

Light Duty Hydrogen Infrastructure Analysis at NREL

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Green Transportation Summit & Expo

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Hydrogen Market Assessment Analysis Overview

Collaborative and peer reviewed analysis developed with multiple stakeholders

- DOE's Fuel Cell Technologies Office (FCTO)
- State agencies (e.g., CEC, CARB)
- Industry consortiums (e.g., H2USA, CaFCP)
- Industry partners and clients (auto OEMs, gas suppliers)

Hydrogen Market Assessment Analysis Scope

- Process techno-economic analysis (production, distribution, dispensing)
- Market status and assessment
- Resource assessment
- Market adoption projections
- Cost benefit analysis
- Emissions and public health impacts
- **Transition dynamics scenario simulations**
- **Business case and financial analysis**

NREL's Hydrogen Infrastructure Systems Analysis Website:
<https://www.nrel.gov/hydrogen/systems-analysis.html>

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Hydrogen & Fuel Cells » Systems Analysis

- Fuel Cells
- Hydrogen Production & Delivery
- Hydrogen Storage
- Manufacturing R&D
- Market Transformation
- Safety, Codes, & Standards
- Systems Analysis**
- Technology Validation

Systems Analysis

NREL's hydrogen systems analysis activities provide direction, insight, and support for the development, demonstration, and deployment of a broad range of hydrogen technologies.

Analysis focuses on hydrogen production, storage, and delivery systems for fuel cell electric vehicles (FCEVs) as well as stationary fuel cells and emerging market applications such as material handling and backup power.

H2FAST: Hydrogen Financial Analysis Scenario Tool
Delivers in-depth financial analysis for hydrogen fueling stations.

NREL's hydrogen systems analysts evaluate R&D goals and perform resource assessments, techno-economic comparisons, market-potential projections, and financial modeling of stakeholder decisions and investment risks. Analysts also develop least-cost scenarios for hydrogen infrastructure rollout in support of the large-scale deployment of FCEVs.

NREL hosts stakeholder workshops to increase coordination among decision makers, raise awareness, develop strategic thinking, and provide input to improve analysis modeling activities.

Learn more about NREL's hydrogen systems analysis data and tools.

Webinars

The following webinars from the U.S. Department of Energy's Fuel Cell Technologies Office include presentations by NREL systems analysis staff.

Overview of Station Analysis Tools Developed in Support of H2USA (May 2015). This webinar provides a basic introduction to two new models designed to address key technical and financial barriers to hydrogen fueling infrastructure deployment: the Hydrogen Refueling Station Analysis Model (HRSAM) and the Hydrogen Financial Analysis Scenario Tool (H2FAST).

Increasing Renewable Energy with Hydrogen Storage and Fuel Cell Technologies (August 2014). This webinar explores opportunities for multi-sector integration using hydrogen systems as well as the capability and cost effectiveness of integrating hydrogen systems into electricity markets.

DOE Analysis Related to H2USA (July 2013). This webinar reviews analysis capabilities supporting hydrogen infrastructure expansion efforts associated with the H2USA public-private collaboration.

Publications

The following technical reports, workshop proceedings, journal articles, conference papers, and presentations provide more information about NREL's hydrogen and fuel cell system analysis activities and findings.

Technical Reports and Workshop Proceedings

California Power-to-Gas and Power-to-Hydrogen Near-Term Business Case Evaluation [\[1\]](#), Joshua Eichman and Francisco Flores-Espino (2016)

Economic Assessment of Hydrogen Technologies Participating in California Electricity Markets [\[2\]](#), Joshua Eichman, Aaron Townsend, and Marc Melaina (2016)

Hydrogen Energy Storage: Grid and Transportation Services [\[3\]](#), Workshop Proceedings, Marc Melaina and Josh Eichman (2015)

Community Energy: Analysis of Hydrogen Distributed Energy Systems with Photovoltaics for Load Leveling and Vehicle Refueling [\[4\]](#), Darlene Steward and Jarret Zuboy (2014)

Novel Electrolyzer Applications: Providing More Than Just Hydrogen [\[5\]](#), Joshua Eichman, Kevin Harrison, and Michael Peters (2014)

Renewable Hydrogen Potential from Biogas in the United States [\[6\]](#), Genevieve Saur and Anelia Milbrandt (2014)

SEIRA
The Scenario Evaluation and Regionalization Analysis (SEIRA) model integrates detailed geographic data, hydrogen infrastructure and supply chain costs, sustainability metrics, and financial analyses within an optimization framework.

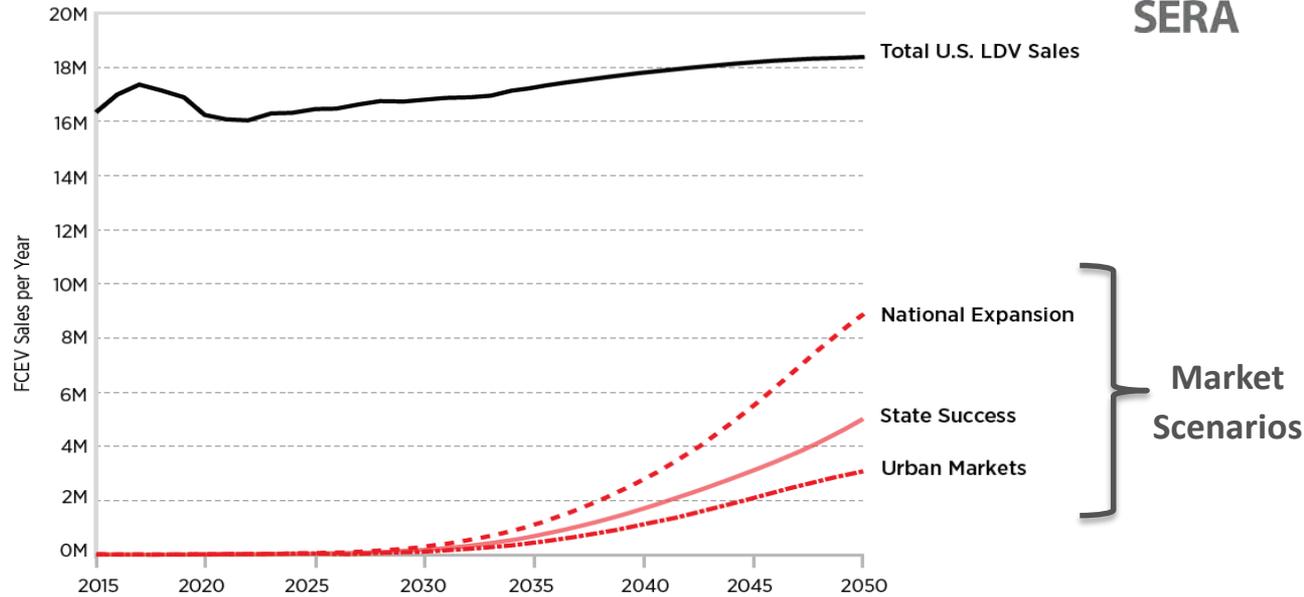
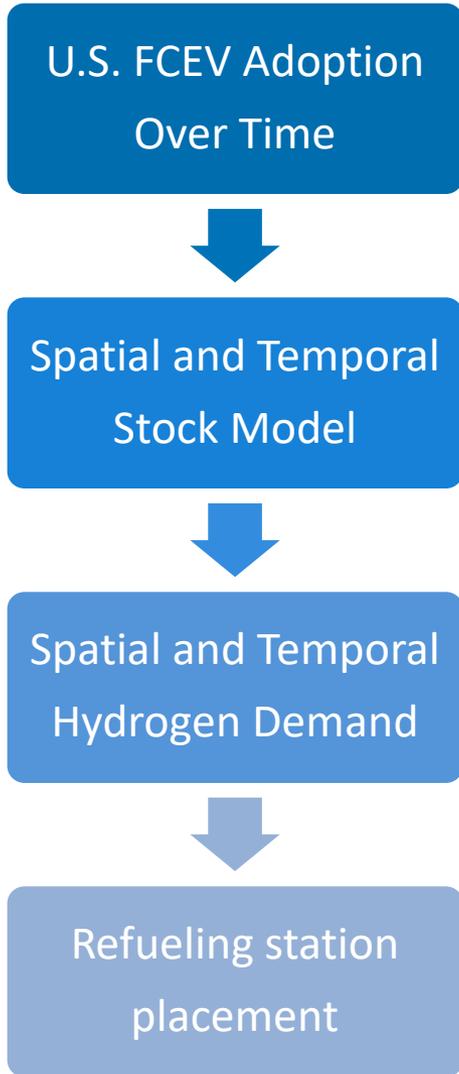
Market Assessment

Demand	National Light-Duty FCEV Adoption Scenarios
Supply	National Light-Duty FCEV Supply Chain Infrastructure Roll-Out
Financial	National Heavy-Duty FCEV Total Cost of Ownership Analysis

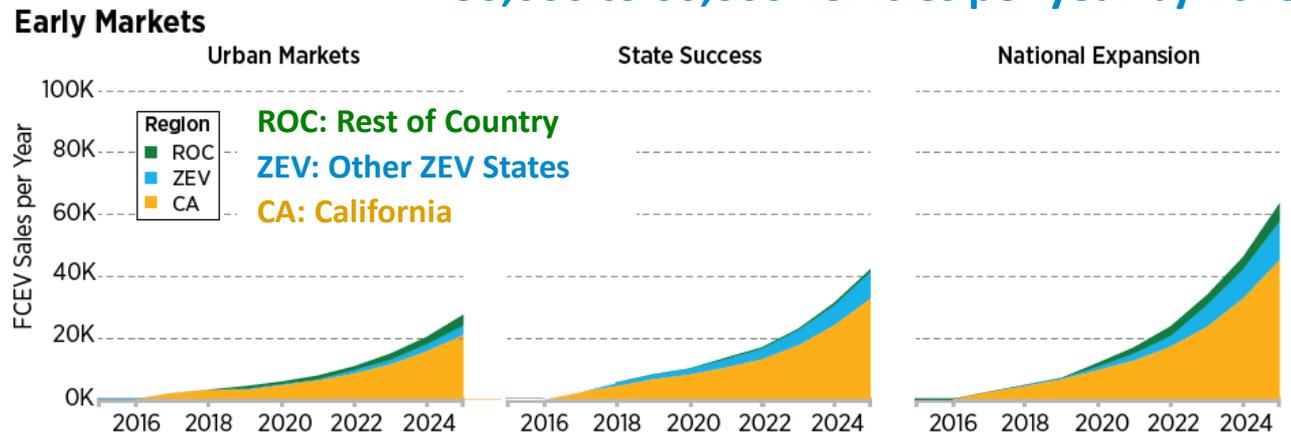
National Light-Duty FCEV Adoption: Different Market Support Scenarios Using the Scenario Evaluation and Regionalization Analysis (SERA) Model



SERA Demand Side Overview



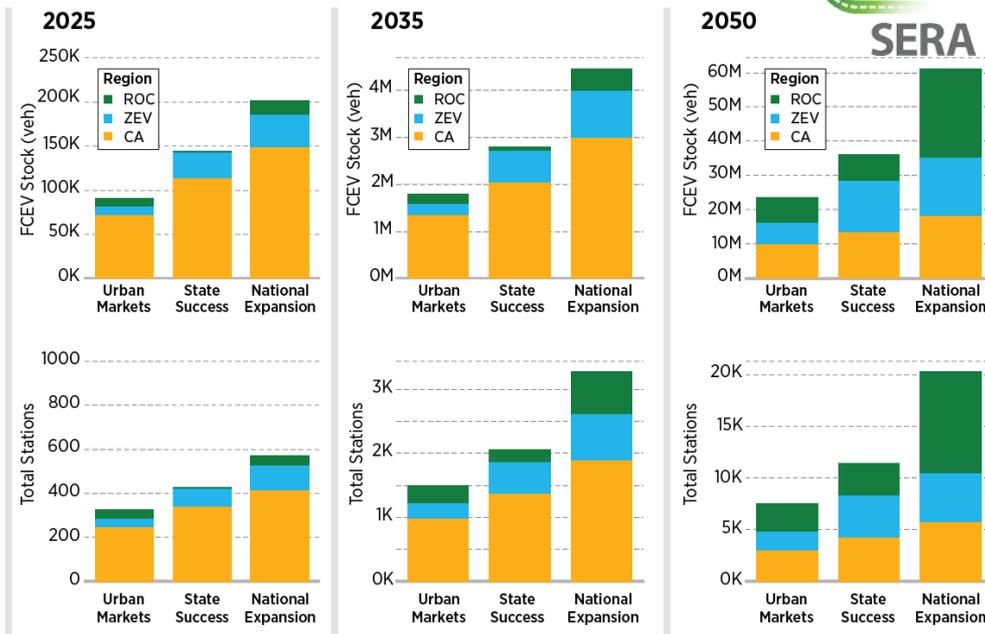
FCEV sales in the near-term range from 30,000 to 60,000 vehicles per year by 2025



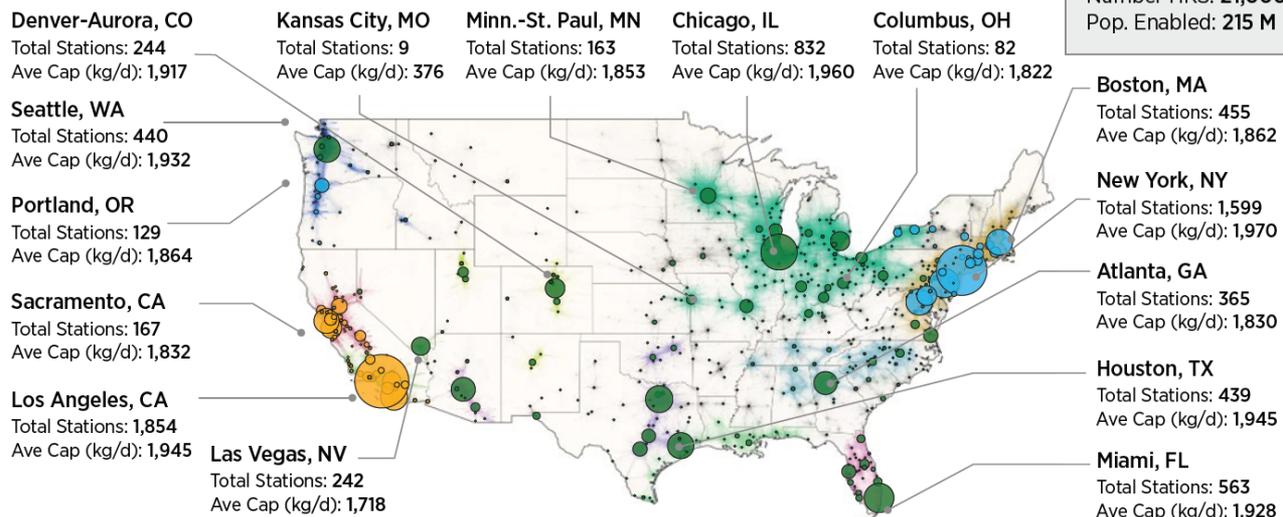
National Light-Duty FCEV Adoption: FCEV Refueling Station Rollout



- **Vehicle Adoption:** FCEV vehicle adoption estimated over time and region
- **Station Size:** SERA estimates the total station capacity needed to support FCEV fleet
- **Station Count:** SERA determines number of stations to build in each area



National Expansion

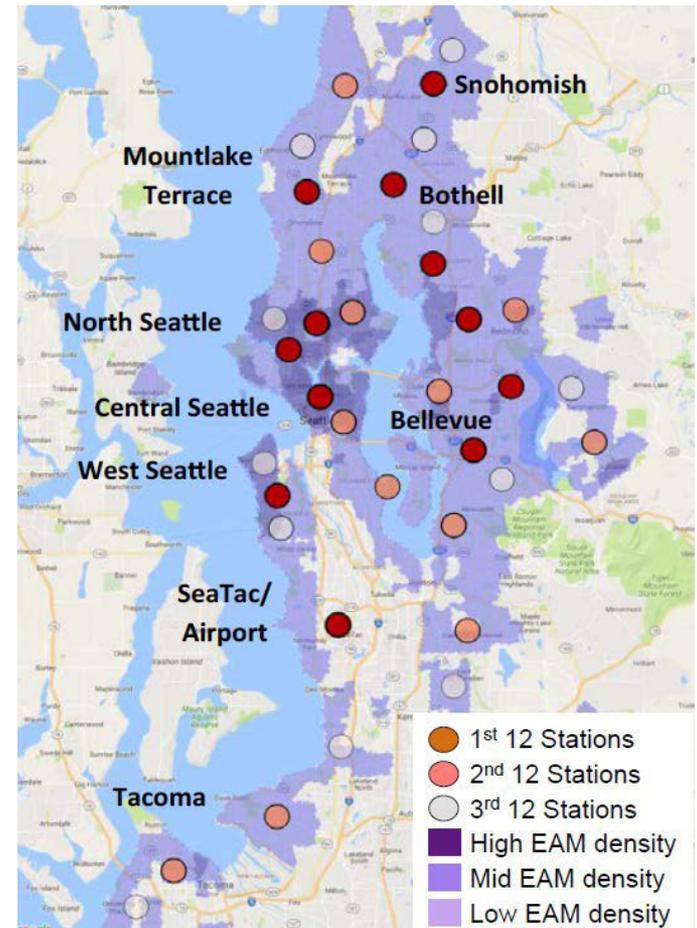


(Above) FCEV stock and total stations over time for each scenario

(Left) The number of stations and average capacity for select urban areas in 2050

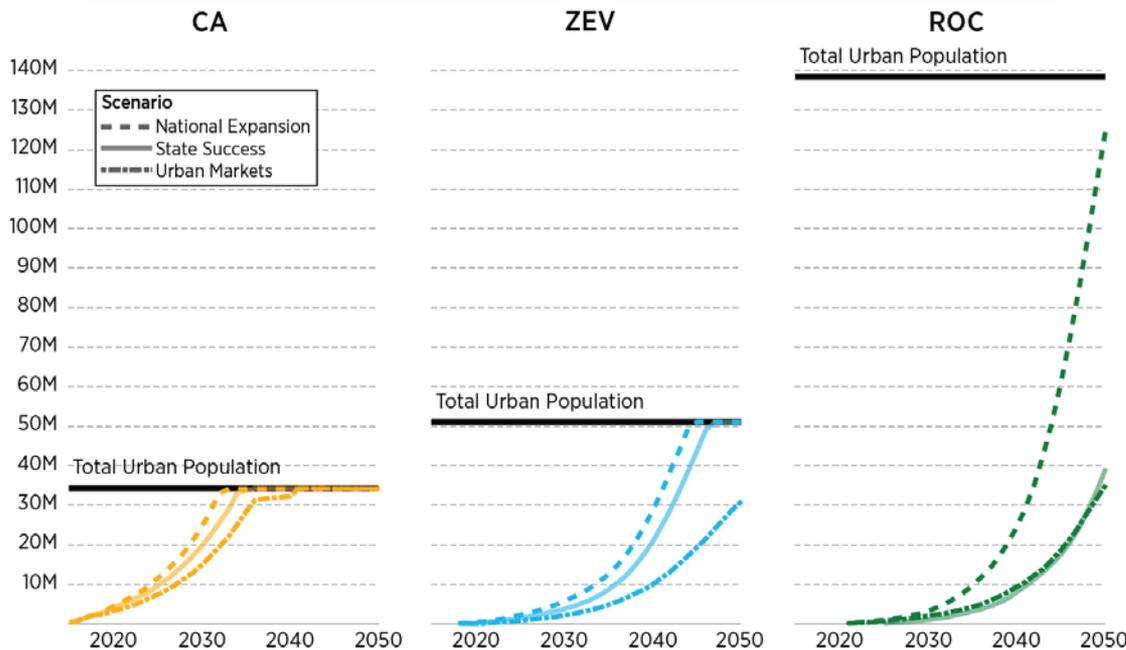
National Light-Duty FCEV Adoption: FCEV Refueling Station Placement and Access

- **Station Timing:** Stations built as demand grows to optimize station financials
- **Station Location:** Stations located to balance coverage and station financials
- **Consumer Access:** SERA maximizes consumer access to stations to encourage FCEV adoption



(Above) Seattle Station Placement:
Estimated that ~36 hydrogen stations could support large volumes of FCEVs sold in the Greater Seattle market

(Below) Population with access to hydrogen refueling



Market Assessment

Demand	National Light-Duty FCEV Adoption Scenarios
Supply	National Light-Duty FCEV Supply Chain Infrastructure Roll-Out
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National Light-Duty FCEV Supply Chain: Overview



SERA

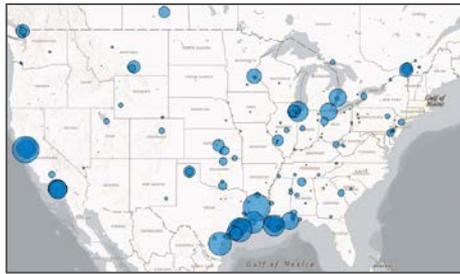
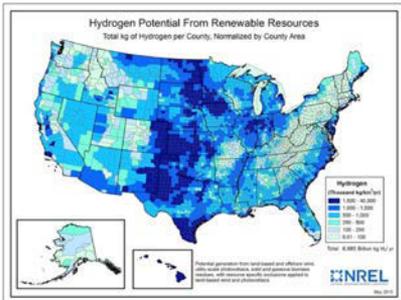
The SERA model simulates least-cost hydrogen infrastructure supply systems for urban FCEV markets

Energy Resources

Hydrogen Production

Storage & Delivery

Retail Station Networks



- Energy prices (natural gas, electricity, etc.)
- Renewables (biomass, solar, wind)
- Terrain, rights of way, etc.

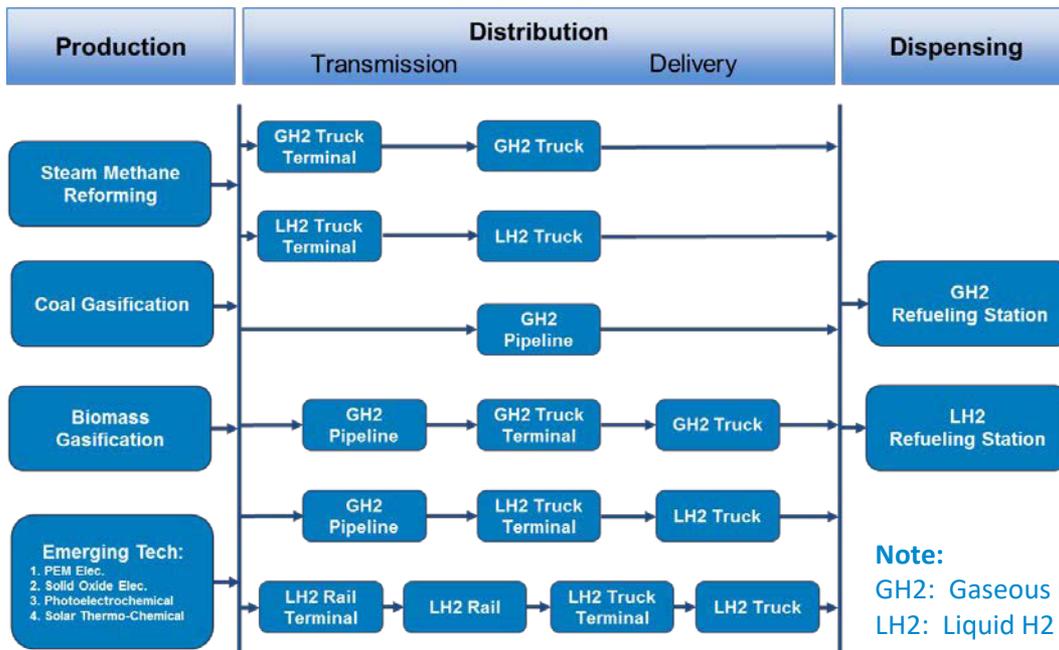
- Central and onsite production facilities
- Capacity sized to meet forecasted demand
- Economies of scale balanced with delivery costs

- Truck delivery, rail, and pipeline.
- Cost is sensitive to volume, distance
- Seasonal and weekly storage
- Networked supply to multiple cities

- Coverage stations for FCEV introductions
- Station sizes increase with market growth
- Liquid and pipeline delivery networks compete for large stations

National Light-Duty FCEV Supply Chain:

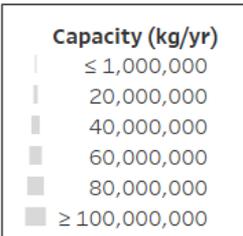
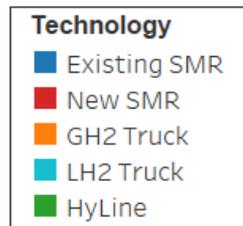
SERA optimizes production, transmission, delivery and dispensing construction technology, timing, and location



- **Inputs:** Resource prices, technology cost and resource data, FCEV demand
- **Optimization:** SERA finds least-cost infrastructure to meet demand, technology, and resource constraints
- **Outputs:** “blueprints” for hydrogen supply chain (production, transmission, delivery, dispensing)

(Above) Example supply chain pathways for SERA to select from

(Right) Visualization of optimized light-duty vehicle hydrogen supply chain in 2050

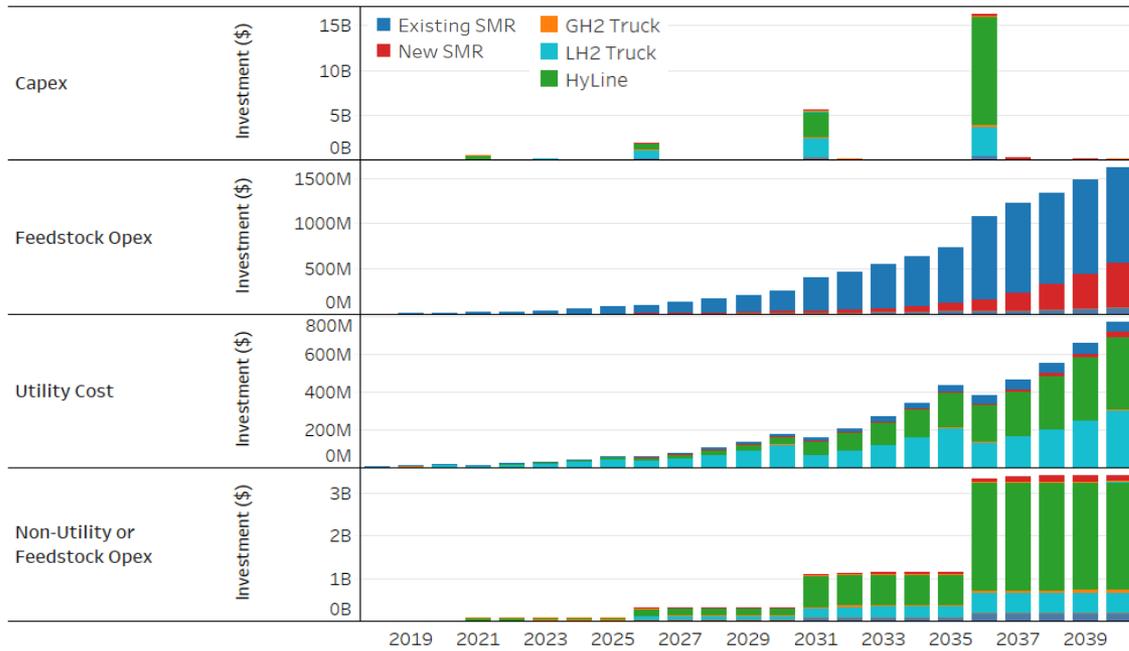


National Light-Duty FCEV Supply Chain: Supply Chain Financial Analysis



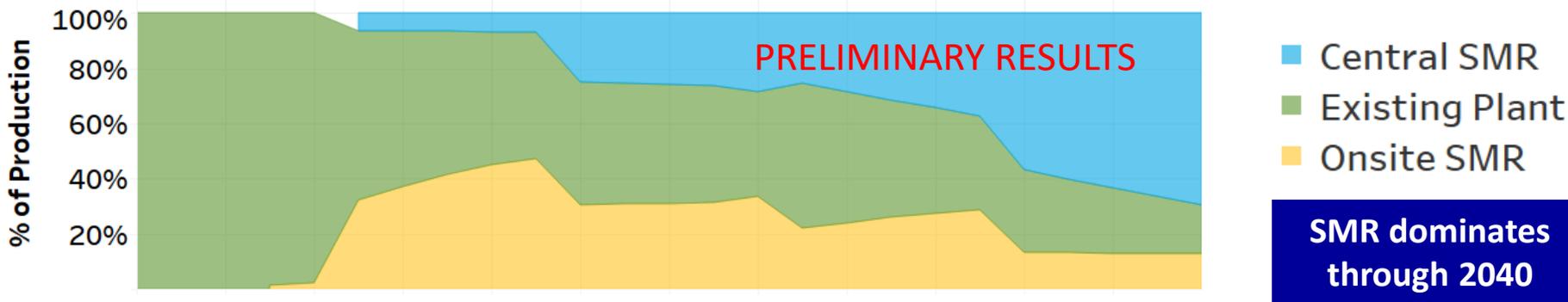
H2FAST

- **Cash Flows:** Capital, operating, and resource cash flows are all tracked for each piece of infrastructure
- **Price:** Minimum required selling hydrogen price can be estimated to achieve desired financial performance of each piece of infrastructure
- **H2FAST:** Rigorous financial model built into SERA and available for download as Excel Model

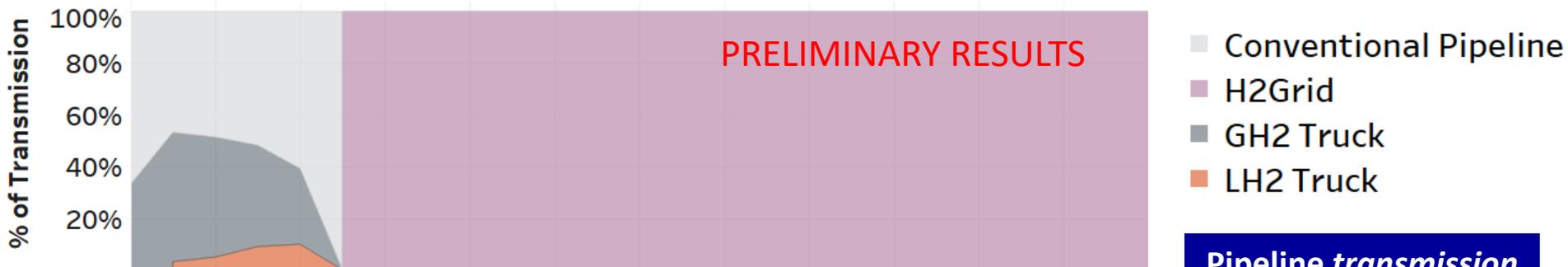


SERA Results: Production, Transmission, and Dispensing Technologies

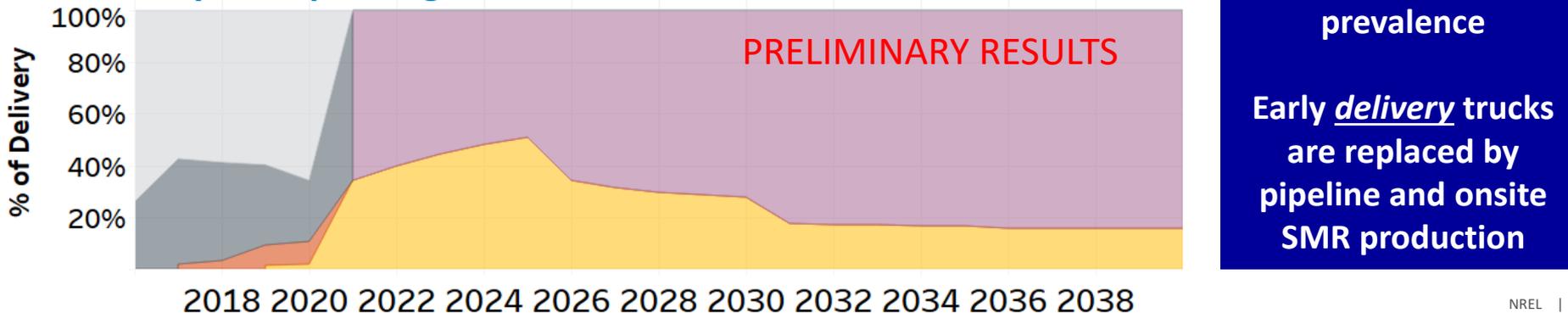
Production Mix



Long-Distance Transmission Mix



Delivery & Dispensing Mix



SERA Results: H2Grid Build-Out In Los Angeles in 2038

PRELIMINARY RESULTS

Characteristics for year	2038
Number of pipeline segments	669
Cumulative length (miles)	1,179.78
Average segment length (miles/segment)	1.76
Delivery throughput (kg/d)	1,251,557
Distribution cost (\$/kg)	\$ 0.51

Los Angeles
Year = 2038

- Station size = 60 - 710 kg/d
- Station size = 710 - 1270 kg/d
- Station size = 1270 - 1900 kg/d
- Station size = 1900 - 2810 kg/d
- Station size = 2810 - 6830 kg/d

H2Grid economically outcompetes other supply chain pathways in major urban areas.

Market Assessment

Demand	National Light-Duty FCEV Adoption Scenarios
Supply	National Light-Duty FCEV Supply Chain Infrastructure Roll-Out
Financial	National Heavy-Duty FCEV Total Cost of Ownership Analysis

Analysis Approach Overview



FASTSim

Vehicle Powertrain Cost Modeling

Inputs:

- Vehicle attribute data
- Drive cycle data
- Powertrain technology cost and performance data

Constraints:

- Powertrains meet target acceleration and gradeability

Outputs:

- Vehicle fuel economy, weight
- Component costs & MSRP



SERA

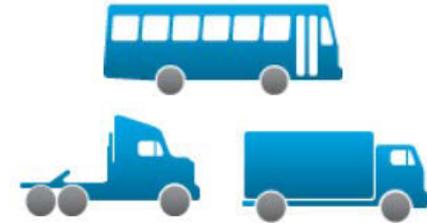
Total Cost of Ownership Modeling

Inputs:

- Cost data
 - Vehicle MSRP (FASTSim)
 - Regional fuel prices
 - Operating & Maintenance cost
 - Payload opportunity cost
 - Dwell (refueling) time cost
- Vehicle data
 - Miles travelled, lifetime
 - Fuel economy, weight
- Financial data (discount rate)

Outputs:

- Total cost of ownership



Market Assessment

Impact on FCTO Barriers:

- Identify key drivers to fuel cell truck competitiveness
- Assess fuel cells for commercial applications

Integration with Other

Projects:

- Coordinated with VTO/FCTO/BETO total cost of ownership analysis (ongoing)
- Potentially provide results to future H2@Scale analysis

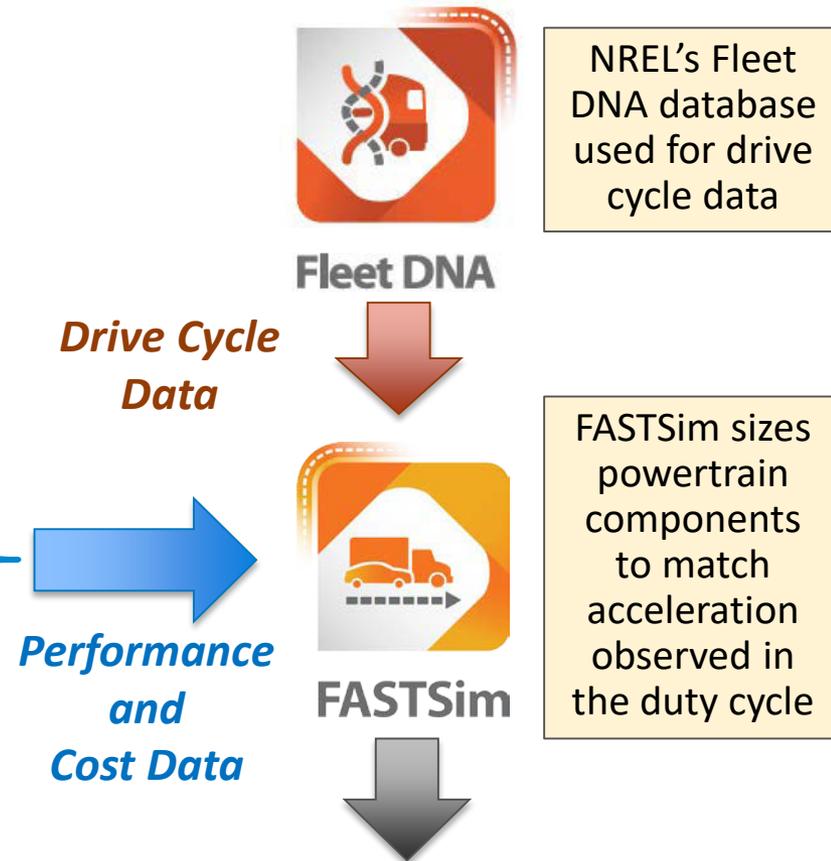
Regional TCO analyzed using established models and OEM specifications

FASTSim Used for Powertrain Optimization

Sample of Current and DOE Target Performance and Cost Data

Target year	Tech Targets		
	2018	2020	Ultimate
Batteries			
Battery Cell Mass [kg/kWh]	4.8	4.2	2.5
BEV Battery Cell Cost [\$/kWh]	145	145	80
Power Electronics			
Power electronics & motor (no boost) [\$/kW]	22.0	17.0	4.0
Boost Converter [\$/kW]	8.5	8.0	2.0
Fuel Cell			
Fuel cell specific power (kW/kg)	1.12	1.12	1.12
Fuel cell cost (\$/kW)	205	40	30
Fuel peak efficiency (%)	61%	61%	61%
Fuel storage			
Hydrogen storage (kWh/kg)	1.4	1.5	2.2
Hydrogen tank cost (\$/kWh)	36.7	10.0	8.0

FASTSim models vehicle fuel economy, weight, and cost for each year and powertrain for direct comparison



Results (by tech status and powertrain):

- **Output:** Fuel economy, weight, costs, MSRP
- **Status:** Current (2018), Tech Targets (2020, ultimate)
- **Powertrains:** Diesel, compressed natural gas (CNG), hybrid-electric (HEV), plug-in hybrid electric (PHEV), battery electric (BEV), fuel cell electric (FCEV)

Total Cost of Ownership Modeling in SERA

Cost Data



Vehicle Price
FASTSim



Fuel Price
AEO Outlook, EPRI, Tesla,
HDRSAM, FCTO Targets



O&M Cost
Literature survey, fuel-cell
bus evaluations



Payload Opportunity Cost
LTL Carrier Rates, National
Research Council, VIUS data



Dwell* Time Cost
ATRI, FMCSA, OOIDA, Nikola,
Tesla

**Dwell time = down time for refueling/recharging*

Financial Data



Discount Rate
US Market Data

Vehicle Data



Fuel Economy & Weight
FASTSim



Vehicle Miles Traveled
Transportation Energy Data
Book, Fleet DNA



Lifetime
Transportation Energy Data
Book, Industry Feedback



SERA



Results:

- **Total cost of ownership** by region, technology status (2018, 2020, Ultimate) and Powertrain (Diesel, HEV, CNG, PHEV, EV, FC)
- Each data source has a **low/med/high** estimate
- Sensitivity analysis around low/mid/high cost estimates

Total Cost of Ownership calculated for all Low/Med/High estimates of all input vehicle data and cost data

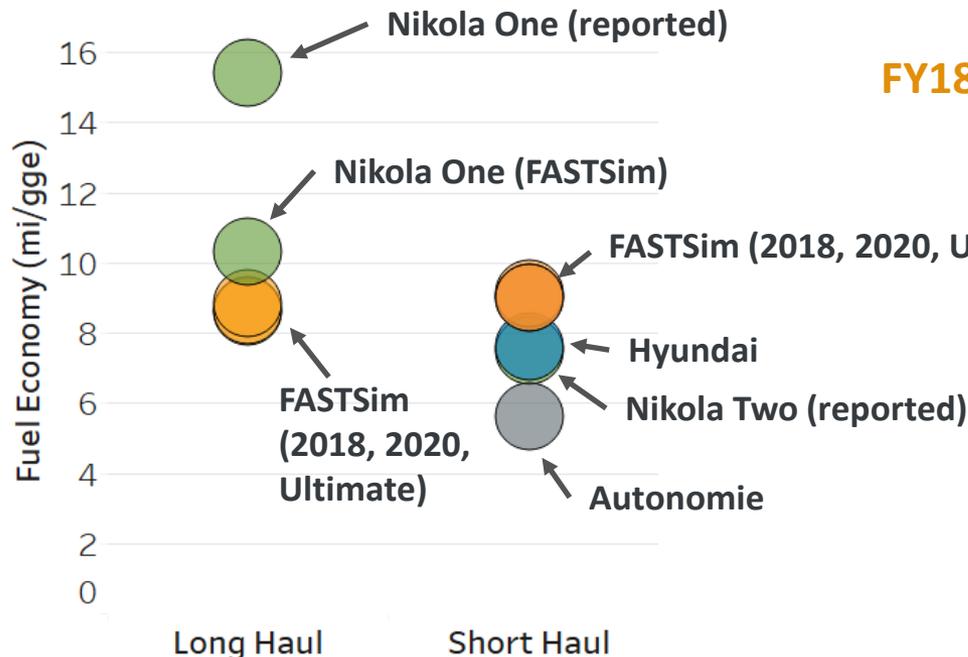
Vehicle Modeling and Benchmarking



FASTSim

Vehicle Modeling Progress Since 2018 AMR

1. Focused on Class 4 Parcel Delivery and Class 8 Short/Long Haul (FY18)
2. Added plug-in hybrid (PHEV)
3. Added Current (2018) Tech Status
4. Completed FASTSim modeling
5. Benchmarked with Toyota, Hyundai, and Nikola data and Autonomie model



	Vehicle Class	Vocation
FY18	Class 4	Parcel Delivery
	Class 5	Van, Basic Enclosed
	Class 6	Parcel Delivery
FY19	Class 7	Truck Tractor
	Class 8	Transit Bus
	Class 8	Refuse, Garbage Pickup
FY18	Class 8	Short Haul
	Class 8	Long Haul

Vocations with large share of fuel consumption in each Class per VIUS

There is a large spread in reported/projected FCET fuel economy and tractor weights. FASTSim estimates are within the spread reported

Total Cost of Ownership Scenario Analysis

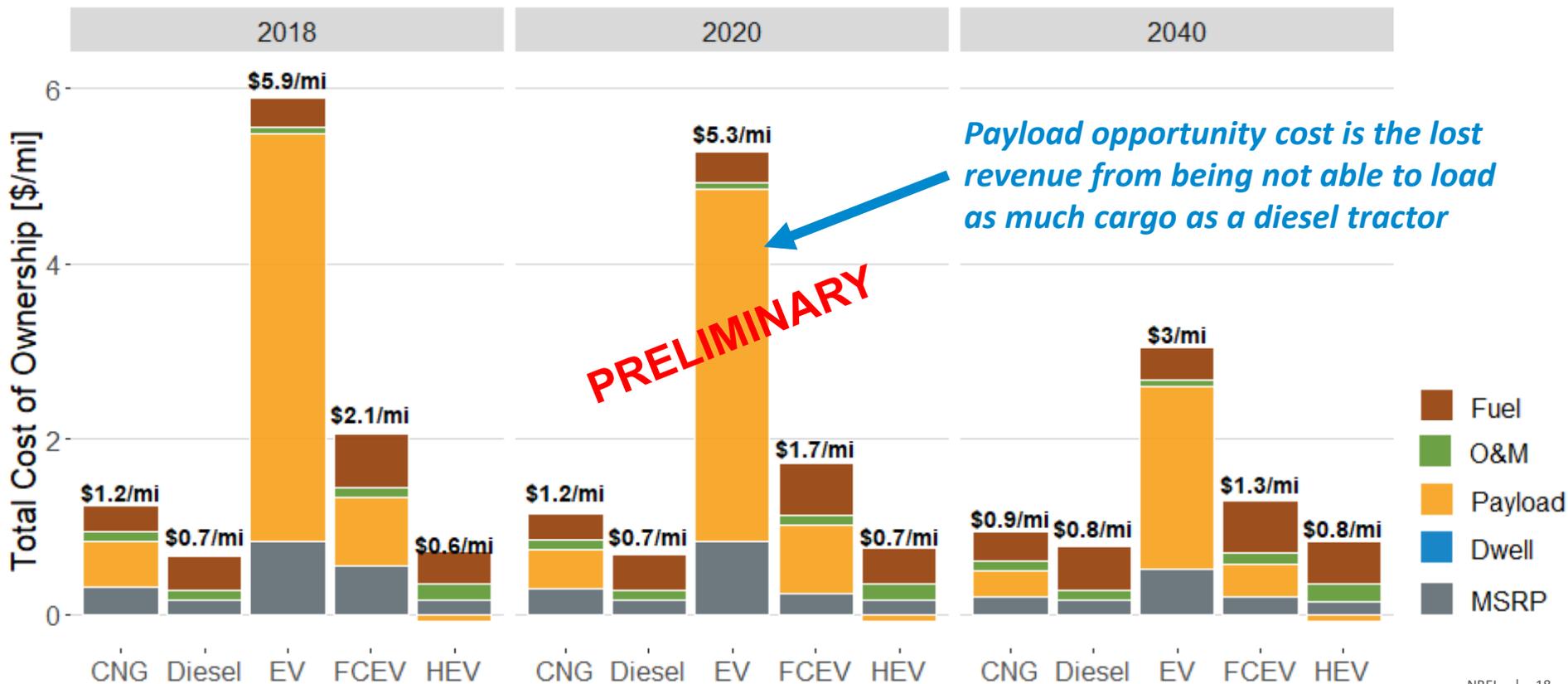


SERA

Scenario Parameters

- Class 8 Long Haul in Pacific Region
- 100,000 mi/yr, 10 year life
- Payload Cost = High, Dwell Cost = None
- Fuel, O&M Costs = Mid
- Discount Rate = 7%

**TCO result in Pacific region.
FCET costs driven by fuel
(\$7/gge H2 in this scenario) and
payload opportunity cost**



Thank You

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NREL/PR-5400-73944

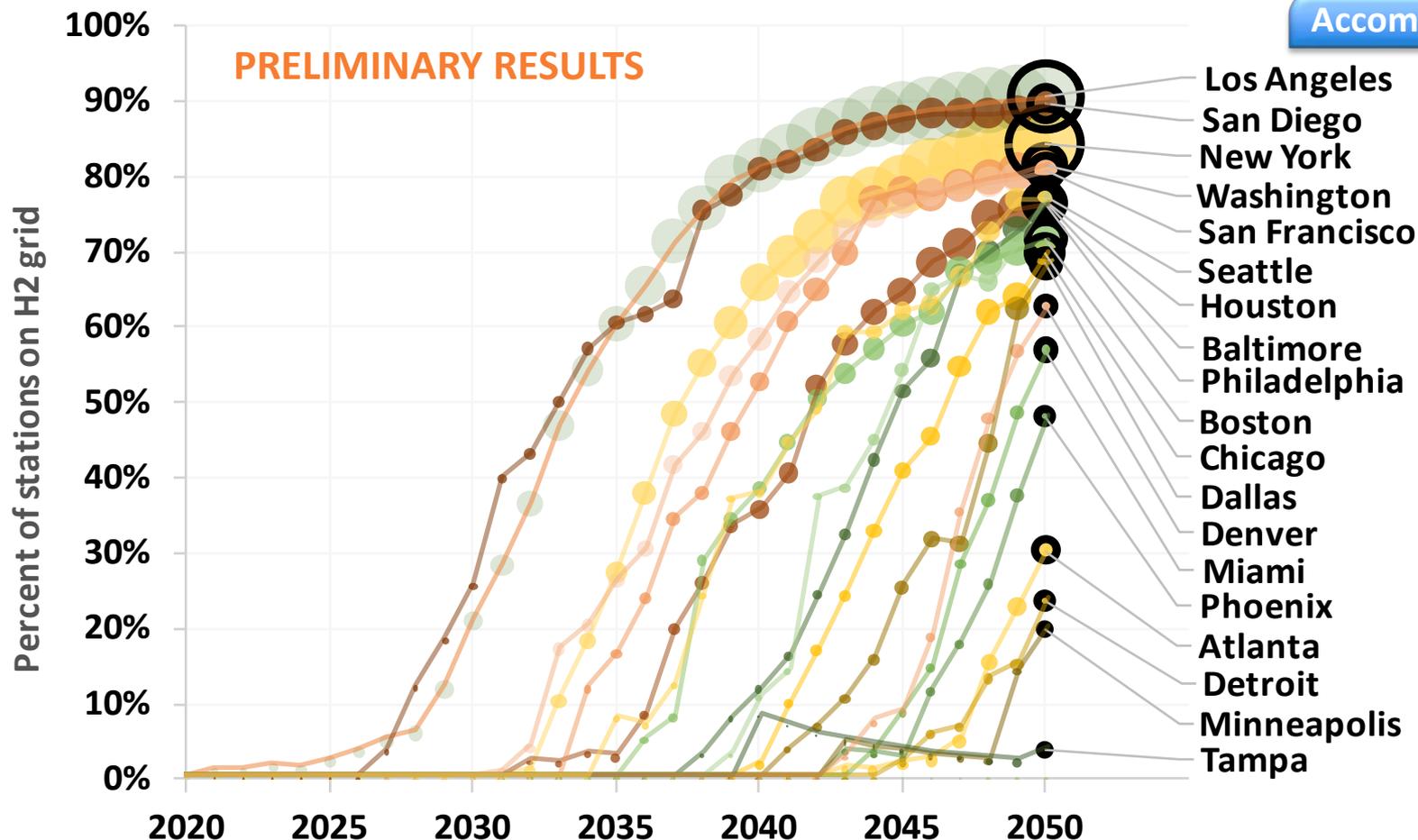
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BACKUP SLIDES

SERA Results: Percent of Stations Connected to the H2Grid (Scenario B: State Success)

Accomplishments 13



Major urban areas show significant economic advantage from H2Grid past 2030

- Hydrogen demand grows significantly
- Distance between refueling stations shrinks

Accomplishments and Progress (3/9): Class 8 Long Haul Vehicle Modeling



FASTSim

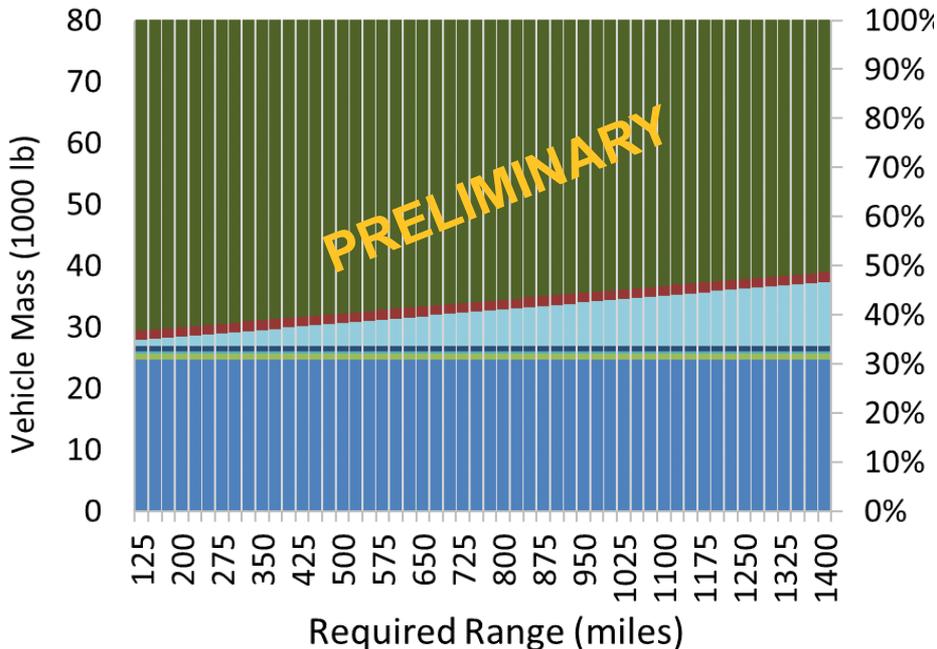
Vehicle Weight and Payload Analysis

- Theoretical sweep across required range (distance traveled on single refueling/charge) completed
- Tractor mass increases due to larger H2 storage and battery needed

Fuel cell trucks show lower total mass than battery trucks due to large battery needed

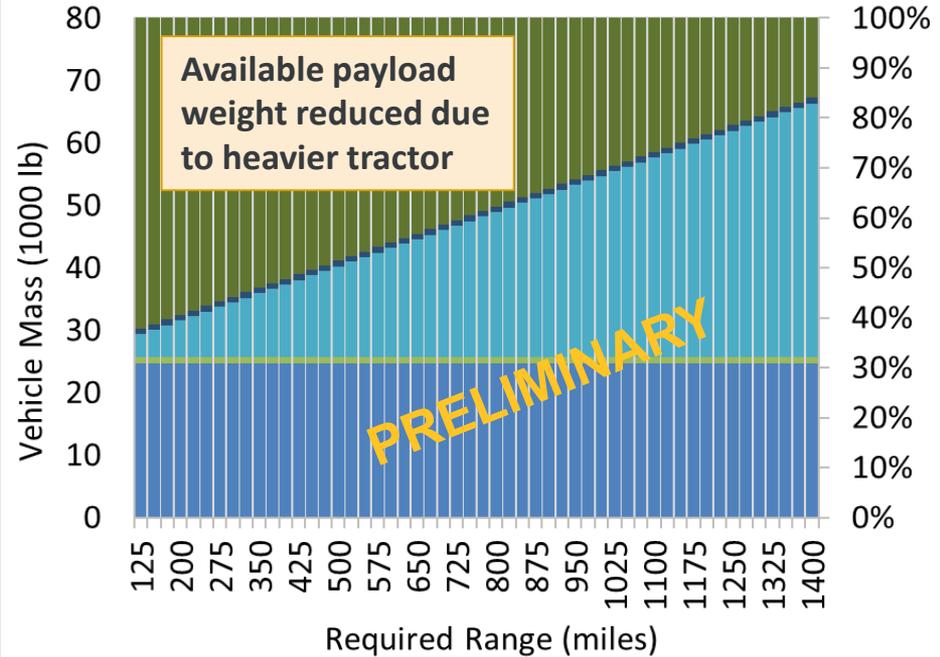
Fuel Cell Powertrain (2020 Tech Targets)

■ Cargo
 ■ Fuel Cell
 ■ Fuel storage
 ■ Motors
■ Batteries
 ■ Transmission
 ■ Glider



Battery Powertrain (2020 Tech Targets)

■ Cargo
 ■ Motors
 ■ Batteries
 ■ Transmission
 ■ Glider



National Light-Duty FCEV Supply Chain: Hydrogen Storage and Sustainability Analysis

- **Storage:** SERA sizes storage based on variable supply or demand data to lower total supply chain cost

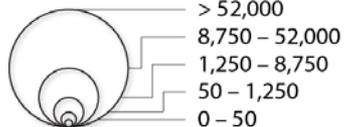
- **Sustainability:** Petroleum displacement and resource consumption/production (e.g. water, GHG) are tracked over time by region

Storage

- Salt Cavern
- LH2 Spheres

Scale

(thousands kg)

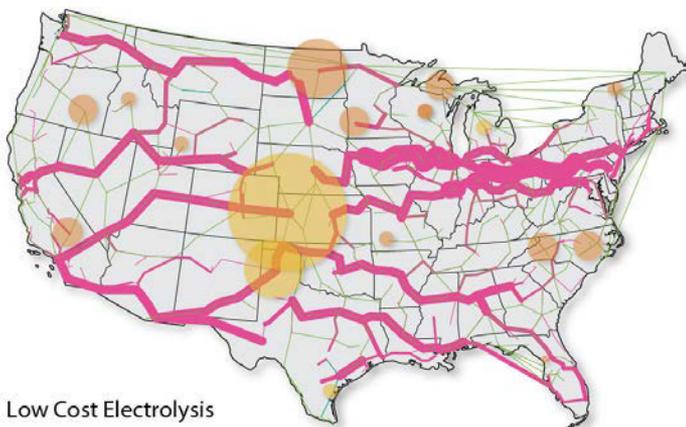
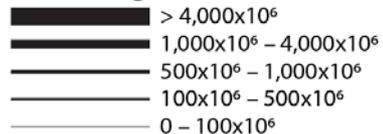


Transport

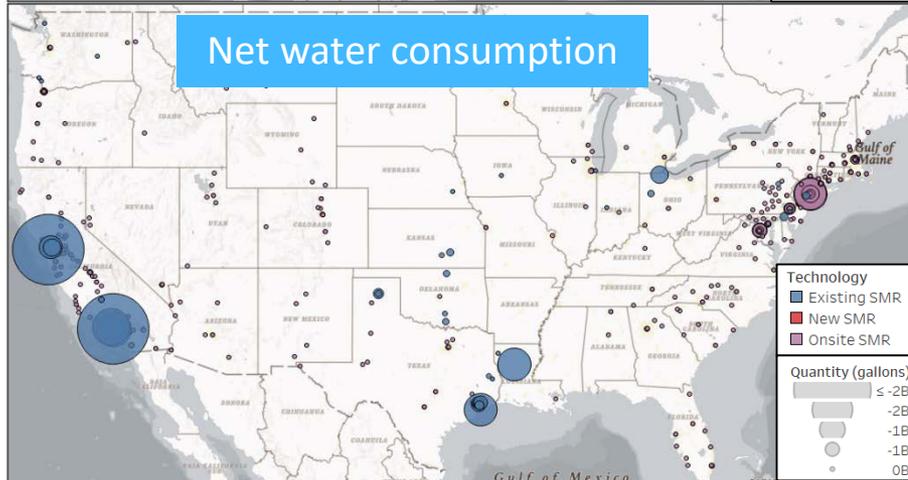
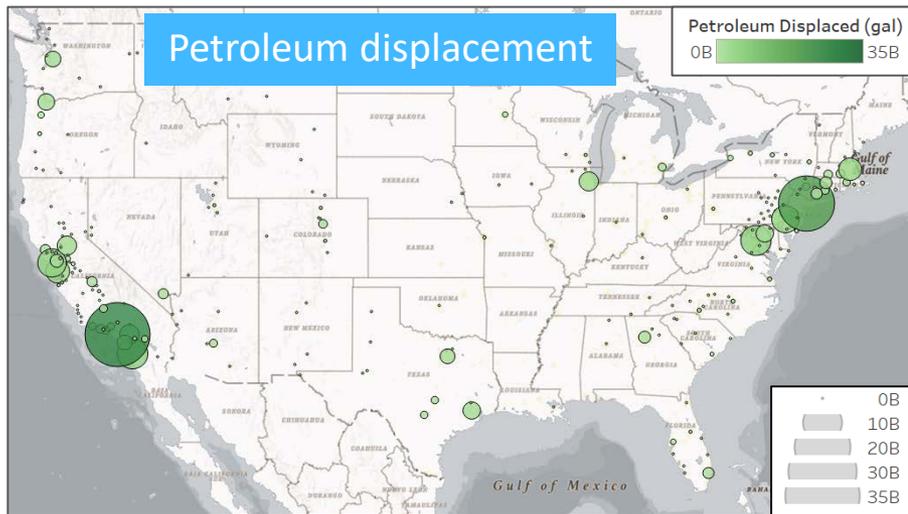
- LH2 Truck
- LH2 Train
- GH2 Truck
- Pipeline

Scale

(millions kg)



H2@Scale Analysis



National Heavy-Duty FCEV Total Cost of Ownership: Overview



FASTSim

Vehicle Powertrain Cost Modeling

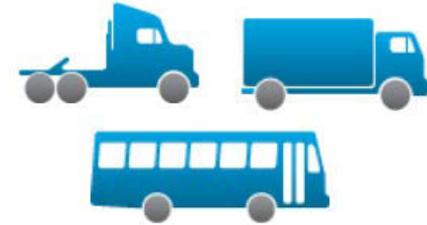
- Future Automotive Systems Technology Simulator model
- Heavy duty vehicle modeling with various powertrains (battery, fuel cell, nat gas)
- Powertrains modeled to meet performance specs required for the duty-cycle
- Vehicle component costs output (engine size, battery cost, fuel cell stack cost, etc.)



SERA

Vehicle Lifetime Cost Modeling

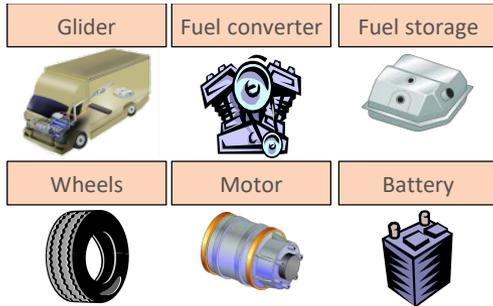
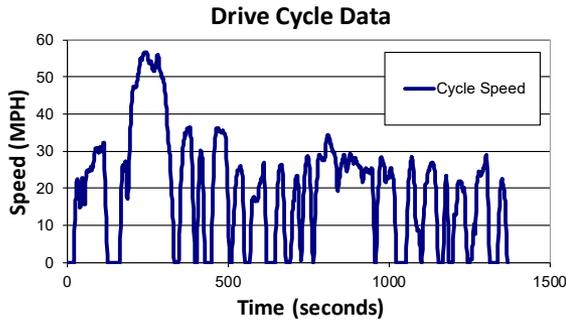
- SERA model used to track regional and temporal costs of vehicle ownership
- Direct costs (purchase price, fuel, O&M) tracked
- Indirect costs (dwell time and payload opportunity costs) tracked
- Net present cost of vehicle determined temporally and geographically



Market Assessment

- Financial performance estimates help identify which powertrains are best for each vehicle/vocation
- National level adoption scenario implications for refueling demands and supply chain needs

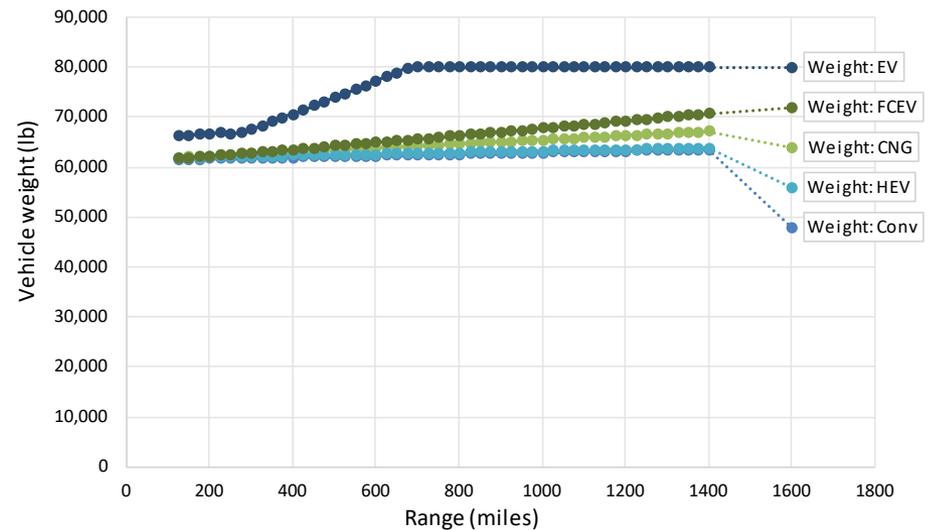
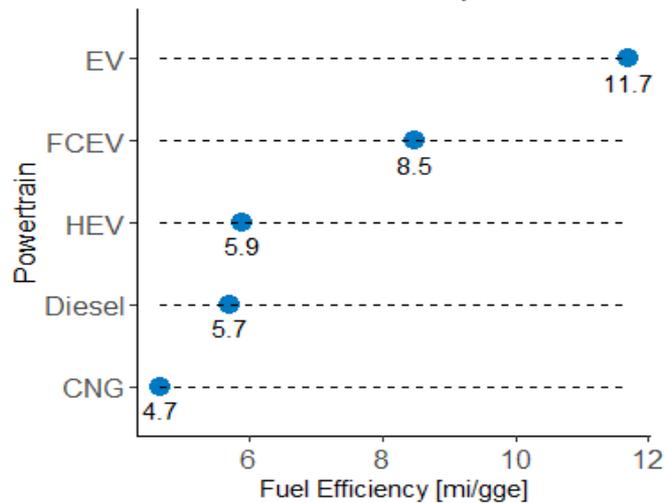
National Heavy-Duty FCEV Total Cost of Ownership: Vehicle Powertrain Modeling in FASTSim



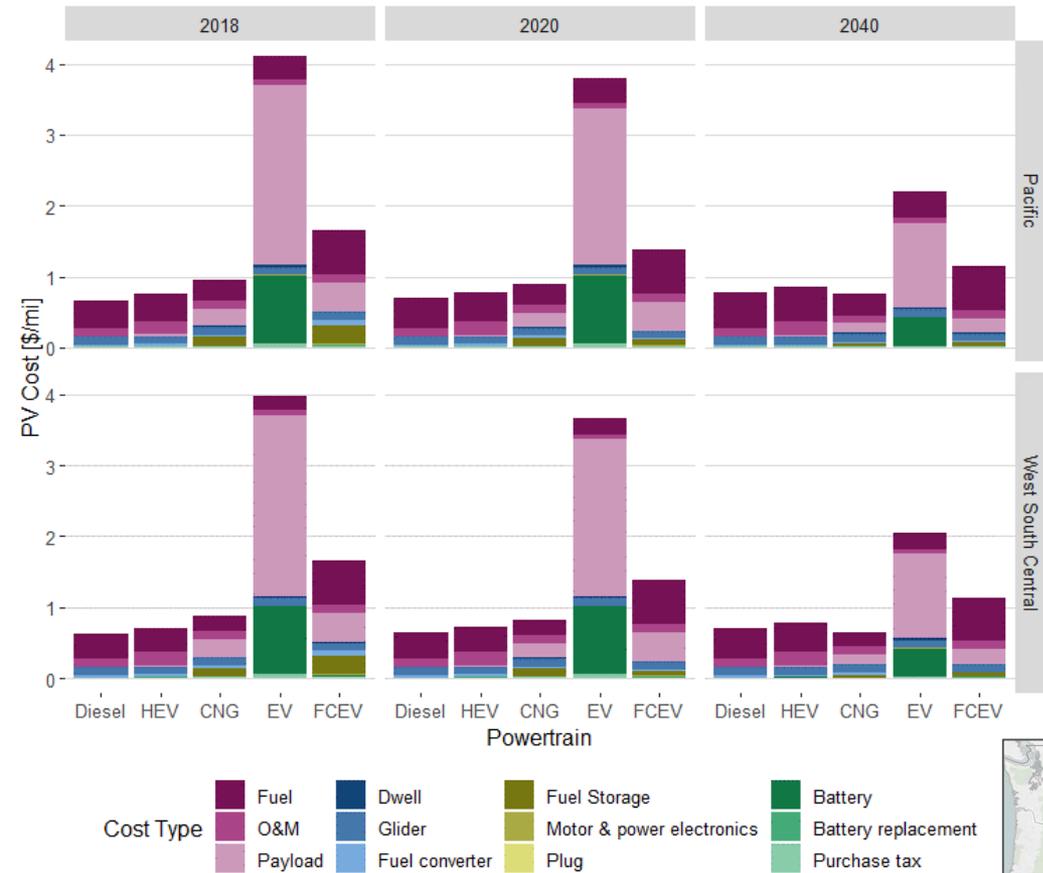
FASTSim

- **Vehicle Price:** FASTSim estimates purchase price based on powertrain component costs
- **Fuel Economy:** Estimated based on duty cycle and technology performance data
- **Weight:** Vehicle weight estimated for each powertrain based on technology data

Class 8 Sleeper



National Heavy-Duty FCEV Total Cost of Ownership: Vehicle Total Cost of Ownership in SERA



- **Total Cost of Ownership:** SERA calculates TCO by region and Model Year based on both direct and indirect costs
- **Stock:** SERA estimates vehicle population through 2040 consistent with AEO Sales outlook
- **Financials:** Detailed financial analysis on refueling stations and trucks can be completed

(Above) Class 8 Long-Haul Tractor total cost of ownership under certain scenario assumptions

(Right) 2040 Truck population by State/Class

