Zero Emissions Locomotives and Impacts

California Air Resources Board Workshop

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ADVANCED POWER & ENERGY PROGRAM
UNIVERSITY of CALIFORNIA · IRVINE

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UCIrvine | UNIVERSITY OF CALIFORNIA

Outline

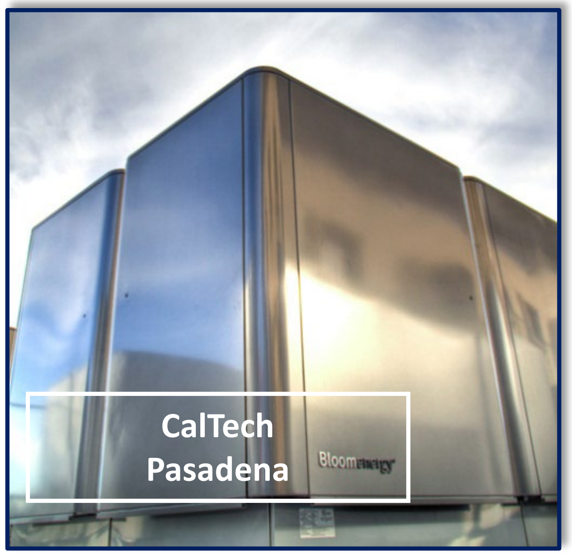
- Hybrid SOFC-GT systems for locomotive applications
- How zero-emissions rail may evolve
- Air Quality, Health & GHG impacts

Background: Solid Oxide Fuel Cells

A solid oxide fuel cell (SOFC) electrochemically converts fuel (hydrogen, syngas ne, …) to electrical energy

- **Higher temperature operation:** $650^oC < T < 1000^oC$
- **Fuel flexible:** *H_2, CO, syngas, hydrocarbons (e.g., CH_4), NH_3(?)*
- **Many companies offer products (stationary power application):**
  e.g., Bloom Energy, SOLIDpower, FuelCell Energy

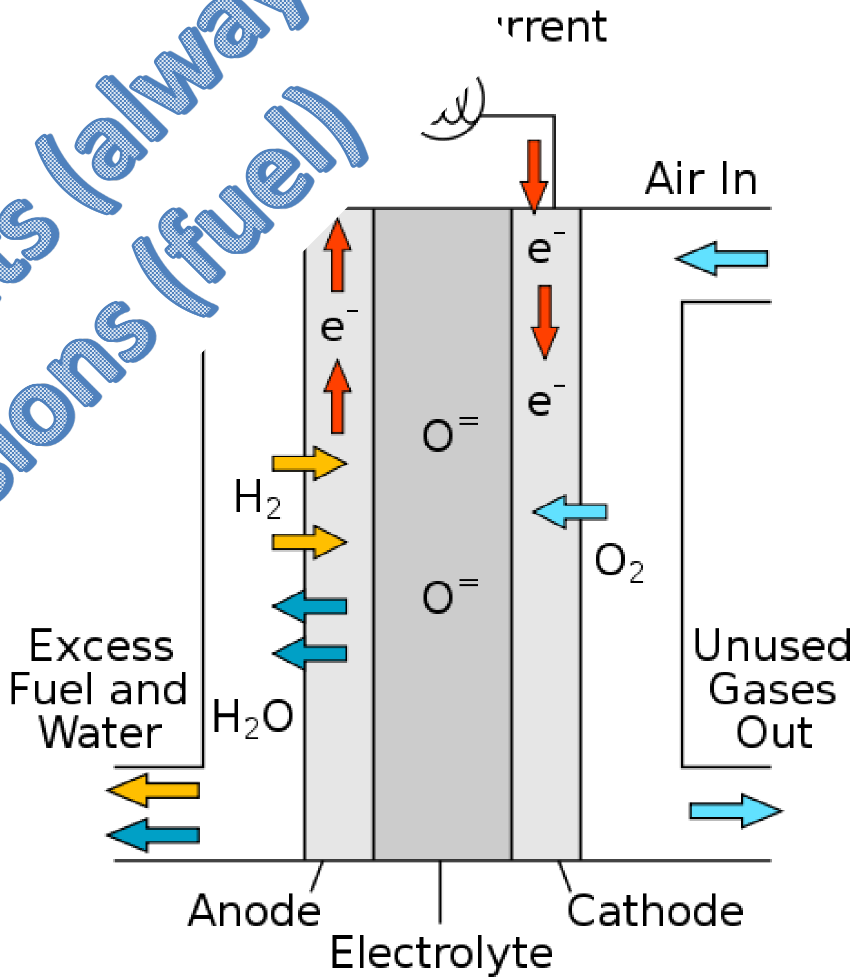
Bloomenergy



CalTech
Pasadena

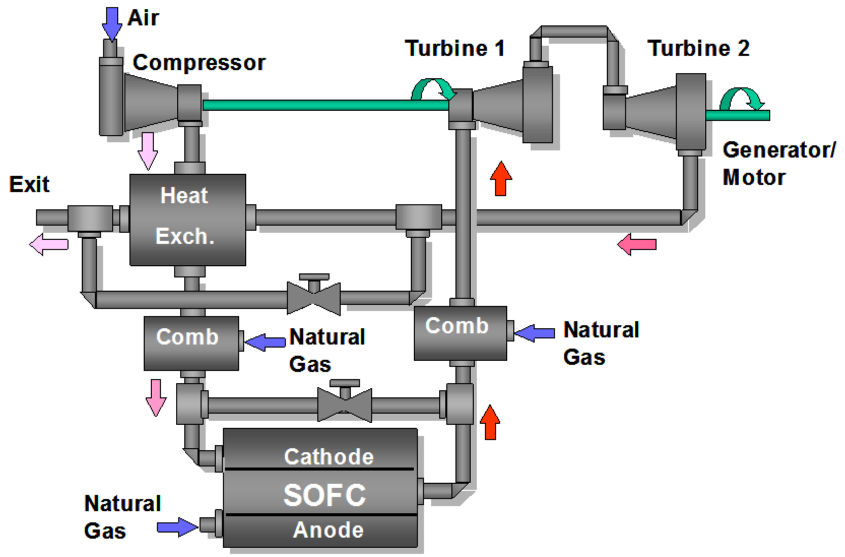
eBay
Silicon Valley

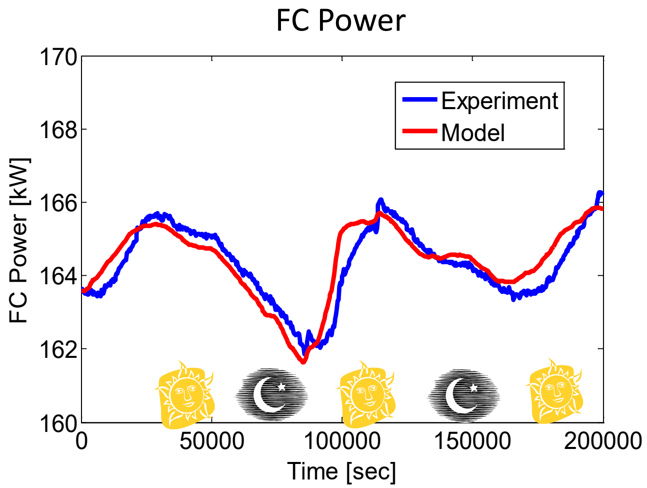
Zero Criteria Pollutants (always)
Zero GHG Emissions (fuel)

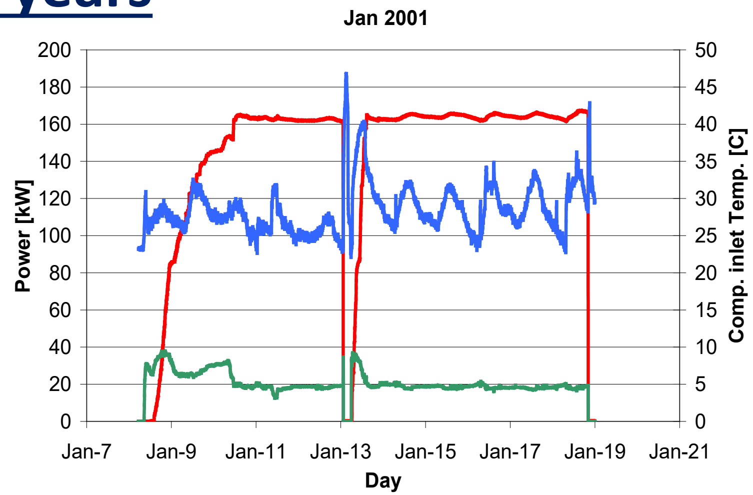


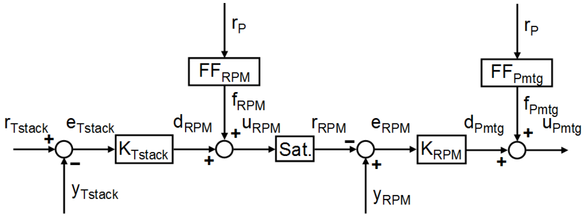
Hybrid SOFC-GT Systems – Highest Efficiency Fueled Generation!

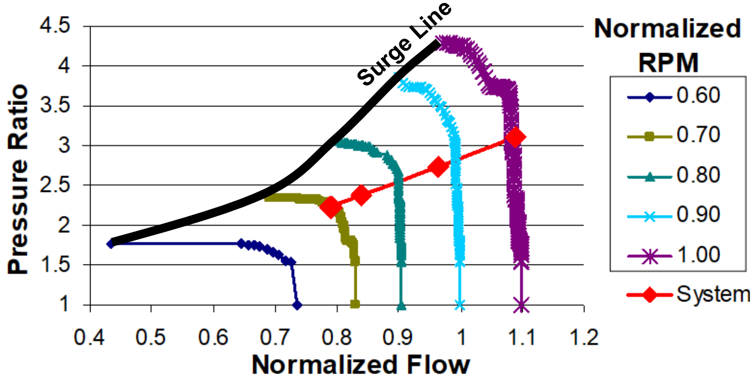
UCI APEP has been advancing hybrid SOFC-GT systems for > 20 years







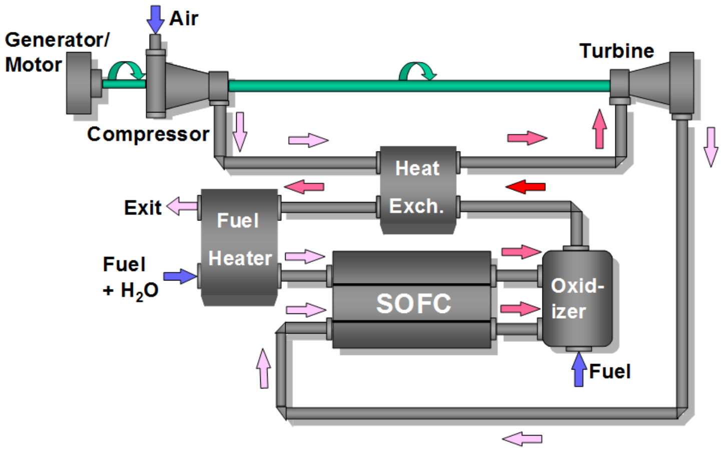




SIEMENS

SOUTHERN CALIFORNIA EDISON — An EDISON INTERNATIONAL Company

World First!



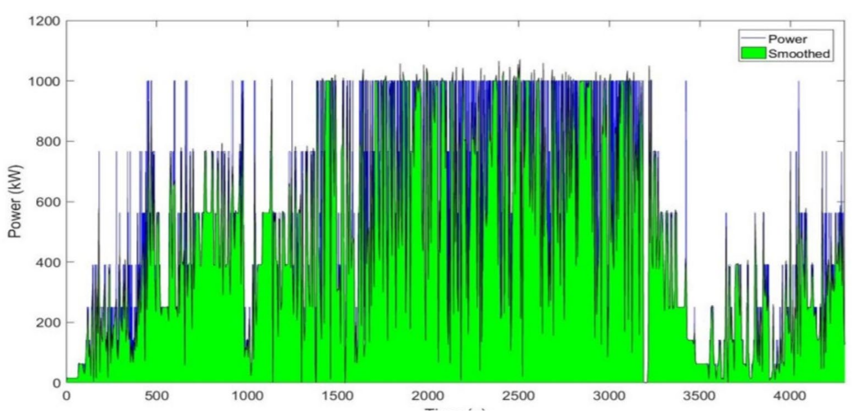
FuelCell Energy — World Leader in Ultra-Clean Power

NFCRC

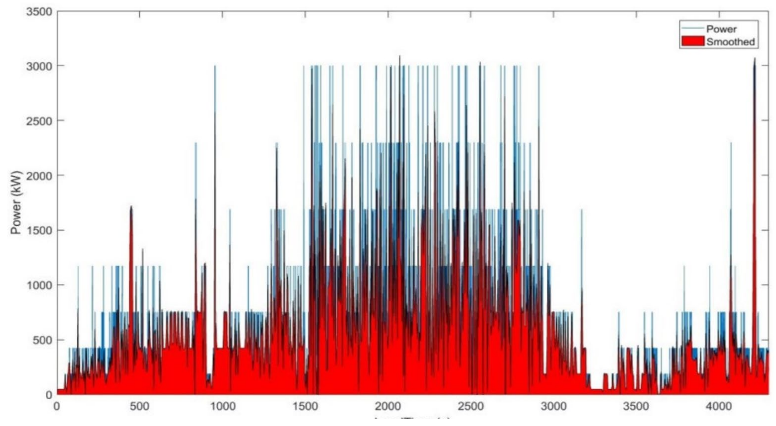
Hybrid SOFC-GT Systems for Locomotives

> 10 years advancement for locomotive applications (funding from FRA, CARB, SCAQMD)

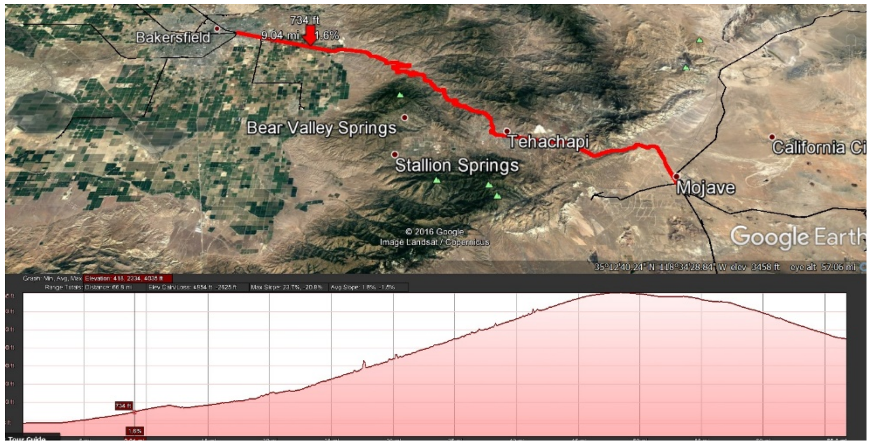
1. Martinez, A.S., Brouwer, J., and G.S. Samuelsen, *Feasibility Study for SOFC-GT Hybrid Locomotive Power: Part I. Development of a Dynamic 3.5 MW SOFC-GT FORTRAN Model*, J. Power Sources, Vol. 213, pp. 203-217, 2012.
2. Martinez, A.S., Brouwer, J., and G.S. Samuelsen, *Feasibility Study for SOFC-GT Hybrid Locomotive Power: Part II. System Packaging and Operating Route Simulation*, J. Power Sources, Vol. 213, pp. 358-374, 2012.
3. Martinez, A.S., Brouwer, J., and Samuelsen, G.S., *Comparative analysis of SOFC–GT freight locomotive fueled by natural gas and diesel with onboard reformation*, Applied Energy, Vol. 148, Pages 421-438, 2015.
4. Azizi, M.A., Ahrend, P.N., Brouwer, J., and Samuelsen, G.S., "Prototype Design and Evaluation of Hybrid Solid Oxide Fuel Cell Gas Turbine Systems for use in Locomotives," Federal Railroad Administration, Office RPD-32, Report Number DOT/FRA/ORD-19/43, 2019.
5. P. Ahrend, A. Azizi, J. Brouwer, and G. S. Samuelsen, "A Solid Oxide Fuel Cell-Gas Turbine Hybrid System for a Freight Rail Application," 2019, ASME 2019 13th International Conference on Energy Sustainability, ES 2019, collocated with the ASME 2019 Heat Transfer Summer Conference, 2019.



1 MW Switcher loco. dynamic demand

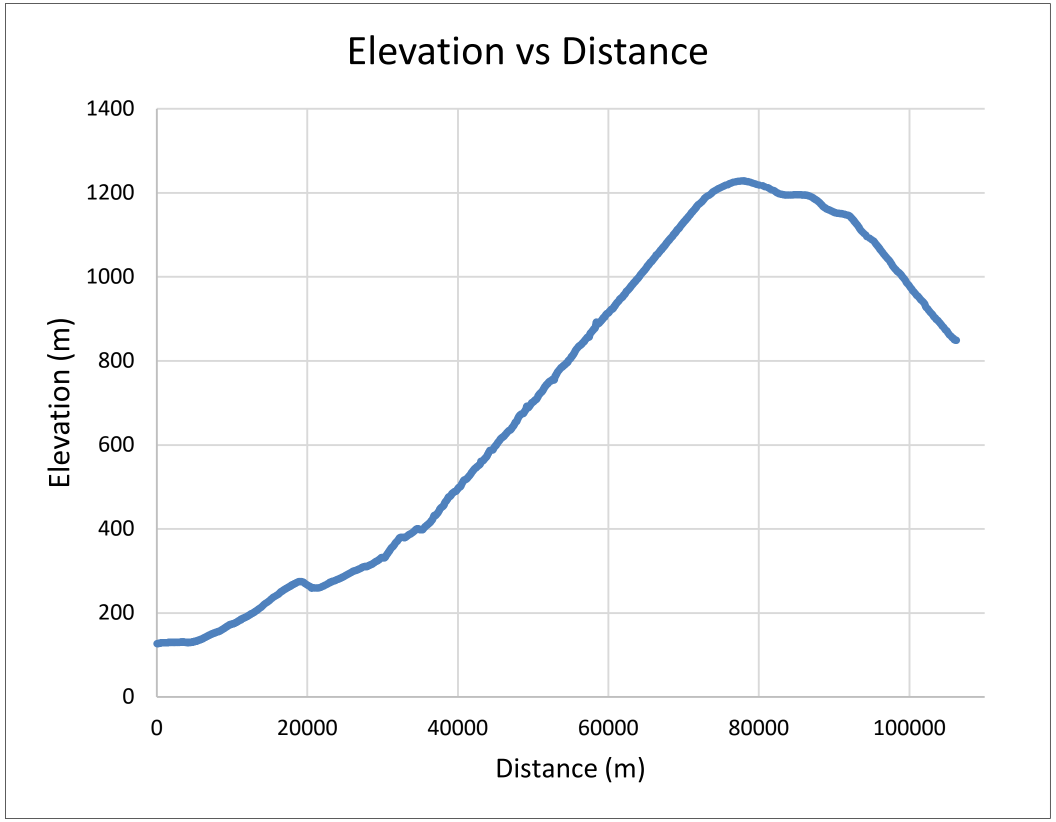


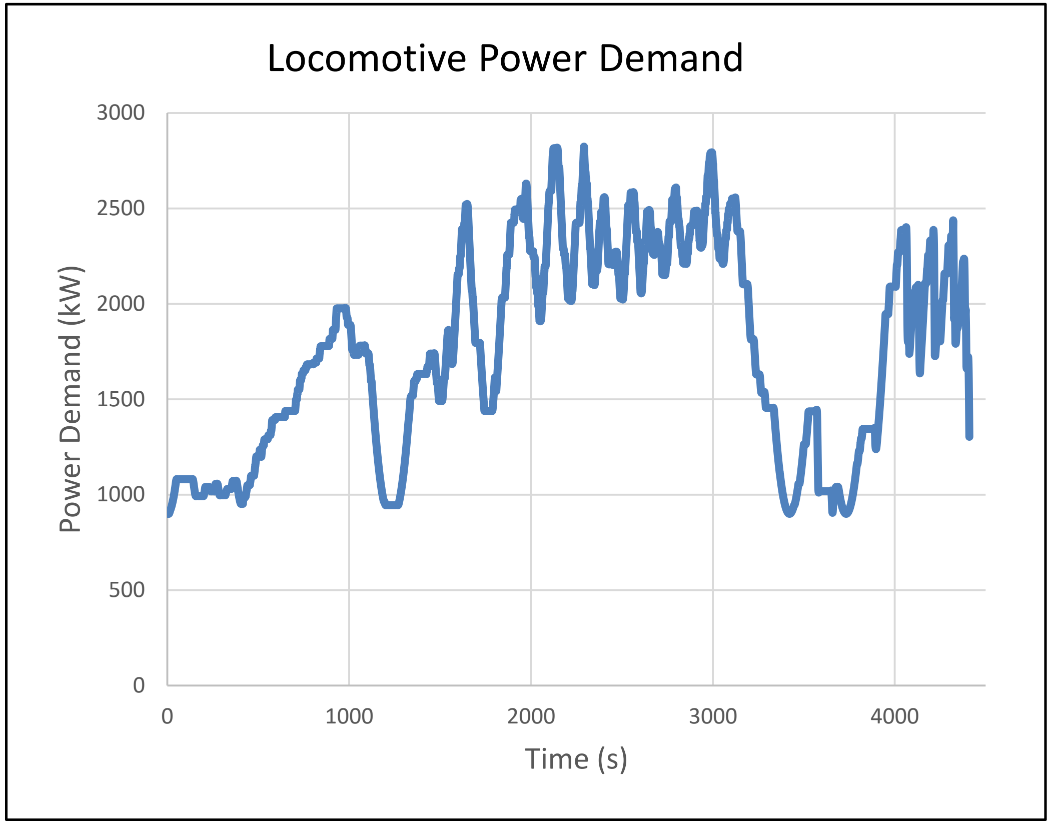
3 MW Long-haul loco. dynamic demand



Bakersfield-Mojave Route

- Investigated use of reformed diesel, LNG, LH_2 fuel options
- Calculated power demand required for a 240 ton, 3 MW locomotive pulling 10 freight cars (1440 tons total)
- Dynamic notching model for target speed between 4.5 and 27 m/s
- Feasibility of carrying fuel (tender requirements) & fitting system in locomotive footprint & volume

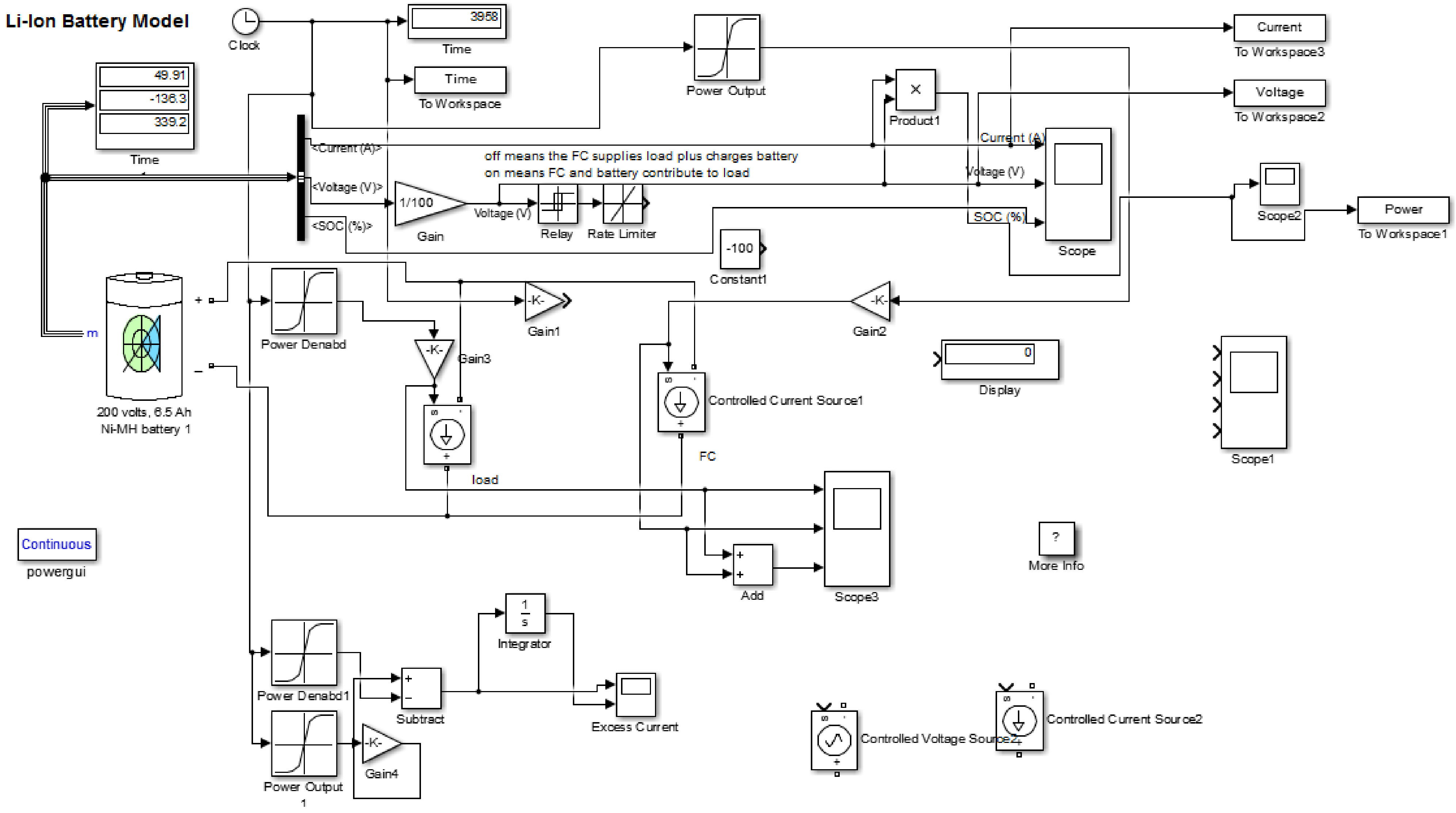




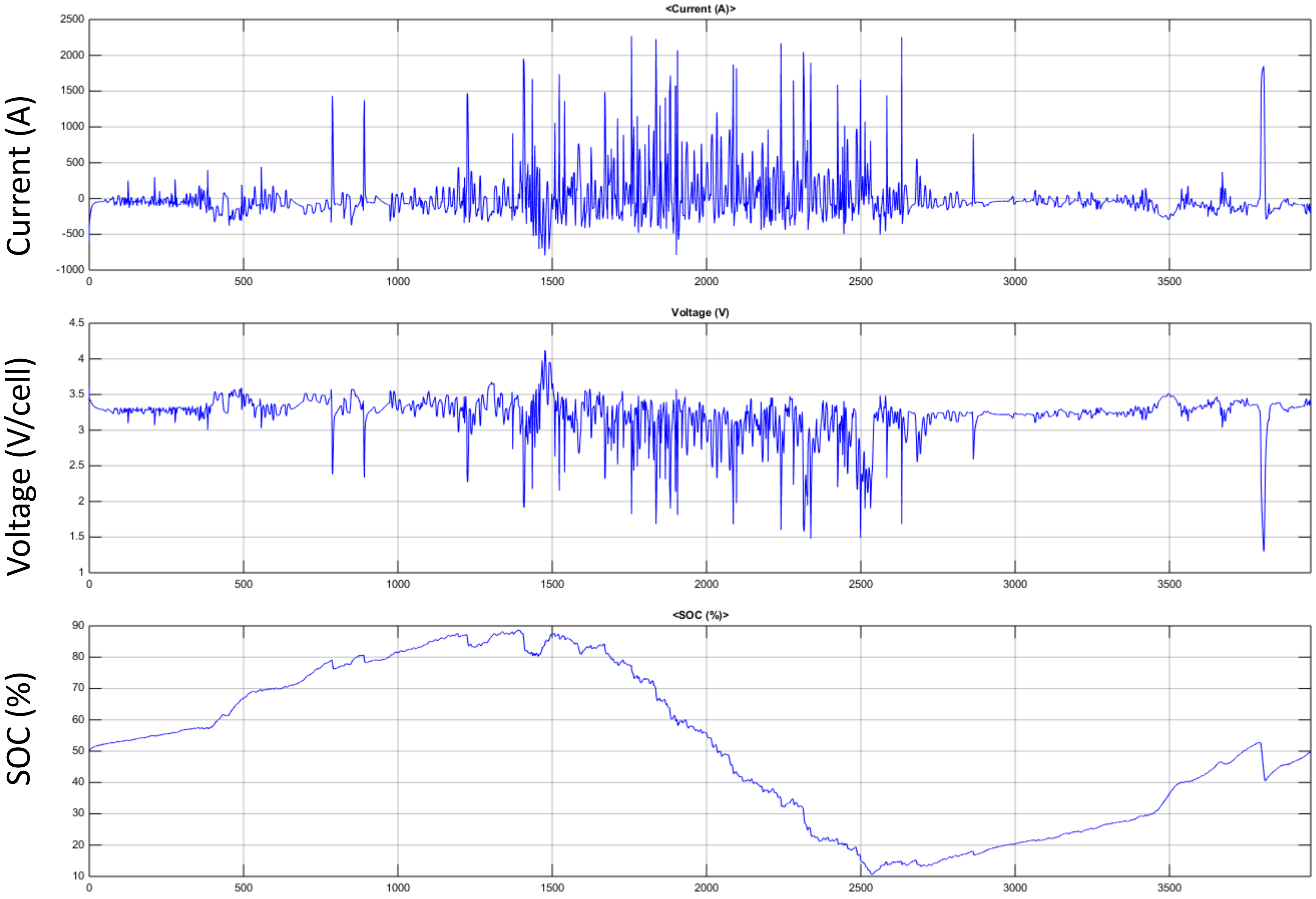
P. Ahrend, A. Azizi, J. Brouwer, and G. S. Samuelsen, "A Solid Oxide Fuel Cell-Gas Turbine Hybrid System for a Freight Rail Application," 2019, *ASME 2019 13th International Conference on Energy Sustainability, ES 2019.*

Hybrid Battery SOFC-GT Locomotive

- **Add Li-Ion battery to design and simulate dynamics**

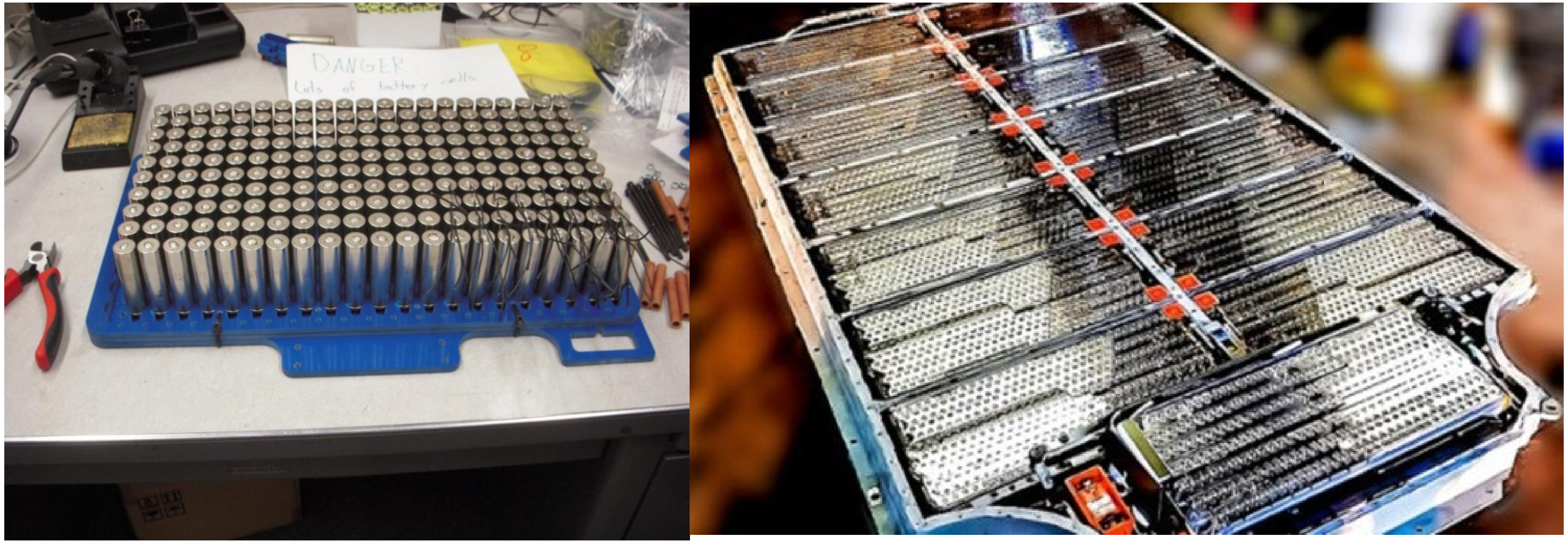


Battery Cycle Data – Bakersfield to Mojave



Battery Requirements

- Demonstrated application in a dynamic battery simulation
- Lithium-ion Battery requires up to 400 kW of power (186 A at 2.15 kV)
- Required energy storage capacity is 100 kWh
- Within range of reasonable power-to-energy ratio (2-13)
- At $200/kWh, cost is estimated to be at most $20K
- Small fraction of the cost of SOFC-GT-LIB system



Tesla Battery Packs

Outline

- Hybrid SOFC-GT systems for locomotive applications
- **How zero-emissions rail may evolve**
- Air Quality, Health & GHG impacts

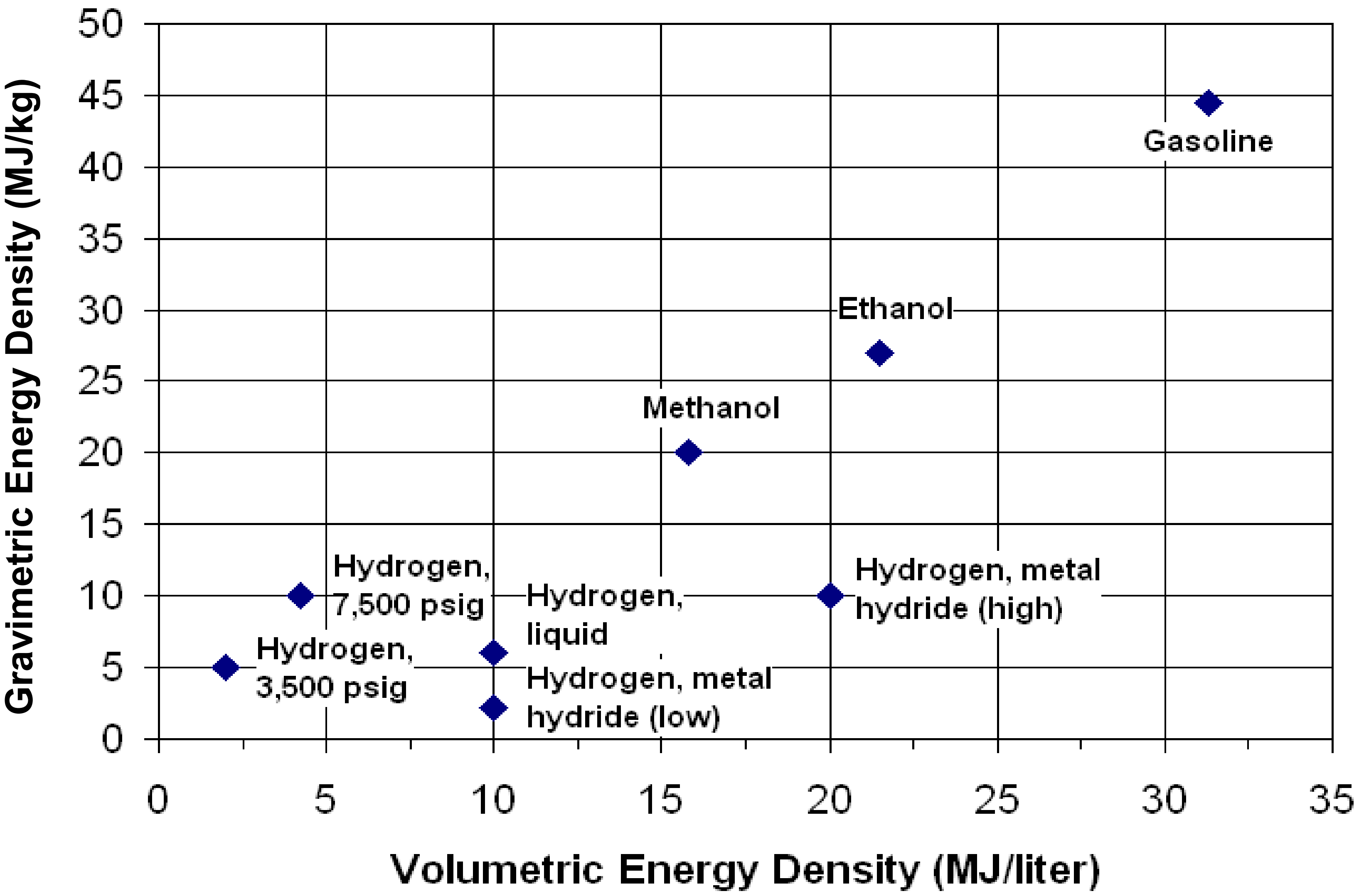
Possible Zero Emissions Rail Evolution

- **Electrify as much as possible – in-port rail, short-range rail, add catenaries for medium-range rail**
- **Battery electric rail**
  - Relatively cost-effective today
  - But limited by short range, lower payload, long fueling/charging time
- **Proton exchange membrane (PEM) fuel cell + hydrogen emerging**
  - Historical switcher demonstrations in U.S. (e.g., BNSF)
  - Current demonstrations in Europe
  - TBD demonstrations in CA (recent CEC GFO)
- **Line-Haul projects all in R&D phase**
  - Require high gravimetric and volumetric energy density
  - Require heavy payload
  - Require long distance (long duration) storage (fuel)

UCI SOFC-GT work
Renewable fuels:
e.g., H_2, RNG

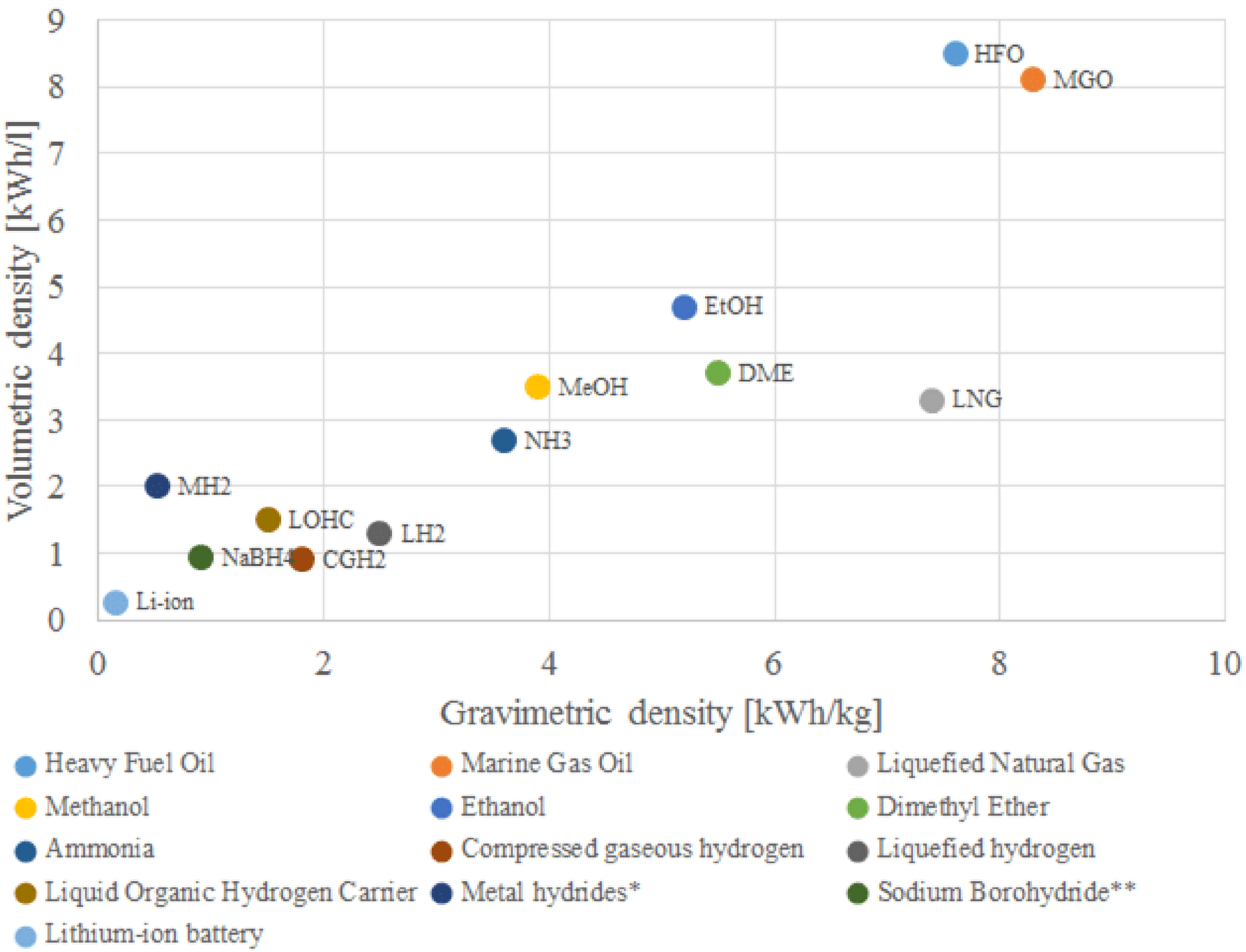
Possible Zero Emissions Rail Evolution

- **Gravimetric & Volumetric Energy Density of various options**



Possible Zero Emissions Rail Evolution

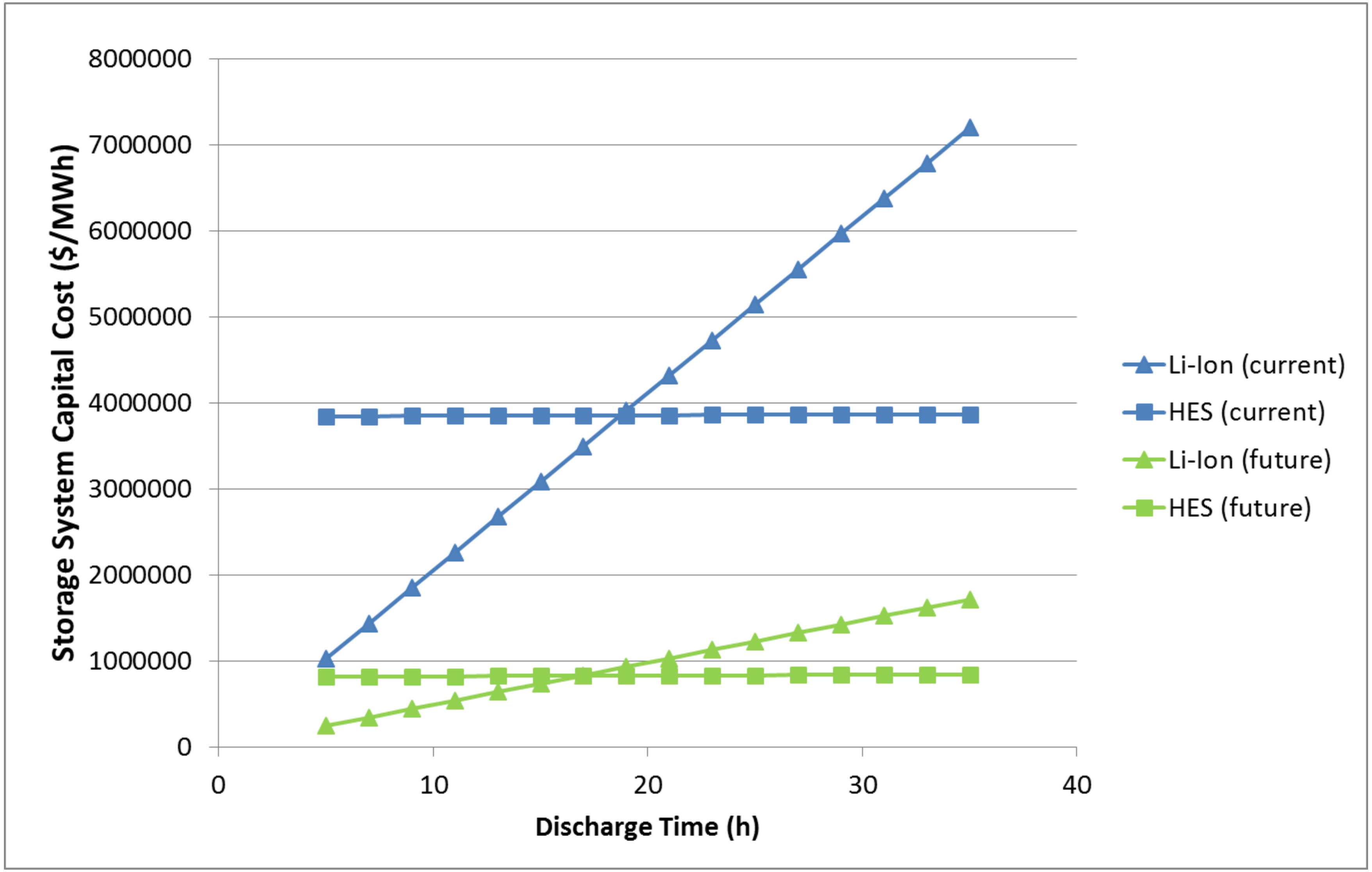
- **Gravimetric & Volumetric Energy Density of various options**
- **NH_3, MeOH, EtOH, DME synthetic LNG may become attractive zero emission options**
- **SOFC can directly use these energy carriers**



Benny Mestemaker, Bernardete Castro, Erik van der Blom, Henk Cornege, *Zero emission vessels from a shipbuilders perspective,* 2nd International Conference on Smart & Green Technology for Shipping and Maritime Industries, 2019.

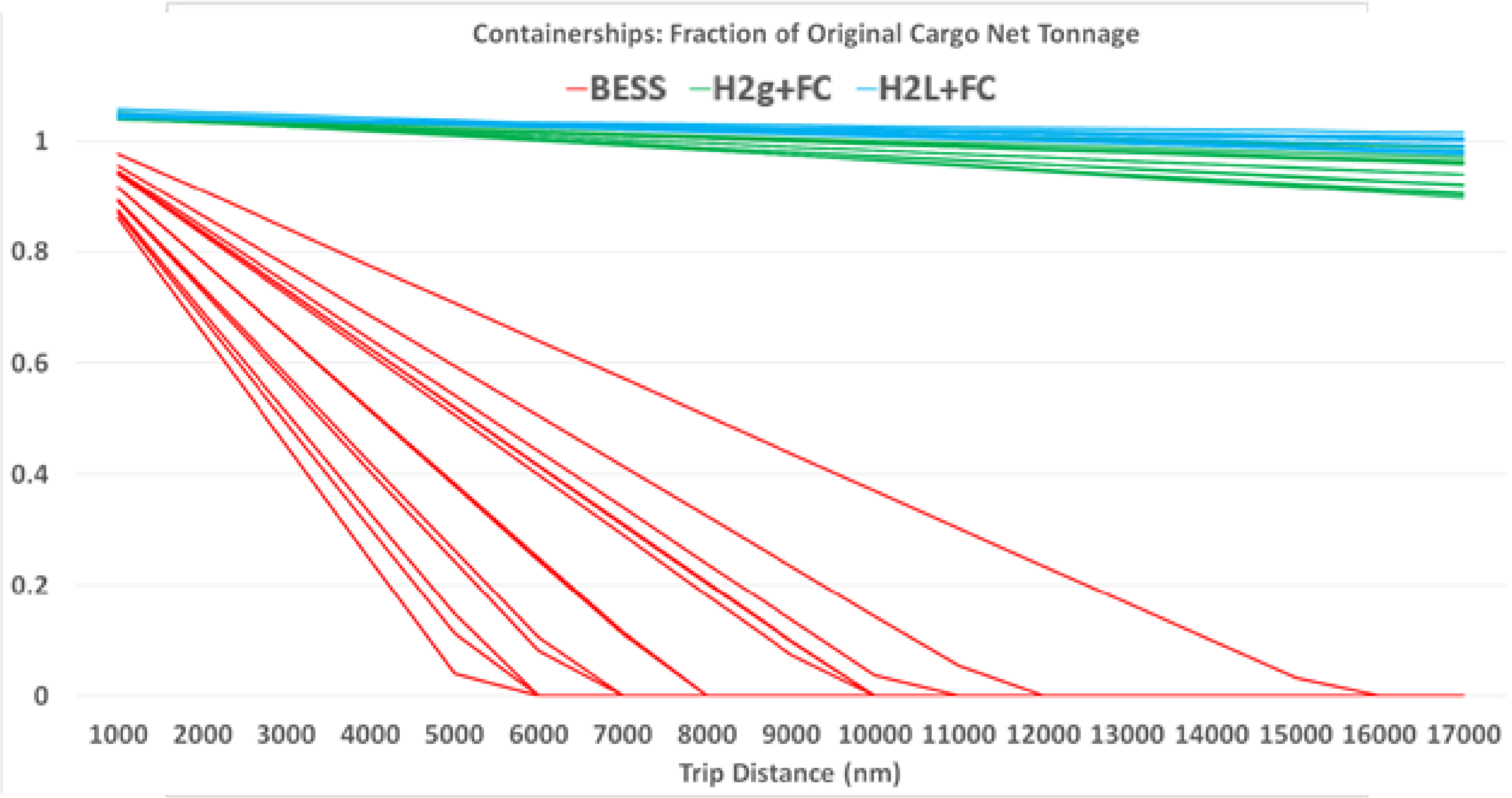
Why Hydrogen? Lower Cost, Weight, Volume Energy Storage

HES has separate power & energy scaling compared to batteries



Why Hydrogen? Rail (& Ship) Payload & Range

Batteries compared to Hydrogen & Fuel Cells for Container Ships



Why Hydrogen? Zero Emission Fuels Required for Some End-Uses

- **Provide zero emissions fuel to difficult end-uses**

Shipping

Aircraft

…l Cell Trains & Locomotives

Fuel Cell Bu…

Toyota Fuel Cell:
Zero Emissions Big Rig

Anything that requires (1) rapid fueling, (2) long range, (3) large payload

ARPA-E CHANGING WHAT'S POSSIBLE

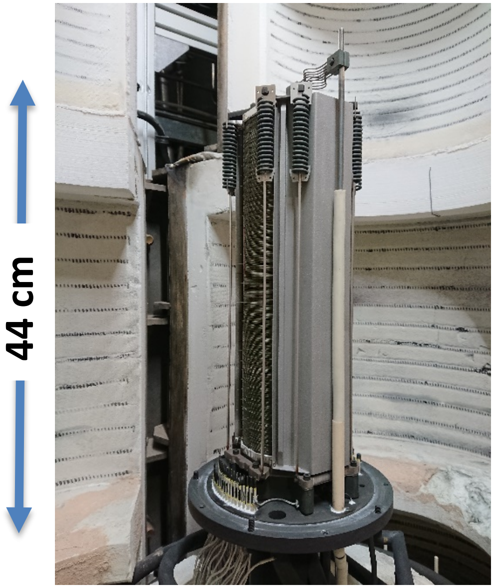
Adaptive SOFC for Ultra High Efficiency Power Systems

FuelCell Energy, Inc., UC Irvine

Prototype Completed in 2022

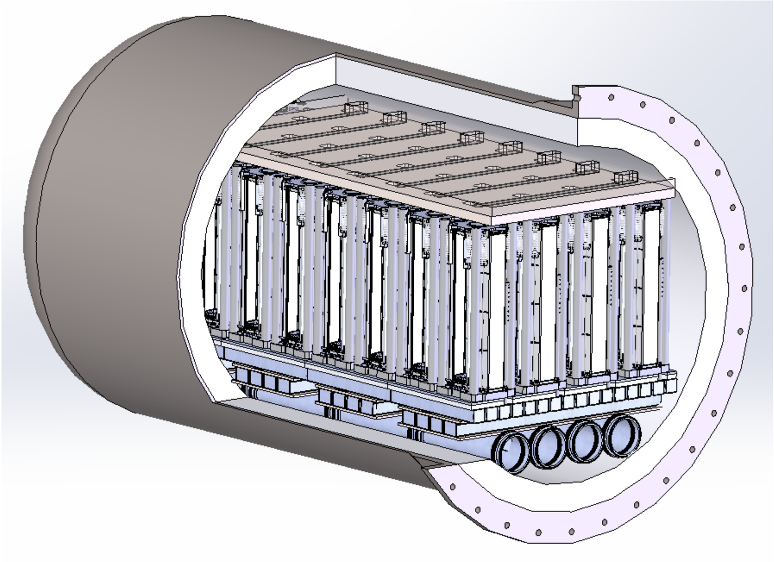
Project Vision

Development of flexible 100kW Solid Oxide Fuel Cell (SOFC) technology suitable for integration with gas turbine equipment achieving > 70% electrical efficiency based on natural gas lower heating value



7 kW Compact SOFC Architecture (CSA) Stack, Atmospheric Pressure

Project Development



SOFC Pressurized Module

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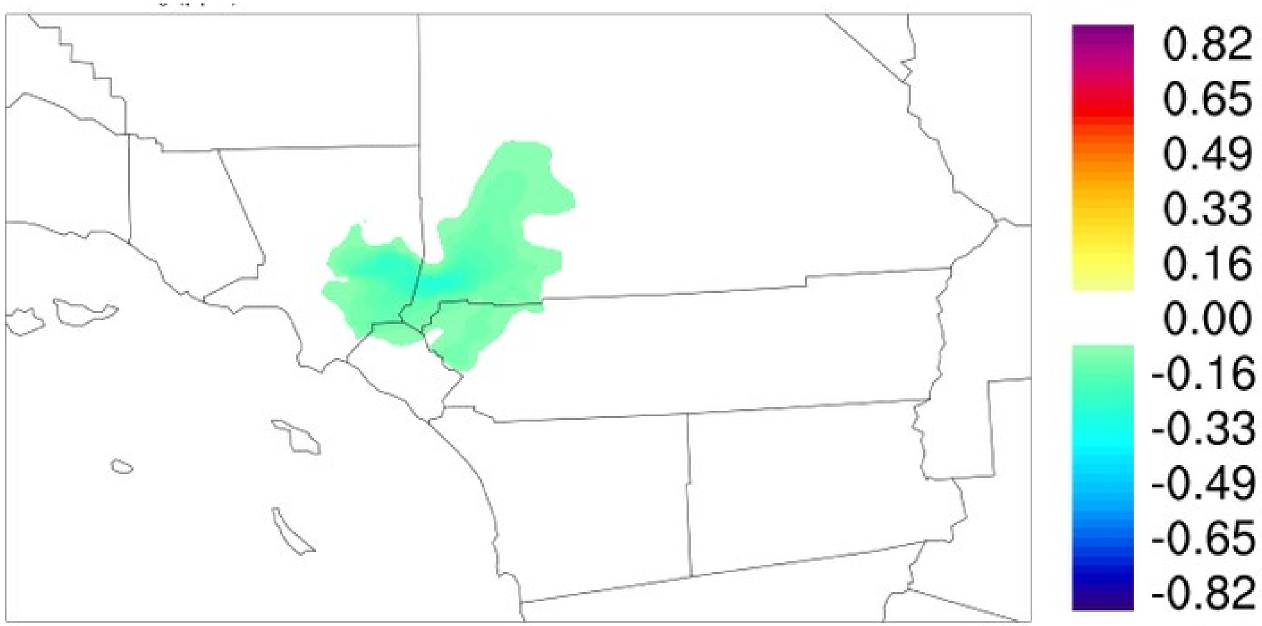
Outline

- Hybrid SOFC-GT systems for locomotive applications
- How zero-emissions rail may evolve
- **Air Quality, Health & GHG impacts**

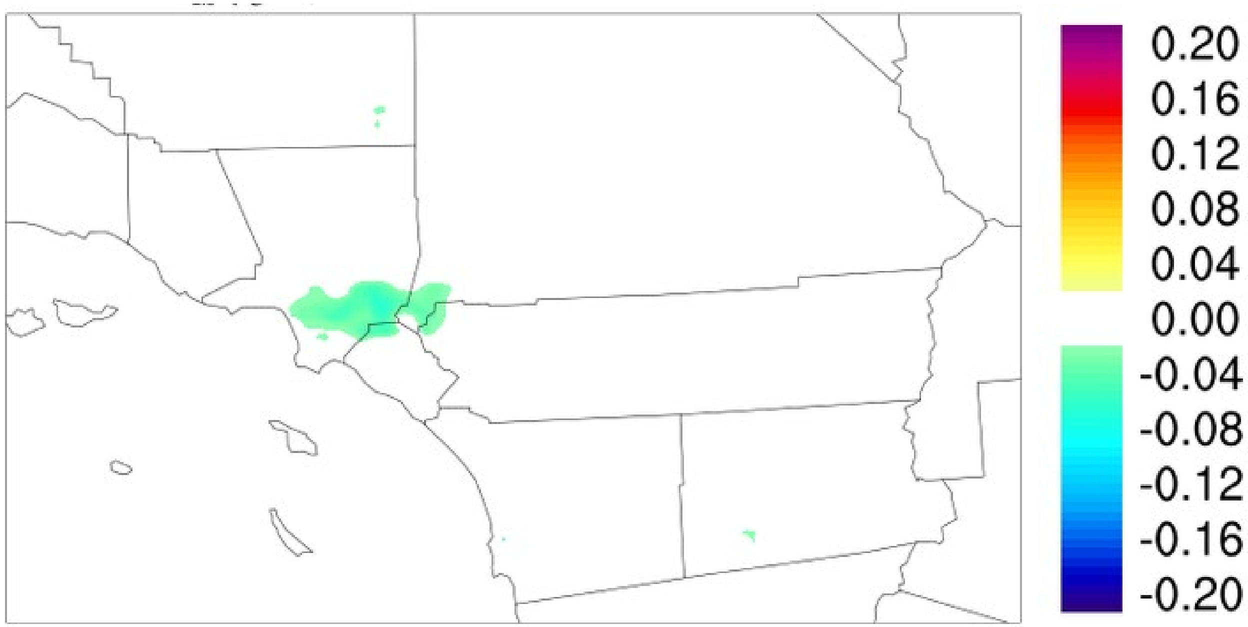
Air Quality Impacts of Rail

- **Low penetration of zero emissions (electric & fuel cell) tech in locomotives (25%)**
- **Difference plots versus BAU case, summer meteorology**

Max Δ8-hr O_3 (ppb)



Max Δ24-hr $PM_{2.5}$ (μg/m³)

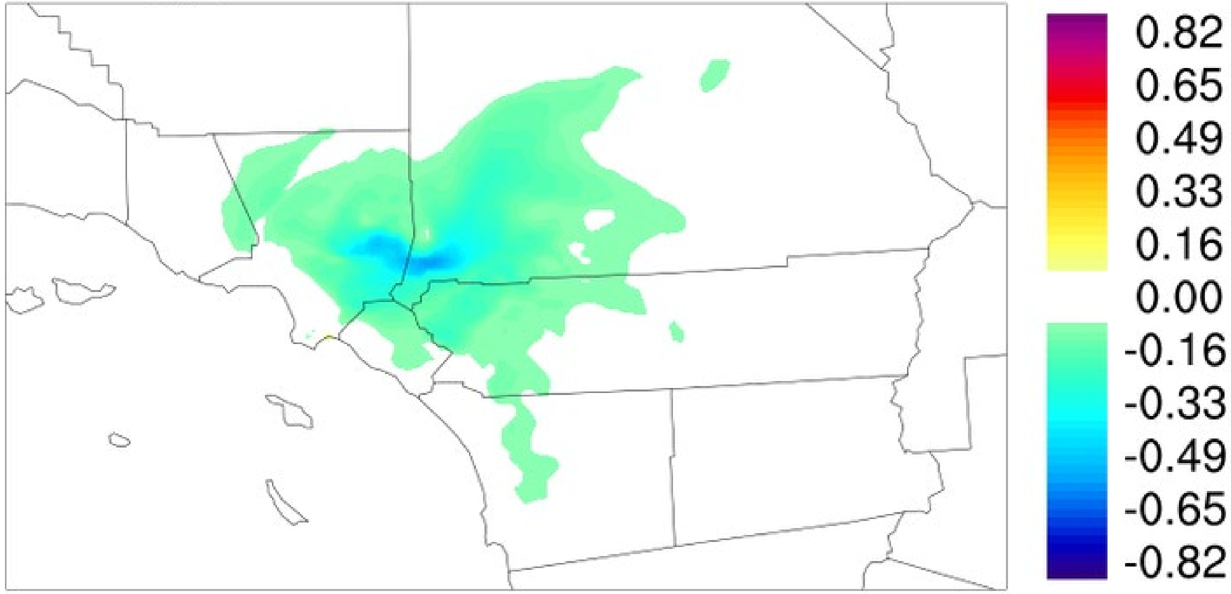


Soukup, James V., *Air Quality, GHG, and Human Health Impacts Associated with Fuel Cell Electric Technologies in Port Applications*, M.S. Thesis, G.S. Samuelsen, advisor, University of California, Irvine, 2019.

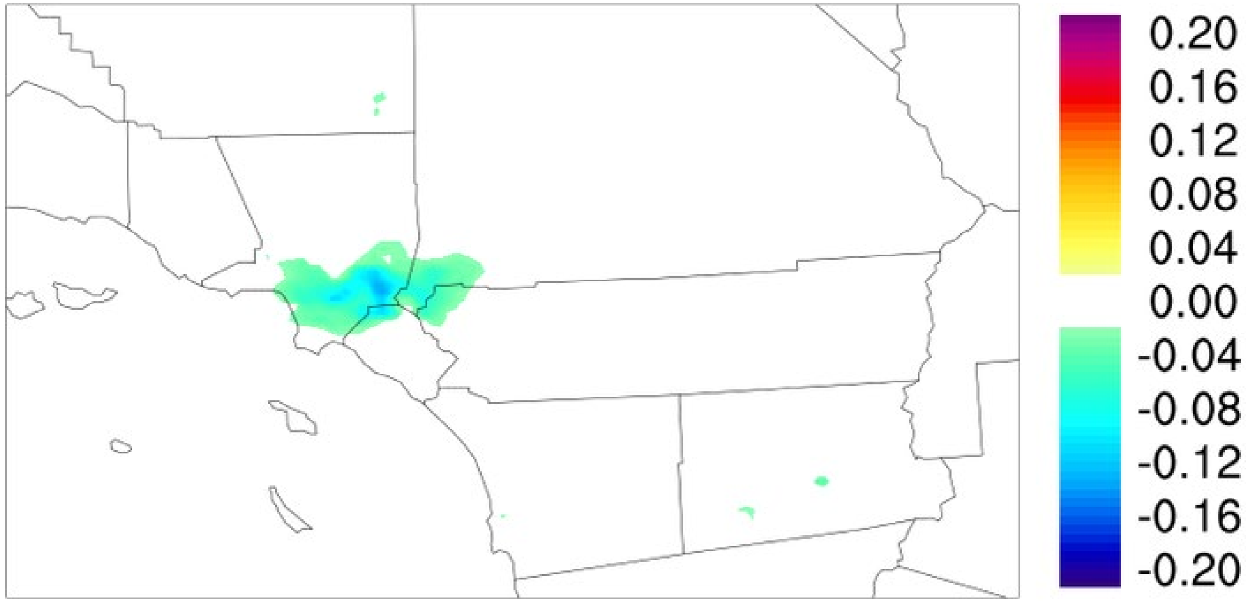
Air Quality Impacts of Rail

- Medium penetration of zero emissions (electric & fuel cell) tech in locomotives (50%)
- Difference plots versus BAU case, summer meteorology

Max Δ8-hr O_3 (ppb)



Max Δ24-hr $PM_{2.5}$ (μg/m³)



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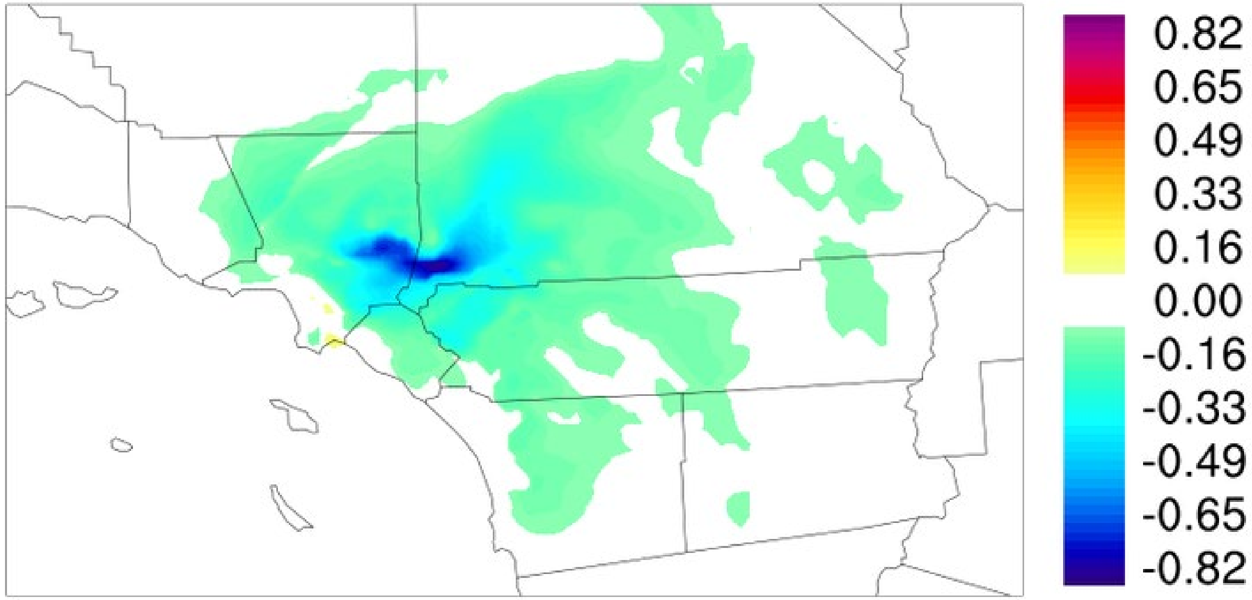
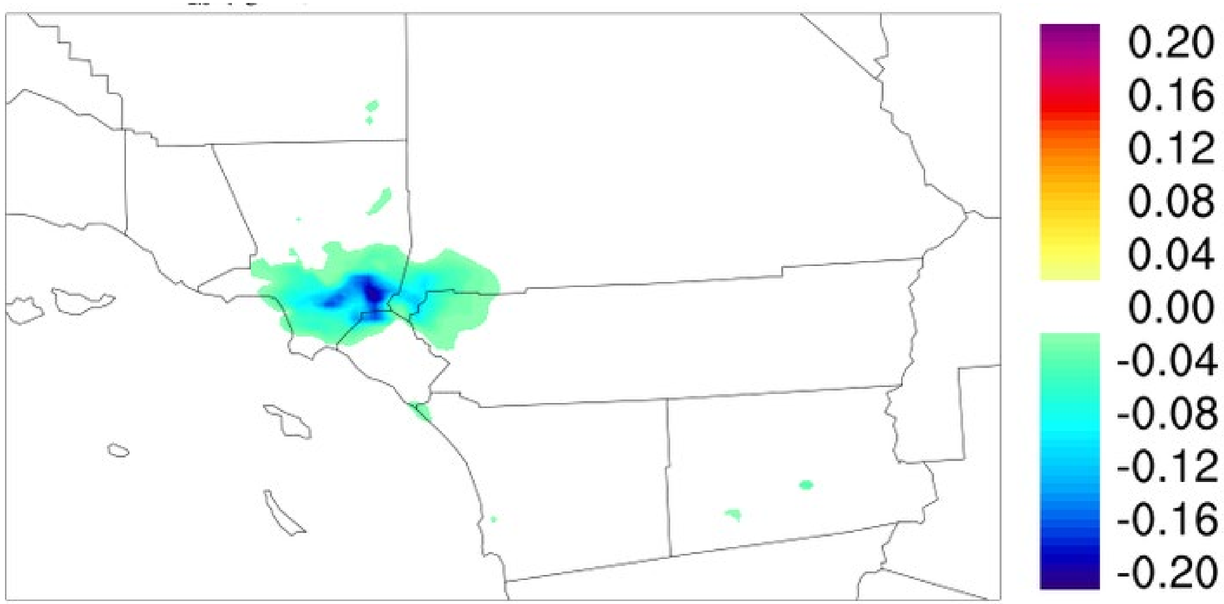
Air Quality Impacts of Rail

- High penetration of zero emissions (electric & fuel cell) tech in locomotives (75%)
- Difference plots versus BAU case, summer meteorology

Max Δ8-hr O_3 (ppb)



Max Δ24-hr $PM_{2.5}$ ($\mu g/m^3$)



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Health Impacts of Rail

- **Health Impacts from the <u>High Penetration (75%)</u> rail case analyzed (SoCAB only)**
- **BenMAP-CE (2019)**

Endpoint	Valuation Estimates (thousands $/day)		
	Mean	2.5 CI*	97.5% CI*
Premature Deaths Avoided, All Causes			
Short-Term Ozone Exposure	199.6	14.5	444.2
Short-Term PM25 Exposure	388.3	172.1	614.8
Total Premature Deaths	587.9	186.6	1058.9
Reduced Morbidity Incidence			
Short-Term Ozone Exposure			
HA, Asthma	0.05	0.02	0.1
HA, All Respiratory	0.4	-0.1	1.0
School Loss Days	3.8	-0.4	8.1
Emergency Room Visits, Asthma	0.1	0.02	0.3
Minor Restricted Activity Days	1.3	0.5	2.0
Total Short-Term Ozone	5.69	-0.01	11.40
Short-Term $PM_{2.5}$ Exposure			
Lower Respiratory Symptoms	0.03	0.01	0.1
Upper Respiratory Symptoms	0.1	0.01	0.1
Asthma Exacerbation, Wheeze Asthma Exacerbation, Cough Asthma Exacerbation, Shortness of Breath	0.1	0.00	0.1
HA and ED Visits, Asthma	0.0	-0.01	0.1
HA, All Respiratory	0.7	0.4	1.0
HA, All Cardiovascular (less Myocardial Infarctions)	0.9	0.6	1.1
HA, Ischemic Stroke	1.2	0.4	2.4
Work Loss Days	2.9	2.5	3.4
Minor Restricted Activity Days	1.6	1.3	1.9
Acute Myocardial Infarction, Nonfatal	1.8	0.6	4.7
Total Short-Term PM2.5	9.30	5.82	14.81
Total Morbidity (PM2.5+Ozone)	15.00	5.81	26.21

*These values represent a 95% confidence interval for the mean

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Greenhouse Gas Emissions of Rail

- **GHG Emissions changes from all Rail Cases analyzed (SoCAB only)**

GHG Emissions Changes (thousand tonnes CO_2e)			
Pathway	Low	Medium	High
RE100	-865.98	-1731.97	-2597.95
RR100	-463.33	-926.66	-1389.99
RG100	-640.85	-1281.71	-1922.56
NGE50/50	-441.78	-883.56	-1325.35
NGR50/50	-240.46	-480.91	-721.37
NGG50/50	-329.22	-658.43	-987.65
NGC50/50	-199.19	-398.38	-597.57
NGO50/50	-220.42	-440.83	-661.25

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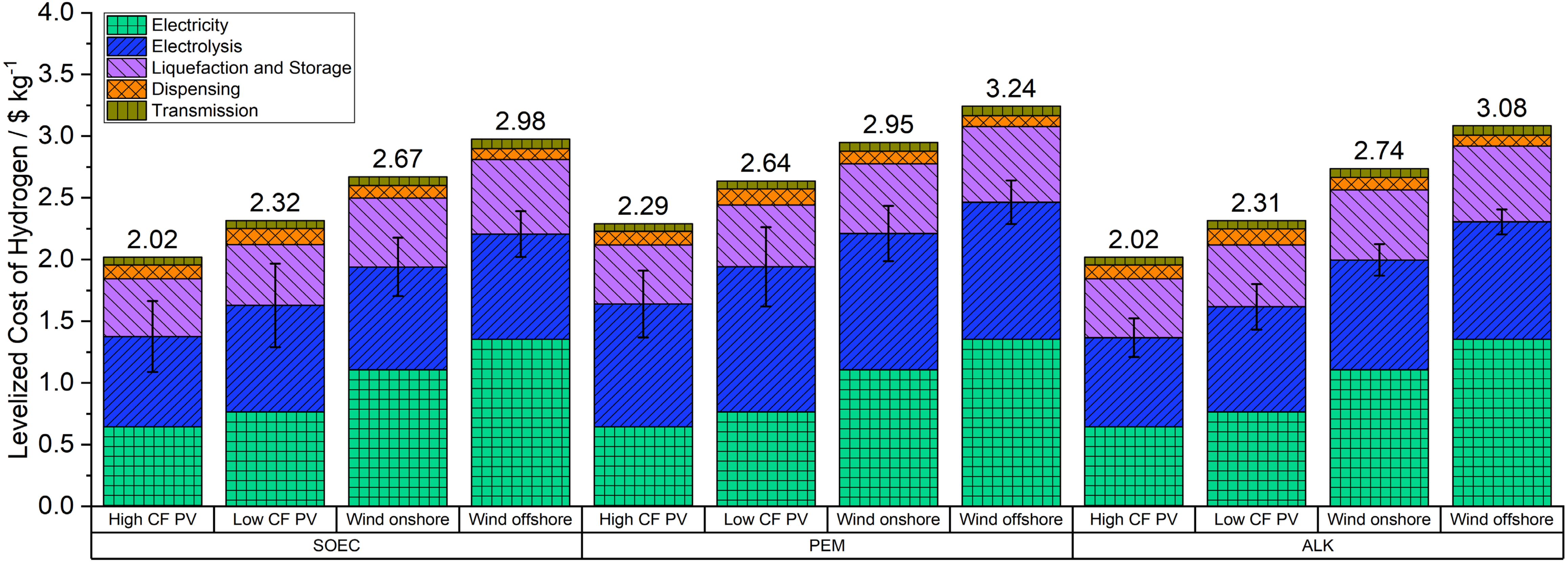
Zero Emissions Rail

- **It is IMPERITIVE to meet our GHG, air quality, and health policy goals**
- **Renewable hydrogen route is important & will become cost competitive with fossil petroleum distillate fuels within a decade (with correct policy & regulatory decisions)**



Levelized cost of hydrogen ($/kg) determined by all-in capital & operating expense analyses

Zero Emissions Rail

The fossil fuel era will end when the first jurisdiction anywhere in the world determines to make their ports (including rail) zero emissions

Thank you for your attention!