FUELS AND FUEL TECHNOLOGIES FOR POWERING 21ST CENTURY PASSENGER AND FREIGHT RAIL: SIMULATION-BASED CASE STUDIES IN A U.S. CONTEXT

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STUDY QUESTIONS

- How effective is a given fueling technology in reducing fuel cycle GHG and pollutant emissions? What is each technology's cost to the equipment owners (i.e. rail firms)?
- Might outcomes for a given fuel vary by service type?
- Are there any major logistical challenges that need to be addressed?
- How might shifts within the freight rail sector impact passenger rail? And vice versa?

STUDY BACKGROUND/MOTIVATION (CONT.)

- As cars shift over to cleaner fuels, how can trains do their part to help achieve sustainability/climate (i.e. CO_2) goals?
- Can rail developments impact progress in LDV/HDV, also (i.e. reverse causal relationship)?
- Technology developments (e.g. batteries) occurring at a rapid pace during this last decade
- EPA has set increasingly stringent criteria pollutant standards for locomotives; California has already suggested new Federal standard!
- ↓ emissions impacts as compared to automobiles; HOWEVER several centralized operators rather than millions of individual operators
- Trains have key role to play → 1 in 4 auto trips in the US is affected by severe and extreme congestion levels (Schrank, Eisele, Lomax, & Bak, 2015)

CANDIDATE FUELS

Prime Mover	Fuel	Rail Service Type(s)
Internal Combustion Engine ("ICE")	Diesel	Passenger, Freight, Switcher
ICE	Natural Gas	Passenger, Freight
ICE	Fischer-Tropsch Diesel	Passenger, Freight
ICE hybridized with batteries	Diesel	Passenger, Switcher
Fuel Cell (FC)	Hydrogen	Passenger, Switcher, Freight
FC hybridized with batteries	Hydrogen	Passenger, Switcher
Overhead Line Electrification (OLE)	Source fuels for electric power (electricity is an "energy carrier")	Passenger

WHAT IS THE BASIS FOR EVALUATING THESE DECISIONS?

- A) Cost
- B) Fuel availability (linked to cost)
- C) Environmental impacts
- D) Ability to meet (environmentally-oriented) regulatory requirements
- E) Safety of the fuel and/or fuel systems
- F) Amount of new learning required by staff
- G) Amount of disruption to current operational processes
- H) Ease of use (i.e. once disruption has already occurred)
- I) Issues that arise from interfacing with the public (e.g. equipment noise, visual effects, etc.)

LOCOMOTIVE EXHAUST EMISSIONS STANDARDS

United States Environmental Protection Agency

	Duty-Cycle [b]	Tier	Year [c]	HC [i] (g/hp-hr)	NOx (g/bhp-hr)	PM (g/bhp-hr)	CO (g/bhp-hr)
Federal [a]	Line-haul	Tier 0	1973-1992 [d, e]	1.00	9.5 [ABT]	0.22 [ABT]	5.0
		Tier 1	1993-2004 [d, e]	0.55	7.4 [ABT]	0.22 [ABT]	2.2
		Tier 2	2005-2011 [d]	0.30	5.5 [ABT]	0.10 [k] [ABT]	1.5
		Tier 3	2012-2014 [f]	0.30	5.5 [ABT]	0.10 [ABT]	1.5
		Tier 4	2015+ [g]	0.14	1.3 [ABT]	0.03 [ABT]	1.5
	Switch	Tier 0	1973-2001	2.10	11.8 [ABT]	0.26 [ABT]	8.0
		Tier 1	2002-2004 [h]	1.20	11.0 [ABT]	0.26 [ABT]	2.5
		Tier 2	2005-2010 [h]	0.60	8.1 [ABT]	0.13 [l] [ABT]	2.4
		Tier 3	2011-2014	0.60	5.0 [ABT]	0.10 [ABT]	2.4
		Tier 4	2015+	0.14 [j]	1.3 [j] [ABT]	0.03 [ABT]	2.4

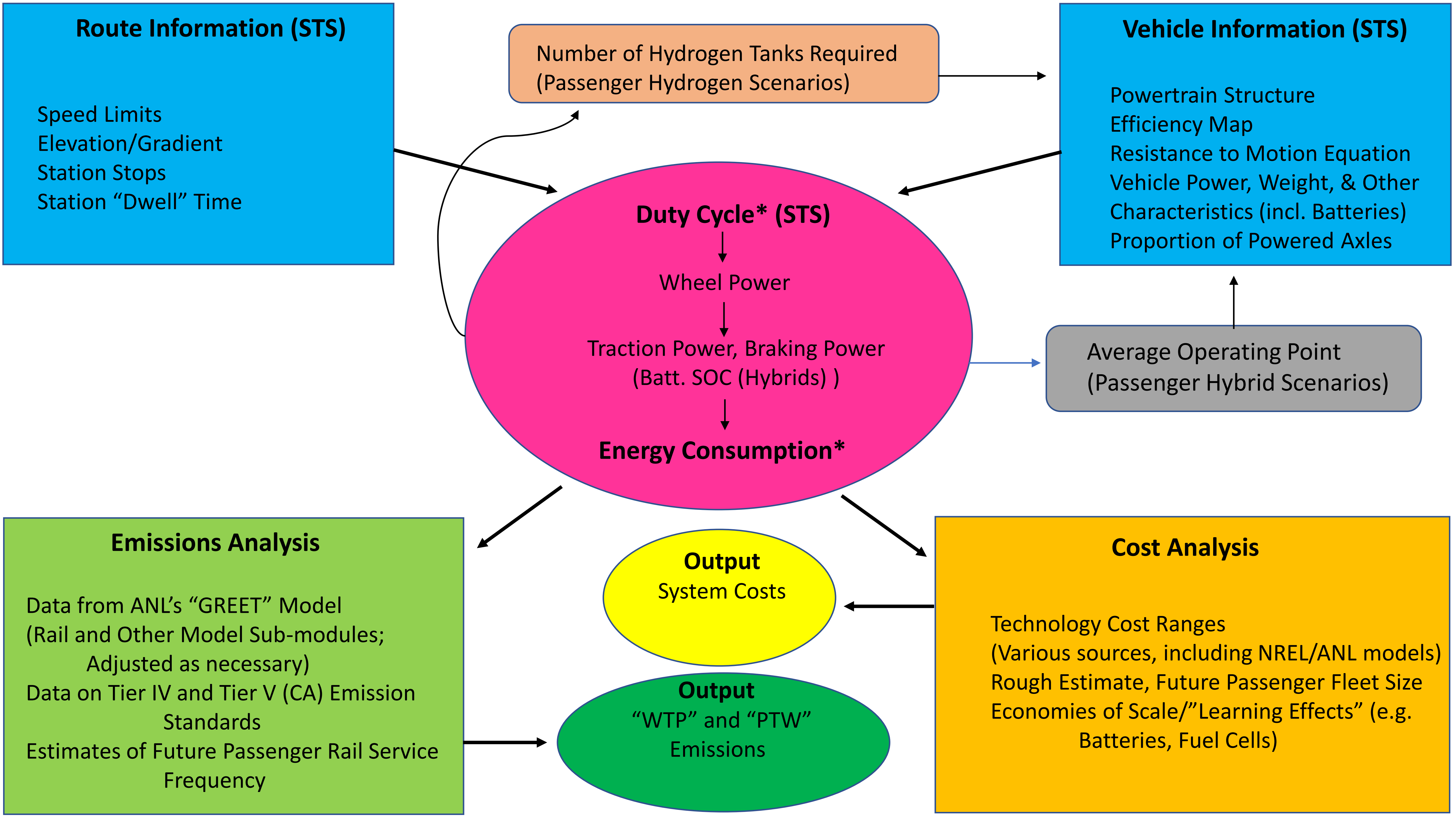
CALIFORNIA'S PROPOSED TIER 5 STANDARD

Potential Amended Emission Standards for Newly Manufactured Locomotives and Locomotive Engines

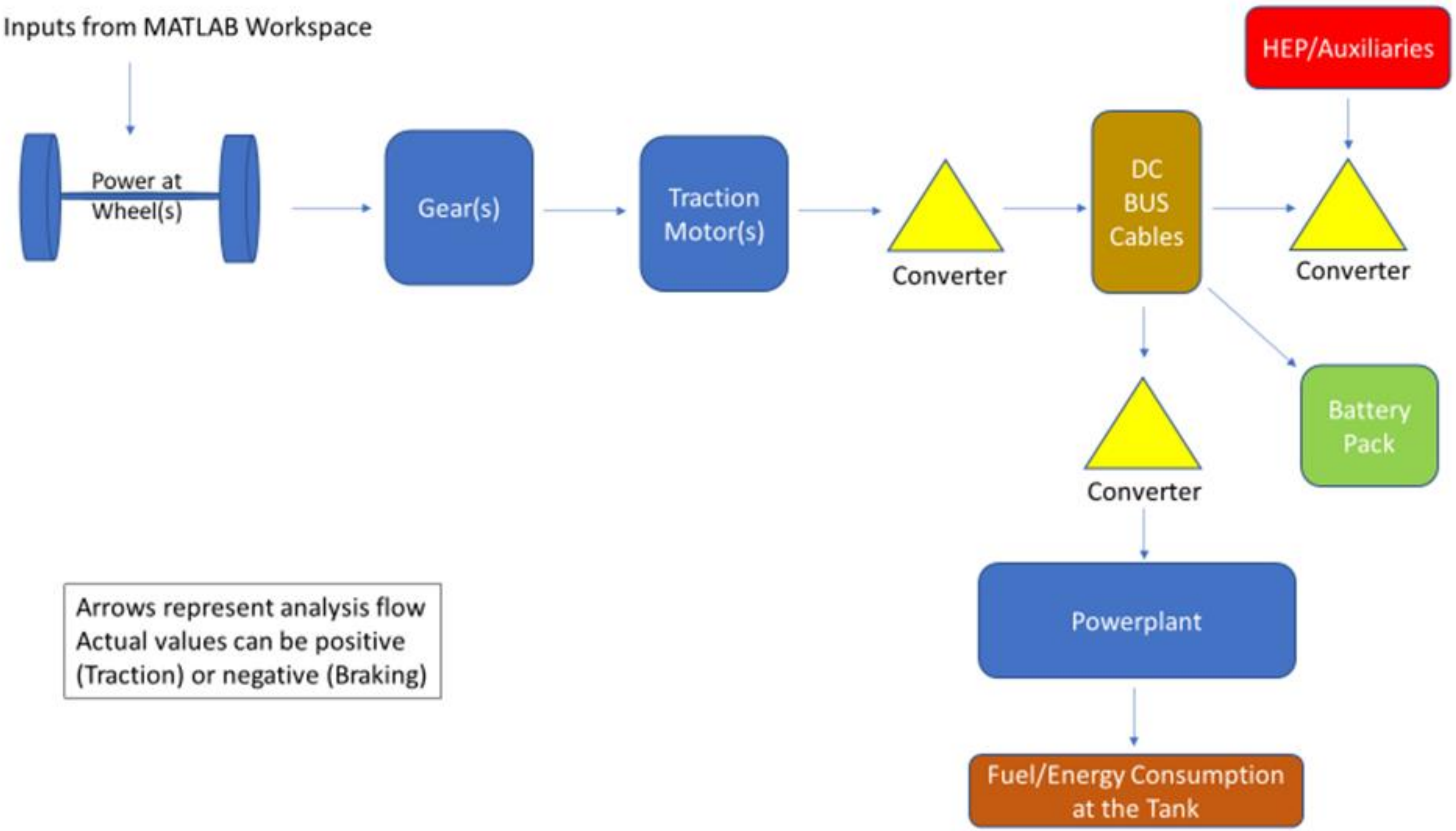
Tier Level	Proposed Year of Manufacture	NOx		PM		GHG		HC		Proposed Effective Date
		Standard (g/bhp-hr)[1]	Percent Control[2]	Standard (g/bhp-hr)[1]	Percent Control[2]	Standard (g/bhp-hr)[1]	Percent Control[1]	Standard (g/bhp-hr)	Percent Control[2]	
5	2025	0.2	99+	<0.01	99	NA	10-25%	0.02	98	2025
		With capability for zero-emission operation in designated areas.								

1. ARB, Technology Assessment: Freight Locomotives, 2016.[3]
2. Compared with uncontrolled baseline, reflects percent control over line haul baseline for illustrative purposes;
   ARB staff assumed older pre-Tier 0 line haul and switch locomotives would be able to emit up to the Tier 0 PM emission standards, based on American Association of Railroads in-use emission testing (required to comply with U.S. EPA in-use emission testing requirements) for older switch locomotives with EMD 645 engines.

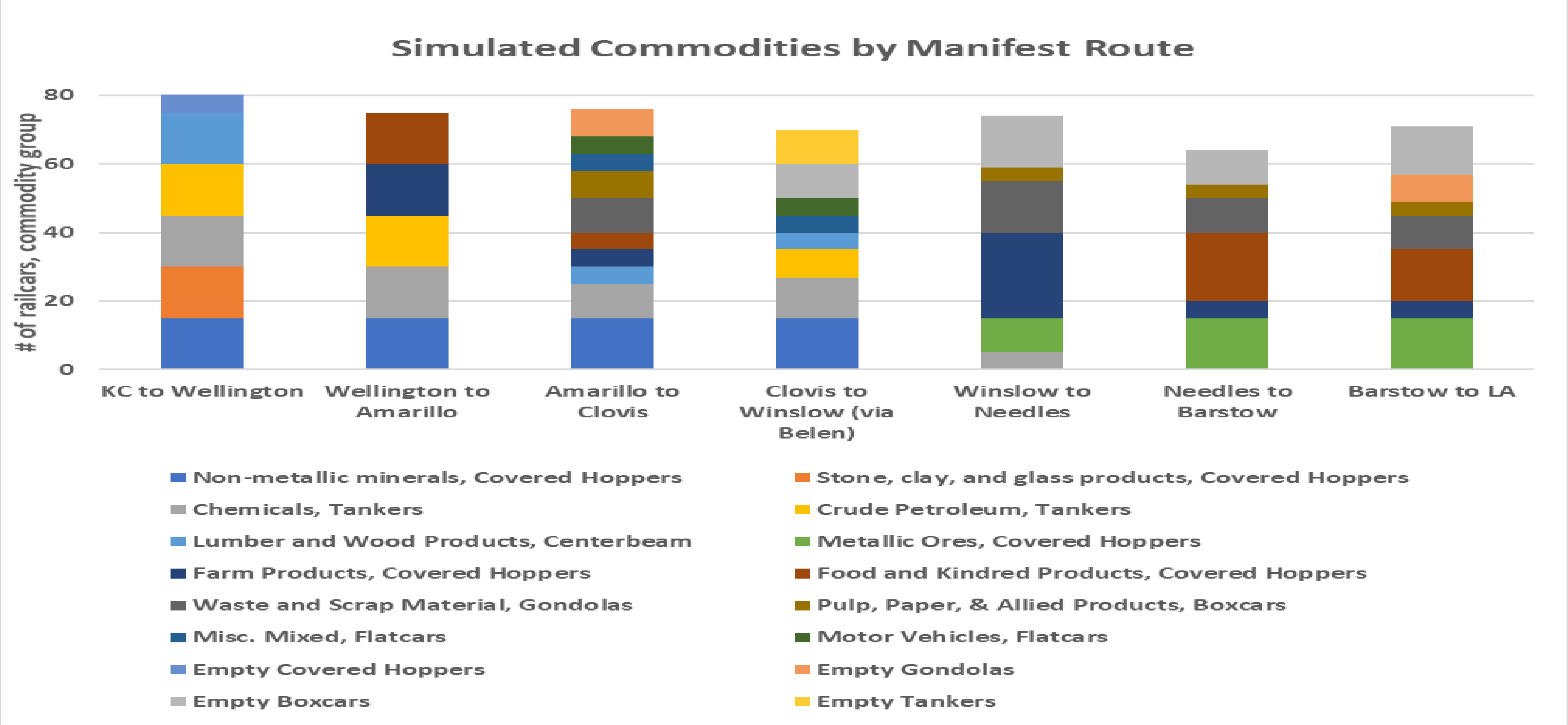
Graphic courtesy of California ARB


Route Information (STS)
Speed Limits
Elevation/Gradient
Station Stops
Station "Dwell" Time
Number of Hydrogen Tanks Required
(Passenger Hydrogen Scenarios)
Vehicle Information (STS)
Powertrain Structure
Efficiency Map
Resistance to Motion Equation
Vehicle Power, Weight, & Other Characteristics (incl. Batteries)
Proportion of Powered Axles
Duty Cycle* (STS)
Wheel Power
Traction Power, Braking Power
(Batt. SOC (Hybrids))
Energy Consumption*
Average Operating Point
(Passenger Hybrid Scenarios)
Emissions Analysis
Data from ANL's "GREET" Model
(Rail and Other Model Sub-modules; Adjusted as necessary)
Data on Tier IV and Tier V (CA) Emission Standards
Estimates of Future Passenger Rail Service Frequency
Output
System Costs
Output
"WTP" and "PTW" Emissions
Cost Analysis
Technology Cost Ranges
(Various sources, including NREL/ANL models)
Rough Estimate, Future Passenger Fleet Size
Economies of Scale/"Learning Effects" (e.g. Batteries, Fuel Cells)

MATLAB SIMULATION STRUCTURE



FREIGHT COMMODITIES CARRIED PER VEHICLE LEG



SIMULATED EQUIPMENT

- **5 Powertrains simulated:**
- **Diesel**
- **Diesel hybrid (Passenger only)**
- **Fuel cell**
- **Fuel cell hybrid (Passenger only)**
- **Overhead Line Electrification (Passenger only)**

- **Natural gas and FTD assessed via post-processing**

(based on similarity to diesel…e.g. uses ICE)

SIMULATED FREIGHT CARS (EXAMPLES)

SIMULATED ROUTES

FREIGHT:

PASSENGER:

PASSENGER RESULTS: CAPITOL CORRIDOR (PART-COMMUTER/PART-REGIONAL TRAIN)

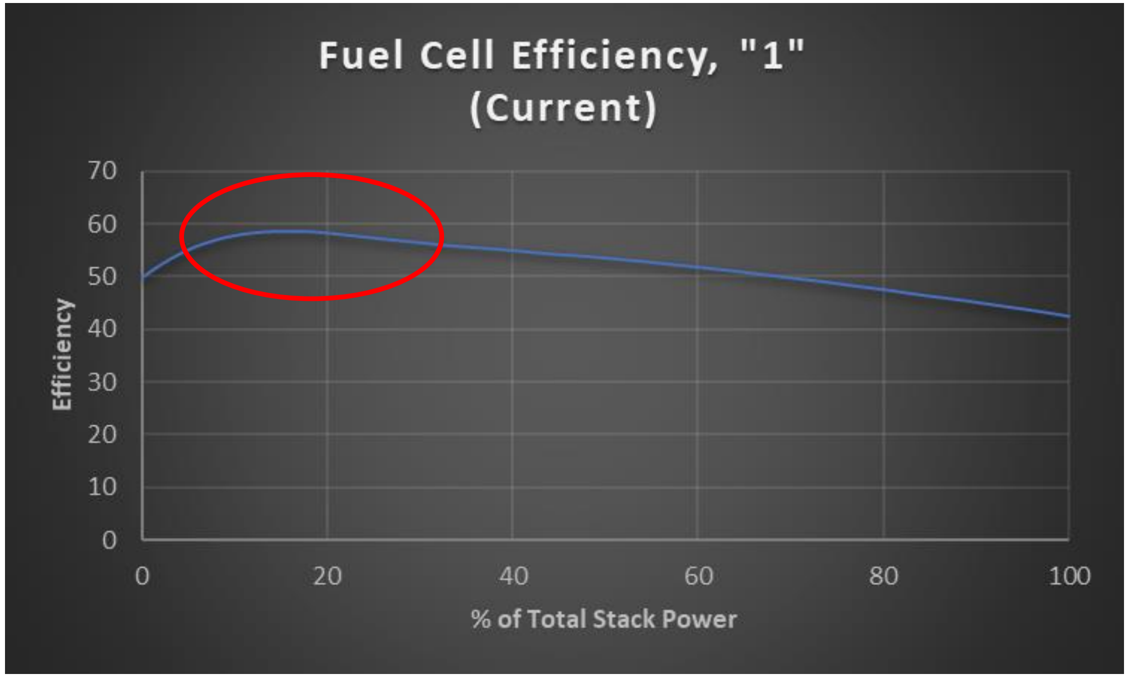
Capitol Corridor: Prime Mover/ Fuel	Maximum Power Capacity, Genset/ Fuel Cell (MW)	Braking Available	Primary Fuel (Diesel/H2/ Electricity) Consumption 1 Round Trip (GJ)	Genset/ FCS Average Efficiency (%)	Vehicle Efficiency (%)	Number of H2 Tanks	Energy Reduction from Diesel "Baseline" %
Diesel	3.3	Regen.	72.706	35.7	33.7	NA	NA
Hydrogen	3.3	Regen.	52.020	54.0	46.7	138	28.5
Electricity (OLE)	3.3	Regen.	21.559	NA	87.7	NA	70.3
Diesel Hybrid	3.3	Regen.	58.788	35.3	42.6	NA	19.1
Hydrogen Hybrid	3.3	Regen.	36.685	56.5	66.6	98	49.5
Diesel Hybrid	1.1	Regen.	64.143	31.9	38.0	NA	11.8
Hydrogen Hybrid	1.1	Regen.	45.492	45.5	53.5	120	37.4

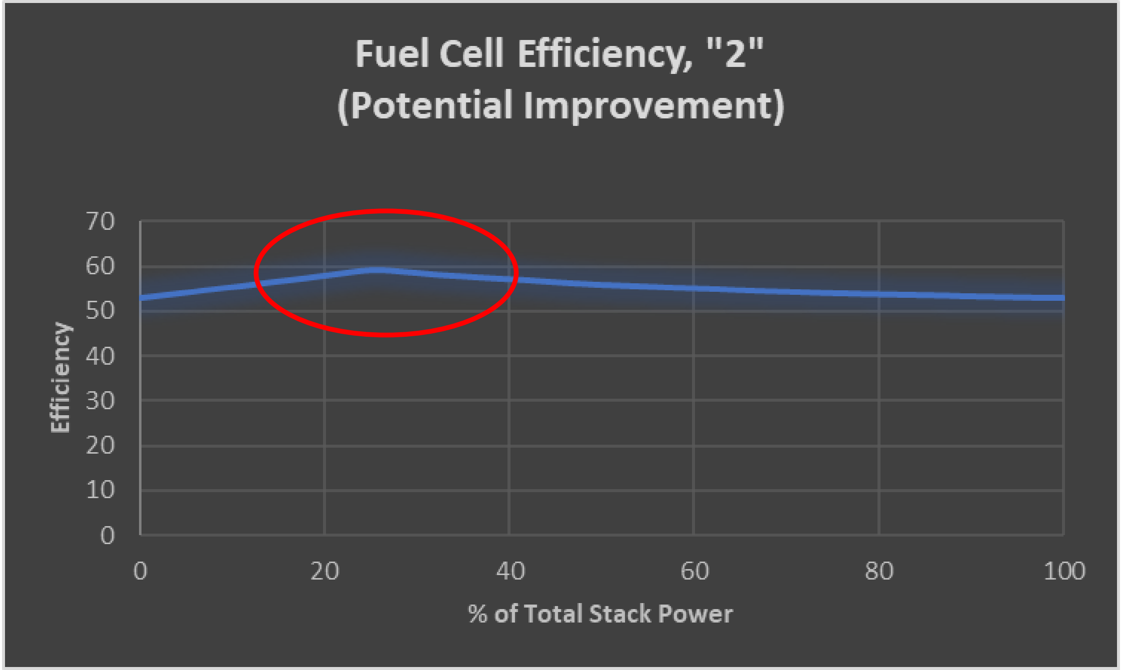
Note: OLE energy consumption is measured where the pantograph meets the overhead catenary wire.

PASSENGER RESULTS: CALTRAIN ("PURE" COMMUTER LINE)

Caltrain: Prime Mover/ Fuel	Max. Power Capacity, Genset/ Fuel Cell (MW)	Braking Available	Primary Fuel Consumption (Diesel/H2/ Electricity) 1 Round Trip (GJ)	Genset/ FCS Average Efficiency (%)	Vehicle Efficiency (%)	Number of H2 Tanks	Energy Reduction from Diesel "Baseline" %
Diesel	3.3	Regen.	39.864	35.4	34.2	NA	NA
Hydrogen	3.3	Regen.	30.195	52.3	44.4	80	24.3
Electricity (OLE)	3.3	Regen.	9.473	NA	87.7	NA	76.2
Diesel Hybrid	3.3	Regen.	25.292	34.0	54.4	NA	36.6
Hydrogen Hybrid	3.3	Regen.	15.408	57.1	87.5	42	61.3
Diesel Hybrid	.95	Regen.	27.573	30.6	48.9	NA	30.8
Hydrogen Hybrid	.95	Regen.	19.449	45.3	69.0	52	51.2

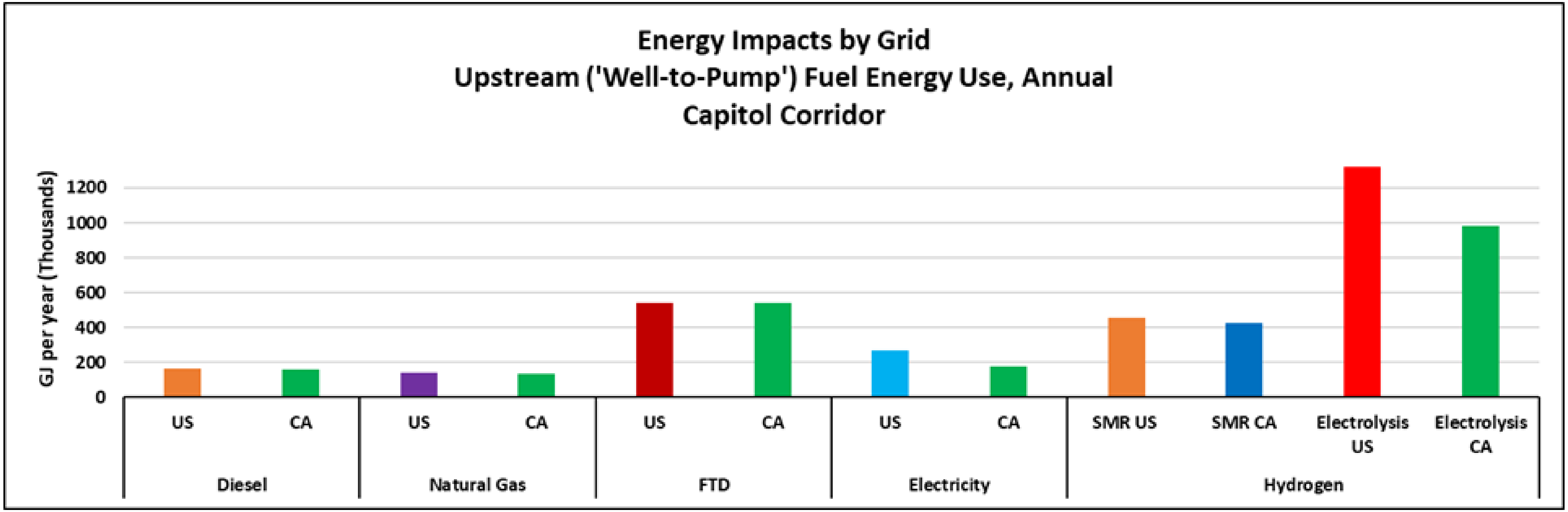
DOWNSIZED HYBRIDS OPERATING IN LESS EFFICIENT AREA



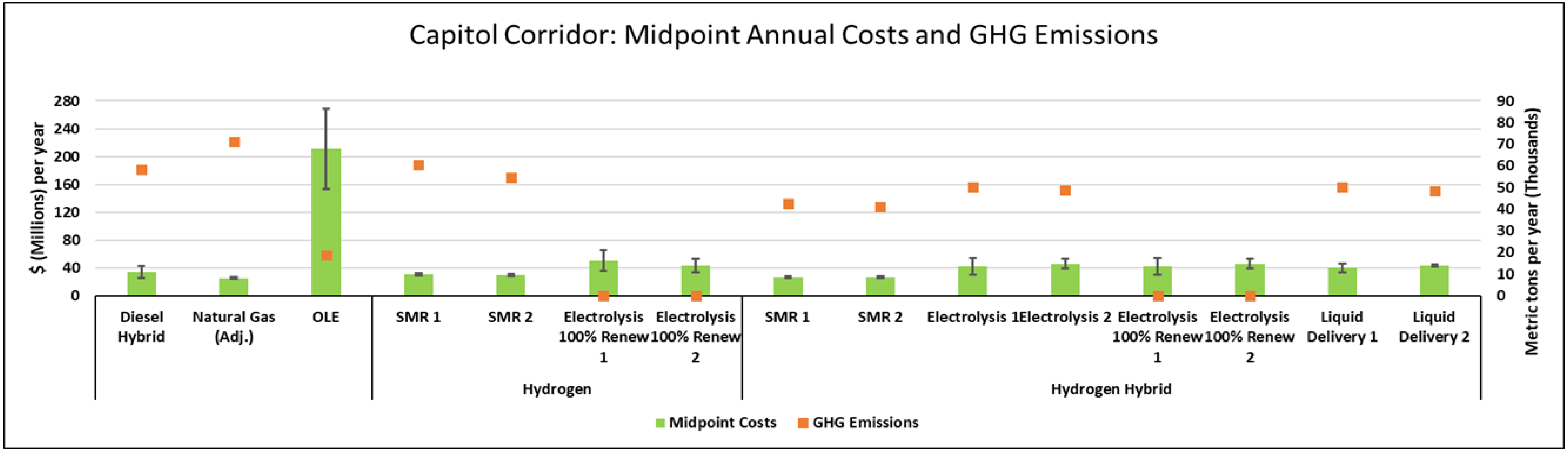


Data derived from Wipke et al, 2012

THE GRID MATTERS…

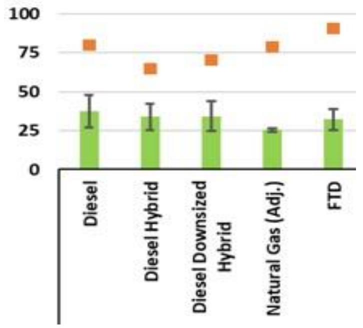


COST RESULTS: CAPITOL CORRIDOR



For H2 Options, 1: Fuel Cell Stack Efficiency ~ current levels

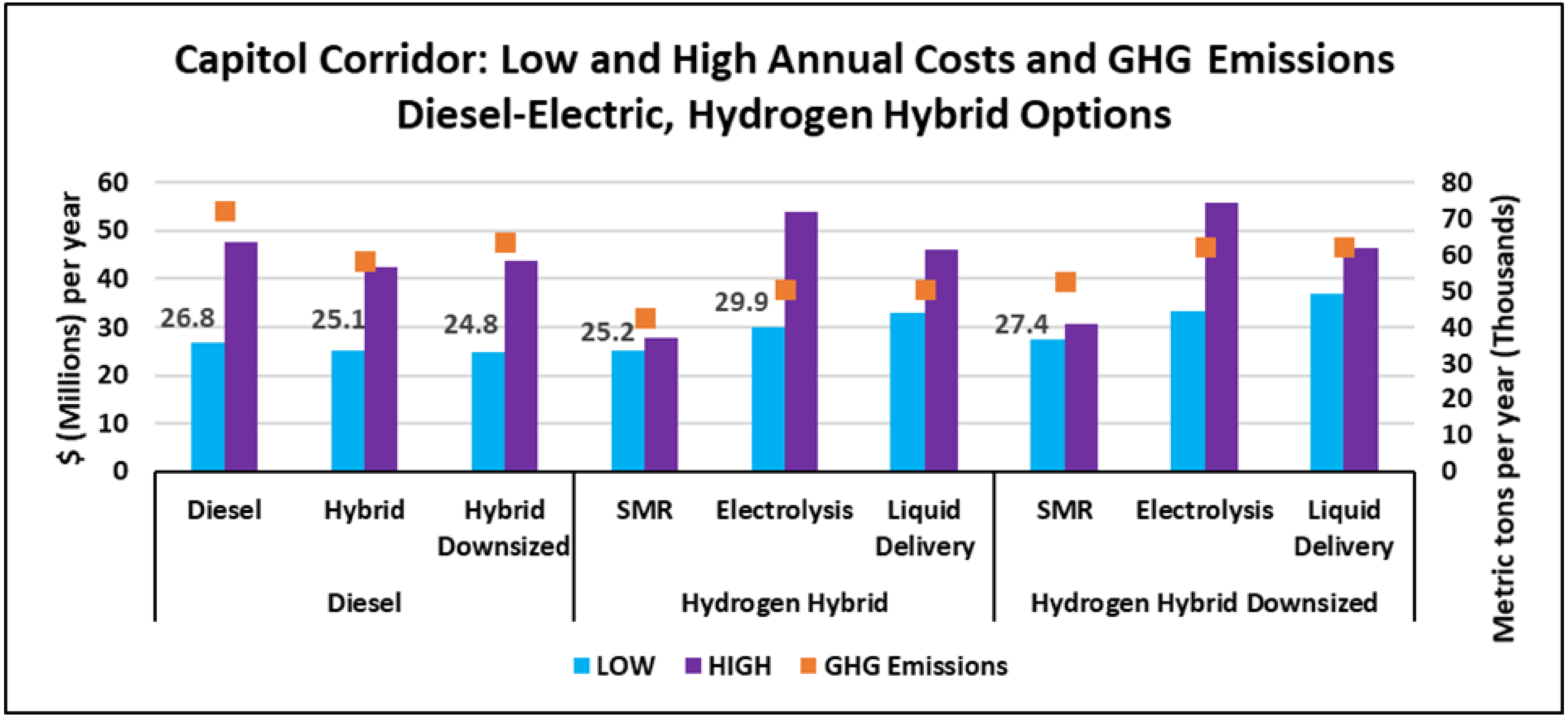
2: Fuel Cell Stack Efficiency at potential future level



Note: Inset to the right shows FTD, which, when NG-derived, ↑ GHG emissions

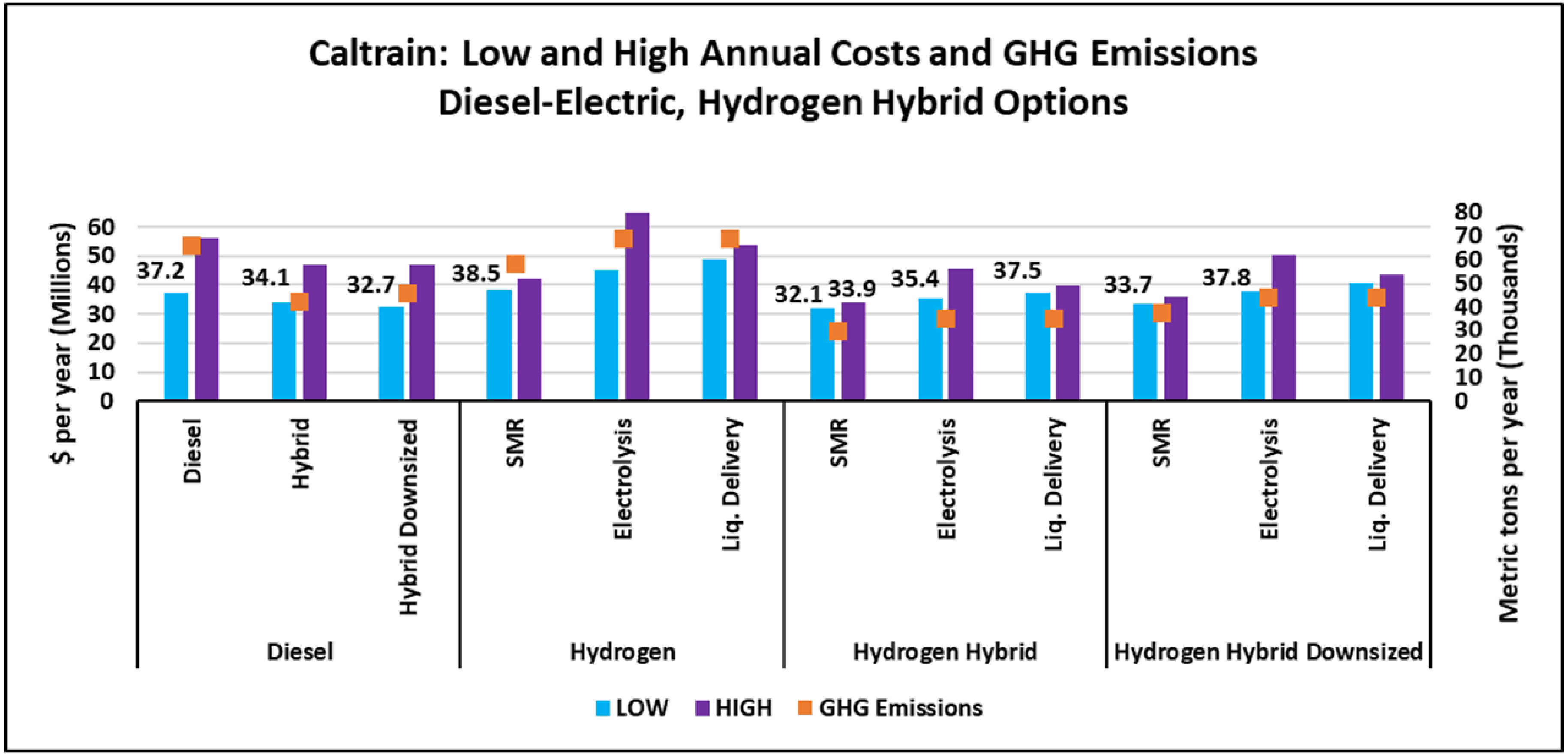
CAPITOL CORRIDOR COSTS: A CLOSER LOOK

Daily Hydrogen Demand: 13,000 kg

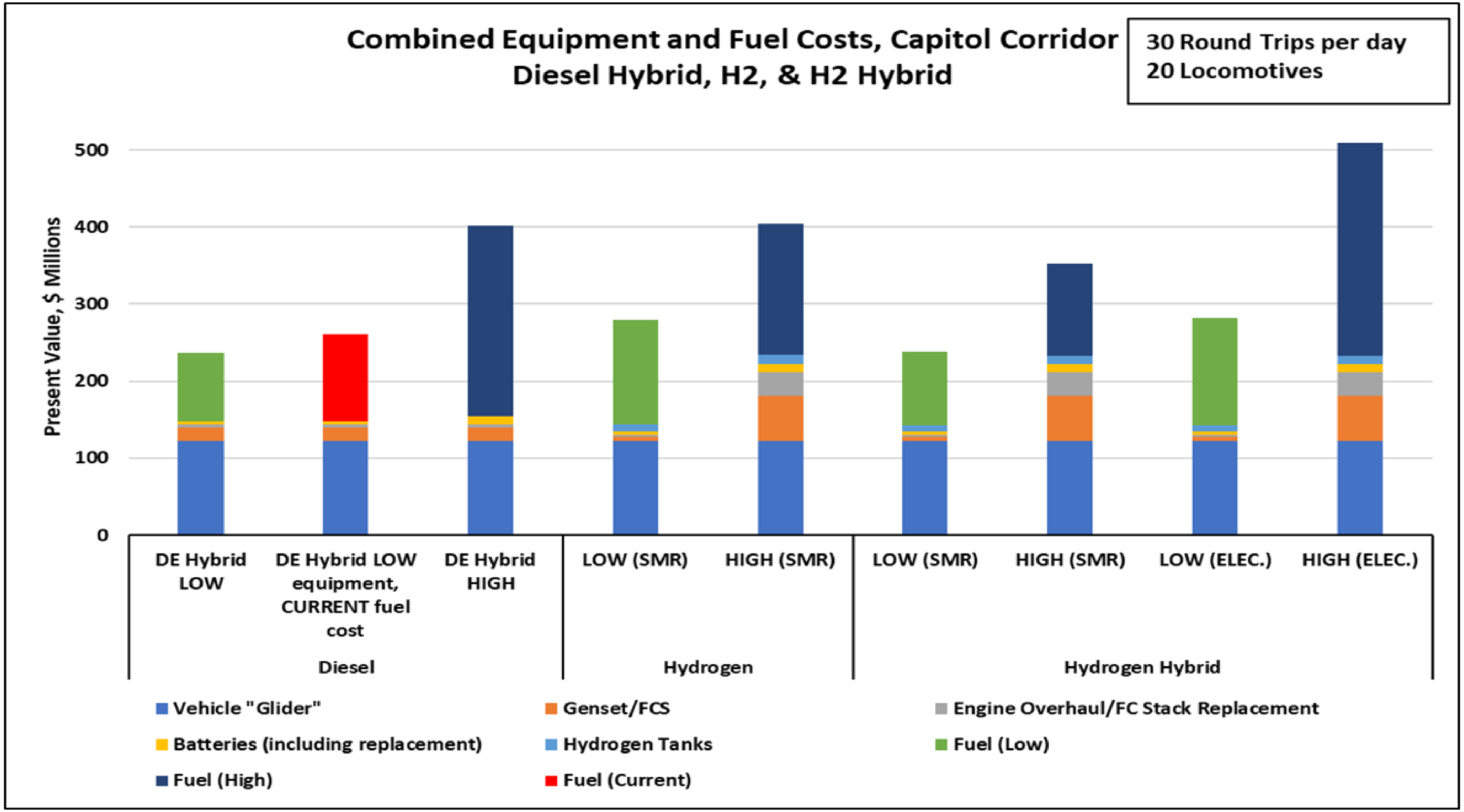


CALTRAIN COSTS: A CLOSER LOOK

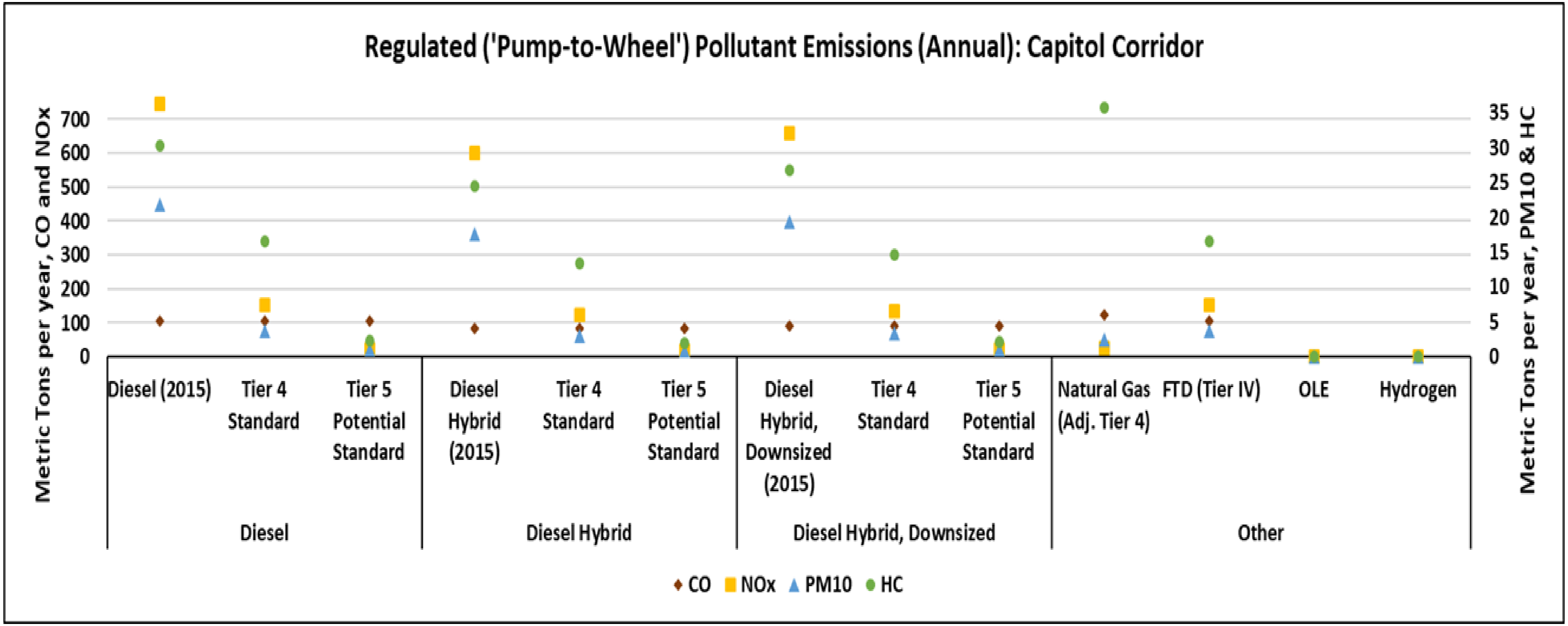
Daily Hydrogen Demand: 13,000 kg



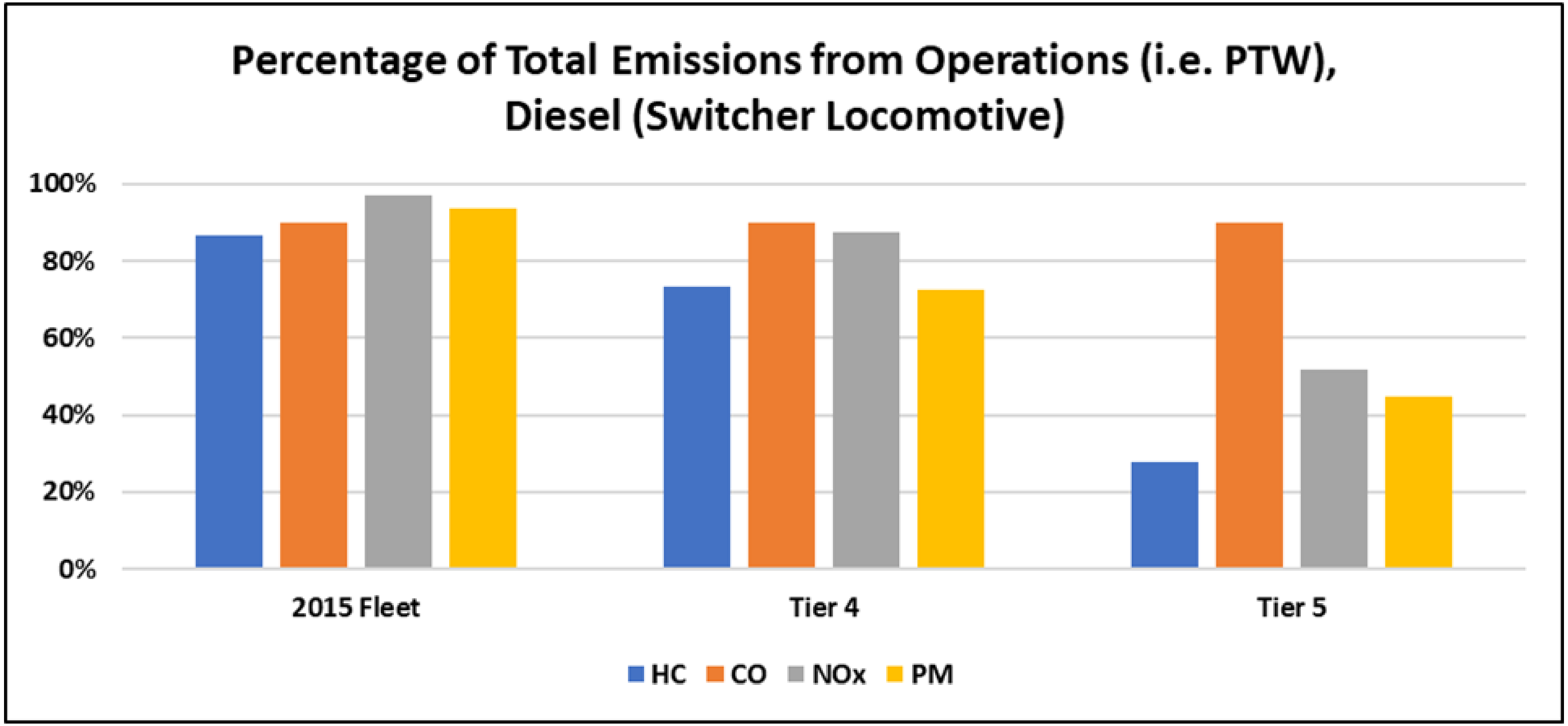
EQUIPMENT AND FUEL COSTS, COMBINED, CAPITOL CORRIDOR

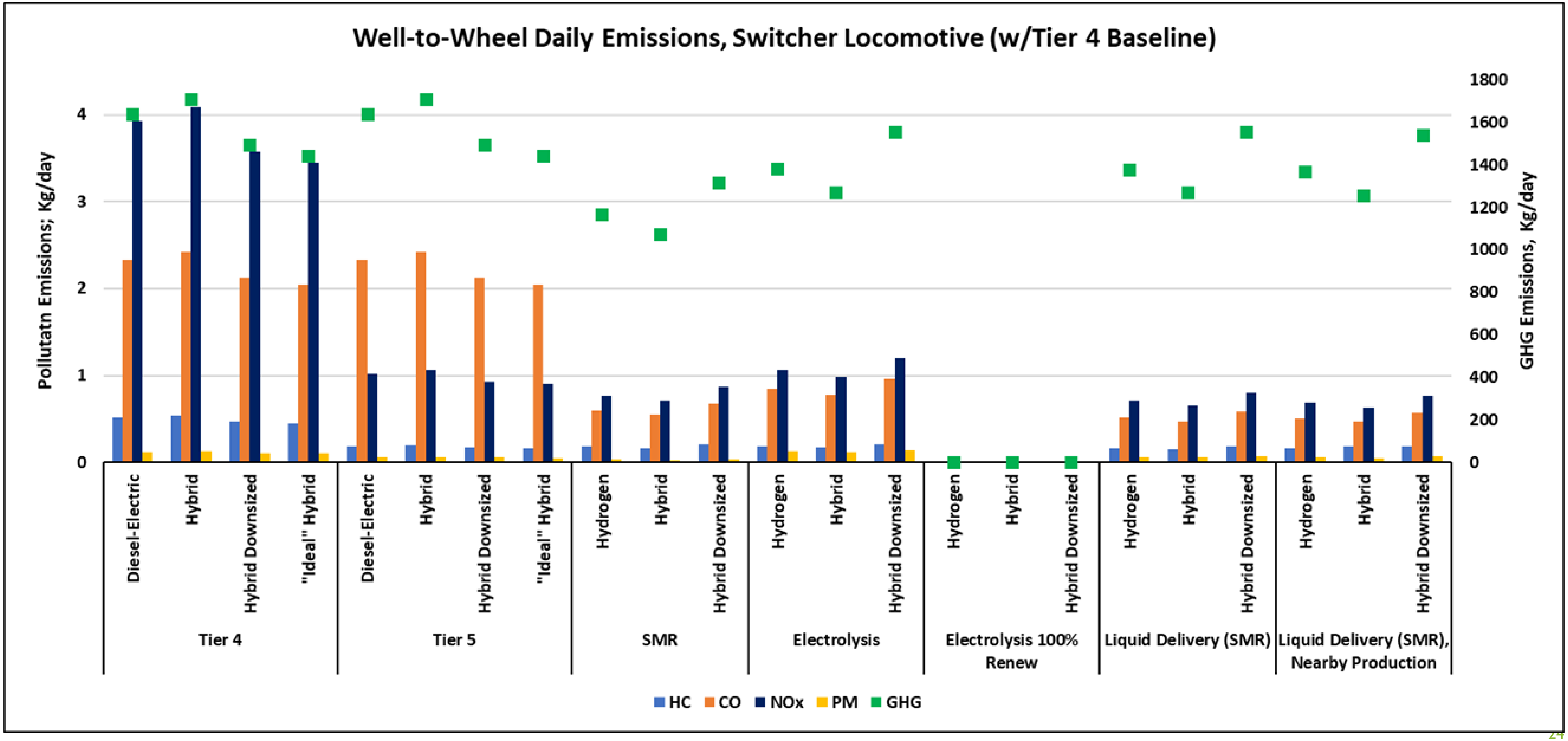


IF STICKING WITH DIESEL, TIER REGULATION IS CRUCIAL!



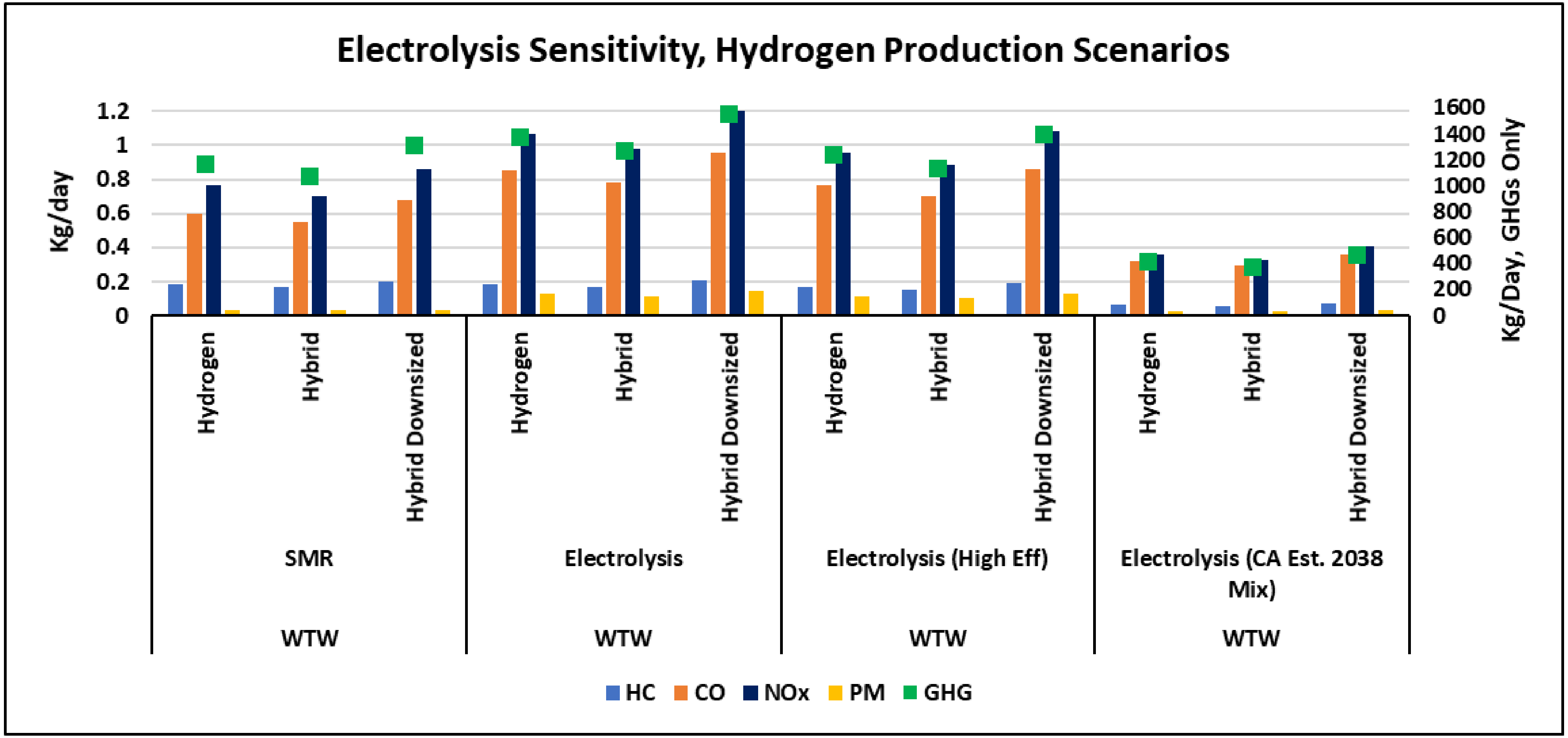
LESSONS FROM MY SWITCHER ANALYSIS: WITH DIESEL, IT'S ALL ABOUT THE OPERATIONS





Well-to-Wheel Daily Emissions, Switcher Locomotive (w/Tier 4 Baseline)
Pollutatn Emissions; Kg/day
GHG Emissions, Kg/day
0
1
2
3
4
0
200
400
600
800
1000
1200
1400
1600
1800
Diesel-Electric
Hybrid
Hybrid Downsized
"Ideal" Hybrid
Hydrogen
Tier 4
Tier 5
SMR
Electrolysis
Electrolysis 100% Renew
Liquid Delivery (SMR)
Liquid Delivery (SMR), Nearby Production
HC
CO
NOx
PM
GHG

…AGAIN, THE GRID MATTERS!



* Absolute numbers here are based on Switcher Emissions Analysis

CONCLUSIONS: PASSENGER

- CNG: ↓ reduced total cost. Depends on cost of natural gas/diesel fuel. Combined cost range: -2% to 32% ↓ GHG emissions only slight. Significant ↑ in Hydrocarbons (HC), slight ↑ CO.
- FTD: Reduced combined equipment and fuel costs(if from CNG) but not by as much as CNG . ↑ GHG emissions (if from CNG). Cost reduction *may* disappear, if BTL. FTD cost estimates highly uncertain.
- Hydrogen: Hybridization (w/batteries) advantageous, especially w/frequent stopping patterns.
  - In a "best case hydrogen" scenario, ↓ of 43% to 47% (for SMR, in both cases).
  - In case of low diesel cost w/high H2 scenario costs, H2 via electrolysis could result in an 11% to 22% ↑ over diesel.
- Adapting locomotive for hydrogen will likely require significant locomotive redesign, but this should be feasible given the space available (including rooftop space) and an "outside-of-the-box" approach.
- Batteries: The more energy density (i.e. energy in a given volume) continues to come down, the greater the role for batteries in rail propulsion

AREAS FOR FURTHER STUDY

- Assess and include well-to-wheel impacts of fuel technology component manufacturing
- Cost of switching to hydrogen via fuel cell powertrain in the freight sector vs. cost of other alternative technologies that would enable locomotives to achieve Tier 5?
- FTD: Secondary emissions impacts of biofuels (with mass scaling)
- Assess, quantitatively, the costs of converting freight system to OLE, and explore, in detail, associated challenges
- Assess viability of battery-OLE hybrids
- Assess costs and logistics of delivering hydrogen to rail refueling sites via pipeline
- Survey rail refueling site sizes (i.e. diesel fuel volumes) to better understand potential hydrogen fuel demands
- Assess hydrogen demand in the trucking industry, and the potential for coordinating between the two sectors
- Explore the feasibility and implications of combining OLE and hydrogen (via fuel cell) propulsion for freight rail

Thank you!

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Photo courtesy of Dr. Andreas Hoffrichter

ADDITIONAL RESOURCE SLIDES

FREIGHT RESULTS: INTERMODAL TRAIN

Intermodal, 80 TOFC (Higher Speed): Fuel	Number of Locomotives per Train	Primary Fuel (Diesel/H2) Consumption 1-Way Trip (GJ)	Genset/ FCS Average Efficiency (%)	Vehicle Efficiency (%)	Average Power at the DC Bus (kW), Train	Energy Reduction from Diesel %
Diesel	3	2,089.326	35.1	33.2	7,541.2	NA
Hydrogen		1,652.386	47.8	42.0		20.9

Note: An approximately 1.5% fuel consumption penalty would be added for tender weight (Intermodals only).
In this example, energy reduction (%) → 19.7

CONCLUSIONS: FREIGHT

- H2: Unclear if costs would be ↓ or ↑ or higher than diesel. Depends on H2 production methods and feedstock costs
  - "Best case scenario": H2 via SMR could result in a 48% ↓ in costs. For electrolysis, "best case" scenario is 25% ↓.
  - W/diesel @ $2.00 per gallon throughout the period, H2 scenarios result in ↑ costs; at least 27% ↑, w/ "worst case scenario" for H2 (high H2 via electrolysis cost range) meaning 3X diesel costs.
  - H2: Tenders are required for the longer-distance intermodal freight trips; should not present a significant cost issue; however, logistically, they could represent a bit of a barrier. However, possibility to avoid with flexibility in refueling patterns.
- CNG: ↓ reduced total cost. (But same caveats as in passenger.) Combined cost range: 1% to 67%
- CNG tenders can be avoided; however, only with lower on-board energy storage than presently the case.
  - Significant re-design to the locomotive interior required, without tender.
- Exhaust emissions: Tier V potentially achievable w/diesel-electric (w/risk of possible obsolesence)

Note: As of 2017, a mere 4.3% of the energy expended in freight rail was at the Tier IV NOx level (based on fleet average data for the South Coast Air Basin)

"SWITCHER" LOCOMOTIVE RESULTS (NON-SIMULATION)

Switcher, 9 Notches: Fuel [i]	Max. Power Output Genset/ Fuel Cell (kW)	Primary Fuel (Diesel/H2) Consumption 10 Hours of Operation (GJ)	Primary Fuel (Diesel/H2) Consumption 10 Hours of Operation	Genset/ FCS Average Efficiency (%)	Vehicle Efficiency (%)	Average Genset/FC Output Power (kW)	Fuel Energy Reduction from Diesel "Baseline" %
Diesel 1	~1,400	18.093	132.44 gallons	32.6	27.7	163.9	NA
Diesel 2	~1,340	21.217	155. 30 gallons	27.3	23.2		-17.3
Hydrogen 1*	~1,400	11.024	91.7 kg	53.5	45.5		39.1
Hydrogen 2	~1,400	10.526	87.6 kg	56.1	47.6		41.8
Diesel 1 Hybrid	~1,400	18.832	137.85 gallons	31.3	26.6		-4.1
Hydrogen Hybrid 1	~1,400	10.134	84.3 kg	58.2	49.5		44.0
Hydrogen Hybrid 2	~1,400	10.553	87.8 kg	55.9	47.5		41.7
Diesel 1 Hybrid	~205	16.495	120.74 gallons	35.8	30.4		8.8
Diesel Hybrid, "Ideal"	~497	15.893	116.34 gallons	37.1	31.6		12.2
Hydrogen Hybrid 1	~205	12.420	103.3 kg	47.5	40.4		31.4
Hydrogen Hybrid 2	~205	10.967	91.2 kg	53.8	45.7		39.4

CURRENT CNG TENDER PILOT (NORFOLK SOUTHERN & CNGMOTIVE)

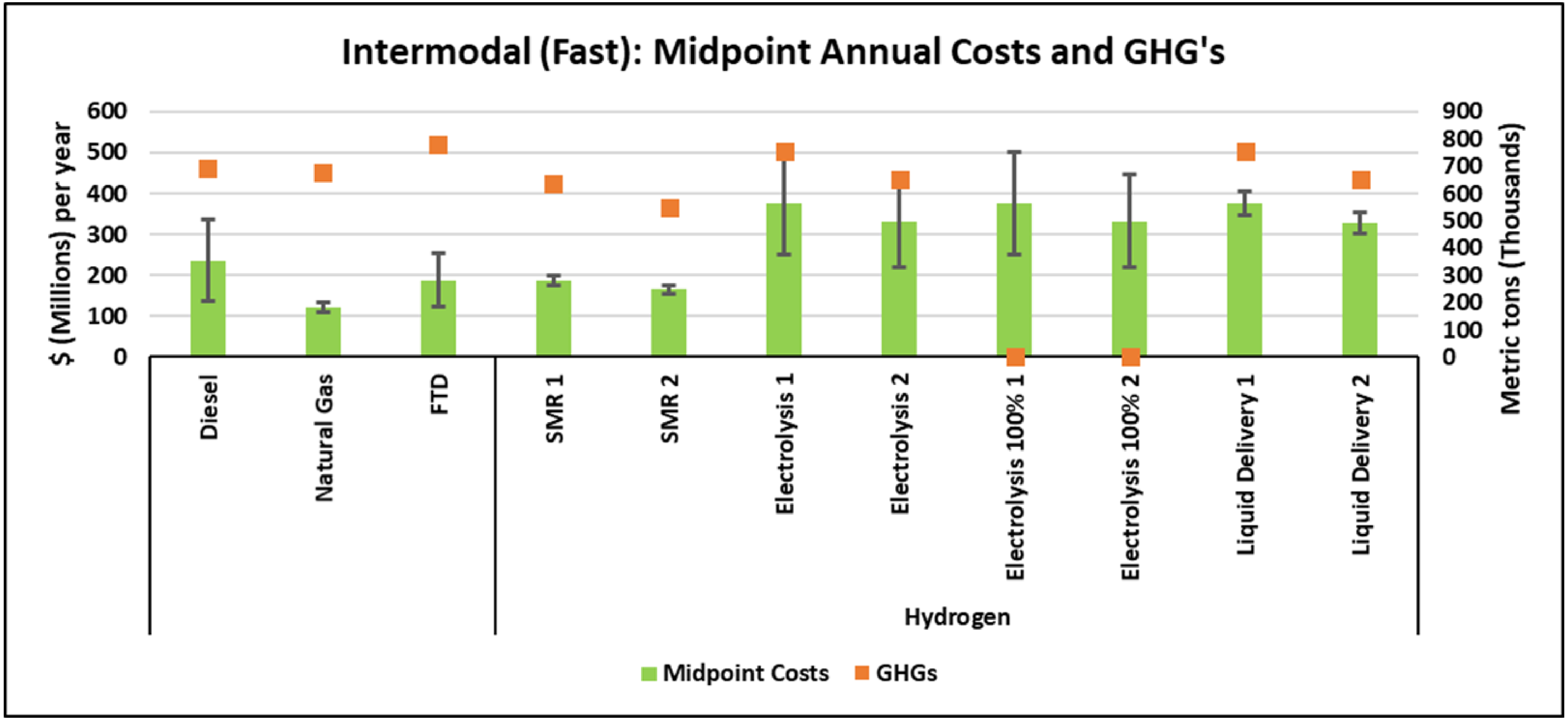
Photo courtesy of William C. Vantuono, and Railway Age (with permission granted)

FREIGHT RESULTS: "MANIFEST" TRAINS

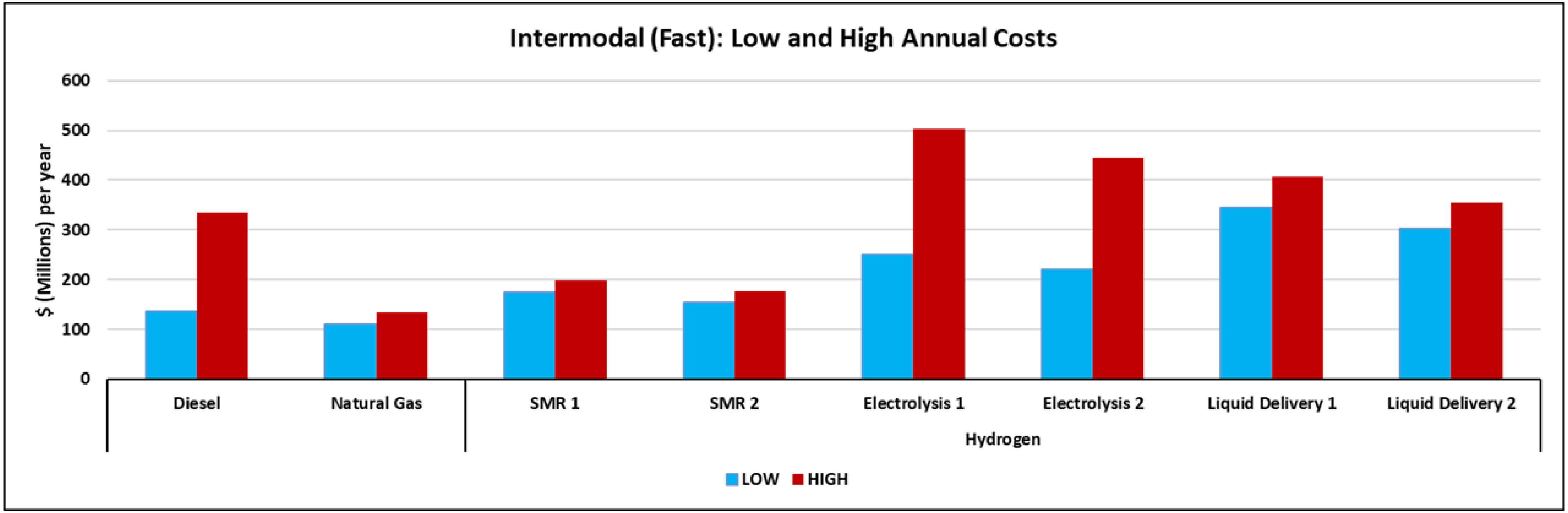
KC to Wellington: Fuel	Number of Locomotives per Train	Primary Fuel (Diesel/H2) Consumption 1-Way Trip (GJ)	Genset/ FCS Average Efficiency (%)	Vehicle Efficiency (%)	Average Power at the DC Bus (kW), Train	Energy Reduction from Diesel %
Diesel	3	292.429	34.4	22.8	7,475.2	NA
Hydrogen		230.882	48.0	41.1		21

Clovis to Winslow (via Belen): Fuel	Number of Locomotives per Train	Primary Fuel (Diesel/H2) Consumption 1-Way Trip (GJ)	Genset/ FCS Average Efficiency (%)	Vehicle Efficiency (%)	Average Power at the DC Bus (kW), Train	Energy Reduction from Diesel %
Diesel	3	643.866	34.0	31.8	8,951.3	NA
Hydrogen		507.040	49.1	40.4		21.2

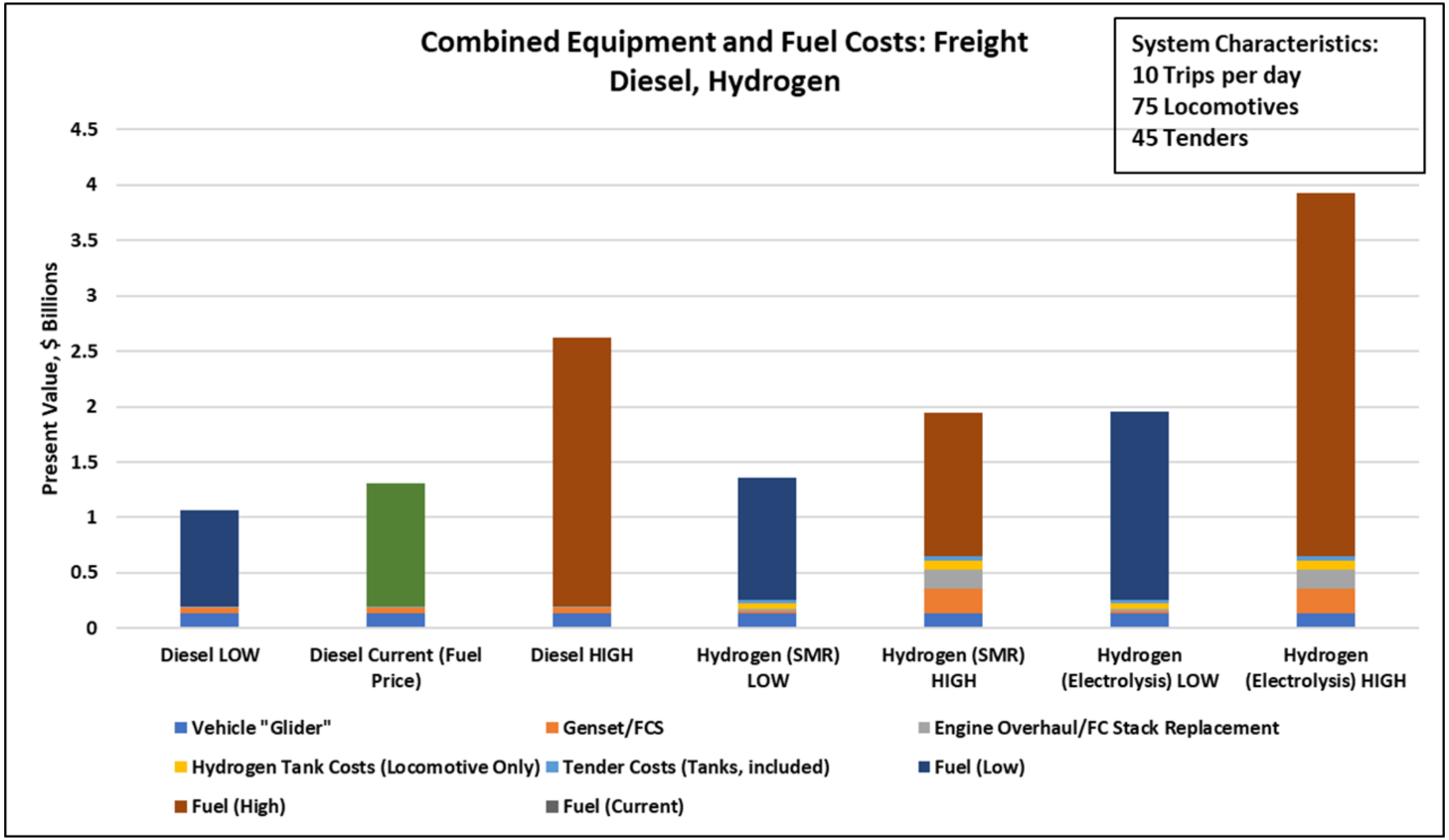
FREIGHT RESULTS: "INTERMODAL", HIGHER SPEED



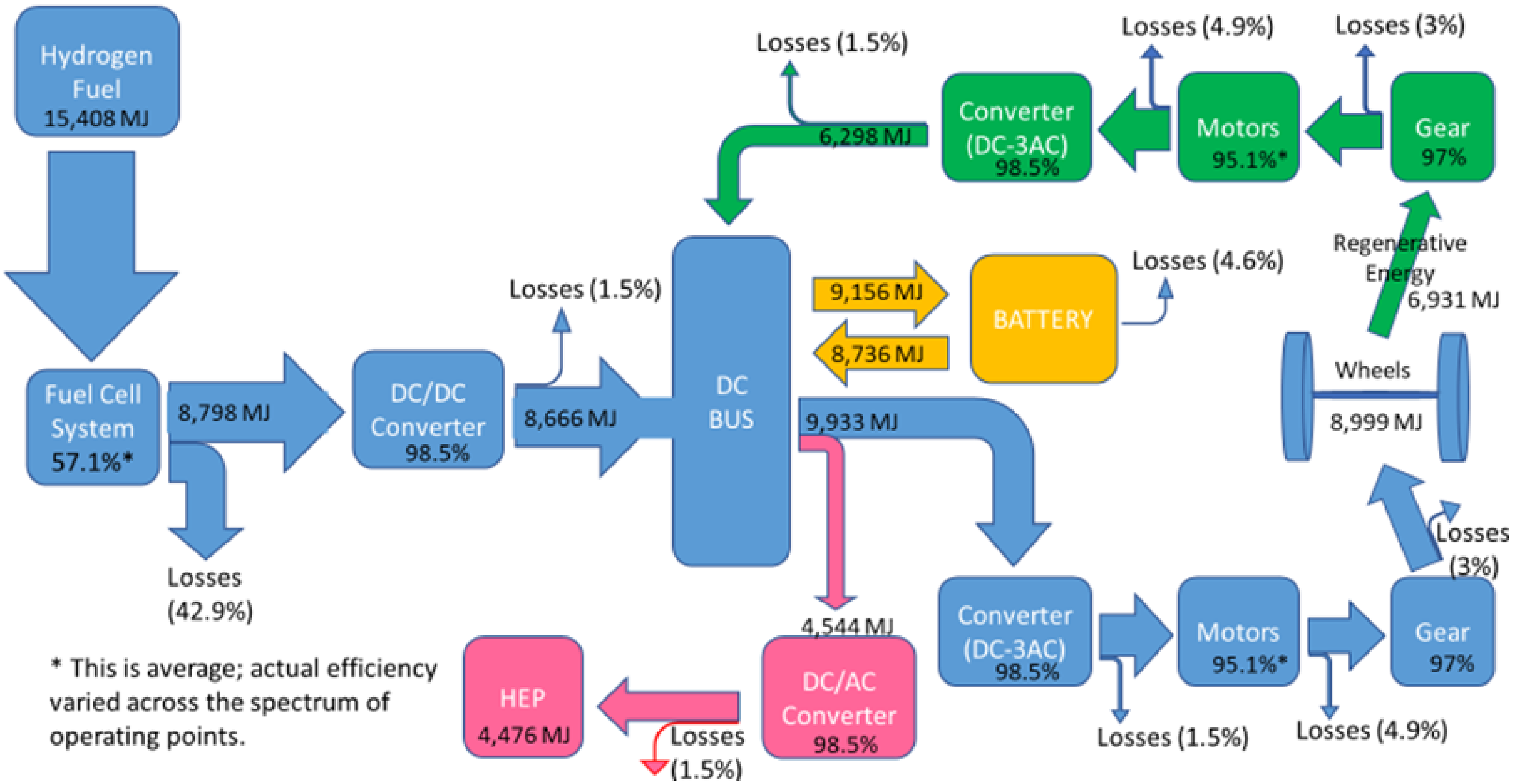
FREIGHT ROUTE COSTS: A CLOSER LOOK



EQUIPMENT AND FUEL COSTS, COMBINED, "INTERMODAL" FREIGHT



FLOW OF ENERGY DIAGRAM – CALTRAIN HYDROGEN HYBRID LOCOMOTIVE



* This is average; actual efficiency varied across the spectrum of operating points.

COST FORMULA USED

$$Annual\ Payment = PV * CRF$$

…where CRF stands for ‘Cost Recovery Factor’