Electrified Aircraft Propulsion Economics

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Outline

- Study introduction – background, objectives, and approach
- Validation of cost model for turboprop and Regional Jet (RJ) applications
- EAP-enhanced aircraft DOC+I impact estimates
- Conclusions

Study Background and Objectives

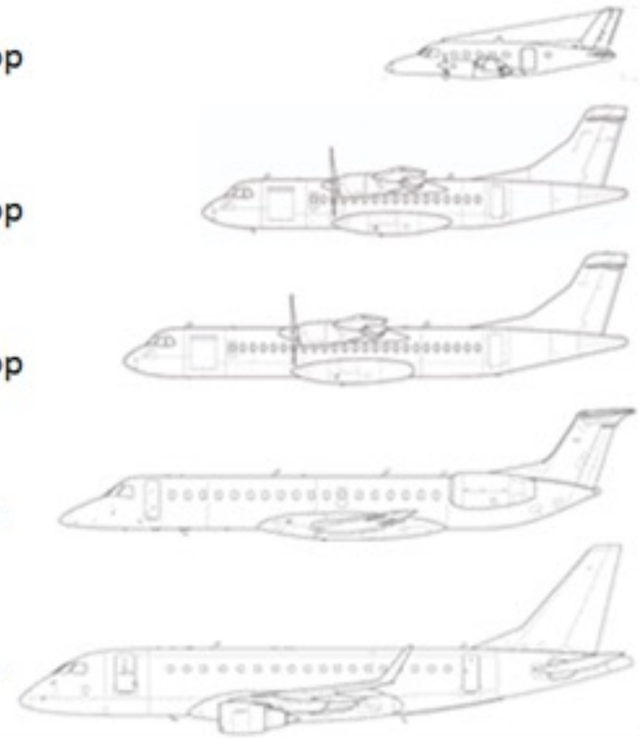
- Ongoing study conducted by NASA Advanced Air Transport Technology (AATT) Project, Systems Analysis and Integration (SA&I) subproject
- Explore design trades associated with applying Electrified Aircraft Propulsion (EAP) to several different sizes of regional-class aircraft between 20 and 80
- Calculate the changes in fuel/energy consumption and Direct Operating Cost (DOC) compared to baseline aircraft
- Understand the contribution of EAP to aircraft sizing and performance when isolated from other advanced technologies
- Establish a tool set and work flow for evaluation of future EAP concepts

Approach

1. Select reference aircraft
2. Establish technical descriptions for reference aircraft
3. Estimate DOCs for reference aircraft using Probabilistic Technology Investment Ranking System (PTIRS) and validate versus actual costs (recalibrate cost model and assumptions as necessary)
4. Establish technical descriptions for 2020 baseline aircraft (update reference aircraft to 2020 state-of-the-art)
5. Establish technical descriptions for technology-enhanced aircraft including Electric Propulsion (EP)
6. Estimate DOC plus Interest (DOC+I) for baseline and EP-enhanced aircraft and compare to quantify economic impacts

Reference Aircraft

Reference Aircraft	Configuration
Embraer EMB 110P	18 Passenger, Turboprop
ATR 42-500	48 Passenger, Turboprop
ATR 72-600	70 Passenger, Turboprop
Embraer ERJ-145	50 Passenger, Turbofan
Embraer E175	78 Passenger, Turbofan

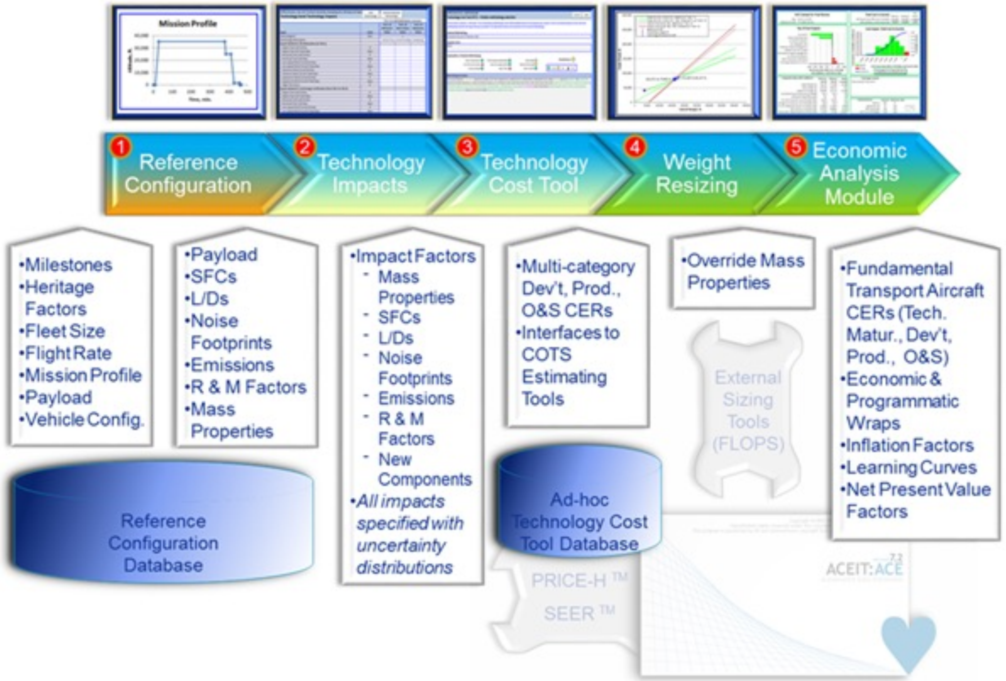


Economic Figure of Merit – DOC+I

- DOC+I is a comprehensive metric that captures all aircraft-driven investment cost as well as aircraft-driven operating costs – **DOC+I improvements correspond directly to profit increases for airlines**
- DOC+I definition
  - Aircraft ownership costs – amortized price or lease cost of aircraft (represents all development and production incurred by manufacturer)
  - Energy costs –cost of jet fuel and ground-supplied electricity used in flight
  - Maintenance costs – labor and material costs of flight-line maintenance as well as scheduled and unscheduled heavy maintenance and overhauls (C-checks and D-checks)
  - Flight crew costs –all cost associated with cockpit personnel
  - Insurance – hull insurance
  - Flight equipment financing cost (the “+I” in DOC+I) –interest paid by airline on money invested in purchasing aircraft during the during the time they own the aircraft

PTIRS

- A business case tool to evaluate incorporating a technology or suite of technologies on a future system
  - What is the probability that a technology will pay for itself over the lifetime of the aircraft?
  - What is the expected magnitude of savings?
- Developed for NASA by Tecolote for the Environmentally Responsible Aviation (ERA) Project in 2012



PTIRS Results

Make-believe configuration

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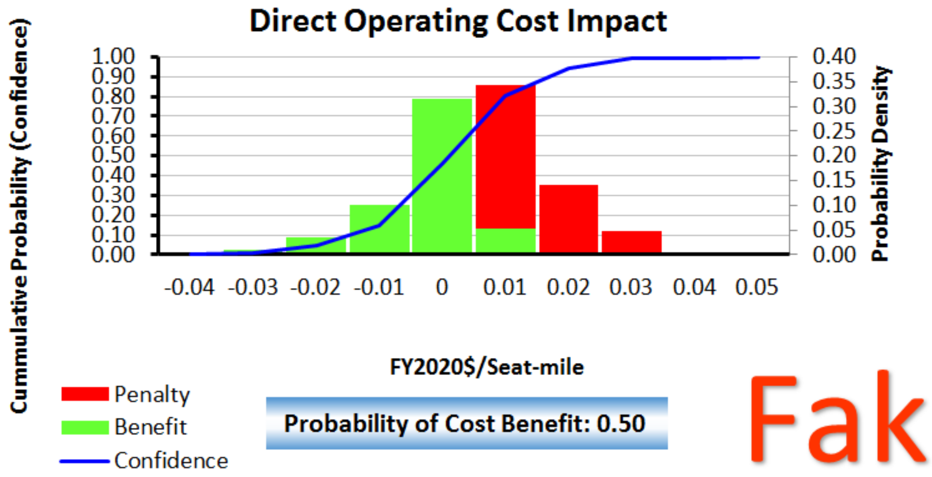
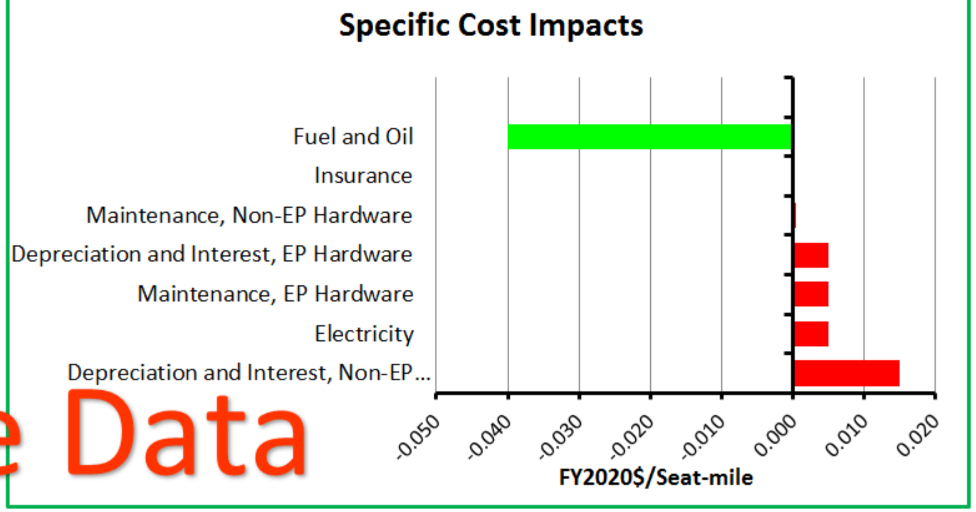
Baseline Aircraft: Make-believe Aircraft

Operator's Cost (50% Confidence)	Reference Aircraft	Enhanced Aircraft	Impact (- is good)
Direct Operating Cost per Seat-mile (FY20$, 50%)	0.200	0.190	-0.010
Total Operating Cost per Seat-mile (FY20$, 50%)	0.450	0.440	-0.010
Minimum Coach Ticket Price (FY20$, 50%)	180.0	175.0	-5.0



Probability of Cost Benefit: 0.50



Comparative Values (50% Confidence)	Reference Aircraft	Enhanced Aircraft	Impact
Takeoff Weight (lb, + impact is bad)	50,000	60,000	10,000
Empty Weight (lb, + impact is bad)	30,000	40,000	10,000
Useable Fuel Weight (lb, + impact is bad)	5,000	3,000	-2,000
Seat-miles (statute) per Gallon (+ impact is good)	90.0	140.0	50.0
Seat-miles per equivalent kWh (+ impact is good)	2.50	3.00	0.50

Technologies Included

- Fake Technology #1

Study Parameters	Assumed	Break-even (50%)
Fleet Size	1,000	>=900
Investment Interest Rate	10%	<=20%
Fuel Price (FY2020$/gal)	4.00	>=3.50
Electricity Price (FY2020$/kWh)	0.10	<=0.12

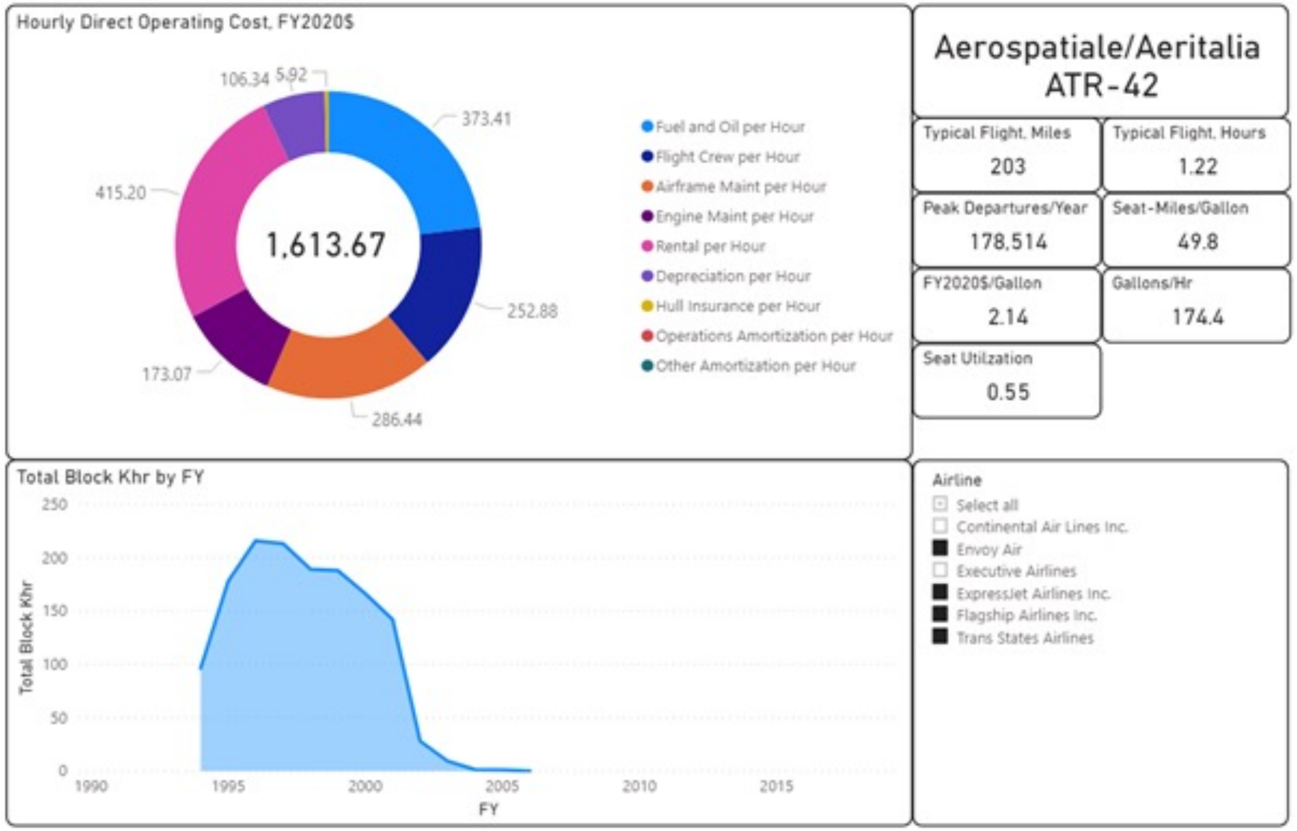
PTIRS

Manufacturer's Investment (50% Confidence)	Reference Aircraft	Enhanced Aircraft	Impact (- is good)
Investment Total (FY2020$M, 50%)	30,000	45,000	15,000
Minimum Unit Price (FY2020$M, 50%)	30.0	45.0	15.0

Validation Approach

- Use PTIRS to estimate DOCs for reference aircraft then compare to actual costs from the Bureau of Transportation Statistics (BTS) Form 41 database

BTS Form 41 Example (publicly available)



Validation Results

	(Estimate - Actual) / Actual
ATR-42	14%
ATR-72	-22%
EMB-110	3%
ERJ-145	2%
ERJ-175	22%

Validation Observations

- Flight crew costs – salaries on larger aircraft much higher than on regional aircraft
- Development scope – development programs for regional aircraft range from three to five prototypes versus eight to ten aircraft for larger aircraft
- Fleet size – need to model the full international fleet size to get correct learning curve and development amortization impacts
- Usage hours – maintenance costs sensitive to utilization – need utilization factors

Aircraft Class	Daily Utilization Hours
Turboprop	7.8
Small RJ	7.3
Large RJ	9.1

https://www.planestats.com/bhsr_2017sep#:~:text=Turboprop%2FRegional%20Jet%20Costs%20and%20Operations%20%2D%2012%20Months%20Ended%20September%202017&text=US%20DOT%20data%20for%20the,operate%209.1%20hours%20per%20day

EAP-enhanced Aircraft DOC+I Impact Estimates – Ground Rules

- Technology-enhanced aircraft sized for mission completion with disabled EAP system
- Entry Into Service of technology-enhanced aircraft will be in 2032 (impacts estimated battery costs)
- Fuel cost is assumed at the 4Q2019 (pre-COVID) worldwide average of $1.86/gal
  (https://www.eia.gov/dnav/pet/hist/eer_epjk_pf4_rgc_dpgM.htm)
- Electricity cost is 2020 US-wide transportation average of $0.10/kWh
  (https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_5_6_a)
- Cost calculations are based on worldwide fleet size for each reference aircraft
- Utilization is 7.5 hr/day for turboprops and small RJs, 9.1 hr/day for large RJs
- The cost of capital assumed to be 10% per year
- Battery life 3650 charge/discharge cycles
- Technology maturation costs prior to full-scale development are excluded

EAP-enhanced Aircraft DOC+I Impact Estimates – Results

- Results for all initial EAP configurations analyzed follow a pattern
  - Additional weight of EP hardware, especially batteries, is significant
  - Because the aircraft have been sized for mission completion with disabled EAP system, additional weight of the EP hardware not compensated for by reduced fuel weight
  - Due to resizing effect, the empty weight of all airframe components (not just EP hardware) increases significantly
  - Increase in overall aircraft empty weight drives an increase in aircraft purchase price and therefore depreciation cost that vastly outweighs any possible benefit in fuel cost
  - **None of the core configurations examined using the ground rules stated above showed net economic benefit over the corresponding baseline aircraft**

Additional Explanation

- Jet fuel burned in modern, efficient turbine engines is not an expensive form of energy:

	$/gal	gal/lb	$/lb	ATR-72 SFC lb/shp-hr	$/shp-hr	kW/shp	Shaft $/kWh
Jet-A (4Q2019)	1.85	6.71	0.28	0.47	0.13	0.75	**0.17**
Jet-A (2Q2008)	3.66	6.71	0.55	0.47	0.26	0.75	0.34

	Grid $/kWh	Typical EV End-to-End Efficiency	Shaft $/kWh
Electricity	0.10	77%	**0.13**

At current (pre-COVID) prices, grid power is not vastly cheaper than Jet-A

http://www.indexmundi.com/commodities/?commodity=jet-fuel&months=300
https://www.fueleconomy.gov/feg/evtech.shtml#:~:text=Energy%20efficient.,to%20power%20at%20the%20wheels.
https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_5_6_a
Energy Information Administration

A What-if Case

- What-if case analyzed with following deviations from study ground rules
  - Fuel cost is assumed to be $8.50 per gallon
  - Battery specific energy is increased to 750 Wh/kg at the pack level
  - Requirement that aircraft be sized for mission completion with disabled EAP system removed
- This case showed that given aggressive but not unreasonable assumptions, a net economic benefit might be achieved when incorporated in regional-class aircraft

Conclusions

- Overcoming the additional cost and weight associated with the EAP systems will be challenging if EAP aircraft are to be economically competitive with conventional aircraft
- Parallel hybrid EAP may become economically feasible for the NASA aircraft configurations modeled here if the following conditions are met:
  - Battery pack specific energy levels are achieved which are much higher than the current lithium ion state-of-the-art
  - Battery pack cost per kWh continues to follow the trend from last ten years over the next ten years
  - Fuel prices become much higher than any historical worldwide average level.
  - Aircraft are sized to take full advantage of electric energy and power in performing their missions (no requirement to fly full mission with disabled EAP system)