

Rail, Aviation, and Maritime Metrics

R. K. Ahluwalia, J-K Peng, F. Cetinbas, D. D. Papadimas, X. Wang, J. Kopasz, and T. Krause
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Project ID: TA034

Project Overview and Relevance



Timeline

- Project start date: 10/01/2020
- Project end date: 9/30/2021

Budget

- FY20 DOE Funding: \$1000K
- FY21 DOE Funding: \$640K

Barriers (MT) Addressed

- B. High hydrogen fuel infrastructure capital costs
- D. Market uncertainty around the need for hydrogen infrastructure versus timeframe and volume of commercial fuel cell applications

Partners/Interactions

- | | |
|---|------------------------------|
| ▪ Caterpillar | ▪ Wabtec |
| ▪ Cummins | ▪ Sandia National Laboratory |
| ▪ Alstom | ▪ Chart Industries |
| ▪ Stadler | ▪ Golden Gate Zero Emission |
| ▪ North County Transit District | ▪ Swift Maritime |
| ▪ San Bernardino County Transit Authority | ▪ Universal Hydrogen |
| ▪ CalTrain | ▪ Ballard Unmanned Systems |
| ▪ Massachusetts Bay Transit Authority | ▪ Alaka'i Technologies |

- This project evaluates and identifies opportunities for heavy-duty fuel cells (100 kW – 100 MW) in rail, maritime and aviation sectors and market introduction of H₂ at large scale (H2@Scale)



Objectives: Determine how hydrogen and fuel cells compare with incumbent technology in applications in rail, maritime, and aviation and what performance metrics are needed for them to be able to compete on a cost of ownership basis

Goals:

- Conduct system level analysis of fuel cell powertrains
- Model and analyze on-board gaseous and liquid hydrogen storage options (and on-board reforming for maritime)
- Analyze hydrogen refueling infrastructure
- Conduct total-cost-of-ownership analysis (TCO) and compare to the incumbent technology (diesel for rail and maritime, aviation gasoline for civil aviation)
- Consistent with H2@Scale program objectives, identify early opportunities for hydrogen and fuel cells in rail, maritime, and aviation applications and which applications have the most impact
 - Rail applications – line-haul locomotives, yard switcher, regional passenger locomotive, multiple units
 - Maritime applications investigated were harbor tugboats, auto/passenger ferries, and feeder container ships
 - Aviation applications – small planes-general aviation, urban air mobility, and unmanned aerial vehicles



Fuel Cell System

- Modular systems built from multiple HD truck stacks to take advantage of increased economies of scale

H₂ Storage

- Liquid hydrogen storage to obtain maximum volumetric storage density

Analysis Methodology

- Chose a representative use case. FCs are more advantageous for duty cycles that operate a significant portion of their time at part-load, where efficiency advantages over combustion engines is greater.
- Designed FC system to match relevant performance of the incumbent (cargo capacity, passenger capacity, range., etc.)
- Calculated TCO for incumbent and FC-powered version using current status
- Calculated TCO for future fuel cell systems assuming advancements consistent with HFTO targets and goals
- Applied a 10% internal rate of return (IRR) to the initial capital investment and an installation cost factor of 20% to the capital cost. The capital cost of each component (e.g., engine, fuel tank, motor etc.) was annualized over its lifetime.

1. Fuel Cells for Rail: Multiple Units (Preliminary Results)



	Units	Diesel (DMU)	Electric (EMU)	Battery (BEMU)	Fuel Cell (HEMU)
Purchase Price	\$M	4.13	5.07	7.32	8.14
Lifetime	yr.	25	30	30	30
Engine/Fuel Cell Power	kW	597			400
Battery	kWh			700	200
Engine/Fuel Cell Cost	\$/kW	503			193
Battery Cost	\$/kWh			175	175
Engine/Battery Lifetime	yr.	13		8	
Fuel Cell Lifetime	hr.				7,700
Fuel Type		Diesel	Electricity	Electricity	Hydrogen (GH2)
Fuel Unit		gal	kWh	kWh	kg
Fuel Cost per Unit (\$)	\$	\$1.94	\$0.0989	\$0.0989	\$7.50
Fuel Usage (Fuel Unit/mi)	Fuel Unit/mi	0.71	12.23	13.50	0.51
Infrastructure Costs					
Diesel Fuel Pad	\$M/MU	0.25			
Catenary System	\$M/MU		19.92		
Battery Charging Station	\$M/MU			1.40	
Hydrogen Fueling Station	\$M/MU				0.00
TCO	\$/mi	18.01	32.20	18.06	20.51
CAPEX - MU Purchase	\$/mi	3.92	4.01	5.79	6.44
CAPEX - Infrastructure	\$/mi	0.24	15.76	1.11	0.00
OPEX - MU Maintenance	\$/mi	6.47	3.39	3.83	4.22
OPEX - Fuel	\$/mi	1.38	1.21	1.34	3.86
OPEX - Infrastructure Maintenance	\$/mi	6.00	7.83	6.00	6.00

Background and Assumptions

- Considers both capital and maintenance costs for MU and Supporting Infrastructure
- Commuter service – 22 miles one-way with 12 3-car vehicles (MUs) in operation
- Infrastructure costs are amortized over 12 vehicles over the lifetime of the vehicle.
- Regenerative braking energy not considered.
- Infrastructure Maintenance OPEX is based on average annual cost for the North County Transit District SPRINTER line from 2014-2019 adjusted to \$2020. EMU includes additional cost for maintaining catenary system.

U.S. Commuter Rail Network

- The number of transit systems providing commuter rail services has increased from 18 systems in 1998 to 67 today
- More than 4.7 billion passenger trips annually in the US.

Multiple Units (MUs)

- Multiple Units are self-propelled passenger cars. .
- First U.S. hydrogen/fuel cell MU slated to enter into service on the San Bernardino County Transit Authority “Redlands Route” in 2024.

TCO .

- Purchase price reflects MUs built to European safety standards which do not meet U.S. standards. Compliance is possible but temporal separation (cannot operate on shared tracks with freight trains during commuter service) may still be required.
- High capital cost for catenary system (\$7.76M/mi²²) for EMUs results in TCO being 57% higher than HEMU and 78% higher than BEMU.
- Infrastructure charging requirements for BEMU (no. of charging stations, need for in-route charging) is highly dependent on the operation (length of route, grade profile, frequency of service, etc.).
- 350 bar gaseous H₂ is the fuel. Infrastructure capital and maintenance costs for H₂ refueling are included in the levelized-cost of H₂ based on Argonne’s HDSAM model.
- H₂ fuel cost represents 19% of the TCO. Vehicle and infrastructure maintenance costs represent 50% of the TCO.
- The cost of electricity is based on the DOE EIA average cost for transportation sector for 2020.
- Electricity cost represents 7% of the TCO. Vehicle and infrastructure maintenance costs represent 54% of the TCO.

Fuel Cells For Rail: Ultimate Targets and Benefit of Regenerative Braking

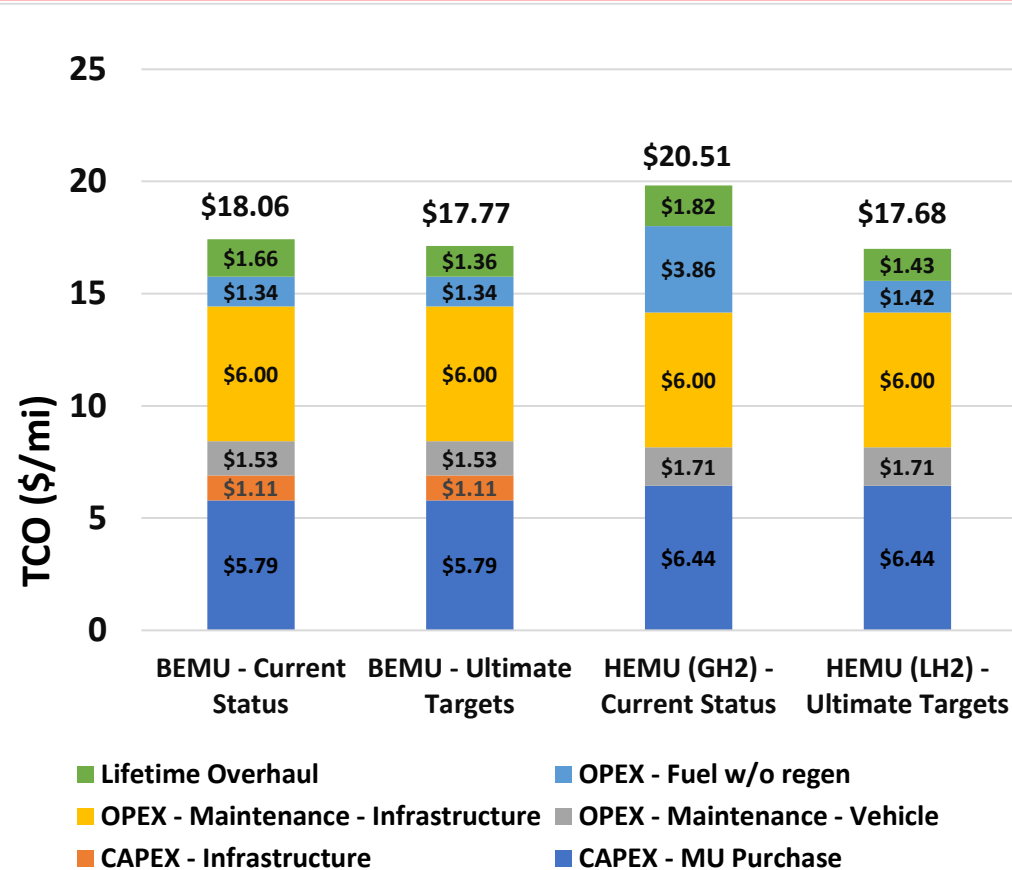


Ultimate Targets for Fuel Cells and Batteries

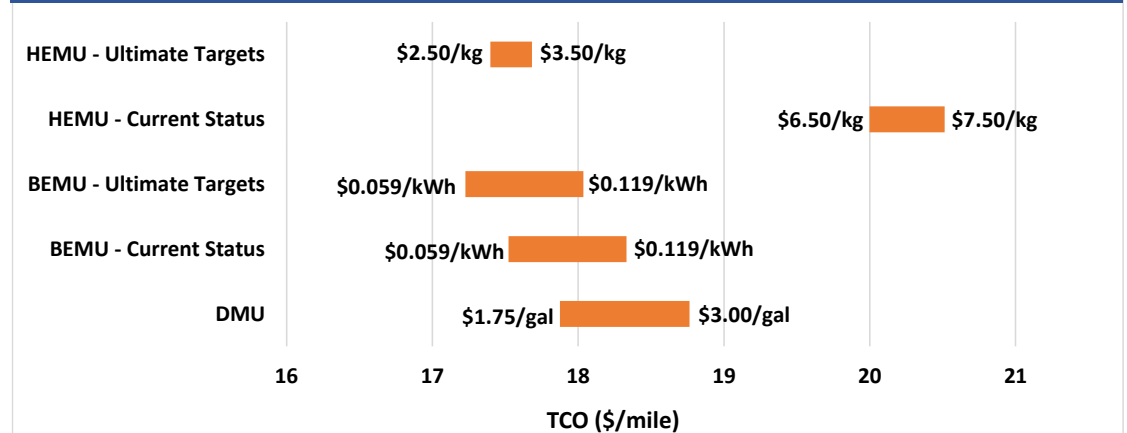
- Decreases FC system cost from \$193/kW current status to \$60/kW.
- Increase in durability from 7,700 h current status to 30,000 h.
- H₂ fuel switches from gaseous 350 bar hydrogen to liquid hydrogen.
- Decrease battery pack cost from \$175/kW current status to \$80/kW.
- Increase in battery lifetime from 8 years in current status to 20 years.

Benefit of Regenerative Braking

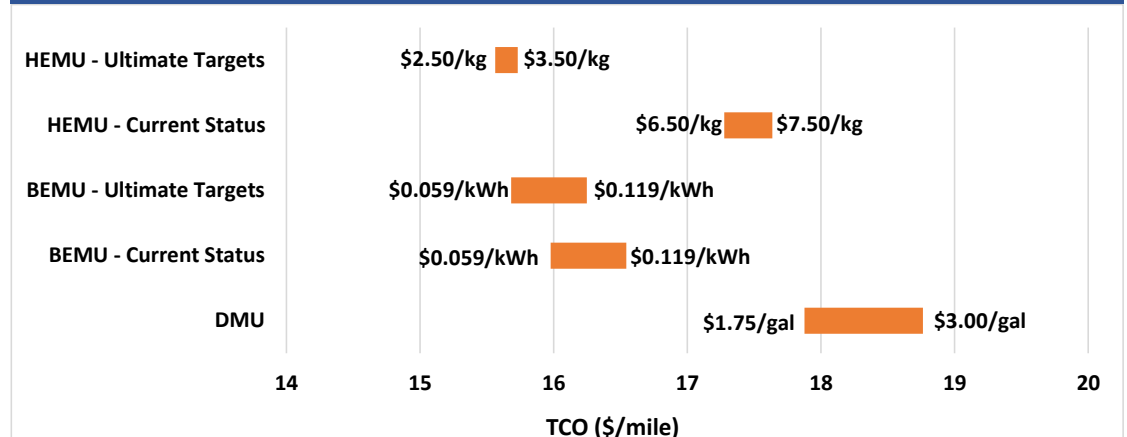
- Can recapture braking energy to reduce fuel consumption.
- Recaptured energy depends on weight of vehicle, speed, rate of deceleration, route profile (grade), number and frequency of stops, direction of travel.
- With regenerative braking HEMU can be competitive with DMU



TCO Sensitivity to Fuel Price assuming 0% Regenerative Braking Energy Recovery



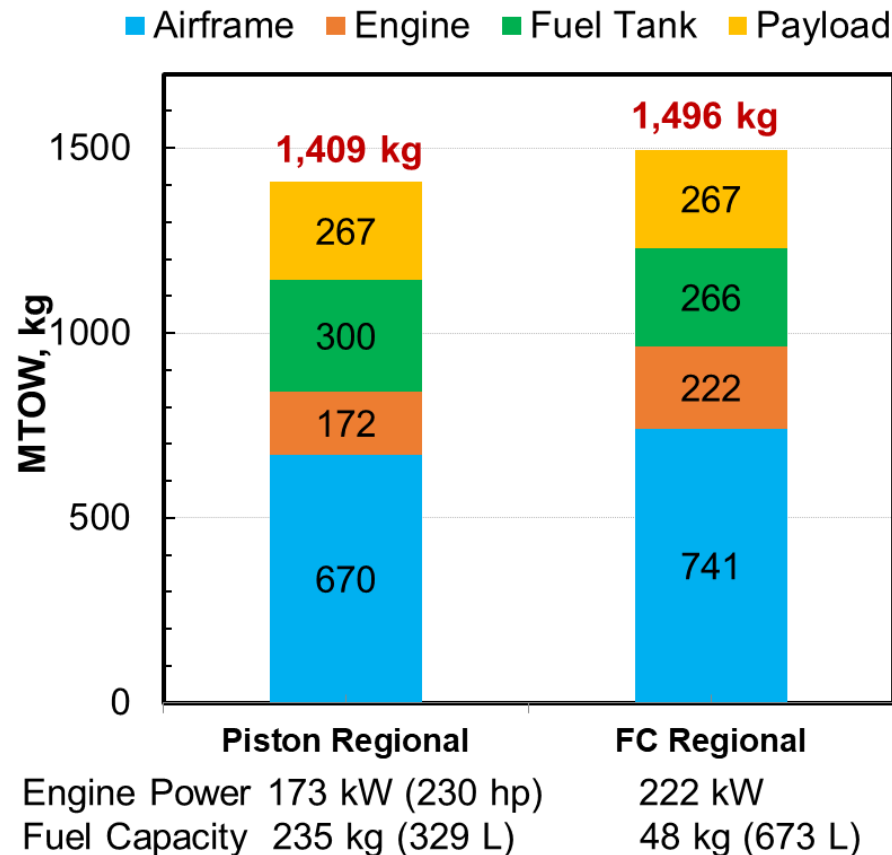
TCO Sensitivity to Fuel Price assuming 30% Regenerative Braking Energy



2.1 Hydrogen Fuel Cells for Regional Planes: Feasibility and Performance



- Objective: Verify that a LH_2 -fueled PEMFCS can replace a turbo-charged, 6-cylinder, aviation gas fueled piston engine in a 4-seat regional plane without sacrificing payload (267 kg), cruise speed (269 km/h) at 10,000 ft altitude, or range (1,695 km)
- Conclusion: Determined FCS rated power (222 kW) and LH_2 tank capacity (48 kg) to satisfy the mission requirements, 0.123 kW/kg power-to-weight ratio, allowing for 10% power degradation at ground over lifetime and boil-off losses
- Main FCS Parameters: 50% higher efficiency, 850 W/L power density, 1000 W/kg specific power
- Main Storage Parameters: 18% gravimetric capacity (kg- H_2 /kg-system)



Notes

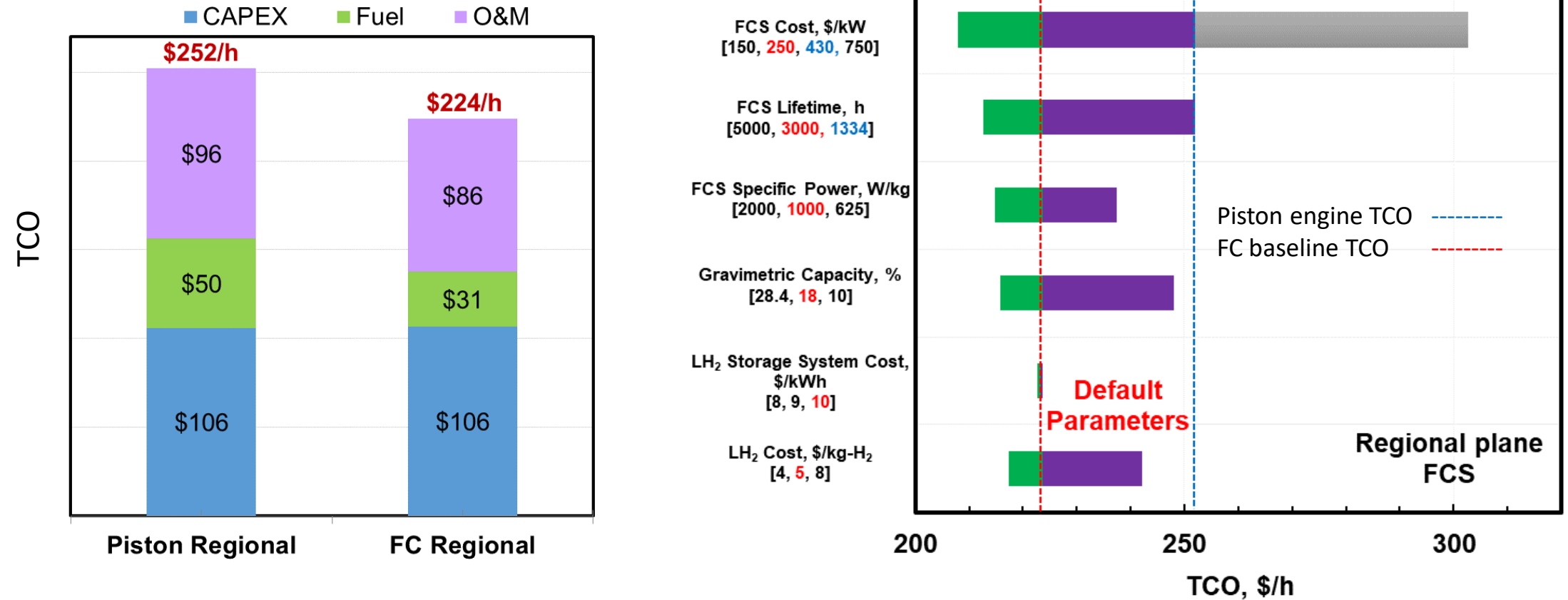
Piston Regional

- Includes 81-kg supplemental fuel, 65-kg empty fuel tank
- 670-kg airframe weight

FC Regional

- Includes fuel reserve for 45-min emergency cruise, 337-min actual cruise time, 218-kg empty tank weight
- Airframe includes 55-kg electric motor, 16-kg inverter
- Results account for fuel cell efficiency dependence on power, elevation, and aging
- FCS sized to provide required cruise and take-off power at end of life

Hydrogen Fuel Cells for Regional Planes: TCO and Single Variable Analysis



- FC Plane can achieve lower TCO than piston engine
- FC system is more efficient, and can be 82-83% more efficient during the climb phase
- Piston engine plane has higher O&M and higher fuel costs
- Break-even FCS cost: \$430/kW_e, affects capital and replacement costs
- Break-even with FCS specific power: >625 W/kg, determined by the maximum take-off weight (MTOW)
- Break-even with FCS lifetime: >1334 h, affects replacement cost and depends on FCS cost
- Break-even LH₂ cost: >\$8/kg

Proposed Targets for Hydrogen and Fuel Cells for Regional Planes



Characteristic	Units	Incumbent ^a	H ₂ and FCS Targets for Regional Planes	
			Interim ^b	Ultimate ^c
Engine Rated Power ^d	[kW]	173	225	275
Engine Cost	[\$ /kW]	552	300 ^e	250 ^e
Engine Specific Power	[W/kg]	980	1,000	2000 ^f
Engine Power Density	[W/L]	295	850	1,000
Engine Lifetime ^g	[hours]	2,000	3,000	3,000
Engine Efficiency at 100% Power ^h	[%]	35	52	52
Amount of Fuel Stored	[kg]	235	50	70
Fuel Storage System Gravimetric Capacity	[kg-fuel/kg]	0.78	0.18	0.225 ⁱ
Fuel Storage System Cost	[\$ /kWh]		10	10
Fuel Storage System Life	[cycles]		5,000	5,000
Boil-off Loss	[%/day]		0.4	0.25
Fuel Cost	[\$ /kg]	2	7.50	7.50

Approach for Specifying Ultimate Targets

- a) Equal propulsion power to propellers provided by piston-engine mechanical drive and FCS electric drive at EOL
- b) Equal weight of propulsion systems: piston engine vs. FCS and electric drive
- c) Fuel and fuel storage system must provide same range

- a) The incumbent technology data are for a commercially available turbo-charged, 6-cylinder, aviation gas fueled piston engine in a 4-seat regional plane (267-kg payload).
- b) Interim targets are for H₂, H₂ storage system and fuel cell system for 4-seat regional planes (267-kg payload).
- c) Ultimate targets are for H₂, H₂ storage system and fuel cell system for 6-seat regional planes (417-kg payload).
- d) Rated power at ground level. At 10,000-ft elevation, the engine also must generate at least 55% of ground rated power for interim target and at least 75% of ground rated power for ultimate target.
- e) Meeting interim and ultimate cost targets for fuel cells may require leveraging automotive/heavy-duty truck production volumes to achieve the necessary economies of scale.
- f) Engine specific power for FCS plus electric drive train to have the same weight as aviation gasoline engine.
- g) Engine lifetime refers to time between overhaul (TBO) for piston engine and time before 10% loss of ground rated power for fuel cell system.
- h) FCS efficiency defined as net system power (stack power minus power consumed by all BOP components) divided by the lower heating value (LHV) of H₂ consumed.
- i) Gravimetric capacity for equal weights of completely refueled H₂ storage system and aviation gasoline fuel tank.



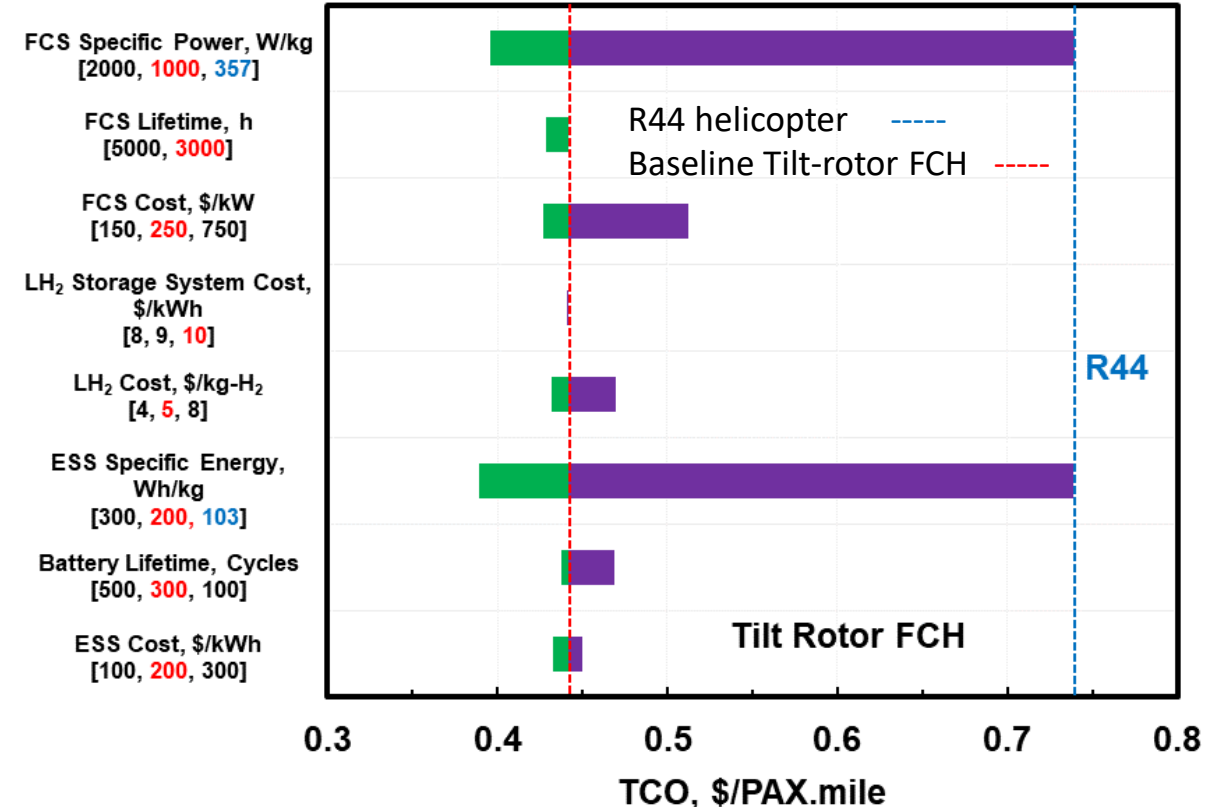
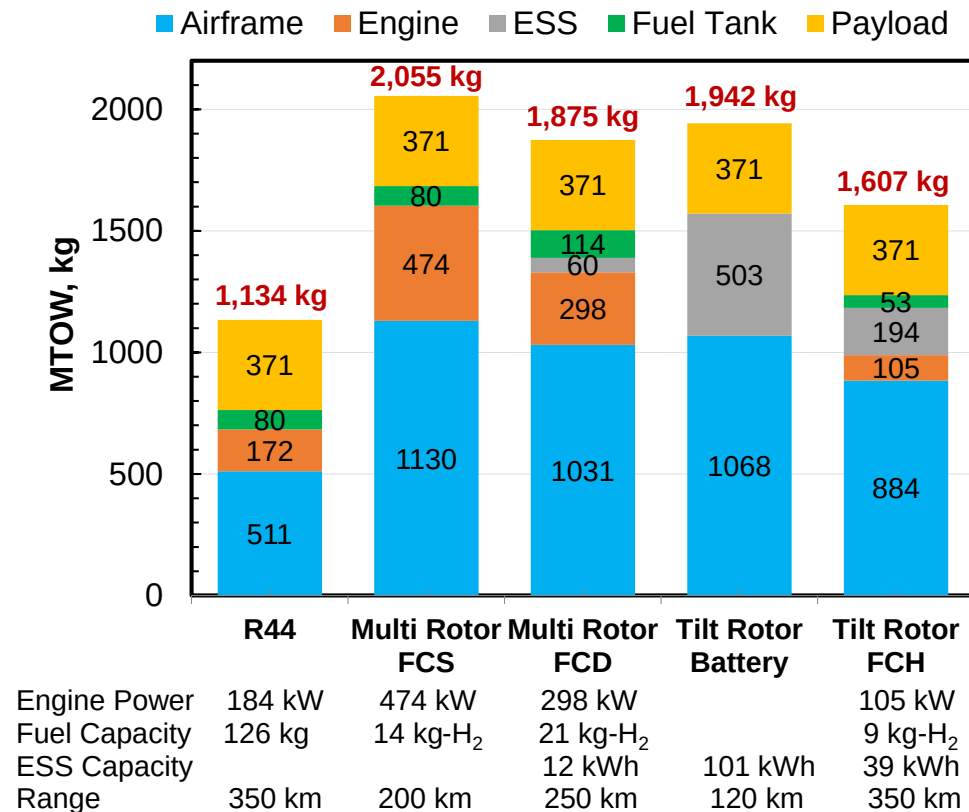
2.2 Hydrogen Fuel Cell Powered Helicopters: Multi-Rotor and Tilt-Rotor Crafts

Objectives: Identify battery and fuel cell air-taxi platforms that can match the published payload (371 kg with 80-kg standard fuel), range (350 km with standard fuel, no reserve) and maximum cruise speed (202 km/h at 1134-kg MTOW) of a commercial helicopter (Robinson R44 Raven II)

- Compare performance (range, MTOW), initial cost and TCO of promising air taxis

Conclusions

- Only FCH tilt-rotor eVTOL can match the range of R44 at 1.4 MTOW
- Batteries are not suitable for the targeted 350-km range
- Hybridizing FCS reduces MTOW and extends the range
- Fuel Cell Size: 426 kW for FC multi rotor, 268 kW for FCD multi rotor, 95 kW for FCH tilt rotor



2.3 Urban Air Mobility (eVTOLs) – Air Taxis

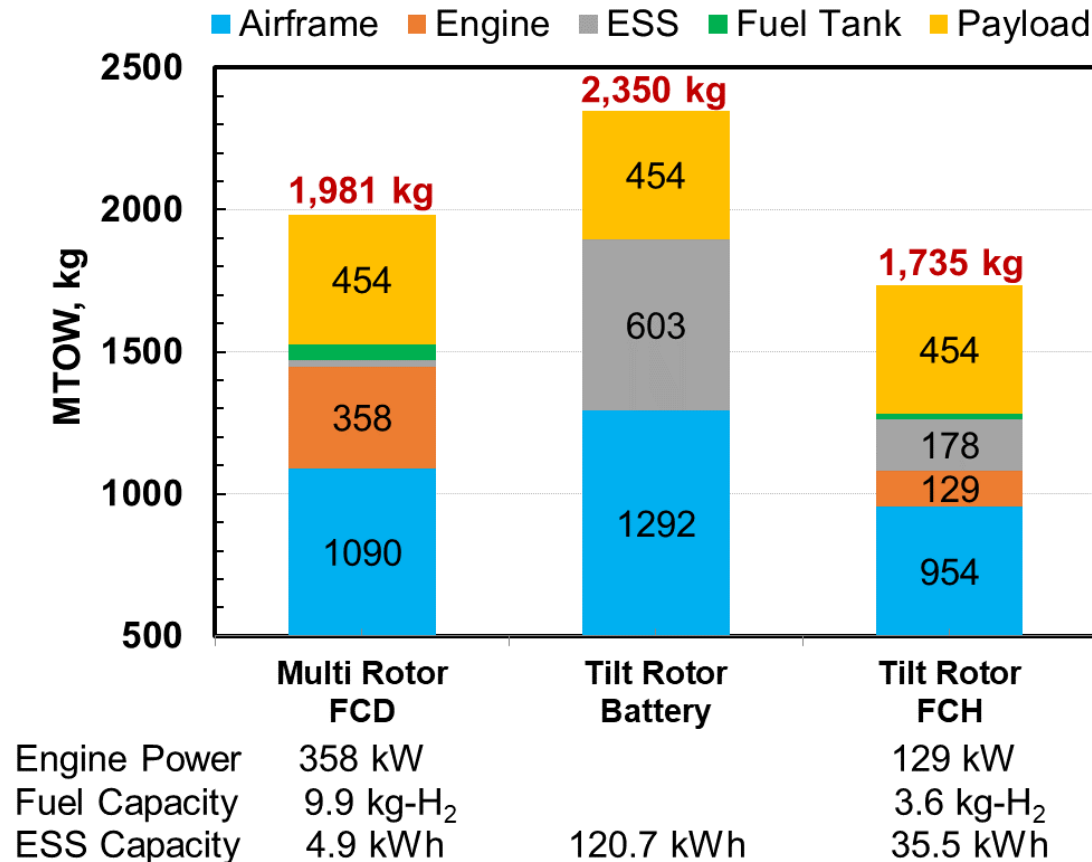


Objectives: Identify fuel cell air-taxi platforms that can match the payload (454 kg), range (96 km) and maximum cruise speed (240 km/h) of battery-powered urban air taxis

- Compare performance (MTOW, FCS/ESS size, LH₂), initial cost and total cost of ownership (TCO)

Conclusions

- Multi-Rotor FCD eVTOL: 358-kW_e FC, 5-kWh battery not required for speeds > 150 mph.
- Fixed-Wing Battery eVTOL: 121-kWh battery, 603 kg battery weight
- Fixed-Wing FCH eVTOL: 129-kW FCS + 36-kWh battery. FCH charges the battery during cruise.
- MTOW: FCH-powered tilt rotor < FCH-powered multi rotor < battery-powered tilt rotor



Total Cost of Ownership of Air Taxis



- Fuel cells can offer performance and cost advantages over batteries for UAM air taxis, but additional study is needed for evaluating LH₂ vs. battery recharging infrastructure

CAPEX

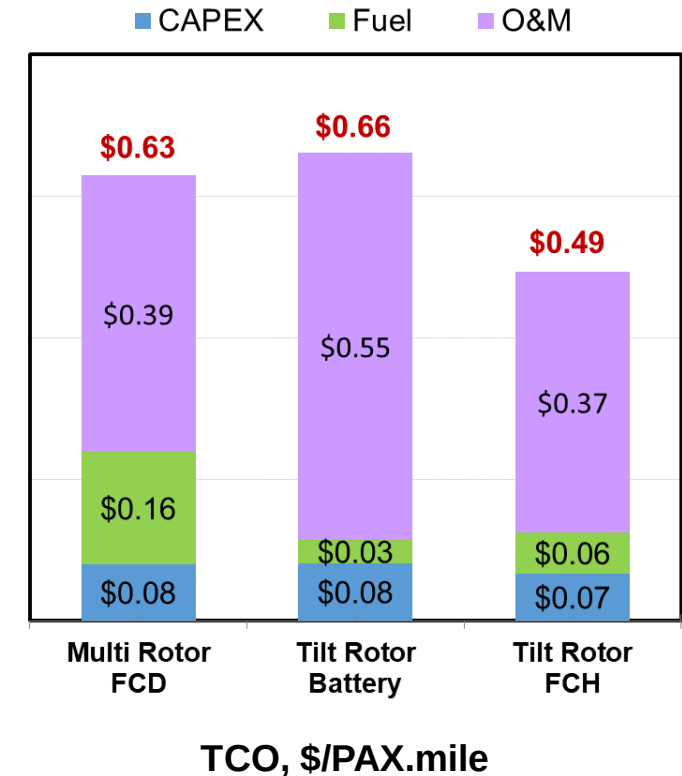
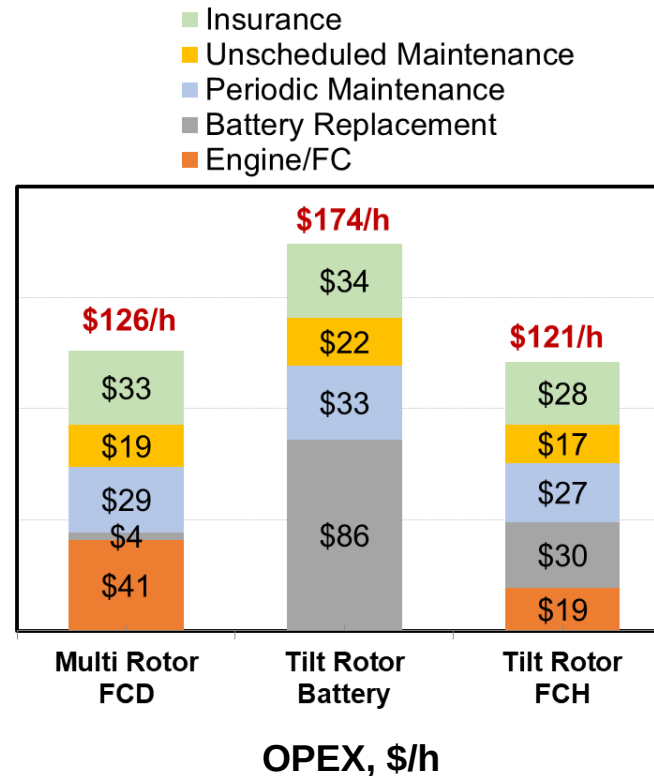
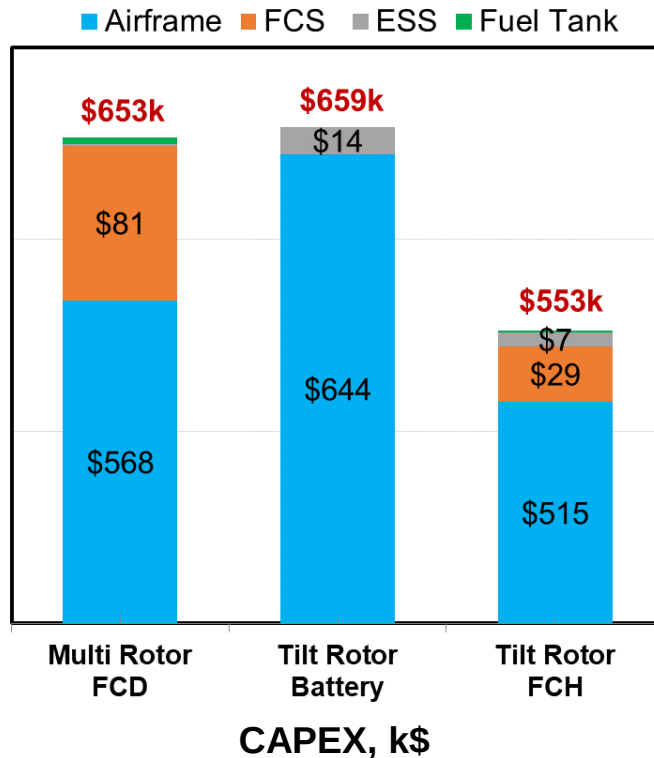
- Tilt-rotor FCH eVTOL is ~\$100k cheaper option
- Cost of LH₂ storage system relatively small

OPEX

- FC eVTOLs have ~\$50/h lower OPEX than battery eVTOL due to lower replacement costs
- Multi-rotor FCD eVOL: \$42/h FCS + \$4/h battery
 - Tilt-motor battery eVTOL: \$86/h
 - FCH tilt-motor eVTOL: \$20/h FCS + \$30/h battery

TCO

- FCH eVTOL << Battery eVTOL
- FCH tilt-rotor eVTOL < FCD multi-rotor eVTOL, but tilt rotors may require additional maintenance cost



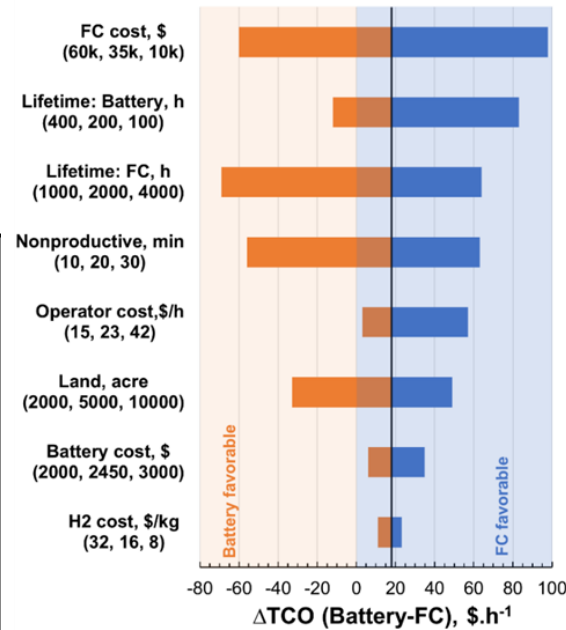
2.4 Fuel Cells for UAVs: Total Cost of Ownership

1. Multi-Rotor Hexa-Copter UAV for Gas Drilling Area Aerial Inspection

- Payload: HDL-32E Lidar, \$85k
- PEMFC Module: 2.2 kW, \$39k*, 2000 h lifetime
- H₂ Tank: 3.9 kg, 6000 psi, 0.24 kg-H₂
- Li-Po Battery Pack: 1400 Wh, \$12.6k**, 200 h lifetime



Sensitivity Analysis



\$18/h Saving in TCO with Fuel Cells

- Higher endurance: Fleet size smaller by 2 drones, \$46/h saving in labor cost***
- 2 fewer LIDARs (\$85k): \$5/h saving in CAPEX fewer LIDARs
- More expensive fuel: \$7/h higher cost of H₂
- More expensive FCS (\$39k): \$25/h higher replacement cost.
- TCO most sensitive to FCS cost, battery/FC lifetime, and nonproductive time

2. Fixed-Wing UAV for Gas Drilling Area Aerial Inspection

- Payload: RIEGL Lidar, \$100k
- PEMFC Module: 650 W, \$13k*, 1000 h lifetime
- H₂ Tank: 2.9 kg, 6000 psi, 0.18 kg-H₂
- Li-Po Battery Pack: 640 Wh, \$2.6k**, 200 h lifetime
- ICE: 2500 W, \$5k, 300 h lifetime

Assumptions	ICE	Battery	Fuel Cell
Analysis time, year		10	
Land size, acre		30,000	
Daily mission time, h		7	
Number of required swap batteries		1	
Endurance, min	576	88	450
Nonproductive time, min	30	30	30
Area scanning speed, acre/h	800	800	800
Fleet size	6	8	6
Operator labor rate, \$/h	\$23	\$23	\$23
Fuel/energy cost, \$/gal, \$/kWh, \$/kg-H ₂	\$2.5	\$0.13	\$16

- Fuel cell vs. ICE: \$43/h saving in TCO because of cheaper FCS replacement cost, longer lifetime
- Fuel cell vs. battery: \$88/h saving in TCO mainly because of fleet size smaller by 2 drones, 4 fewer operators and spotters

Includes H₂ tank and pressure booster*; Includes swap batteries and charger**; FAA requires 1 pilot per drone***

3. Fuel Cells for Small Ferries: TCO with Status Technology



Assumptions	Units	Small RoPax		Passenger Ferry	
		Diesel	FC	Diesel	FC
Fuel ^{1,10-11}	\$/kg (¢/MJ)	0.7 (1.6)	5 (4.2)	0.7 (1.6)	5 (4.2)
Engine Life ¹²	hours	100,000	7,700	100,000	7,700
Overhaul/Replacement Time Span	hours	20,000	7,700	20,000	7,700
System Performance					
Engine Power	kW	2 x 375	430	2 x 750	1,597
Peak Power Demand	kW	390	390	1,547	1,547
Duty Cycle Efficiency	%	35	55.1	35	55.1
Fuel Consumption	kg/week	4,681	1,102	10,162	2,365
CAPEX	\$	824,000	750,600	1,624,800	1,722,900
Main Engine ^{6,12-15}	\$/kW	641	193	587	193
Auxiliary Engine ^{6,13}	\$/kW	760		760	
Gearbox ⁶	\$/kW	92		92	
Shaft ⁶	\$/kW	130	96	130	96
SCR ¹⁶	\$/kW	160		160	
Switchboard & Power Conditioning ^{13,17}	\$/kW	80	80	80	80
Variable Frequency Drive ^{17,18}	\$/kW		160		160
Electric Motor ^{13,17,19}	\$/kW		120		120
Fuel Storage System ^{4,20}	\$/kg	7	313	7	287
TCO	\$/Pax	0.65	1.06	1.53	2.66
CAPEX - Propulsion	\$/Pax	0.25	0.13	0.54	0.36
CAPEX - Storage	\$/Pax	0.00	0.11	0.00	0.23
CAPEX - Ship Upgrade	\$/Pax		0.04		0.06
CAPEX - Stack Replacement	\$/Pax		0.14		0.43
OPEX - Fuel	\$/Pax	0.37	0.61	0.90	1.50
OPEX - Boiloff	\$/Pax		0.01		0.03
OPEX - O&M	\$/Pax	0.03	0.02	0.09	0.04

Background and Assumptions

- TCO only includes the powertrain components, ship upgrade, fuel, and fuel storage. Common elements such as the hull, crew wages, and insurance are excluded to emphasize the costs related to fuel cell system and hydrogen.
- CAPEX annualized over 20 years assuming 10% internal rate of return (IRR). Higher IRR (cost of borrowing) will shift the balance of TCO toward CAPEX.

Small RoPax Ferry (Washington State)

- 150 passengers, 28 cars, 12 nm/h cruise speed
- 2 x 375 kW main diesel engines
- 15-min one-way trip including 3.3-min transit, 2 NM

Small High-Speed Passenger Ferry (NY – NJ)

- 150 passengers, 38 nm/h cruise speed
- 2 x 750 kW diesel engines
- 60-min trip; 20-min slow cruise, 20-min full cruise, 18 NM

Engine and System

- Diesel engines need a major overhaul every 20,000 h

CAPEX

- Electric drivetrain more expensive than the fuel cell power system
- CAPEX of FC ferries within \$50-120k of diesel CAPEX. The incurred cost of electric drive train and LH₂ storage offsets the cost saving in the propulsion system

TCO

- LH₂ storage system CAPEX is 64-85% of the propulsion system CAPEX
- Stack replacement cost: \$0.03/Pax for RoPax and \$0.09/Pax for small ferry
- Fuel cost accounts for 65% of TCO in FC ferries and 57-59% of TCO in diesel ferries
- Higher fuel cost accounts for 76-77% of the difference in diesel and FC TCOs



Fuel Cells and Hydrogen for Small Ferries: Status and Proposed Draft Targets

Characteristic	Units	Targets for Small Ferries		
		Status	Interim	Ultimate
Fuel Cell System Lifetime ^{a,b}	[hours]	7,700	25,000	30,000
Fuel Cell System Cost ^{c,d}	[\$ /kW]	1,000 (193)	80	60
BOL Peak FCS Efficiency ^e	[%]	63	68	72
BOL FCS Efficiency at 100% Power ^g	%	54	55	55
EOL FCS Efficiency at 90% Power ^g	%	49	50	50
Hydrogen Storage System Cost ^h	[\$ /kWh]	9.5	9	8
Amount of Hydrogen Stored ⁱ	[kg]	1,071	1,060	307-1,060
H ₂ Storage System Life ^j	[cycles]	5,000	5,000	5,000
Boil-off Loss ^j	%/day	0.6	0.5	0.25
LH ₂ Bunkered Cost ^k	[\$ /kg]	5	4	3.50

- a) Status is currently based on models and data from related projects and will be revised after field data is received.
- b) Fuel cell systems are assumed to be replaced after reaching the stack lifetime defined as 10% loss in cell voltage at 100% power at beginning of life (BOL). 25,000-h status lifetime is from the fuel cell electric bus (FCEB) project¹ and lifetime for the ferry duty cycle is to be determined. Interim and ultimate lifetime targets are same as for heavy-duty trucks.²
- c) status estimate of \$1,000/kW is based on personal communications with industrial vendors for cost at low production volumes. Depending on FCS size, the vendors recommended a range of \$1000-1800/kW. FCS cost estimate at medium production volumes of (\$193/kW) was estimated using cost correlations for heavy-duty vehicles with today's technology produced at 1,000 units per year manufacturing volume.³
- d) Interim and ultimate cost targets assume 100,000 275-kW units per year production volumes. Meeting these cost targets may require leveraging automotive/HD truck production volumes to achieve the necessary economies of scale.³
- e) Fuel cell peak system efficiency includes parasitic losses for balance-of-plant (BOP) components and loss in current efficiency due to hydrogen cross-over. The assumed combined losses are 10.3% for status, 7.7% for interim, and 6.5% for ultimate targets.
- f) Beginning of life (BOL) FCS efficiency defined as net system power (stack power minus power consumed by all BOP components) divided by the lower heating value (LHV) of H₂ consumed.
- g) Status hydrogen storage system cost based on industrial data.⁴ Interim and ultimate costs are same as targets for heavy-duty trucks.²
- h) A small 150-passenger, 28-car RoPax ferry (15-min trip duration, 2x215 kW fuel cell system) refueled at 7-d interval requires 1071-kg H₂ storage. A 150-passenger, high-speed ferry (60-min trip duration, 1.6 MW fuel cells) refueled at 7-d interval requires 2336-kg H₂ storage.^{5,6}
- i) The storage system cycle life target is intended to exceed the minimum number of operational cycles required for the 20-year analysis period: 1040 cycles for 7-d and 3650 cycles for 2-d refueling interval. Safety codes and standards may have additional requirements of safety factor.
- j) Status boil-off loss taken from stationary liquid H₂ (LH₂) storage system of similar capacity.⁷ Interim and ultimate losses may require advances in vacuum insulation or mitigation strategies.⁸
- k) LH₂ bunkered cost includes costs of H₂ production, delivery and refueling.⁹ Reported minimum, average and maximum delivered LH₂ costs in SARTA FCEB demonstration projects are \$5/kg, \$5.14/kg, and \$5.88/kg, respectively.¹

TCO of RoPax Ferry Boats – Sensitivity Analysis



TCO: 7-d LH₂ Storage

TCO with \$2.44/gal diesel and \$3.5-5/kg^a bunkered LH₂

- Diesel: \$0.65/Pax
- Status FC: \$1.06/Pax
- Interim FC: \$0.76/Pax
- Ultimate FC: \$0.67/Pax

FC TCO is dominated by fuel cost accounting for 60-65% TCO

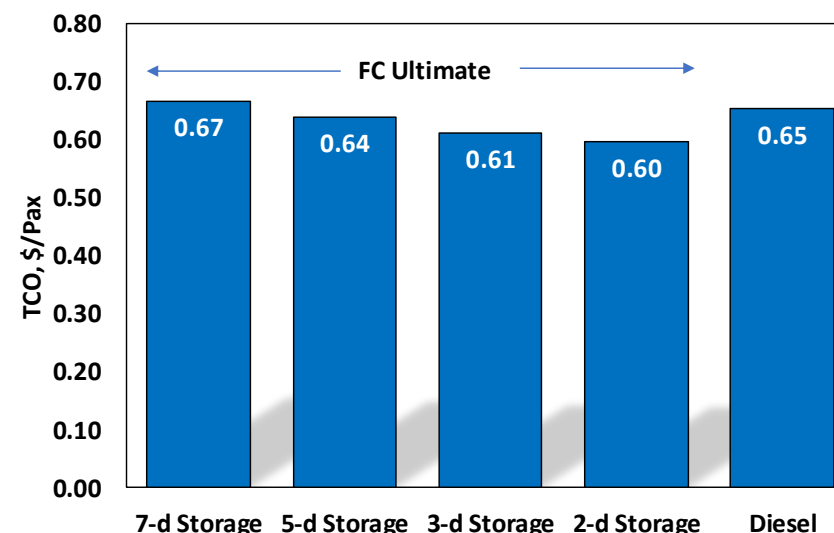
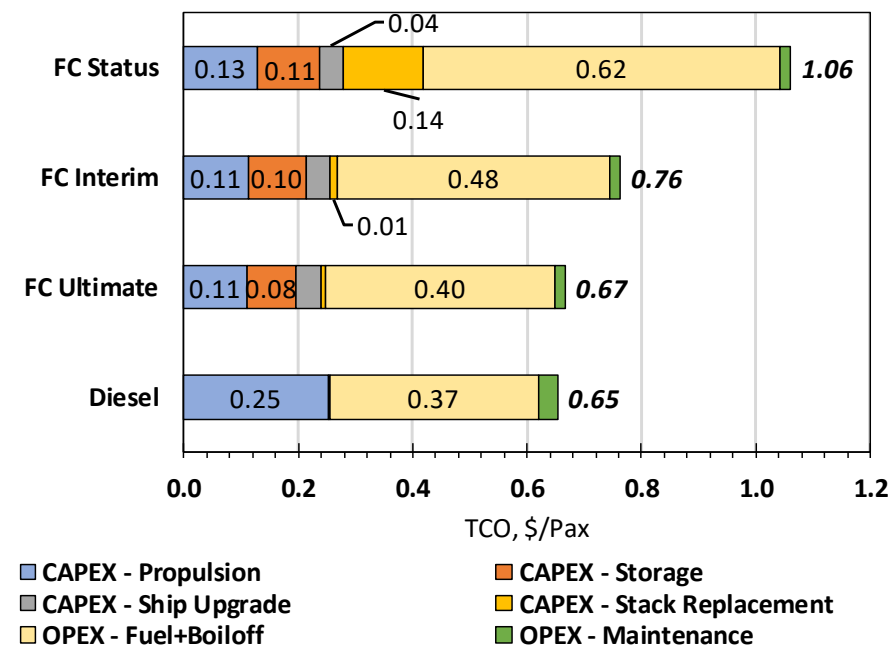
- Breakeven bunkered LH₂ cost with diesel at \$2.44/gal
 - Status FC: \$1.72/kg
 - Interim FC: \$3.07/kg
 - Ultimate FC: \$3.38/kg

TCO: Ultimate FC, \$3.5/kg LH₂

LH₂ storage system accounts for 12-14% of TCO

- Diesel: \$0.65/Pax
- Ultimate FC with 7-d LH₂ storage
\$0.67/Pax (LH₂ breakeven = \$3.38/kg)
- Ultimate FC with 5-d LH₂ storage
\$0.64/Pax (LH₂ breakeven = \$3.63/kg)
- Ultimate FC with 3-d LH₂ storage
\$0.61/Pax (LH₂ breakeven = \$3.87/kg)
- Ultimate FC with 2-d LH₂ storage
\$0.60/Pax (LH₂ breakeven = \$4.00/kg)

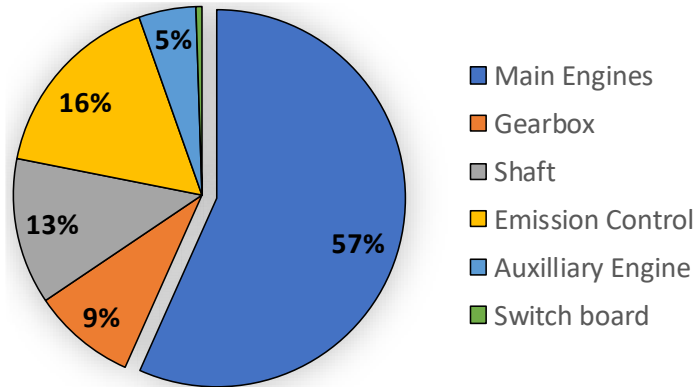
^aLH₂ Cost: Status = \$5/kg; Interim = \$4/kg, Ultimate = \$3.5/kg



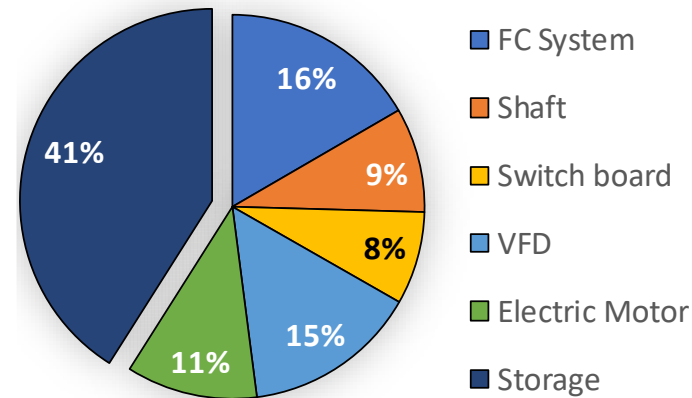


TCO High-Speed FC Ferry

Diesel Mechanical: \$1.55 million

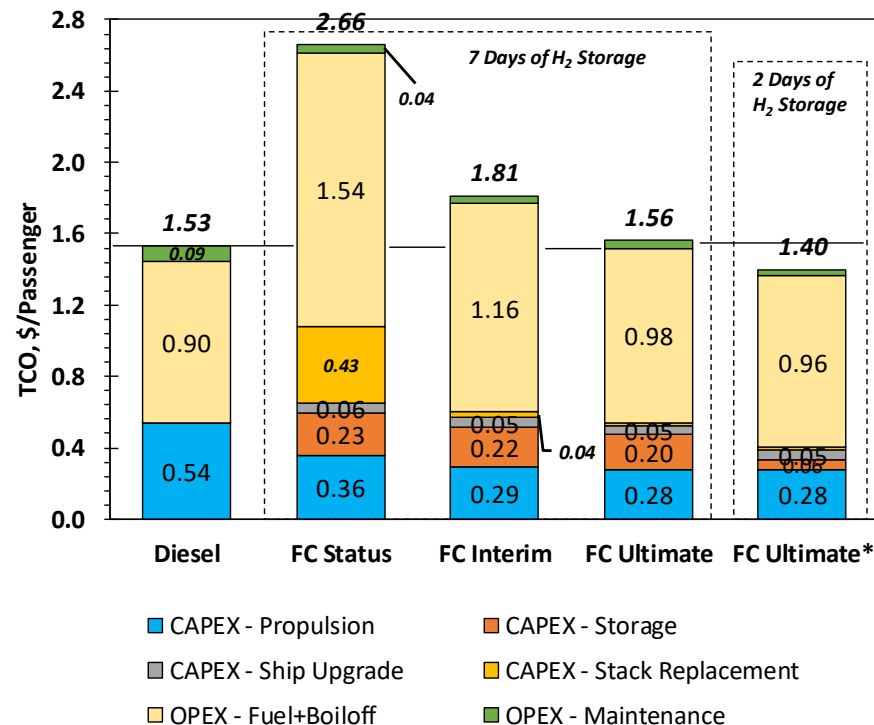


Fuel Cell System: \$1.72 million



Conclusions:

- Fuel cost is a main contributor to the TCO. H₂ costs must decrease for FC ferries to be competitive.
- FC ferries can be cost competitive with today's diesel technology if the ultimate targets are reached.



Cost Item	DM	FC (\$/I/U)
Main Engine/Stack (\$/kW)	587	193/80/60
Auxilliary Engine (\$/kW)	760	N/A
Gearbox (\$/kW)	92	N/A
Shaft (\$/kW)	130	96
SCR (\$/kW)	120	N/A
Switchboard+Power conditioning (\$/kW)	80	80
Variable Frequency Drive (\$/kW)	N/A	160
Electric Motor (\$/kW)	N/A	120
Storage System Cost (\$/kg)	7	287/287/266
Fuel Cost (DM-\$/kg, FC-\$/kg)	0.7	5/4/3.5
Engine/FC life (years)	20	2/7/9
Overhaul time span (hours)	20,000	Regular Maintenance
Passengers (PAX)/year	410,400	410,400
Fuel Consumption/week	10,162	2,365/2,237/2,149

S=Status, I=Interim, U=Ultimate



H2@Rail

1. Caterpillar
2. Cummins
3. Alstom
4. Stadler
5. North County Transit District
6. San Bernardino County Transit Authority
7. CalTrain
8. Massachusetts Bay Transit Authority
9. Federal Railroad Administration
10. Wabtec
11. Sandia National Laboratory
12. Chart Industries

H2@Ports

1. Caterpillar
2. Chart Industries
3. Golden Gate Zero Emission
4. Swift Maritime

H2@Planes

1. Ballard Unmanned Systems
2. Alaka'i Technologies
3. Universal Hydrogen
4. University of Illinois, Urbana Champaign
5. General Electric
6. PowerCell Sweden

TCO Presentations at Workshops

- R. K. Ahluwalia, C. F. Cetinbas, J-K Peng, X. Wang and D. Papadimas, "Total Cost of Ownership (TCO) Analysis of Hydrogen Fuel Cells in Aviation – Preliminary Results," H2@Airports Virtual Workshop, Hosted by the U.S. Department of Energy in partnership with the Department of Transportation and Department of Defense, Nov. 4-6, 2020
- D. Papadimas, R. K. Ahluwalia, E. Connelly and P. Devlin, "Total Cost of Ownership (TCO) Analysis for Hydrogen Fuel Cells in Maritime Applications – Preliminary Results," H2@Ports Workshop, Sep. 10-12, 2019, San Francisco, CA
- R. K. Ahluwalia, D. Papadimas, J-K Peng, T. Krause, S. Chan and P. Devlin, "Total Cost of Ownership for Line Haul, Yard Switchers and Regional Passenger Locomotives – Preliminary Results," H2@Rail Workshop, March 26-27, 2019, Lansing, MI

Remaining Future Work

This task ends on 4/31/2021.

- Issue report on TCO and technical targets for hydrogen use in unmanned aerial vehicles, air taxis, fixed-wing, and single-aisle aircraft.
- Complete draft of DOE record for hydrogen-fueled, fuel cell/fuel cell-battery hybrid multiple units (MU) for regional commuter passenger operations defining the technical targets for fuel cell and hydrogen technologies. Compare the TCO for hydrogen-fueled, fuel cell MU to diesel, electric, and battery MUs for regional commuter operations. TCO includes the impact of the infrastructure costs associated with electric, battery, and fuel cell MUs.
- Issue final report to DOE that includes life-cycle and technoeconomic analyses in at least 4 types of aircrafts (i.e., unmanned aerial vehicles, air taxis, and fixed-wing, single-aisle aircraft) as well as a system cost analysis to enable developing cost targets to guide future R&D.
- Issue final report on fuel cells for maritime, documenting TCO analysis results and technical cost and performance targets

Next Step

- Perform TCO studies of off-road trucks used in construction and agricultural equipment.

Summary



Relevance:	Economic analysis for non-road transportation applications that could increase hydrogen demand and spur hydrogen infrastructure development
Approach:	Develop cost-of-ownership models for representative use cases. Calculate TCO for current and future fuel cell systems assuming advancements consistent with HFTO targets and goals
Progress:	• Compared TCO for H₂ fuel cell ferries with diesel ferries and determined improvements in fuel cell technology needed to compete with diesel powered ferries. FC ferries can be competitive with \$3.50/kg H₂ and improvements in FC cost and durability. • Determined hydrogen and fuel cells can be competitive on a TCO basis in aviation applications for UAV, UAM, air taxis, and small planes. These applications are much less sensitive to fuel cost than marine applications and H₂ costs as high as \$8/kg can still lead to competitive TCO for FCs for small planes. • Determined TCO for FC for multiple units in commuter rail operations. Updated TCO for line-haul, switcher, and regional commuter locomotives.
Collaborations:	Organizations: Alaka'i Technologies, Ballard Unmanned Systems, Caterpillar, Chart Industries, Cummins, Golden Gate Zero Emission, Sandia National Laboratory, Swift Maritime, Universal Hydrogen, University of Illinois, Alstom, Stadler, North County Transit District, San Bernardino County Transit Authority, CalTrain, Massachusetts Bay Transit Authority, Federal Railroad Administration, Wabtec
Proposed Future Work:	Perform TCO studies of off-road trucks used in construction and agricultural equipment



Backup Slides and Additional Information

Response to Reviewers' Comments



- Not applicable. The project was not reviewed in 2020 or prior years.



Presented TCO Results to Stakeholders at DOE Workshops

- R. K. Ahluwalia, C. F. Cetinbas, J-K Peng, X. Wang and D. Papadias, “Total Cost of Ownership (TCO) Analysis of Hydrogen Fuel Cells in Aviation – Preliminary Results,” H2@Airports Virtual Workshop, Hosted by the U.S. Department of Energy in partnership with the Department of Transportation and Department of Defense, Nov. 4-6, 2020
- D. Papadias, R. K. Ahluwalia, E. Connelly and P. Devlin, “Total Cost of Ownership (TCO) Analysis for Hydrogen Fuel Cells in Maritime Applications – Preliminary Results,” H2@Ports Workshop, Sep. 10-12, 2019, San Francisco, CA
- R. K. Ahluwalia, D. Papadias, J-K Peng, T. Krause, S. Chan and P. Devlin, “Total Cost of Ownership for Line Haul, Yard Switchers and Regional Passenger Locomotives – Preliminary Results,” H2@Rail Workshop, March 26-27, 2019, Lansing, MI

Stakeholders Contacted in One-on-One Meetings

H2@Rail

1. Caterpillar
2. Cummins
3. Alstom
4. Stadler
5. North County Transit District
6. San Bernardino County Transit Authority
7. CalTrain
8. Massachusetts Bay Transit Authority
9. Federal Railroad Administration
10. Wabtec
11. Chart Industries

H2@Ports

1. Caterpillar
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3. Golden Gate Zero Emission
4. Swift Maritime

H2@Planes

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2. Alaka'i Technologies
3. Universal Hydrogen
4. General Electric
5. PowerCell Sweden

Remaining Barriers and Challenges



Proposed Targets for Hydrogen and Fuel Cells for Regional Planes

Characteristic	Units	Incumbent ^a	H ₂ and FCS Targets for Regional Planes	
			Interim ^b	Ultimate ^c
Engine Rated Power ^d	[kW]	173	225	275
Engine Cost	[\$/kW]	552	300 ^e	250 ^e
Engine Specific Power	[W/kg]	980	1,000	2000 ^f
Engine Power Density	[W/L]	295	850	1,000
Engine Lifetime ^g	[hours]	2,000	3,000	3,000
Engine Efficiency at 100% Power ^h	[%]	35	52	52
Amount of Fuel Stored	[kg]	235	50	70
Fuel Storage System Gravimetric Capacity	[kg-fuel/kg]	0.78	0.18	0.225 ⁱ
Fuel Storage System Cost	[\$/kWh]		10	10
Fuel Storage System Life	[cycles]		5,000	5,000
Boil-off Loss	[%/day]		0.4	0.25
Fuel Cost	[\$/kg]	2	7.50	7.50

Fuel Cells and Hydrogen for Small Ferries: Status and Proposed Draft Targets

Targets for Small Ferries				
Characteristic	Units	Status	Interim	Ultimate
Fuel Cell System Lifetime ^{a,b}	[hours]	7,700	25,000	30,000
Fuel Cell System Cost ^{c,d}	[\$/kW]	1,000 (193)	80	60
BOL Peak FCS Efficiency ^e	[%]	63	68	72
BOL FCS Efficiency at 100% Power ^g	%	54	55	55
EOL FCS Efficiency at 90% Power ^g	%	49	50	50
Hydrogen Storage System Cost ^h	[\$/kWh]	9.5	9	8
Amount of Hydrogen Stored ⁱ	[kg]	1,071	1,060	307-1,060
H ₂ Storage System Life ^j	[cycles]	5,000	5,000	5,000
Boil-off Loss ^j	%/day	0.6	0.5	0.25
LH ₂ Bunkered Cost ^k	[\$/kg]	5	4	3.50

Progress toward Milestones

	Milestone		% complete
Progress measure	report on total cost of ownership and technical targets for hydrogen use in unmanned aerial vehicles, air taxis, fixed-wing, and single-aisle aircraft.	12/31	100%
Progress measure	complete draft of DOE RECORD for hydrogen-fueled, fuel cell/fuel cell-battery hybrid multiple units (MU) for regional commuter passenger operations defining the technical targets for fuel cell and hydrogen technologies and comparing the Total Cost of Ownership (TCO) for hydrogen-fueled, fuel cell MU) to diesel, electric, and battery MUs for regional commuter operations. TCO includes the impact of the infrastructure costs associated with electric, battery, and fuel cell MUs.	12/31	
Progress measure		12/31	
Progress measure	final report to DOE that includes life-cycle and technoeconomic analyses in at least 4 types of aircrafts (i.e., unmanned aerial vehicles, air taxis, and fixed-wing, single-aisle aircraft) as well as a system cost analysis to enable developing cost targets to guide future R&D.	03/31	95%
Progress measure	Final Report –Maritime Final report documenting TCO analysis results and technical cost and performance targets	04/31	95%

Comparison of LDV, Rail, Maritime and Aviation Applications

Sector	Application	System Size (kW)	H ₂ storage size (kg H ₂)	Potential Yearly H ₂ demand (kg/unit)
Passenger vehicle	Passenger Vehicle	80-100	5-6 kg	~ 225-245
Rail	Line-haul Locomotive	3300	4000-7500 kg (LH ₂ tender)	150,000-200,000
	Multiple Unit Passenger	200-400	260 kg	15,000-30,000
Maritime	High-speed Ferry	1597	2365	118,250
	RoPax Ferry	470	1102	55,100
Aviation	4-6 Seat Plane	225-275	70	1,896-4,760
	UAM	129-358	3.6-9.9	12,000-30,000

Non-road transportation applications can increase demand for hydrogen and help spur development of a hydrogen fueling infrastructure

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Supplemental Slides-Maritime Duty cycles



High-speed ferry

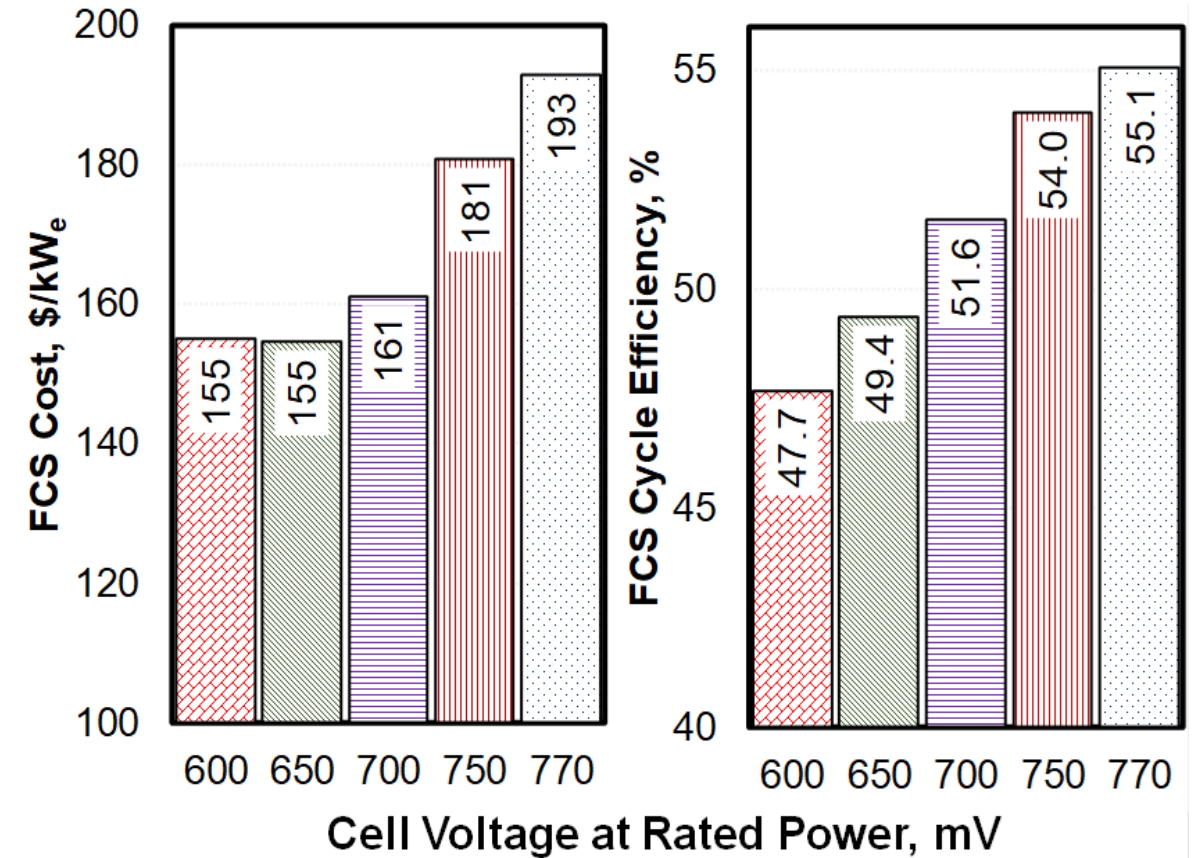
Operational stage	% Time	% Engine Load
Idle	32	13
Maneuvering	32	25
Precautionary	18	49
Slow Cruise	10	85
Full Cruise	8	100

RoPax ferry

Route Segment	Time (min)	Time (%)	Engine #1 Load (%)	Engine #2 Load (%)	Engine Power (kW)
Loading	4.1	27	20	0	75
Departure	0.95	6	40	20	225
Transit	3.3	22	80	10	338
Arrival	1.25	8	40	20	225
Unload	4.1	27	20	0	75
Slack	1.3	9	5	0	19

Supplemental Slides- FC System Performance/sizing tradeoffs

- In LDV applications, initial vehicle costs are a major factor in purchase decisions and FC systems are designed to minimize FC system cost
- In HDV and marine applications, the fuel costs are major factor driving TCO and fuel cell system cost is a smaller fraction of the TCO.
- Examined potential for operating regimes with increased efficiency at rated power to determine their effect on over the ferry duty cycles, durability, and the TCO.
- Operating at higher voltages at rated power (0.77V at BOL decreasing to 0.70V at EOL) provides higher efficiency but results in lower power density and increased fuel cell cost.
- Performance models suggest operating at 0.77V at rated power at BOL provides a good balance between efficiency and durability. Long-term testing will be needed to determine the impact of this design strategy on durability.



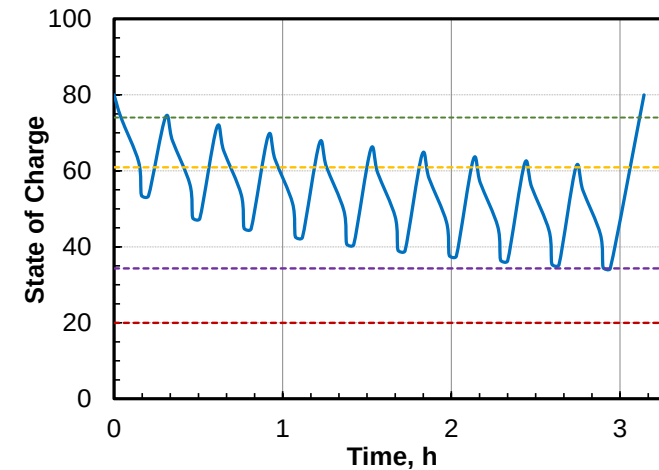
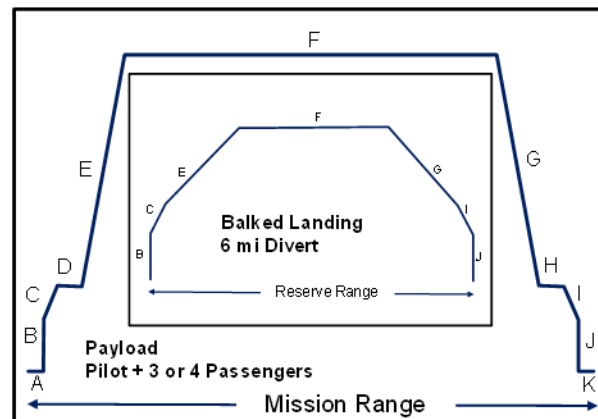
Tradeoff between fuel cell system cost and efficiency over the ferry duty cycles investigated. Testing has determined that operating at high voltage may also increase the rate of degradation.

Supplemental Slides – UAM duty cycle



UES flight segments³

	Segment	Distance (mi)	Vertical Speed (ft/min)	Horizontal Speed (mph)	AGL Ending Altitude (ft)
A	Ground Taxi	No Distance Credit	0	3	0
B	Hover Climb		0 to 500	0	50
C	Transition + Climb	Sizing Repeated 60 25	500	0 to 1.2*Vstall	300
D	Departure Terminal Procedures		0	1.2*Vstall	300
E	Accel + Climb		500	1.2*Vstall to 150	1500
F	Cruise		0	150	1500
G	Decel + Descend		500	150 to 1.2*Vstall	300
H	Arrival Terminal Procedures		500	1.2*Vstall	300
I	Transition + Descend		500 to 300	1.2*Vstall to 0	50
J	Hover Descend	No Distance Credit	300 to 0	0	0
K	Ground Taxi		0	3	0
L	Reserves	Balked Landing, 6 mil divert at 500 ft AGL			



UAM duty cycle and battery state-of-charge during 3 hour operating window. The scenario does not allow full recharge of the battery between flight segments. The battery schedule has been adjusted to limit the upper SOC to 80%.

Supplemental slide- FC Performance at Altitude

Modeled steady-state performance map of FCS efficiency vs. power at BOL and EOL for different altitudes (blue 0 km, red 2 km, green 5 km). The model results are shown for portions of the flight in which the ram air serves as the heat sink in the radiator without relying on the blower fan . FCS power on x-axis is net of the power produced in the stack and the power consumed by the air management, water management and fuel management systems.

