Total Cost of Ownership for Line Haul, Yard Switchers and Regional Passenger Locomotives – Preliminary Results

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Total Cost of Ownership (TCO)

Freight and Regional Passenger Locomotives ($/mile)

- Lifetime cost of locomotive, maintenance/refurbishment and fuel levelized over total miles travelled

Yard Switcher Locomotives ($/h)

- Lifetime cost of locomotive, maintenance/refurbishment and fuel levelized over total service hours

TCO for 30-y locomotive service life, 15-y engine lifetime, and $3/gal diesel fuel

	Freight	Regional	Switcher
Locomotive Lifetime	3,6000,00 miles	4,800,000 miles	138,000 h
Engine (HP)	4,400	3,600	1,500
Fuel Tank Capacity (gal)	5,000	2,000	2,000
Fuel Consumption	0.40 mpg	0.49 mpg	9.5 gal/h
Total Locomotive Cost ($)	3,000,000	2,500,000	1,350,000
Maintenance Cost ($/year)	125,000	125,000	75,000
Overhaul Lifetime Cost ($)	300,000	250,000	175,000
Fuel Cost	**7.50 $/mile**	**6.12 $/mile**	**28.05 $/h**
Levelized Cost	**9.46 $/mile**	**7.48 $/mile**	**55.41 $/h**

- Freight and regional locomotives: Fuel accounts for ~80% of TCO. Besides engine reliability and availability, fuel economy and cost are extremely important.
- Switcher locomotives: Fuel accounts for 55% of TCO. Capital, maintenance & refurbishment, and fuel costs are important.

Fuel Cell System Cost

System costs projected using 90-kW_e automotive style stacks, 2 stacks/module, 2 modules for 360-kW_e heavy-duty vehicles (HDV)*

Current PEM systems ($285/$kW_e$)

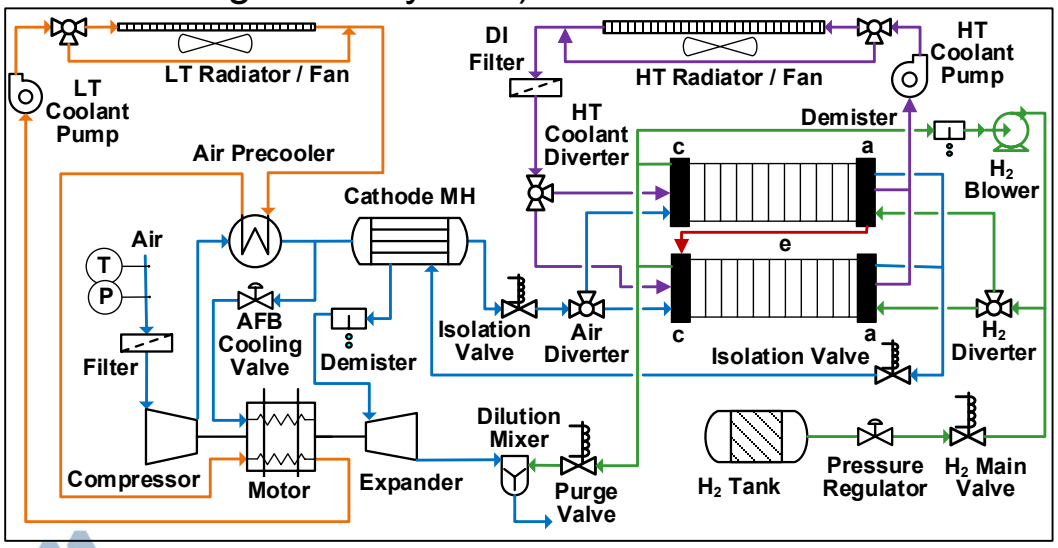
- Pt or Pt alloy cathode electrodes with 0.35 mg/cm^2 Pt loading, 400-kW_e gross power, assembled at low production volumes (100 HDV systems/year)

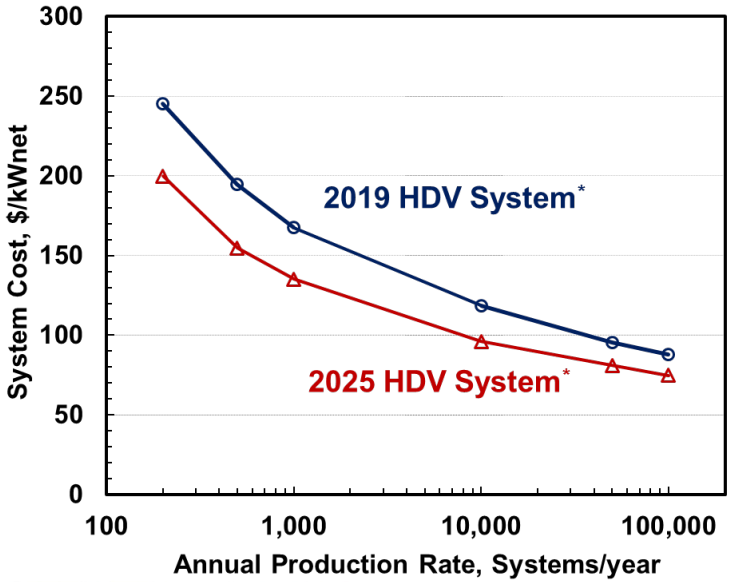
Interim PEM systems ($130/$kW_e$)

- Same configuration as current systems, cost savings due to higher production volumes (5,000 HDV systems/year)

Ultimate PEM systems ($60/$kW_e$)

- Cost savings from higher production volumes (>100,000 HDV systems/year) and technology advancements (higher activity catalysts with lower Pt loading, improved air management system)





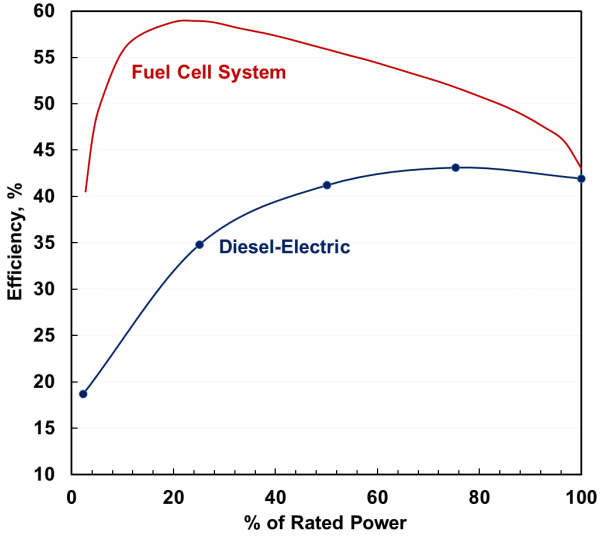
*Strategic Analysis, Fuel Cell System Analysis, Fuel Cell Tech Team Meeting, 20 February 2019

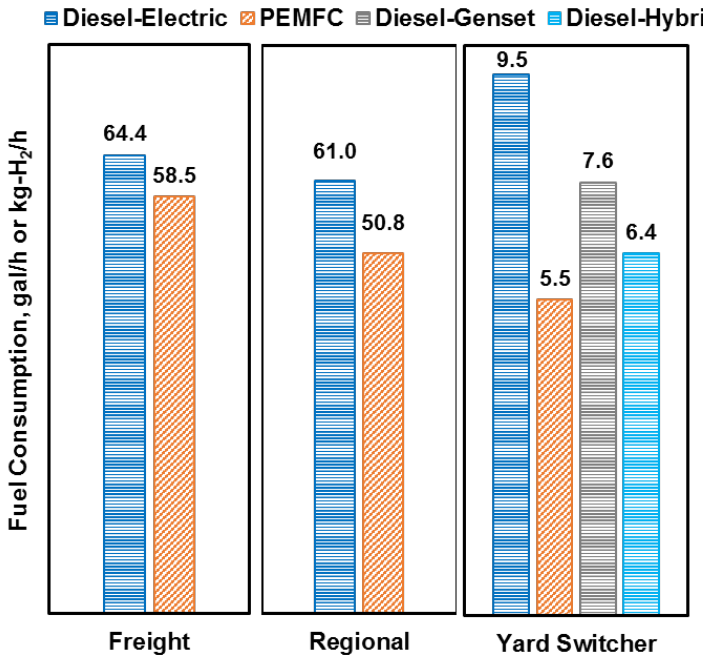
Fuel Economy

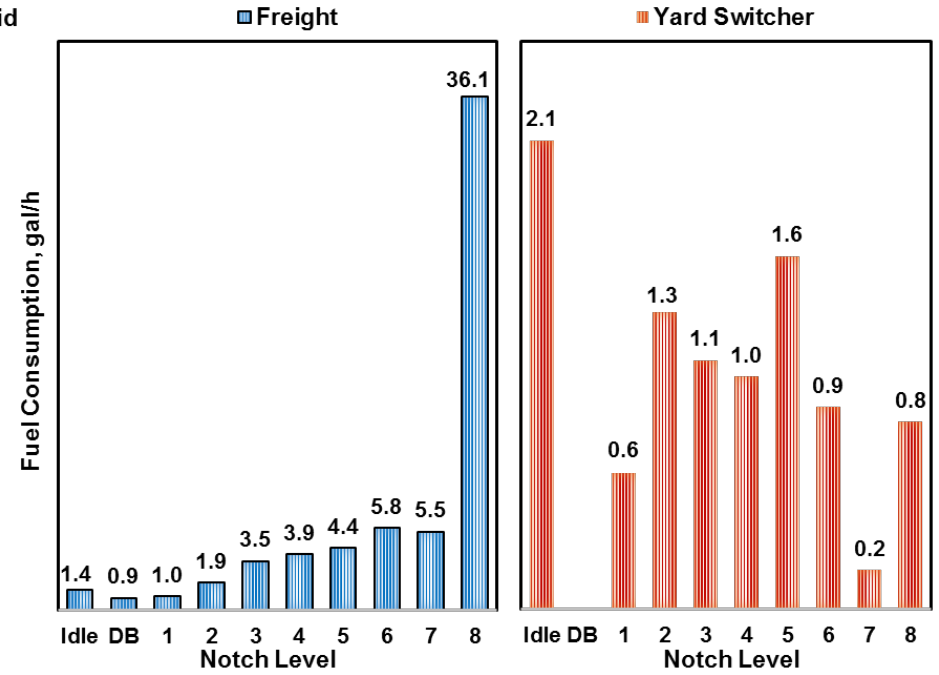
Fuel Economy (FE) on EPA Duty Cycles

FE Multiplier (FEM): Ratio of FCS to diesel fuel economy

- Freight duty cycle: Significant fuel consumption at high notch levels where diesel is most efficient, FEM = 1.1
- Regional duty cycle: Frequent start-stops, actual cycle depends on service route, FEM = 1.2*
- Yard-switcher duty cycle: Significant fuel consumption at idle and low notch levels where FCS has distinct advantages, FEM = 1.7







*Alstom Lint (Coradia Specs, Ludwig-Bölkow-Systemtechnik GmbH,12th International Hydrail Conference, Graz, 27-28 June, 2017)

Hydrogen Storage System Cost

Cryo-Compressed Hydrogen (CcH_2) Storage System for Freight and Regional Locomotives

Freight Locomotives: One tender car needed, 4850 kg-H_2 stored at 500 bar, 70 K

- 93 m^3 and ~48.5 tonne required storage volume and weight for ~10 wt% gravimetric and 50 g/L volumetric capacities

Regional Locomotives: Tender car not needed, if 2 refuelings/day, 500-kg stored H_2

Liquid H_2 tender in lieu of CcH_2 tender also needs to be investigated

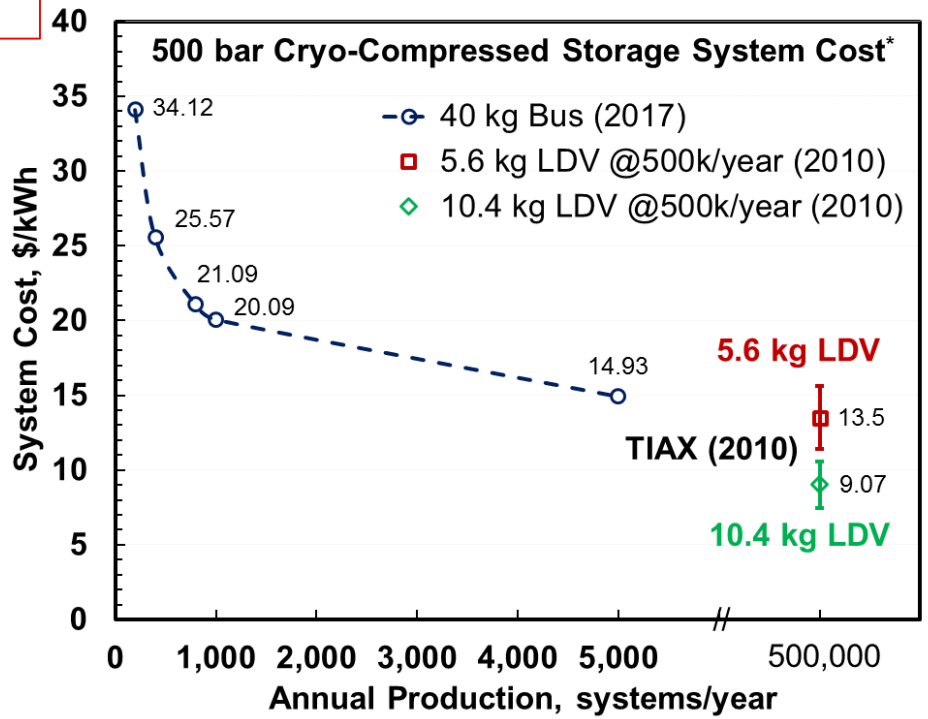
350-bar Compressed Hydrogen (cH_2) Storage System for Switcher Locomotives

Tender car not needed for 100 kg-H_2 stored at 350 bar, room temperature

- 5 m^3 required storage volume for 6-7 wt% gravimetric and ~19 g/L volumetric capacities

Projected CcH_2 Storage System Costs

- **Current PEM:** \$1130/kg-H_2 (200 HDV systems/year)
- **Interim PEM:** \$500/kgkg-H_2 (5000 HDV systems/year)
- **Ultimate PEM:** \$266/kg (DOE target)



Dispensed Hydrogen Cost

- AC Transit, CA: 13 buses, 2 stations, liquid H_2 delivery / electrolysis
- Sunline, CA: 10 buses, on-site SMR, new station electrolysis based
- OCTA, CA: 1 bus, H_2 purchased from local retail stations
- SARTA, OH: 7 buses, liquid H_2 delivery
- Fuel cost: \$9/kg-H_2 (current), \$7/kg-H_2 (interim), \$4/kg-H_2 (ultimate)

Agency	AC Transit[1]	SunLine[2]	OCTA[3]	SARTA[4]
Data period	2/13-7/17	3/12-10/18	3/16-12/18	2/18-12/18
Number of months	54	80	34	11
Average H2 cost, $/kg	8.39	10.17	13.95	5.14
Maximum H2 cost, $/kg	10.26	26.02	16.99	5.88
Minimum H2 cost, $/kg	6.49	2.53	12.99	5.00
Overall FCEB fuel cost, $/mile	1.41	1.82	1.47	1.03
Baseline technology	Diesel	CNG	CNG	CNG/diesel hybrid
Average fuel cost, $/gal or gge	2.43	0.96	1.15	1.89 / 2.30
Overall baseline fuel cost, $/mile	0.57	0.32	0.32	0.45 / 0.51

Overall cost Comparison to baseline

Fuel cost is based on data provided by agencies, not all are equal comparisons

[1]Delivered cost
[2]Includes station O&M
[3]Retail cost from local public stations
[4]Delivered cost

Leslie Eudy, Summary of Fuel/Energy Costs for NREL Evaluation Projects, NREL ZEB Technology Showcase and Symposium, February 6, 2019

Fuel Cell System Maintenance Cost

Average long term or life-cycle maintenance costs

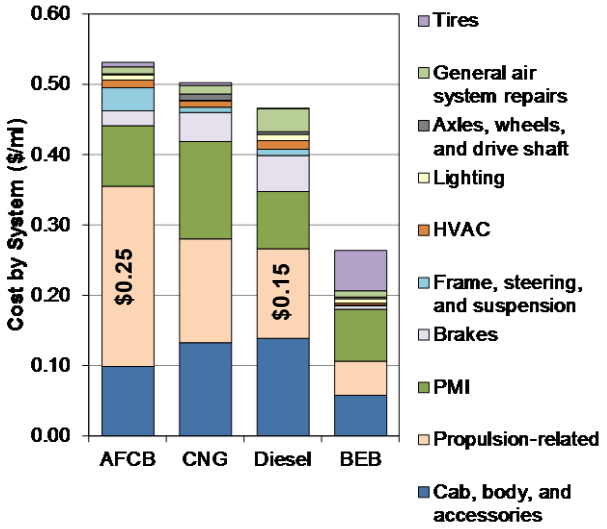
- Diesel electric locomotives: 1-1.5 $/mile (Prices and costs in the railway sector, J.P. Baumgartner, 2001, LITep)
- Diesel electric locomotives: $125,000/year (California Air Resources Board)
- Diesel electric locomotives: 30-40% maintenance cost due to engine (Ephraim, M. Maintenance and Capital Costs of Locomotives, Electro-Motive Division, GM)

FCS vs. diesel engine relative maintenance cost from FCEB data: 1.67 (current)

- Majority of issues with FCS are due to balance of plant and not stack: air handling, blowers, cooling pumps, plumbing

Summary of FCEB Data through February 2018

	2017 Fleet Average	2018 Fleet Max	2018 Fleet Average	2016 Target	Ultimate Target	Target Met
Bus lifetime (years)	4.7	7.5	5.5	12	12	
Bus lifetime (miles)	118,989	189,168	128,656	500,000	500,000	
Powerplant lifetime[a] (hours)	13,801	27,330	13,041	18,000	25,000	2016
Bus availability (%)	76	90	71	85	90	
Roadcall frequency[b] (bus)	4,710	4,715	4,516	3,500	4,000	Ultimate
Roadcall frequency (fuel cell system)	20,705	23,741	18,026	15,000	20,000	Ultimate
Maintenance cost ($/mi)	1.03	0.56	0.53	0.75	0.40	
Fuel economy (mpdge)[c]	6.51	7.82	7.01	8	8	
Range (miles)[d]	247	357	300	300	300	



Leslie Eudy, Technology Validation: Fuel Cell Bus Evaluations. DOE Hydrogen and Fuel Cells Program, 2018 Annual Merit Review and Peer Evaluation Meeting

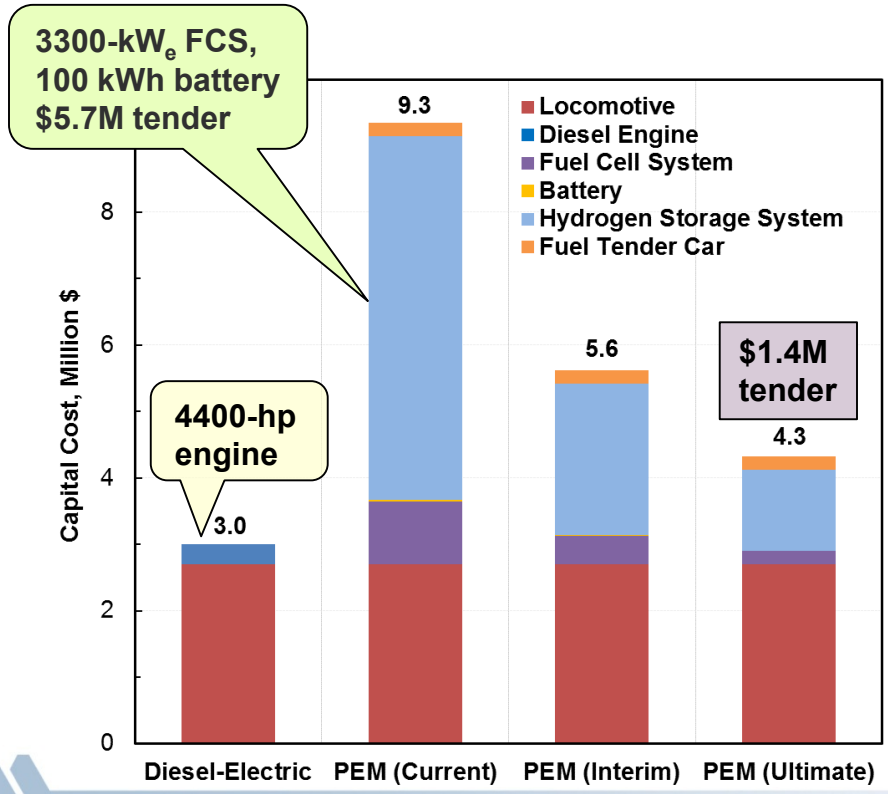
Preliminary Total Cost of Ownership – Fuel Cell Freight Locomotives

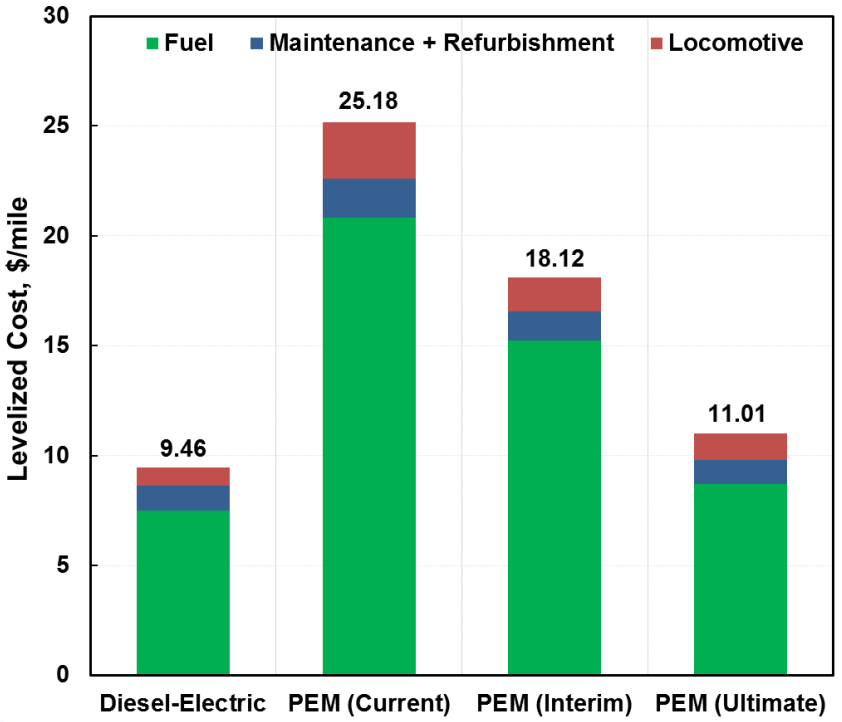
A challenging application for fuel cells because ~75% of fuel is consumed in freights at notches 6, 7 and 8 where diesel engines are most efficient

- Projected gain in fuel economy is ~10% for fuel cells
- **Break-even delivered hydrogen cost relative to $3/gal diesel: $3.30/kg**

Other factors that may favor fuel cells

- Stricter emission standards for diesel locomotives
- More expensive diesel fuel: EIA projects increase of 21% by 2030 and 27% by 2035
- Carbon credits and if hydrogen is produced from renewables

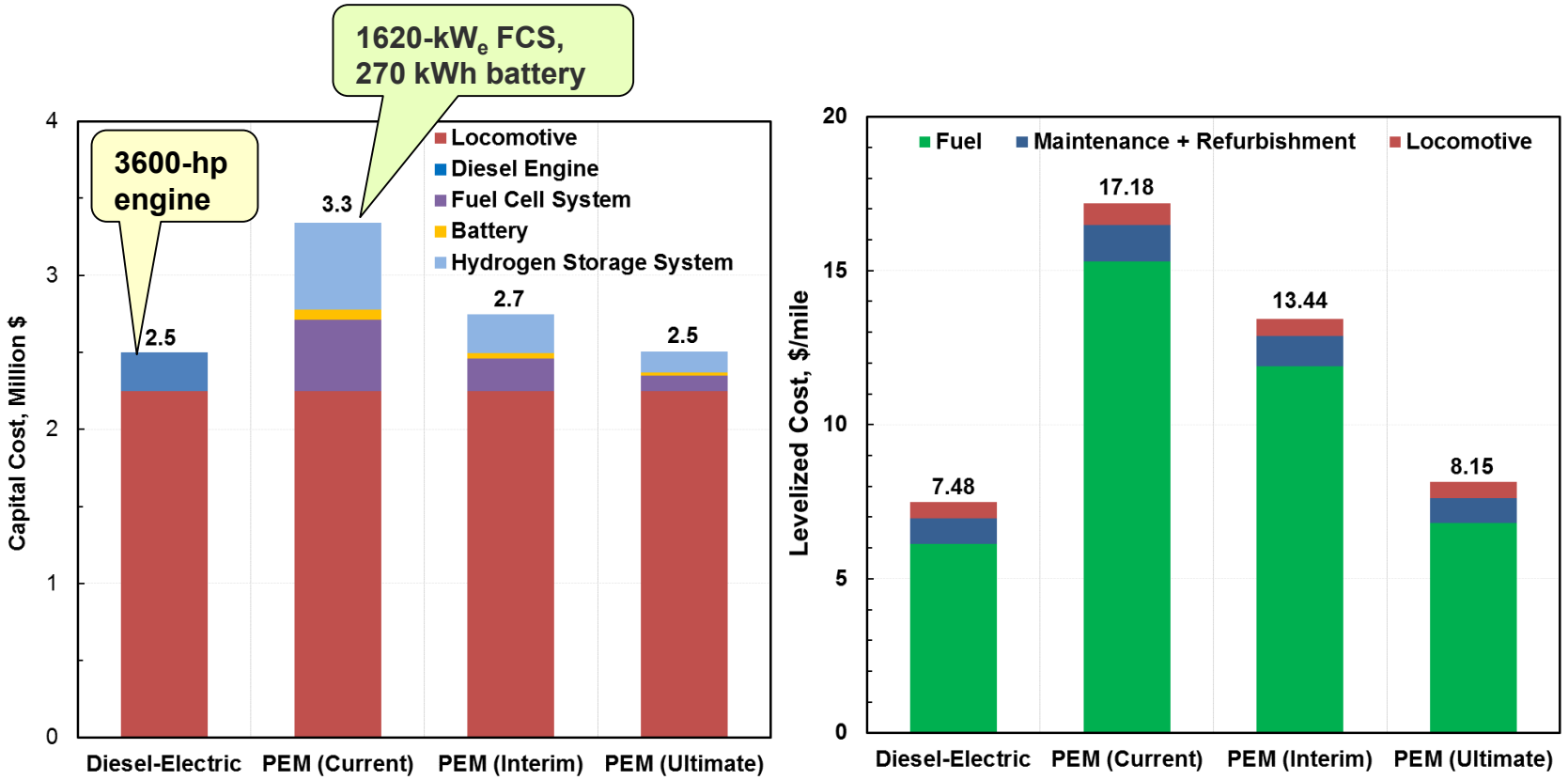




Preliminary Total Cost of Ownership
Fuel Cell Regional-Passenger Locomotives

Preliminary TCO of fuel cells slightly more suitable for regionals than freights

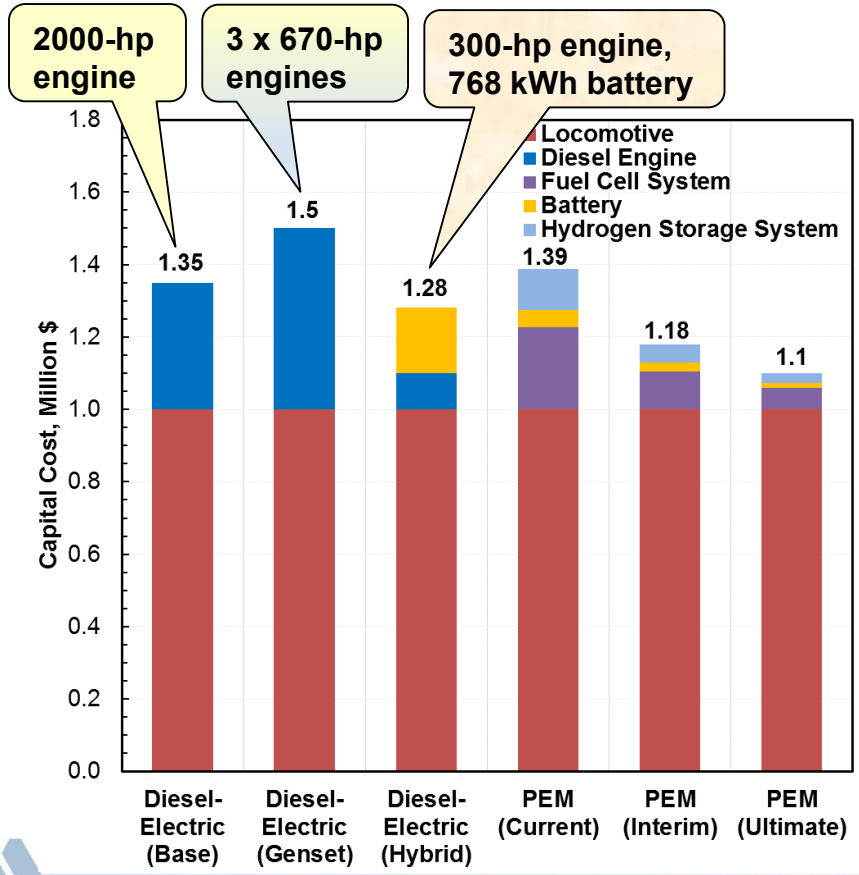
- Higher gain in fuel economy (1.2x vs 1.1x) because the metropolitan duty cycle includes frequent stops and low speeds
- With 2 refueling/day, only 500-kg H_2 storage is required and can be accommodated without a tender car if H_2 stored as cryo-compressed gas. May also be feasible to eliminate the tender car with 350-bar cH_2 storage system.
- **Break-even delivered hydrogen cost relative to $3/gal diesel: $3.60/kg**

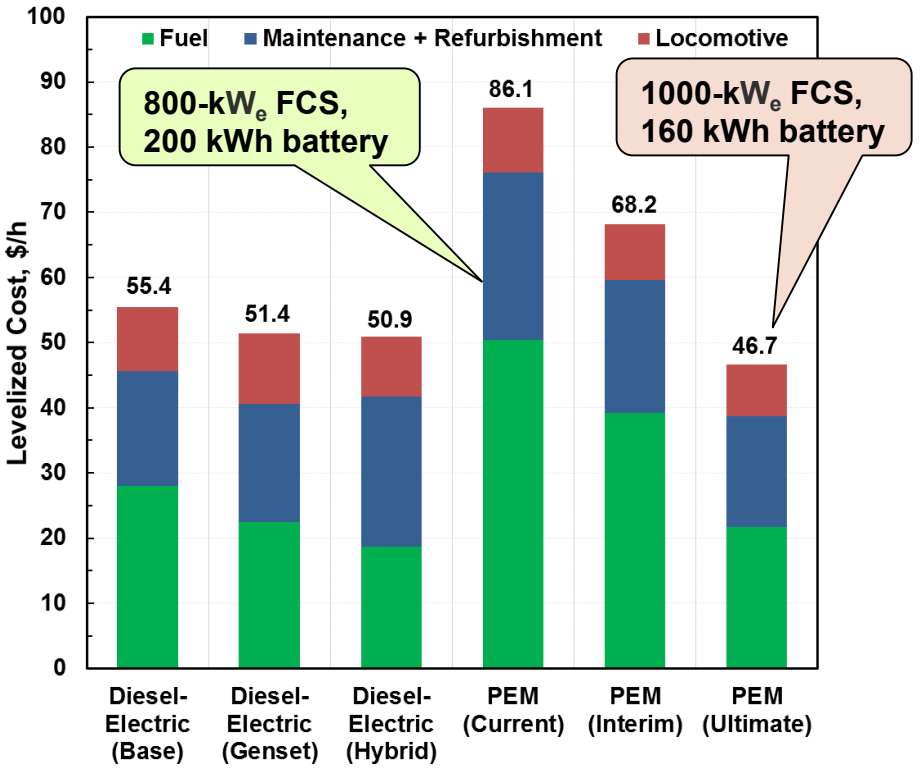


Preliminary Total Cost of Ownership
Fuel Cell Yard-Switcher Locomotives

Preliminary TCO of fuel cells more favorable for yard switchers than freights or regionals

- 70% higher fuel economy than diesels on EPA duty cycles for switchers
- On TCO basis, fuel cells can be >15% cheaper if they are developed to meet the ultimate performance and cost targets and if hydrogen is delivered at $4/kg
- **Break-even delivered hydrogen cost relative to $3/gal diesel: $5.60/kg**
- No loss of functionality as in a hybrid with an undersized 300-hp diesel engine





Summary and Outlook

Preliminary TCO of fuel cells more favorable for yard switchers than freights and regionals

- Future targets favor a 1000-kW_e fuel-cell dominant hybrid with 160 kWh battery
- 70% lower fuel consumption than diesels on EPA duty cycles
- On TCO basis, fuel cells can be >15% cheaper if they are developed to meet the ultimate performance and cost targets and if hydrogen is delivered at $4/kg

Break-even delivered hydrogen cost relative to $3/gal diesel

- Freight locomotives: $3.30/kg
- Regional passenger locomotives: $3.60/kg
- Yard switcher locomotives: $5.60/kg

Hydrogen storage for locomotives

- Fuel tender car with liquid hydrogen refueled CcH_2 storage system for freight locomotives: 4,800 kg stored H_2, 80 kg/min refueling rate for 1-h refueling time
- CcH_2 or 350-bar cH_2 storage for regional locomotives, 500 kg stored H_2
- 350-bar cH_2 storage for yard switcher locomotives, 100 kg stored H_2

Areas for further development

- MEA durability exceeding 1.8-2.4 million miles for freights and regionals, 70,000 h for yard switchers
- Availability and reliability of FCS BOP components including air management
- May be desirable to develop single stacks >250 kW_e
- Methods for meeting and exceeding the critical target of $4/kg-$H_2$ at pump