **Step 1**: Identifying the appropriate conversion cost, as a percentage of the price of a new conventional aircraft, based on industry views (*Upside: 25 percent*, *Baseline: 30 percent*, *Downside: 40 percent*).
- **Step 2**: Calculating the estimated conversion cost by multiplying conventional aircraft cost by the estimated conversion cost percentage.
- **Step 3**: Adjusting projected costs for inflation, using the forecast rate of price inflation.

With an estimated price for converting existing example aircraft to electric, a total aircraft conversion market size can be calculated.

- **Step 1**: Multiplying the number of example aircraft converted to electric by the projected conversion cost.
- **Step 2**: Calculating total aircraft conversion market size by dividing the example aircraft market size by the estimated percent of the active personal-use general aviation fleet represented by the example aircraft.

B.2 Model Assumptions: Flight Service Providers

The model structure follows a similar structure between turboprop airliner, Commuter aircraft, and light air cargo as these use cases share a similar set of assumptions. However, the values used for these assumptions differ between the use cases. Assumptions include annual flight hours, service cost, and aircraft load factor.

The flight training use case follows a different structure owing to the unique qualities of the pilot training business case. Assumptions include annual flight hours, aircraft rental cost per hour, and flight instructor cost per hour.

Note: A flight service provider (FSP) market is assumed to not exist for the personal-use general aviation use case.

Flight Service Provider Market Size: Turboprop Airliner

The first step in determining the market size for hybrid-electric or electric aircraft airliner flight services is to calculate the percentage of the total volume of conventional aircraft sales and the active conventional aircraft fleet represented by the example aircraft. This is done in three steps:

- **Step 1**: Identifying the size of the active conventional example aircraft fleet and the number of conventional example aircraft produced each year from previous sections.
- **Step 2**: Determining the total number of active conventional aircraft active in each use case and the number of conventional aircraft sold each year in each use case from previous sections.
- **Step 3**: Evaluating the percentage of the total market represented by the example aircraft by dividing the number of example aircraft active and sold each year by the total number of aircraft active and sold.

The next factor that must be determined is the total number of hybrid-electric aircraft flight hours expected in a year from the example aircraft.

- **Step 1**: Identifying the appropriate assumption for the average number of annual flight hours per aircraft for each scenario (*Upside: 4,380 hours per year, Baseline: 3,468 hours per year, Downside: 2,600 hours per year*).
- **Step 2**: Progressively summing the number of example hybrid or fully electric aircraft sold and converted each year to determine the number of active example hybrid or fully electric aircraft.

- **Step 3**: Calculating the number of example electric aircraft flight hours by multiplying the number of active example electric aircraft by the average number of annual flight hours per aircraft.

From the number of example electric aircraft flight hours, the number of annual flights made can be calculated from the following steps.

- **Step 1**: Identifying the average flight length of conventional turboprop airliners from the ATR Turboprop Market Study.
- **Step 2**: Determining the cruise speed for each example aircraft.
- **Step 3**: Calculating an average flight length for each example electric aircraft by dividing the average flight length by the example aircraft cruise speed.
- **Step 4**: Appraise the total number of example aircraft flights by dividing the total example electric aircraft flight hours by the average flight length.

To determine the flight services market value, the model then calculated the estimated revenue per passenger seat mile for the 2025 to 2030 period.

- **Step 1**: Determining the current average revenue per passenger mile for the regional carrier from the FAA's Aerospace Forecast for 2019 to 2039.
- **Step 2**: Identifying the predicted annual growth rate for revenue per passenger for the 2019 to 2029 period.
- **Step 3**: Calculating the average revenue per passenger mile for the 2025 to 2030 period using the predicted annual growth rate and the current average.

As revenue is measured in passenger seat miles, the total number of annual flight miles for the example hybrid-electric aircraft must be determined.

- **Step 1**: Identifying the average length for current turboprop airliner flights.
- **Step 2**: Calculating the number of annual flight miles by multiplying the annual number of example hybrid-electric aircraft flights by the identified average flight length.

Utilizing the estimated number of hybrid-electric example turboprop airliner flights per year and the average revenue per passenger mile, the model then calculates the total flight services market size, for example, hybrid-electric aircraft in the following steps:

- **Step 1**: Identifying the passenger capacity for each example aircraft.
- **Step 2**: Identify the average load factor per flight for regional airliner operations (*Upside: 90 percent, Baseline: 85 percent, Downside: 80 percent*).
- **Step 3**: Calculating the potential annual revenue for each example hybrid-electric aircraft by multiplying the number of flight miles by the number of aircraft seats by the average aircraft load factor by the estimated revenue per passenger mile.

- **Step 4**: Calculating a total example hybrid-electric aircraft market size by summing the potential revenues for each example aircraft.

From the estimated market size for the example aircraft, the total hybrid-electric turboprop airliner market size can be calculated in one step.

- **Step 1**: Dividing the example hybrid-electric aircraft market size by the estimated percent of the total volume of active aircraft and annual aircraft sales represented by the example aircraft.

Flight Service Provider Market Size: Commuter Aircraft

The first step in determining the market size for electric aircraft flight services is to calculate the percentage of the total volume of conventional aircraft sales, and the active conventional aircraft fleet represented by the example aircraft. This is done in three steps:

- **Step 1**: Identifying the size of the active conventional example aircraft fleet and the number of conventional example aircraft produced each year from previous sections.
- **Step 2**: Determining the total number of active conventional aircraft active in each use case and the number of conventional aircraft sold each year in each use case from previous sections.
- **Step 3**: Evaluating the percentage of the total market represented by the example aircraft by dividing the number of example aircraft active and sold each year by the total number of aircraft active and sold.

The next factor that must be determined is the total number of electric aircraft flights expected in a year from the example aircraft.

- **Step 1**: Identifying the appropriate assumption for the average number of annual flight hours per aircraft for each scenario. *(Upside: 500 hours per year, Baseline: 435 hours per year, Downside: 370 hours per year).*
- **Step 2**: determining the average flight length for conventional commuter aircraft from the U.S. Department of Transportation (DOT) aviation transportation database.
- **Step 3**: Progressively summing the number of fully electric example aircraft sold and converted each year to determine the number of active example electric aircraft.
- **Step 4**: Calculating the number of example electric aircraft flights by multiplying the number of active example electric aircraft by the average number of annual flight hours per aircraft and dividing by the average flight length.

Using the estimated number of electric example aircraft flights per year, the model then calculates the total flight services market size, for example, electric aircraft, in the following steps:

- **Step 1**: Identifying the passenger capacity for each example aircraft.
- **Step 2**: Identify the average load factor per flight for commuter aircraft operations (*Upside: 58 percent, Baseline: 51 percent, Downside: 45 percent*).

- **Step 3**: Estimating the average passenger ticket price based on pricing models from three air taxi and commuter air services (*Upside: $92, Baseline: $106, Downside: $120*).
- **Step 4**: Calculating the potential annual revenue for each example electric aircraft by multiplying the number of flights by the number of aircraft seats by the average aircraft load factor by the estimated passenger ticket price.
- **Step 5**: Calculating a total example electric aircraft market size by summing the potential revenues for each example aircraft.

From the estimated market size for the example aircraft, the total electric commuter aircraft market size can be calculated in one step.

- **Step 1**: Dividing the example electric aircraft market size by the estimated percent of the total volume of active aircraft and annual aircraft sales represented by the example aircraft.

Flight Service Provider Market Size: Light Air Cargo

The first step in determining the market size for electric aircraft flight services is to calculate the percentage of the total volume of conventional aircraft sales and the active conventional aircraft fleet represented by the example aircraft. This is done in three steps:

- **Step 1**: Identifying the size of the active conventional example aircraft fleet and the number of conventional example aircraft produced each year from previous sections.
- **Step 2**: Determining the total number of active conventional aircraft active in each use case and the number of conventional aircraft sold each year in each use case from previous sections.
- **Step 3**: Evaluating the percentage of the total market represented by the example aircraft by dividing the number of example aircraft active and sold each year by the total number of aircraft active and sold.

The next factor that must be determined is the total number of electric aircraft flights expected in a year from the example aircraft.

- **Step 1**: Identifying the appropriate assumption for the average number of annual flight hours per aircraft for each scenario (*assumed to be fixed at 370 hours per year*).
- **Step 2**: Determining the average flight length for conventional light air cargo aircraft from the U.S. DOT aviation transportation database.
- **Step 3**: Progressively summing the number of fully electric example aircraft sold and converted each year to determine the number of active example electric aircraft.
- **Step 4**: Calculating the number of example electric aircraft flights by multiplying the number of active example electric aircraft by the average number of annual flight hours per aircraft and dividing by the average flight length.

Using the estimated number of electric example aircraft flights per year, the model then calculates the total flight services market size for example electric aircraft in the following steps:

- **Step 1**: Identifying the cargo capacity for each example aircraft.
- **Step 2**: Identify the average load factor per flight for light air cargo operations (*Upside: 33 percent, Baseline: 32 percent, Downside: 30 percent*).
- **Step 3**: Estimating the average per pound cargo price based on pricing models from two light air cargo services (*Upside: $0.91, Baseline: $1.04, Downside: $1.16*).
- **Step 4**: Calculating the potential annual revenue for each example electric aircraft by multiplying the number of flights by the aircraft cargo capacity by the average aircraft load factor by the estimated cargo price per pound.
- **Step 5**: Calculating a total example electric aircraft market size by summing the potential revenues for each example aircraft.

From the estimated market size for the example aircraft, the total electric light air cargo market size can be calculated in one step.

- **Step 1**: Dividing the example electric aircraft market size by the estimated percent of the total volume of active aircraft and annual aircraft sales represented by the example aircraft.

Flight Service Provider Market Size: Flight Training

The first step in determining the market size for electric aircraft flight services is to calculate the percentage of the total volume of conventional aircraft sales, and the active conventional aircraft fleet represented by the example aircraft. This is done in three steps:

- **Step 1**: Identifying the size of the active conventional example aircraft fleet and the number of conventional example aircraft produced each year from previous sections.
- **Step 2**: Determining the total number of active conventional aircraft active in each use case and the number of conventional aircraft sold each year in each use case from previous sections.
- **Step 3**: Evaluating the percentage of the total market represented by the example aircraft by dividing the number of example aircraft active and sold each year by the total number of aircraft active and sold.

The next factor that must be determined is the total number of electric aircraft flight hours expected in a year from the example aircraft.

- **Step 1**: Identifying the appropriate assumption for the average number of annual flight hours per aircraft for each scenario. *(Upside: 459 hours per year, Baseline: 435 hours per year, Downside: 370 hours per year)*
- **Step 2**: Progressively summing the number of fully electric example aircraft sold and converted each year to determine the number of active example electric aircraft.
- **Step 3**: Calculating the number of example electric aircraft flight hours by multiplying the number of active example electric aircraft by the average number of annual flight hours per aircraft.

Using the estimated number of electric example aircraft flight hours per year, the model then calculates the total flight service market size for example electric aircraft, in the following steps:

- **Step 1**: Estimating the per hour aircraft rental cost for flight training from a survey of several flight training schools *(Upside: $95 per hour, Baseline: $108 per hour, Downside: $120 per hour).*
- **Step 2**: Identifying the average per hour cost of flight instruction (*assumed to be fixed across scenarios*).
- **Step 3**: Calculating the example electric aircraft pilot training market by summing the per hour aircraft rental cost and the per hour flight instruction cost and multiplying by the total example aircraft flight hours.

From the estimated market size for the example aircraft, the total electric flight training market size can be calculated in one step.

- **Step 1**: Dividing the example electric aircraft market size by the estimated percent of the total volume of active aircraft and annual aircraft sales represented by the example aircraft.

B.3 **Model Assumptions: MRO**

The model structure for the maintenance, repair, and overhaul (MRO) market segment remains the same for commuter aircraft, light air cargo, flight training, and personal-use general aviation use cases. The primary assumption, MRO cost savings, will only vary between the upside, baseline, and downside scenarios as these use cases are all expected to use fully electric propulsion.

Turboprop Airliners, assumed to leverage hybrid-electric propulsion, use a different set of values for MRO cost savings.

MRO Market Size: Commuter Aircraft, Light Air Cargo, Flight Training, and Personal-Use General Aviation

Determining the potential market size for electric aircraft MRO services across the use cases begins by estimating the per flight hour maintenance costs for the example electric aircraft.

- **Step 1**: Identifying baselines estimate for conventionally power example aircraft maintenance costs.
- **Step 2**: Determining the estimated MRO cost-savings assumptions for electric aircraft over conventionally powered platforms (*Upside: 50 percent savings, Baseline: 35 percent savings, Downside: 20 percent savings*).
- **Step 3**: Calculating the estimated costs for electric example aircraft by multiplying the baseline maintenance cost estimates by one minus the appropriate electric cost-savings percentage.
- **Step 4**: Determining estimated MRO costs for the example aircraft during the 2025 to 2030 period by adjusting the MRO per hour cost to account for the predicted inflation rate.

From the estimated hourly MRO costs for the example hybrid-electric aircraft, the total electric MRO market size can be calculated with the following steps:

- **Step 1**: Multiplying the estimated example electric aircraft MRO cost per flight hour by the calculated total flight hours per year for the example electric aircraft fleet.
- **Step 2**: Producing a total MRO market size for all example aircraft by summing the MRO market for the individual example aircraft.
- **Step 3**: Calculating the total estimated MRO market size for electric aircraft by dividing the example electric aircraft market size by the estimated percent of the total conventional aircraft volume, active fleet, and annual sales, represented by the example aircraft.

MRO Market Size: Turboprop Airliner

Determining the potential market size for electric aircraft MRO services across the use cases begins by estimating the per flight hour maintenance costs for the example electric aircraft.

- **Step 1**: Identifying baselines estimate for conventionally power example aircraft maintenance costs.
- **Step 2**: Determining the estimated MRO cost-savings assumptions for electric aircraft over conventionally powered platforms (*Upside: 30 percent savings, Baseline: 20 percent savings, Downside: 0 percent savings*).
- **Step 3**: Calculating the estimated costs for electric example aircraft by multiplying the baseline maintenance cost estimates by one minus the appropriate electric cost-savings percentage.
- **Step 4**: Determine estimated MRO costs for the example aircraft during the 2025 to 2030 period by adjusting the MRO per hour cost to account for the predicted inflation rate.

From the estimated hourly MRO costs for the example hybrid-electric aircraft, the total electric MRO market size can be calculated with the following steps:

- **Step 1**: Multiplying the estimated example electric aircraft MRO cost per flight hour by the calculated total flight hours per year for the example electric aircraft fleet.
- **Step 2**: Producing a total MRO market size for all example aircraft by summing the MRO market for the individual example aircraft.
- **Step 3**: Calculating the total estimated MRO market size for electric aircraft by dividing the example electric aircraft market size by estimated percent of the total conventional aircraft volume, active fleet, and annual sales, represented by the example aircraft.

B.4 **Model Assumptions: Infrastructure Development**

The model structure for the infrastructure development market segment does not vary in procedure between the five use cases. The primary assumption, charger cost per kilowatt (kW), changes only between the upside, baseline, and downside scenarios.

Infrastructure Development Market Size: All Use Cases

Evaluating the potential market size centers on estimating the power consumed by the example electric aircraft during an average flight. For calculating the amount of electricity consumed during average operations, the model follows these steps for each use case:

- **Step 1**: Identifying the power level, in kW, of the example aircraft electric motors.
- **Step 2**: Determining the estimated amount of time, in minutes, an example electric aircraft spends in each of the following flight phases: departure taxi, takeoff, cruise, descent, and arrival taxi based on average flight length of each use case and input from an aviation authority.
- **Step 3**: Ascertaining the estimated percent of available propulsion power required for each flight phase based on input from an industry authority.
- **Step 4**: Calculating the electricity used in each phase by multiplying the aircraft motor power level, by the time spent in each flight phase, by the required amount of propulsion power.
- **Step 5**: Dividing the calculated electricity amount by 60 to obtain kilowatt-hours (kWh).

The next phase is to determine the charger capacity necessary to support the example electric aircraft operations.

- **Step 1**: Identifying the required charging time in hours, based on the pace of conventional aircraft operations in each use case.
- **Step 2**: Calculating the necessary charger capacity by dividing the calculated electricity expenditure by the required charging time.

From the calculated requirements for charger capacity, the total cost per charger can be determined.

- **Step 1**: Determining the estimated charger cost per kW for each scenario (*Upside: $395 per kW, Baseline: $464 per kW, Downside: $553 per kW*).
- **Step 2**: Calculating charger cost by multiplying the estimated per kW charger cost by the required charger capacity.

The next required metric is the number of chargers necessary to support the fleet of active example electric aircraft. This is determined in the following two steps:

- **Step 1**: Identifying an estimated number of chargers required per example electric aircraft, based on operational tempo and the number and concentration of potential destinations.
- **Step 2**: Calculating the total number of chargers necessary to support the active example aircraft fleet by multiplying the estimated number of chargers per aircraft by the number of active aircraft each year.

Finally, the potential size of the total electric aircraft charging infrastructure market for each use case can be calculated using the following steps:

- **Step 1**: Calculating the infrastructure market size for active example electric aircraft by multiplying the calculated cost per charger by the number of chargers required to support active example electric aircraft operations.
- **Step 2**: Evaluating the total infrastructure market size for electric aircraft operations by dividing the market size for example electric aircraft by the previously calculated percent of the total conventional aircraft volume, active fleet, and annual sales, represented by the example aircraft (calculated in Section B.2, Model Assumptions: Flight Service Providers).

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APPENDIX C

Electric Aircraft Characteristics for Airport Planning

Manufacturer / Lead OEM	Aircraft Model	Propulsion Type	Role	Power Source	Crew	Passenger(s)	Wingspan (ft.)	Length (ft.)	Height (ft.)	Airplane Design Group (ADG)	No. of Batteries	No. of Motors	First Flight	Country
Agusta Westland	Project Zero	eVTOL (tilt rotor)	Experimental (UAV)	Battery	0-1	0	39.4	28.8	4.6	I	-	2	2011	Italy
A2-Cal	Aptos Blue	eVTOL (tilt rotor)	Emergency Medical Service	Battery	1	2	52	-	-	II	8	8	-	United States
ACS Aviation	Z-300	eVTOL (tilt rotor)	Air Taxi	Battery	0-1	1-2	-	-	-	-	-	4	-	Brazil
AeroG Aviation LLC	aG-4 Liberty	VTOL	Commuter / Cargo	Hybrid	2	10	48.55	42	17.5	I	-	4	-	United States
Air Energy	AE-1 Silent	Propeller (Motor glider)	Experimental	Battery	1	0	39.4	-	-	I	1	1	1998	Germany
Airbus A^3	Vahana	Propeller	Experimental	Battery	0	1	20.6	18.7	9.3	I	1	8	2018	United States
Airbus	City Airbus	eVTOL	Air Taxi	Battery	1	4	26.3	26.3	-	I	4	8	2019	Multinational
Airbus	E-Fan	eVTOL	Experimental	Battery	1	1	31.2	21.9	6.65	I	1	2	2014	Multinational
Airbus	E-Fan x	eCTOL	Experimental	Hybrid	2	70-112	86	102	28.2	III	-	2	-	Multinational
Airbus	Zero E Turbofan	CTOL	Regional	Fuel Cell	2	< 100	-	-	-	-	-	-	-	Multinational
Airbus	Zero E Turboprop	CTOL	Regional	Fuel Cell	2	<200	-	-	-	-	-	-	-	Multinational
AirCar Corp	AirCar	eVTOL	Air Taxi	Battery	1	2	-	-	-	-	-	8	2018	United States &Turkey
Airspace Experience Technologies	MOBi-ONE V1	eVTOL (tilt wing)	Air Taxi	Battery	0-2	2-4	40	30	10	I	-	7	-	United States
Ampaire	Echo Otter SX	CTOL (Propeller)	Regional	Hybrid	1-2	19	65	51.9	19.6	II	-	4	-	United States
Ampaire	Electric Eel	CTOL (Propeller)	Air Taxi	Hybrid	1	3	38.1	29.8	9.4	I	-	2	2019	United States
AMSL Aero Pty Ltd	Vertiia	eVTOL	Air Taxi	Battery	1	1	-	-	-	-	-	8	2020	Australia
APEV	Pouchelec	Ultralight	Recreational	Battery	1	0	23.11	-	-	I	-	1	2009	France
Apus	I-2	CTOL (Propeller)	Air Taxi	Fuel Cell	1	3	41	27.9	10.8	I	-	1	2019	Germany
Archer Aviation	Maker	eVTOL (tilt rotor)	Air Taxi	Battery	1	4	-	-	-	-	-	12	2021	United States
AstroFlight	Sunrise	CTOL (Propeller)	Experimental (UAV)	Solar	0	0	32	14.3	-	I	1	1	1975	United States
Aura Aero	Integral E	CTOL (Propeller)	Aerobatic	Battery	1	1	28.8	23.82	8.1	I	-	1	2022	France

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Manufacturer / Lead OEM	Aircraft Model	Propulsion Type	Role	Power Source	Crew	Passenger(s)	Wingspan (ft.)	Length (ft.)	Height (ft.)	Airplane Design Group (ADG)	No. of Batteries	No. of Motors	First Flight	Country
Aura Aero	ERA	CTOL (Propeller)	Regional / Cargo	Battery	0-1	19	-	-	-	-	-	-	2024	France
Aurora Flight Sciences	Pegasus	Lift and Cruise	Air Taxi	Battery	1	1	28	30	-	I	-	8	2019	United States
AutoGyro	Cavalon	Rotorcraft	Experimental	Battery	1	1	27.7	15.1	9.2	I	-	1	2013	Germany
Autonomous Flight	Y6S	eVTOL (tilt rotor)	Air Taxi	Battery	1	1	-	-	-	-	-	6	2018	United Kingdom
Baaz	Baaz B5	eVTOL (tilt rotor)	Air Taxi	Battery / Hybrid	1	4	44.4	25.7	4.9	I	-	9	-	Germany
Bartini	Bartini eVTOL	eVTOL (tilt rotor)	Air Taxi	Battery	1	3	14.8	17.1	5.6	I	-	4	2018	United States
Bell	Nexus 4EX	eVTOL (tilt rotor)	Air Taxi	Battery	1	4	40	40	-	I	-	4	-	United States
Bell	Nexus 6HX	eVTOL (tilt rotor)	Air Taxi	Battery	1	4	40	40	-	I	-	6	-	United States
Beta	AVA	eVTOL	Air Taxi	Battery	1	1	34	-	-	I	2	8	2019	United States
Beta	ALIA 250	Lift and Cruise	Commuter/ Cargo	Battery	1	5	50	-	-	II	-	5	2020	United States
Boeing	Diamond DA36 E-Star	Propeller (Motor glider)	Experimental	Hybrid	1	1	52.6	23	5.5	II	-	1	2008	United States
Braunwagner	SkyCab	Lift and Cruise	Air Taxi	Battery	1	4	39.4	33.1	9.7	I	-	6	2023	Germany
Bye Aerospace	eFlyer 2	CTOL (Propeller)	Trainer	Battery	1	1	38	-	-	I	6	1	2018	United States
Bye Aerospace	eFlyer 4	CTOL (Propeller)	Air Taxi / Recreational	Battery	1	3	38	-	-	I	-	1	-	United States
Bye Aerospace	eFlyer 800	CTOL (Propeller)	Commuter / Cargo	Battery	1-2	7-8	-	-	-	-	4	2	-	United States
Dante AeroNautical	DAX-19	CTOL (Propeller)	Regional	Hybrid	1-2	19	-	-	-	-	-	-	2024	Spain
DLR/ Pipistrel	HY4	CTOL (Propeller)	Air Taxi	Fuel Cell	1	3	70	24	4.7	II	1	1	2016	Germany
Dufour Aerospace	aEro 1	eVTOL (tilt wing)	Aerobatic	Battery	1	0	14.8	-	-	I	-	1	2016	Switzerland
Dufour Aerospace	aEro 2	eVTOL (tilt wing)	Air Taxi	Battery	0-1	1-2	33	-	-	I	-	2	2016	Switzerland
Dufour Aerospace	aEro 3	eVTOL (tilt wing)	Emergency Medical Service	Battery	1	7	14.8	-	-	I	-	4	-	Switzerland
Ehang	Ehang 184	eVTOL (Multicopter)	Air Taxi	Battery	0	1	18.1	12.8	4.9	I	-	8	2016	China

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Manufacturer / Lead OEM	Aircraft Model	Propulsion Type	Role	Power Source	Crew	Passenger(s)	Wingspan (ft.)	Length (ft.)	Height (ft.)	Airplane Design Group (ADG)	No. of Batteries	No. of Motors	First Flight	Country
Ehang	Ehang 216	eVTOL (Multicopter)	Air Taxi	Battery	0	2	-	18.5	5.9	-	-	16	2019	China
Electric Aircraft Corporation	ElectraFlyer C	Propeller (Motor glider)	Recreational	Battery	1	0	45.7	-	-	I	1	1	2008	United States
Electric Aircraft Corporation	ElectraFlyer ULS	Propeller (Motor glider)	Recreational	Battery	1	0	-	-	-	-	1 or 2	1	2012	United States
Electric Aircraft Corporation	ElectraFlyer X	Propeller (Motor glider)	Light-sport aircraft	Battery	1	1	49.3	-	-	II	-	1	2009	United States
Elroy Air	Chaparral	eVTOL	Cargo	Battery	0	0	-	-	-	-	-	6	2019	United States
Eve Air Mobility	Eve	eVTOL (tilt rotor)	Air Taxi	Battery	1	4	-	-	-	-	-	8	-	Brazil
Eviation	Alice	Propeller	Commuter	Battery	2	9	59.1	56.1	12.7	II	1	3	2022	Israel
Faradair Aerospace	BEHA	Ducted fan	Regional	Hybrid	1	18	57	48.2	14.1	II	-	2	-	United Kingdom
HB-Flugtechnik	Militky MB-E1	CTOL (Propeller)	Experimental	Battery	1	1	54	9.8	-	II	1	1	1973	Germany
Heart Aerospace	ES-19	CTOL (Propeller)	Regional	Battery	1	19	-	-	-	-	-	-	-	United States
Horizon Aircraft	Cavorite X5	Lift and Cruise	Air Taxi / Cargo	Hybrid	1	4	50.3	38	9.2	II	-	17	-	Canada
Hyundai	S-A1	eVTOL (tilt rotor)	Air Taxi	Battery	1	4	-	-	-	-	7	8	-	South Korea
IFB-Stuttgart	e-Genius	Propeller	Experimental	Battery	1-2	0-1	55.5	26.7	-	II	4	1	2011	Germany
Joby Aviation	Monarch	eVTOL (tilt wing)	Personal Air Vehicle	Battery	1	0	37	22	-	I	-	8	-	United States
Joby Aviation	S4	Propeller	Air Taxi	Battery	1	4	-	24	-	-	-	6	2019	United States
KARI	OPPAV	eVTOL (tilt rotor)	Air Taxi	Battery	1	4-5	23	20	-	I	-	8	2022	South Korea
Kitty Hawk Corporation	Heaviside	eVTOL (tilt rotor)	Personal Air Vehicle	Battery	0-1	0	20	-	-	I	-	6	2019	United States
Lange Aviation	Antares 20E	Propeller (Motor glider)	Experimental	Battery	1	0	65.7	24.3	5.4	II	-	1	2003	Germany
Lange Aviation	Antares 23E	Propeller (Motor glider)	Experimental	Battery	1	0	75.5	24.4	6.2	II	-	1	2012	Germany
Lilium GmbH	Eagle	eVTOL	Air Taxi	Battery	0	2	-	-	-	-	-	36	2017	Germany
Lilium GmbH	Lilium Jet	eVTOL	Commuter	Battery	1	6	45.6	27.6	-	I	-	36	2019	Germany
MagniX	Cessna Caravan	Propeller	Experimental	Battery	1-2	1-2	52.1	37.7	14.1	II	-	1	2020	United States

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Manufacturer / Lead OEM	Aircraft Model	Propulsion Type	Role	Power Source	Crew	Passenger(s)	Wingspan (ft.)	Length (ft.)	Height (ft.)	Airplane Design Group (ADG)	No. of Batteries	No. of Motors	First Flight	Country
NASA	Centurion	Propeller	UAV	Solar	0	0	206	12	-	-	-	14	1998	United States
NASA	Helios	Propeller	UAV	Battery	0	0	247	12	-	-	-	14	1999	United States
NASA	Pathfinder	Propeller	UAV	Solar	0	0	98.4	12	-	III	-	6	1993	United States
NASA	Puffin	eVTOL (tilt rotor)	Experimental	Battery	1	0	13.6	12	-	I	-	2	2010	United States
NASA	X-57 Maxwell	Propeller	Experimental	Battery	1	1	31.6		-	I	2	14	2020	United States
Opener Inc	BlackFly	eVTOL	Air Taxi	Battery	1	0	13.7	13.5	5	I	16	8	2014	United States
Orca Aerospace	Orca eVTOL	eVTOL (tilt rotor)	Emergency Medical Service	Battery	1	2	43	26.5	7.2	I	6	7	2021	Hungary
Overair, Inc.	Butterfly	eVTOL (tilt rotor)	Air Taxi	Battery	1	4	-		-	-	-	4	-	United States
Phoenix	U-14 Electra	Propeller (Motor glider)	Recreational	Battery	1	0	47.5	21	-	I	-	1	2011	Czech Republic
Phoenix Air	ΦNIX	Propeller (Motor glider)	Recreational	Battery	1	1	49.3	21.5	-	II	-	1	2018	Czech Republic
Pipistrel	Alpha Electro	CTOL (Propeller)	Flight Training	Battery	1	1	34.5	21.4	6.9	I	-	1	2011	Slovenia
Pipistrel	Nuuva V300	eVTOL	Cargo	Hybrid	0	0	43.4	33.1	10	I	-	8	-	Slovenia
Pipistrel	Panthera Electro	Propeller	Air Taxi	Battery	1	1	35.8	26.6	7.2	I	-	1	2013	Slovenia
Pipistrel	PRVK-1	CTOL (Propeller)	Regional	Fuel Cell	1	19	68.8	48.4	15.7	II	1	-	-	Slovenia
Pipistrel	Taurus Electro G2	Propeller (Motor glider)	Recreational	Battery	1	1	49.5	24	8.9	II	4	1	2011	Slovenia
Pipistrel	Taurus	Propeller (Motor glider)	Recreational	Battery	1	1	49	-	-	II	-	1	2011	Slovenia
Pipistrel	Taurus Electro	Propeller (Motor glider)	Recreational	Battery	1	1	49	-	-	II	-	1	2020	Slovenia
QinetiQ	Zephyr 7	CTOL (Propeller)	Patrol (UAV)	Solar	0	0	74	-	-	II	-	2	2008	United Kingdom
QinetiQ	Zephyr 8	CTOL (Propeller)	Patrol (UAV)	Solar	0	0	92	-	-	III	-	2	2008	United Kingdom
Regent	Seaglider	CTOL (Propeller)	Seaplane	Battery	-	-	-	-	-	-	8	-	-	United States
Sabrewing	Draco-2	eVTOL (tilt rotor)	Experimental	Battery	-	-	38.1	28.2	6.9	I	-	8	-	United States
Sabrewing	Rhaegal RG-1	eVTOL (tilt rotor)	Cargo	Hybrid	0	0	55.8	47.9	15.1	II	-	4	2021	United States

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Manufacturer / Lead OEM	Aircraft Model	Propulsion Type	Role	Power Source	Crew	Passenger(s)	Wingspan (ft.)	Length (ft.)	Height (ft.)	Airplane Design Group (ADG)	No. of Batteries	No. of Motors	First Flight	Country
Smart flyer	SFX1	CTOL (Propeller)	Commuter	Hybrid	1	3	39.3	27.2	11.5	I	4	1	2021	Switzerland
Tecnam	P-Volt	CTOL (Propeller)	Commuter	Battery	2	9	45.9	-	-	I	-	2	2026	Italy
Transcend Air	Vy 400	eVTOL (tilt wing)	Air Taxi	Hybrid	1	5	-	-	-	-	-	1	2022	United States
TU Delft	Greenliner	eCTOL	Regional	Fuel Cell	2	19	50	-	-	II	-	18	2018	Netherlands
Uber Elevate	eCRM-001	eVTOL (tilt rotor)	Air Taxi	Battery	1	4	-	-	-	-	-	6	-	United States
Vertical Aerospace	VA-X1	eVTOL	Experimental	Battery	0	4	-	-	-	-	-	4	2018	United Kingdom
Vertical Aerospace	VA-X2	eVTOL	Air Taxi	Battery	0	2	26.3	26.3	9.9	I	-	12	2019	United Kingdom
Vertical Aerospace	VA-X4	eVTOL (tilt rotor)	Air Taxi	Battery	1	4	49.2	42.8	13.1	II	-	8	2021	United Kingdom
Volocopter	VoloCity	eVTOL	Air Taxi	Battery	1	2	37	-	8.2	I	9	18	2013	Germany
Volocopter	VoloConnect	eVTOL	Air Taxi	Battery	1	3	-	-	-	-	-	6	-	Germany
VoltAero	Cassio 330	CTOL (Propeller)	Commuter	Hybrid	1	3	-	-	-	-	-		2020	France
VoltAero	Cassio 480	CTOL (Propeller)	Commuter	Hybrid	1-2	4-5	-	-	-	-	-	3	-	France
VoltAero	Cassio 600	CTOL (Propeller)	Commuter	Hybrid	1-2	8-9	-	-	-	-	-		-	France
Wisk	Cora	eVTOL	Air Taxi	Battery	0	2	36	21	-	I	-	12	2018	United States
Zunum Aero	ZA10	CTOL (turbine)	Commuter	Hybrid	0-2	12	52	42	18	II	-	-	-	United States

Notes:

- *These data are provided for information purposes based on preliminary figures and drawings released by original equipment manufacturer (OEMs). Almost all electric aircraft listed are at the conceptual, development, or prototype stage. These data should be considered as preliminary and subject to significant changes.*
- *CTOL = conventional takeoff and landing; and eVTOL = electric vertical takeoff and landing.*
- *More information on these aircraft can be found in the Electric Aircraft List Spreadsheet in the toolbox.*

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APPENDIX D

Electric Aircraft Safety Review

Throughout the research project, airport safety hazards were identified for further investigation. They are listed and discussed in the following table. They might be considered when planning and designing facilities accommodating or supporting electric aircraft operations, as well as in the definition of operating procedures.

Note 1: This appendix is not intended to provide an aviation safety risk assessment for the introduction of electric aircraft at airports. It only provides safety perspectives identified during the research project that might benefit such risk assessment. It is the responsibility of airport operators, flight operators, and other stakeholders of airport operations to perform a safety risk assessment when introducing changes to their operations as part of their safety management system.

Note 2: Few electric aircraft accidents and incidents have occurred due to the novelty of the technology. All flights were experimental. Recorded accidents include:

- *Forced landing of the Piper PA-46 G-HYZA in April 2021 near Cranfield Airport, United Kingdom. The aircraft received substantial damages after running on uneven terrain at low speed. The aircraft was modified by ZeroAvia with an electric engine powered by fuel cells.*

- *Fire during the ground testing of an Eviation Alice in January 2020 at Prescott Regional Airport, Arizona. The fire may have been caused by a ground-based battery system.*

- *Crash of the Pipistel Alpha Electro LN-ELA in August 2019 near Gullknapp Flpl Airport, Norway following a sudden loss of motor power during the final part of a demonstration fligh (NSIA Report of March 2021).*

Hazard	Safety Risks	Potential Cause(s)	Assessment & Potential Mitigation
Electric Aircraft (All Technologies)			
General hazards related to non-typical aircraft configurations and propulsion system of electric aircraft.	For instance: unusual location of propellers and lower noise level increase risk of deadly accident on the ramp when motors are on.	Location and design of powertrain can make it difficult for ramp personnel to identify propellers in motion.	Most clean-sheet electric aircraft designs adopt relatively conventional configurations. Some electric vertical takeoff and landing aircraft (eVTOLs) have innovative design features including tiltrotors. Risk should be assessed for each new aircraft type or general configuration as part of the safety management system of the stakeholders. Joint training sessions with the ramp operations community to educate on these new aircraft might be considered.
Charging/refueling/swapping operations adversely interact with other ground handling operations.	Likelihood and severity of existing risks are increased.	Placement and maneuvers of ground support equipment and/or actions of ground handlers could hinder other operations.	The turnaround process at the gate should be taken into consideration in the design and development of electric aircraft. Mitigation could include, for instance, electric or hydrogen port locations on the aircraft that minimize adverse impacts and additional ports for providing alternatives to ground handlers.
Electric Battery Technologies			
Collision of aircraft with a retractable charging unit (e.g., hatch) that is not retracted when the aircraft is moving.	Damage to aircraft and/or ground support equipment.	Ground handling agent forgot to put the hatch or bay in position “DOWN.”	Some charging equipment might be installed in underground chambers on the ramp. The plugs might be accessible through a deployable hatch or bay. This technology is already available for 400 hertz (Hz) alternating current group power support. Risk might be mitigated the same way through awareness or alert systems (e.g., visual system and/or alarm paired with sensors, smart system on tablet or smartphone).
Battery-specific hazards hinder airport rescue and firefighting (ARFF) operations.	Response time is lengthened. Operations are complexified. Firefighters sustain injuries.	ARFF does not have the adequate equipment and procedures to operate.	Larger batteries have been introduced on transport aircraft nearly two decades ago with the Airbus A350 and the Boeing 787. Their safety issues are known and documented. Potential novel risks from new battery technologies should be addressed the same way.
Electric risk to ground handlers including undesired arcing/discharge when swapping batteries.	Injuries to ground handlers and passengers, and damage to aircraft battery systems.	Short circuit, switching device in poor condition, etc.	Industry standards and best practices exist to mitigate the risk of undesired arcing/discharge from electric systems and batteries. They should be considered in the design of electric aircraft and equipment and incorporated into procedures for ground handlers and maintenance.
Ramp worker or passenger trips on wiring between the aircraft and electric chargers.	Injuries due to fall on the ground.	Cables are on the path of other operations including boarding/deplaning. Cables are not conspicuous.	Standard operating procedures that minimize exposure of ramp personnel to cables should be defined, as well as walk-in/walk-out boarding/deplaning procedures that would avoid cables. Provide different charging options on the aircraft that would increase operational flexibility with different stand geometries/charger locations. Design and install charging stations that would minimize cable length.
Batteries can generate intense heat/smoke in the event of a thermal runaway on the airside.	Battery generates fire and/or toxic gas emissions.	Short circuit or damage due to shock in the aircraft (e.g., during maintenance or battery swap) or on the ramp (e.g., battery falls during swap or was on a	The occurrence of this event might be more frequent with battery swapping as the battery can be hurt during transport or handling. Standard operating procedures and equipment to perform operations on batteries should take this risk into account.

Hazard	Safety Risks	Potential Cause(s)	Assessment & Potential Mitigation
		truck that runs into a road accident).	
Batteries can generate intense heat/smoke in the event of a thermal runaway when stored.	Battery generates fire and/or toxic gas emissions.	Same as above from an inventory of battery (swapping) or at a repair shop or maintenance center.	Industry practices exist to store batteries safely.
The battery increases the severity of a low-energy aviation accident or incident (e.g., collision on taxiway/ramp), a runway excursion, or an undershoot.	Batteries can go through a thermal runaway, catch fire, emit toxic gas, or leak.	Battery is damaged during the accident or incident.	Electric aircraft batteries should be able by design to withstand these events or not increase the severity of such occurrences (assuming reasonable scenarios).
The battery increases the severity of a high-energy aviation accident (e.g., aircraft collision on runway).	Batteries can go through a thermal runaway, catch fire, emit toxic gas, or leak.	Battery is damaged during the accident.	Electric aircraft batteries should not increase the typical severity of such occurrences. Battery runaway is not expected to be a significant factor in such event typically involving the partial or total destruction of the aircraft.
Hydrogen Fuel Cell Technologies			
Hydrogen-specific hazards hinder ARFF operations.	Response time is lengthened. Operations are complexified. Firefighters sustain injuries.	ARFF does not have the adequate equipment and procedures to operate.	Hydrogen, or H_2, is a well-known industrial gas. Standards [including the National Fire Protection Association (NFPA) standards], procedures, and practices exist within the firefighting community to handle accidents and incidents involving large quantities of hydrogen. They may have to be adapted to the airport environment (e.g., through a revision of NFPA standards).
Vehicle transporting hydrogen tanks or containers at the airport is involved into a roadway or vehicle service road accident.	Hydrogen fire or explosion.	Tanks explode due to extreme heat (fire) or mechanical stress (due to accident).	This risk can be mitigated through tank design. Standards already exist for hydrogen tanks. Also, the U.S. Department of Transportation (DOT) recommends that: • Cylinders exposed to fire may vent and release flammable gas through pressure relief devices. • Fight hydrogen fires from maximum distance or use unmanned hose holders or monitor nozzles. • Cool containers with flooding quantities of water until well after fire is out.
Hydrant system or pipeline transporting hydrogen at the airport sustains an accident.	Hydrogen line or chamber is damaged. Large quantities of hydrogen are discharged in the air. Potential fire and explosion.	Vehicle or object collides with above-the-ground pipeline or hydrant equipment. Underground line is damaged during construction.	There are few accidents or accidents related to hydrogen pipelines as of today. However, the introduction of such infrastructure in the airport environment might create new exposure/vulnerability that should be assessed and mitigated accordingly. At the local (airport) level, the airport community should be educated about these new hazards through joint training sessions with the stakeholders.
Pit of a hydrogen hydrant system leaks or is damaged.	Large quantities of hydrogen are discharged	Same as today’s fuel pits.	NFPA 407 guidance on hydrant system (esp. separation distances) should be revised to take into consideration hydrogen lines.

Hazard	Safety Risks	Potential Cause(s)	Assessment & Potential Mitigation
	in the air. Potential fire and explosion.		
For storing H_2 on-site airport, there are risks of leakages, fire, and explosion	Potential leakages, fire, and explosion	Damage to container or tank	To store pressurized gaseous hydrogen containers: • Store with adequate ventilation in warehouse. • Temperature of the warehouse should not exceed 125°F (52°C). • Secure hydrogen containers and tanks to prevent falling or being knocked over. • Use of flash arrestor on tanks is recommended. • Store full and empty cylinders separately. • Warehouse should be equipped with an automatic sprinkler or deluge system in case of fire. NFPA standards could be modified to consider H_2 storage.
During delivery of H_2 to aircraft, there are risks of leakages, fire, and explosion	Potential leakages, fire, and explosion	Issue during loading or fueling, or damage to tank due to fall during swapping or shock	Standard operating procedures should be developed on the standard dimensions and techs of H_2 containers. H_2 hydrant system could be used in the long-term future and standards regarding the type of materials, the temperature, separation between two tanks or pipelines, and certification of technicians manipulating during the delivery to the aircraft should be established. One method of energy risk reduction is to isolate discrete amounts of H_2 to minimize spread.
Extreme heat on the ramp causes safety issues on hydrogen tanks or pods.	Heat increases tank internal pressure which triggers the safety valves.	Airport under hot climate. Extreme weather conditions at temperate airports.	Design of hydrogen equipment and standard operating procedures should take extreme weather conditions into consideration.
The hydrogen tanks or pods increase the severity of a low-energy aviation accident or incident (e.g., collision on taxiway/ramp), a runway excursion, or an undershoot.	Rupture and explosion of hydrogen tanks or pods.	Hydrogen tanks or pods are damaged during the accident or incident.	Hydrogen tanks or pods should be able by design to withstand these events or not increase the severity of such occurrences (assuming reasonable scenarios).
The hydrogen tanks or pods increase the severity of a high-energy aviation accident (e.g., aircraft collision on runway).	Rupture and explosion of hydrogen tanks or pods.	Hydrogen tanks or pods are damaged during the accident.	Not addressed during this research effort.

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APPENDIX E

Industry Standards: Applicability and Needs

E.1 **Needs for Standardization**

Throughout this research project, the needs for standardization of the aspects of electric aircraft in relation to the aircraft/airport interface were identified. These needs, which are listed and discussed in Table E-1, are associated with existing standards and proposed opportunities for further standardization. ACRP is not a standardization or regulating body, and this project does not intend to list all existing or expected standards pertaining to electric aircraft. This list is provided for informational purpose and should be considered as non-comprehensive “food for thought” material to groups and organizations developing industry standards.

TableE-1. Electric aircraft needs for standardization.

Need	Description	Existing Standards	Relevant or Potentially Relevant Organization/Body
Interoperability of electric connectors	Electric charger connectors should be designed to be compatible with various electric aircraft charging equipment to ensure easy accessibility and consistency. *Note: Similar issues exist with (ground) electric vehicles.*	Electric Power, Aircraft, Characteristics, and Utilization AS1212A	SAE International
Interoperability of electric chargers	Electric chargers should be designed to be compatible with various electric aircraft charging equipment to ensure easy accessibility and consistency. Different categories might co-exist, depending on the characteristics of aircraft (power required, fast chargers, etc.). *Note: Similar issues exist with (ground) electric vehicles.*	Connection Set of Conductive Charging for Light Electric Aircraft AS6968 Standard (work in progress)	SAE International
Procedures for alternative energy vectors (electricity and hydrogen)	To implement alternative energy vectors, there is the need for general precautions, emergency planning and preparedness, and storage of hazardous materials.	2018 International Fire Code	International Code Council (ICC)
Battery handling and storage	Battery hazards are associated with its high-energy density and flammable organic electrolyte, thus creating challenges for use, storage, and handling.	IEC 62133-2:2017 - Safety requirements for portable sealed secondary lithium cells and batteries made from them for use in portable applications	International Electrotechnical Commission (IEC)
Provision of safe backup power supply	To ensure the continuity of electric aircraft operations, uninterrupted power supply is needed thus creating a need for guidelines on emergency and backup power supply systems.	NFPA 110 – Standard for Emergency and Standby Power Systems	National Fire Protection Association (NFPA)

Need	Description	Existing Standards	Relevant or Potentially Relevant Organization/Body
Integration of electric aircraft into electrical distribution systems	Airports require power, monitoring, information exchange, control, and protection of interfaces that are based on technological maturity, accepted practices, and allowances for future technology insertions such as the integration of electric aircraft.	IEEE 1826-2020 – IEEE Standard for Power Electronics Open System Interfaces in Zonal Electrical Distribution Systems Rated Above 100 kW. Airports are included in this standard	Institute of Electrical and Electronics Engineers (IEEE)
Safe integration of high-pressure hydrogen fuel cell storage system	High-pressure hydrogen requires the development of advanced storage methods that have the potential for higher energy density and safe integration of storage, distribution, and appropriate electrical systems into the aircraft.	EUROCAE/SAE WG80/AE-7AFC Hydrogen Fuel Cells Aircraft Fuel Cell Safety Guidelines	European Organization for Civil Aviation Equipment (EUROCAE)/SAE International
Hydrogen fuel quality	There is a need for hydrogen fuel quality standards that would be used in hydrogen fuel cell vehicles including aircraft.	Hydrogen Fuel Quality for Fuel Cell Vehicles J2719_201511	SAE International
Safety and fire hazards on the airside due to new energy vectors (batteries and hydrogen)	This standard outlines vital safety provisions for procedures, equipment, and installations to protect people, aircraft, and other property during ground fuel servicing of aircraft using liquid petroleum fuels.	NFPA 407 – Standard for Aircraft Fuel Servicing *Note: Standard should be adapted to include new energy vectors such as hydrogen.*	NFPA
	As of March 2021, NFPA 440 is a proposed standard that is in a custom cycle due to the Emergency Response and Responder Safety Document Consolidation Plan as approved by the NFPA Standards Council. As part of the consolidation plan, NFPA 440 is combining Standards NFPA 402 and NFPA 424.	NFPA 440 – Guide for Aircraft Rescue and Firefighting Operations and Airport/Community Emergency Planning *Note: Standard should be adapted to include new energy vectors such as hydrogen.*	
	As of March 2021, NFPA 460 is a proposed standard that is in a custom cycle due to the Emergency Response and Responder Safety Document Consolidation Plan as approved by the NFPA Standards Council. As part of the consolidation plan, NFPA 460 is combining Standards NFPA 403, NFPA 405, and NFPA 412.	NFPA 460 – Standard for Aircraft Rescue and Firefighting Services at Airports, Recurring Proficiency of Airport Fire Fighters, and Evaluating Aircraft Rescue and Firefighting Foam Equipment *Note: Standard should be adapted to include new energy vectors such as hydrogen.*	
Generation, storage, and handling of hydrogen in compressed gas form	The hazardous properties of hydrogen, especially in a compressed gaseous form, necessitate safe ways towards the storing, handling, and use of H_2.	NFPA 2 – Hydrogen Technologies Code	NFPA

Note: Existing standards identified in the table do not necessarily adequately address electric aircraft in their current version.

E.2 Standardization Groups on Electric Aviation

Apart from the groups listed above, other institutions have formed committees that are developing standards, recommended practices, and information reports concerned about electric aircraft and potentially by the airport interface of these vehicles. The following groups have been identified:

- American Institute of Aeronautics and Astronautics Electric Propulsion Technical Committee

- American Society for Testing and Materials (ASTM) F39/F44 Hybrid Electric Vehicle Steering Committee
- European Organization for Civil Aviation Equipment (EUROCAE)
- General Aviation Manufacturer's Association (GAMA) Electric Propulsion & Innovation Committee
- Radio Technical Commission for Aeronautics
- SAE International
  - Electrified Propulsion Committee (E-40)
  - Electromagnetic Compatibility (AE-4)
  - Distributed Propulsion, Maintenance (G-11)
  - Cockpit Indicators (A-4)
  - Electrical Wiring & Interconnect Systems (AE-8)
  - Aerospace Electrical Power & Equipment (AE-7)
  - Electronic Engine Controls (E-36)
  - Electrical Materials (AE-9)

E.3 **Other Standards**

There are other standards that may need to be revised to take into consideration the specificities of electric aircraft. These standards include the following SAE International documents:

- AS6285: Aircraft Ground Deicing/Anti-Icing Processes
- AS6286A: Aircraft Ground Deicing/Anti-Icing Training
- ARP1247: Aircraft Ground Support Equipment
- AIR7975: Aircraft Fuel System Design Guidelines
- ARP4084B: Aircraft Ground Service Connections Locations and Type

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APPENDIX F

Summary of Electric Aircraft Workshops

F.1 **About the Workshop**

The electric aircraft industry working group created for the ACRP Project 03-51 workshop panel brought together over 40 participants working for or involved with various stakeholders, including state departments of transportation; airport operators; aircraft and original equipment manufacturers (OEMs); aviation think tanks and research centers; aviation professional organizations; and industry associations, state energy commissions, energy providers, energy research centers, federal agencies, universities, and standardization bodies.

This working group met for three separate workshops to discuss the interim findings and guidance of the ACRP Project 03-51 research team as well as specific emerging issues related to electric aviation. The goals of the workshop were the following:

- Bringing together the stakeholders and experts of electric aviation at airports;
- Sharing information on the challenges of integrating e-aircraft;
- Discussing the findings and interim guidance of ACRP Project 03-51; and
- Ensuring that the ACRP Project 03-51 deliverables address the needs of the aviation community.

F.2 **Main Takeaways**

This section provides a summary of the main discussion points and outputs of the workshop sessions.

Airport Compatibility Assessment

- All electric aircraft technologies should meet today's endurance and turnaround time compatibility. If not, there will be strong pushback from flight operators.
- Electric aircraft charging equipment should follow industry standards similar to those for (ground) electric vehicles as well as other equipment used for the generation and distribution of electricity.
- Aviation/airside safety issues should be considered when developing standards for electric aircraft. For example, a standard operating procedure could be developed for battery loading and unloading. Also, the implications for airport rescue and firefighting (ARFF) operations should be documented and addressed.

- Running a mobile diesel or petrol generator to charge batteries would not help with the zero-emission goal of electric aviation. The approach to electric aircraft must be holistic and include low-carbon solutions for charging batteries.
- Regarding fixed electric chargers:
  - Charging ports on the aircraft should maximize compatibility with the various types and configurations of charging stations. They should minimize the impact of the charging process on the turnaround time.
  - From a ramp safety perspective, minimizing the length of wiring between the port and the charger reduces the impact on the other ground handling operations and is better for ramp safety. Multiple ports on the aircraft (left/right, front/back) could greatly facilitate their integration to existing ramps and minimize adverse interactions with other ground handling operations.
  - Aircraft electric ports/wiring/connection features to electric chargers should be standard to maximize compatibility.
  - Chargers at rural and smaller airports should be available as a self-service following the model of self-service fuel farms where users can swipe their card to fuel.
- Regarding mobile electric chargers:
  - Truck with a supercharger-like device to charge aircraft batteries could be charged off-ramp and brought to the aircraft for loading the batteries. A prototype was developed in Utah for small general aviation aircraft.
- Battery swapping:
  - Battery swapping may be faster than recharging batteries enabling very short turnaround times.
  - Aircraft with battery swap should be able to recharge at fixed or mobile charging stations as well to access airports where a battery inventory is not available.
  - Due to the potentially large inventory of lithium-ion batteries needed at busy airports, the safety hazards from their storage and maintenance should be considered.

Environmental Impact

The environmental impact items included air quality, noise exposure, greenhouse gas emissions, and toxic discharge and water quality:

- Electric aviation might have a significantly positive impact on the environment because of significantly less emissions and noise.
- Electric aviation can be a way out of lead emissions from 100LL-based general aviation.
- Electric aircraft should be included in the Aviation Environmental Design Tool (AEDT) database.
- As these aircraft are quieter, they may facilitate the implementation of more precise Area Navigation (RNAV) flight procedures that "concentrate" flight paths and aircraft noise.

Power Supply

- Current and near-future airport electrification is not just on aircraft but goes from the curbside to the airside. It includes, but is not limited to, building heating systems, landside electric vehicles, airside electric vehicles. Examples are airport buses, ground support equipment (GSE), taxis and TNCs, and shuttle buses.
- Airport electric infrastructure design should consider peak load ‘worst case scenarios’ (e.g., a hot summer day with air conditioning and several large electric aircraft charging at the same time).

Hydrogen

- The physical properties of hydrogen make it hard to store it into the wings like conventional jet fuels. Hydrogen tanks are typically in or above the fuselage, which might result in a tradeoff of payload and passengers on retrofitted aircraft.
- Who will provide hydrogen fueling services—either through hydrogen containers or direct fueling? These tasks could fall under the current duties of ground handlers. Hydrogen container swapping needs to be cleared by the regulator as a minor alteration of the aircraft. Otherwise, it will need to be performed by certified aircraft mechanics, which may adversely affect the appeal of this option.
- Hydrogen containers should not increase the severity of low-energy aircraft incidents, meaning that they should withstand a collision with GSE and obstacles on taxiways and the non-movement area, runway excursion and undershoot, etc. What about high-energy events?

Federal and State Policies

- There is a need to start working on updating regulations and policies to incorporate electric aircraft and emerging aviation fuels. Some of the questions to be addressed include electric aircraft infrastructure funding to ensure that the National Airspace System (NAS) is accessible to electric aircraft users, and grant assurances (e.g., “self-charging” of aircraft, use of electric plugs in aircraft hangars for low-speed charging of aircraft).
- Resiliency is not a topic funded through the Airport Improvement Program (AIP). As airports are becoming increasingly electrified and threats are growing (e.g., more frequent adverse weather conditions due to climate change), power supply resiliency is now a critical issue for the operational resiliency of the NAS.
- Microgrids, advanced backup systems (e.g., energy storage based on large batteries), solar farms, and other power generation and storage systems can be cost-prohibitive.
- There is a need for policies on electricity that would articulate the purpose of metering and allow regulation of costs. For instance, current tenant and landlord submetering policies and regulations do not consider aviation needs. Many of these issues are regulated at the state level. Should it be a federal mandate when it comes to the electricity used for aviation (flight) purposes?