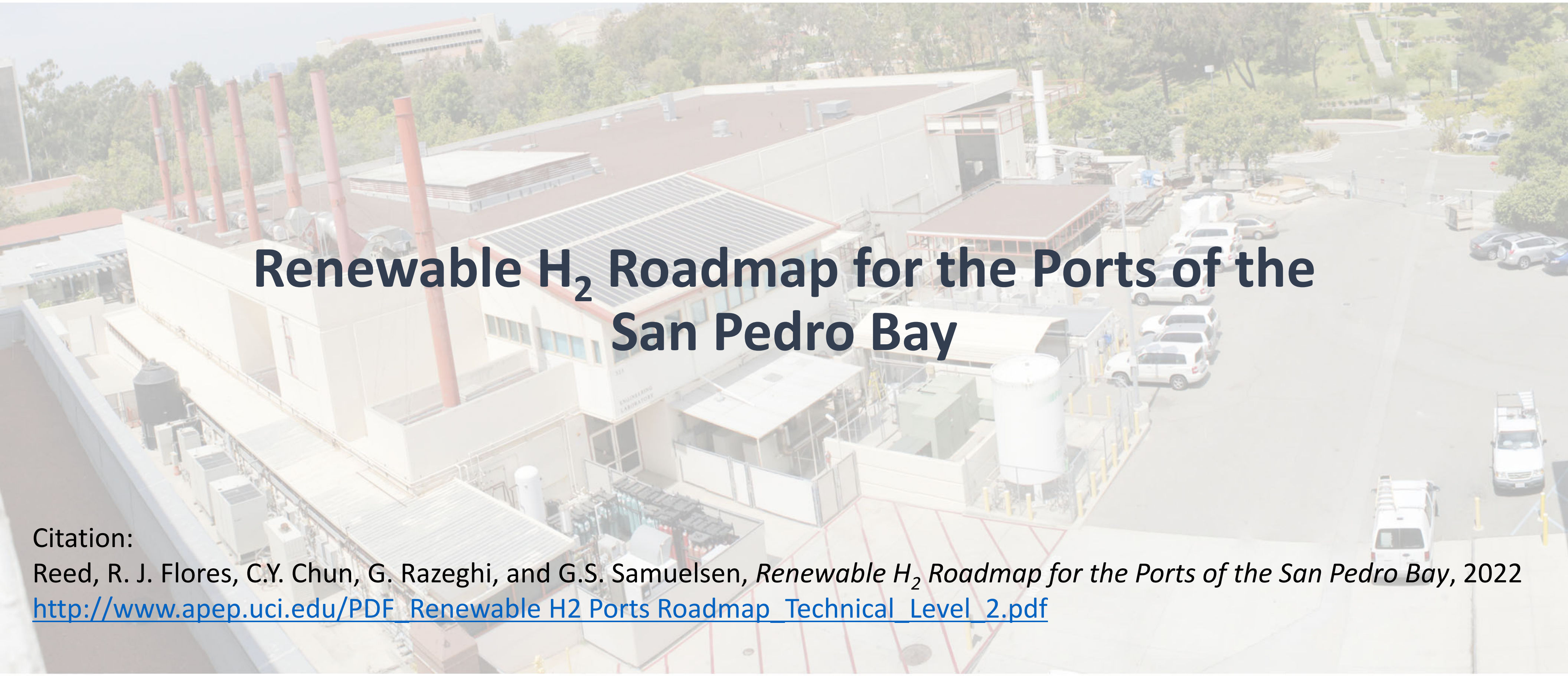


Renewable H_2 Roadmap for the Ports of the San Pedro Bay

Citation:
Reed, R. J. Flores, C.Y. Chun, G. Razeghi, and G.S. Samuelsen, *Renewable H_2 Roadmap for the Ports of the San Pedro Bay*, 2022
http://www.apep.uci.edu/PDF_Renewable H2 Ports Roadmap_Technical_Level_2.pdf

#RH2@APEP
RENEWABLE HYDROGEN
UCI ADVANCED POWER AND ENERGY PROGRAM

ADVANCED POWER & ENERGY PROGRAM
UNIVERSITY of CALIFORNIA · IRVINE

September, 2022

Presentation Outline

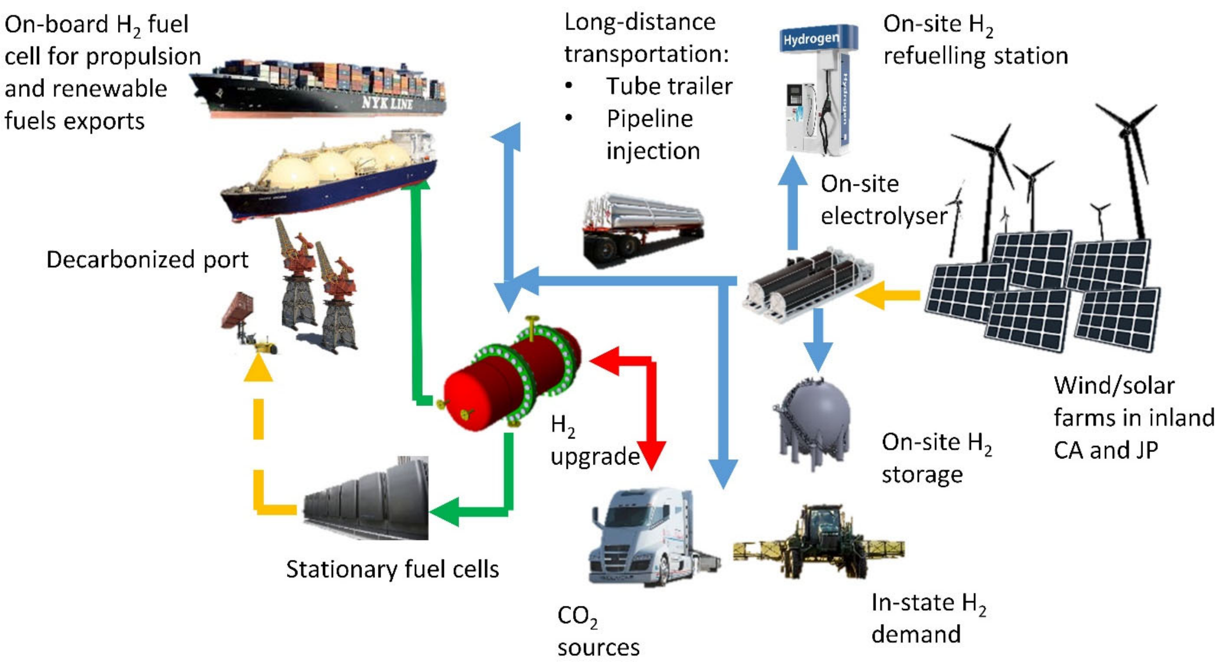
- Objectives, Approach and Principal Conclusions
- Policy Drivers, Emissions Target and Applications in Scope
- Comparative Drive Train / Prime-mover Feasibility and Costs
- Potential Demand for Hydrogen and Electricity at the Ports
- Infrastructure Considerations
- Emissions Reductions from Hydrogen Adoption
- High-level Roadmap for Hydrogen Deployment at the Ports
- Appendices:
  - Drive-Train Comparative Economics
  - Summary of Demonstrations and Commercialization Activity

Overview

Goal: Develop a Roadmap for Adoption of Renewable Hydrogen Solutions as Part of a Least-cost Decarbonization Approach for Ports and Connected Freight.

Time Frame: 2022 through 2050

Approach: Compare full cost of fuel cell versus battery solutions and assess the timing of reaching cost parity with incumbent technology (predominantly diesel ICE) – 9-month 20,000 foot effort



Why Hydrogen as a Decarbonization Vector at Ports?

- We will need fuel with diesel-like functionality in the future
- Renewable hydrogen costs are declining rapidly
- Hydrogen fuel cells produce zero emission
- California can take advantage of the global scaling of “hydrogen economies”
- California renewable resource potential is unrivaled
- A new renewable hydrogen sector will create green jobs in vocations otherwise bypassed by electrification (e.g., pipe fitters)
- Huge opportunity to create an export hub for RH2-derived renewable fuels, fertilizers, and chemicals
- The Infrastructure Bill includes $8 billion for hydrogen hubs and ports are viewed as anchor users
- LA and Long Beach City Council Resolutions to pursue hydrogen hub funding to support port decarbonization

There is growing international interest in hydrogen for port applications

Major logistics companies (e.g., Maersk, NYK, Hyundai Glovis pursuing hydrogen and hydrogen carrier strategies

<u>Port of Rotterdam, Netherlands</u>
- H2 infrastructure including wind-powered electrolysers.
- Use of biofuel and ammonia.

<u>Port of Antwerp, Belgium</u>
- Import solar energy from Middle East and Africa to convert to H2 and send back to the port.
- Power-to-Methanol Project.
- First hydrogen fueled tugboat.

<u>Port of Los Angeles/Long Beach, USA</u>
- Hydrogen fuel cell electric freight demonstration for "shore-to-store" advances zero-emissions transit across supply chain.
- Development of new hydrogen refueling infrastructure.

<u>Port of Singapore</u>
- Use Liquid Organic Hydrogen Carrier – MCH.
- Renewable energy and smart grid adoption

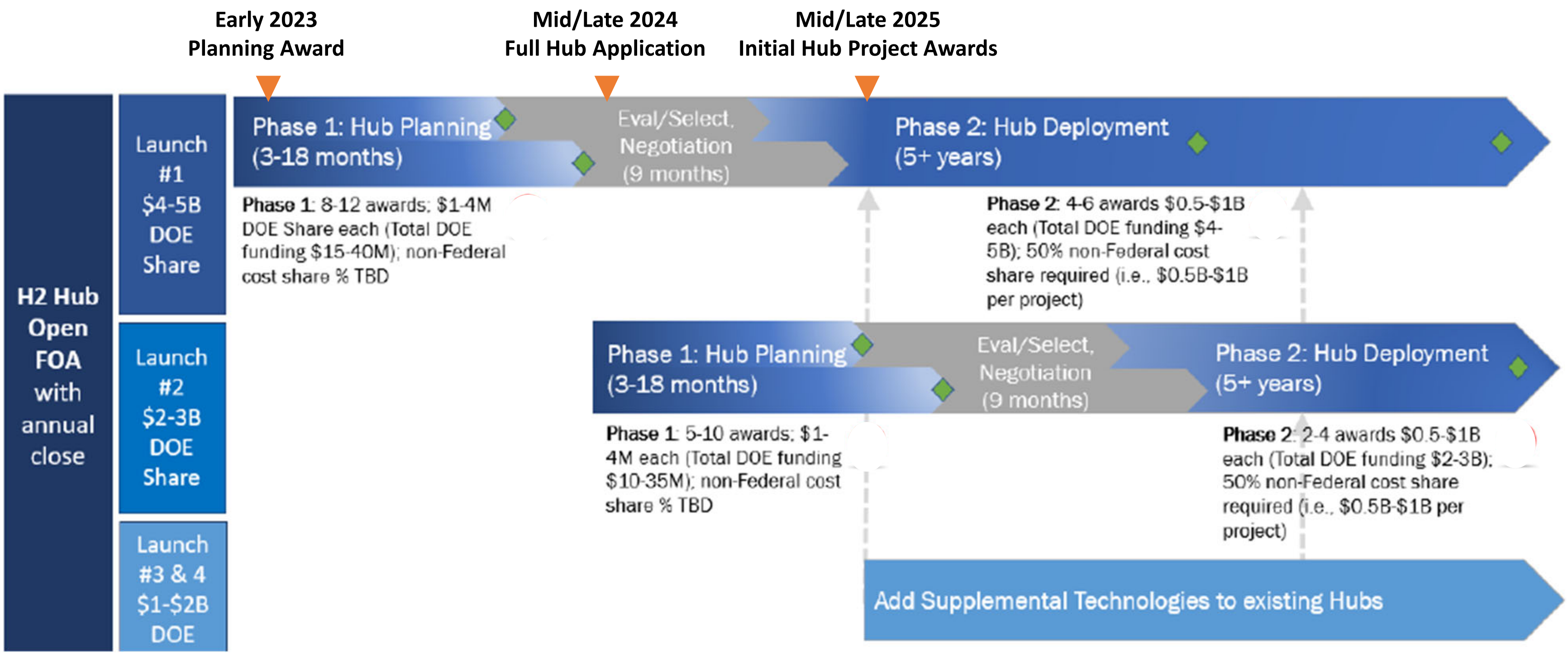
<u>Port of Houston, USA</u>
- Extensive hydrogen network along the Gulf Coast.
- Comprehensive Hydrogen Hub Plan published.

<u>Port of Brisbane, Australia</u>
- Investigate opportunities in renewable energy, hydrogen, biofuels and batteries.
- Replace with new technology including renewables, energy storage and zero emission fuels.

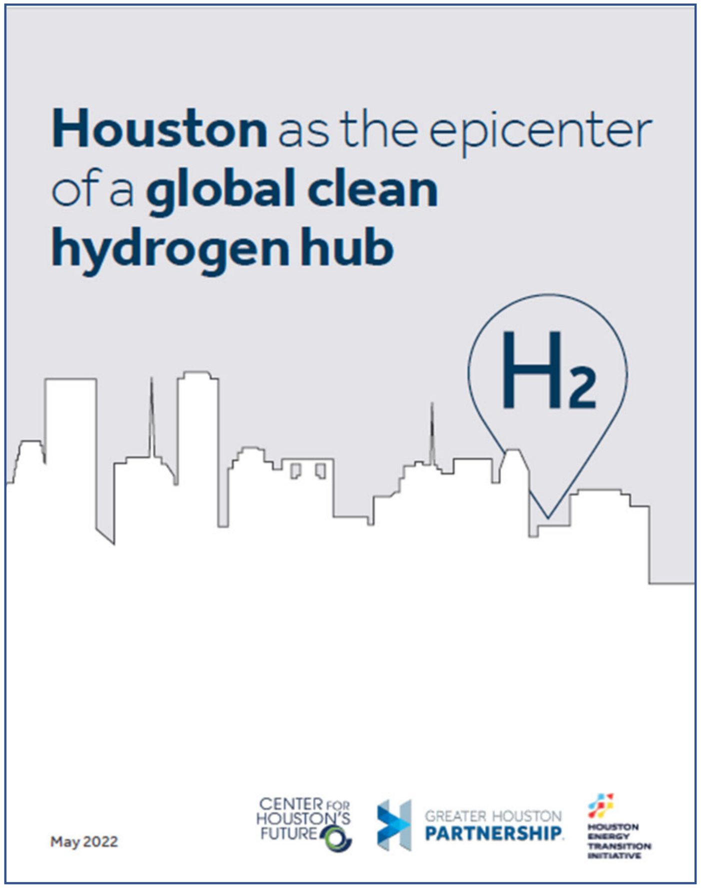
<u>Port of Valencia, Spain</u>
- First experience for fuel Cell technologies in port handling equipment in Europe.
- Hydrogen mobile supply station.

Map Source: https://www.vox.com/2014/8/26/6063749/38-maps-that-explain-the-global-economy

DOE Hydrogen Hub program offers a unique opportunity to jump start hydrogen at the Ports



Others are moving rapidly to seize the opportunity



Source: C-Job

- **Houston hub strategy features the port as a major anchor cluster and targets 10 billion kg per year export operation**

Principal Conclusions

- Hydrogen fuel cell drive trains project to be the least-cost, zero-emissions solution for most applications for port operations and connected freight (50% to 60% of current fuel use)
- Electrification is also viable for many applications and may be least-cost solution for applications with lower power and on-board storage requirements
- For applications with high horsepower and on-board fuel requirements, all-electric solutions pose packaging and logistic challenges making hydrogen an attractive alternative
- Electric-drive solutions are 2 – 5 years ahead of hydrogen-fueled drivetrains, but, with user demand, the gap can be closed quickly (gap is system engineering and in-use validation not basic science)
- For large vessels, hydrogen-derived liquid fuels (ammonia or methanol) likely the preferred solution and the San Pedro Bay ports have the opportunity to become a fueling hub (although others, such as the Port of Stockton, may have similar ambitions)
- A hydrogen-fueled microgrid can improve reliability and resilience while reducing the amount of upgrading otherwise needed to support electrification at the ports
- The DOE hydrogen hubs program provides the opportunity to jump start the adoption of hydrogen at the ports beginning in around 2026 – commercial demonstrations should be pursued aggressively in advance

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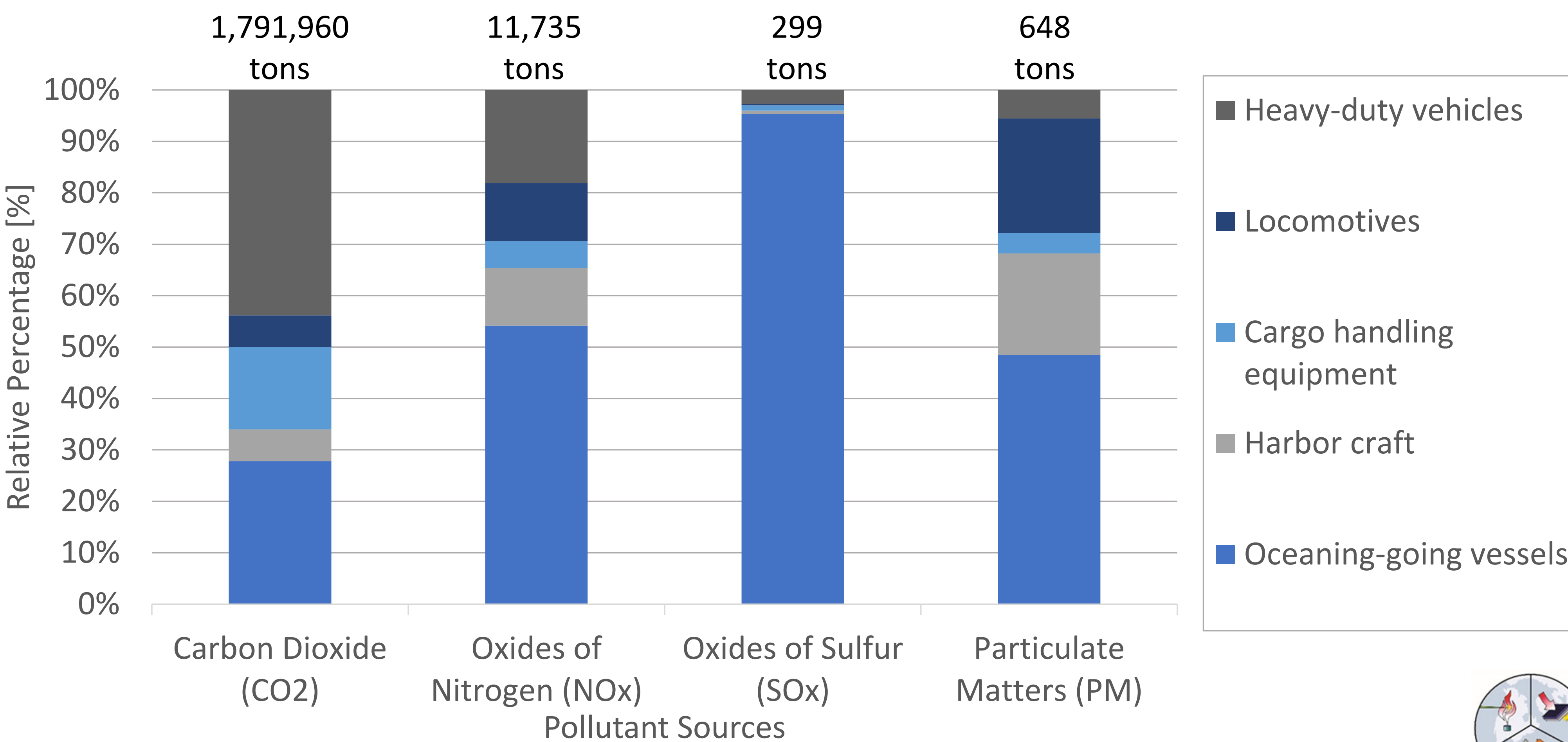
California Emissions Reduction Drivers and Targets

- **State, national and international regulations and policies target evolution to zero or near-zero emissions (GHG and criteria) ports by 2050**
  - **California ARB and SCAQMD**
  - **U.S. EPA**
  - **International Maritime Organization**
  - **Clean Air Action Plans of the ports**

- **Emissions reduction assumptions**
  - **GHG 40% below 1990 levels by 2030 and 80% below by 2050 *and evaluate***

    GHG 50% below 1990 levels by 2030 and net zero by 2050
  - **NO_x, PM and SO_x are eliminated for systems converting to fuel cell drive while systems employing combustion of hydrogen or hydrogen-derived fuels (locomotive and vessels) meet emissions standards**

Port Emissions Breakdown by Pollutant and Source in 2020



Applications Overview

Application	CO_2 (tonnes)	NOx (tons)	SOx (tons)	PM (tons)	H_2 vs. e-	Reason
Cargo Handling						
Forklift	5,491	22	0	1	Hydrogen	Cost + Packaging
Top handler	94,271	210	1	7	Hydrogen	Cost + Packaging
Yard Tractor	142,937	175	2	11	Hydrogen	Cost + Packaging
Gantry Crane	26,256	149	0	4	Hydrogen	Cost + Packaging
Harbor Craft						
Assist Tug	26,285	290	0	28	Hydrogen	Packaging
Ocean Tug	25,828	341	0	33	Hydrogen	Packaging
Commercial Fishing	10,039	123	0	12	Hydrogen	Cost + Packaging
Ferry	14,643	176	0	18	Hydrogen	Cost + Packaging
Locomotives						
Switching	9,454	68	0	2	Hydrogen	Cost + Packaging
Line Haul	100,986	1,253	1	143	Hydrogen	Cost + Packaging
HDV						
<250 Mile Range	79,761	315	1	1	Battery (mixed)	Very Similar
>250 Mile Range	705,909	1,811	7	33	Hydrogen	Packaging
OGV						
Containership	265,587	3,843	137	164	Hydrogen	Cost + Packaging
Cruise	34,880	571	22	28	Hydrogen	Cost + Packaging
Tanker	151,945	1,326	98	89	Hydrogen	Cost + Packaging
Microgrid	Hydrogen microgrid to support electrified applications				Hydrogen to e-	N/A

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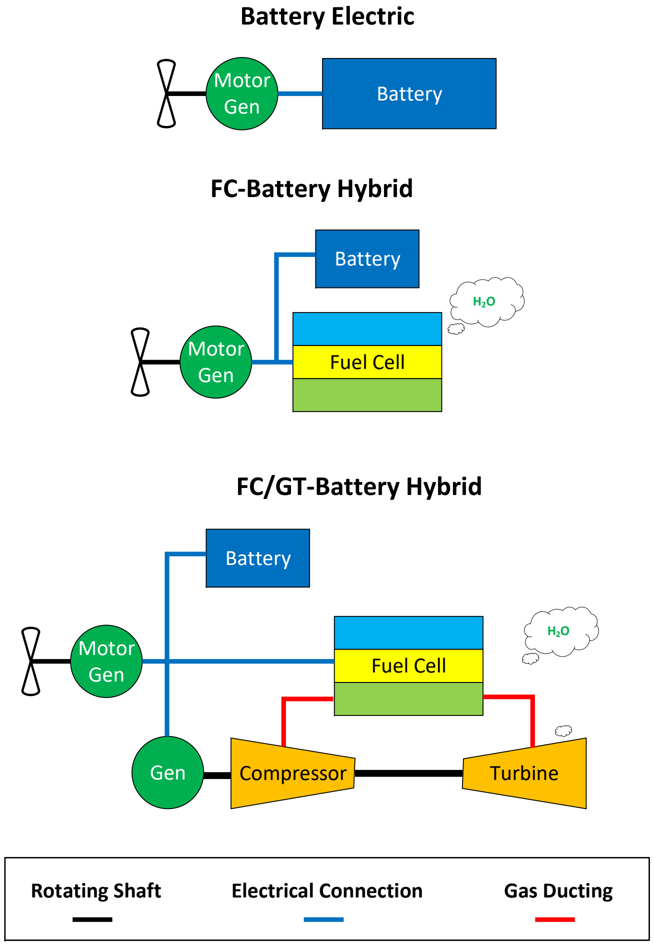
Cost Analysis Approach

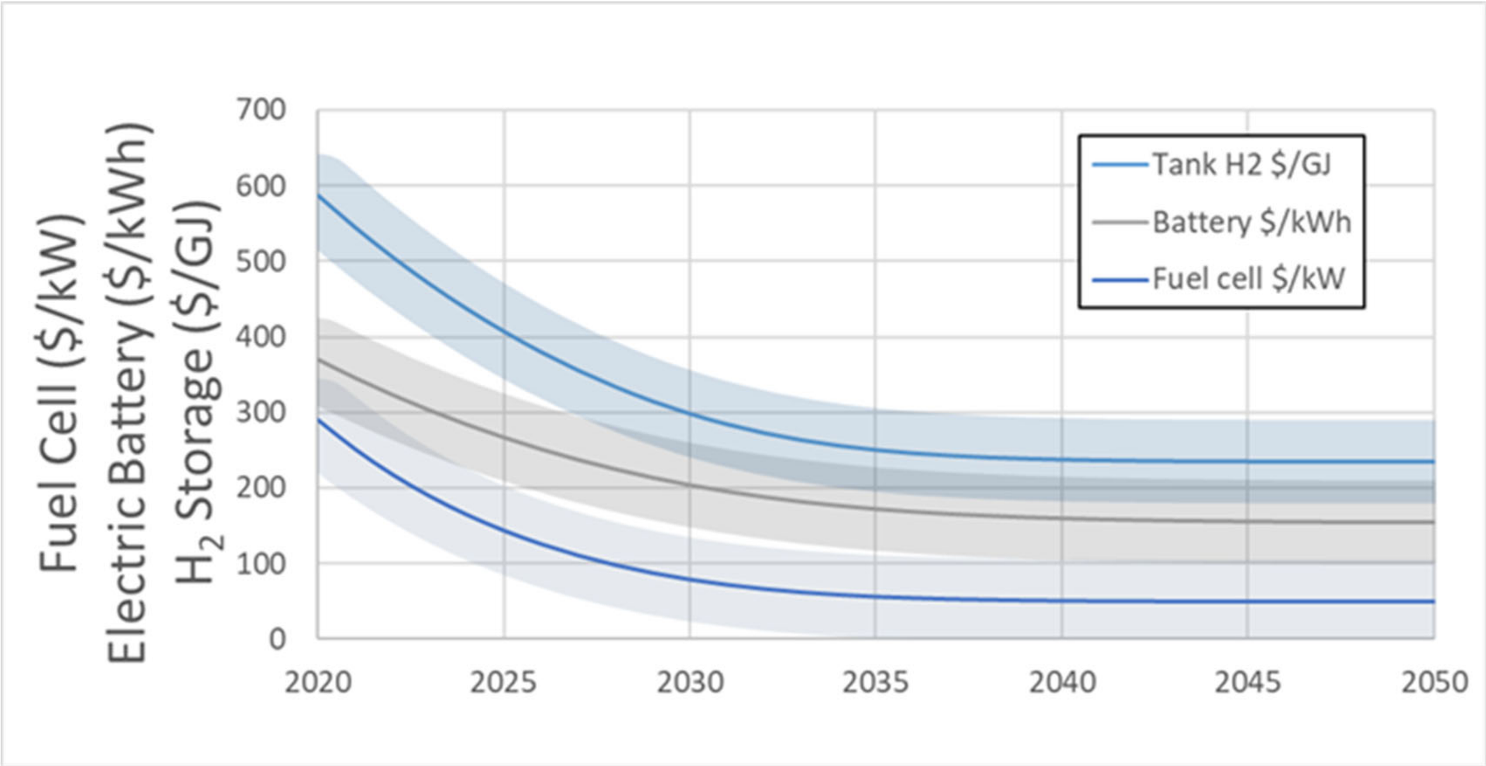
- Peak power and daily fuel requirement was established for each application
- Drivetrain was sized to meet requirements
- Standard cost curves were used to develop a unit cost for each drivetrain projected over time
- Unit cost metric depends on applications (e.g., cost per hour or cost per mile)
- Non-drivetrain platform costs (e.g., “gliders” and retrofit “hosts”) were assumed to be the same for all drivetrains but integration costs considered
- Dispensed cost of hydrogen and electricity drawn for detailed analysis conducted in a parallel project
- ZEV drive train weight and volume feasibility based on comparison to current platforms
- Commercial maturity assessment is qualitative based on secondary research

Zero Emission Powertrain Attributes

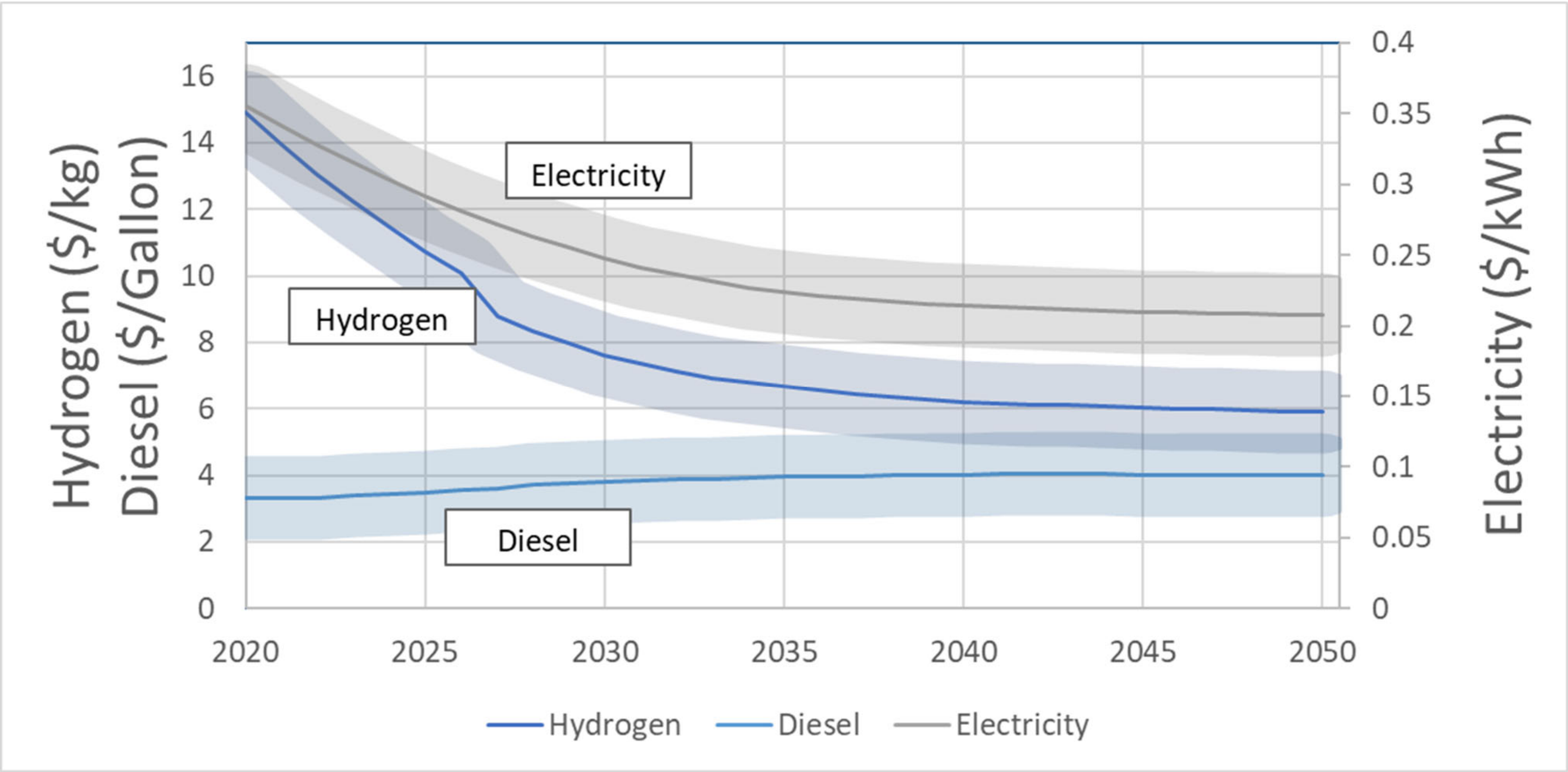


- **Battery electric:**
  - Highest efficiency, simple and robust design, commercially available today
  - Lowest energy to mass and volume density, slowest recharging/refueling times
- **Fuel cell (FC-Battery Hybrid)**
  - Higher efficiency that CHE, HDV, and harbor craft diesel powertrains, higher energy density than battery electric, components are commercially available today
  - Comparable efficiency to diesel for train and OGV applications
  - Lower energy density than diesel
- **Fuel Cell/Gas Turbine Hybrid (FC/GT-Battery Hybrid)**
  - Higher efficiency than diesel and fuel cell based powertrains considered in this work, fuel flexible (not considered in the current work)
  - Low technology readiness level – only stationary demonstration systems to date
  - Potential challenges with system durability in heavy duty applications

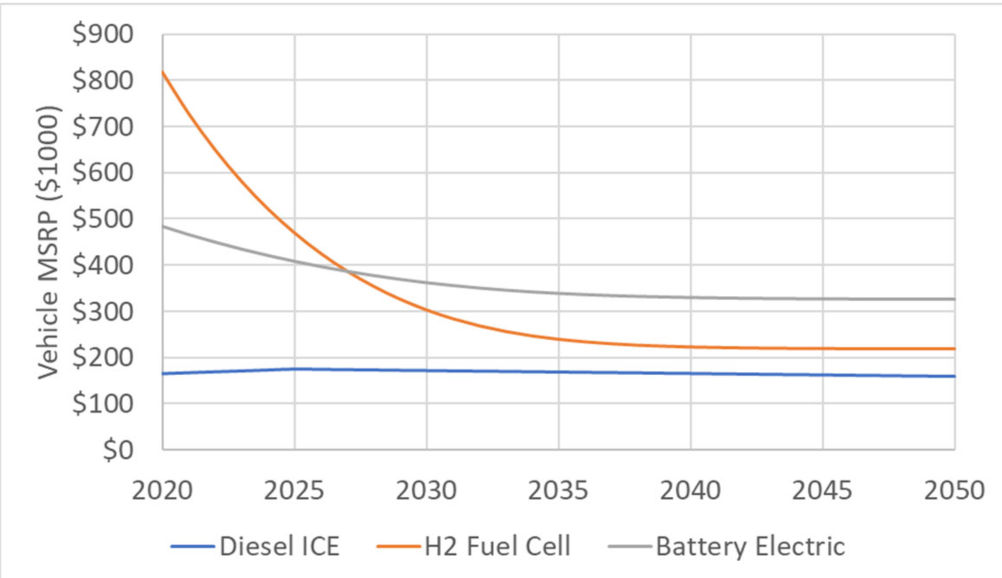
Technology Cost Progressions Used for Cost Comparisons

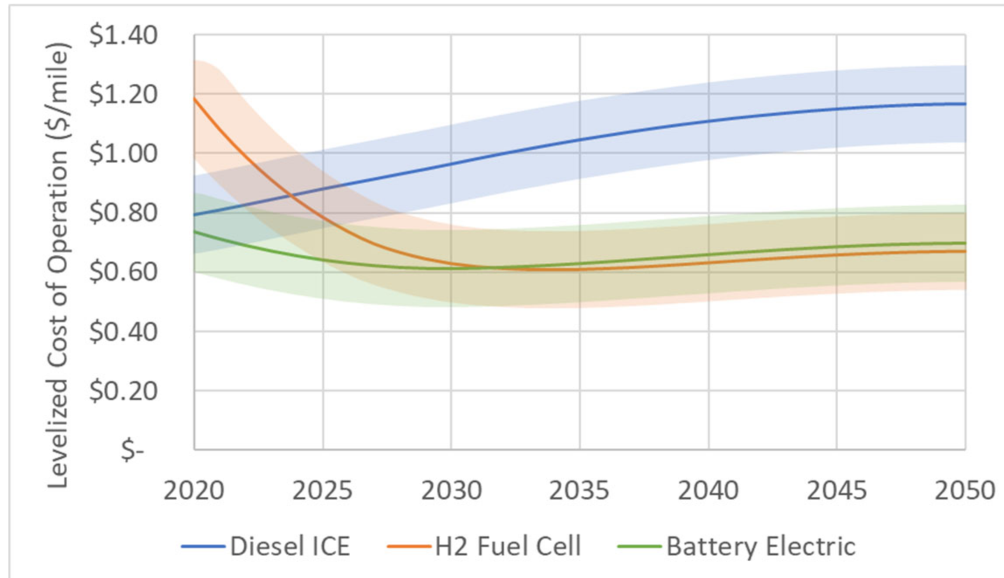


Fuel Cost Progressions Used for Cost Comparisons



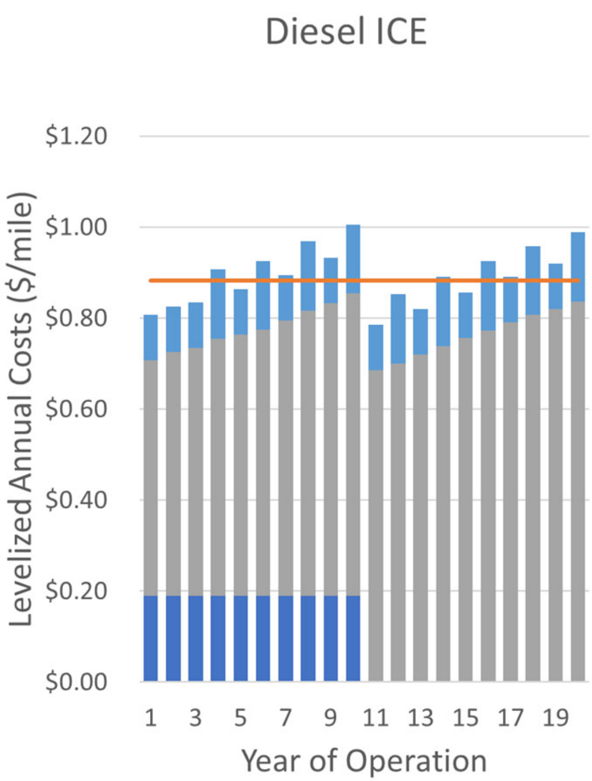
Long Haul HDV Comparative Economics with Complete MSRP

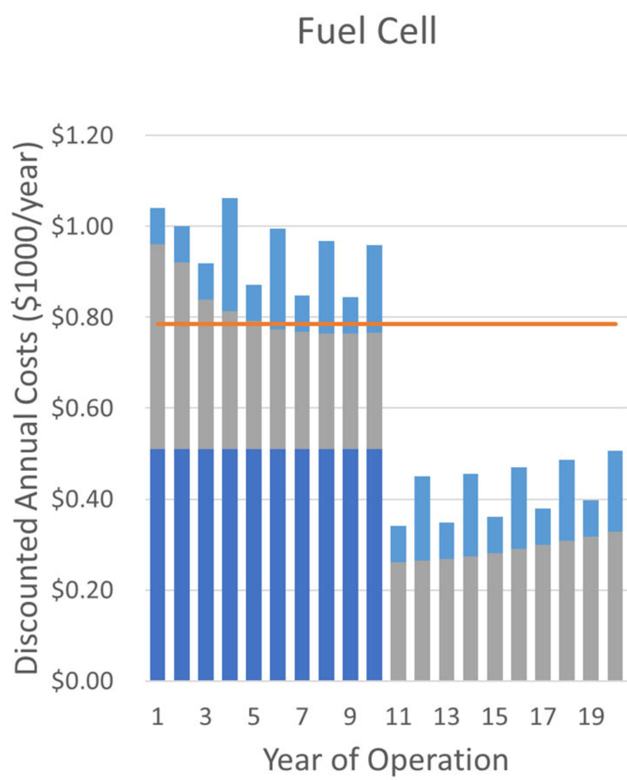


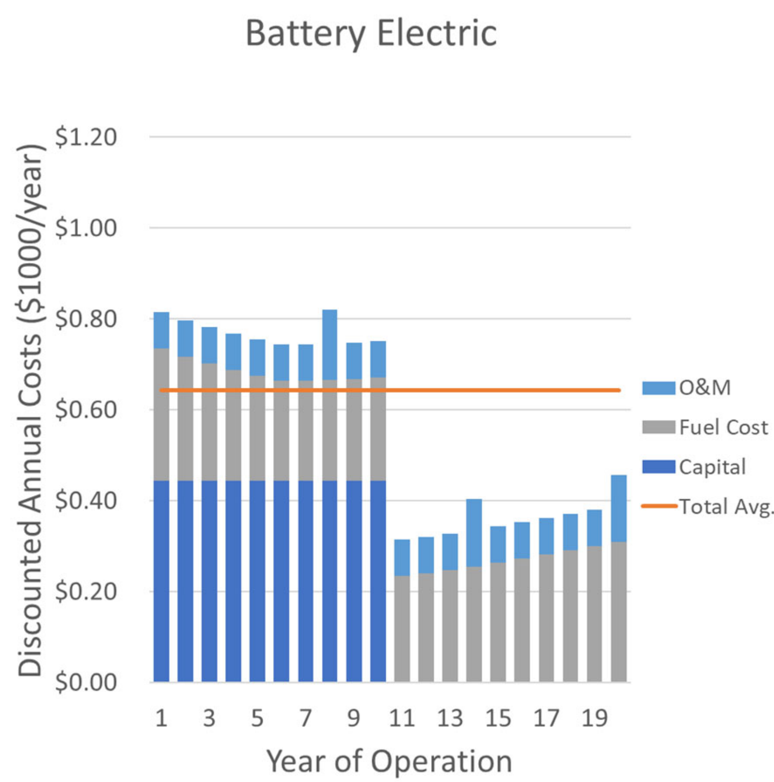


- Glider & other truck components: $150k
- Fuel cell & battery electric adoption premiums that disappear within 10 years
- $200 LCFS

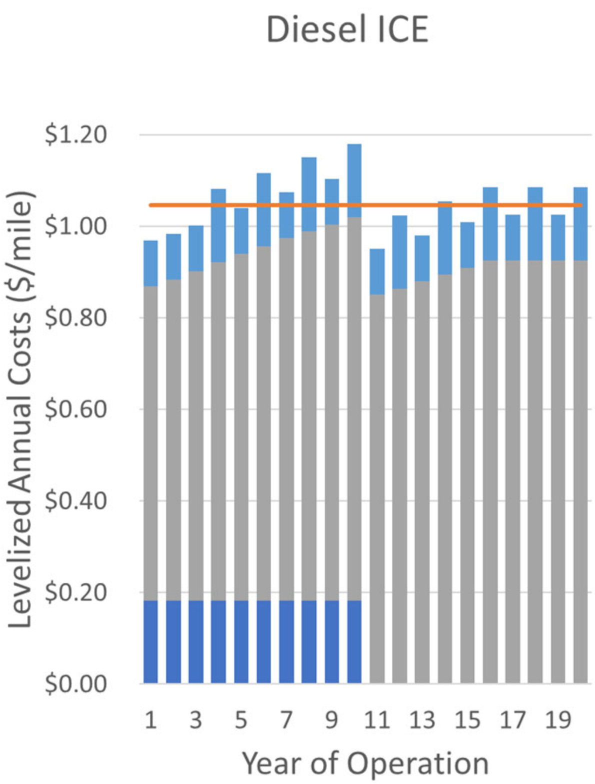
Levelized Cost of Operation - 2025

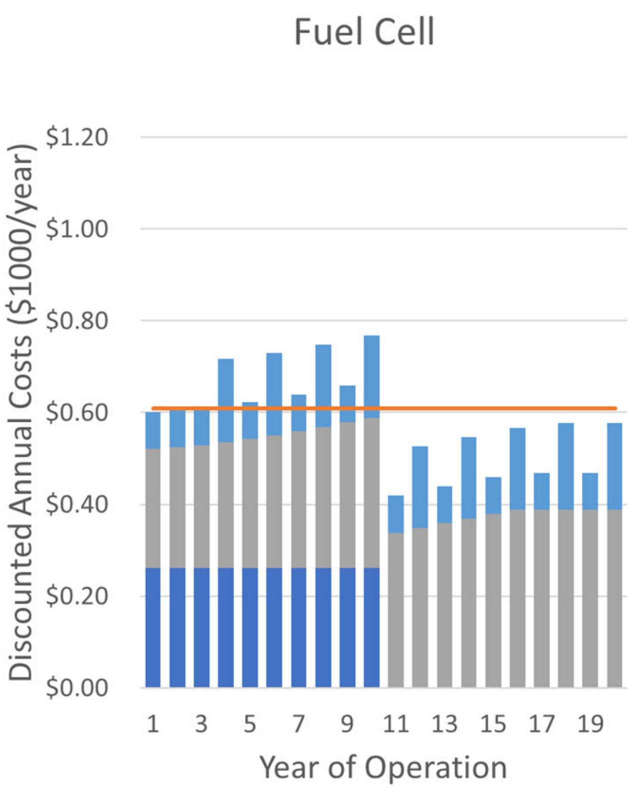


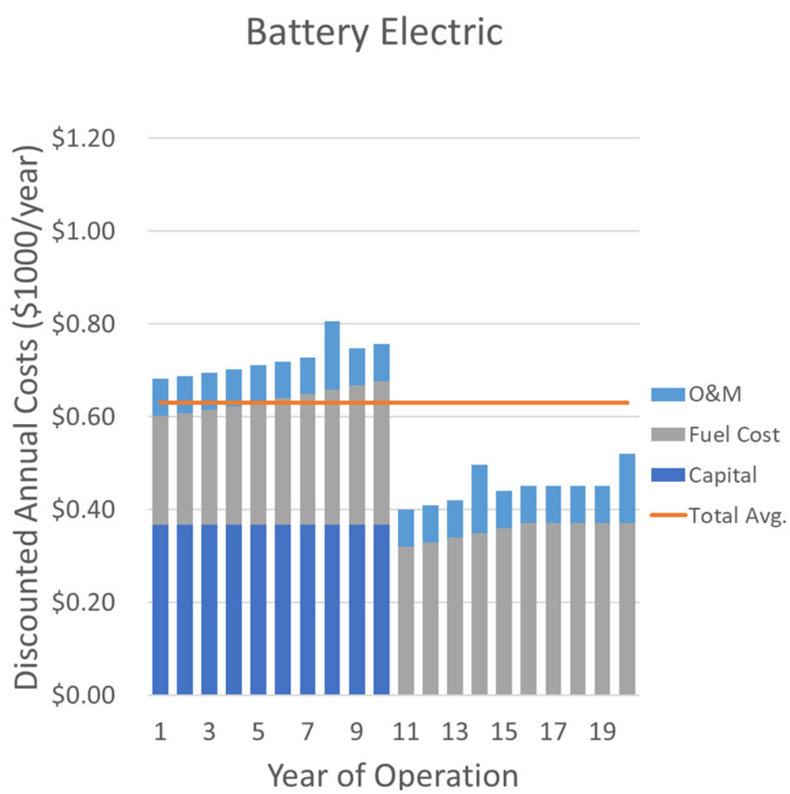




Levelized Cost of Operation – 2035



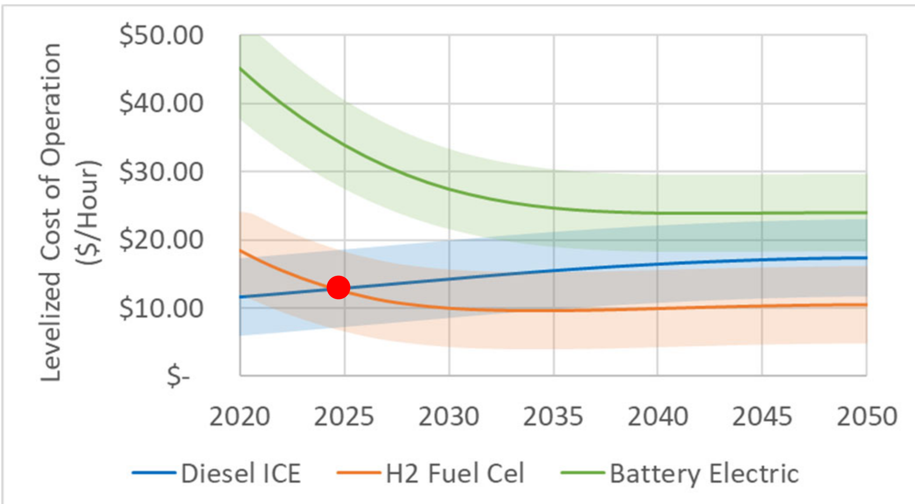




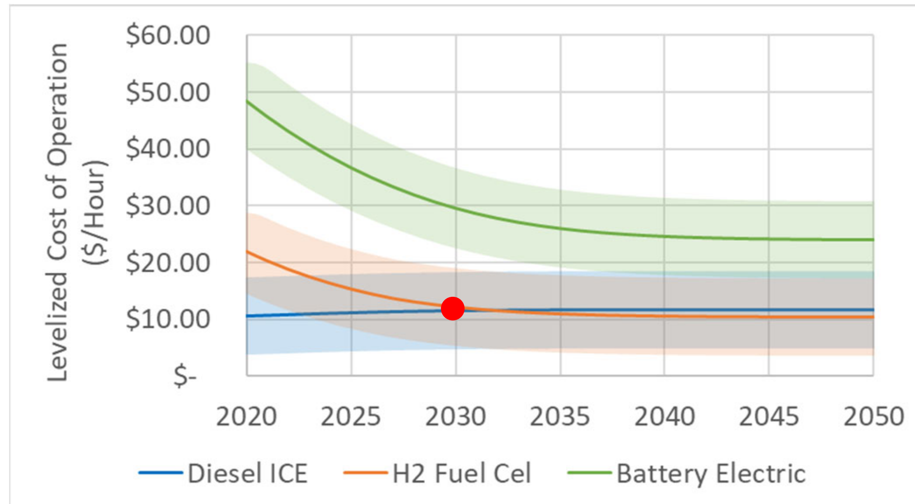
Analysis Example: Diesel Forklifts – ZEV Economics, Feasibility and Fit

See Appendix for complete set of results

With LCFS



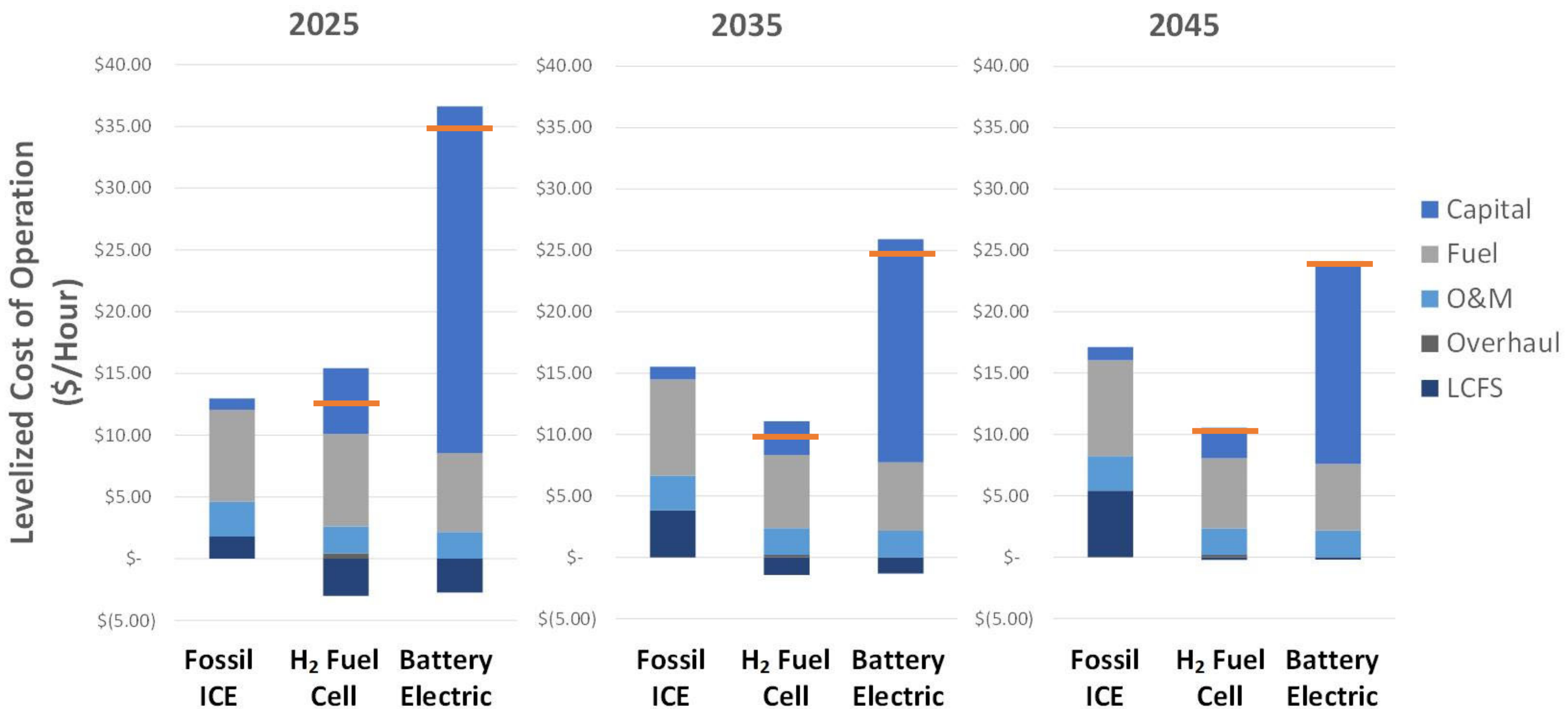
Without LCFS



- **Fuel cell drive economics project to be superior to battery drive and cost parity with diesel is projected by 2025**
- **On-board storage and packaging support hydrogen. Current battery electric require 3x larger mass and 2x volume to meet standard 2-shift.**
- **Battery electric charger requirements: 1-shift: 20 kW, 2-shift: 100 kW**
- **80% ultimate adoption of hydrogen expected with initial commercial deployment within 3 – 5 years**

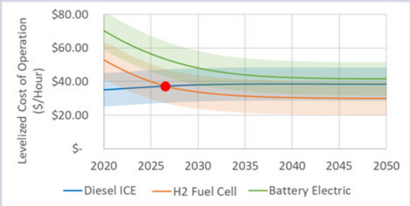
Analysis Example: Diesel Forklifts – Cost Components

See Appendix for complete set of results



Note: Red lines represent cost not of credits

Overview of Cost and Commercial Maturity Assessment

Application	Fuel Use DGE	Deployment Readiness	Feasibility	Economics 2035+
Forklifts 	0.4 MM	• Hydrogen at the demonstration phase • Electric drive demonstrated and commercial units available		Hydrogen least cost by ~20% 
Top Handler 	6.9 MM	Precommercial pilot at POLA Commercial product ~2025	• Battery weight and volume a significant constraint • Changes in operating profile or duplicate equipment required	Similar to forklifts
Yard Tractor 	10.4 MM	Full commercial pilots in late 2010s (POLB, PONY). Commercial product ~2025		Similar to forklifts

https://www.toyotaforklift.com/lifts/internal-combustion-forklifts-pneumatic-tire/mid-ic-pneumatic-forklift
https://www.toyotaforklift.com/resource-library/material-handling-solutions/products/toyota-heavy-duty-container-handler-solutions
https://pressroom.toyota.com/toyota-and-fenix-demonstrate-first-hydrogen-fuel-cell-electric-utr/

Applications Overview (2/5)

Application	Fuel Use DGE	Deployment Readiness	Feasibility	Economics 2035+
RTG Crane 	1.9 MM	Electric solution available Hydrogen FC at demo stage Commercial ~2026/27	Both platforms feasible Hydrogen has packaging and logistics advantage	Hydrogen least cost by ~20%
Drayage Truck 	5.9 MM	See line haul.	Both platforms feasible Hydrogen has superior fueling logistics	Electric least cost by ~10%
Line Haul Truck 	51.8 MM	Commercial products at the introduction stage and multiple manufacturers have announced product launches over the next few years.	Both platforms feasible Hydrogen has superior fueling logistics	Hydrogen and electric project equal cost

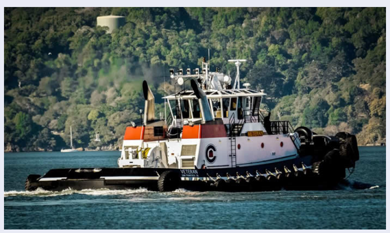
https://www.konecranes.com/en-us/equipment/container-handling-equipment/rubber-tired-gantry-cranes
https://www.caclimateinvestments.ca.gov/2018-profiles/2018/3/15/california-collaborative-advanced-technology-drayage-truck-demonstration-project
https://ocean-logistic.com/services/

Applications Overview (3/5)

Application	Fuel Use DGE	Deployment Readiness	Feasibility	Economics 2035+
Switcher Locomotive 		Commercial product available in the next five years.	Both drives feasible	Hydrogen least-cost by ~20%
Line Haul Locomotive 		Design phase – first deployment ~2030	Both drives feasible with tender but electric would require catenary or tender swapping	Hydrogen least-cost by ~20%
Ferry 		All-electric ferries available today, applications depend on speed.	Next page	Next page

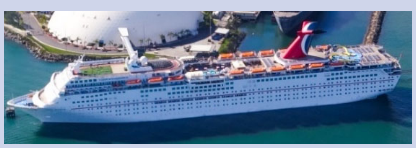
https://en.wikipedia.org/wiki/Tanker_%28ship%29#/media/File:Supertanker_AbQaiq.jpg
https://www.american-rails.com/switchers.html
https://www.ttnews.com/articles/union-pacific-posts-lower-net-income-revenue-q3

Applications Overview (4/5)

Application	Fuel Use DGE	Deployment Readiness	Feasibility	Economics 2035+
Assist Tugboat 	2 MM	Early demonstration phase for some harbor craft for both battery and diesel	Both drivetrains potentially feasible but hydrogen and derivates with fuel cell or combustion drive appear to the advantage	Hydrogen and derivatives Lower cost than fossil
Ocean Tugboat 	1.9 MM			
Commercial Fishing Boat 	0.8 MM			

https://www.bairdmaritime.com/work-boat-world/tug-and-salvage-world/harbour-tugs-and-operation/vessel-review-jamie-ann-tanker-escort-and-ship-assist-tug-for-los-angeles-long-beach-ports/
https://www.seafarers.org/crowley-to-deploy-veteran-in-port-of-long-beach-4/
https://www.mywestshore.com/wp-content/uploads/2018/03/Commercial-Fishing-Boat.jpeg

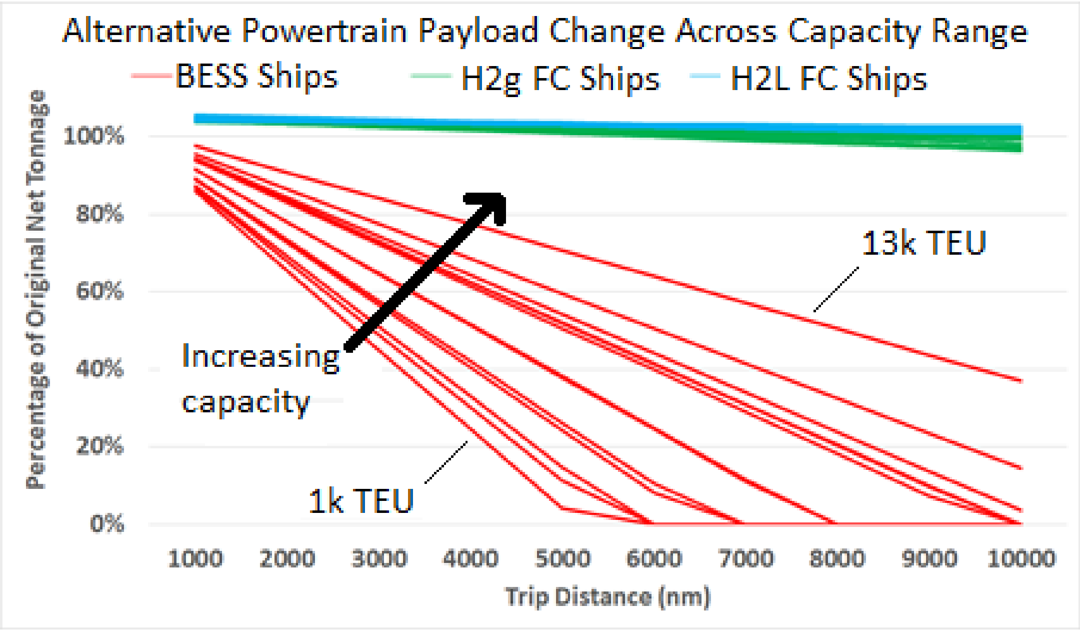
Applications Overview (5/5)

Application	Fuel Use DGE	Deployment Readiness	Feasibility	Economics 2035+
Tanker Ship 	11.2 MM	• Paper design phase • First in-service ships ~2030	Hydrogen and hydrogen derivative designs found to be feasible in principle Electric drive typically found to be infeasible during paper study phase.	Hydrogen and derivatives Lower cost than fossil
Container Ship 	19.5 MM			
Cruise Ship 	2.6 MM			

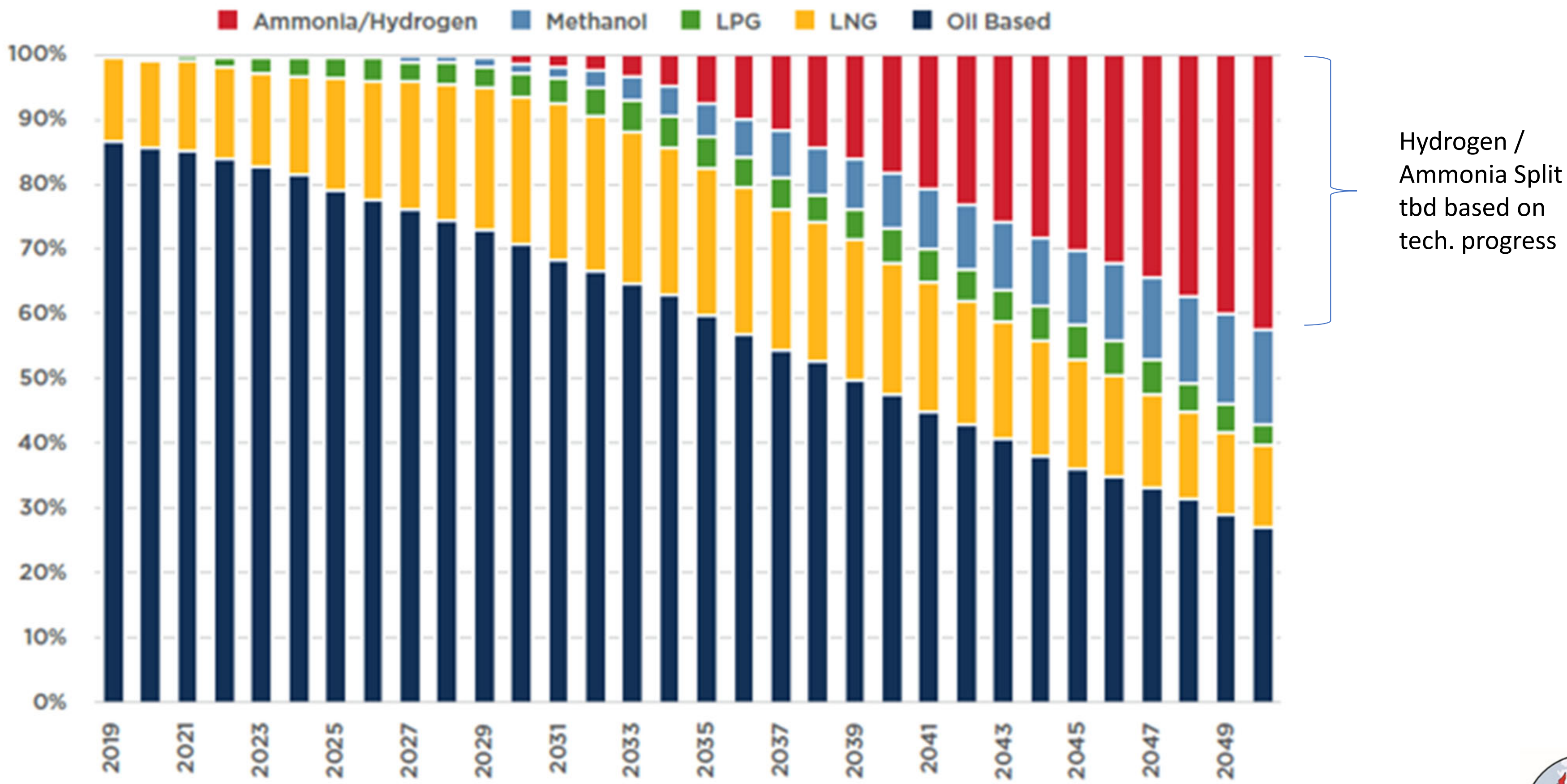
https://www.catalinaexpress.com/catalina-island.html
https://www.cbsnews.com/losangeles/news/record-backlog-at-ports-of-la-long-beach-hurting-small-businesses/
https://www.longbeachlocalnews.com/2017/04/17/carnival-cruise-line-city-long-beach-start-renovations-long-beach-cruise-terminal/

Battery Drive Displaces Dramatically More Cargo than RH2 or derivatives – effectively infeasible

- Batteries Compared to Hydrogen and Fuel Cells for Cont



American Bureau of Shipping Long-term Outlook for OGV Fuel – Over 50% Hydrogen Based



Source: American Bureau of Shipping's Zero Carbon Outlook, May 2022

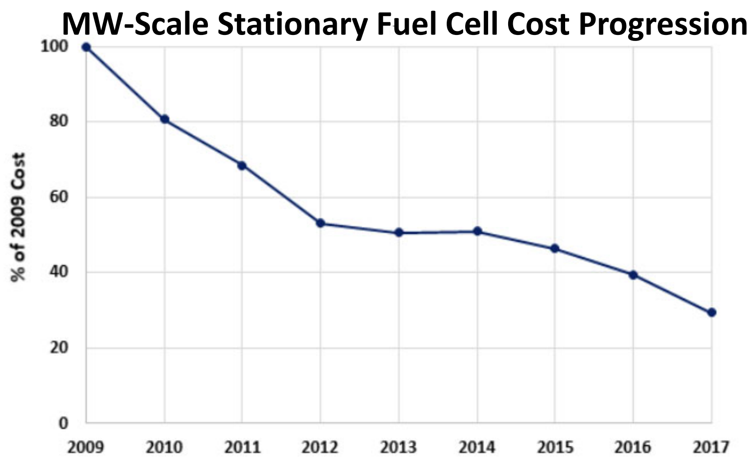
Hydrogen Fuel Cell Microgrid

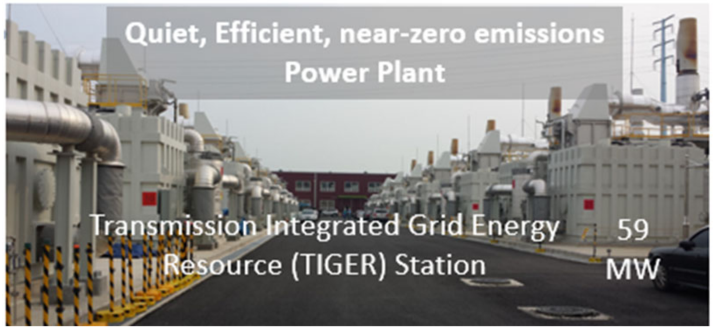
Potential Benefits of Hydrogen-fueled Microgrid at the San Pedro Bay Ports

- **Protect critical port infrastructure from power loss**
- **Sustain port operations during grid outages**
- **Facilitate integration of renewable energy and distributed generation**
- **Better manage resources resulting in higher efficiency and lower costs**
- **Avoid costly investments in electric gird infrastructure**
- **Provide services to the grid as well as adjacent critical facilities in case of an emergency or unforeseen occurrence**

Commercial Readiness of Fuel Cell Technology for Microgrids

- Fuel Cell technology is mature and commercially available for operation on natural gas
  - Alkaline and PEM systems have significant installed base on order of 1 GW globally U.S. EPA
  - Solid oxide fuel cells are commercial but are newer to the market
- Fuel cells have reached 1 GW in global annual sales and installations are projected to grow at over 23% annually over the next decade[1]
- Fuel cells designed for pure hydrogen are now commercially available at the market-entry stage
- Fuel cells exhibit a learning rate similar to other electrochemical technologies estimated to show an 18% cost improvement for each doubling of global capacity – translates to 45% reduction per decade at 23% growth rate



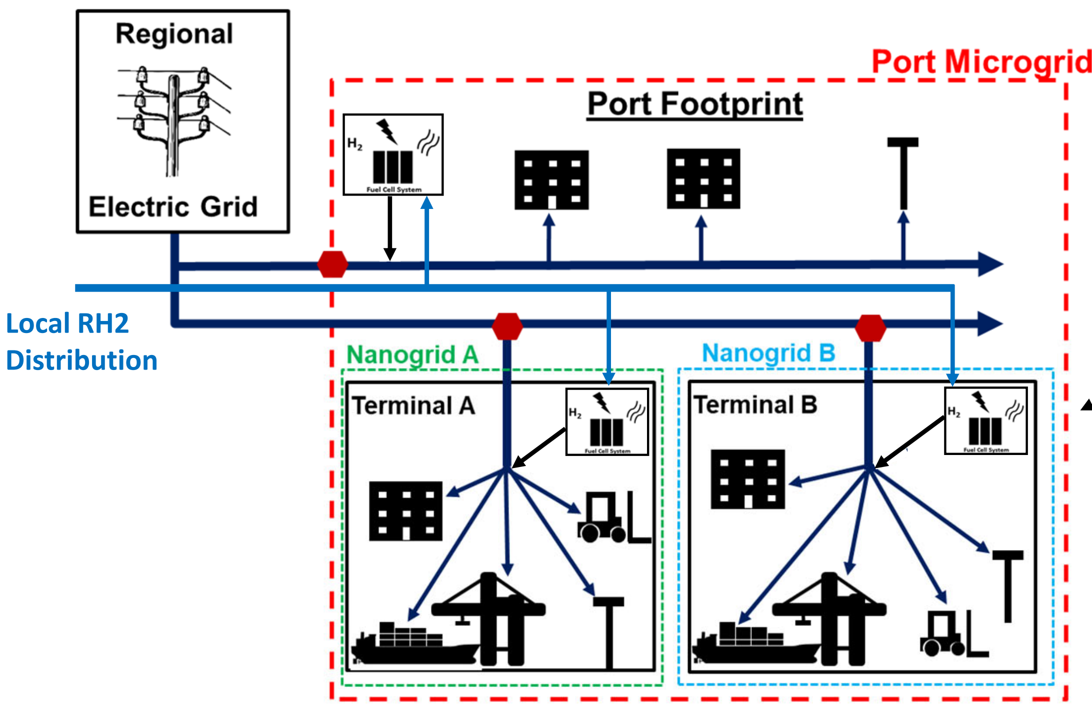


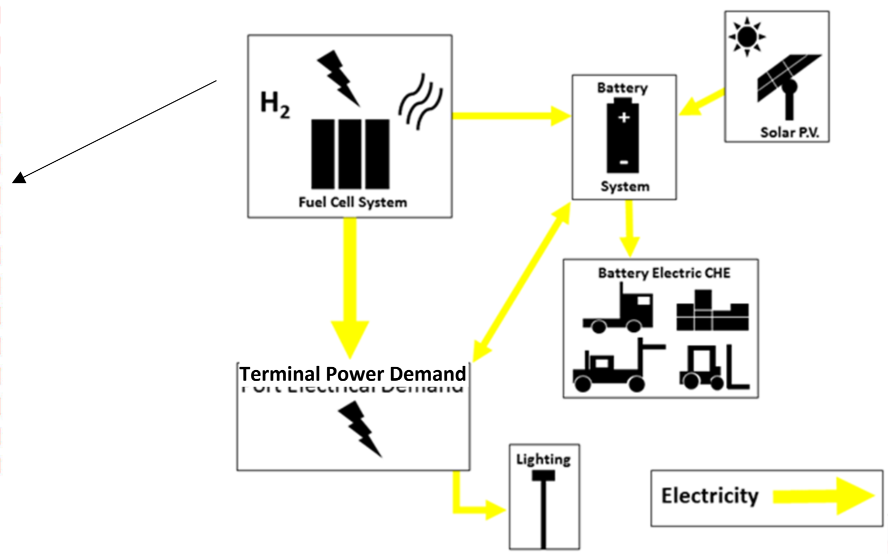
1 Power Engineering International 2019, Grand View Research 2020

Potential for Resilient, Cost-effective Firm Power Generation

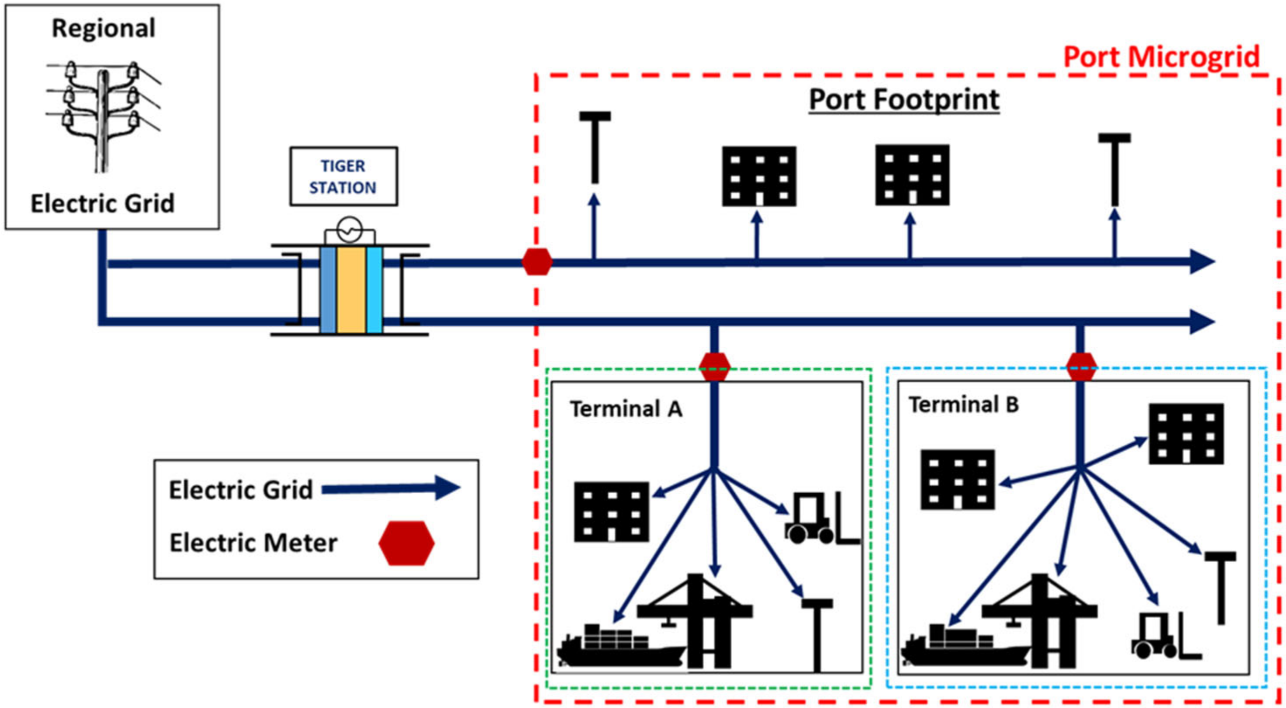
Port Microgrid (Nested Nano-grid Concept

- On-site production and use of power
- Interconnected to macrogrid at one or more points
- Fuel cells and renewable fuel to achieve zero-emissions performance





A dedicated fuel cell power system or systems at the substations serving the ports would provide firm renewable generation and improve resilience



- Base concept: Edison-owned system serving the ports through existing meters
- Cost of firm renewable power ~$0.12/kwh
- Potential to provide power during grid outages by isolating the circuits serving the ports
- Avoided investment in substation upgrades improves the business case (non-wires solution)
- Could deploy for initial operation on natura gas or reformed natural gas and transition to green H2 delivered via pipe by ~2030

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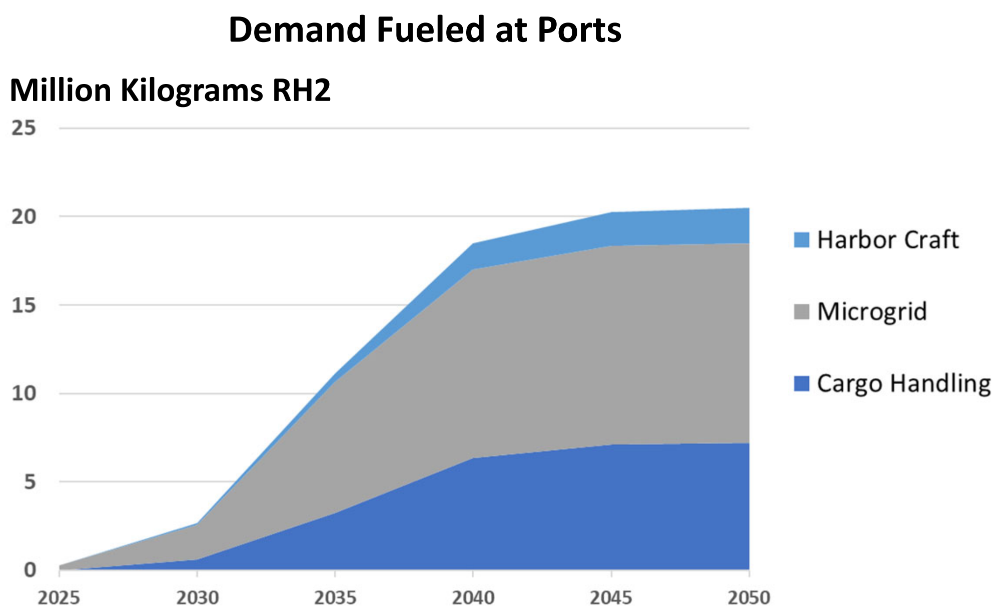
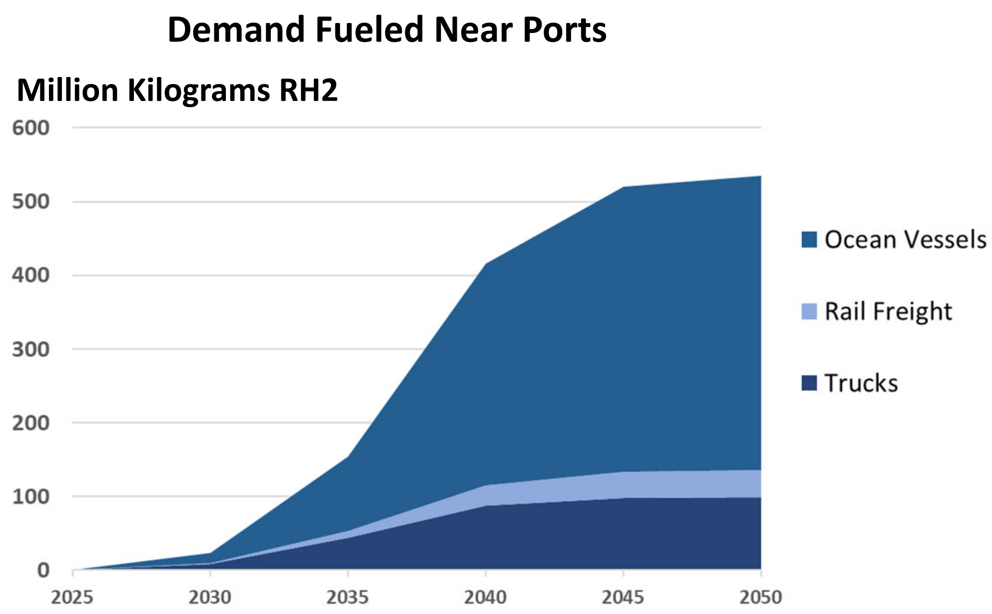
Demand Evolution

- **Land freight and ocean vessels have 20x the demand potential for port operations and harbor craft**
- **Adoption of for port operations can begin shortly after 2025 with other applications launching around 2030**





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- High-level Roadmap for Hydrogen Deployment at the Ports

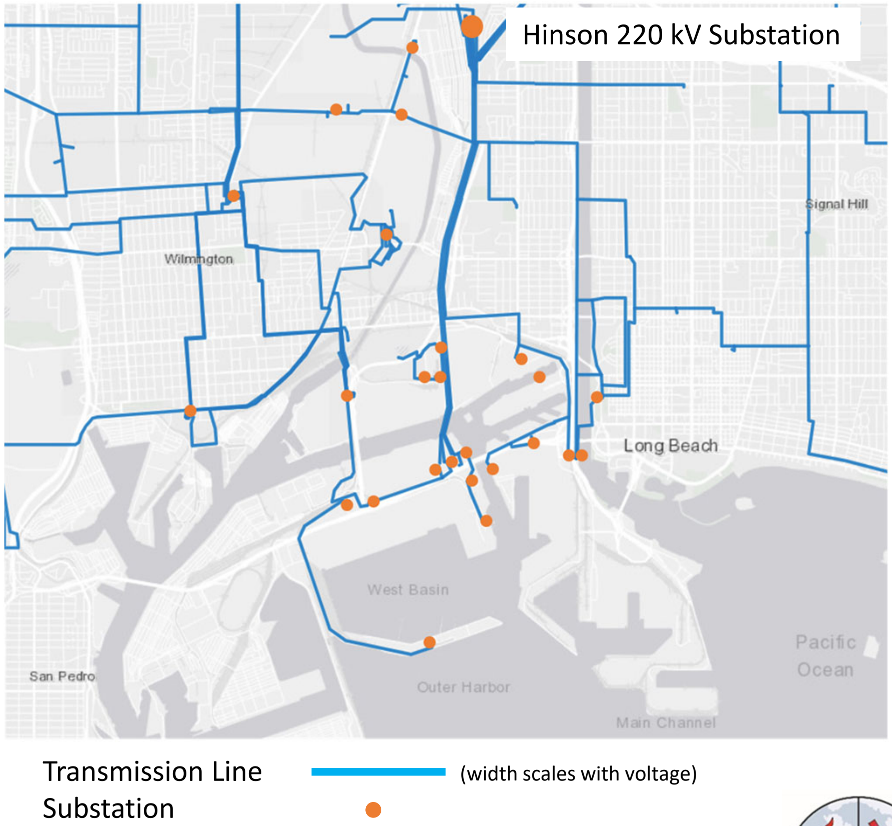
Significant infrastructure will need to be added to support the ports' transition to zero emissions

- **A recent study for the Port of Long Beach projects that peak electric demand would grow by up to twelve-fold under a full electrification scenario requiring upgrades to the 66 kV transmission system serving the port and the addition of a new substation**
- **Hydrogen would offset this increase but the amount of hydrogen required to play a significant role in port decarbonization would require a dedicated hydrogen pipeline**
    - **The proposed Angeles Link would provide low-cost transport in the 2030 time frame**
- **In addition, fueling infrastructure in the form of electric charging facilities and hydrogen fueling facilities will need to be added**
- **Hydrogen offers the potential for fueling operations similar to the current diesel fueling operations via mobile fuelers**
- **A hydrogen fuel cell microgrid would improve resilience and reduce the need for new electric transmission infrastructure**

ENGIE Impact

Electrical Infrastructure Requirements

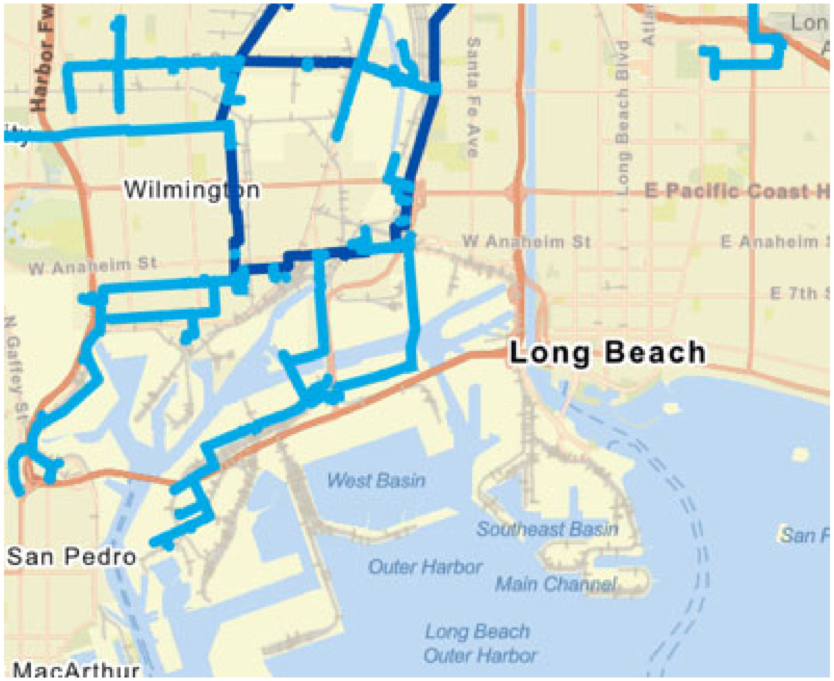
- Ports are served by 66 kV transmission stepping down to 12 kV
- Edison assesses the system as capable of absorbing a potential 4x increase in power flow
- ENGIE estimates that full electrification would lead to a 9x to 12x increase in peak load and require upgrade of the Hinson substation within a few years at cost of $150M
- Installing fast charging infrastructure to serve a peak load of 500 MW would cost on the order of $200 MM (at $400/kw)
- Installing a networked microgrid would improve resilience and reduce the need for grid infrastructure upgrades
- Hydrogen adoption will also decrease the upgrade requirements for the local electric grid
- A more complete analysis of electric system upgrade/expansion requirements, timing and cost is needed to better understand the optimal mix of direct electric and fuel-cell electric power at the ports



Hydrogen Infrastructure Requirements

- **Adoption of hydrogen at the ports will require the addition of local storage, receiving / transfill infrastructure and fuel-dispensing infrastructure and equipment to replace the current diesel systems**
- **Initially, hydrogen will need to be delivered to the port by truck in the form of compressed gas or cryogenic liquid**
- **A hydrogen pipeline delivering renewable hydrogen to the port area in the 2030 timeframe is envisioned as part of a regional hydrogen hub**
- **A local hydrogen pipeline network at the ports may be cost-effective given the level of demand**
- **Transition from methane to hydrogen requires detailed planning (as has been undertaken in the UK)**

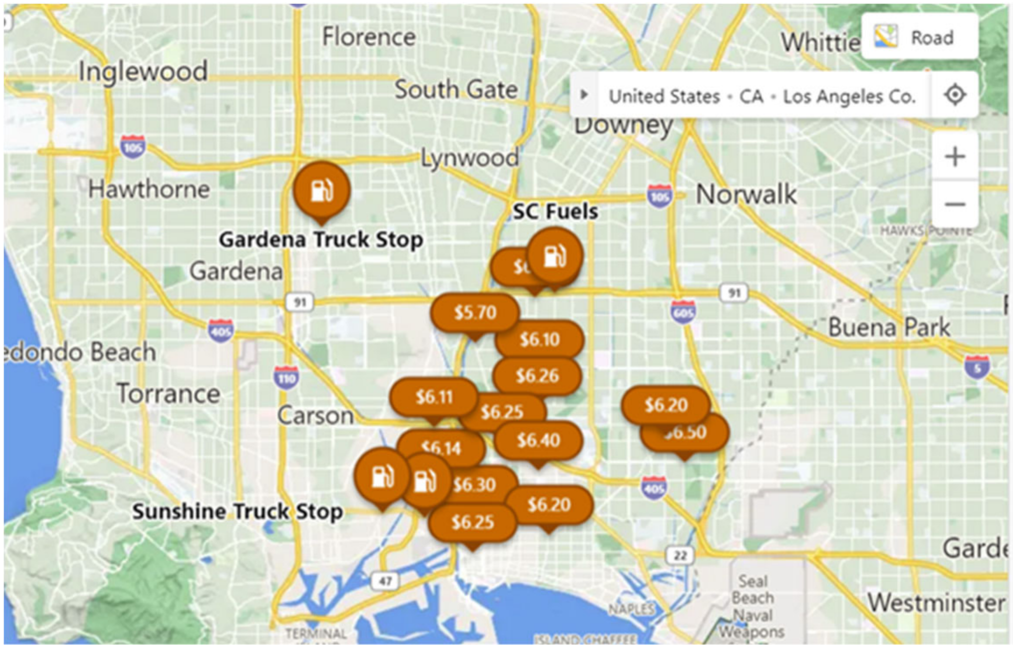
Natural Gas Infrastructure at Ports



On-road Truck Fueling Infrastructure

- **There are 16 truck fueling locations in the vicinity of the San Pedro Bay ports**
- **Locomotives fuel at the Dolores Locomotive facility**
- **We assume that the necessary infrastructure will be developed via the California Energy Commission hydrogen refueling program**
- **The CEC is currently funding blueprints toward this objective**
- **The California Air Resources Board is ensuring readiness of heavy-duty fuel cell vehicle refueling standards**
- **Need to assess what fueling infrastructure is needed / desirable on the property of the Ports**

Current Truck Fueling Locations



A regional hydrogen pipeline network would greatly improve the economics of hydrogen use at the ports

- **Pipeline Transport ~ $0.30/kg versus $2+/kg for trucking**
- **SoCalGas Angeles Link proposal would bring pipeline transport to the ports area around 2030**

Presentation Outline

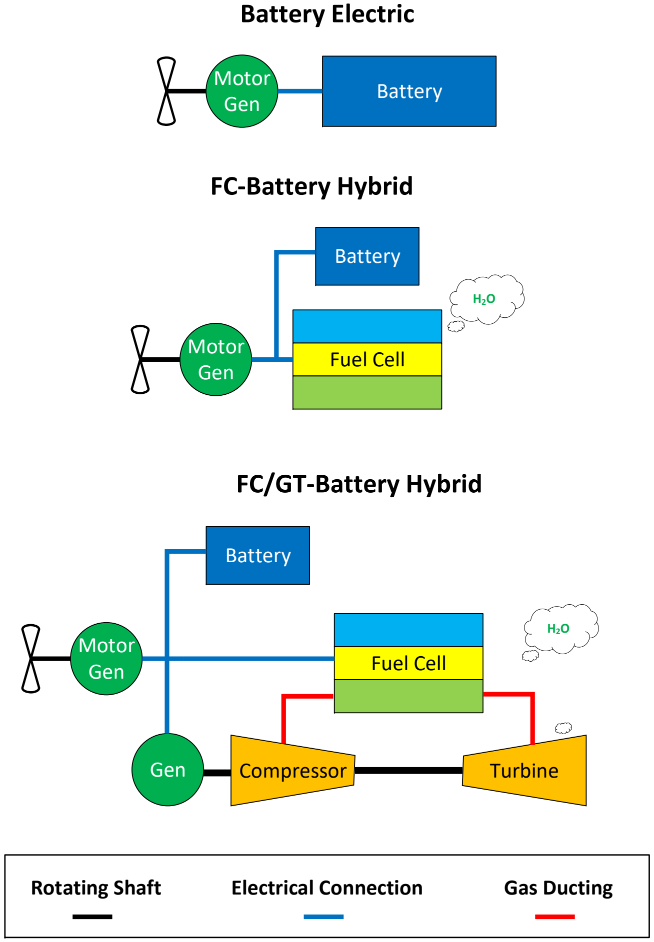
- Objectives, Approach and Principal Conclusions
- Policy Drivers, Emissions Target and Applications in Scope
- Comparative Drive Train / Prime-mover Feasibility and Costs
- Potential Demand for Hydrogen and Electricity at the Ports
- Infrastructure Considerations
- **Emissions Reductions from Hydrogen Adoption**
- High-level Roadmap for Hydrogen Deployment at the Ports

Emissions Analysis Comments

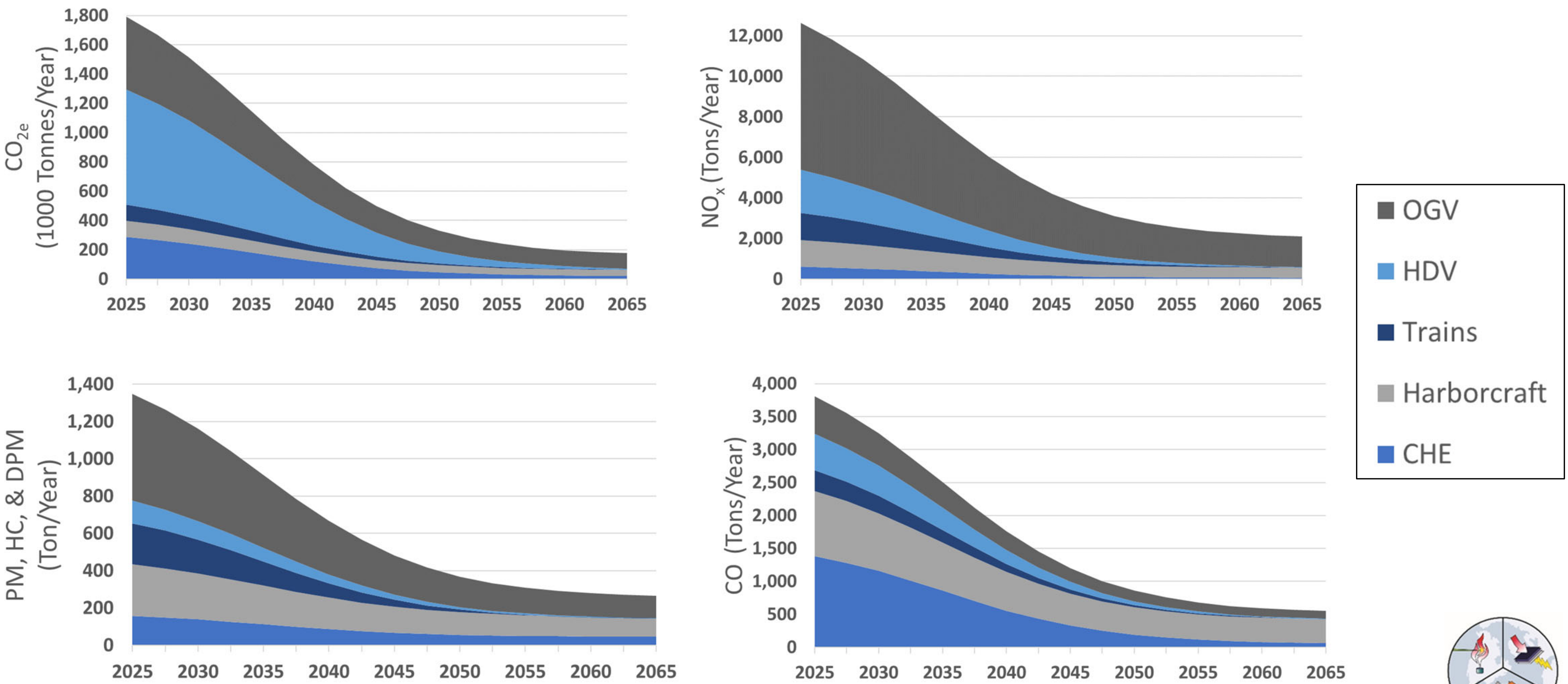
- The timing of product availability makes attainment of the 40% - 50% GHG reduction targets in 2030 challenging with a typical adoption cycle (initial assessment is ~25% - 30% for CHE and trucks)
- Hub funding may allow accelerated transition of CHE and trucks
- CHE and trucking will be fuel-cell drive therefore 100% reduction achieved for all criteria emissions
- Vessels and locomotives may use combustion of hydrogen or derivatives in hybrid drive systems – these will need to be compliant using combustion system design and after treatment

Pollutant Emissions Characteristics of Powertrains

- Local air quality is affected by PM, DPM, & HC emissions. Regional air quality is affected by NO_x
- Most pollutant emissions are driven by combustion of liquid/diesel fuels (CO increases in smaller engines)
- Switch to gaseous fuel virtually eliminates PM, DPM, and HC emissions
- Fuel cell and battery electric systems eliminate all pollutant emissions
- FC/GT-Battery Hybrid have no PM, DPM, or HC emissions
- FC/GT-Battery NO_x and CO are 90% lower than SCAQMD stationary generation limits, > 90% lower than Tier 4 diesel engine limits

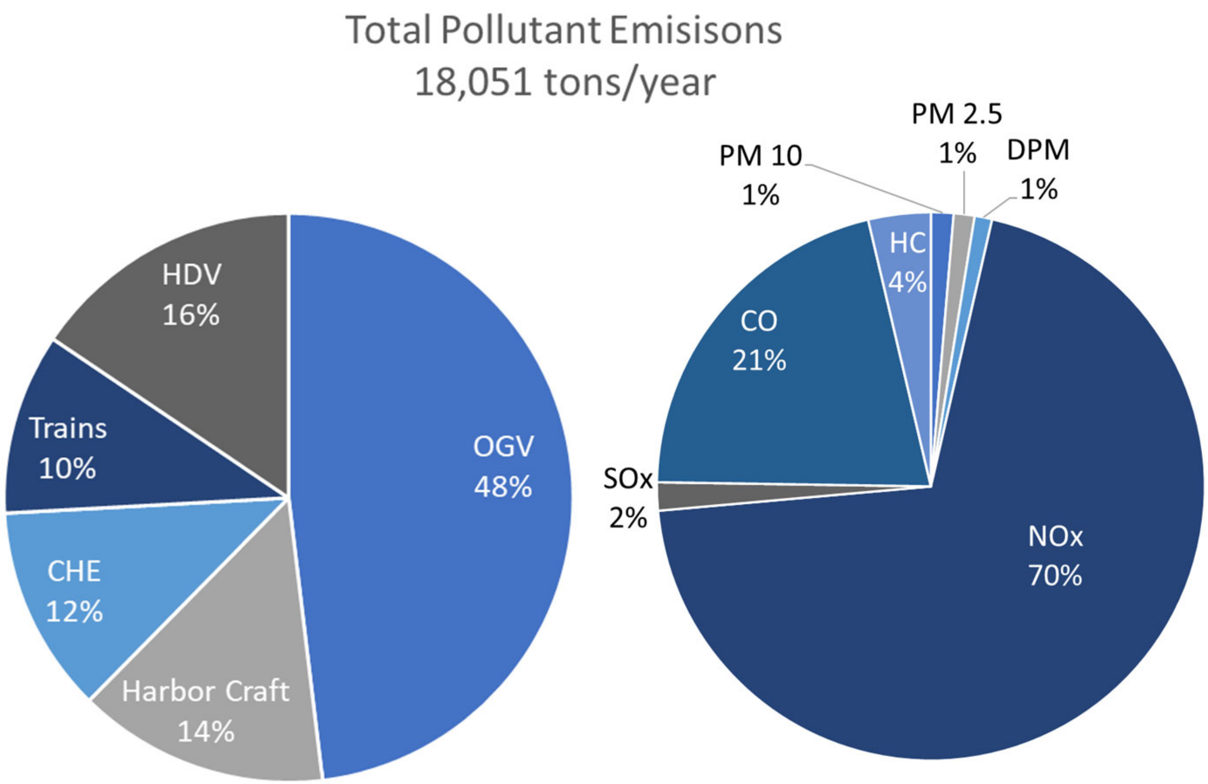


Emission Reductions within Ports Reporting Scope



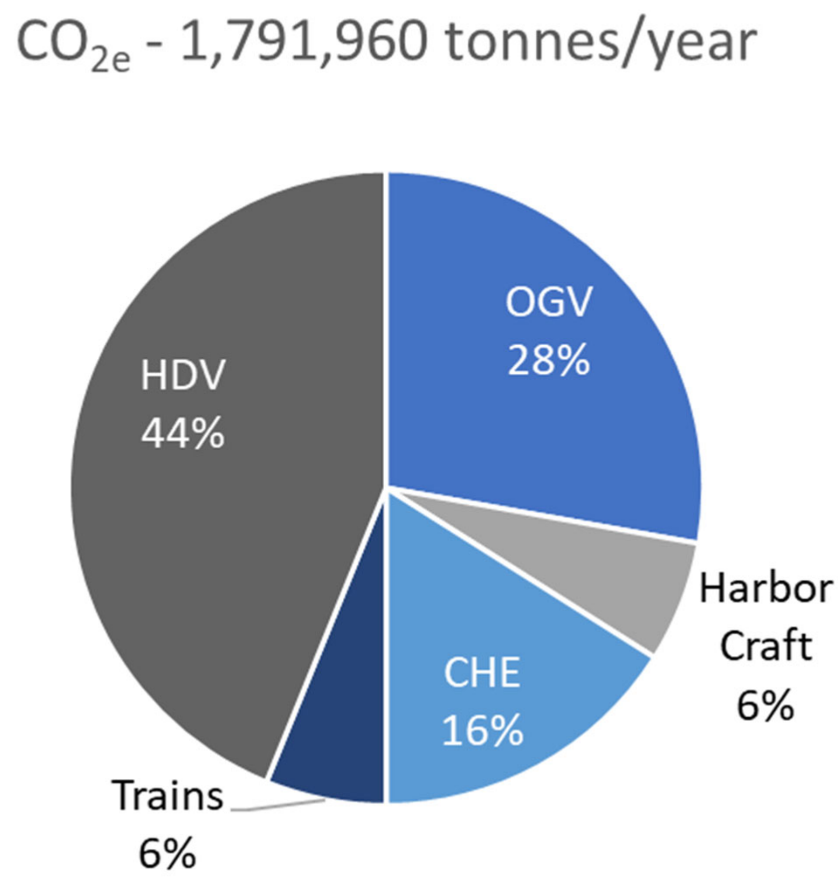
Pollutant Emission Reductions at the Ports

- Reductions depend on replaced engine emissions tier
- Electrification of OGVs reduce:
  - SO_x: 95%
  - NO_x: 57%
  - $PM_{2.5}$ & PM_{10} : > 50%
  - Diesel PM & HC: 40%
- Harbor craft & Trains:
  - Diesel PM: ~25% each
  - $PM_{2.5}$ & PM_{10} : ~20% each
  - CO: 26% & 10% respectively
  - NO_x: 10% each
- HDV: 17% NO_x, 15% CO, 13% HC
- CHE: 36% CO, ~4% all else



GHG Emissions at the Ports

- Reductions directly correlated to total activity
- 2030 GHG emission reductions:
  - 73% OGV emissions – hoteling loads
  - 51% OGV emissions – hoteling at berth
  - Not achievable without HDV
  - 44% reduction achievable w/ cold ironing vessels at birth, replace all CHE, & replace 1/3 HDV
- Reductions don't capture "out of scope" pollutant and GHG emissions



“Out of Scope” Pollutant and GHG emissions

- Acceleration of ZE drivetrains creates benefits outside or regulated ports areas
- OGV GHG emissions:
  - In port: 0.5 million tonnes/year
  - In transit: 9.5 million tonnes/year

HDV Vehicles Annual Emissions				
Emissions Type	Units	Port Activities	SCAQMD Control Area[1]	CA State[1]
PM & DPM	Ton per Year	36	817	3,450
NO_x	Ton per Year	2,127	11,921	50,374
SO_x	Ton per Year	8	60	254
CO	Ton per Year	553	4,473	18,899
HC	Ton per Year	85	666	2,813
CO_{2e}	Tonne per year	785,669	6,913,895	29,214,845

Freight Rail Annual Emissions				
Emissions Type	Units	Port Activities	Rail from Southern CA[2]	CA State[1]
PM & DPM	Ton per Year	144	565	869
NO_x	Ton per Year	1,322	5,187	7,980
CO	Ton per Year	316	1,239	1,907
HC	Ton per Year	76	298	458
CO_{2e}	Tonne per year	110,440	433,368	666,720

[1]: https://arb.ca.gov/emfac/emissions-inventory
[2]: Values scaled using VMT from: https://ww2.arb.ca.gov/sites/default/files/2020-06/final_rail_tech_assessment_11282016%20-%20ADA%2020200117.pdf

Presentation Outline

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- Emissions Reductions from Hydrogen Adoption
- High-level Roadmap for Hydrogen Deployment at the Ports

High-level timeline for hydrogen at the Ports

3 – 6 Months

- Develop concept for DOE hub application
- Join application for hub planning grant
- Define commercial validation plans (demonstrations / technical exchange)
- Develop engagement plan for port operators, labor and impacted communities
- Assess regulatory barriers and develop plans to address
- Develop international collaboration strategy (sister Ports)

7 – 24 Months

- Develop detailed hydrogen blueprint including:
  - ➢ Refined adoption forecasts and develop hydrogen sourcing plan
  - ➢ Fueling logistics and infrastructure evolution
  - ➢ Cost estimates and funding sources
  - ➢ Workforce requirements and plan
  - ➢ Community engagement plan
- Develop refined electric demand analysis and microgrid concept
- Define objectives, funding sources and hosting for demonstrations necessary to validate commercial readiness
- Participate in development of full Hydrogen Hub application

2025 - 2030

- Secure hydrogen supply contracts
- Complete pilots and begin deployment of ZEV trucks and cargo-handling equipment
- Initiate microgrid development and T&D system upgrades
- Deploy initial fueling infrastructure (e.g., mobile fueling operation)
- Plan for adaptation of fueling and supply logistics in context of pipeline delivery
- Conduct pilots for vessels and locomotives
- Carry out workforce development and community engagement

Beyond 2030

- Begin deployment of hydrogen and derivatives for vessels and rail
- Complete microgrid development and achieve 100% hydrogen operation
- Connect port operations to hydrogen pipeline network
- Develop in-port hydrogen distribution network (evaluate conversion of gas distribution to H2
- Institutionalize workforce and community engagement processes
- Track and report progress toward zero-emissions

Next Steps

- **Engage port leadership, operators, labor and equipment manufacturers to communicate findings**

- **Develop a workplan for creating a detailed roadmap in the context of the Hydrogen Hub solicitation (applications due in April)**

#RH2@APEP

RENEWABLE HYDROGEN

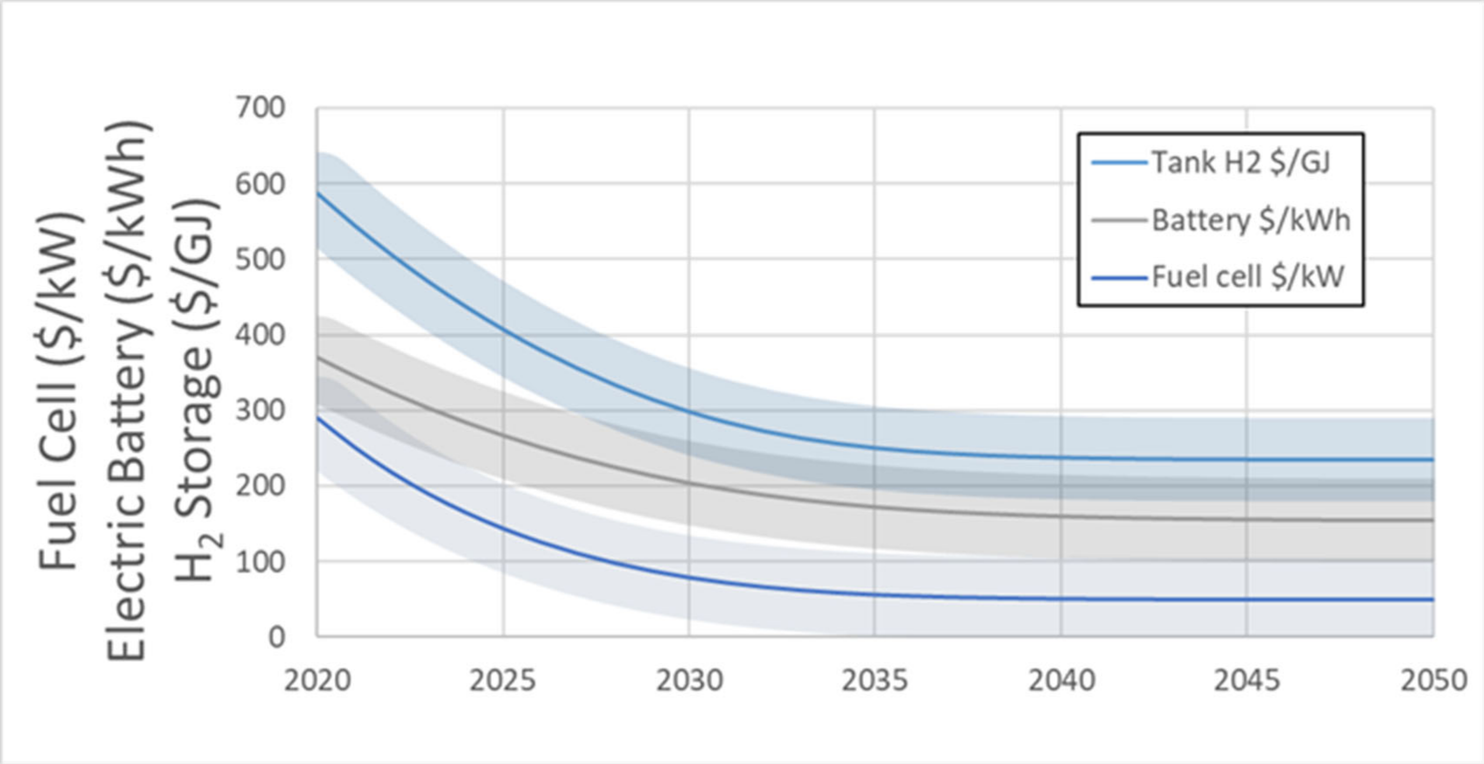
UCI ADVANCED POWER AND ENERGY PROGRAM

ADVANCED POWER & ENERGY PROGRAM

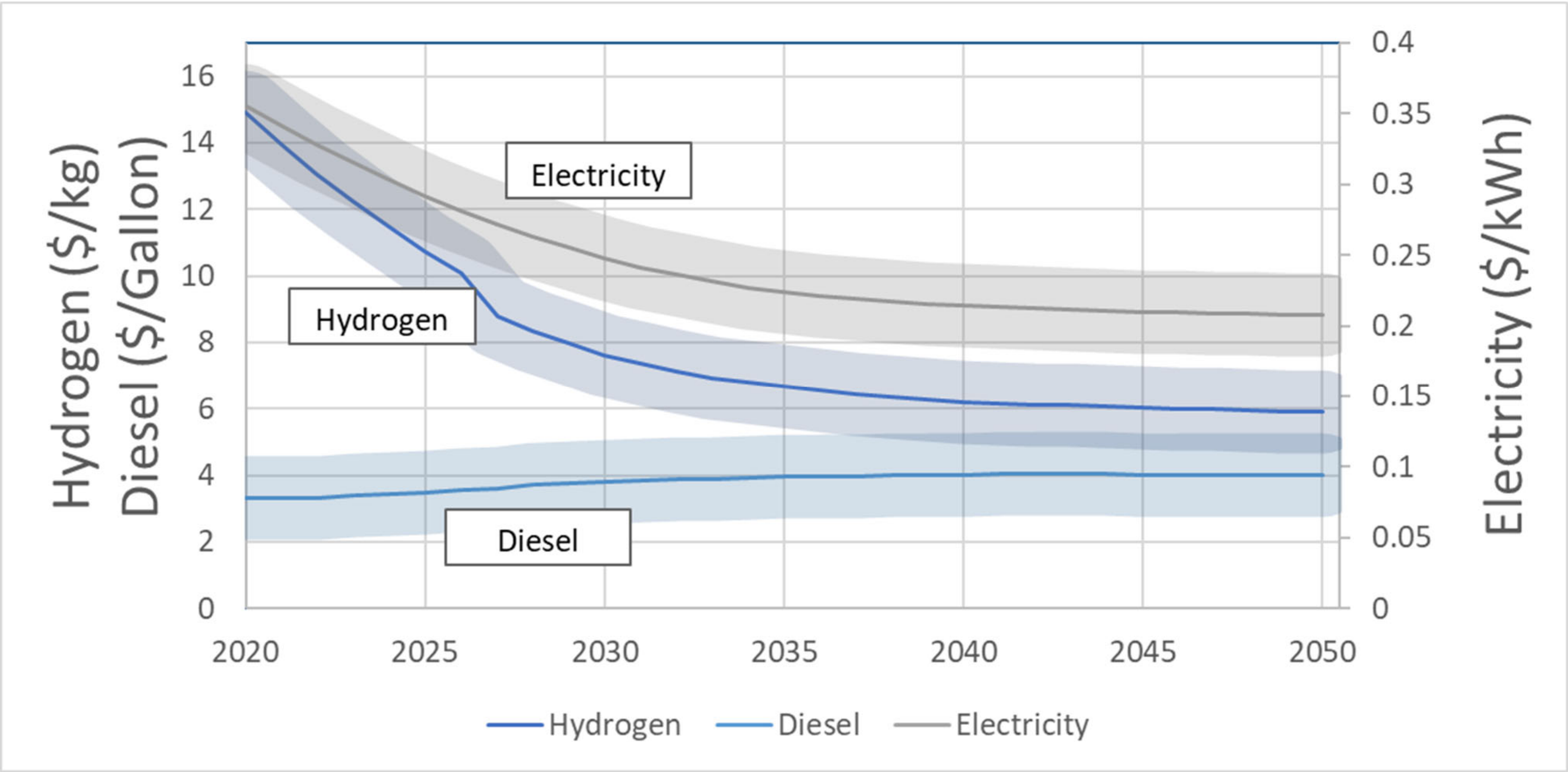
UNIVERSITY of CALIFORNIA • IRVINE

Appendix A:
Techno-economic Analysis Results

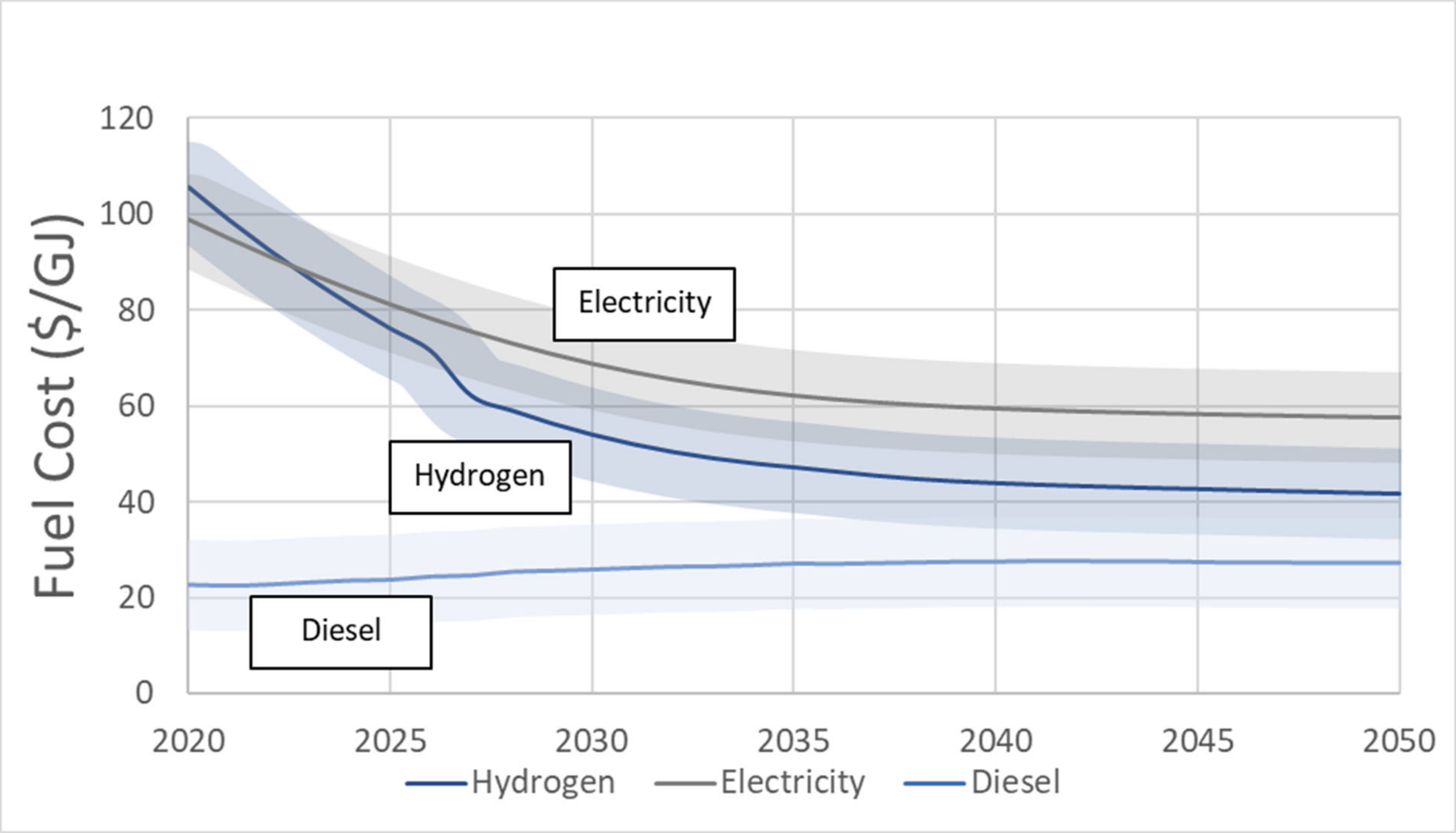
Technology Cost Progressions Used for Cost Comparisons



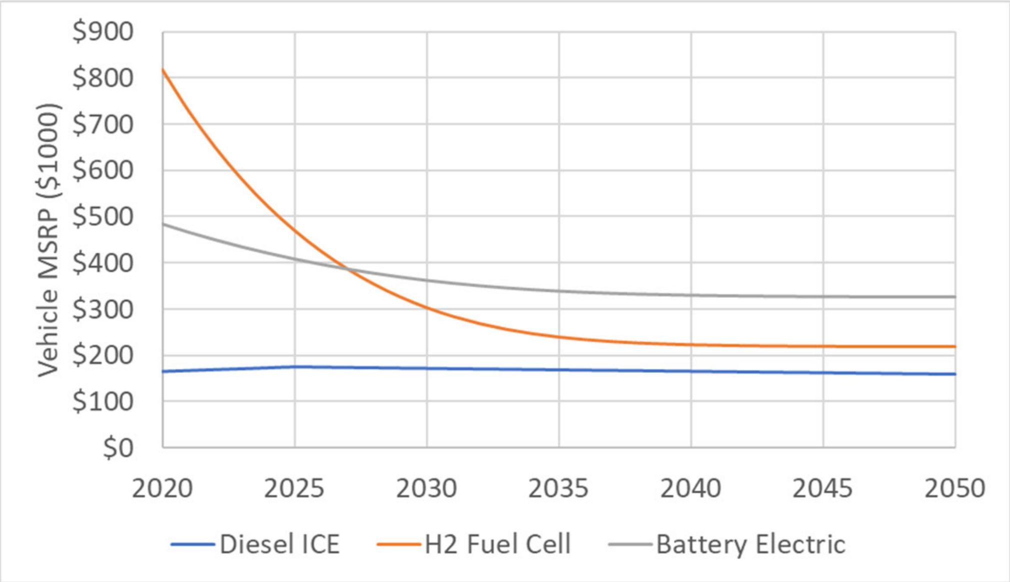
Fuel Cost Progressions Used for Cost Comparisons

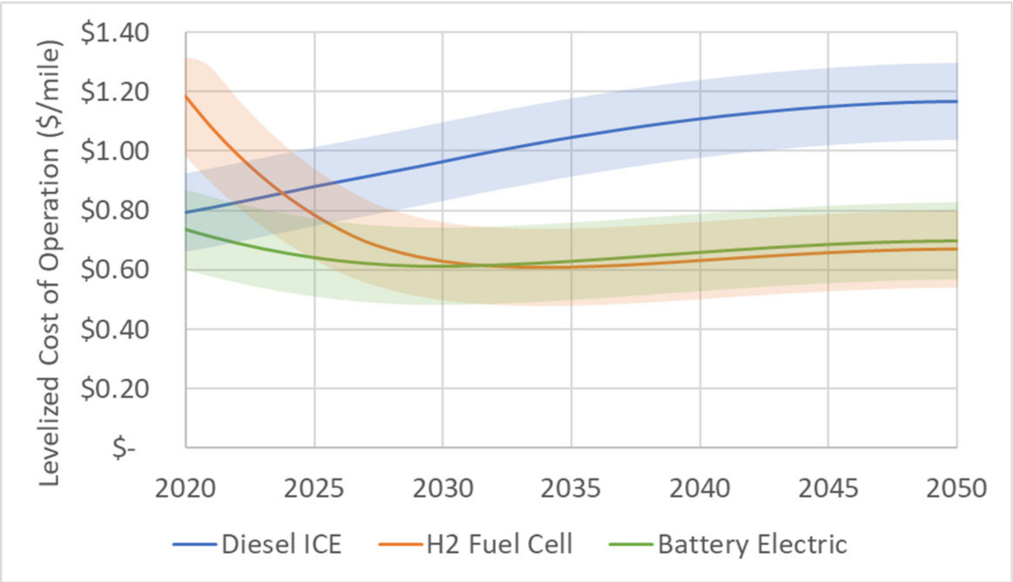


Fuel Cost Progressions Used for Cost Comparisons



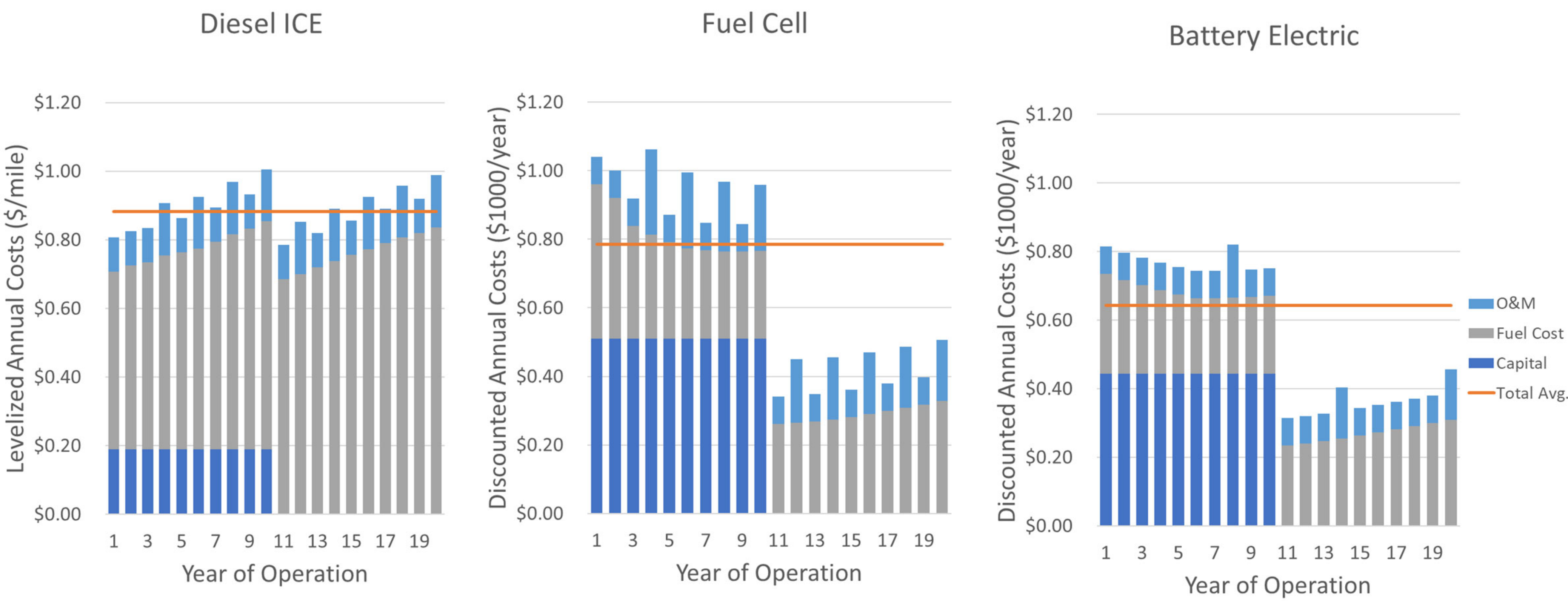
Long Haul HDV Comparative Economics with Complete MSRP



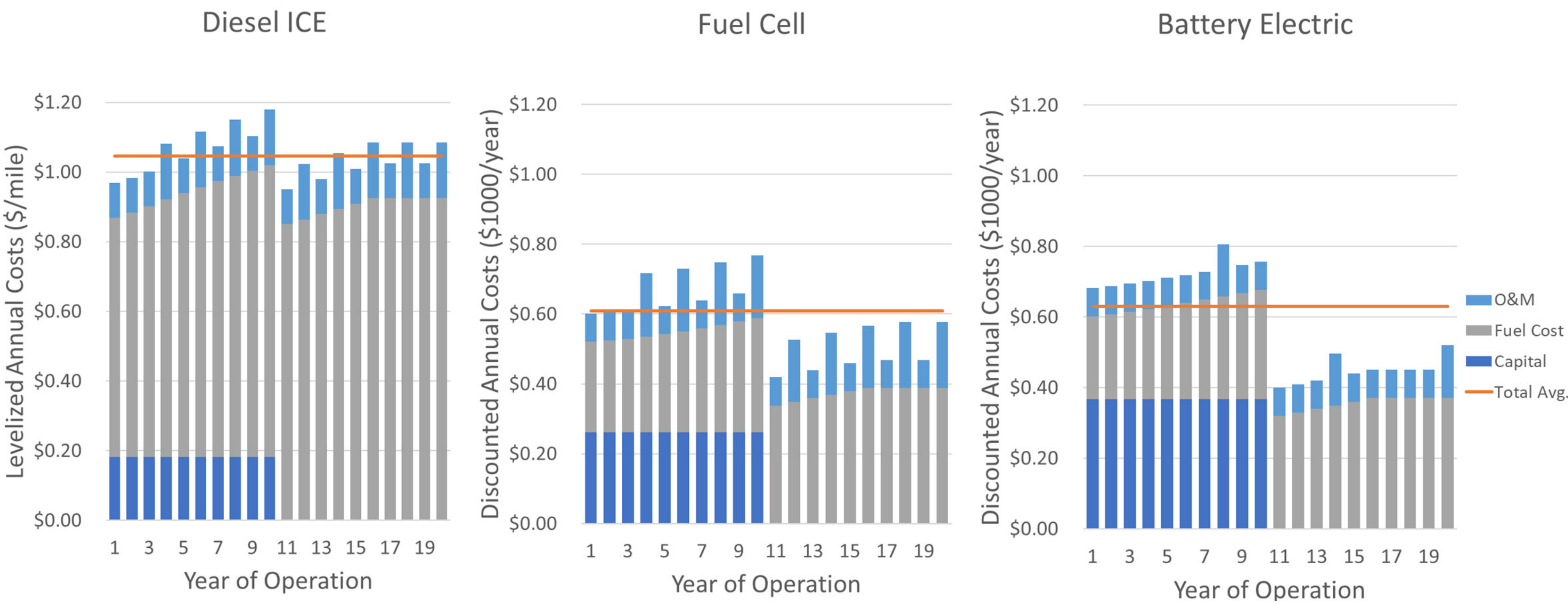


- Glider & other truck components: $150k
- Fuel cell & battery electric adoption premiums that disappear within 10 years
- $200 LCFS

Levelized Cost of Operation - 2025



Levelized Cost of Operation – 2035



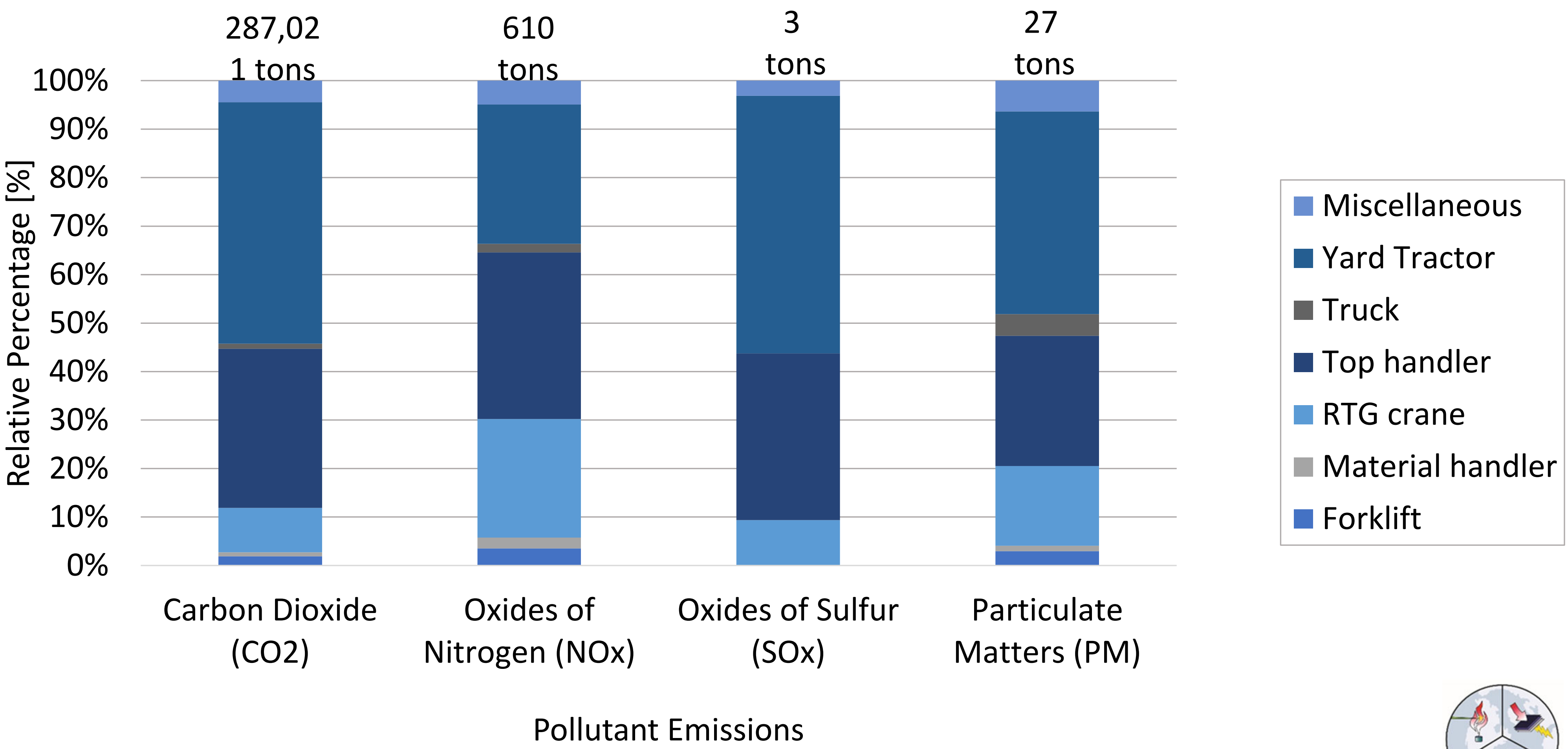
Cargo Handling Equipment

[https://www.atlantaforklifts.com/product/loaded-container-handler/

https://www.toyotaforklift.com/resource-library/material-handling-solutions/products/toyota-heavy-duty-container-handler-solutions

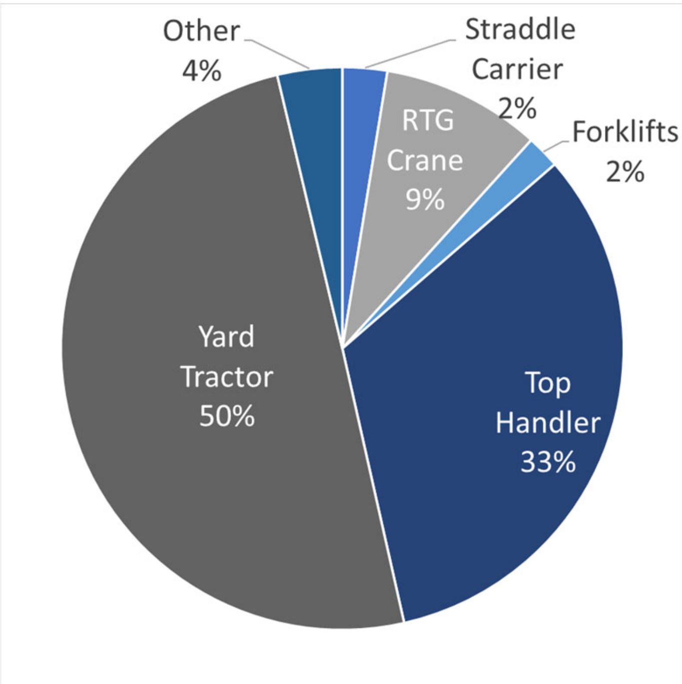
https://www.trucks.com/2019/11/07/toyota-unveils-hydrogen-utility-truck/

Top Handlers and Yard Tractors Largest Opportunity for CHE



Fossil fuel use is dominant across all CHE applications

Annual CHE Fuel Use: 28.2 MM DGE/Year



Over 70% of equipment (by count) fueled by diesel

Table 5.3: 2020 Count of CHE Equipment by Fuel Type

Equipment	Electric	LNG	Propane	Gasoline	Diesel	Total
Forklift	29	0	181	6	105	321
Wharf crane	86	0	0	0	0	86
RTG crane	0	0	0	0	103	103
Straddle carrier	0	0	0	0	67	67
Top handler	2	0	0	0	194	196
Yard tractor	5	22	158	0	781	966
Other	40	0	1	4	131	176
Total	**162**	**22**	**340**	**10**	**1,381**	**1,915**

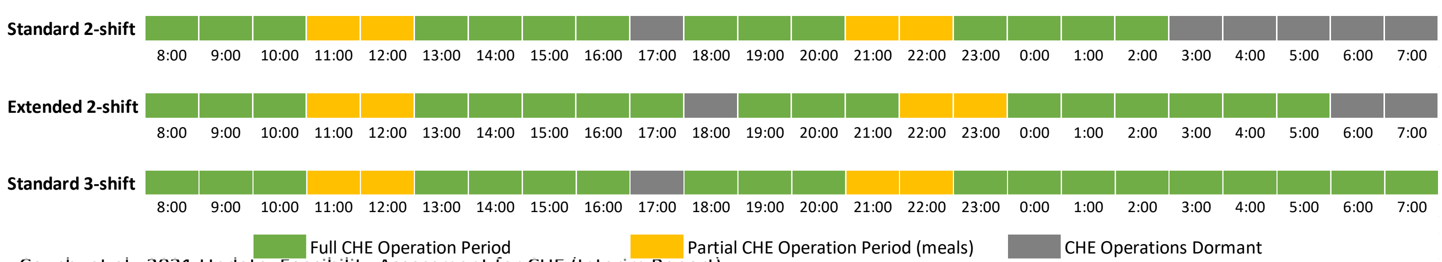
DB ID235

Starcrest Consulting. POLA Inventory of Air Emissions - 2020

CHE – Powertrain Parameters and Duty Cycle

Vehicle	Base Fuel	Powertrain & Fuel Mass (kg)			Powertrain + Fuel Volume (m^3)		
		Diesel	Fuel Cell	Battery	Diesel	Fuel Cell	Battery
Forklifts	Diesel	583	414	1,668	1.15	1.24	1.67
Forklifts	Propane	288	252	1,118	0.44	0.64	1.12
Top Handler	Diesel	1,378	1,456	6,890	3.79	4.57	6.89
Yard Tractor	Diesel	765	654	2,867	1.75	2.01	2.87
Yard Tractor	Gasoline	1,268	1,210	5,536	3.58	4.15	5.54
Yard Tractor	Propane	782	790	3,683	1.64	2.04	3.68
RTG	Diesel	2,022	2,136	3,995	7.66	7.64	4.00

- **Systems designed for “Extended 2-shift”: 17 hours on, 4 hours partial on, 3 hours off**
- **Difficult to design battery systems for “Standard 3-Shift” without subsequent downtime**



Couch, et.al., 2021 Update: Feasibility Assessment for CHE (Interim Report)

Heavy-duty Forklifts Commercial Readiness of ZEV Platforms

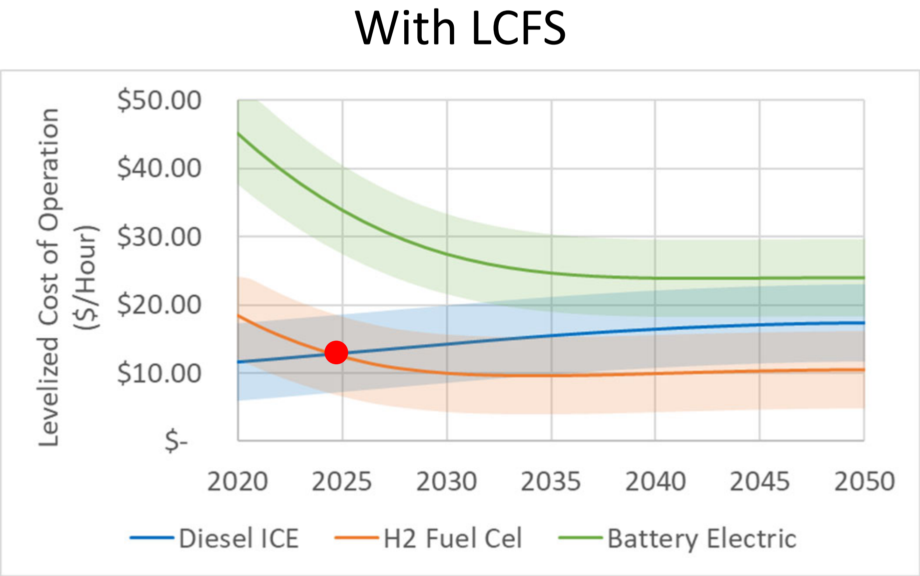
- **Light duty/indoor battery electric and H2 forklifts are available today.**
- **All heavy-duty battery electric are available today but not proven for port operations**
- **Heavy-duty H2 fuel cell designs in development for demonstration at POLA, Port of Hueneme.**
- **Current battery electric feasibility assessments based on lower intensity applications.**
- **Battery electric port feasibility depend on usage and charging power (e.g., 1 shift vs. 2 shift)**

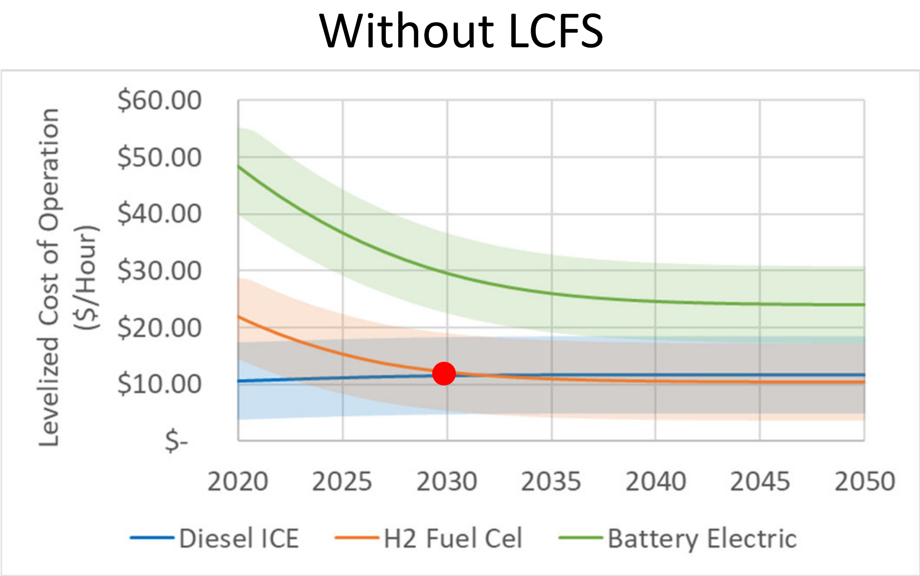
https://www.hyster.com/en-us/north-america/industry-solutions/power-sources/electrification/#b703dc70-6b10-47c8-ad29-0104bda76bb4

HYUNDAI CONSTRUCTION EQUIPMENT

https://fuelcellsworks.com/news/hyundai-construction-equipment-to-develop-hydrogen-forklifts-for-warehouses/

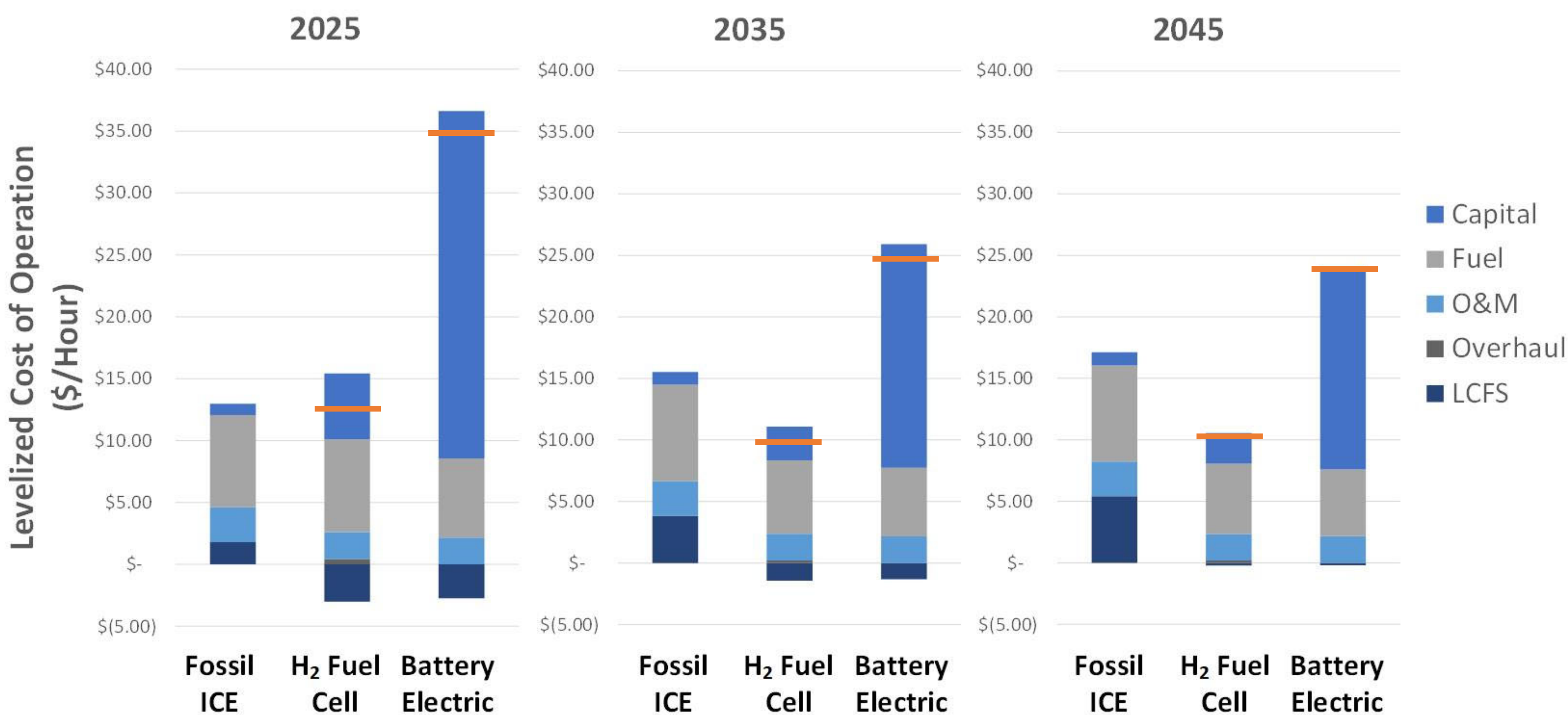
Diesel Forklifts – ZEV Economics, Feasibility and Fit





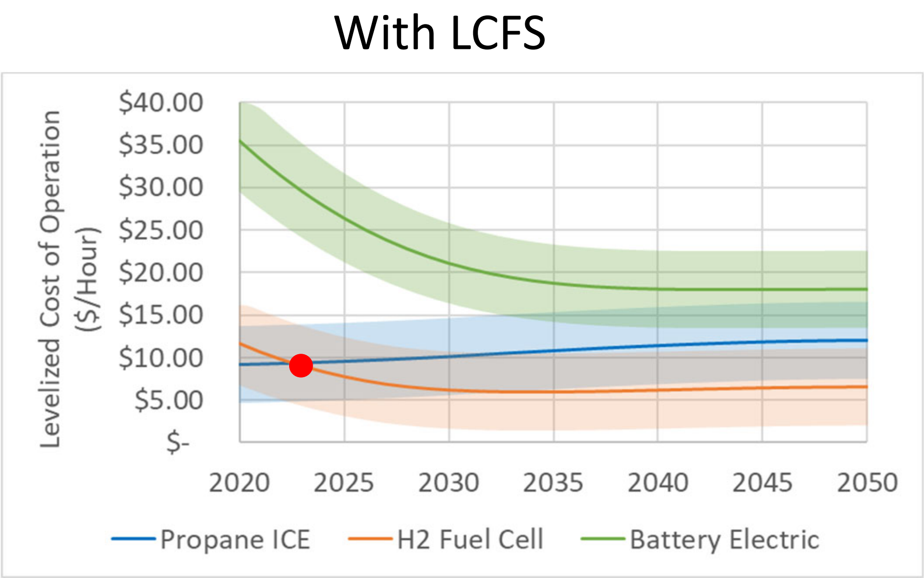
- **Fuel cell drive economics project to be superior to battery drive and cost parity with diesel is projected by 2025**
- **On-board storage and packaging support hydrogen. Current battery electric require 3x larger mass and 2x volume to meet standard 2-shift.**
- **Battery electric charger requirements: 1-shift: 20 kW, 2-shift: 100 kW**
- **80% ultimate adoption of hydrogen expected with initial commercial deployment within 3 – 5 years**

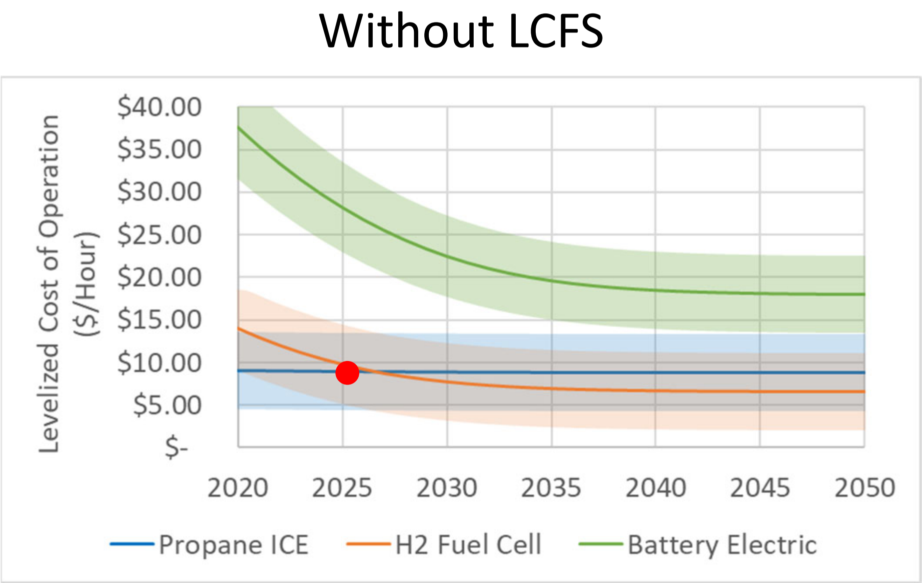
Diesel Forklifts – Cost Components



Note: Red lines represent cost not of credits

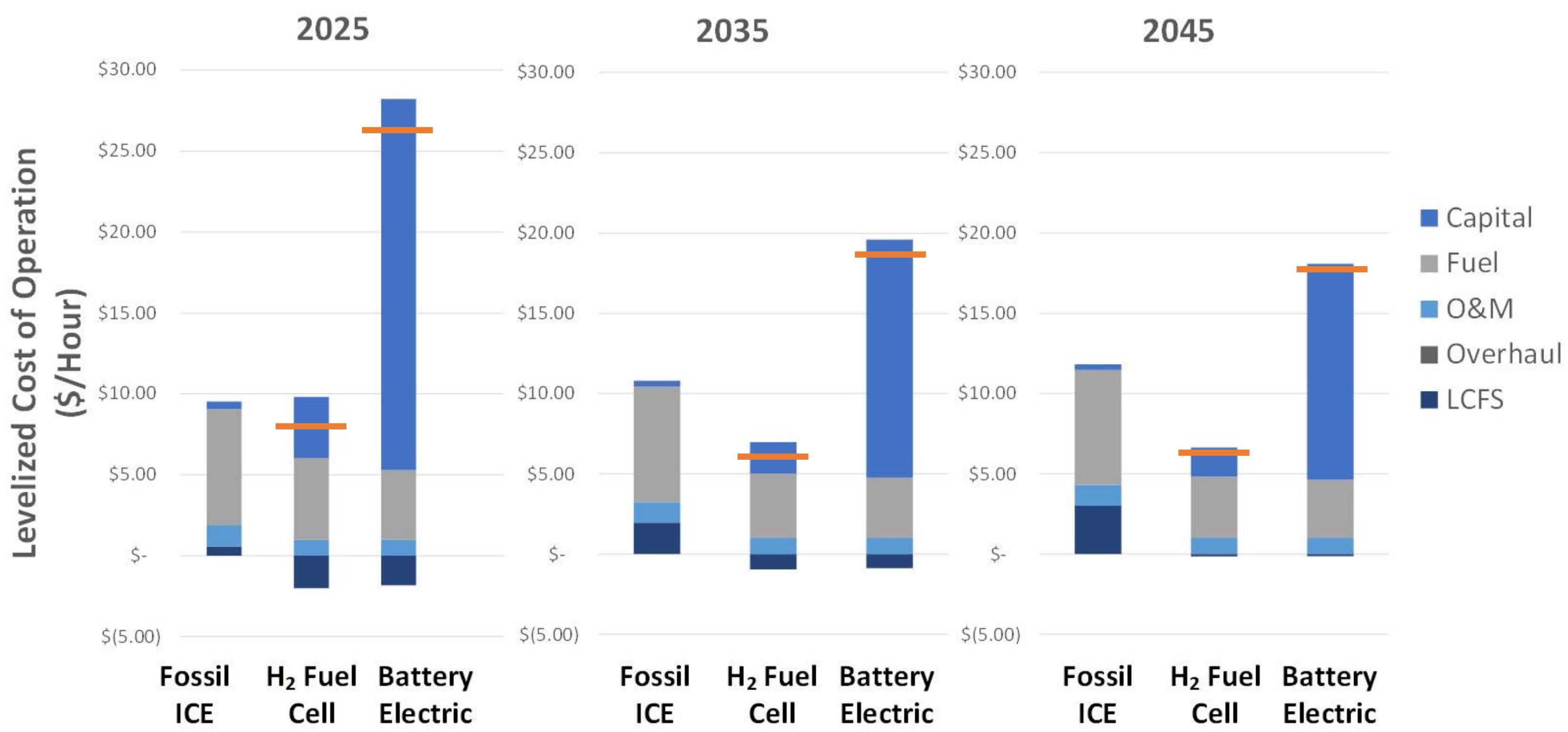
Propane Forklifts – Similar Conclusion as for Diesel





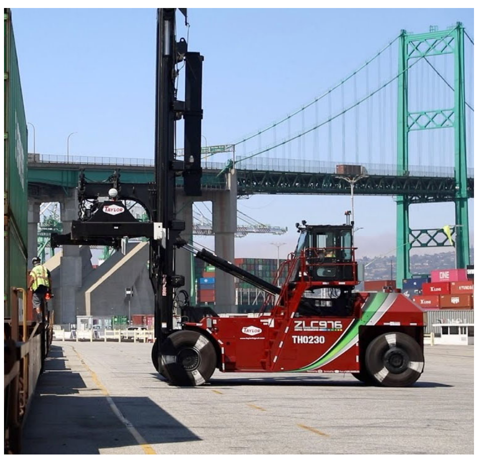
- **Fuel cell drive economics project to be superior to battery drive and cost parity with propane is projected before 2025 due to higher propane costs**
- **On-board storage and packaging support hydrogen. Current battery electric require 3x larger mass and 2x volume to meet standard 2-shift.**
- **Battery electric viable if short duration vehicles are feasible or if forklift platforms are redesigned.**
- **100% ultimate adoption of hydrogen expected with initial commercial deployment within 3 to 5 years**

Propane Forklifts – Cost Elements

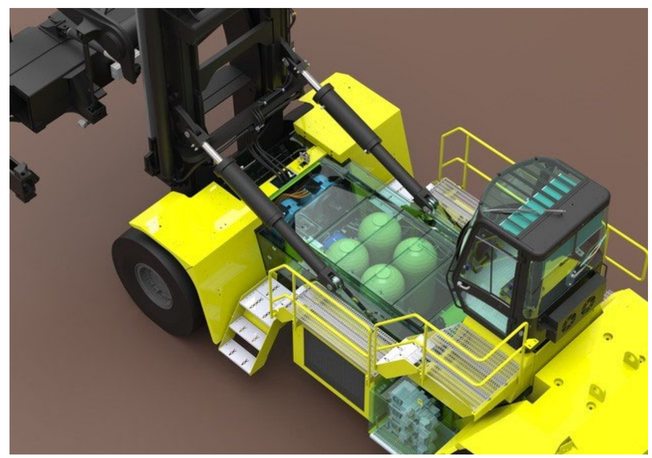


Top Handler Commercial Readiness of ZEV Platforms

- **Battery electric top loader faces similar packaging issues as heavy duty forklifts**
- **Battery electric demonstration: Everport Container Terminal demonstration at POLA in 2020: "Top handlers performing well"**
  - **Real battery top loaders match UCI top loader estimated battery capacities**
- **H2 fuel cell top loaders being designed for demonstration at Port of Valencia, Spain, and at POLA.**

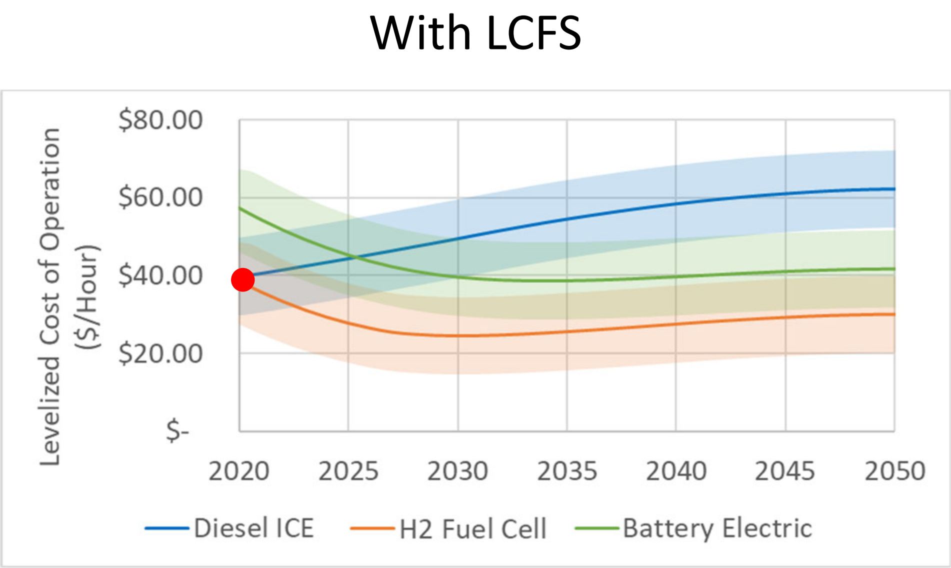


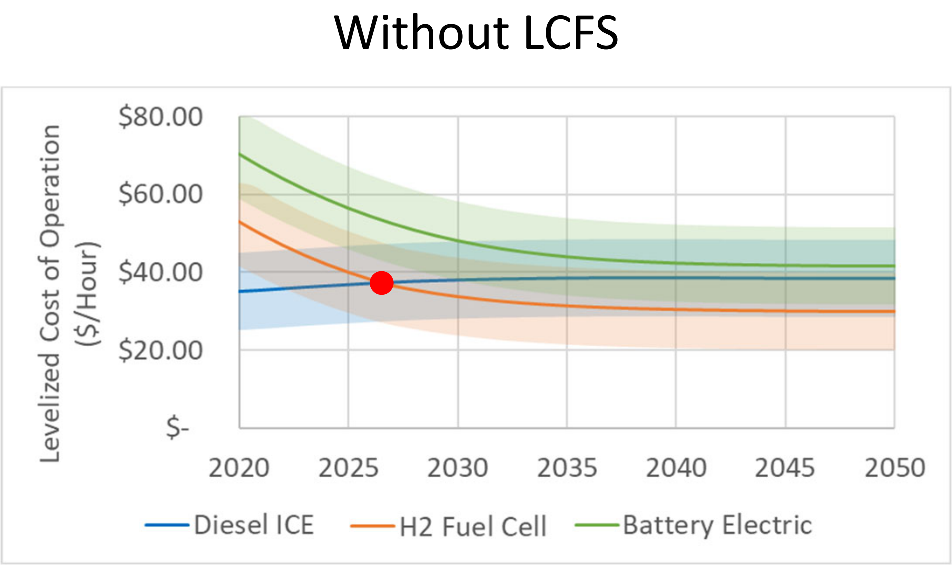
https://www.taylorforklifts.com/blog-post.php?id=159



https://www.onthemosway.eu/zero-emissions-fuel-cell-container-handlers/

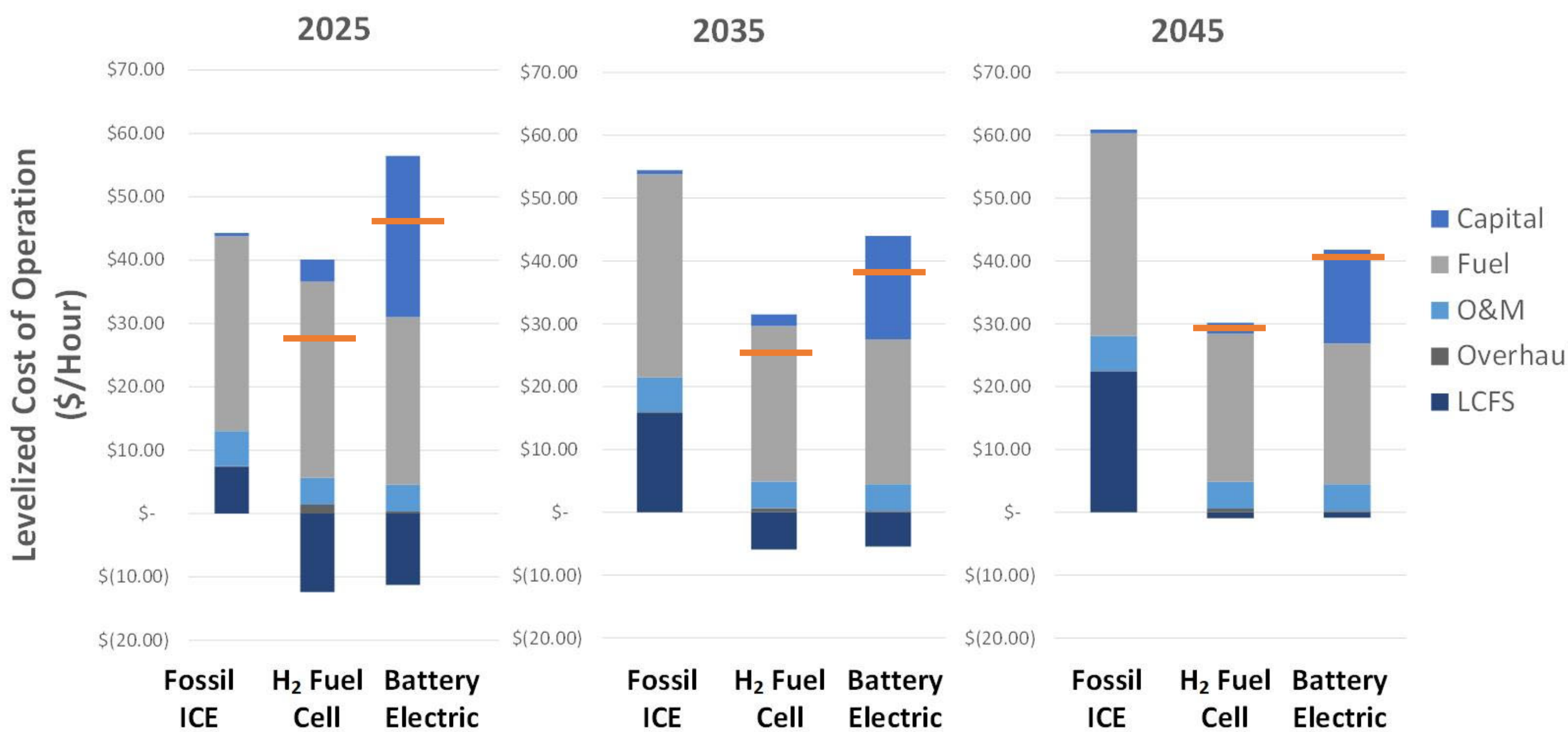
Top Handler - Diesel





- **Fuel cell drive economics project to be superior to battery drive and cost parity with diesel is projected before 2025 with LCFS, and 2026 without LCFS**
- **On-board storage and packaging support hydrogen but battery electric systems have been built and deployed. Extended operations are more feasible using H2 fuel cells.**
- **Redesigned battery top loaders are feasible but are difficult to operate beyond multiple "standard 2-shift"**
- **80% - 100% ultimate adoption of hydrogen expected with initial commercial deployment within 3 to 5 years**

Top Handler – Cost Components

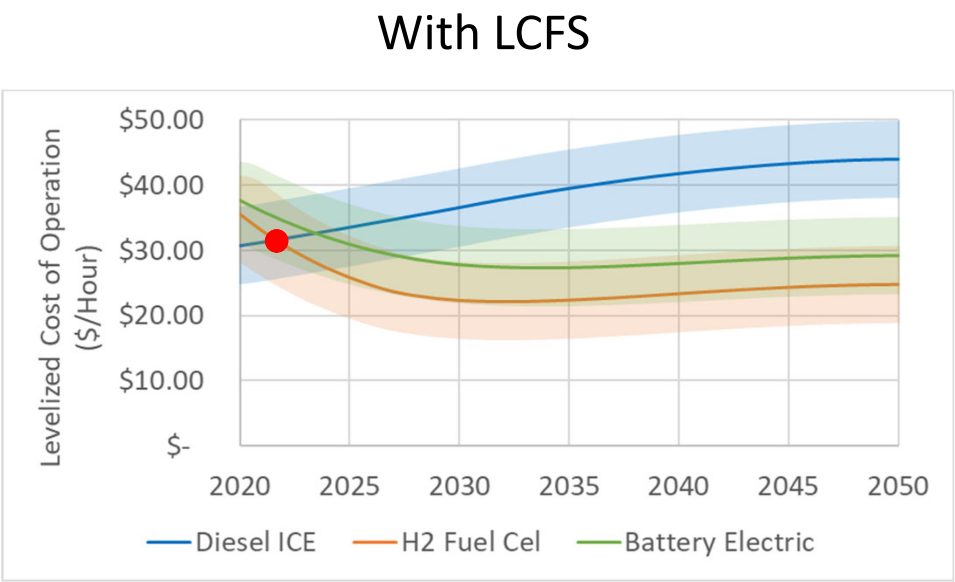


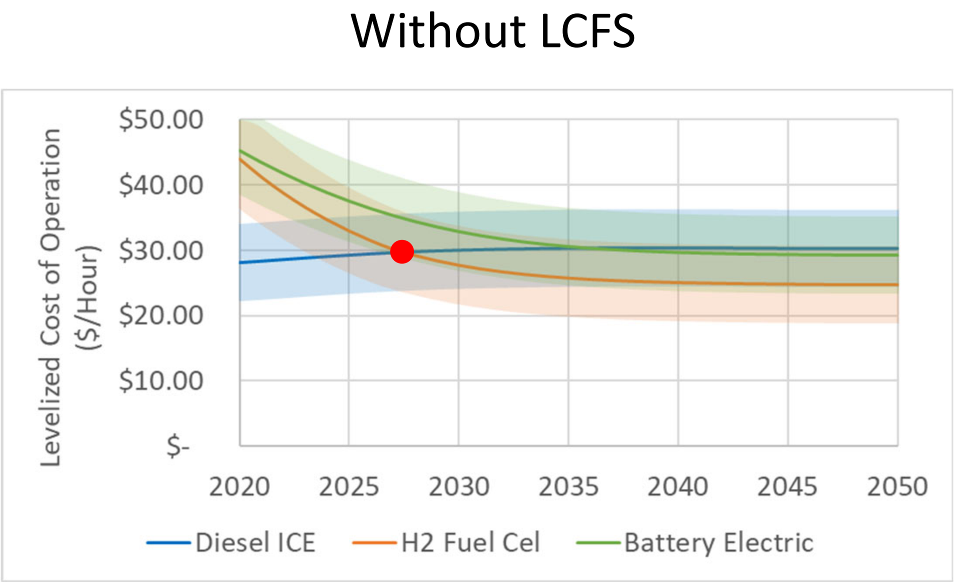
RTG Crane Commercial Readiness of ZEV Platforms

- **Grid powered electric RTGs are available today but can require infrastructure modification and create new operational challenges**
- **Battery electric without grid support is difficult**
- **Hydrogen designs in progress (Mitsui E&S Machinery at POLA)**
- **Small crane demonstration – Shanghai Port**
- **Hydrogen fuel cell demonstration occurring in China (Shanghai & Qingdao Ports)**
- **Unusual extreme power cycle requires additional hybrid systems or changing operational profile**

https://container-mag.com/2021/09/02/mitsui-receives-grant-to-develop-rtg-powered-by-hydrogen-fuel-cell/

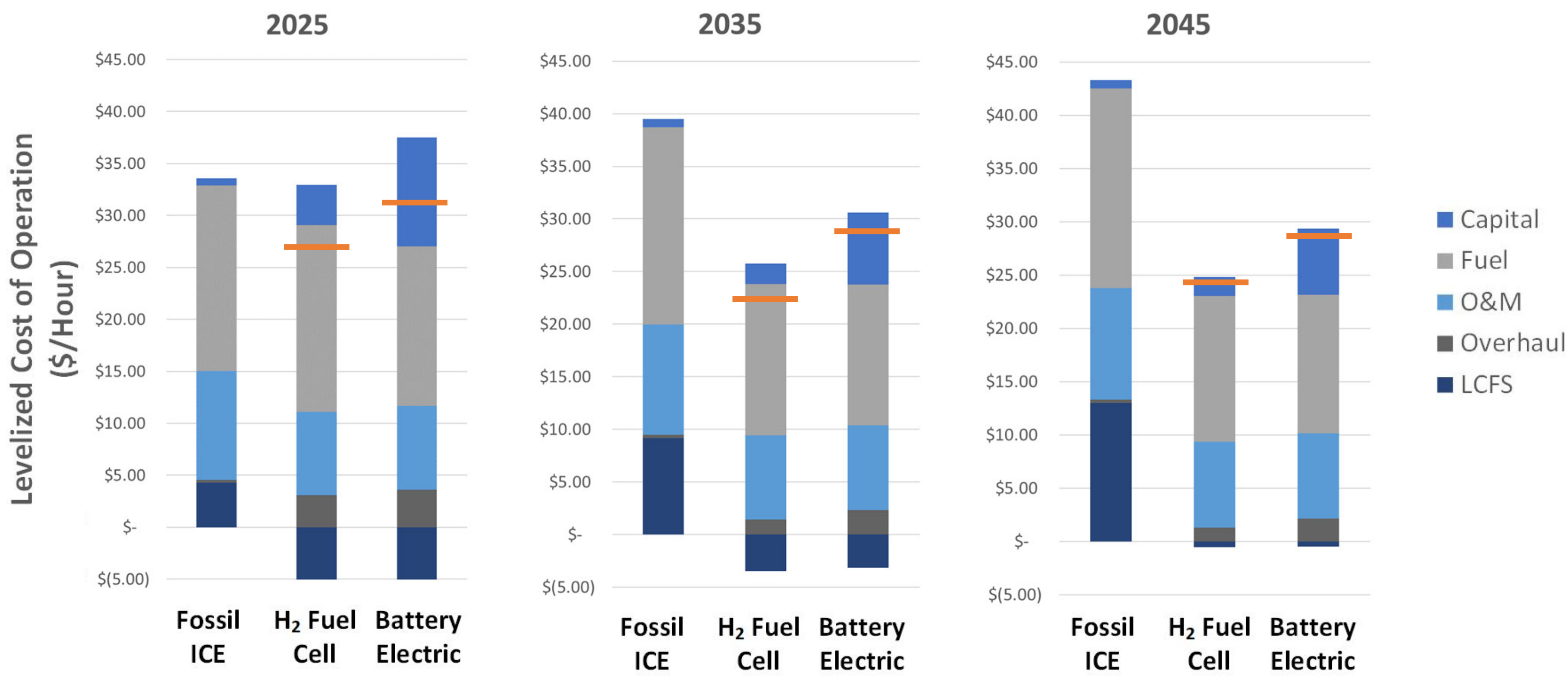
RTG Crane - Diesel





- **Fuel cell drive economics project to be superior to battery drive and cost parity with diesel is projected before 2025 with LCFS, and 2028 without LCFS**
- **On-board storage and packaging support hydrogen but battery electric systems have been built and deployed. This does not capture the cost benefits of a grid tied system, which would have a significantly smaller battery**
- **100% ultimate adoption of hydrogen expected with initial commercial deployment within 5 to 10 years**

Top Handler – Cost Components



Trucking and Rail

Heavy Duty Vehicles (HDVs) – Powertrain Parameters and Duty Cycle

Vehicle	Base Fuel	Estimated Equipment Count	Powertrain + Fuel Mass (kg)			Powertrain + Fuel Volume (m^3)		
			Diesel	H2 Fuel Cell	Battery Electric	Diesel	H2 Fuel Cell	Battery Electric
Drayage	**Diesel**	16,000	1,215	612	1,923	4.20	4.09	1.92
Line-Haul	**Diesel**	13,500	1,673	1,049	3,922	5.96	6.06	3.92

- Some commercial demonstrations:

POLA demonstrated 5 H2FC electric trucks built by Toyota & Kenworth.
- Class 8 truck.
- 560 horsepower.
- 300 miles range.
- 20% grade.

https://www.fleetowner.com/emissions-efficiency/press-release/21166545/port-of-los-angeles-demonstrates-hydrogen-fuel-cell-electric-freight

Nikola battery electric truck.
- 645 horsepower.
- 753 kWh battery.
- 350 miles range.
- 120 mins refuel time (to 80%).
- Available now.

https://nikolamotor.com/tre-bev

Nikola FC electric truck.
- Class 8 truck.
- 645 horsepower.
- 900 miles range.
- 20 mins refuel time.
- Available 2024.

https://nikolamotor.com/two-fcev

Heavy-duty Trucks Commercial Readiness of ZEV Platforms

Hydrogen

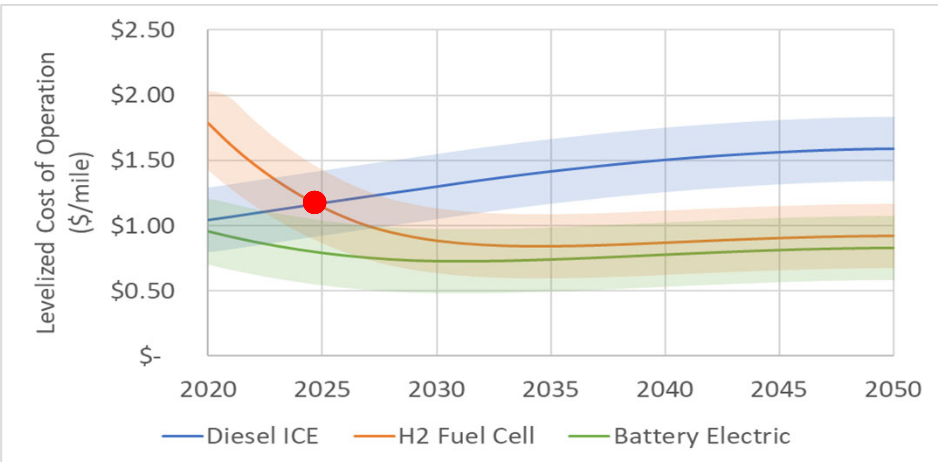
- Hyzon motors has delivered 29 commercial Class 8 trucks to China
- Toyota and Hyundai have developed prototype Class 8 trucks; Nikola and Cummins also developing prototypes
- Volvo has announced that it will launch a Class 8 FCEV offering in 2027
- A hydrogen fuel cell drayage truck demonstration was successfully completed at the Port of LA in 2021.
- Yard Tractor at the demonstration phase – could be commercial by 2025

Electric

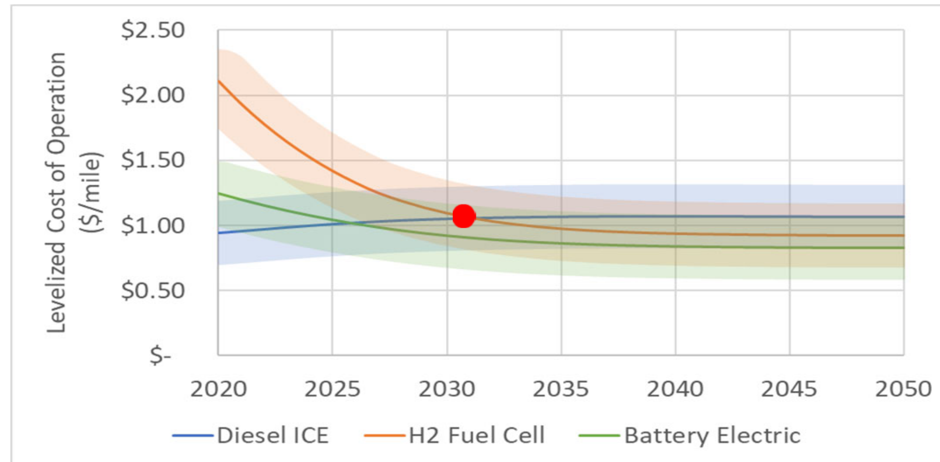
- Volvo has a commercial Class 8 electric platform with 150-mile range and 70-minute charging time
- Orange EV is currently offering a fully commercial yard tractor
- Manufacturers working to extend range, but line haul a challenge for battery electric drive

Drayage

With LCFS

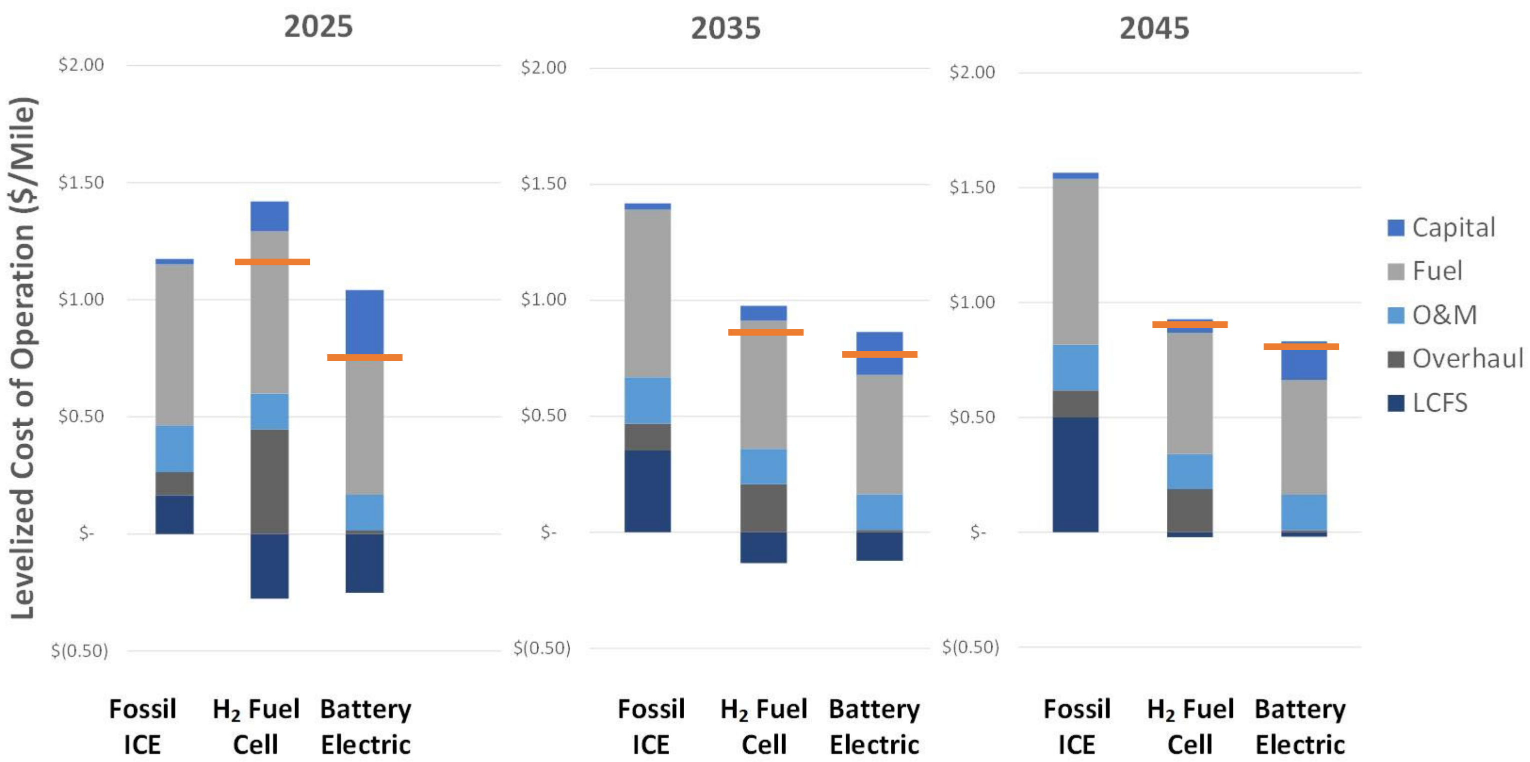


Without LCFS

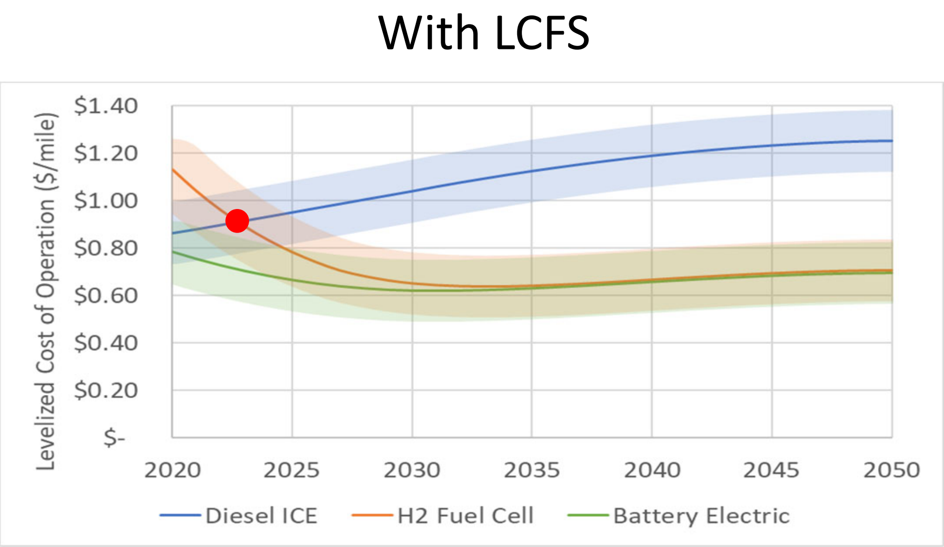


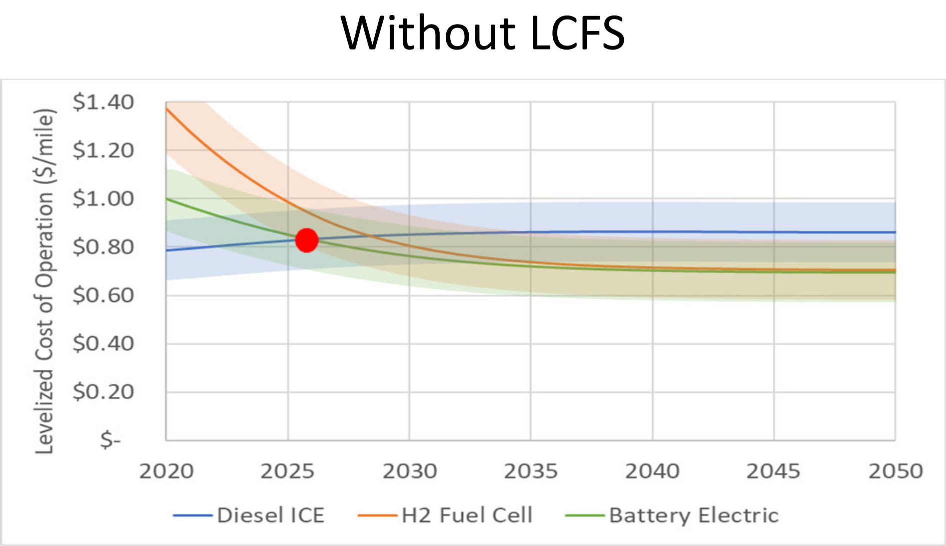
- **With incentives, battery electric and fuel cell drive economics project to achieve cost parity with diesel before 2025. Without incentives, it is projected to be around 2030.**
- **On-board storage, packaging and fueling logistics supports battery if:**
  - **If we only need 1 to 2 trips per day, with a range less than 200 miles.**
- **On-board storage, packaging and fueling logistics supports fuel cell if:**
  - **We need more than 2 trips per day, with a range larger than 200 miles.**
- **Market Projection: 50% battery/50% fuel cell over the long term with deployment beginning around 2025 – 2027**

Drayage – Cost Components



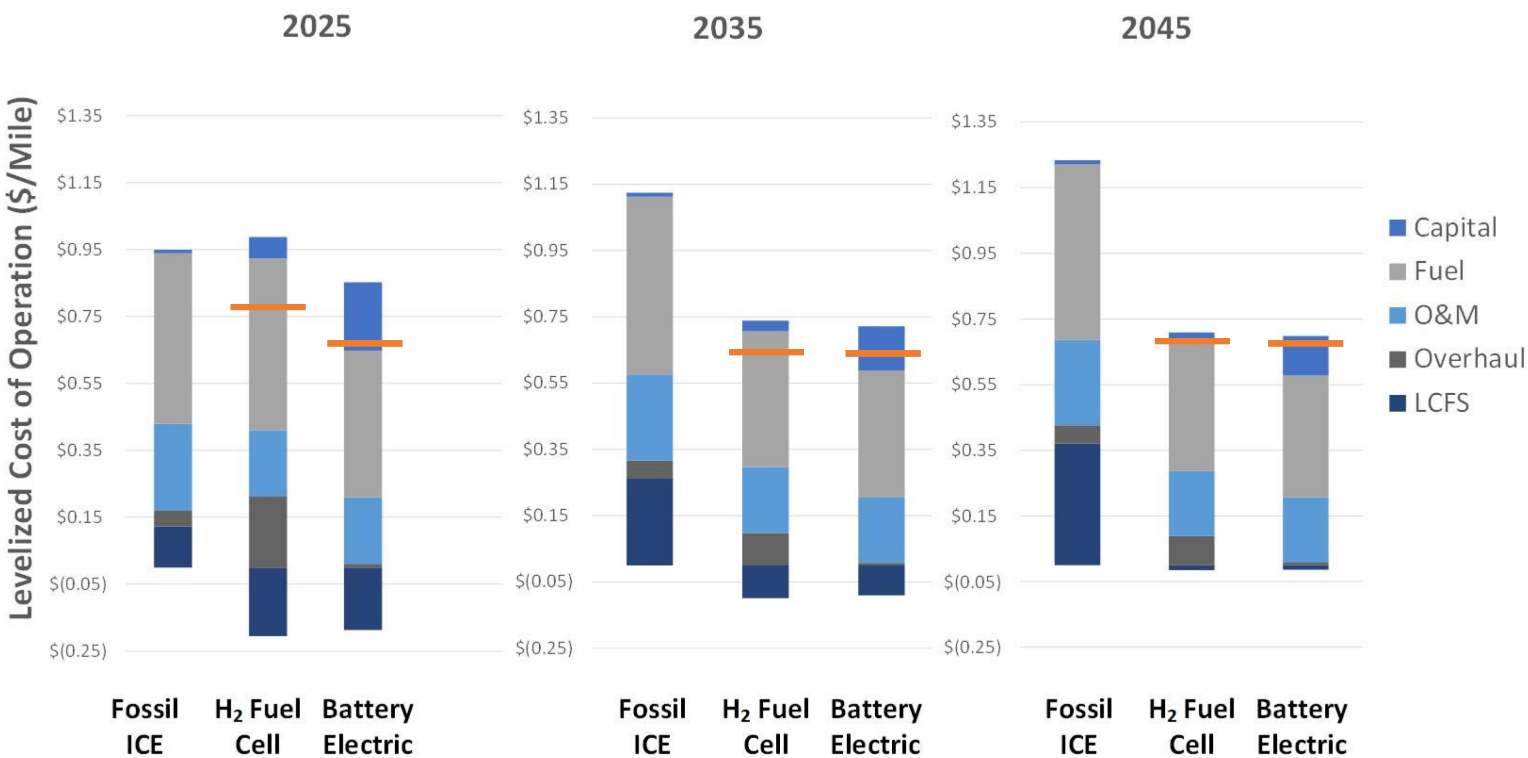
Line Haul





- **With incentives, battery electric and fuel cell drive economics project to both achieve cost parity with diesel before 2025, and before 2030 without incentives.**
- **On-board storage, packaging, and fueling logistics support hydrogen fuel cell drive.**
- **Market Share: 20% battery/80% fuel cell with deployment beginning around 2025 – 2027.**

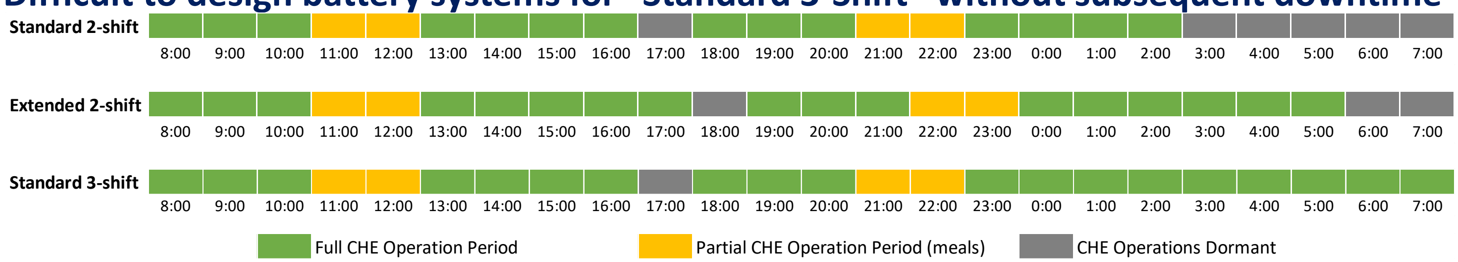
Long Haul – Cost Components



Yard Tractors – Powertrain Parameters and Duty Cycle

Vehicle	Base Fuel	Powertrain & Fuel Mass (kg)			Powertrain + Fuel Volume (m^3)		
		Diesel	Fuel Cell	Battery	Diesel	Fuel Cell	Battery
Yard Tractor	Diesel	765	654	2,867	1.75	2.01	2.87
Yard Tractor	Gasoline	1,268	1,210	5,536	3.58	4.15	5.54
Yard Tractor	Propane	782	790	3,683	1.64	2.04	3.68

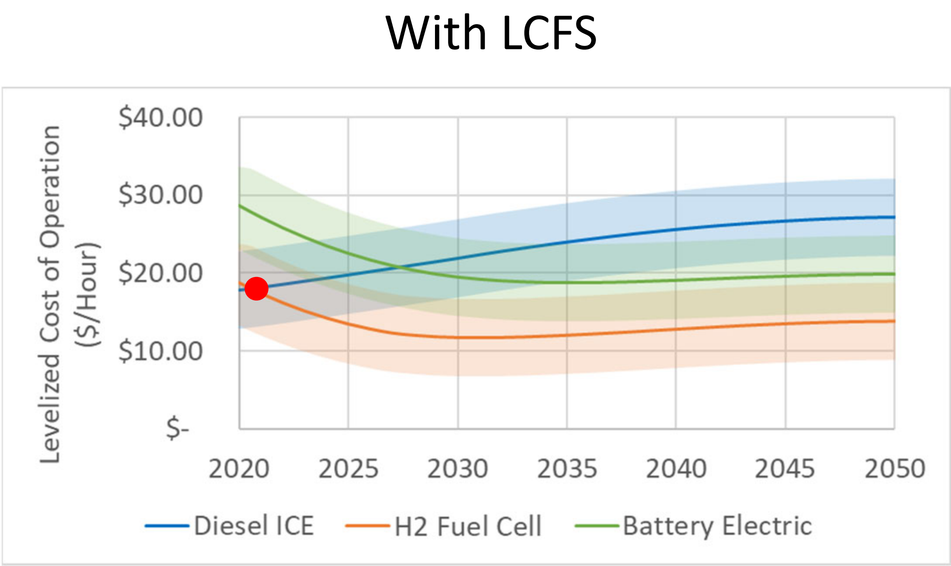
- **Systems designed for “Extended 2-shift”: 17 hours on, 4 hours partial on, 3 hours off**
- **Difficult to design battery systems for “Standard 3-Shift” without subsequent downtime**

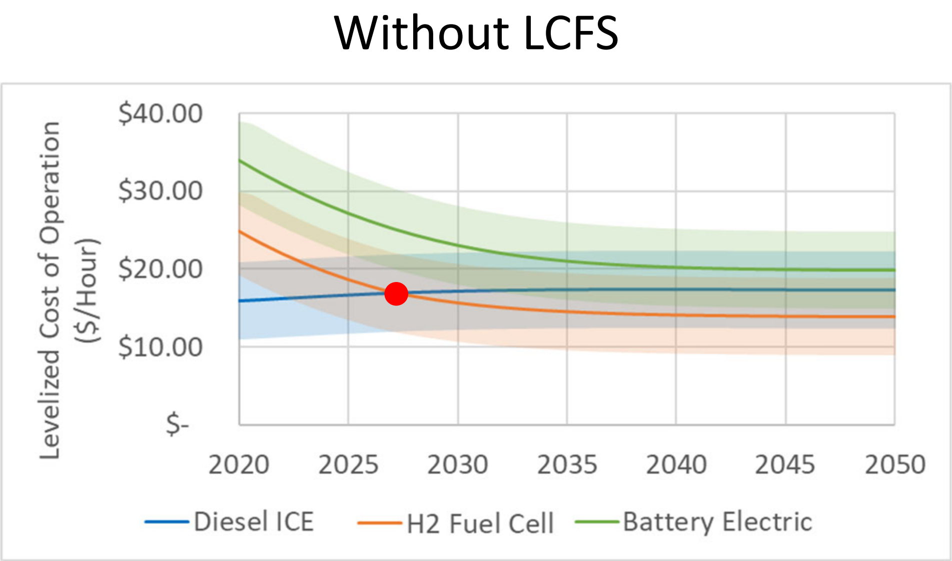


Couch, et.al., 2021 Update: Feasibility Assessment for CHE (Interim Report)

- **Yard tractor analysis difference - based on emissions inventory**
- **System sized to operational hours, vs. drayage and line haul – designed for range**
- **Current long-haul battery electric systems could meet gasoline yard tractor range specs**
- **Current drayage battery electric systems could meet diesel yard tractor range specs**

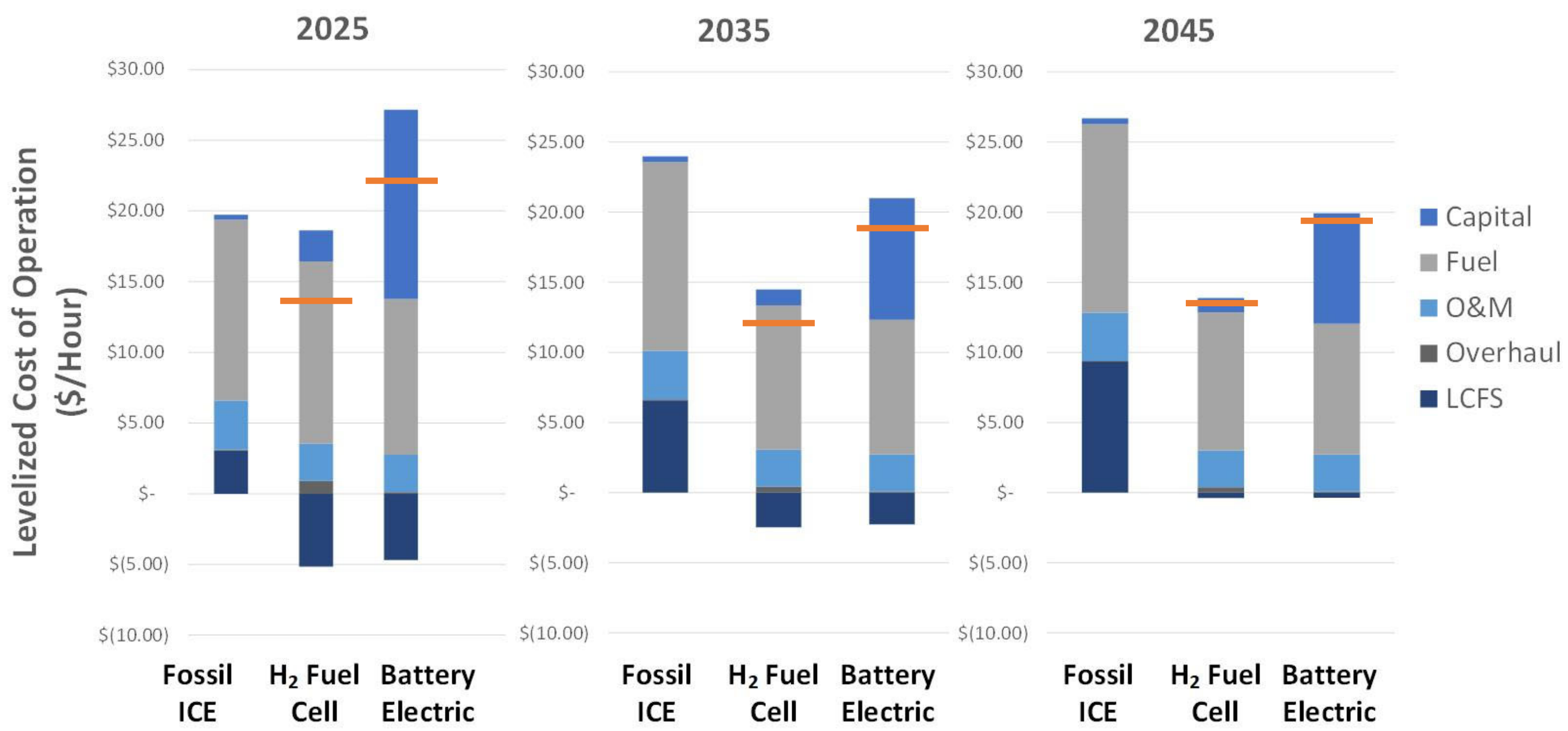
Yard Tractor - Diesel





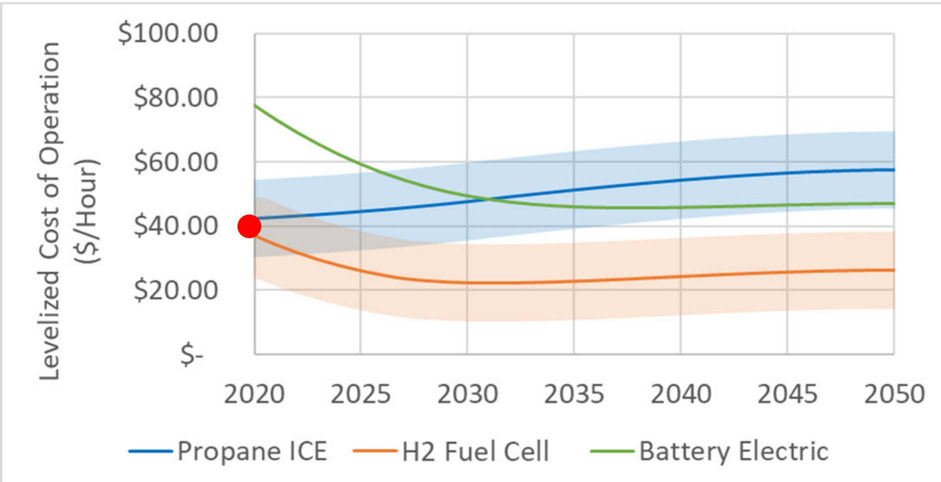
- **Fuel cell drive economics project to be superior to battery drive and cost parity with diesel is projected before 2025 with LCFS, and 2027 without LCFS**
- **On-board storage and packaging support hydrogen due to “extended 2-shift” energy density.**
  - **Long haul vehicle meets yard tractor specs, but would incur higher costs**
- **80% - 100% ultimate adoption of hydrogen expected with initial commercial deployment within 3 to 5 years**

Yard Tractor – Diesel Cost Elements

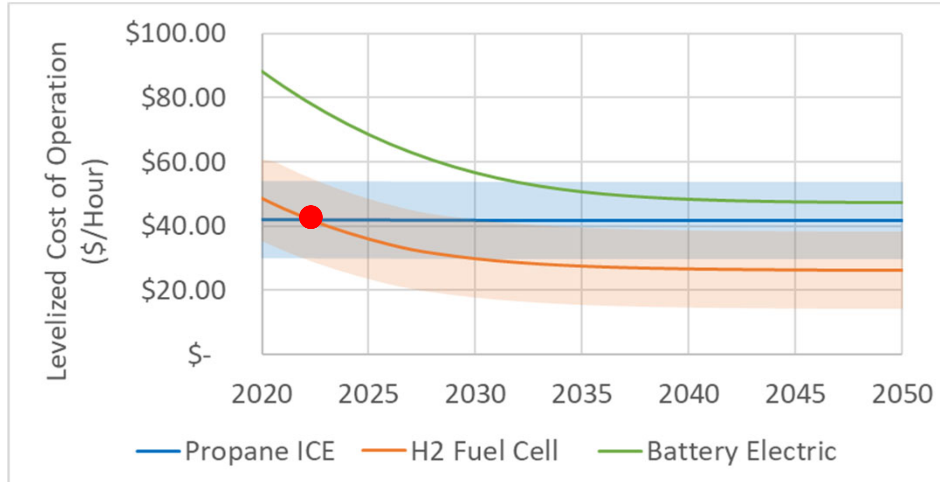


Yard Tractor - Gasoline

With LCFS

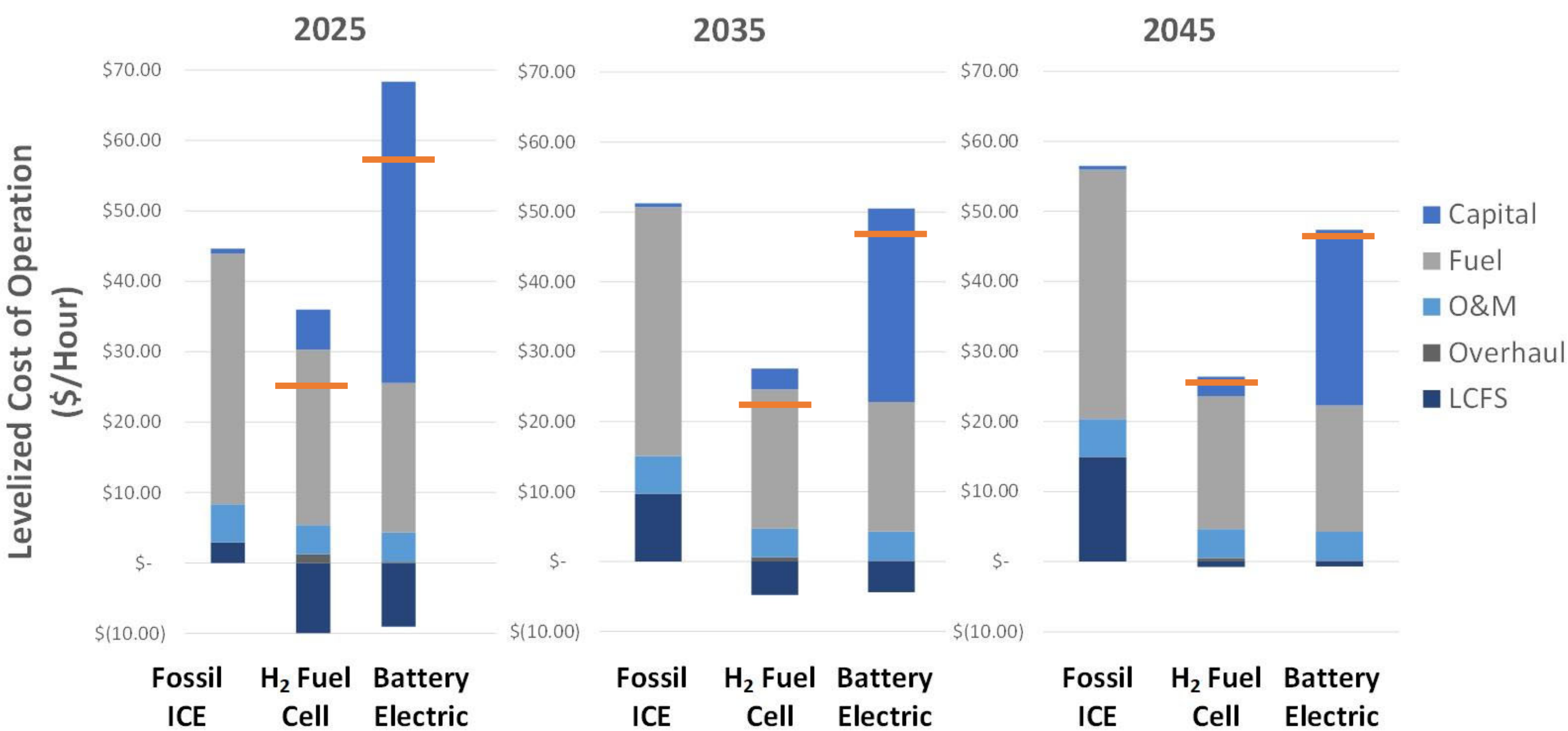


Without LCFS

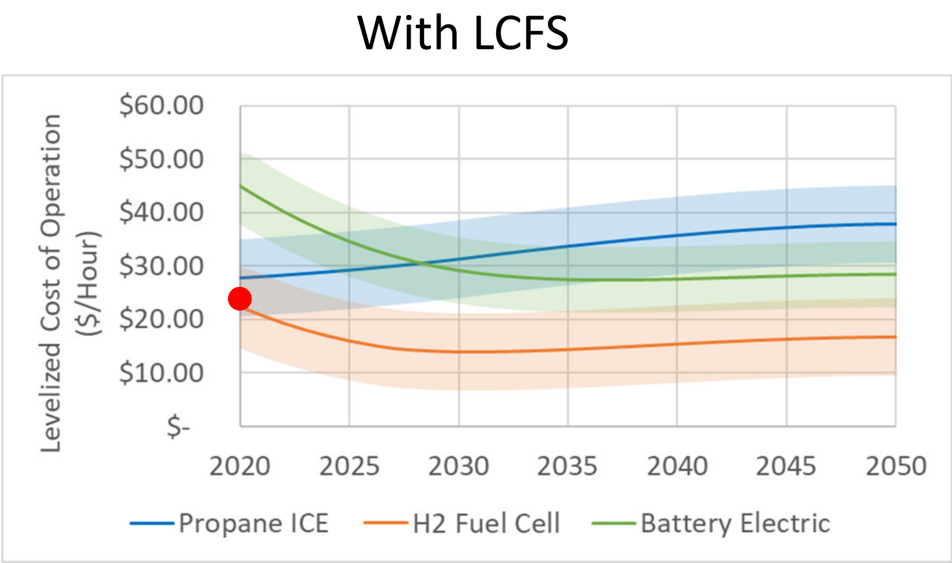


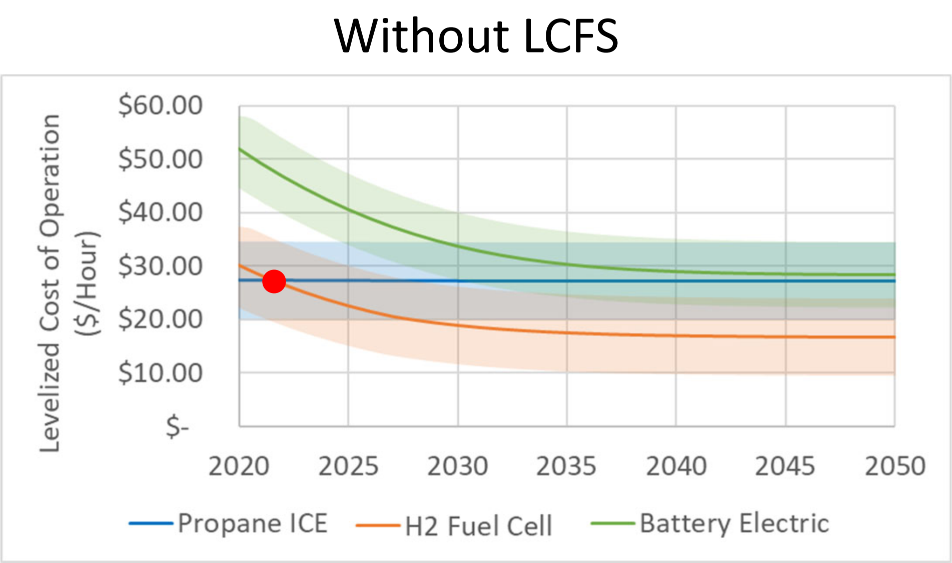
- **Fuel cell drive economics project to be superior to battery drive and cost parity with gasoline is projected before 2025**
- **On-board storage and packaging support hydrogen due to “extended 2-shift” energy density.**
    - **Long haul vehicle meets yard tractor specs, but would incur higher costs**
- **100% ultimate adoption of hydrogen expected with deployment beginning around 2025 – 2027**

Yard Tractor – Gasoline Cost Elements



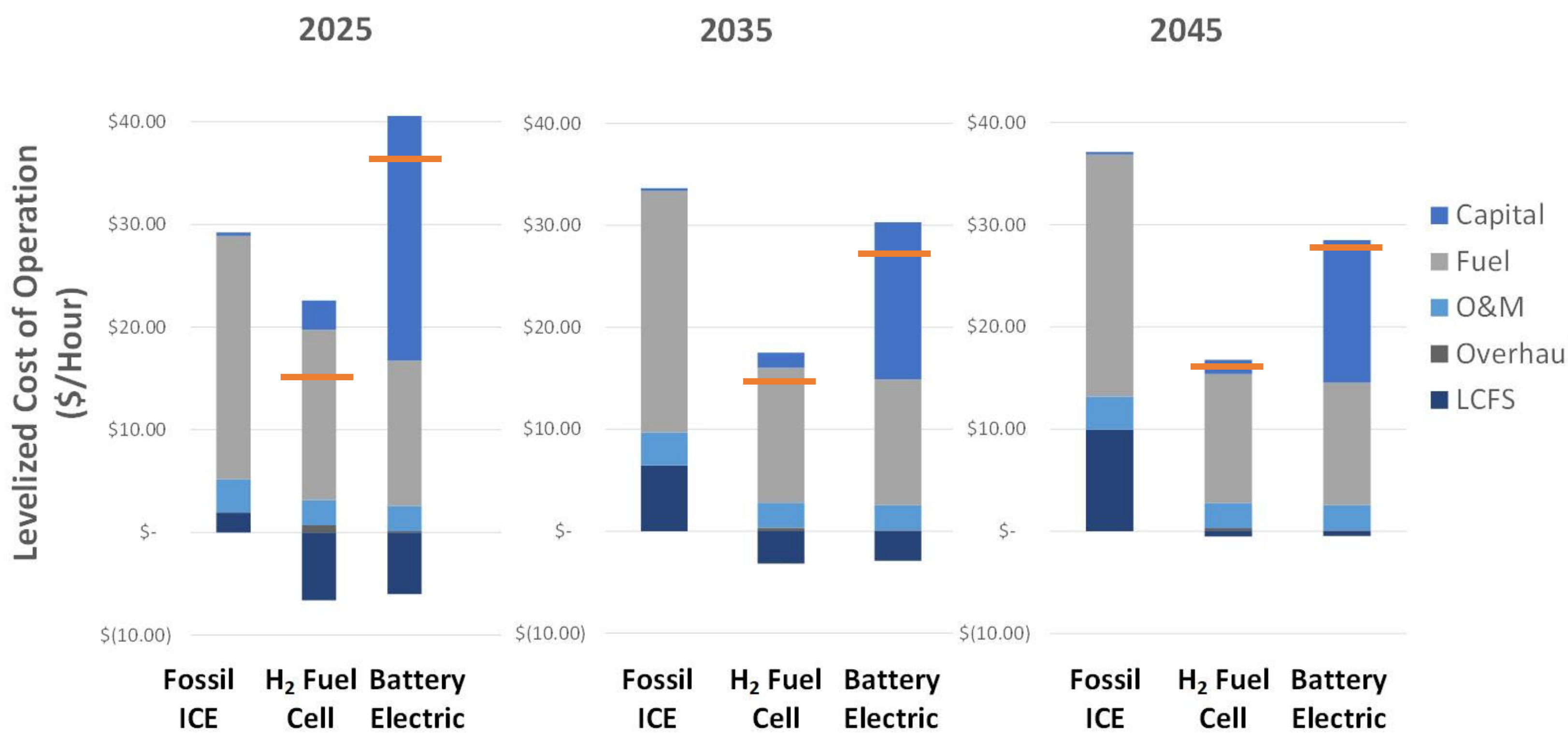
Yard Tractor - Propane





- **Fuel cell drive economics project to be superior to battery drive and cost parity with propane is projected before 2025**
- **On-board storage and packaging support hydrogen due to "extended 2-shift" energy density.**
  - **Long haul vehicle meets yard tractor specs, but would incur higher costs**
- **100% ultimate adoption of hydrogen expected with deployment beginning around 2025 – 2027**

Yard Tractor – Propane Cost Elements



Freight Trains Commercial Readiness of ZEV Platforms

Hydrogen

- Canadian Pacific developing the 1st hydrogen fuel cell line-haul locomotive (started in 2020)
- Parallel development of similar vehicle in China by CRRC Datong Co., LTD> (started 2021).
- MOU between Caterpillar, BNSF, and Chevron Hydrogen Locomotive established in 2022.
- Initial analysis shows a fuel tender is required, but levelized cost addition is minimal.

Electric

- Generally found to be limited in range and appropriate for short distances.
- Electric freight train with tender range < 500 miles
- Widespread development would depend on:
    1. Battery tender swapping
    2. Supporting electric catenary system
- Battery electric systems demonstrated by Wabtec out of Pittsburgh, PA.

Freight Trains

Linehaul – Wabtec ES58ACi

http://www.rrpicturearchives.net/showPicture.aspx?id=1621154

Powertrain Details
- 4.3 MW
- 23,00 liters, 6,208 gallons fuel

Powertrain	Range w/out Tender (miles)	Range w/ Tender (miles)	Design Constraint
Fuel Oil	2570	16,724	n/a
PEMFC	555	2,230	Volume
Battery	150	390	Weight
SOFC-GT	882	2,976	Volume

*Diesel and H_2 fuel tender car add 3% to lifetime costs

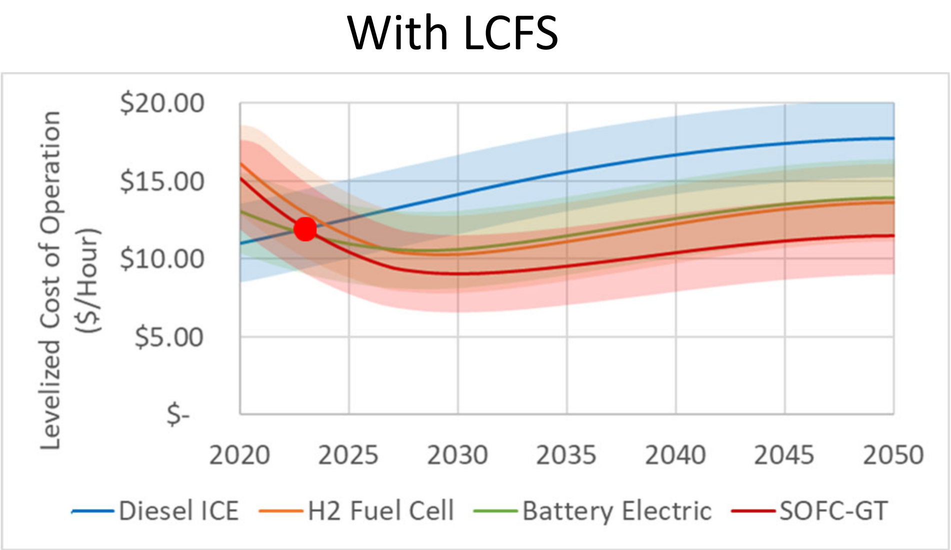
Switcher – Wabtec C20ACi

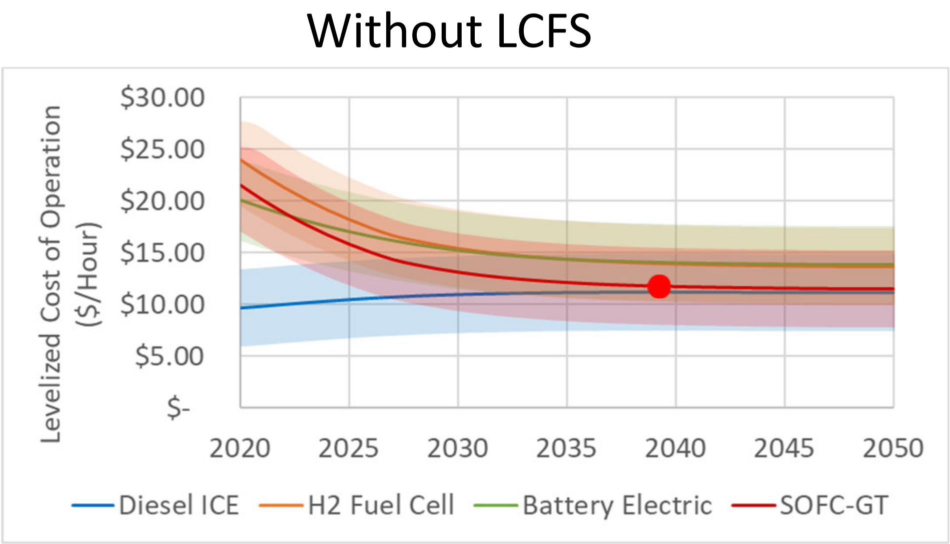
https://www.wabteccorp.com/locomotive/light-weight-locomotives

Powertrain Details
- 1.67 MW
- 4,600 liters, 1,215 gallons fuel
- Assume gas H_2

Powertrain	Range (miles)	Weight (tonne)	Volume (m^3)
Fuel Oil	500	10	33.3
PEMFC	130	6.9	33.3
Battery	42	10	10
SOFC-GT	233	7.9	33.3

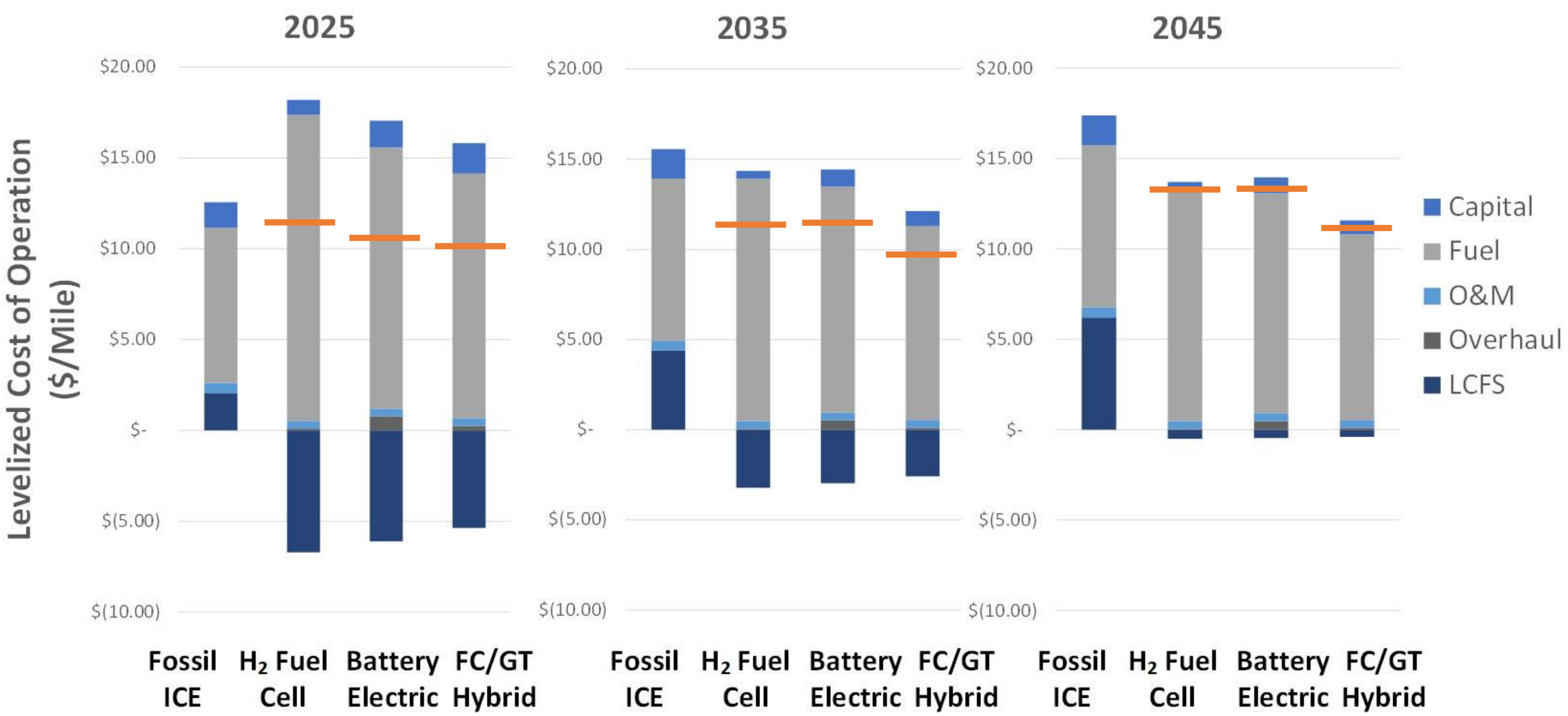
Switcher Train



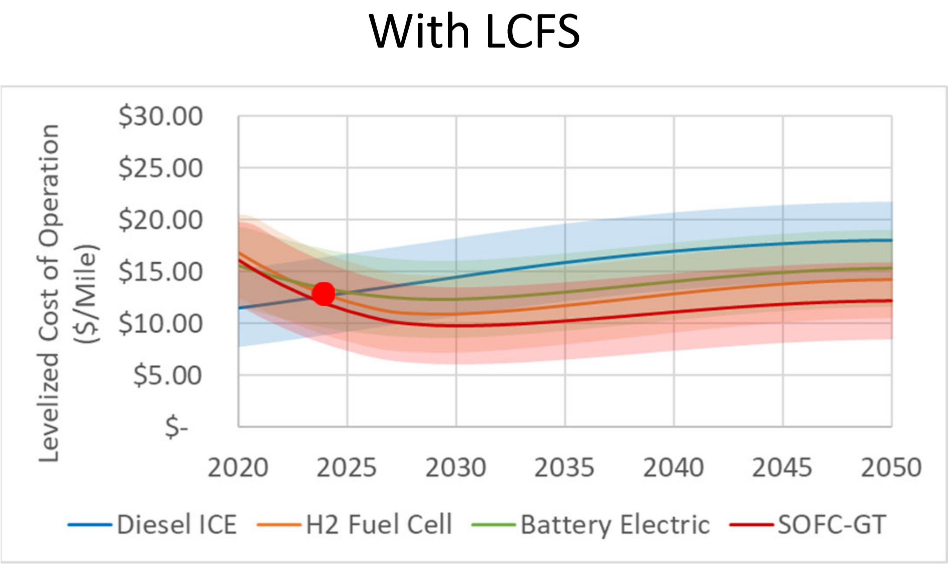


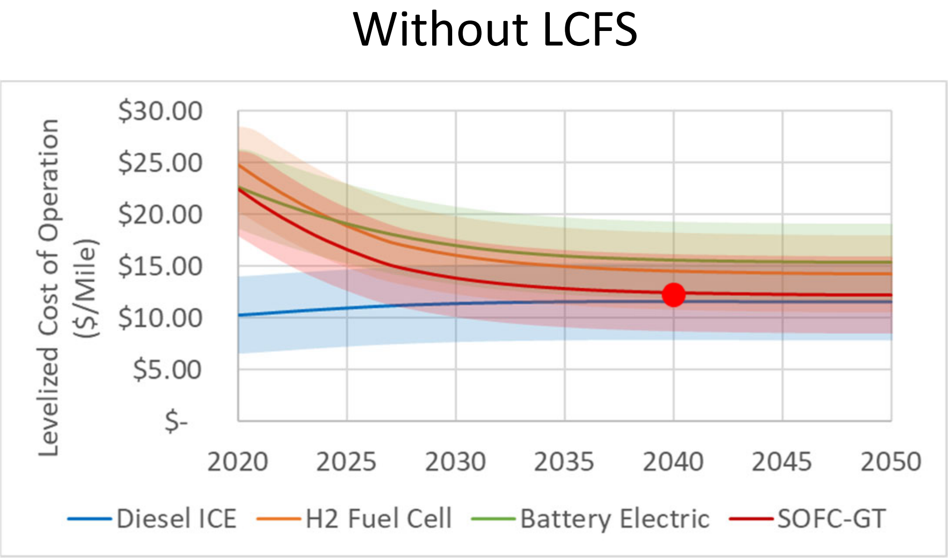
- **Battery electric and fuel cell drive economics project to be comparable and to reach cost parity with diesel before 2025 with LCFS, or increase cost 25% over diesel without LCFS**
- **SOFC-GT hybrid drive preferable on a cost basis w/ and w/out LCFS**
- **On-board storage and packaging also support hydrogen via SOFC-GT due to higher system efficiency**
- **If SOFC-GT drive is unavailable, FC and battery electric are comparable in cost and ultimate decision depends on presence of catenary system or battery charging system capacity**
- **100% ultimate adoption of hydrogen expected with initial commercial deployment in late 2020s**

Switcher Train – Cost Components



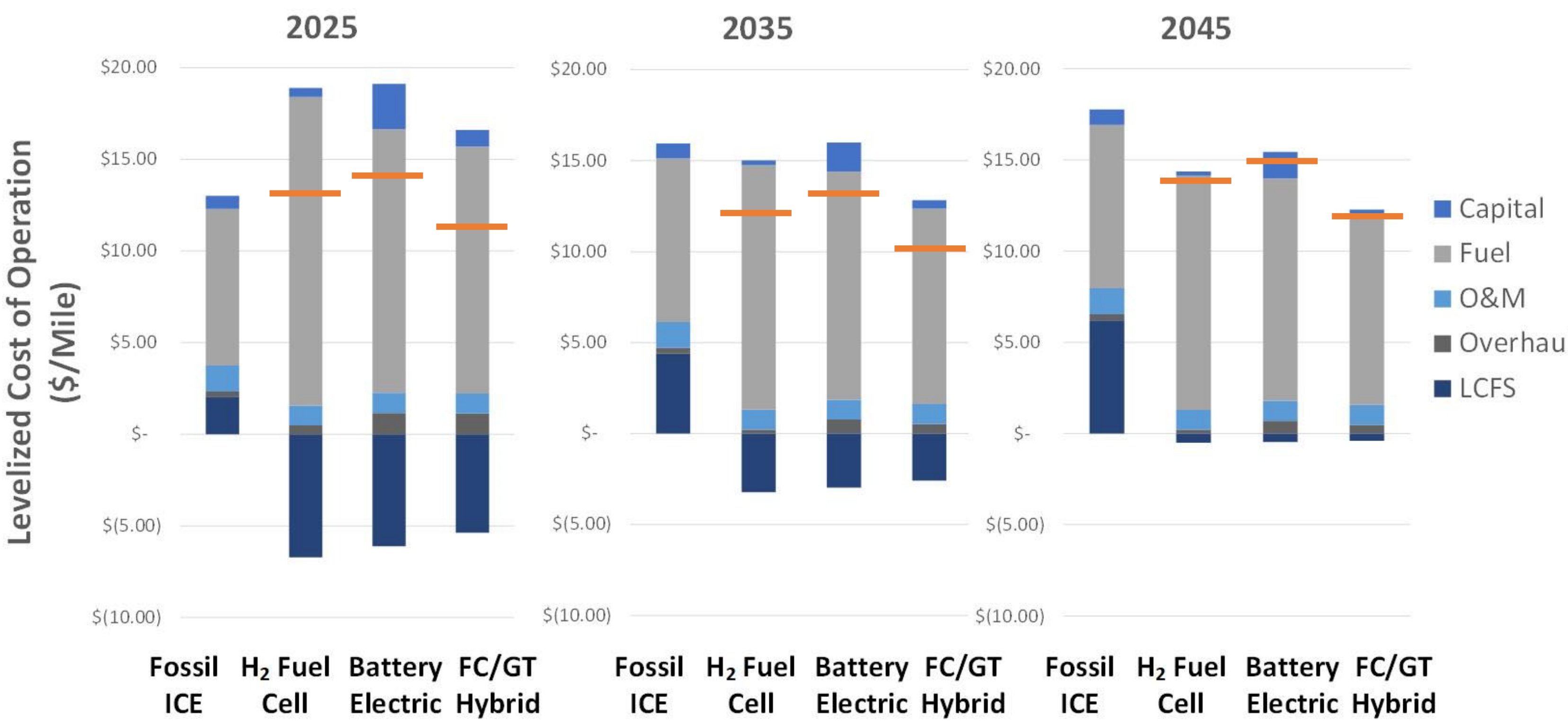
Line Haul – With Fuel Tender





- **Battery electric and fuel cell drive economics project to be comparable and to reach cost parity with diesel before 2025 with LCFS, or increase cost 25% over diesel without LCFS**
- **SOFC-GT hybrid drive preferable on a cost basis w/ and w/out LCFS**
- **On-board storage, packaging and fueling logistics also support hydrogen via SOFC-GT due to energy density and high system efficiency**
- **If SOFC-FT drive is unavailable, FC drive likely preferrable due to longer range, allowing for more centralized infrastructure**
- **100% ultimate adoption of hydrogen expected with initial commercial deployment in the late 2020s**

Line Haul with Fuel Tender – Cost Components



Harbor Craft

Harbor craft Powertrain Parameters and Duty Cycle

Vehicle	Base Fuel	Equipment Count	Powertrain + Fuel Mass (kg)			Powertrain + Fuel Volume (m^3)		
			Diesel	H2 Fuel Cell	Battery Electric	Diesel	H2 Fuel Cell	Battery Electric
Ocean Tug	Diesel	7	111,732	94,996	111,732	154	154	112
Assist Tug	Propane	13	57,835	47,441	54,437	93	93	54
Commercial Fishing	Diesel	95	10,742	8,841	10,783	16	16	11
Ferry	Diesel	12	7,386	4,252	14,971	31	31	15

Vehicle	Operational Days Between Fueling		
	Diesel	H2 Fuel Cell	Battery Electric
Ocean Tug	21	7	1.5
Assist Tug	21	7.5	1.6
Commercial fishing	53	20	4.5
Ferry	1*	1*	1*
*Ferry operation: fuel for 1 day operation			

- Other alternative fuels are under consideration by ship operators
- Hydrogen is least dense but easiest to use

LOHC couple	B.p., deg C	Wt. % H	Energy density, kWh/L	E^0, V	η, %
Synthetic gasoline	69-200	16.0	**9.7**	-	-
Biodiesel	340-375	14.0	**9.2**	-	-
Methanol	64.7	12.6	4.67	1.18	96.6
Ethanol	78.4	12.0	**6.30**	1.15	97.0
Formic acid (88%)	100	3.4	2.10	1.45	105.6
Ammonia	-33.3	**17.8**	**4.32**	1.17	88.7
Hydrazine hydrate	114	8.1	**5.40**	**1.61**	**100.2**
Liquid hydrogen	-252.9	100	2.54	1.23	83.0

G.Soloveichik, *Beilstein J. Nanotechnol.* **2014**, *5*, 1399

Harbor Craft Commercial Readiness of ZEV Platforms

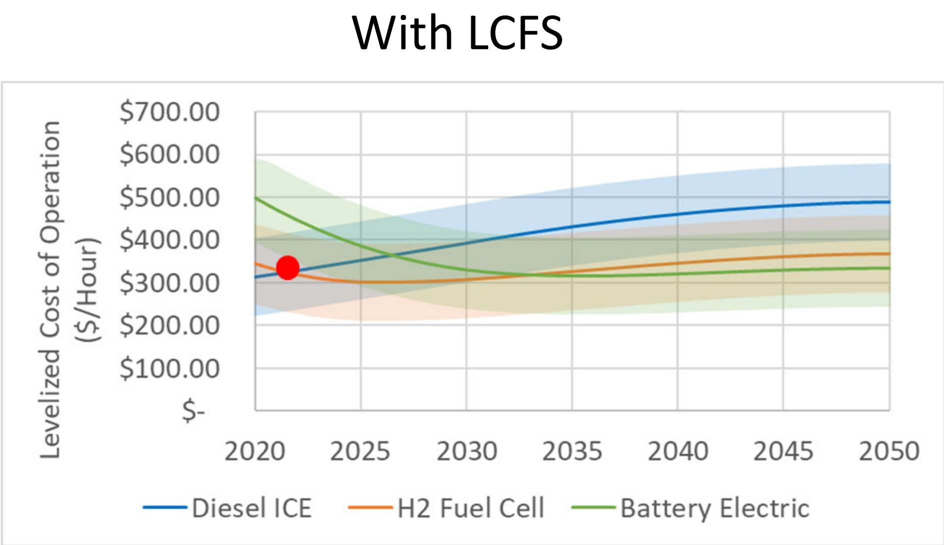
Hydrogen

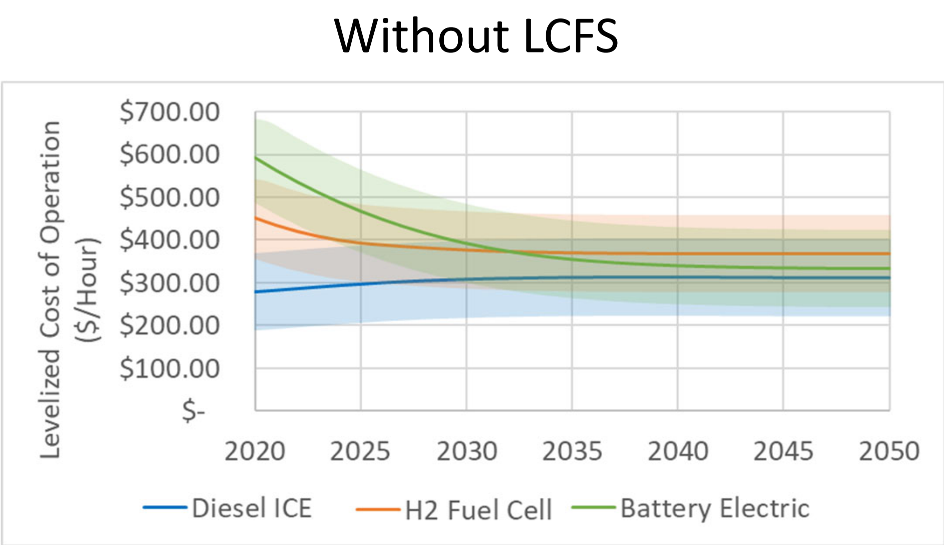
- Hydrogen propulsion systems have been designed for tugboat, ferry, and fishing boat applications.
- Pushboat construction occurring at Port of Lüneburg, Berlin, Germany
- Hydrogen combustion tug being built for Port of Antwerp and Port of Ijmuiden
- Golden Gate Zero Emission Marine "Water-Go-Round" ferry demonstration
- Other ferry demonstrations: HySeas III (Scotland), MF Hydra (Norway), FreCO2ast (Norway), NYK H2 (Japan), Sea Change (CA), Hydro Bingo (Japan).

Electric

- Electric tugboat demonstrations in San Diego and New Zealand.
- Electric ferries are available today
- Range/speed limitations must be accounted for

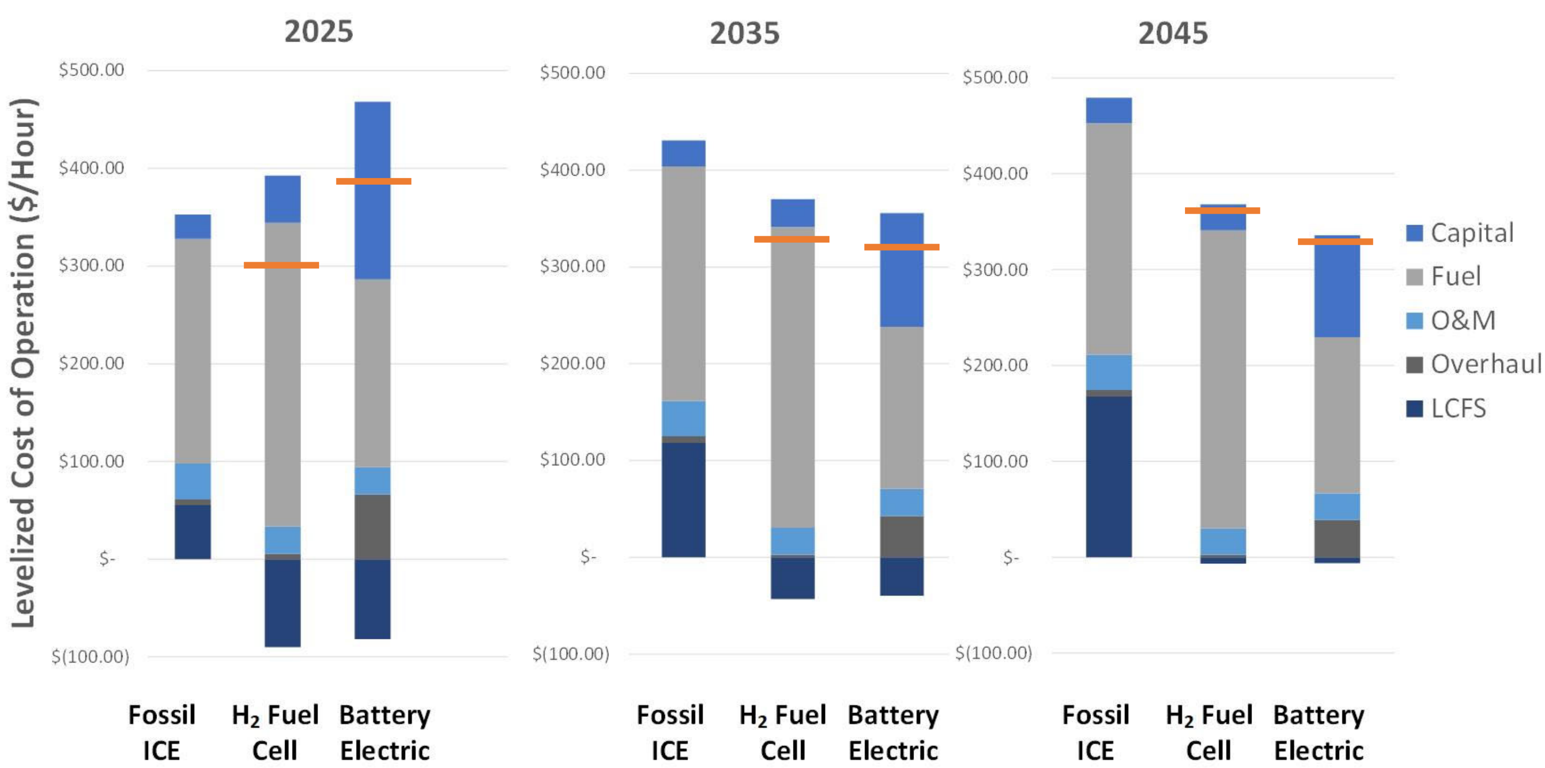
Ocean Tug



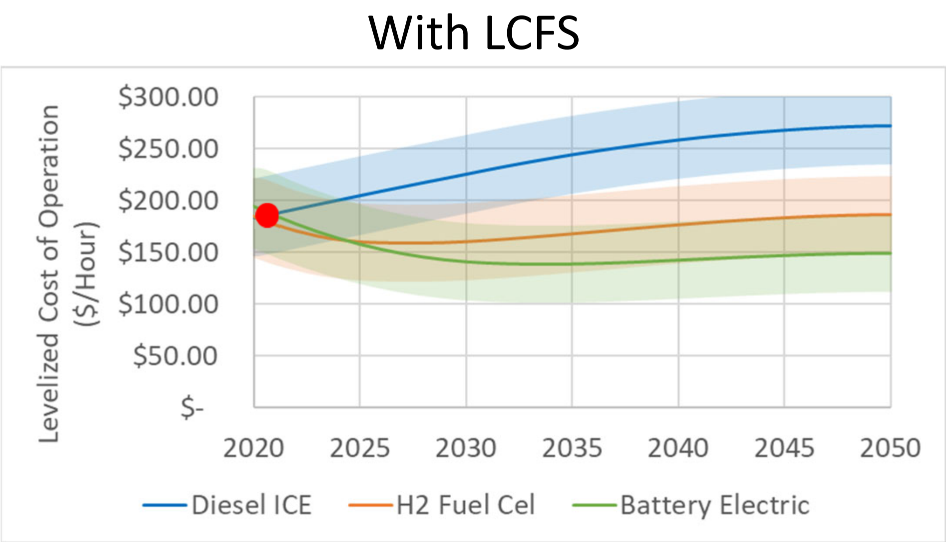


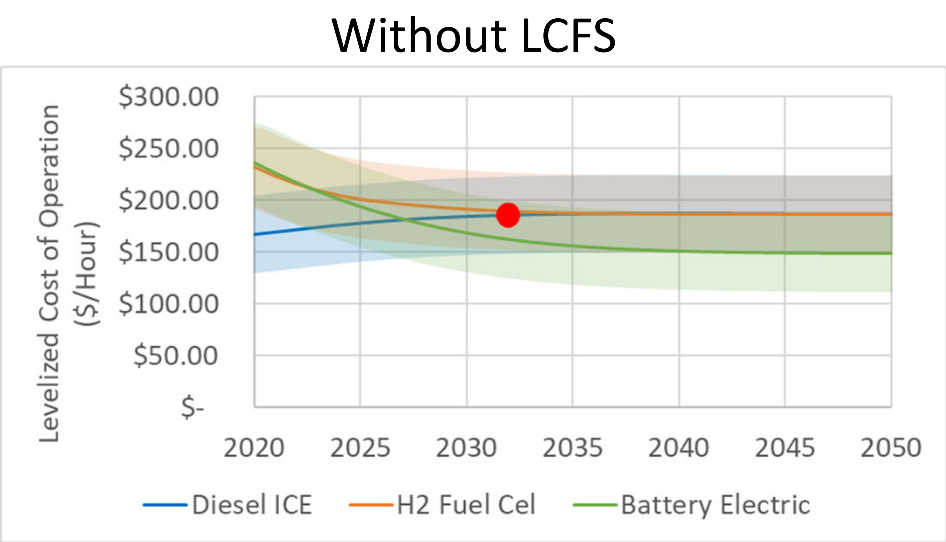
- **Battery electric and fuel cell drive economics project to be comparable and to reach cost parity with diesel before 2025 with LCFS, or increase cost 20% over diesel without LCFS**
- **On-board storage, packaging, and range requirements support hydrogen. Batteries achieve lower cost due to mass/weight limits. Operation must change for both ZNE powertrains, but H2 based powertrains are more flexible and provide longer ranges.**
- **100% ultimate adoption of hydrogen expected with initial commercial deployment in late 2020s, early 2030s**

Ocean Tug – Cost Components



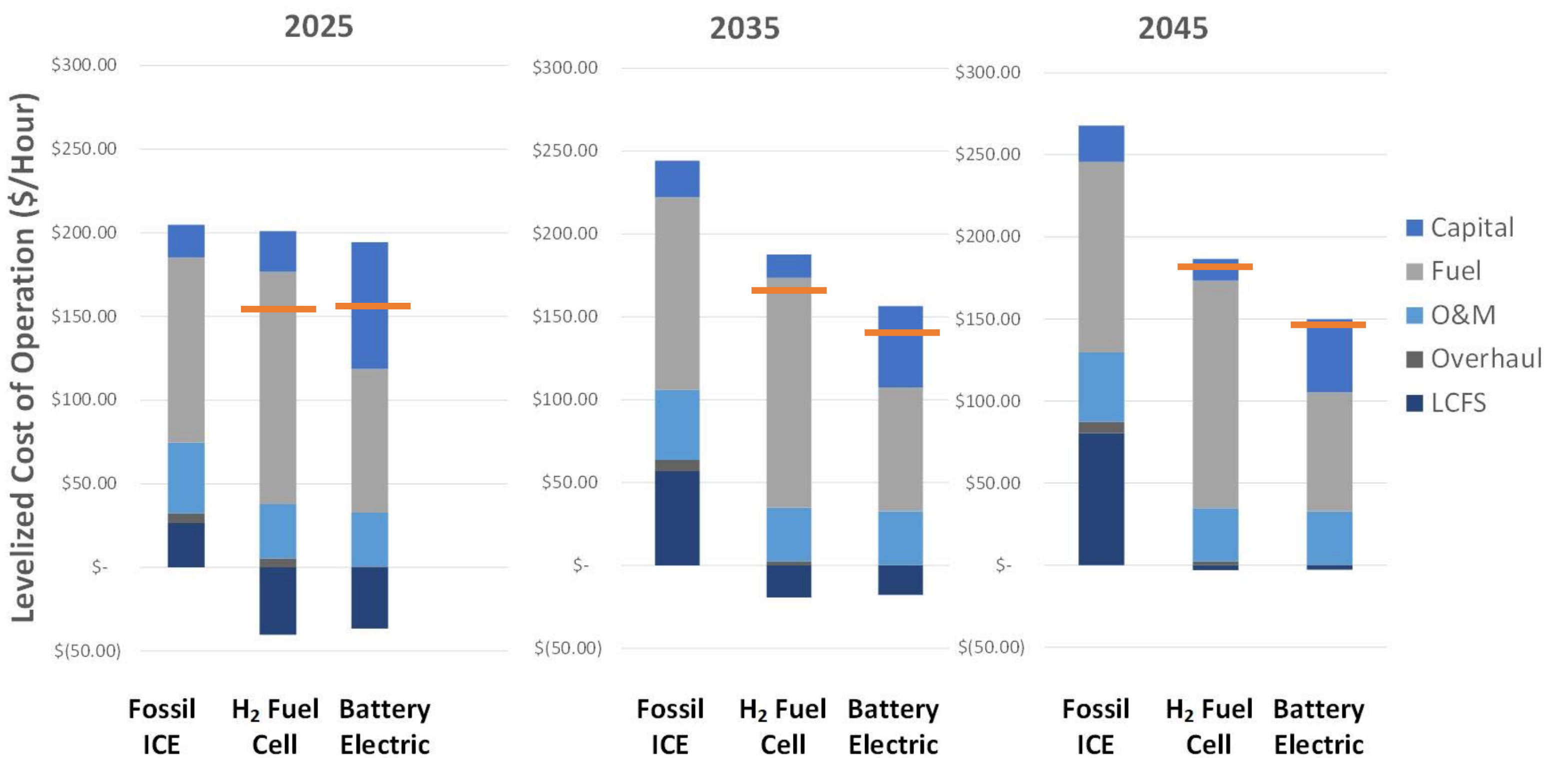
Assist Tug



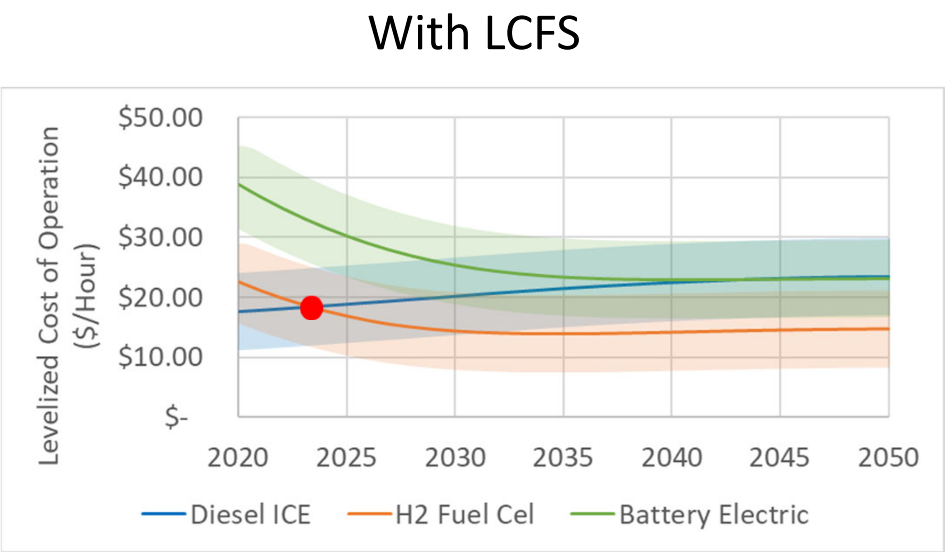


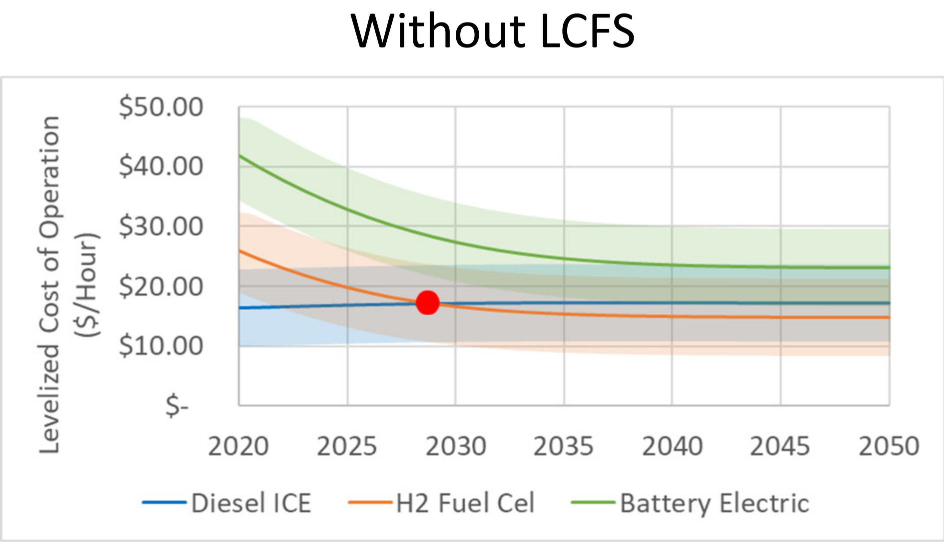
- **Battery electric and fuel cell drive economics project to be comparable and to reach cost parity with diesel before 2025 with LCFS. Battery electric achieves lower cost without LCFS**
- **On-board storage, packaging, and range requirements support hydrogen. Batteries achieve lower cost due to mass/weight limits. Operation must change for both ZNE powertrains, but H2 based powertrains are more flexible and provide longer ranges.**
- **100% ultimate adoption of hydrogen expected with initial commercial deployment in late 2020s, early 2030s**

Assist Tug – Cost Components



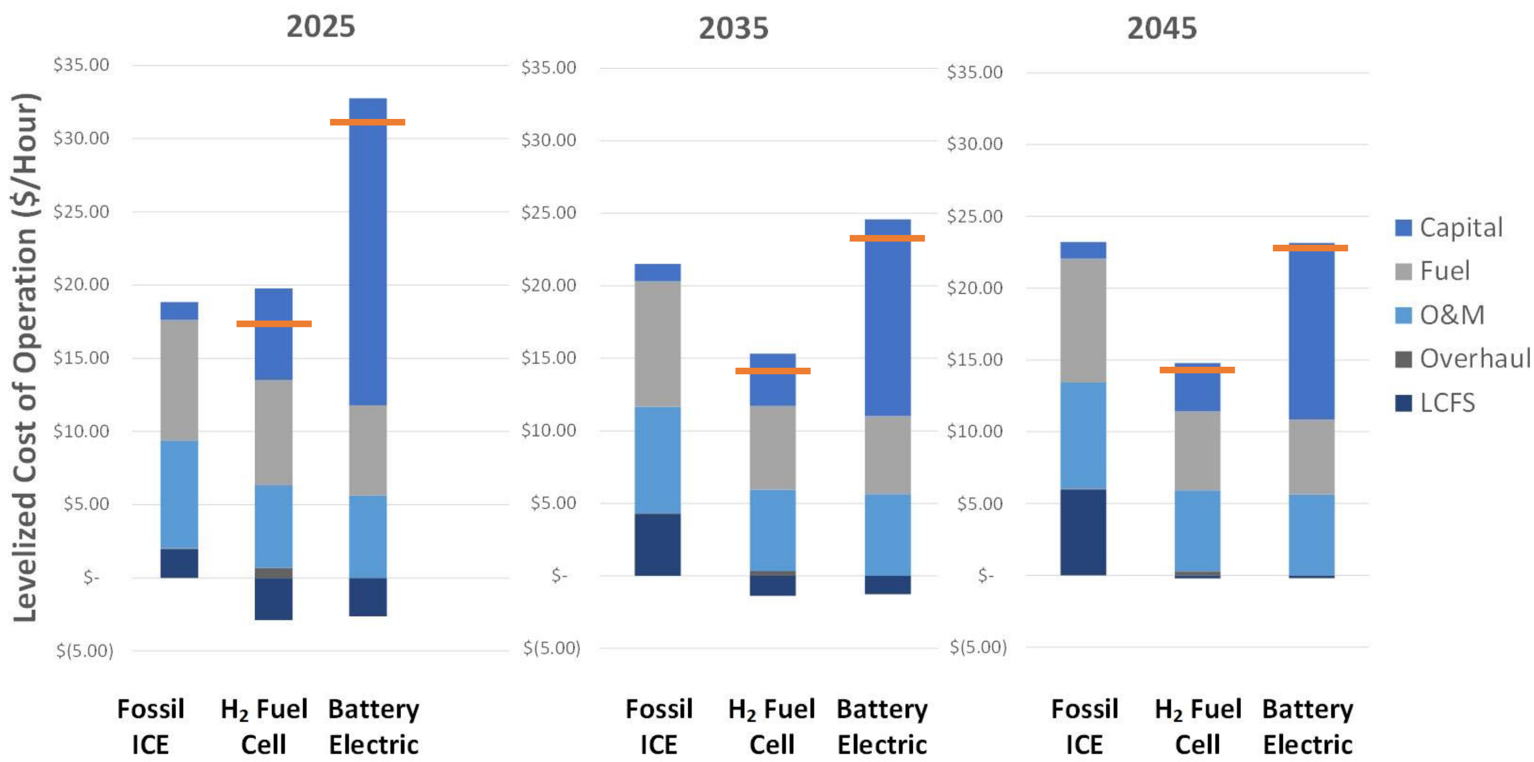
Commercial Fishing





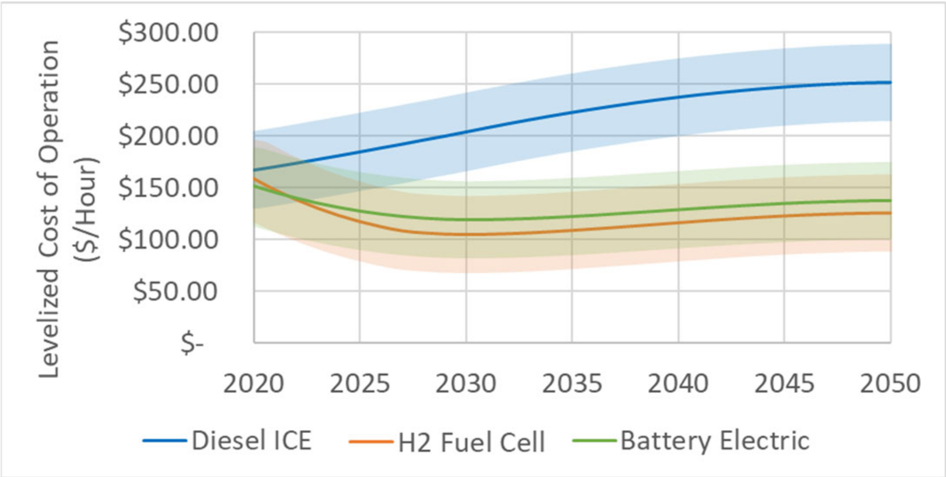
- **Fuel cell drive economics project to be superior to battery electric and to reach cost parity with diesel before 2025 with LCFS and 2030 without LCFS.**
- **On-board storage, packaging, and range requirements support hydrogen. Battery systems approach fishing operational range and practical boats would need to carry backup systems to enable safe operation.**
- **100% ultimate adoption of hydrogen expected with initial commercial deployment in late 2020s, early 2030s**

Commercial Fishing – Cost Components

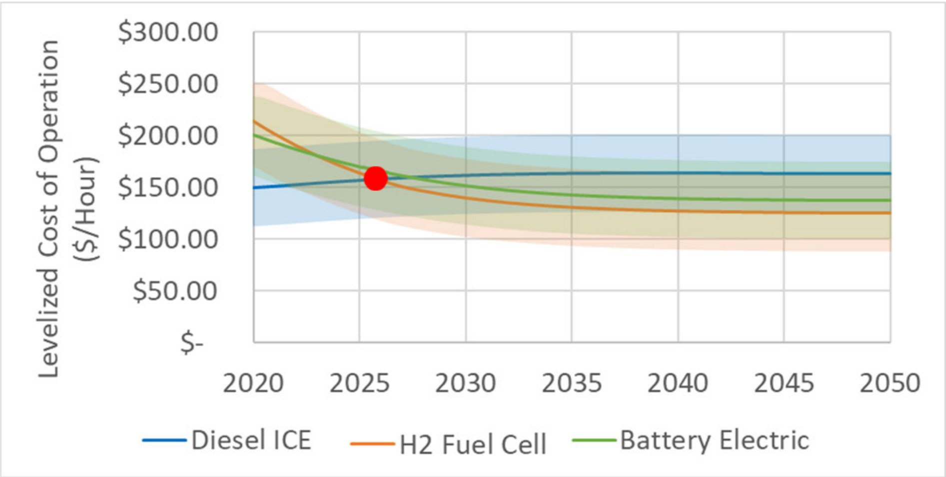


Ferry

With LCFS

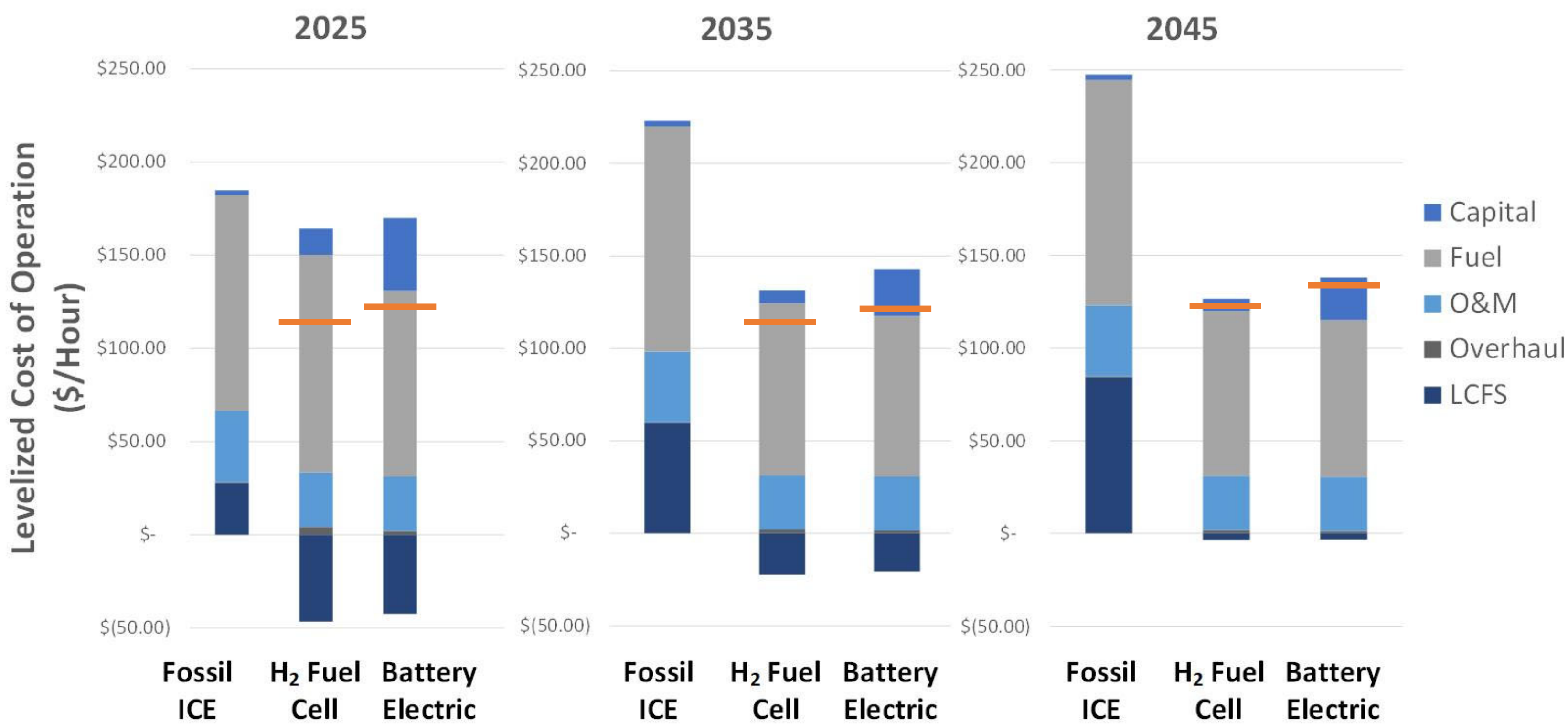


Without LCFS



- **Battery electric and fuel cell drive economics project to be comparable and to reach cost parity with diesel before 2025 with LCFS, or before 2030 without LCFS**
- **POLA/POLB speed and range requirements support hydrogen. Battery electric only feasible if ferry speed is reduced, battery swapping occurs, or if ferry fleet size is increased.**
- **100% ultimate adoption of hydrogen expected with initial commercial deployment in late 2020s, early 2030s**

Ferry – Cost Components



Ocean Going Vessels

Ocean Going Vessels Commercial Readiness of ZEV Platforms

Hydrogen

- Hydrogen propulsion systems have been designed for cruise applications for both propulsion and hotel loads.
- Containership fuel cell "Project Seashuttle" under development in Norway for trips between Poland and Sweden
- Diesel powered LH2 carrier Suiso Frontier developed and operating between Australia and Japan
- HyShip project in Norway includes LH2 powered ship and fuel bunkering design.
- HyEnergy project in Australia to result in the design of a compressed gas H2 ship

Battery

- Demonstrations and development are planned. However, batteries are unsuitable for medium to long distance OGV applications

Ocean Going Vessels

OGV Type	Avg. Engine Size (MW)	Annual H2 Demand (kg/year)
Auto Carrier	14	17,629,500
Bulk	7.3	11,165,350
2000 TEU	21	33,930,750
4000 TEU	44	72,864,000
8000 TEU	64	136,896,000
9000 TEU	56	44,114,000
23000 TEU	76	1,748,000
Cruise	51	47,213,250
Tanker - Chemical	9	12,190,000
Aframax + Suexmax	50	50,312,500
All Others		273,848,350
Total		701,911,700

- Results assume 14 transpacific trips/year
- Must use liquid H_2
- PEMFC efficiency comparable to heavy fuel oil
- Consider higher efficiency SOFC-GT powertrain
- Cruise ship range: ~1500 nm
- All others:
  - Transpacific: 6000 nm
  - Panama Canal: 1500 nm

Spiegelgracht

Ship/Powertrain Details
- Bulk Cargo
- 12 MW
- 2,350 m^3
- 1,837 tonnes

https://www.fleetmon.com/vessels/suomigracht_9288057_34764/

Colombo Express

- 8,750 TEU
- 68.6 MW
- 15,086 m^3
- 13,131 tonnes

https://www.marinetraffic.com/en/ais/details/ships/shipid:134576/mmsi:211433000/imo:9295244/vessel:COLOMBO_EXPRESS

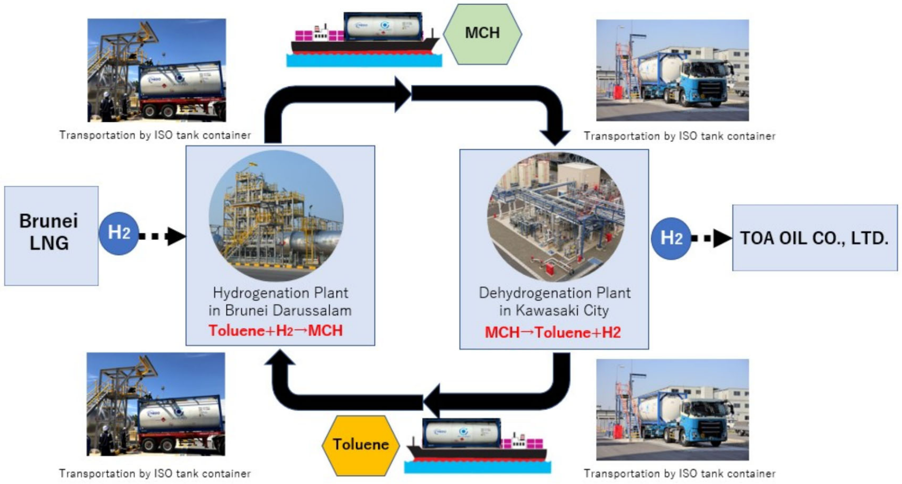
Emma Maersk

- 14,000 TEU
- 80.1 MW
- 18,615 m^3
- 15,082 tonnes

https://www.marinetraffic.com/en/ais/details/ships/shipid:159196/mmsi:220417000/imo:9321483/vessel:EMMA_MAERSK

Decarbonization Strategies of Logistic Companies

- **Maersk**
  - **Building 8 large OGVs to operate on hydrogen derived methanol by 2024.**
  - **Nominal capacity of approx. 16,000 containers**
- **NYK Line**
  - **World's first global hydrogen supply chain demonstration projects via LHC – MCH.**
  - **Collaboration with Chiyoda SPERA H2 Technology**
- **Hyundai Glovis**
  - **Build hydrogen supply chain to introduce clean hydrogen and green ammonia.**
  - **Collaboration with Air Products.**

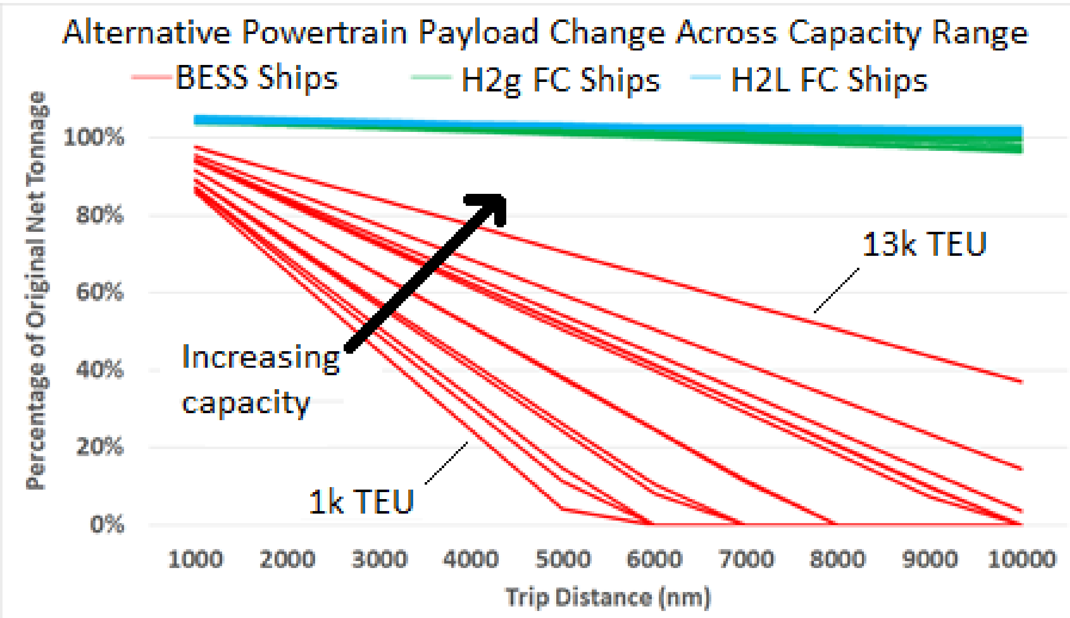


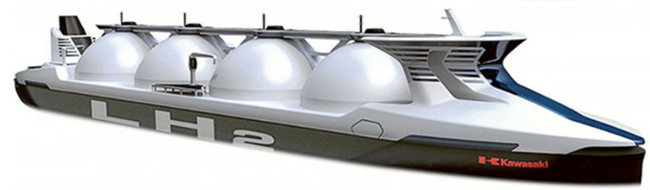
Sources:
[A.P. Moller - Maersk accelerates fleet decarbonisation with 8 large ocean-going vessels to operate on carbon neutral methanol | Maersk]
[World's First Global Hydrogen Supply Chain Demonstration Project Starts in Earnest | NYK Line]
[Hyundai Glovis to build hydrogen supply chain with Air Products - The Korea Economic Daily Global Edition (kedglobal.com)]

Battery Drive Displaces Dramatically More Cargo than RH2 or derivatives NH3 and MeOH

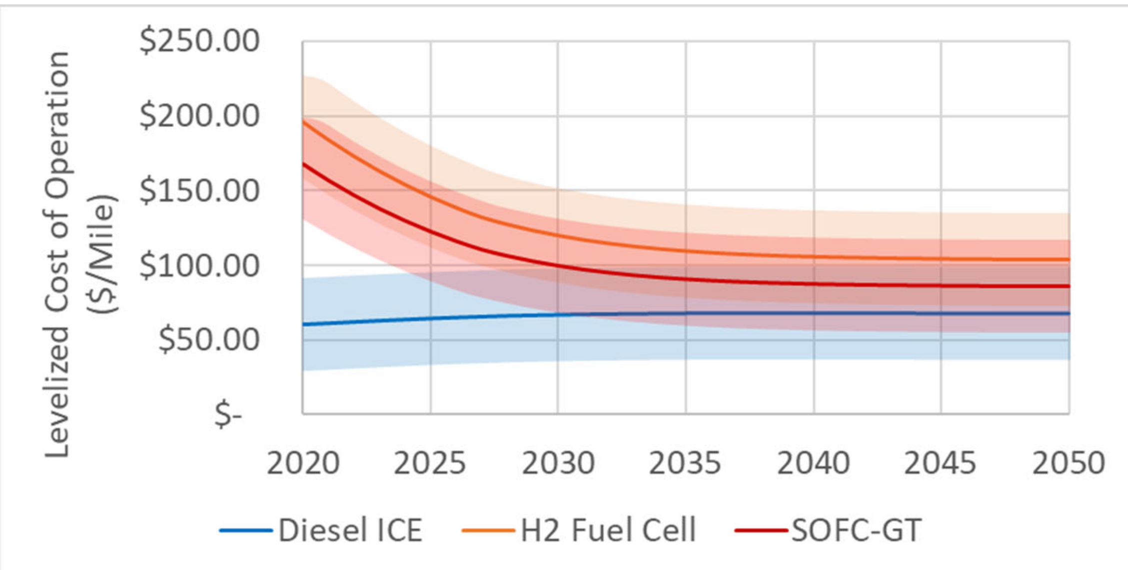
Electrification of Ocean Going Vessels

- Batteries Compared to Hydrogen and Fuel Cells for Cont





Spiegelgracht – Transpacific Bulk Cargo



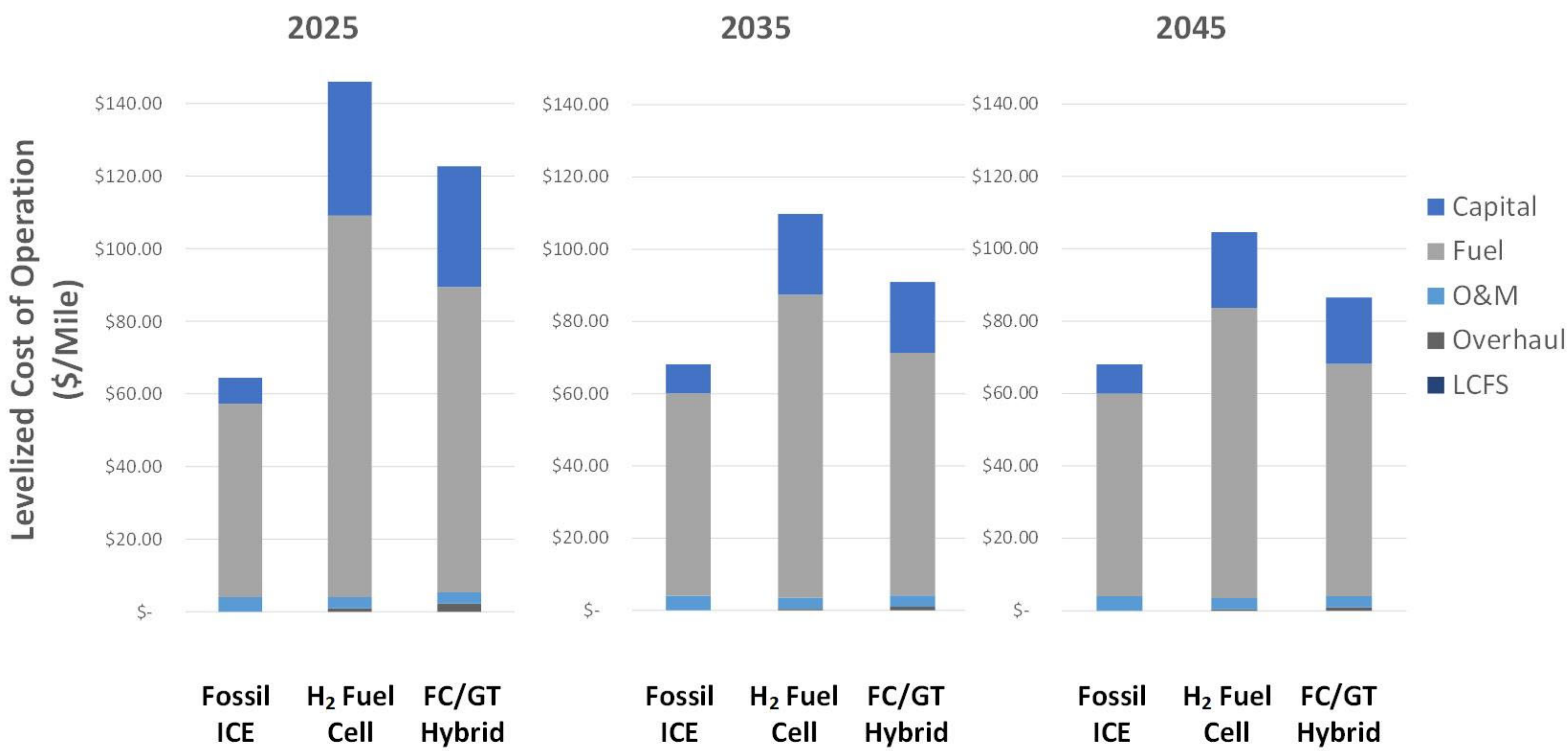
Current Powertrain Details

- 12 MW
- 2,350 m^3
- 1,837 tonnes

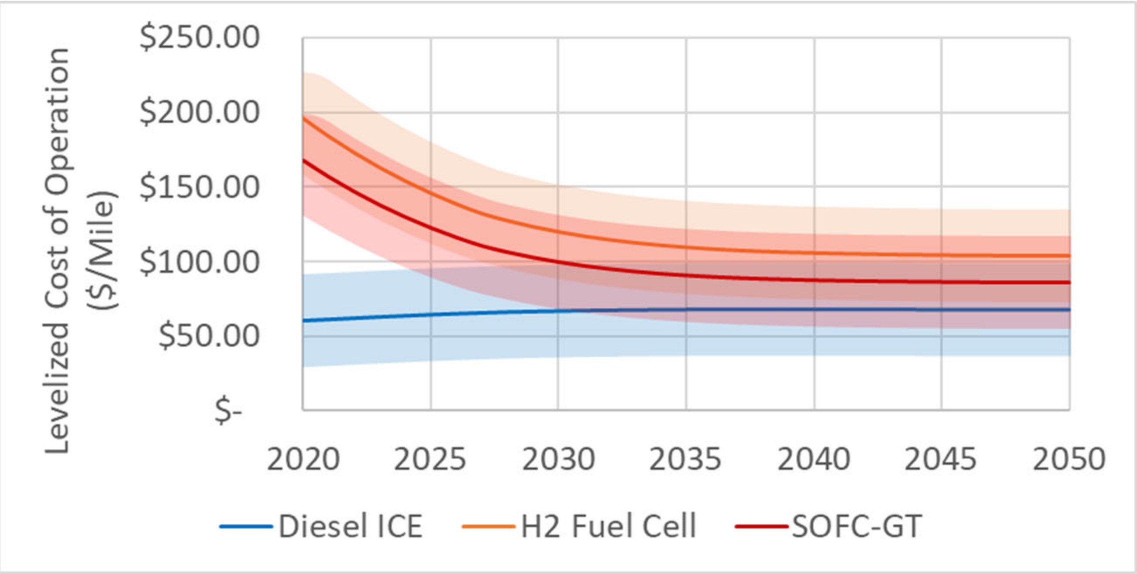
Powertrain	Size (m^3)	Mass (tonne)
Fuel Oil	558	335
PEMFC	2,207	1,116
Battery	8,763	8,764
SOFC-GT	1,782	1,613

- PEMFC reaches parity at $200/tonne cost of carbon
- SOFC-GT hybrid at $100/tonne

Spiegelgracht Bulk Cargo – Cost Components



Colombo Express –Transpacific 8,750 TEU



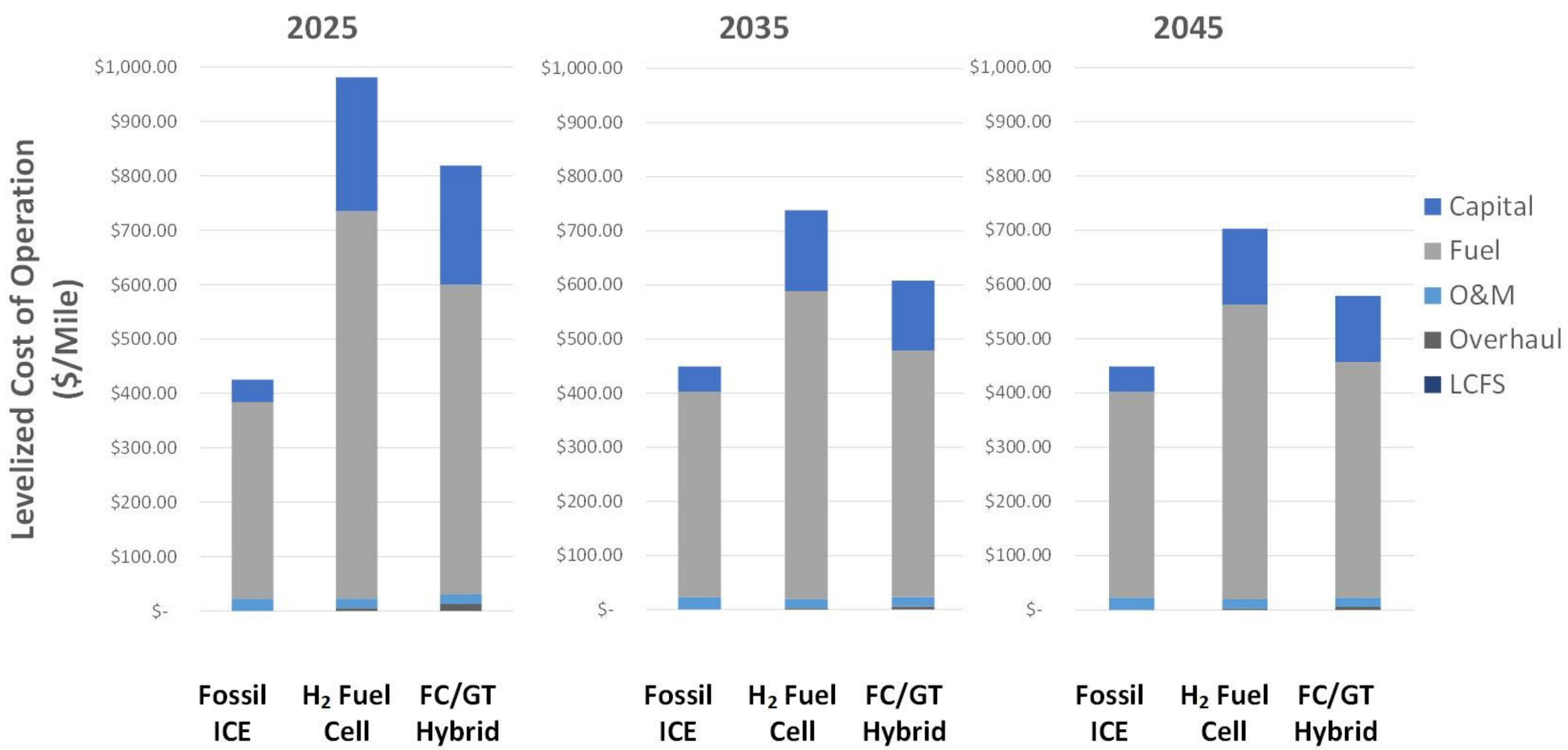
Current Powertrain Details

- 68.6 MW
- 15,086 m^3
- 13,131 tonnes

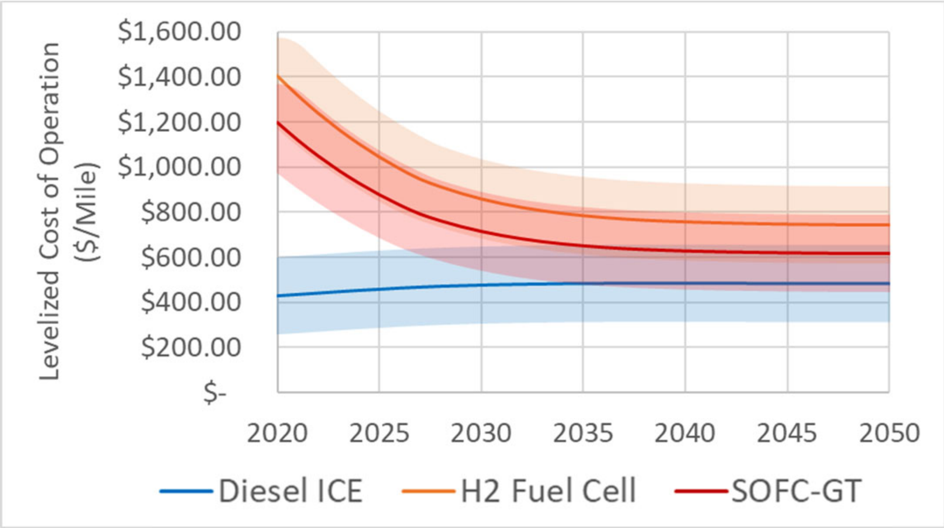
Powertrain	Size (m^3)	Mass (tonne)
Fuel Oil	3,545	2,222
PEMFC	14,741	10,565
Battery	59,364	59,364
SOFC-GT	11,885	10,873

- PEMFC reaches parity at $200/tonne cost of carbon
- SOFC-GT hybrid at $100/tonne

Colombo Express 8,750 TEU – Cost Components



Emma Maersk–Transpacific 14,000 TEU



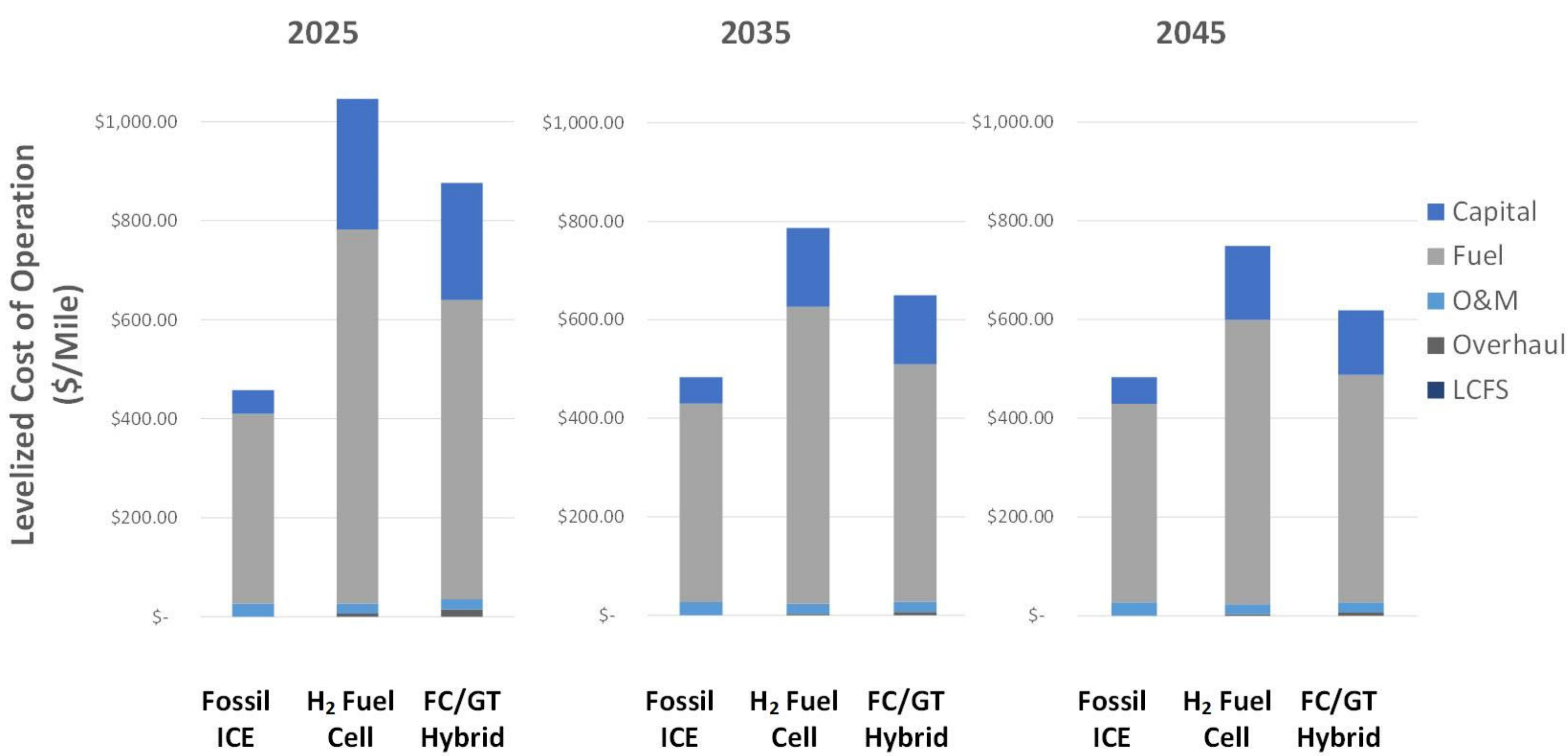
Current Powertrain Details

- 80.1 MW
- 18,615 m^3
- 15,082 tonnes

Powertrain	Size (m^3)	Mass (tonne)
Fuel Oil	3,893	2,384
PEMFC	15,766	11,286
Battery	63,007	63,000
SOFC-GT	12,720	11,572

- PEMFC reaches parity at $200/tonne cost of carbon
- SOFC-GT hybrid at $100/tonne

Emma Maersk 14,000 TEU – Cost Components



Appendix B: International Demonstration Activity

Research Performed by Gladstein Neandross and Associates

Research Summary Information

- **Total number of projects: 60**
  - **Cargo handling equipment: 15 (25%)**
  - **Harbor craft: 14 (24%)**
  - **Heavy-duty vehicles: 7 (12%)**
  - **Locomotives: 8 (13%)**
  - **Ocean going vessels: 10 (17%)**
  - **Miscellaneous: 5 (9%)**

- **Projects range from 2008 into the 2030s, 40 of the 60 projects (67%) are either currently in progress or expected to occur in the near future**

Research Summary Information

- **Geographic range**
  - North America: 23 (38%)
    - ✓ Canada, California, New York, New Jersey, Texas, Illinois, Hawaii, and Washington
  - Asia: 10 (17%)
    - ✓ China and Japan
  - Europe: 23 (38%)
    - ✓ Spain, Denmark, Germany, Belgium, Scotland, Norway, France, England, Netherlands, and Finland
  - Australia: 3 (5%)
  - Not specified: 2 (3%)

- **Funding breakdown**
  - Privately funded: 2 (3%)
  - Publicly/government funded: 37 (62%)
  - Funding information not available: 21 (35%)

Cargo Handling Equipment

Yard Trucks

PANYNY BYD Electric Yard Truck Demo (2017)

LOCATION: Port of New York and New Jersey; New York, New York and Newark, New Jersey; USA

Project Details

- **Equipment Demonstrated:** Yard Truck
- **Project Partners:** BYD, Red Hook Container Terminal
- **Fuel Type:** Battery Electric
- **Funding Received ($):** N/A
- **Funding Source:** N/A
- **URL:** https://www.masstransitmag.com/technology/press-release/12328808/byd-motors-llc-demo-begins-of-byd-electric-yard-truck-at-port-authority-of-new-york-and-new-jersey
- https://www.panynj.gov/port/en/our-port/sustainability/pilot-and-demonstration.html
- https://metroairportnews.com/red-hook-container-terminal-heavy-duty-zero-emission-battery-electric-terminal-tractors/

Project Description

PANYNJ demoed a battery-electric F Class 8 yard truck over several weeks as a one-to-one replacement for the diesel yard truck. The truck has a 10+ hour operating range on a single charge. Results indicate predictive run time between 37 and 109 hours.

In 2022, the Red Hook Container Terminal deployed 10 BYD heavy-duty zero-emission battery-electric terminal tractors. After their first full quarter of operating, the fleet achieved an 81% decline in fuel costs and a 90% drop in CO_2 emissions, all while achieving 100% uptime.

Developing, Demonstrating, and Testing Advanced Ultra-Low-Emission Natural Gas Engines in Port Yard Trucks (2019-2020)

LOCATION: Port of Los Angeles, Los Angeles and Wilmington, CA, USA

Project Details

- **Equipment Demonstrated:** Yard Truck
- **Project Partners:** SCAQMD-TOA, National Renewable Energy Lab, POLA, PMSA, EverPort Terminal Services, California Cartage, Cummins Westport, Cummins Engine Company, Clean Energy/CNGYP, SoCal Gas, Renewable Natural Gas Coalition, CEC, GNA, UC-Riverside CE-CERT
- **Fuel Type:** LNG
- **Funding Received ($):** $1,383,270
- **Funding Source:** California Energy Commission
- **URL:** https://www.energy.ca.gov/sites/default/files/2021-07/CEC-500-2021-037.pdf

Project Description

The purpose of this project was to (1) demonstrate and emissions-test two yard tractors equipped with the emerging ISB6.7 G natural gas engine in a typical seaport cargo handling operation, while comparing results with other yard tractor options; and (2) demonstrate and assess the efficacy of UC Riverside's novel sensor that can measure natural gas fuel quality and potentially enable automatic engine adjustments in real-time.

Both types of liquefied natural gas tractors had lower NOx emissions than the diesel tractor. Cummins Westport Inc. was able to certify the B6.7N engine to the most stringent 0.02 grams per brake horsepower-hour NOx heavy-duty on-road emission level. Demonstration results corroborated that the two B6.7N-equipped tractors performed as well as the L9N-equipped yard tractors while improving fuel efficiency by 15 to 20 percent. Capacity Trucks indicates that commercialization of near-zero emission natural gas yard tractors will focus on the B6.7N rather than the larger L9N. This project has shown that liquefied natural gas yard tractors with the B6.7N can provide an operationally feasible, low NOx alternative to diesel units for use by California marine terminal operators.

Zero Emissions for California Ports (2019-2022)

LOCATION: Port of Los Angeles, Los Angeles, CA, USA

Project Details

- **Equipment Demonstrated:** Yard Trucks
- **Project Partners:** GTI, REV Group (Capacity), BAE Systems, Ballard Power Systems, ZEN Clean Energy Solutions, Hydrogen Technology Energy Corporation, Frontier Energy, TraPac
- **Fuel Type:** Hybrid Fuel Cell-Electric
- **Funding Received ($):** $11,805,413
- **Funding Source:** CARB contributions with matching funds from GTI
- **URL:** https://ww2.arb.ca.gov/sites/default/files/movingca/pdfs/zecap.pdf

Project Description

ZECAP was intended to demonstrate to port terminal operators that fuel cell powered, zero-emissions yard trucks are a safe, reliable, and operationally preferable solution to meet the port's clean air action plan. GTI and its technology partners deployed two hybrid fuel cell – electric yard trucks at the Port of Los Angeles, operated by TraPac for 12 months. The two Capacity Trailer Jockey Series TJ9000 gliders were configured with a BAE Systems HDS200 powertrain, the Ballard Power Systems FCveloCity, and the HTEC's stationarily-placed mobile tube-trailer hydrogen fueling system.

C-PORT Zero-Emissions Demonstration Project (2018-2021)

LOCATION: Port of Long Beach, Long Beach, CA, USA

Project Details

- **Equipment Demonstrated:** Yard Truck, Top Handler
- **Project Partners:** Academy of Global Logistics, Air Products, BYD, CARB, CNHTC/Sinotruk UQM, Grant Farm, Green Education, Inc., ILWU, Kalmar Transpower, Long Beach Container Terminal, Loop Energy, SCAQMD, SSA Marine, Taylor Machine Works, Tetra Tech, Meritor, UCR CE-CERT, Long Beach City College
- **Fuel Type:** Hybrid Fuel Cell-Electric, Battery Electric
- **Funding Received ($):** $5,249,820
- **Funding Source:** CARB
- **URL:** https://polb.com/download/379/zero-emissions/6761/c-port-zero-emissions-demonstration-fact-sheet-082918.pdf
- https://ww2.arb.ca.gov/lcti-commercialization-polb-road-technology-c-port-demonstration

Project Description

The Port of Long Beach, in partnership with SSA Marine and Long Beach Container Terminal, will demonstrate five zero-emissions cargo handling vehicles. The demonstration included three never-before-tested battery-electric top handlers and was intended to feature a unique, head-to-head comparison of a hydrogen fuel cell yard truck versus a battery-electric yard truck, however only a battery-electric yard truck was deployed.

Three battery-electric top handlers, developed Taylor Machine Works and BYD:

- One top handler was deployed at Pier E and two top handlers were deployed at Pier J
- 931 kWh lithium iron phosphate (LiFePO4) battery pack
- One 200 kW BYD charging station per top handler
- Top handler was deployed at Pier E and two top handlers were deployed at Pier J

One battery-electric yard truck, developed by Kalmar Global and TransPower:

- Deployed at Pier E
- 154 kWh LiFePO4 battery pack
- 70 kW charging station

The Sinotruk hydrogen yard tractor project was halted in 2019 due to numerous technical, engineering, and safety issues.

Cranes

“Hydrogen + 5G" Smart Ecological Terminal (2020-2021)

LOCATION: Qingdao Port, Qingdao, Shandong, China

Project Details

- **Equipment Demonstrated:** RMG Crane
- **Project Partners:** CCRC Yangtze, Qingdao Port, Qingdao New Qianwan Container Terminal, Shanghai Academy of Spaceflight Technology, Shanghai Institute of Space Power-Sources, Shandong Port Group
- **Fuel Type:** Hydrogen Fuel Cell
- **Funding Received ($):** Not Applicable
- **Funding Source:** Not Applicable
- **URL:** http://www.fuelcellchina.com/cnt_53.html

Project Description

Display of hydrogen-powered crane technology and system by developing a hydrogen energy-driven solution for the fueling of equipment needed for the operation of a large port. The system reduces carbon emissions by some 3.5kg and sulfur dioxide emissions by 0.11kg per TEU. Calculated based on an annual capacity of 3 million TEUs, 21,000 tons of carbon dioxide and 640 tons of sulfur dioxide emissions are estimated to be cut annually. Shanghai Academy of Spaceflight Technology, Shanghai Institute of Space Power-Sources (811) 60kW fuel cell recently accomplished the installation in the world’s first “Hydrogen + 5G” Smart Ecology Harbor-Qingdao Port. The fuel cell provides “rail-mounted gantry crane (RMG)” power with clean and efficiency container lifting operations. This is the first-time fuel cell has been used in RMG globally at a port.

Hydrogen Fuel Cell Mobile Crane (2021 – Ongoing)

LOCATION: Shanghai Port, Shanghai, Zhejiang, China

Project Details

- **Equipment Demonstrated:** RTG Crane
- **Project Partners:** Shanghai Zhenhua Heavy Industries (ZPMC), Shanghai International Port Group
- **Fuel Type:** Hydrogen Fuel Cell
- **Funding Received ($):** Not Applicable
- **Funding Source:** Not Applicable
- **URL:** https://www.seatrade-maritime.com/ports-logistics/zpmc-launches-trial-worlds-first-hydrogen-fuel-cell-mobile-crane

Project Description

The hydrogen fuel cell powered mobile crane, independently developed by ZPMC, is the world's first successful application of hydrogen fuel cell hybrid power system for mobile crane, filling the gap in the application of hydrogen energy battery in port machinery industry, realizing net-zero emissions of CO2 of the equipment and contributing to build green port machinery equipment. The equipment provides electricity for the whole machine by hydrogenation, and only discharges purified water during the whole process.

Zero-Emissions Terminal Equipment Transition Project (2018-2022)

LOCATION: Port of Long Beach, Long Beach, CA, USA

Project Details

- **Equipment Demonstrated:** RTG Crane, Yard Tractor, Drayage Truck
- **Project Partners:** SSA Marine, Port of Long Beach, Total Transportation Services, Inc., Southern California Edison, International Brotherhood of Electrical Workers, Long Beach City College, Clean Energy Fuels, Cavotec, BYD Motors, US Hybrid, International Transportation Service, Long Beach Container Terminal
- **Fuel Type:** Battery Electric
- **Funding Received ($):** $9,700,000
- **Funding Source:** California Energy Commission
- **URL:** https://www.pacificports.org/electric-stacking-cranes-enter-service-at-port-of-long-beach/
- https://polb.com/download/379/zero-emissions/6768/zero-emissions-terminal-equipment-transition-fact-sheet-081018.pdf

Project Description

Each piece of equipment will be demonstrated in a rigorous seaport environment for 12 months. The project is anticipated to be completed at the end of 2020.

Repower nine rubber-tire gantry cranes at SSA Marine Pier J to full electric power.

Develop and demonstrate 12 zero-emissions yard tractors.

Demonstrate the feasibility of “smart” yard tractor charging to support widespread deployment of zero-emissions equipment.

Convert four liquefied natural gas drayage trucks to plug-in hybrid capability, or electric trucks with an LNG range extender.

The Port is partnering with Long Beach City College and the International Brotherhood of Electrical Workers to evaluate existing workforce development and training programs and to determine the extent to which they support the Port’s goal of transitioning to zero-emission port equipment by 2030.

Communicate and engage with communities on the benefits of and progress made toward zero emissions through public education events, tours, news releases, equipment demonstrations and other outreach.

Collaborative Industry-Academia-Government R&D Project for Solving Common Challenges Toward Dramatically Expanded Use of Fuel Cells and Related Equipment (2022-2026)

LOCATION: Port of Los Angeles, Los Angeles, CA, USA

Project Details

- **Equipment Demonstrated:** RTG Crane
- **Project Partners:** PACECO Group (PACECO), Mitsui E&S Machinery (MES-M), Toyota Tsusho, Toyota Tsusho America, Hino Motor Manufacturing, and Hino Motor Manufacturing USA
- **Fuel Type:** Hydrogen Fuel Cell
- **Funding Received ($):** Not Applicable
- **Funding Source:** Privately funded grant through New Energy and Industrial Technology Development Organization (NEDO)
- **URL:** https://www.worldcargonews.com/news/news/mitsui-es-machinery-gets-grant-for-zero-emissions-rtg-67023

Project Description

Mitsui E&S Machinery Co., Ltd. and its US subsidiary, PACECO® Corp., were awarded a grant by the New Energy and Industrial Technology Development Organization (NEDO), Japan's largest public management organization, for the development and deployment of a hydrogen fuel cell powered ZE Transtainer RTG. A three-year demonstration is expected to begin in the Port of Los Angeles by Q2 2024.

Top Handler

Fuel Cell Hybrid Electric Top Loader (2018-2022)

LOCATION: Port of Los Angeles, Los Angeles, California, USA

Project Details

- **Equipment Demonstrated:** Top Loader
- **Project Partners:** CTE, Hyster-Yale Group, Nuvera, WAVE, Fenix Marine Services, California Climate Investments, Port of LA
- **Fuel Type:** Hydrogen Fuel Cell
- **Funding Received ($):** $6,500,000
- **Funding Source:** California Climate Investments
- **URL:** https://ww2.arb.ca.gov/sites/default/files/movingca/pdfs/fuelcelltoploader.pdf

Project Description

The project team, led by Center for Transportation and the Environment (CTE), built and demonstrated an electric top loader with fuel cell range extension and wireless charging capability. The objective of the project was to promote future commercialization that will significantly transform the industry while achieving greenhouse gas, criteria pollutant, and toxic emission reduction. The demonstration will generate performance data that will be analyzed to determine the project's effectiveness in meeting its objectives. The electric top loader is built and integrated by Hyster-Yale Group; two 45-kW fuel cell engines built by Nuvera Fuel Cells, LLC; 250-kW wireless charging equipment built by Wireless Advanced Vehicle Electrification (WAVE); and IGX Group provided hydrogen fuel via mobile refueler. Fenix Marine Services is demonstrating the electric top loader in regular container handling service at the Port of Los Angeles.

Everport Advanced Cargo-Handling Demonstration Project (2020-2021)

LOCATION: Port of Los Angeles, Los Angeles, CA, USA

Project Details

- **Equipment Demonstrated:** Top Handler
- **Project Partners:** Port of Los Angeles, Everport Terminal Services, Taylor Machine Works
- **Fuel Type:** Battery Electric
- **Funding Received ($):** $4,500,000
- **Funding Source:** CEC
- **URL:** https://www.portoflosangeles.org/references/news_100219_top_handler
- https://www.portoflosangeles.org/references/news_080520_top_handlers_performing_well

Project Description

The Port of Los Angeles hosted the demonstration of the world's first zero-emissions top handlers. The two pre-commercial battery-electric top handlers were designed and built in the U.S. by Taylor Machine Works. Taylor's zero-emissions top handlers run on a one-megawatt battery designed to operate for up to 18 hours between charges. Each top handler has a data logger for tracking hours of operation, charging frequency, energy usage and other performance indicators. They were tested at the Everport Container Terminal. As of August 2020, the zero-emission top handlers were being used in daily operations at the Everport Container Terminal, and the Port was pleased with the performance results.

H2Ports (2022-2025)

LOCATION: Port of Valencia, Valencia, Spain

Project Details

- **Equipment Demonstrated:** Top Handler
- **Project Partners:** Mediterranean Shipping Company, Hyster-Yale's Group, Fundacion Valenciaport, Centro Nacional del Hidrogeno, MSC Terminal Valencia, Grup Grimaldi, Atena Distretto Alta Tecnologia Energia Ambiente, Ballard Power Systems Europe, Enagas, CNH2
- **Fuel Type:** Hydrogen Fuel Cell
- **Funding Received ($):** €4,000,000 ($4,190,400)
- **Funding Source:** Fuel Cells and Hydrogen 2 Joint Undertaking, EU Horizon 2020
- **URL:** https://h2ports.eu/pilots/

Project Description

Hyster Hydrogen-Powered Reach Stacker, The hydrogen 4x4 terminal yard tractor was designed and developed by the ATENA consortium with the support of ENEA, Cantieri del Mediterraneo and the Universities of Naples ‘Parthenope’ and Salerno. Moile Hydrogen Refuelling Station developed by CNH2. The hydrogen Fuel Cell Reach Stacker will be tested at MSC Terminal Valencia (MSCTV). As the first of its kind, the Reach Stacker will be able to support continuous operations while providing zero emissions and achieving comparable full shift performance to a conventional Reach Stacker powered with a diesel engine.

Forklifts

HyLIFT-DEMO (2011-2014)

LOCATION: Copenhagen & Herning, Denmark; Halle, Belgium; Frankfurt, Hamburg, Cologne, Oppenau, Germany

Project Details

- **Equipment Demonstrated:** Forklift, Tow Tractor
- **Project Partners:** Ludwig-Boeljow-Systemtechnik GmbH, Nel Hydrogen AS, Dantruck A/S, Danmarks Tekniske Universitet, Tuv Sud Automotive GmbH, Linde AG, JRC-Europen Commission, Stiftelsen Sintef, FAST, Tuv Sud Industrie Service
- **Fuel Type:** Hydrogen Fuel Cell
- **Funding Received ($):** EUR 2,877,294 ($2,166,147)
- **Funding Source:** Fuel Cells and Hydrogen Joint Undertaking (FCH JU)
- **URL:** https://cordis.europa.eu/project/id/256862/reporting
- http://www.hylift-europe.eu/

Project Description

HyLIFT-DEMO addressed a specific and proven value proposition where hydrogen and fuel cells replace use of diesel / LPG in 2.5-3.5 ton material handling vehicles where batteries cannot provide a satisfying solution. The project was conducted by a consortium of European partners that for several years have invested significantly in developing and testing hydrogen and fuel cell technology for material handling vehicles. In total, 11 vehicles were tested. The ambition and driving force of the HyLIFT-DEMO activities and partners were to enable a following deployment and market introduction.

HyLIFT-EUROPE, the follow-up project of HyLIFT-DEMO, started in 2013 and will conduct the demonstration of up to 200 material handling vehicles in growing fleets through 2018 with €6,896,871 in EU funding.

HyLIFT-EUROPE (2013-2018)

LOCATION: Vendin Le Viel, France; Saint-Cyr-en-Val, France

Project Details

- **Equipment Demonstrated:** Forklift, Tow Tractor
- **Project Partners:** Carrefour, Prelocenter, Ludwig bolkow systemtechnick, STILL, Air Liquide, European Hydrogen Association, Federazione delle associazioni scientifiche e techniche
- **Fuel Type:** Hydrogen Fuel Cell
- **Funding Received ($):** EUR 6,896,871
- **Funding Source:** Fuel Cells and Hydrogen Joint Undertaking (FCH JU)
- **URL:** http://www.hylift-europe.eu/
- https://cordis.europa.eu/project/id/303451/reporting

Project Description

The aim of HyLIFT-EUROPE is to demonstrate more than 200 fuel cell materials handling vehicles and associated refuelling infrastructure at 2 sites in Europe, making it the largest European trial of hydrogen fuel cell materials handling vehicles so far. The project efforts are in continuation of the previous FCH JU supported HyLIFT-DEMO project. In the HyLIFT-EUROPE project the partners demonstrate fuel cell systems in materials handling vehicles from the partner STILL and other non-participating OEMs.

Toyota FC Forklift Overseas Demo (2018)

LOCATION: TMCA's Auto Parts Warehouse, Melbourne, Victoria, Australia

Project Details

- **Equipment Demonstrated:** Forklift
- **Project Partners:** Toyota Motor Corporation, Toyota Motor Corporation Australia, Toyota Material Handling Australia
- **Fuel Type:** Hydrogen Fuel Cell
- **Funding Received ($):** Not Applicable
- **Funding Source:** Not Applicable
- **URL:** https://www.toyota-industries.com/news/2018/11/20/005008/

Project Description

Toyota Motors Corporation conducted its first overseas proving tests with two FC forklifts jointly with Toyota Motor Corporation Australia Ltd. at TMCA's auto parts warehouse located in Melbourne, starting by the end of 2018. Toyota Industries FC forklifts are powered with the same FC cells used in Mirai, TMC's FCEV, and are equipped with an FC system designed exclusively for forklifts featuring high power generation efficiency. This was the first proving test overseas for the forklift equipped with Toyota Industries FC system. The FC forklift's maintenance and operation were be monitored via Toyota Material Handling Australia to investigate operation methods and business potential and prepare for wider sales and use in other countries.

Zero- and Near-Zero-Emission Freight Facilities (2019-2023)

LOCATION: Port of Los Angeles, Los Angeles, CA, USA and Port of Hueneme, Port Hueneme, CA, USA

Project Details

- **Equipment Demonstrated:** Drayage Truck, Yard Truck, RTG Crane
- **Project Partners:** Kenworth Truck Company, Toyota Motor North America, Shell Oil Products USA, Port of Hueneme, South Coast Air Quality Management District and National Renewable Energies Laboratory, Toyota Logistics Services, UPS, Total Transportation Services Inc. and Southern Counties Express, Coalition for a Safe Environment
- **Fuel Type:** Hydrogen Fuel Cell
- **Funding Received ($):** $41,122,260
- **Funding Source:** California Air Resource Board
- **URL:** https://www.greencarcongress.com/2019/04/20190423-tfcv.html

Project Description

Toyota and Kenworth are deploying a total of 10 trucks as part of the Zero and Near-Zero Emissions Freight Facilities Project (ZANZEFF), hauling cargo received at the Ports of Los Angeles and Long Beach, throughout the LA Basin. The first Kenworth/Toyota Fuel Cell Electric Truck (FCET) under the ZANZEFF project will began drayage operations in Q4 2019, increasing the ports' zero emission trucking capacity and further reducing the environmental impact of drayage operations. The Fuel Cell Electric truck utilizes the Kenworth T680 Class 8 model combined with Toyota's fuel cell electric technology and is part of the ZANZEFF project. Pioneered by the Port of Los Angeles with leading support from Toyota, Kenworth, and Shell, the endeavor provides a large-scale "Shore-to-Store" plan and a hydrogen fuel-cell-electric technology framework for freight facilities to structure operations for future goods movement.

Harbor Craft

Tugboats

Foss Maritime Diesel/Electric Tugboat (2009)

LOCATION: Port of Los Angeles, Los Angeles, CA, USA and Port of Long Beach, Long Beach, CA, USA

Project Details

- **Equipment Demonstrated:** Assist Tug
- **Project Partners:** Foss Maritime, Port of Long Beach, Port of Los Angeles
- **Fuel Type:** Diesel Electric Hybrid
- **Funding Received ($):** $1,400,000
- **Funding Source:** Port of Long Beach, Port of Los Angeles
- **URL:** https://ww2.arb.ca.gov/sites/default/files/2020-12/hybridreport1010_remediated.pdf

Project Description

The Carolyn Dorothy was the first hybrid tugboat delivered in 2009. Since then, it has been retrofitted as a Diesel-Electric Hybrid Twin ASD. With 3,600 horsepower and 58 tons of bollard pull, the Carolyn Dorothy assists ships in the Columbia Snake River region. Carolyn Dorothy which plies Southern California's San Pedro Bay, emits 73 percent less soot, 51 percent fewer nitrogen oxides, and 27 percent less carbon dioxide than a standard tug of comparable size.

e5 Tug (2019-2022)

LOCATION: Port of Yokohama, Yokohama, Japan and Port of Kawasaki, Kawasaki, Japan

Project Details

- **Equipment Demonstrated:** Assist Tug
- **Project Partners:** Tokyo Kisen Co., Ltd. and e5 Lab Inc; Ministry of Land, Infrastructure, Transport and Tourism; ClassNK; Tanker Co.; Exeno Yamamizu Corporation; Mitsubishi Corporation
- **Fuel Type:** Hydrogen Fuel Cell
- **Funding Received ($):** Not Applicable
- **Funding Source:** Not Applicable
- **URL:** https://e5ship.com

Project Description

Tokyo Kisen Co., Ltd. and e5 Lab Inc. have jointly developed the new concept design of "e5 Tug," electric propulsion harbor tugboat powered by large-capacity battery and a hydrogen fuel cell. The e5 Tug is a harbor tug fully electrified and designed to minimize environmental footprint. Initially the team considered equipping the tugboat with hydrogen fuel cells for enhanced environmental performance and conducted a risk assessment (HAZID analysis) in cooperation with the project partners, but decided not to adopt the cells. The Taiga is slated for completion in December 2022 and will operate mainly in the ports of Yokohama and Kawasaki as a harbor tug after delivery.

Hydrogen-Powered Push Boat – Elektra (2022 – Ongoing)

LOCATION: Westhafen and the Port of Lüneburg, Berlin, Germany

Project Details

- **Equipment Demonstrated:** Assist Tug
- **Project Partners:** The Department of Maritime Systems Design and Operations at the Technical University of Berlin, BEHALA (Berliner Hafen- und Lagerhausgesellschaft), Hermann Barthel, Ballard Power Systems
- **Fuel Type:** Hydrogen Fuel Cell
- **Funding Received ($):** $8,850,000 USD (€8m)
- **Funding Source:** German Federal Ministry of Transport and Digital Infrastructure
- **URL:** https://www.est-floattech.com/elektra-first-hydrogen-canal-tug/

Project Description

With 750 kilos of high-pressure compressed hydrogen on board and a battery capacity of about 2,500 kilowatt hours, the push boat has a range of about 215 nautical miles when pushing its companion barge, the Ursus. Combined with one other charging station, this is enough range to carry Elektra along the region's waterways to the Ruhr, Hamburg and Stettin. The first stations for the changeover of the push boat's hydrogen tanks and electric charging stations will be operational in Berlin's Westhafen and the port of Lüneburg in 2023. The removable H2 tanks can be exchanged with the onboard crane, and the shore power cables are mechanically handled to save time. Testing of the Elektra will initially take place in the Berlin area. Beginning in 2023, the tests will be continued on long-distance routes towards Hamburg.

Hydrotug (2022-2023)

LOCATION: Armón Shipyard, Navia, Spain and Port of Antwerp, Flanders, Belgium

Project Details

- **Equipment Demonstrated:** Assist Tug
- **Project Partners:** CMB.TECH, Armón Shipyards, Port of Antwerp-Bruges, ABC, BeHydro
- **Fuel Type:** Hydrogen, Diesel
- **Funding Received ($):** Not Applicable
- **Funding Source:** Not Applicable
- **URL:** https://cmb.tech/divisions/marine/hydrotug

Project Description

A world-first project, CMB.TECH's Hydrotug will be the first tugboat in the world to be powered by combustion engines that burn hydrogen in combination with diesel. The Hydrotug consists of two BeHydro V12 dual fuel medium speed engines that can run on hydrogen and traditional fuel. This ground-breaking development will be used by Port of Antwerp-Bruges as an important step in the transition to a sustainable, climate neutral port by 2050 and will be operational in the first quarter of 2023.

Ferries

Water-Go-Round (2018-2021)

LOCATION: Port of San Francisco, San Francisco, California

Project Details

- **Equipment Demonstrated:** Ferry
- **Project Partners:** Golden Gate Zero Emission Marine, Switch E-Maritime, Bay Ship & Yacht, BAE Systems, Cummins, Red and White Fleet, Port of San Francisco, and Sandia National Laboratories
- **Fuel Type:** Hydrogen Fuel Cell
- **Funding Received ($):** $3,000,000
- **Funding Source:** CARB contributions with matching funds from Switch E-Maritime
- **URL:** https://ww2.arb.ca.gov/sites/default/files/movingca/pdfs/hydrogenferry.pdf

Project Description

The Water-Go-Round is a 70-foot aluminum catamaran, designed by Incat Crowther that has a top speed of 22-knots and a capacity to transport up to 84 passengers. The vessel was built in Alameda, CA by Bay Ship & Yacht. The fuel cell electric propulsion system from BAE Systems is be powered by three independent 120 kW fuel cells built by Hydrogenics. The Water-Go-Round has enough on-board hydrogen storage capacity for up to two days of normal operation

Ferguson Marine Hydrogen Ferry - HySeas III (2018-2022)

LOCATION: Kirkwall Harbor, Orkney Islands, Scotland

Project Details

- **Equipment Demonstrated:** Ferry
- **Project Partners:** Ferguson Marine, University of St Andrews, Orkney Islands Council, Kongsberg Maritime, Ballard Power Systems Europe, McPhy, DLR and Interferry, Caledonian Maritime Assets, European Ferry Company, Arc Silea
- **Fuel Type:** Hydrogen Fuel Cell
- **Funding Received ($):** EUR 7,886,390.14 ($8,261,782.31)
- **Funding Source:** EU Horizon 2020 Research and Innovation Fund
- **URL:** https://www.hyseas3.eu/the-project/

Project Description

HySeas III is the final part of a three-part research program that began in 2013 looking into the theory of hydrogen powered vessels (HySeas I), followed by a detailed technical and commercial study to design a hydrogen fuel cell powered vessel (Hyseas II 2014-2015). The HySeas III project brough to market the world's first zero-emission, sea-going ferry powered by hydrogen from renewable sources. The project developed and validated this advanced ferry concept, but a prototype version has been constructed and demonstrated in operational service with co-funding from the regional Government in Scotland (which will commission the building of the ferry).

MF Hydra (2019-2021)

LOCATION: Hjelmeland-Nesvik, Stavanger, Rogaland, Norway

Project Details

- **Equipment Demonstrated:** Ferry
- **Project Partners:** LMG Marin, Weston, Ballard Marine Center of Expertise, Linde, LMG Marin, Norled, Sembcorp Marine
- **Fuel Type:** Hydrogen Fuel Cell
- **Funding Received ($):** Not Applicable
- **Funding Source:** Not Applicable
- **URL:** https://absinfo.eagle.org/acton/attachment/16130/f-bd25832f-8a70-4cc9-b75f-3aadf5d5f259/1/-/-/-/-/hydrogen-as-marine-fuel-whitepaper-21111.pdf

Project Description

MF Hydra uses liquid hydrogen, two 200 kW fuel cells, a 1.36 MWh battery, and two 440 kW diesel generators. The hydrogen tanks and the fuel cells are located on top of the ferry. The hydrogen is trucked from Leipzig in Germany. The ferry qualifies as zero emission waterborne transport, or ZEWT. MF Hydra is 82.4 meters long with the ability to carry up to 300 passengers and 80 cars. Delivered in June 2021.

Hav Hydrogen FreeCO2ast Project (2020-2023)

LOCATION: Bergen to Kirkenes, Bergen, Norway

Project Details

- **Equipment Demonstrated:** Ferry
- **Project Partners:** Havyard Group, Norwegian Electrical Systems, Havyard Design, Havila, Linde, PowerCell, Sintef Ocean, Prototech
- **Fuel Type:** Hydrogen Fuel Cell
- **Funding Received ($):** NOK 104,300,000 ($10,586,450)
- **Funding Source:** Pilot - E (Research Council of Norway, Innovation Norway, Enova)
- **URL:** https://www.havhydrogen.no/hav-hydrogen/freeco2ast/

Project Description

Bergen-based system integrator Norwegian Electrical Systems (NES) intends to plant a 3.2MW hydrogen fuel cell onto a large tourist ferry currently being designed by Havyard Design for the shipowner Havila. It would be the largest fuel cell ever placed on a major ship, replacing the more frequently used compressed gas. Batteries are planned to store additional energy to make the system fully emissions-free.

NYK Hydrogen Powered Ferry (2020-2024)

LOCATION: Port of Yokohama, Yokohama, Japan.

Project Details

- **Equipment Demonstrated:** Ferry
- **Project Partners:** NYK Line, Toshiba, Eneos, ClassNK, Japanese Government
- **Fuel Type:** Hydrogen Fuel Cell
- **Funding Received ($):** Not Applicable
- **Funding Source:** Not Applicable
- **URL:** https://maritime-executive.com/article/nyk-leads-

Project Description

A Japanese consortium headed by NYK Line plans to develop and deploy a 100-passenger tour boat powered by electric batteries and hydrogen fuel cells. It will be Japan's first fuel cell venture with a vessel this large. The project will entail the development of new shipboard technology, including the fuel supply system and an energy management system to combine power from the battery with power from the fuel cell.

JPNH2YDRO: Dual-Fuel Hydrogen Ferry HydroBingo (2021 – Ongoing)

LOCATION: Tokuyama-Kudamatsu Port, Seto Inland Sea, Yamaguchi, Japan

Project Details

- **Equipment Demonstrated:** Ferry
- **Project Partners:** Tsuneishi Craft & Facilities Co, CMB Tech, Tokuyama
- **Fuel Type:** Hydrogen Fuel Cell, Diesel
- **Funding Received ($):** Not Applicable
- **Funding Source:** Not Applicable
- **URL:** https://www.maritime-executive.com/article/first-dual-fuel-hydrogen-ferry-completed-in-japan

Project Description

Japan's Tsuneishi Craft & Facilities Co. built the new ferry in coordination with CMB.Tech. The vessel, the Hydro Bingo, is a 19-ton two-deck passenger ferry able to transport 80 passengers with a crew of two. The vessel is a catamaran built of aluminum alloy and equipped with a hydrogen co-firing engine that combines the hydrogen with diesel fuel. One of the other innovations used on the vessel is a movable hydrogen storage tank at the rear of the ship. It is designed to supply hydrogen to the engine through a separate line from light oil for co-firing. The advantage that the tank design offers is that there is no need for hydrogen filling equipment and transportation to supply hydrogen. Refueling is done with a trailer via roll-on/roll-off hydrogen storage.

Sea Change: Hydrogen Fuel Cell-Powered Ferry (2021 – Ongoing)

LOCATION: San Francisco Bay, San Francisco, California, USA

Project Details

- **Equipment Demonstrated:** Ferry
- **Project Partners:** Switch Maritime, All American Marine, West Coast Clean Fuels, BayoTech, Zero Emission Industries, ZEI, Cummins, Hexagon Purus, BAE Systoms, XALT
- **Fuel Type:** Hydrogen Fuel Cell
- **Funding Received ($):** $3,000,000
- **Funding Source:** California Air Resources Board (CARB), Privately Funded by SWITCH
- **URL:** https://www.allamericanmarine.com/hydrogen-vessel-launch

Project Description

The new 75-passenger ferry, which is a 70-foot catamaran ferry designed by Incat Crowther, is equipped with a hydrogen fuel cell system from ZEI. The system includes 360 kW of fuel cells from Cummins and 246 kg of hydrogen storage tanks from Hexagon Purus. A 600 kW electric propulsion system from BAE Systems includes 100kWh of lithium-ion battery storage from XALT. It was built at All American Marine and launched in August. The Sea Change is unique in that it uses gaseous hydrogen in its fuel cell. Other demonstrate vessels are burning liquid hydrogen in a more traditional combustion engine. Switch says the Sea Change will use the hydrogen in fuel cells producing electricity to power electric motors for distances up to 300 nautical miles and speeds up to 20 knots. That will give the vessel similar capabilities to similar diesel-powered vessels.

Inland Cargo & Commercial Fishing

Loran (2021 - Ongoing)

LOCATION: Port of Aalesund, Longyearbyen, Tromso, and Batsfjord; Godoy, Alesund, and Tromso, Norway

Project Details

- **Equipment Demonstrated:** Commercial Fishing Vessel
- **Project Partners:** Skipsteknisk, Innovation Norway
- **Fuel Type:** Hydrogen Fuel Cell, Diesel Hybrid
- **Funding Received ($):** NOK 92,500,000 ($9,300,000)
- **Funding Source:** Enova (Ministry of Climate and the Environment)
- **URL:** https://www.shipinsight.com/articles/enova-funds-world-first-hydrogen-powered-fishing-vessel

Project Description

Naval architects and engineers at the Norwegian company Skipsteknisk designed the first hydrogen-powered fishing vessel. The fishing boat will be out at sea for 4-6 weeks in a row and will need more energy sources to cover its power needs. The basic idea for this vessel is container-based storage of hydrogen, two 185 kW fuel cells, and a 2000 kWh battery in addition to conventional diesel engines. The hydrogen auxiliary power is expected to reduce fossil fuel use by 40%.

Zemships: FCS Alsterwasser (2008-2013)

LOCATION: River Alster, Hamburg, Germany

Project Details

- **Equipment Demonstrated:** Inland Passenger Ship
- **Project Partners:** ATG, Hamburg Department for Urban Development, Germanischer Lloyd, Hochbahn, hySOLUTIONS, The Linde Group, Proton Motor Fuel Cell GmbH, Czech Nuclear Research Institute UJV, Hamburg University of Applied Sciences
- **Fuel Type:** Hydrogen Fuel Cell
- **Funding Received ($):** Not Applicable
- **Funding Source:** Not Applicable
- **URL:** https://sectormaritimo.es/wp-content/uploads/2018/01/MS_Alsterwasser.pdf

Project Description

Germany was home to one of the first fuel cell-powered ship demonstrations, the Alsterwasser, a sightseeing passenger ship that operated in Hamburg from 2008 to 2013. The Alsterwasser was considered a technical success, but the project was ended because the hydrogen supply infrastructure failed to materialize. A major lesson learned from this project is that the application and the hydrogen infrastructure must be considered together.

Flagships Project: Zulu, FPS Waal (2022 – Ongoing)

LOCATION: River Seine, Paris, France and Stavanger, Jæren, Norway

Project Details

- **Equipment Demonstrated:** Inland Cargo
- **Project Partners:** Compagnie Fluvial de Transport, VTT Technical Research Centre of Finland, ABB Marine & Ports, Balalrd, LMG Marin, Norled, Sogestion, Sogestran, Westcon Power & Automation, NCE Maritime CleanTech, Pers-Eem, Seam, Future Proof Shipping
- **Fuel Type:** Hydrogen Fuel Cell
- **Funding Received ($):** EUR 5,000,000 ($5,238,000)
- **Funding Source:** EU Research and Innovation Programme Hydrogen Partnership (previously Fuel Cells and Hydrogen 2 Joint Undertaking)
- **URL:** https://www.offshore-energy.biz/flagships-set-to-debut-worlds-1st-hydrogen-powered-commercial-cargo-ship/

Project Description

The European innovation project Flagships is preparing to deploy the world's first commercial cargo transport vessel operating on hydrogen. The ship will be an inland vessel, set to ply the river Seine in Paris, and is scheduled for delivery in September 2021. It will be fitted with by hydrogen power generation system, i.e., hydrogen fuel cells. The hydrogen cargo transport vessel will be owned by French inland shipowner Compagnie Fluvial de Transport (CFT), a subsidiary of the Sogestran Group. The company is currently developing a new business for urban distribution with transport vessels in the Paris area. One Zulu vessel has also been put into operation in Paris, and an additional two Zulu ships are currently under construction for the same market.

Heavy-Duty Vehicles

Drayage Trucks

Hydrogen Fuel-Cell Electric Hybrid Truck Project (2012-2017)

LOCATION: Port of Houston, Houston, Texas, USA

Project Details

- **Equipment Demonstrated:** Drayage Truck
- **Project Partners:** US Hybrid, GTI, University of Texas, United States Department of Energy, H-GAC, EDF, Richardson Trucking, Air Liquide
- **Fuel Type:** Hydrogen Fuel Cell
- **Funding Received ($):** $3,400,000
- **Funding Source:** United States Department of Energy, H-GAC
- **URL:** https://blogs.edf.org/texascleanairmatters/2015/07/07/houston-as-a-hydrogen-haven/
- https://www.osti.gov/servlets/purl/1496037

Project Description

The purpose of the project was to demonstrate three (3) fully developed, operational, advanced vehicle technology prototypes for ON-ROAD goods movement applications. The major vehicle OEM for this demonstration was Navistar International Trucks, with the fuel cell and power control hybrid technology provided and integrated by US Hybrid. CEM was to provide independent data collection and analysis, while EDF would provide education, outreach, and communication for the project. GTI managed the partnership and arranged for hydrogen fuel for the demonstration.

Project had been initially planned with Tyrano HFC trucks from Vision Industries, however the company failed to make delivery and subsequently ceased operations.

In June 2017 the remaining project partners, which now included Air Liquide, agreed that the project would be unlikely to move forward with the vehicle demonstration, primarily due to the lack of a viable cargo truck fleet partner in the Port of Houston area willing to make a sufficient commitment of resources to operate the vehicles for the demonstration. While several of the project objectives were not met and no meaningful operating data was generated, there were useful learnings to be gained from the project (see Final Report).

Zero Emission Cargo Transport II (2014-2023)

LOCATION: Port of Los Angeles, Los Angeles, CA, USA and Port of Long Beach, Long Beach, CA, USA

Project Details

- **Equipment Demonstrated:** Drayage Truck
- **Project Partners:** South Coast Air Quality Management District, US Hybrid, BAE Systems, Kenworth, TransPower, CTE, Hydrogenics, Dewei, Navistar
- **Fuel Type:** Hydrogen Fuel Cell, Hybrid Electric
- **Funding Received ($):** $20,259,820
- **Funding Source:** United States Department of Energy, Funding Partners, Contractors
- **URL:** https://www.energy.gov/sites/default/files/2021-06/elt158_Ha_2021_o_6.7_3.03pm_ls.pdf

Project Description

Using existing ElecTruck developed in ZECT I project as a platform, this project aimed to build an extended range zero-emission truck using fuel cell technology. This project helped to advance the technologies for on-road heavy-duty battery-electric and hybrid-electric systems and to move these technologies closer to commercial readiness. Included in this project is six demonstration trucks including fuel cell range extended and CNG hybrid truck completed demonstration.

Long-Haul Heavy-Duty Trucks

Fast Track Fuel Cell Truck Project "FAST TRACK" (2018-2020)

LOCATION: Port of Los Angeles, Los Angeles and Fontana, California, USA

Project Details

- **Equipment Demonstrated:** Long-Haul Heavy-Duty Truck
- **Project Partners:** gti, OneH2, TTSI, Daylight Transport, TransPower, Frontier Energy, Center for Sustainable Energy, Peterbilt, LOOP, Hydrogenics, California Climate Investments
- **Fuel Type:** Hydrogen Fuel Cell
- **Funding Received ($):** $5,100,000
- **Funding Source:** California Climate Investments
- **URL:** https://ww2.arb.ca.gov/sites/default/files/movingca/pdfs/fasttrack.pdf

Project Description

GTI and its technology partner, TransPower deployed a total of five plug-in hybrid fuel cell-electric Class 8 trucks in Southern California, operated by two major truck fleet operators in a phased rollout. The plug-in hybrid fuel cell-electric trucks were be supported by charging and mobile hydrogen fueling infrastructure at the Port of Los Angeles and in Fontana. The vehicles were be fueled onsite from "drop-and-swap" mobile tube-trailers. Frontier Energy coordinated training, data collection and reporting, and Center for Sustainable Energy coordinated local community outreach.

Mercedes GenH2 Truck (2022-2025)

LOCATION: Company Test Tracks & B462 Road Near Rastatt, Rastatt, Barden-Württemberg, Germany

Project Details

- **Equipment Demonstrated:** Long-Haul Heavy-Duty Truck
- **Project Partners:** Mercedes, Daimler Trucks
- **Fuel Type:** Hydrogen Fuel Cell
- **Funding Received ($):** N/A
- **Funding Source:** N/A
- **URL:** https://www.commercialfleet.org/truck/reviews/mercedes-benz-genh2

Project Description

The GenH2 is the first prototype and has been under the research and development team at Mercedes-Benz Trucks from April 2021, the first trials on the open road are due to start before the end of the year. Customer trials are scheduled for 2023 and from 2027 the first series-produced GenH2 Trucks will be handed over to customers. This is a vehicle meant to operate on a fuel-cell setup and aims to have a range of up to 1,000 km (622 mi) while carrying a load up to 25 tons (50,000 lbs) in weight.

XCIENT Fuel Cell Heavy-Duty trucks (2023)

LOCATION: Port of Oakland, Oakland, CA, USA

Project Details

- **Equipment Demonstrated:** Long-Haul Heavy-Duty Truck
- **Project Partners:** CARB, CEC, Alameda County Transportation, Bay Area Air Quality Management District
- **Fuel Type:** Hydrogen Fuel Cell
- **Funding Received ($):** $41,183,725
- **Funding Source:** California Air Resource Board
- **URL:**https://www.hyundai.com/worldwide/en/company/newsroom/hyundai

Project Description

For Hyundai's NorCAL ZERO project, also known as Zero-Emission Regional Truck Operations with Fuel Cell Electric Trucks, Hyundai Motor teamed with public and private partners in the U.S. to operate 30 units of Class 8 XCIENT Fuel Cell trucks, starting from the second quarter of 2023. This will be the largest commercial deployment of Class 8 hydrogen-powered fuel cell trucks in the U.S.

Volvo Trucks Hydrogen Fuel Cell Semis (2022 – Ongoing)

LOCATION: Not specified

Project Details

- **Equipment Demonstrated:** Long-Haul Heavy-Duty Truck
- **Project Partners:** Volvo Trucks, CellCentric, Daimler Truck Automotive Group
- **Fuel Type:** Hydrogen Fuel Cell
- **Funding Received ($):** Not Applicable
- **Funding Source:** Not Applicable
- **URL:** https://www.prnewswire.com/news-releases/volvo-trucks-showcases-new-zero-emissions-truck-301571323.html

Project Description

Volvo's commercial trucking division is testing hydrogen fuel cell semi trucks in the hopes of getting ahead of the maturing technology. Volvo claims its trucks are capable of 1,000 kilometers of range (about 621 miles) and can be refueled in under 15 minutes. Company president, Roger Alm, said hydrogen fuel cells will be suitable for long-distance hauling and could work in countries with limited battery charging infrastructure. Customer pilots will start in a few years from 2022 and commercialization is planned for the latter part of this decade.

General Motors Hydrogen-Powered Long-Haul Trucks (2021 – Ongoing)

LOCATION: Not specified

Project Details

- **Equipment Demonstrated:** Long-Haul Heavy-Duty Truck
- **Project Partners:** General Motors, Navistar, JB Hunt Transport Services, OneH2
- **Fuel Type:** Hydrogen Fuel Cell
- **Funding Received ($):** Not Applicable
- **Funding Source:** Not Applicable
- **URL:** https://news.navistar.com/2021-01-27-Navistar-Collaborates-with-General-Motors-And-OneH2-To-Launch-Hydrogen-Truck-Ecosystem

Project Description

General Motors has teamed up with Navistar, OneH2, and JB Hunt Transport Services to roll out a complete solution for a fleet of heavy-duty zero-emission hydrogen fuel cell trucks. In 2024, Navistar will introduce a new fuel cell vehicle (International RH Series truck) with test versions rolling out in 2022. The companies are aiming for a fuel cell vehicle with a powertrain capable of 500+ miles of range and a refueling time of less than 15 minutes.

The International RH Series FCEV (fuel cell electric vehicle) will get its energy from two GM Hydrotec fuel cell power cubes. Each Hydrotec power cube contains 300-plus hydrogen fuel cells along with thermal and power management systems. They are compact and easy to package into many different applications.

The combined propulsion system within the International RH Series FCEV will feature better power density for short-range travel, better short-burst kW output and a per-mile cost expected to be comparable to diesel in certain market segments.

Locomotives

Line Haul

CP Hydrogen Locomotive Program (2020 – Ongoing)

LOCATION: CP Railyards in Calgary and Edmonton, Alberta, Canada

Project Details

- **Equipment Demonstrated:** Line Haul
- **Project Partners:** Canadian Pacific (CP)
- **Fuel Type:** Hydrogen Fuel Cell
- **Funding Received ($):** $30,000,000
- **Funding Source:** Emissions Reduction Alberta
- **URL:** https://www.cpr.ca/en/media/canadian-pacific-expands-hydrogen-locomotive-program-to-include-additional-locomotives-fueling-stations-with-emissions-red

Project Description

CP announced it would design and build North America's first line-haul hydrogen-powered locomotive using fuel cells and batteries to power the locomotive's electric traction motors. With the grant announced today, CP will build upon its early program research to convert an additional line-haul locomotive and a yard switcher locomotive and add hydrogen production and fueling facilities This work will refine the process of converting diesel-electric powertrains to hydrogen-electric powertrains over a series of three categories of locomotive, which collectively represent most locomotives in use throughout North America.

CRRC HFC Locomotive (2021 – Ongoing)

LOCATION: Jinbai railway transportation, Inner Mongolia Autonomous Region, China

Project Details

- **Equipment Demonstrated:** Line Haul
- **Project Partners:** CRRC, State Power Investment Corporation, Hydrogen Energy Co of SPIC, CRRC Datong
- **Fuel Type:** Hydrogen Fuel Cell
- **Funding Received ($):** Not Applicable
- **Funding Source:** Not Applicable
- **URL:** https://www.greencarcongress.com/2021/11/20211102-chinah2loco.html

Project Description

The first China-developed hydrogen fuel cell hybrid locomotive produced by CRRC Datong Co., Ltd. on Wednesday is designed to run at a speed of 80 km per hour, with 700 kW of continuous power for 24.5 hours. Its maximum traction load on a straight track exceeds 5,000 tons. The locomotive uses a combination of a hydrogen fuel cell system and a high-power lithium battery. Compared with traditional fuel and electric locomotives, hydrogen-fueled hybrid locomotives are not only safer and more environmentally friendly but also quieter, cheaper and easier to maintain. The modular design of the locomotive gives it the flexibility to utilize different power levels and power modes to cater to customers' demands for multiple applications, such as operating in tunnels and mines.

Caterpillar, BNSF, and Chevron Hydrogen Locomotive Demonstration (2022 – Ongoing)

LOCATION: Deerfield, IL; Fort Worth, TX; San Ramon, CA, USA

Project Details

- **Equipment Demonstrated:** Line Haul
- **Project Partners:** Progress Rail, BNSF Railway Company, Chevron
- **Fuel Type:** Hydrogen Fuel Cell
- **Funding Received ($):** Not Applicable
- **Funding Source:** Not Applicable
- **URL:** https://www.bnsf.com/news-media/news-releases/newsrelease.page?relId=caterpillar-bnsf-and-chevron-agree-to-pursue-hydrogen-locomotive-demonstration

Project Description

Progress Rail, a Caterpillar Inc. Company, BNSF Railway Company, and Chevron U.S.A. Inc. announced a memorandum of understanding (MOU) to advance the demonstration of a locomotive powered by hydrogen fuel cells. The goal of the demonstration is to confirm the feasibility and performance of hydrogen fuel for use as a viable alternative to traditional fuels for line-haul rail.

Switching

Sierra Northern Railway (2021 – Ongoing)

LOCATION: Port of West Sacramento, Sacramento, CA, USA

Project Details

- **Equipment Demonstrated:** Switching
- **Project Partners:** GTI, Railpower Tech LLC, Ballard Power Sysems, Optifuel Systems LLC, Velocity Strategies, Southern California Gas Company, Sacramento Metropolitan Air Quality Management District
- **Fuel Type:** Hydrogen Fuel Cell
- **Funding Received ($):** $4,000,000
- **Funding Source:** California Energy Commission
- **URL:** https://www.valleyvision.org/projects/zero-emission-hydrogen-locomotive-pilot-west-sacramento/

Project Description

Sierra Northern Railway will be building and testing a new hydrogen fuel cell locomotive at the Port of West Sacramento that will demonstrate how hydrogen-fueled switching locomotives improve air quality, reduce greenhouse gas emissions, and increase the quality of life for surrounding communities. The purpose of this project is to convert an existing diesel locomotive into a zero-emission hydrogen-fueled locomotive.

People Movers

Coradia iLint (2018 – Ongoing)

LOCATION: EVB's Elbe-Weser Network, Bremervörde, Germany

Project Details

- **Equipment Demonstrated:** Commuter Train
- **Project Partners:** Alstom, Selectron Systems, Hydrogenics, Hexagon Xperion
- **Fuel Type:** Hydrogen Fuel Cell
- **Funding Received ($):** EUR 8,000,000 ($9,400,000)
- **Funding Source:** German Ministry of Economy and Mobility, National Innovation Program for Hydrogen and Fuel Cell Technology (NIP)
- **URL:** https://www.alstom.com/solutions/rolling-stock/coradia-ilinttm-worlds-1st-hydrogen-powered-train

Project Description

Coradia iLint, the latest in the Coradia range of modular trains manufactured by Alstom Transport, is the world's first passenger train to use hydrogen fuel cells for traction power. The zero-emission regional train has low levels of noise and only emits steam and condensed water. The world's first two hydrogen trains successfully operated for one year and half between 2018 and 2020 in regular passenger service in Germany and covered more than 180,000 kilometres. Alstom has already sold 41 of these hydrogen-powered trains in Germany in order to replace the existing diesel fleet. The first hydrogen series trains will be in regular service in Germany from 2022.

Foshan Gaoming Modern Hydrogen Tram Demonstration Line (2019-2021)

LOCATION: Foshan, Guangdong, China

Project Details

- **Equipment Demonstrated:** Tram
- **Project Partners:** Ballard, CRRC
- **Fuel Type:** Hydrogen Fuel Cell
- **Funding Received ($):** ¥1,070,000,000 yuan ($166,000,000)
- **Funding Source:** Chinese Government
- **URL:** https://www.ballard.com/docs/default-source/motive-modules-documents/case-study-foshan-gaming-tram-final-web.pdf

Project Description

Five hydrogen trams operate on the tram line. The trams were jointly developed by CRRC Corporation Limited (CRRC), the world's largest railway equipment supplier, and Ballard Power Systems. The trams took two years of research and development to complete and are each powered by two of Ballard FCveloCity®-XD fuel cell modules. With six hydrogen cylinders installed overhead, the newly-developed tram can travel up to 125 kilometers per refueling. The trams employ 100% low-floor technology for their structural design. The interior structure of the tram is split into three sections with 60 seats and spacious interior design. With cabs on both ends, the design allows for two direction operation.

HydroFlex (2019 – Ongoing)

LOCATION: Birmingham Center for Railway Research and Education, Birmingham, England

Project Details

- **Equipment Demonstrated:** Commuter Train
- **Project Partners:** Birmingham Center for Railway Research and Education, Porterbrook, Innotrans, Rail Operations Group, QRTC, Jeff Vehicles, DG8, Chrysalis Rail, DB Cargo Crewe, Ballard Fuel Cell Systems, Luxfer, Denchi Group, Aura Graphics, Derby Engineering Unit, SNC Lavalin
- **Fuel Type:** Hydrogen Fuel Cell
- **Funding Received ($):** Not Applicable
- **Funding Source:** Not Applicable
- **URL:** https://www.birmingham.ac.uk/news/2018/university-of-birmingham-signs-joint-initiative-to-develop-hydroflex-the-uks-first-hydrogen-train

Project Description

The UK's first hydrogen powered train was created following a new joint initiative between the University of Birmingham's Birmingham Centre for Railway Research and Education ('BCRRE') and Porterbrook. Porterbrook provided a 'Class 319' electric unit to BCRRE for conversion by their technical and research experts into a hydrogen powered train. This allowed both organizations to demonstrate how this fuel-of-the-future might be deployed across the UK's rail network. The project has developed rapidly from the collaboration agreement in September 2018 to full mainline test runs in September 2020 and provided service at COP 26 in 2021, albeit on electricity to allow visitors to look inside the hydrogen chamber.

H2goesRail (2022)

LOCATION: Pforzheim–Horb–Tübingen route; Krefeld, North Rhine-Westphalia, Germany

Project Details

- **Equipment Demonstrated:** Commuter Train
- **Project Partners:** DB Energy, DB AG, DB Regio, Siemens
- **Fuel Type:** Hydrogen Fuel Cell
- **Funding Received ($):** EUR 13,740,000 ($14,389,902)
- **Funding Source:** Federal Ministry for Digital and Transport (BMDV)
- **URL:** https://energyindustryreview.com/tools-machines/h2goesrail-project

Project Description

Deutsche Bahn and Siemens Mobility present the Mireo Plus H – the next generation of hydrogen trains – at the production plant in Krefeld. The newly designed, mobile hydrogen storage trailer is also part of the presentation. As a two-car train, the Mireo Plus H has a range of up to 800 kilometers. The hydrogen train is as powerful as electric multiple units. It features a high traction power of 1.7 MW for up to 1.1 m/s^2 acceleration and a maximum speed of up to 160 km/h. The three-car version of the train has a range of 1,000 kilometers.

Ocean Going Vessels

Cruise

Pa-X-ell 2 (AIDAnova) (2015-2020)

LOCATION: Meyer Werft Shipyards, Papenburg, Lower Saxony, Germany

Project Details

- **Equipment Demonstrated:** Cruise
- **Project Partners:** Meyer Werft, Freudenberg Sealing Technologies, AIDA Cruises
- **Fuel Type:** (HT)-PEM Fuel Cell, LNG
- **Funding Received ($):** EUR 12,231,945.53 ($12,882,685)
- **Funding Source:** German Federal Ministry of Transport and Digital Infrastructure
- **URL:** https://www.shipinsight.com/articles/gev-gets-aip-from-abs-for-compressed-hydrogen-carrier

Project Description

The Pa-X-ell2 research project enters its next phase with a consortium of eight project partners. The aim of the participating companies was to investigate and develop a decentralized energy network and a hybrid energy system with a new generation of fuel cells for use on ocean-going passenger ships. In this phase, the new fuel cells were tested on the cruise ship AIDAnova. AIDAnova is the only cruise ship worldwide to be operated entirely with low-emission liquefied natural gas (LNG) AIDAnova has a length of 337m, a width of 42m and a maximum draught of 8.8m.

German shipyard Lürssen has announced the sale of its first-ever luxury yacht using ‘Project Pa-X-ell’ fuel cell technology in 2021.

Hybrid-Powered Hurtigruten Expedition Cruise Ships (2018-2019)

LOCATION: Ulsteinvik, Ulstein, Troms og Finnmark, Norway

Project Details

- **Equipment Demonstrated:** Cruise
- **Project Partners:** Hurtigruten, Kleven Yards
- **Fuel Type:** Diesel Electric Hybrid
- **Funding Received ($):** Not Applicable
- **Funding Source:** Not Applicable
- **URL:** https://www.theexplorer.no/solutions/the-worlds-first-hybrid-cruise-ships/

Project Description

Hurtigruten launched the MS Roald Amundsen in 2019, the first of a series of hybrid-battery powered expedition cruise ships. A sister ship, MS Fridtjof Nansen, was launched in 2020. A third ship is planned. will reduce fuel consumption and carbon emissions by more than 20 percent. It runs on Rolls Royce-built engines powered by low sulfur diesel fuel and batteries, which, according to the ship's developer, lowers the ship's CO2 emissions by 20%.

Project Evolution: Hybrid Cruise Ship (2023)

LOCATION: Meyer Werft Shipyards, Papenburg, Lower Saxony, Germany

Project Details

- **Equipment Demonstrated:** Cruise
- **Project Partners:** Royal Caribbean Group, Meyer Werft Shipyard
- **Fuel Type:** Hydrogen Fuel Cell, Battery Electric, LNG
- **Funding Received ($):** Not Applicable
- **Funding Source:** Not Applicable
- **URL:** https://www.cruisehive.com/royal-caribbean-group-to-launch-first-hybrid-powered-cruise-ship/58361

Project Description

Silversea Cruises' Project Evolution to be first cruise ship to use fuel cells to provide 100% of power while at port.

Fuel Cell System – this hydrogen-based technology will supplement the main power supply and carry the ship's total hotel load — up to four megawatts — the first large-scale fuel-cell installation at sea in the cruise industry.

LNG (Liquid Natural Gas) – a cleaner-burning fuel, LNG-fueled propulsion systems emit less CO2 and 97% fewer particles than standard fuel oil used on ships.

Battery – Battery support optimizes the overall ship power system, saving fuel.

Waste to Energy – Micro Auto Gasification System (MAGS) reduces onboard waste volume, resulting in lower incineration emissions.

Containerships

Project Seashuttle (2018 – Ongoing)

LOCATION: Oslo Fjord in Færder, Norway

Project Details

- **Equipment Demonstrated:** Containership
- **Project Partners:** Samskip, Norwegian Government, FlowChange, Kongsberg Maritime, HYON, Massterly
- **Fuel Type:** Hydrogen Fuel Cell
- **Funding Received ($):** EUR 15,000,000
- **Funding Source:** Norwegian Ministries of Food and Fishing, Climate and Environment, Petroleum and Energy and Transport and Communications
- **URL:** https://safety4sea.com/samskip-will-develop-autonomous-zero-emissions-containerships/

Project Description

Samskip, announced that it will lead the challenging initiative to develop autonomous, zero-emissions containerships. The project is expected to develop two all-electric ships slated to connect Poland, Swedish west coast ports and the Oslo fjord. The vessels will draw on state-of-the-art hydrogen fuel cells for their propulsion power.

Hydrocat 48 (2019-2022)

LOCATION: Port of Ijmuiden, Velsen, Netherlands

Project Details

- **Equipment Demonstrated:** Crew Transfer Vessel (CTV)
- **Project Partners:** CMB, Windcat Workboats
- **Fuel Type:** Hydrogen Fuel Cell, Hybrid
- **Funding Received ($):** £100,000 ($104,760)
- **Funding Source:** Carbon Trust (Low Emissions Vessels Competition)
- **URL:** https://cmb.tech/news/windcat-workboats-cmb-tech-present-the-first-hydrogen-powered-crew-transfer-vessel-ctv-the-hydrocat-48-ready-for-immediate-operation

Project Description

The Joint Venture between CMB and Windcat Workboats will design and build the first crew transfer vessel (CTV) which will be powered by dual fuel hydrogen – diesel combustion engines. The vessel will store 205kg of pressurized hydrogen at 350bar. The hydrogen CTV, called Hydrocat, will be able to transport 24 service engineers towards an offshore wind park at a cruise speed of 25kn. The maximum speed will be 31kn.

HESC Project (Suiso Fronter) (2019-2030s)

LOCATION: Port of Kobe, Kobe, Hyogo, Japan & Port of Hastings, Hastings, Victoria, Australia

Project Details

- **Equipment Demonstrated:** Ocean Tanker (Liquid Hydrogen Carrier)
- **Project Partners:** Kawasaki Heavy Industries, Electric Power Development, Iwatani Corp., Marubeni Corp., AGL Energy and Sumitomo Corp. Shell, ENEOS and Kawasaki Kisen Kaisha
- **Fuel Type:** Diesel
- **Funding Received ($):** A$500,000,000 ($359,000,000)
- **Funding Source:** Australian and Japanese governments
- **URL:** https://www.shipinsight.com/articles/gev-gets-aip-from-abs-for-compressed-hydrogen-carrier

Project Description

The Hydrogen Energy Supply-chain Technology Research Association (HySTRA) responsible for the pilot project will demonstrate marine transportation with the liquid hydrogen carrier Suiso Frontier, designed and built by Kawasaki Heavy Industries and launched in 2019. The Suiso Frontier is the world's first liquefied hydrogen carrier. The ship build was completed in 2020, designed and constructed using the technical knowledge of Kawasaki Heavy Industries. Its main feature is special tanks / tanks for storing liquefied hydrogen, equipped with vacuum insulation. The vessel was launched in 2019 and at the end of last year went on its first voyage to the shores of Australia.

HyShip Project – Topeka (2020-2024)

LOCATION: Stavanger, Haugesund, Bergen, and Kristiansund, Norway

Project Details

- **Equipment Demonstrated:** Containership
- **Project Partners:** Wilhelmsen, Kongsberg Maritime, LMG Marin, Equinor, Norled, PersEE, Diana Shipping, Stolt-Nielsen Inland Tanker Service, Air Liquide, NCE Maritime CleanTech, DNV GL, ETH Zürich, Strathclyde University and Demokritos
- **Fuel Type:** Hydrogen
- **Funding Received ($):** EUR 8,000,000 ($9,440,000)
- **Funding Source:** EU's Research and Innovation Programme Horizon 2020
- **URL:** https://hydrogen-central.com/topeka-hydrogen-vessels-reality/

Project Description

The HyShip project involves 14 European partners collaborating on the design and construction of a new ro-ro demonstration vessel running on liquid green hydrogen (LH2), as well as the establishment of a viable LH2 supply chain and bunkering platform. The ship, to be named Topeka, will be built for zero emissions through a combination of 1,000 kWh battery capacity and a three-megawatt proton exchange membrane hydrogen fuel cell.

HyEnergy Project (C-H2 Ship) (2021-2023)

LOCATION: Shire of Carnarvon, Carnarvon, Western Australia, Australia

Project Details

- **Equipment Demonstrated:** Containership
- **Project Partners:** Global Energy Venture (GEV), Ballard Power Systems, HyEnergy Project, Province Resources and Total Eren
- **Fuel Type:** Hydrogen Fuel Cell
- **Funding Received ($):** $300,000
- **Funding Source:** Western Australia Renewable Hydrogen Fund Round 2 and private funds
- **URL:** https://www.shipinsight.com/articles/gev-gets-aip-from-abs-for-compressed-hydrogen-carrier

Project Description

The Australian-based Global Energy Ventures announced it is entering into a two-year project with Ballard Power Systems to design and develop a hydrogen fuel cell system for the company's proposed large-scale ocean-going hydrogen transport ship. The Compressed H2 Ship (C-H2) is a concept design to transport up to 2,000 tons of compressed hydrogen at 250 bar. GEV projects that the C-H2 ship at scale will have a power requirement of 26MW. The company is also developing a design for a smaller pilot ship that would have a power requirement of under 10MW.

Research Vessels

MARANDA (2017-2021)

LOCATION: Helsinki, Ulusimaa, Finland

Project Details

- **Equipment Demonstrated:** Ocean Going Research Vessel
- **Project Partners:** VTT, Powercell Sweden AB, ABB OY, OMB Saleri SpA, PerSee, Suomen Ymparistokesku, The Finnish Environment Institute, Swiss Hydrogen
- **Fuel Type:** Hydrogen Fuel Cell
- **Funding Received ($):** EUR 2,939,457.50 ($3,079,081.73)
- **Funding Source:** EU FCH-JU
- **URL:** https://www.fch.europa.eu/sites/default/files/4.%20Laurence%20Grand-Cl%C3%A9ment%20-%20MARANDA.pdf

Project Description

The MARANDA project is the first hydrogen fuel cell deep-sea vessel funded by FCH JU. The 165 kW fuel cell-battery hybrid powertrain will be used for dynamic positioning of the Aranda research vessel. Hydrogen is stored on board using a 350-bar hydrogen storage container that could be removed from the vessel, transported on the roads and refilled at any 350-bar hydrogen refueling station. Getting ship approval was a more lengthy and costly process than anticipated.

Hydrogen-Hybrid Powered Research Vessel (2021-2024)

LOCATION: Scripps Institution of Oceanography, San Diego, California, USA

Project Details

- **Equipment Demonstrated:** Ocean Going Vessel
- **Project Partners:** Scripps Institution of Oceanography, MARAD, Sandia National Laboratories, Glosten, MARAD
- **Fuel Type:** Hydrogen Fuel Cell, Hybrid
- **Funding Received ($):** $35,000,000
- **Funding Source:** State of California
- **URL:** https://www.maritime-executive.com/article/scripps-gets-35m-to-build-hydrogen-hybrid-powered-research-vessel

Project Description

The hybrid-hydrogen design of this new vessel is a novel development. The ship will feature a hybrid propulsion system that integrates hydrogen fuel cells with a conventional diesel-electric power plant, enabling zero-emission operations. The design is scaled so that the ship will be able to operate 75 percent of its missions entirely using hydrogen fuel, which can be carbon neutral if provided by a renewable energy-powered electrolysis plant. For longer missions, extra power will be provided by diesel generators. A feasibility study on the hydrogen fuel-cell propulsion technology for the vessel was completed in 2020 by Sandia National Laboratories, Glosten and Scripps, with funding from MARAD.

Microgrid

Maritime Hydrogen Fuel Cell Generator Project (2015-2016)

LOCATION: Port of Honolulu, Honolulu, HI, USA

Project Details

- **Equipment Demonstrated:** Microgrid
- **Project Partners:** Sandia Lab, Young Brothers Ltd., Hydrogenics Corp.
- **Fuel Type:** Hydrogen Fuel Cell
- **Funding Received ($):** $1,700,000
- **Funding Source:** United States Department of Energy Hydrogen and Fuel Cell Technologies Office $885,000, United States Department of Defense/MARAD $815,000
- **URL:** https://energy.sandia.gov/programs/sustainable-transportation/hydrogen/fuel-cells/maritime-applications/maritime-hydrogen-fuel-cell-generator-project/

Project Description

A first-of-its kind hydrogen fuel cell power generator for marine applications was designed, built, and demonstrated to verify increased energy efficiency at part loads and reduced emissions. The project goals were to demonstrate the use of the generator in the maritime environment, identify areas requiring additional research and development, analyze the business case, and address regulatory and other market barriers. A 100 kW generator with 72 kg of hydrogen storage was designed and built by Hydrogenics with safety and regulatory reviews by the Hydrogen Safety Panel, US Coast Guard, and American Bureau of Shipping. Young Brothers operated the generator for 10 months powering refrigerated containers in Honolulu, HI. The project showed it is possible to increase energy efficiency by up to 30% at part load and reduce emissions to zero through the use of hydrogen fuel cells and identified paths forward to wider adoption of the technology in this sector.

Surf 'n' Turf Project: Hydrogen Fuel Cell (2017 – Ongoing)

LOCATION: Kirkwall Harbor, Orkney, Scotland

Project Details

- **Equipment Demonstrated:** Microgrid
- **Project Partners:** Arcola Energy, FCH-JU, Local Energy Scotland, Scottish Government's Local Energy Challenge Fund, Community Energy Schotland, EMEC, Orkney Islands Council, Eday Renewable Energy, ITM Power, BIG HIT
- **Fuel Type:** Hydrogen Fuel Cell
- **Funding Received ($):** £1,460,000 ($1,776,236)
- **Funding Source:** Local Energy Scotland and the Scottish Government's Local Energy Challenge Fund. Other funding from EU FCH-JU
- **URL:** https://www.bighit.eu/hydrogen-fuel-cell

Project Description

The fuel cell at Kirkwall harbor was installed in 2017 as part of the Surf 'n' Turf project. The dockside system was supplied by Arcola Energy and provides electricity on demand for ships (cold ironing) and for activity within Kirkwall Harbor. Heat produced by the fuel cell as a by-product of the chemical reaction will be piped into nearby buildings. The hydrogen fuel cell at Kirkwall Harbor has a rated power output of 75kW. The system contains three Proton Motor PM 400 fuel cell stacks which are designed for industrial applications and can be used in maritime stationary applications. Each of the three PM 400 stacks has a nominal electrical power output range from 4.0 kW to 30.0 kW and is almost completely silent in operation with zero emissions.

Hydrogen Fuel Cell Backup Generator System (2021-2024)

LOCATION: Microsoft Data Center, Quincy, WA, USA

Project Details

- **Equipment Demonstrated:** Microgrid
- **Project Partners:** Caterpillar, Microsoft, Ballard Power Systems, United States Department of Energy, National Renewable Energy Lab
- **Fuel Type:** Hydrogen Fuel Cell
- **Funding Received ($):** N/A
- **Funding Source:** Partially DOE Funded
- **URL:** https://www.caterpillar.com/en/news/corporate-press-releases/h/caterpillar-demonstration-project-hydrogen-backup-power-microsoft.html

Project Description

The project is meant to demonstrate a power system incorporating large-format hydrogen fuel cells to produce reliable and sustainable backup power for data centers. Caterpillar is providing the overall system integration, power electronics, and controls that form the central structure of the power solution which will be fueled by low-carbon-intensity hydrogen. Microsoft is hosting the demonstration project at a company data center in Quincy, Washington, while Ballard is supplying an advanced hydrogen fuel cell module.

Miscellaneous

Port-Based Hydrogen Refueling Station (2022-2026)

LOCATION: Qingdao Port, Qingdao, Shandong, China

Project Details

- **Equipment Demonstrated:** Hydrogen Refueling Station
- **Project Partners:** Shandong Port Group
- **Fuel Type:** Hydrogen Fuel Cell
- **Funding Received ($):** Not Applicable
- **Funding Source:** Not Applicable
- **URL:** https://news.cgtn.com/news/2022-06-27/China-s-first-port-based-hydrogen-refueling-station-starts-operation--1bcxkFTf1Qc/index.html

Project Description

The station has two phases and was designed for a daily hydrogen supply capacity of 1,000 kilograms, serving 50 hydrogen fuel cell vehicles every day. Shandong Port Group plans to build three hydrogen refueling stations, a hydrogen-powered energy supply system and 10 hydrogen-powered gantry cranes at the port areas in three to four years and add 600 hydrogen-powered vehicles.

Hydrogen Energy Demonstration Port (2021-2025)

LOCATION: Yangshan Deep-Water Port, Shanghai, Zhejiang, China

Project Details

- **Equipment Demonstrated:** Drayage, RTG Crane, Forklift, Top Handler, Yard Truck
- **Project Partners:** Shanghai International Port Group
- **Fuel Type:** Hydrogen Fuel Cell
- **Funding Received ($):** 12,800,000,000 yuan ($1,950,000,000)
- **Funding Source:** Not Applicable
- **URL:** https://h2worldnews.com/shanghais-yangshan-port-to-embrace-hydrogen/

Project Description

Shanghai's Yangshan Deep-Water Port, the world's largest container port, plans to power automated vehicles and handling equipment with low-emission hydrogen fuel-cell batteries, to reduce its carbon emissions. a production base for the batteries will be built in the next two to three years. The proposed port plan includes improving the layout of shoreline hydrogen refueling facilities, carrying out demonstrations of hydrogen powered fuel cell vessels such as official boats and cruise ships, and promoting commercial application of hydrogen energy in the maritime industry.