Light Duty Hydrogen Infrastructure Analysis at NREL

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Hydrogen Market Assessment Analysis Overview

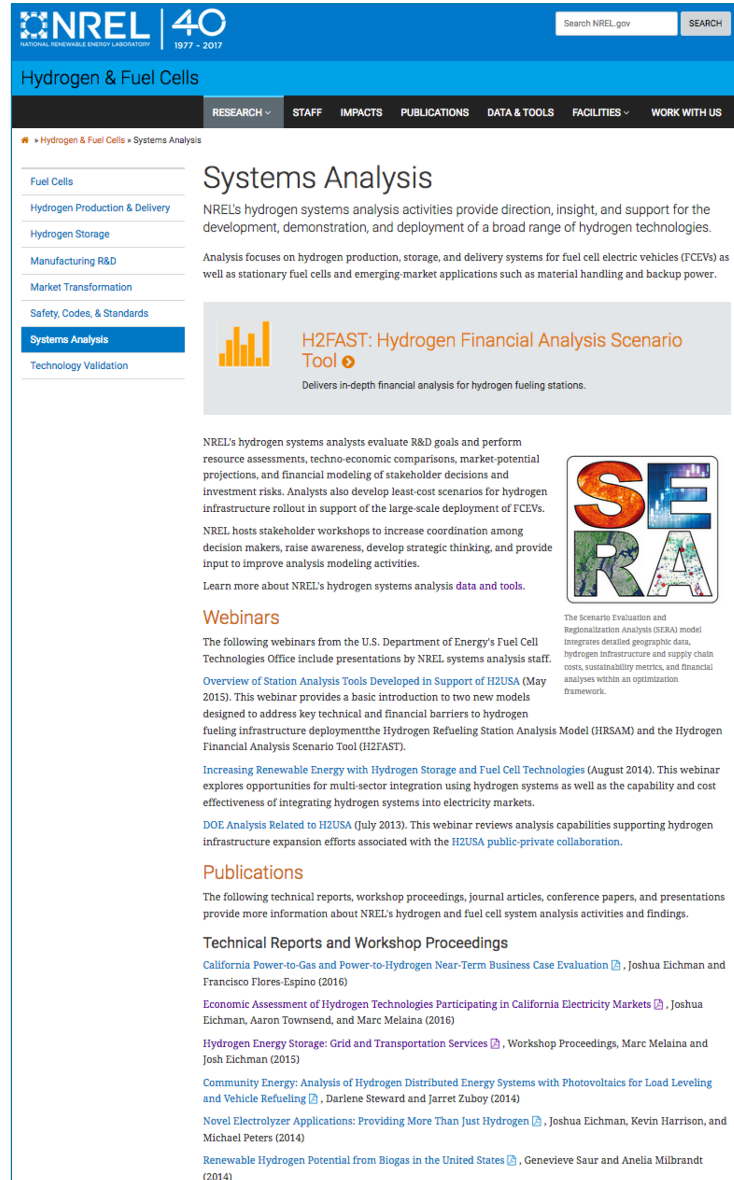
Collaborative and peer reviewed analysis developed with multiple stakeholders

- 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



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

SERA Demand Side Overview

U.S. FCEV Adoption Over Time

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Spatial and Temporal Stock Model

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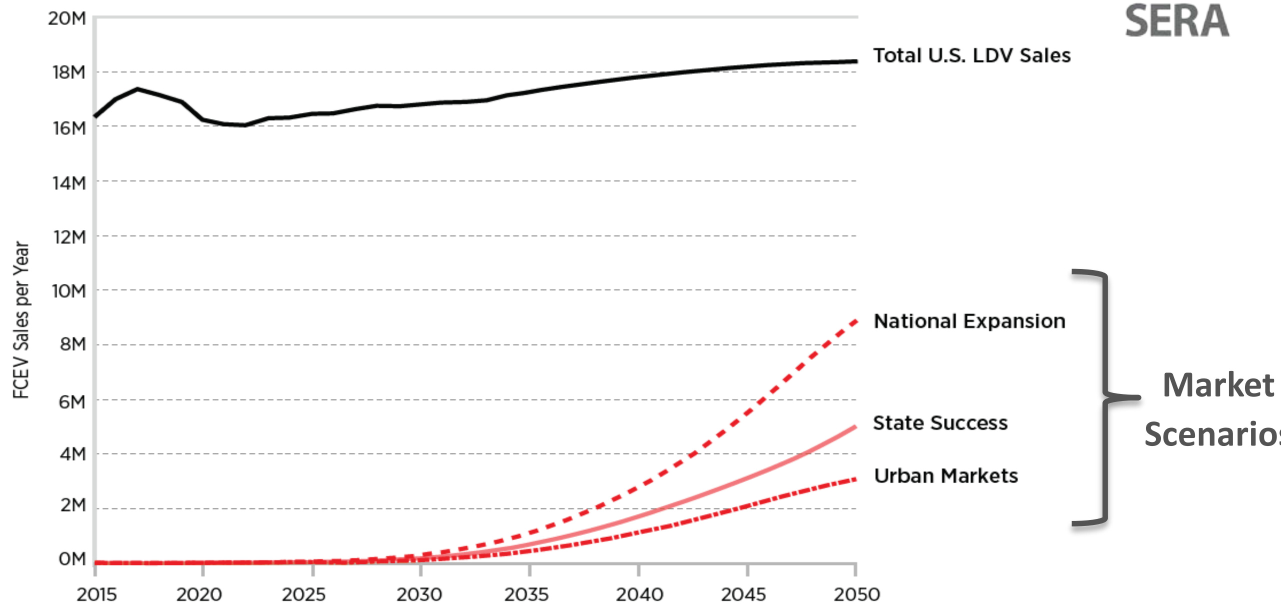
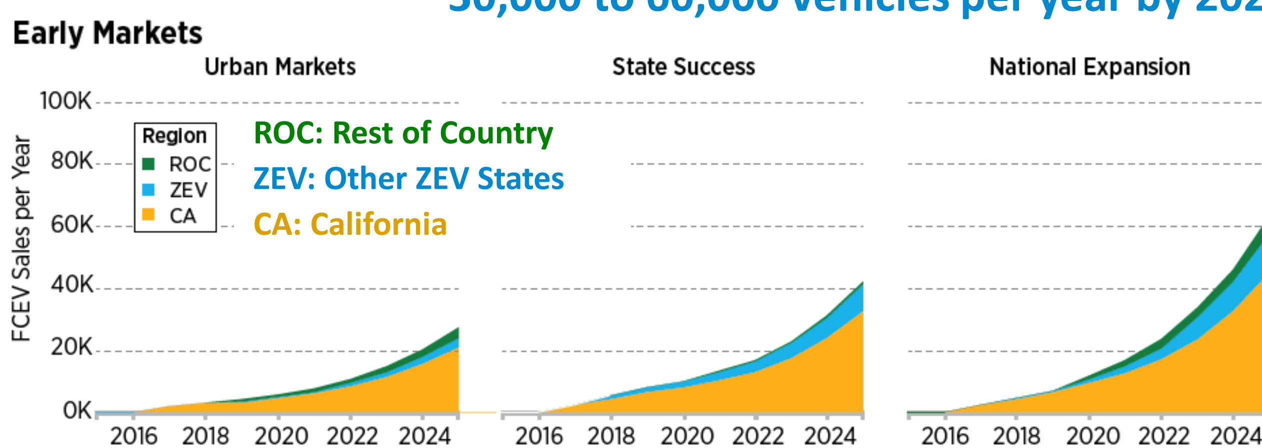
Spatial and Temporal Hydrogen Demand

↓

Refueling station placement

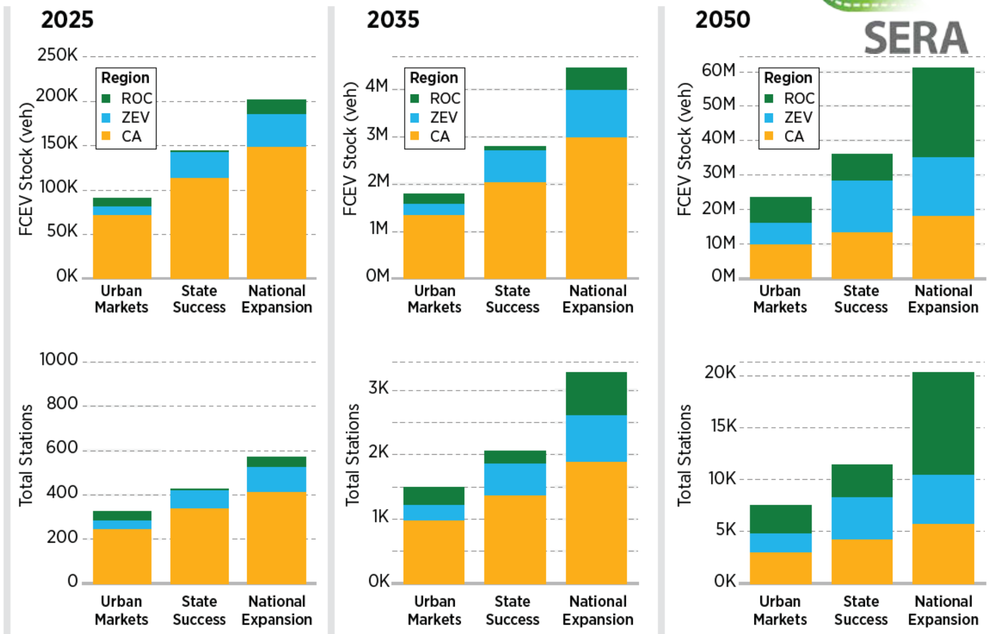


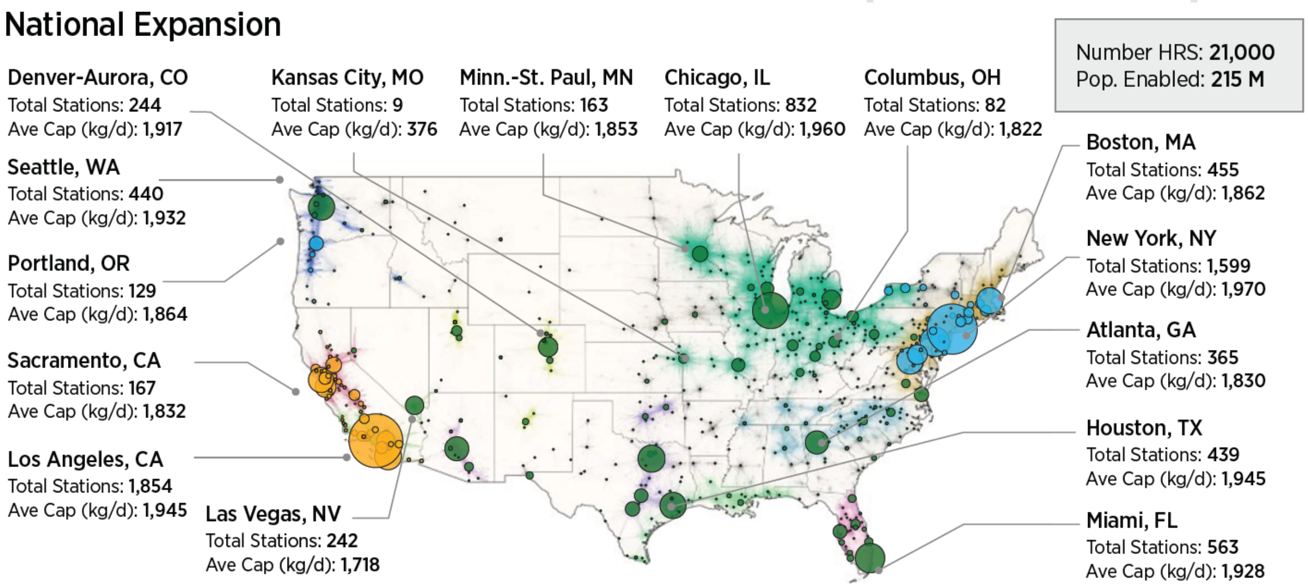
FCEV sales in the near-term range from 30,000 to 60,000 vehicles per year by 2025



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





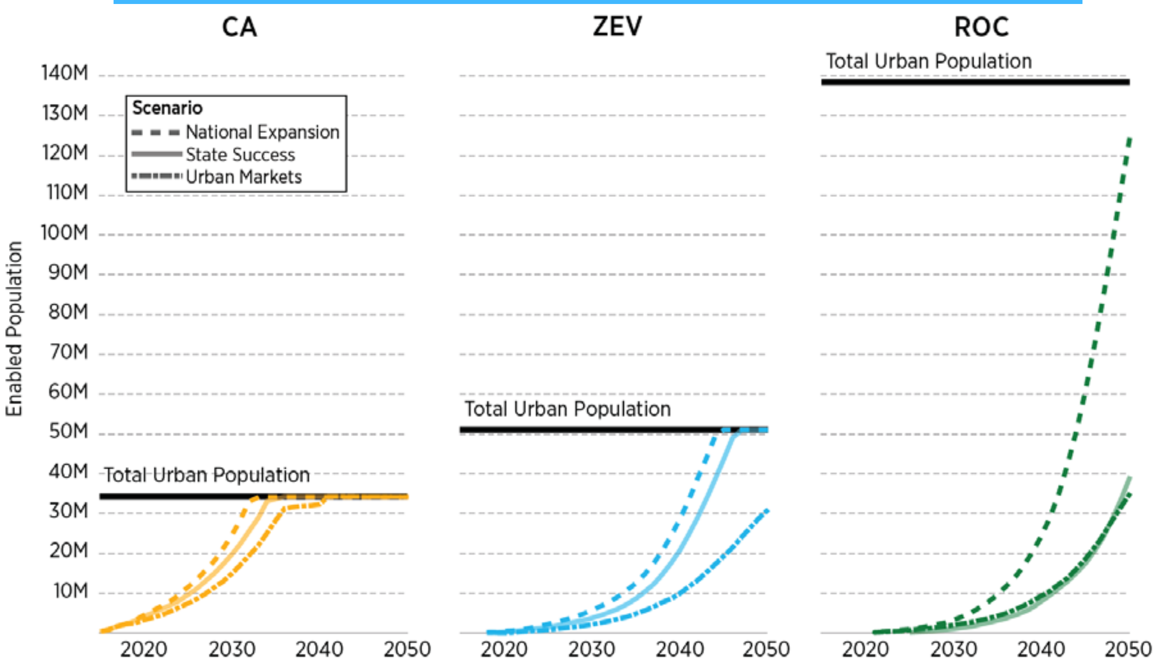
(Above) FCEV stock and total stations over time for each scenario

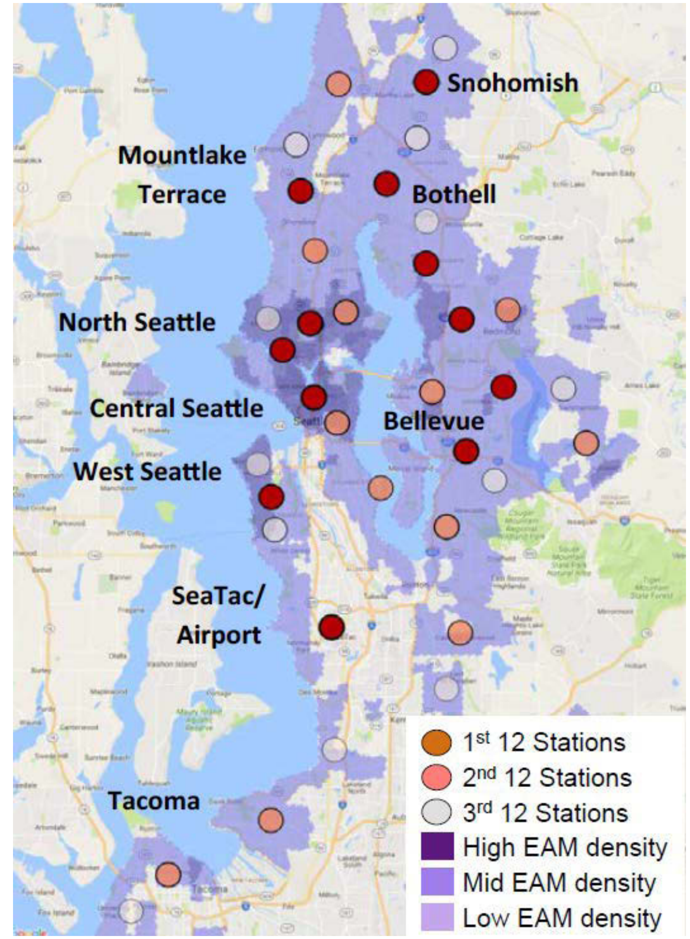
(Left) The number of stations and average capacity for select urban areas in 2050

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

(Below) Population with access to hydrogen refueling





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

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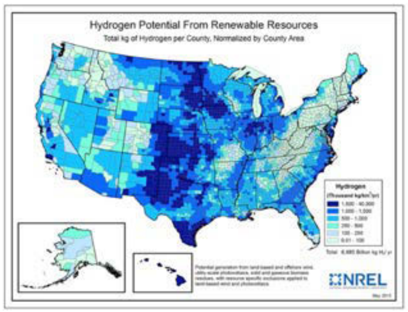
National Light-Duty FCEV Supply Chain: Overview

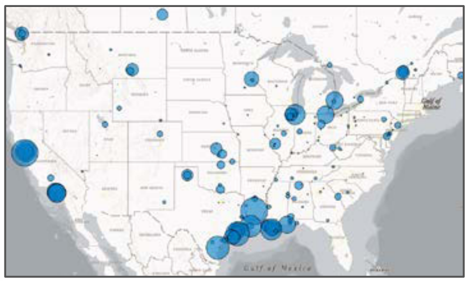
SERA

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

Energy Resources → **Hydrogen Production** → **Storage & Delivery** → **Retail Station Networks**

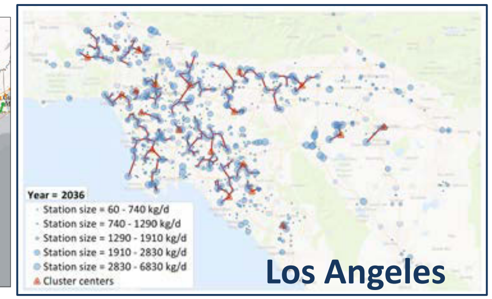


- Energy prices (natural gas, electricity, etc.)
- Renewables (biomass, solar, wind)
- Terrain, rights of way, etc.



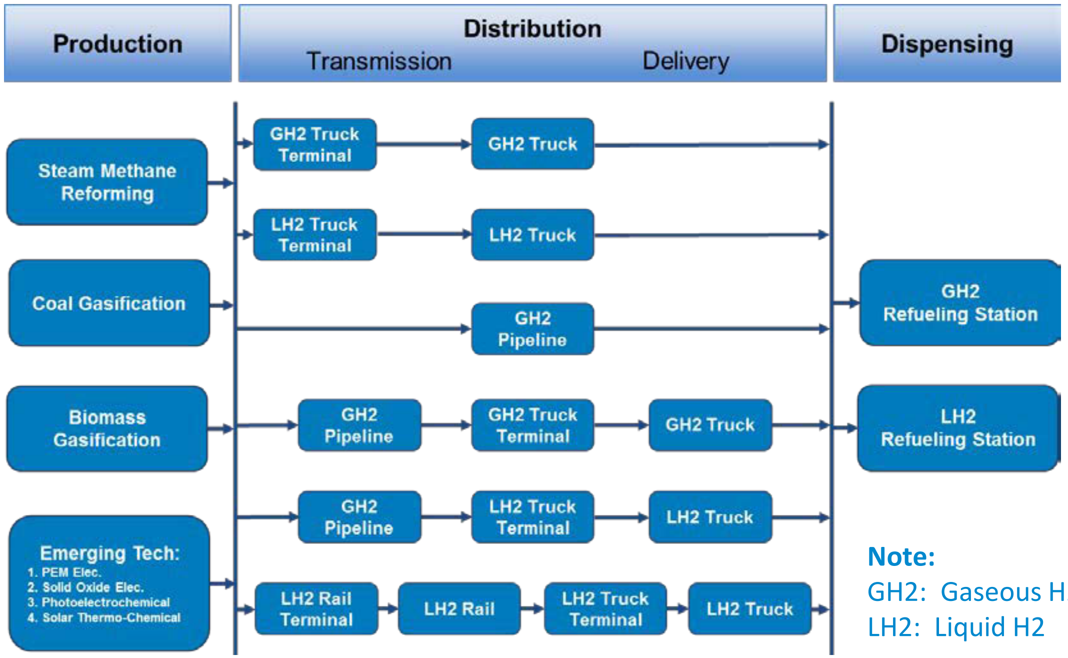
- Central and onsite production facilities
- Capacity sized to meet forecasted demand
- Economies of scale balanced with delivery costs

- 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

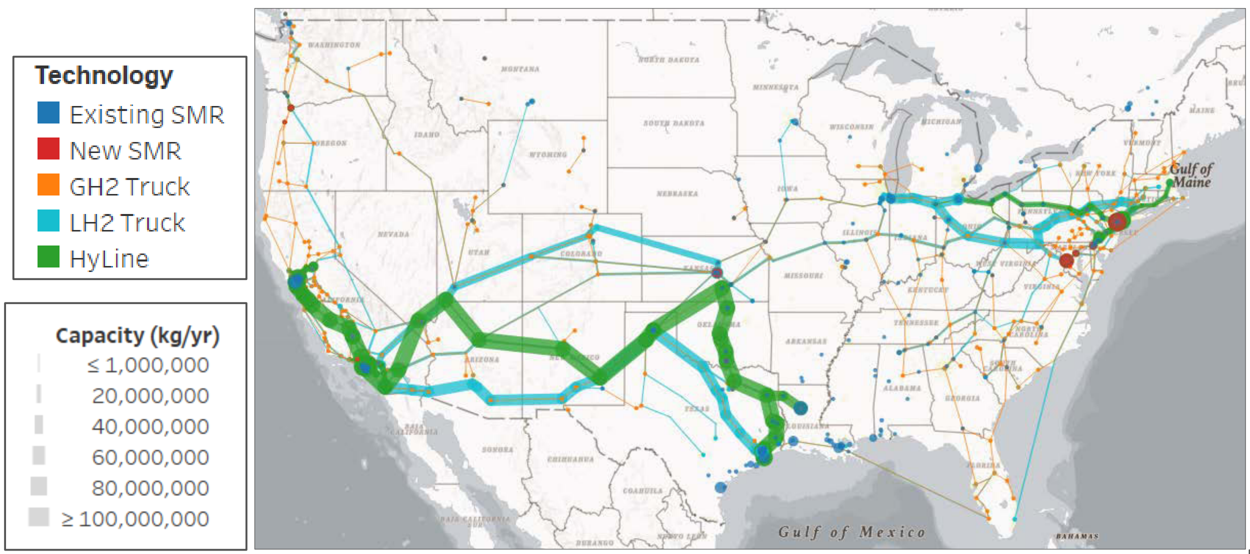


Note:
GH2: Gaseous H2
LH2: Liquid H2

- **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)

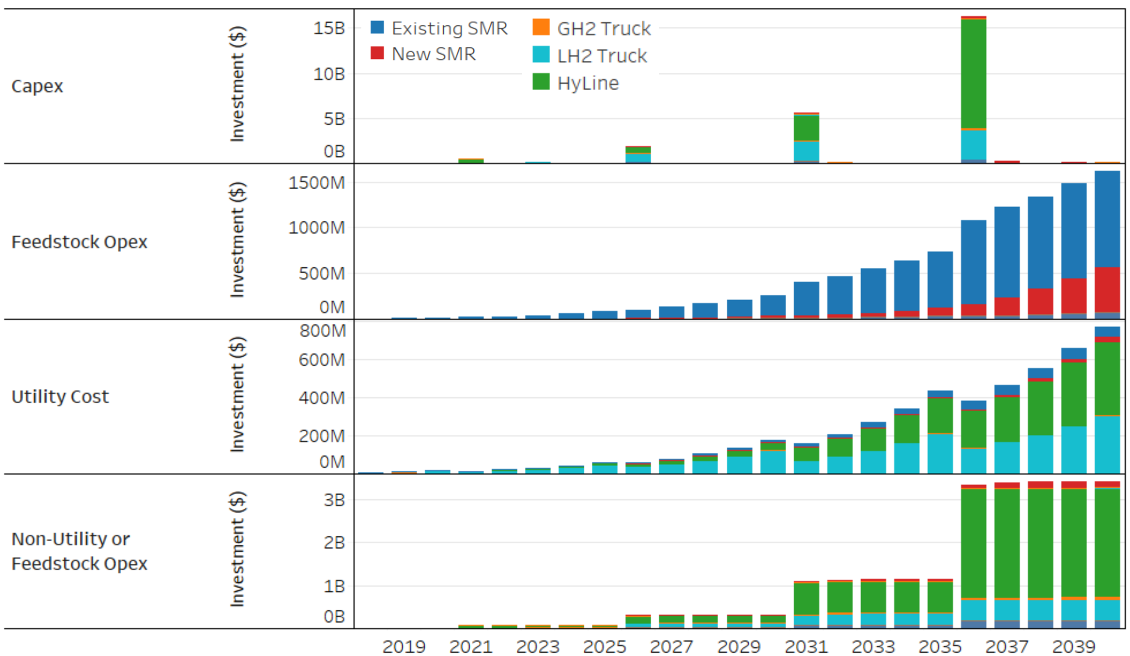
(Above) Example supply chain pathways for SERA to select from

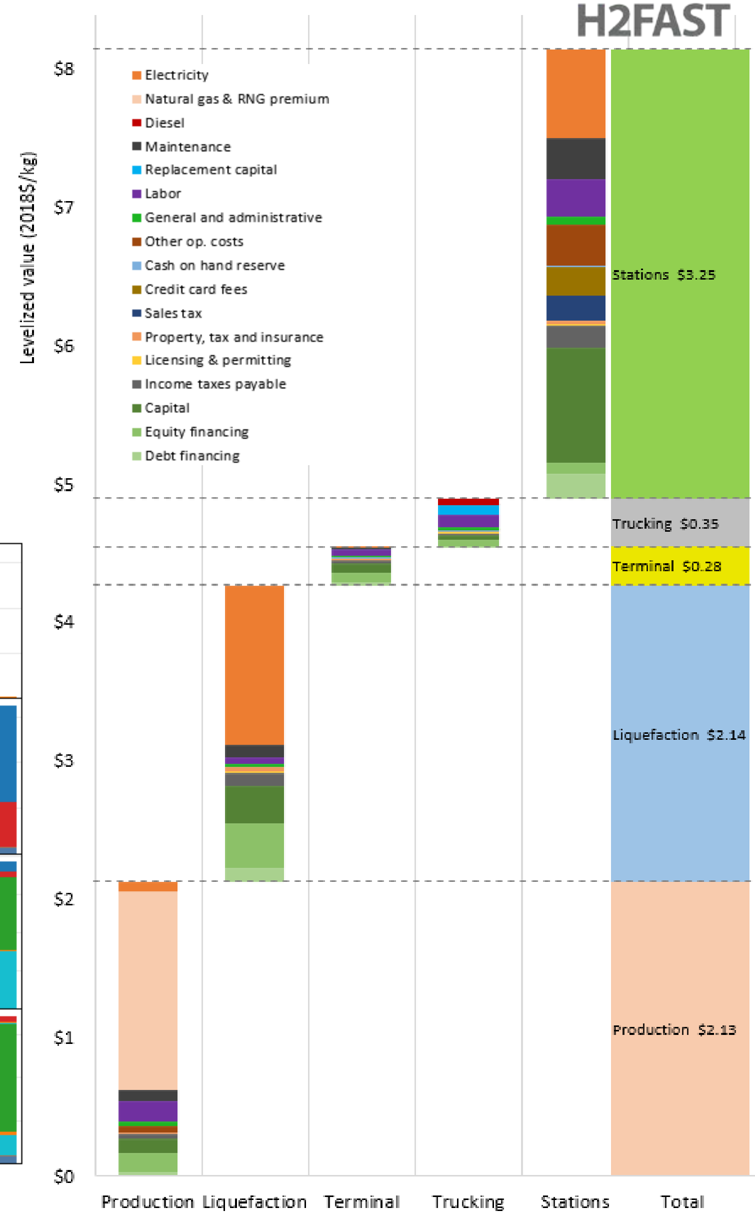
(Right) Visualization of optimized light-duty vehicle hydrogen supply chain in 2050



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

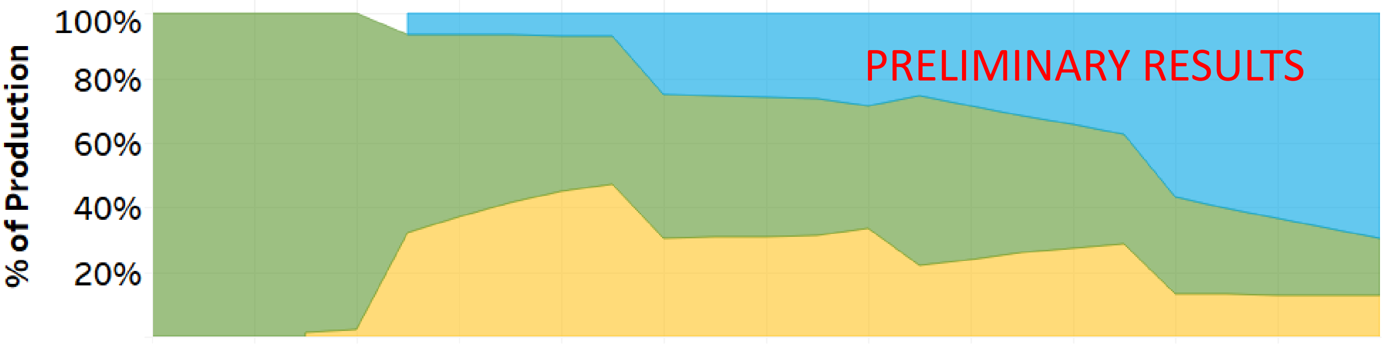
- **Cash Flows:** Capital, operating, and resource cash flows are all tracked for each piece of infrastructure
- **Price**: Minimum required selling hydrogen price can be estimated to achieve desired financial performance of each piece of infrastructure
- **H2FAST:** Rigorous financial model built into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





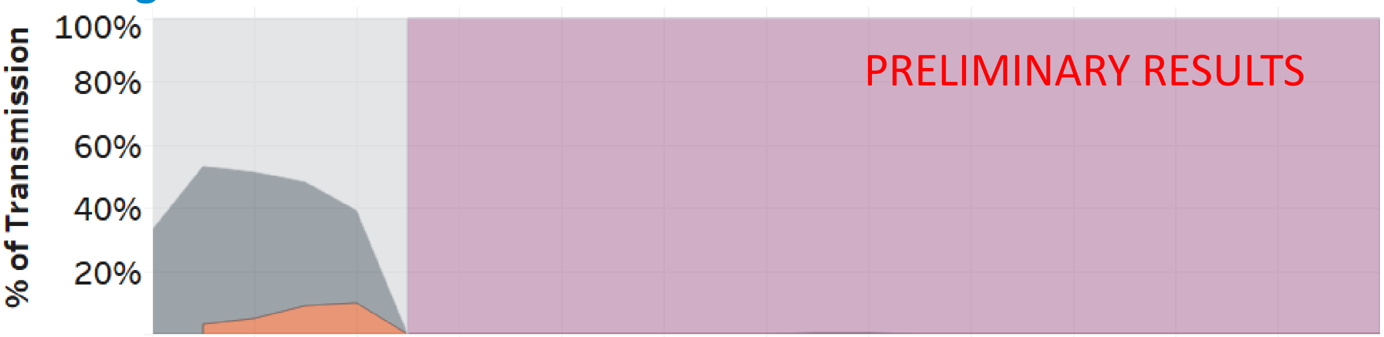
SERA Results: Production, Transmission, and Dispensing Technologies

Production Mix

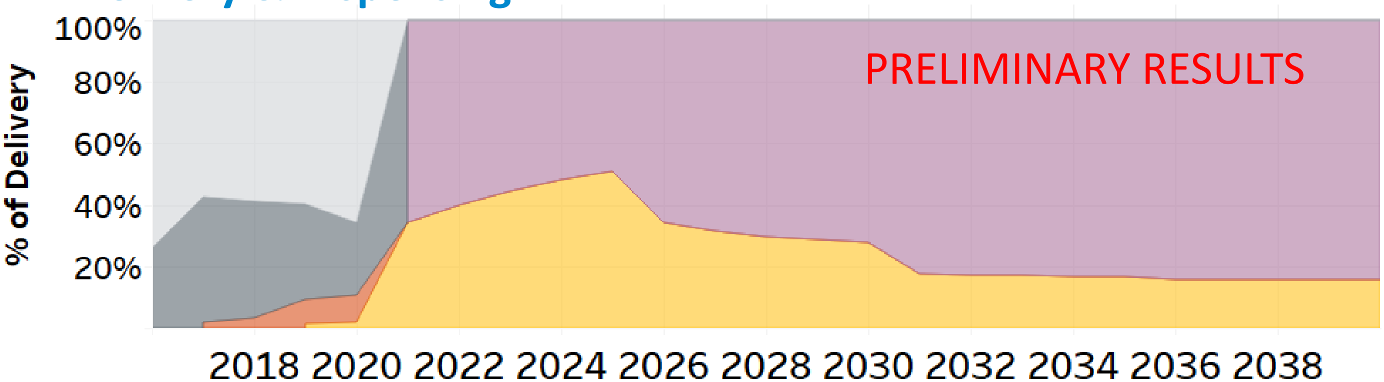


SMR dominates through 2040

Long-Distance Transmission Mix



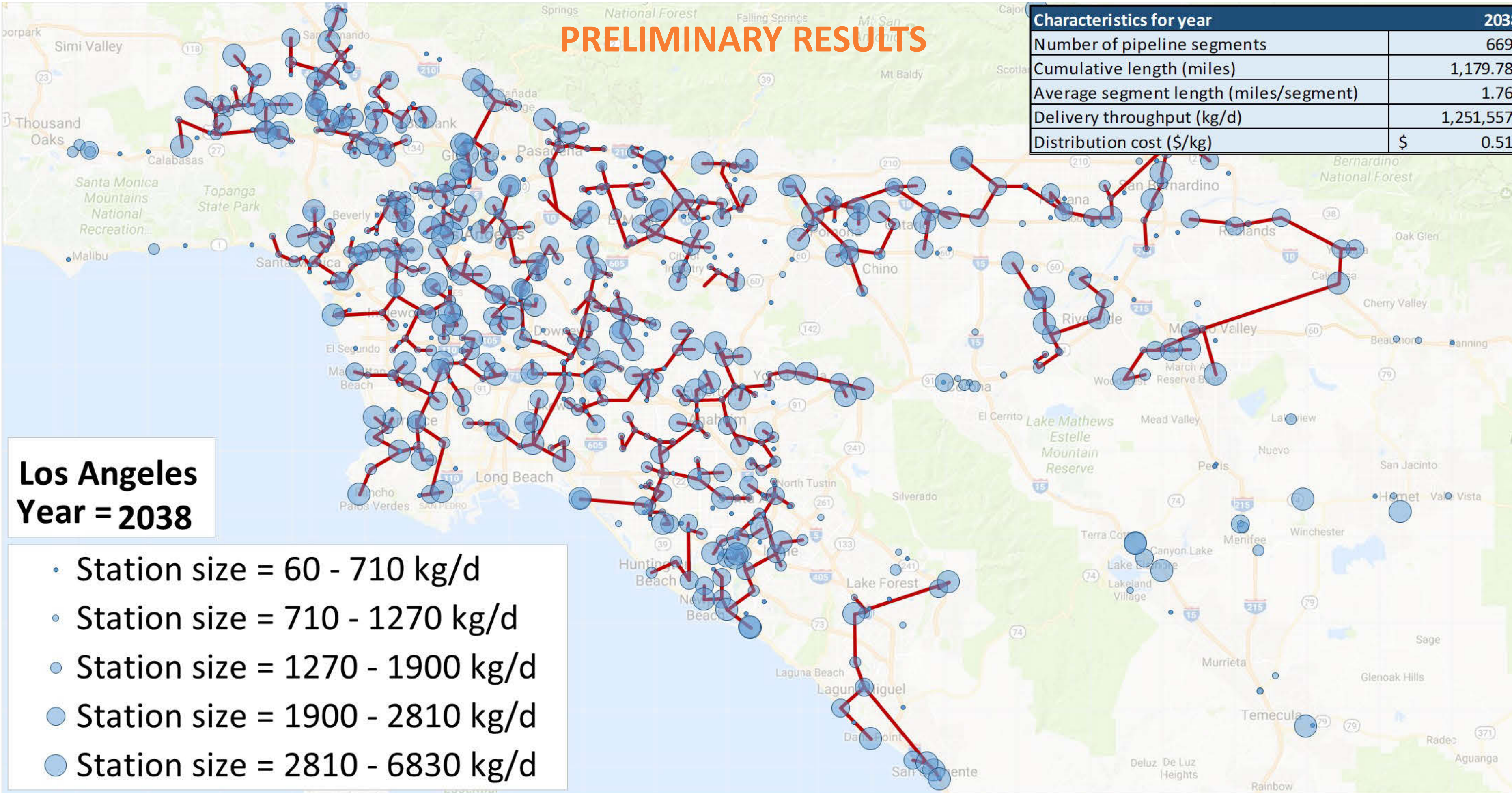
Delivery & Dispensing Mix



Pipeline *transmission* has highest economic prevalence

Early *delivery* trucks are replaced by pipeline and onsite SMR production

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



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

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

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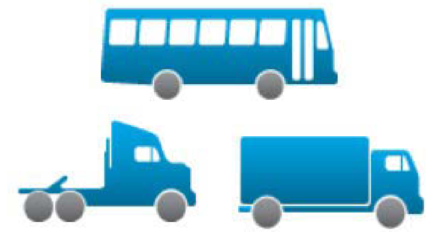
Analysis Approach Overview

FASTSim

SERA



Vehicle Powertrain Cost Modeling	Total Cost of Ownership Modeling	Market Assessment

Vehicle Powertrain Cost Modeling

<u>Inputs</u>:
- Vehicle attribute data
- Drive cycle data
- Powertrain technology cost and performance data

<u>Constraints</u>:
- Powertrains meet target acceleration and gradeability

<u>Outputs</u>:
- Vehicle fuel economy, weight
- Component costs & MSRP

Total Cost of Ownership Modeling

<u>Inputs</u>:
- 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)

<u>Outputs</u>:
- Total cost of ownership

Market Assessment

<u>Impact on FCTO Barriers</u>:
- Identify key drivers to fuel cell truck competitiveness
- Assess fuel cells for commercial applications

<u>Integration with Other Projects</u>:
- 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

		Tech Targets	
Target year	**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

Fleet DNA

NREL's Fleet DNA database used for drive cycle data

Drive Cycle Data

Performance and Cost Data

FASTSim

FASTSim sizes powertrain components to match acceleration observed in the duty cycle

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

Emissions benefits were not included in TCO framework but could be added in future analyses

Vehicle Modeling and Benchmarking

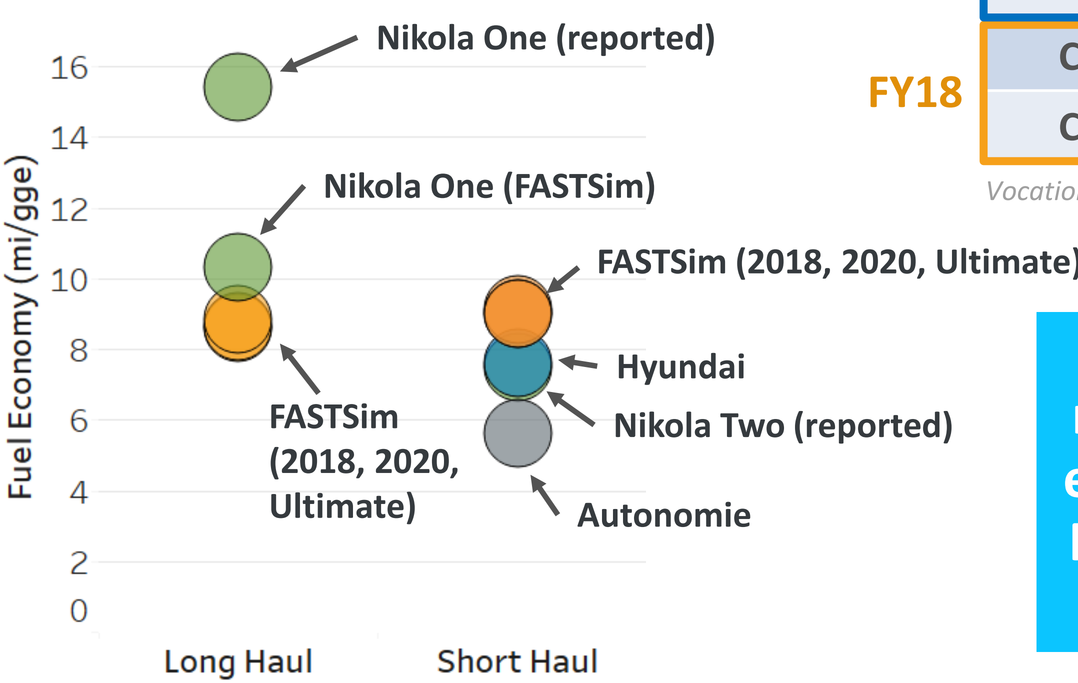
FASTSim

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

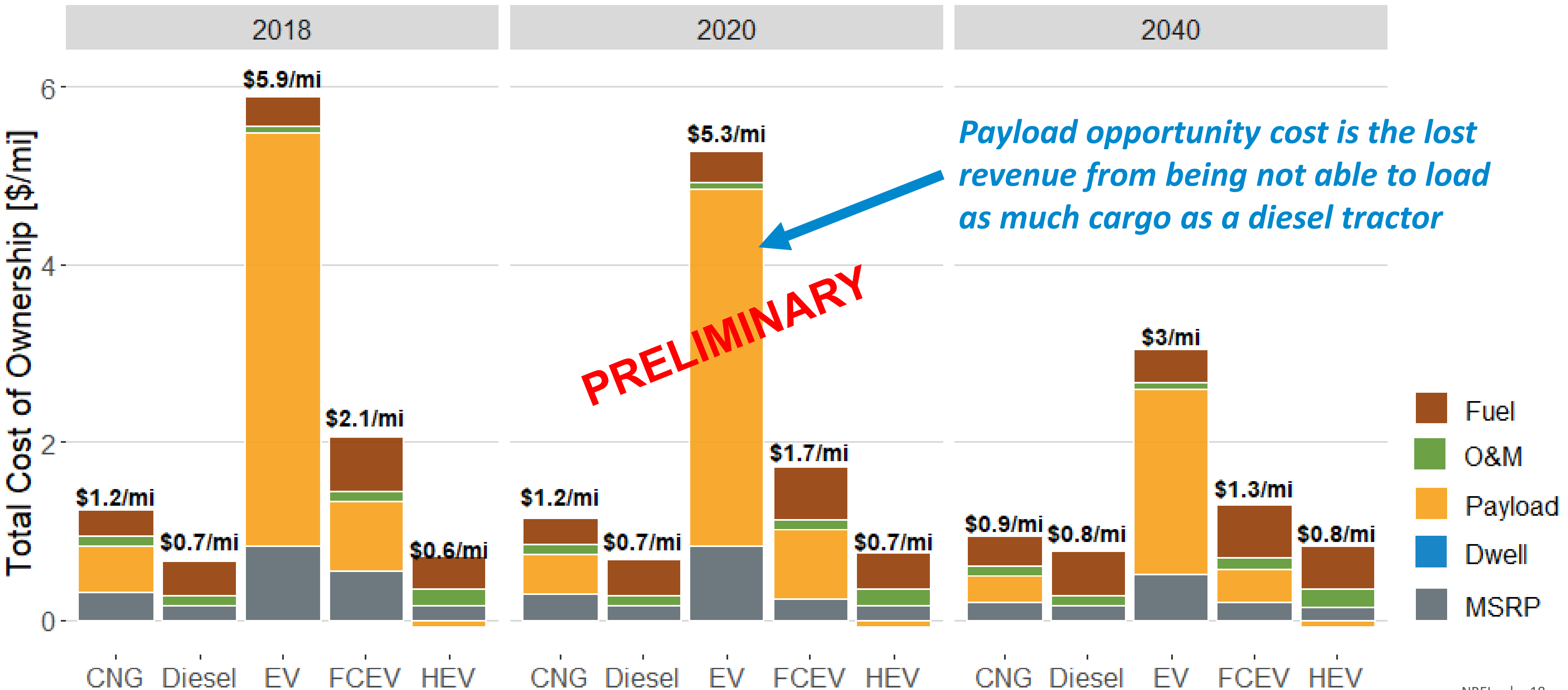
Total Cost of Ownership Scenario Analysis

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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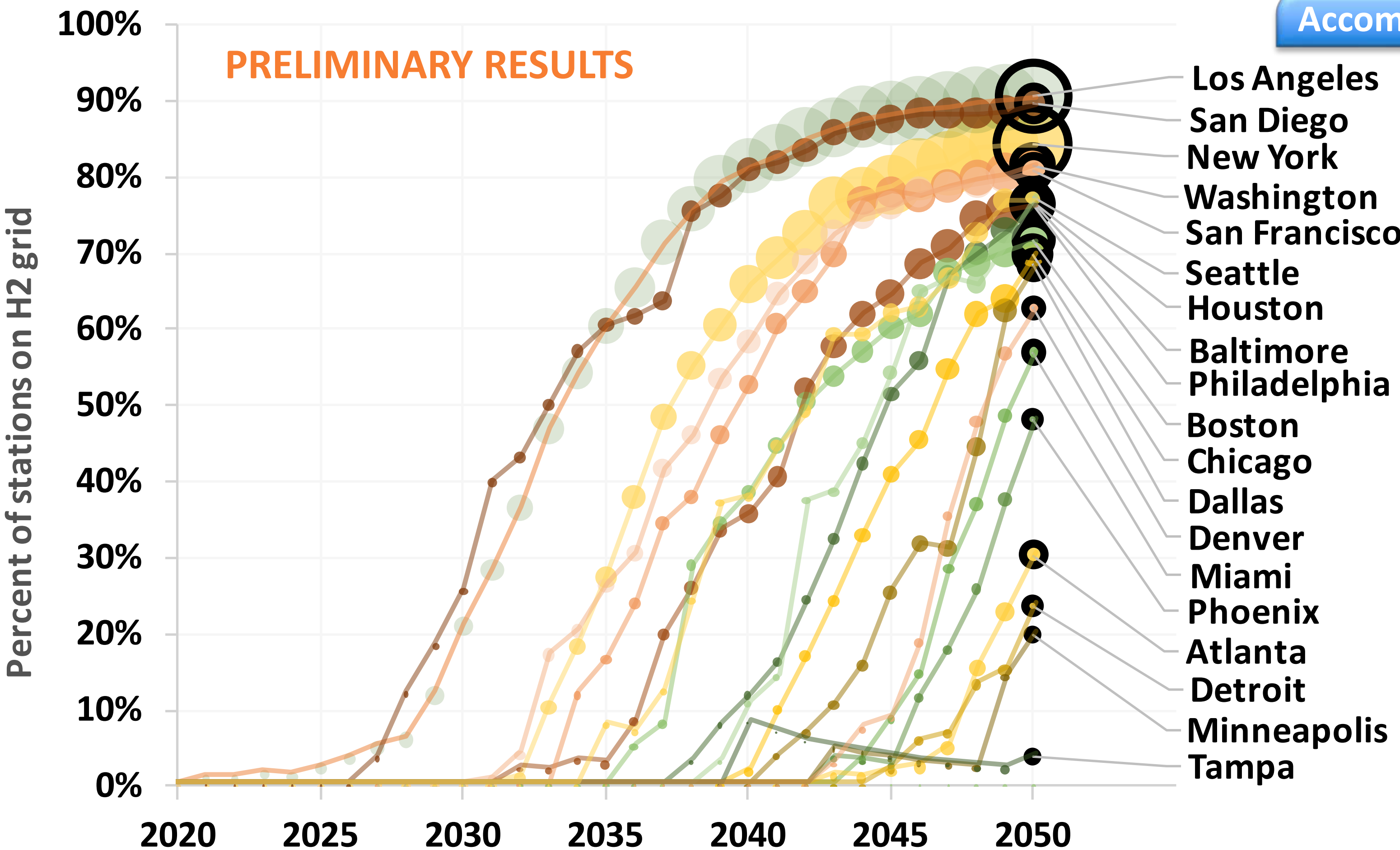
Transforming ENERGY

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

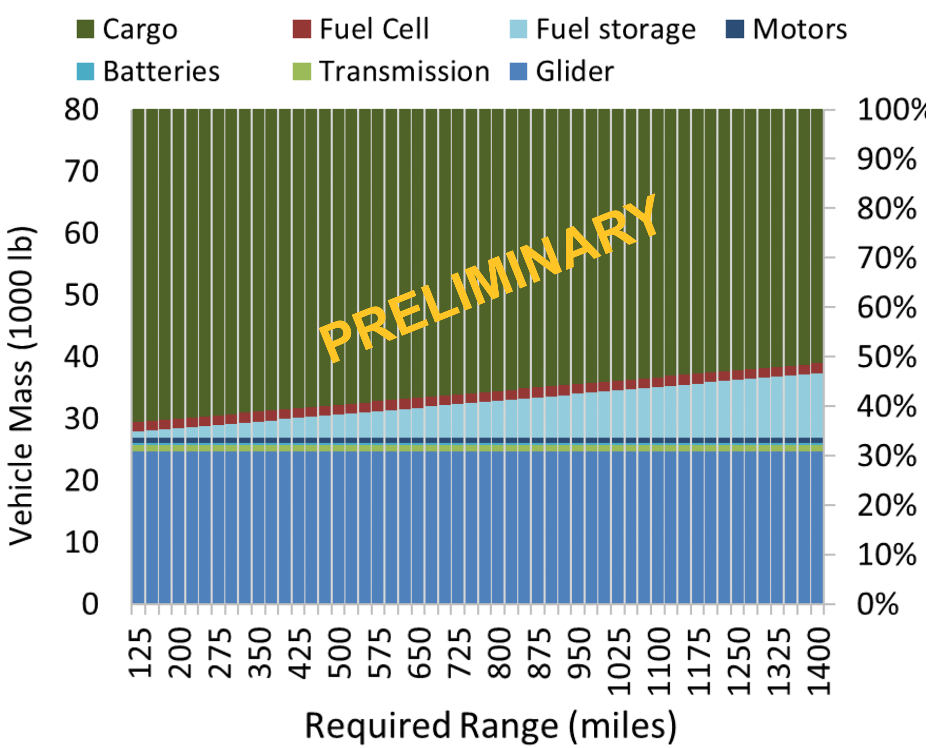
FASTSim

Vehicle Weight and Payload Analysis

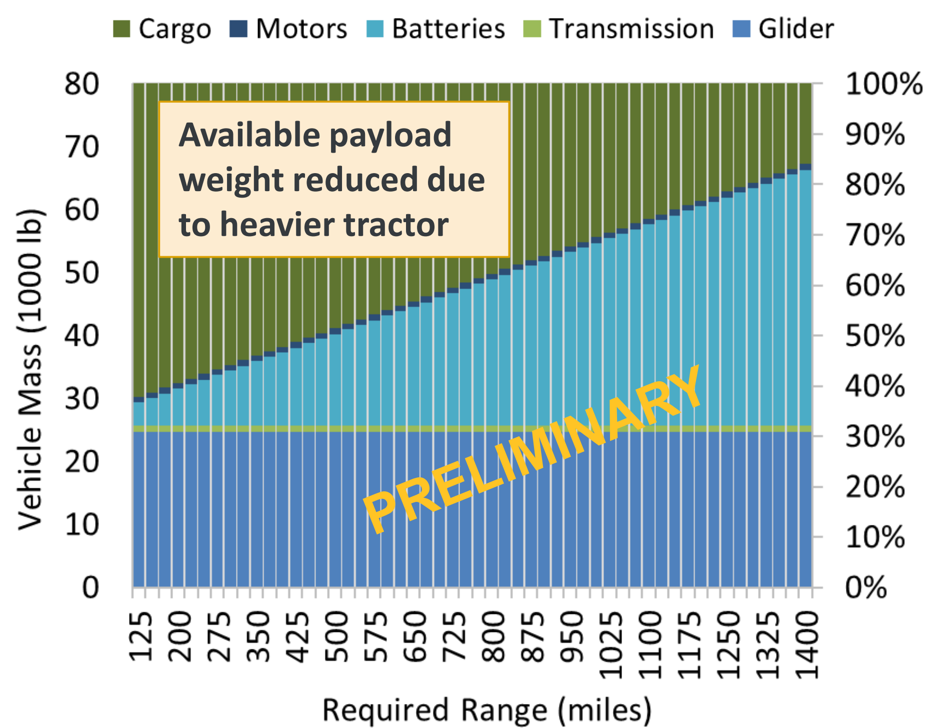
- Theoretical sweep across required range (distance traveled on single refueling/charge) completed
- Tractor mass increases due to larger H2 storage and battery needed

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

Fuel Cell Powertrain (2020 Tech Targets)

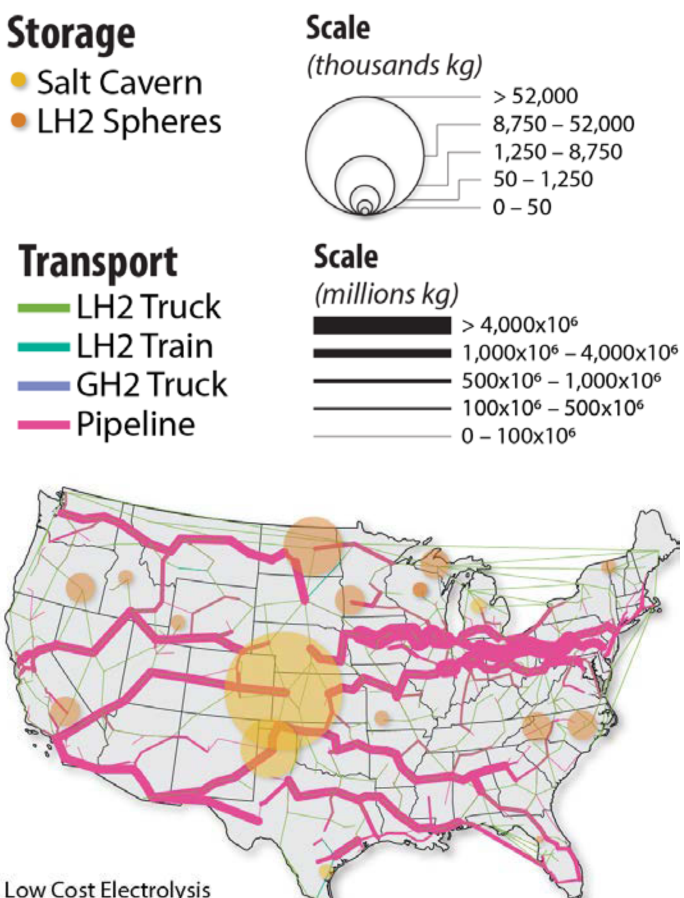


Battery Powertrain (2020 Tech Targets)

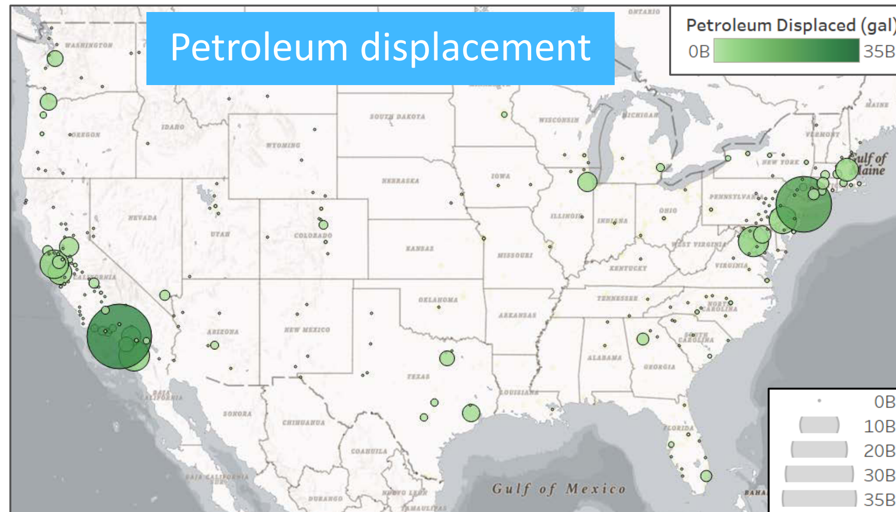


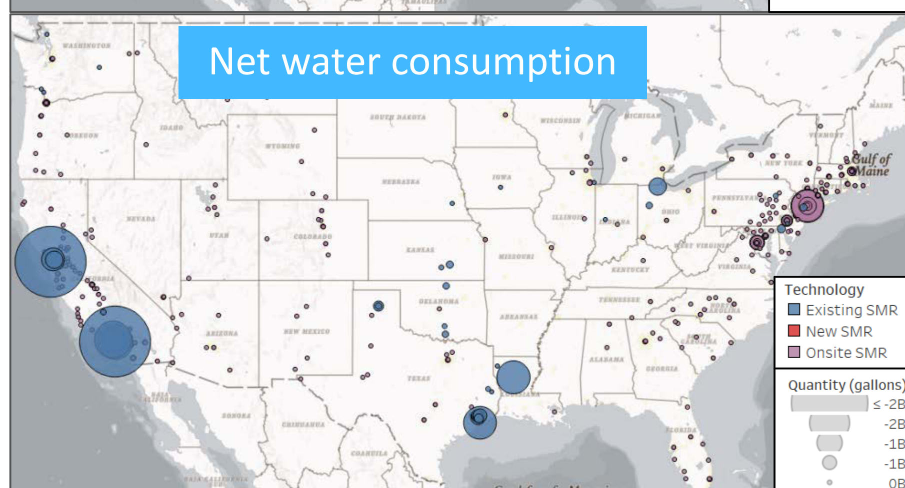
National Light-Duty FCEV Supply Chain:
Hydrogen Storage and Sustainability Analysis

- **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



H2@Scale Analysis

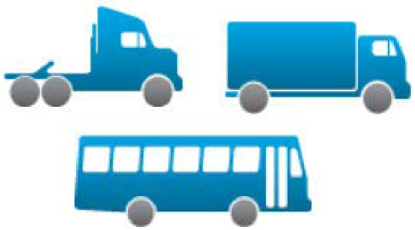




National Heavy-Duty FCEV Total Cost of Ownership: Overview

FASTSim

SERA



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.)

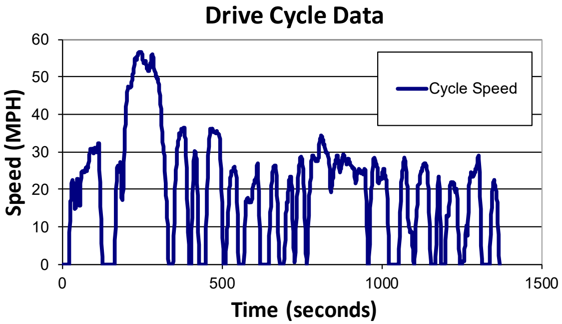
Vehicle Lifetime Cost Modeling

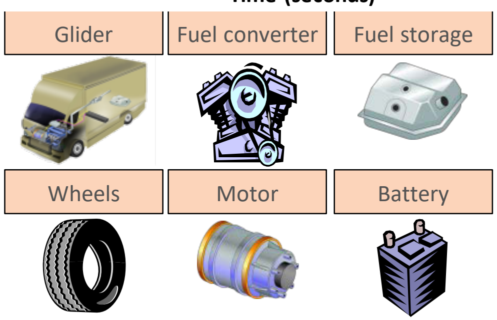
- SERA model used to track regional and temporal costs of vehicle ownership
- Direct costs (purchase price, fuel, O&M) tracked
- Indirect costs (dwell time and payload opportunity costs) tracked
- Net present cost of vehicle determined temporally and geographically

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

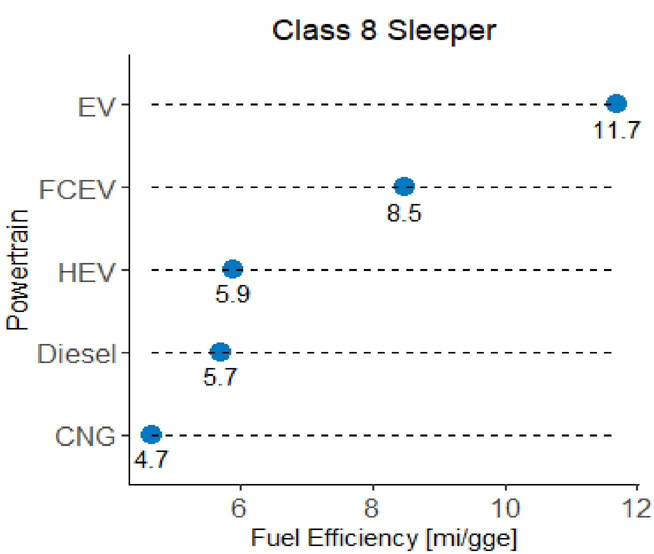
National Heavy-Duty FCEV Total Cost of Ownership: Vehicle Powertrain Modeling in FASTSim

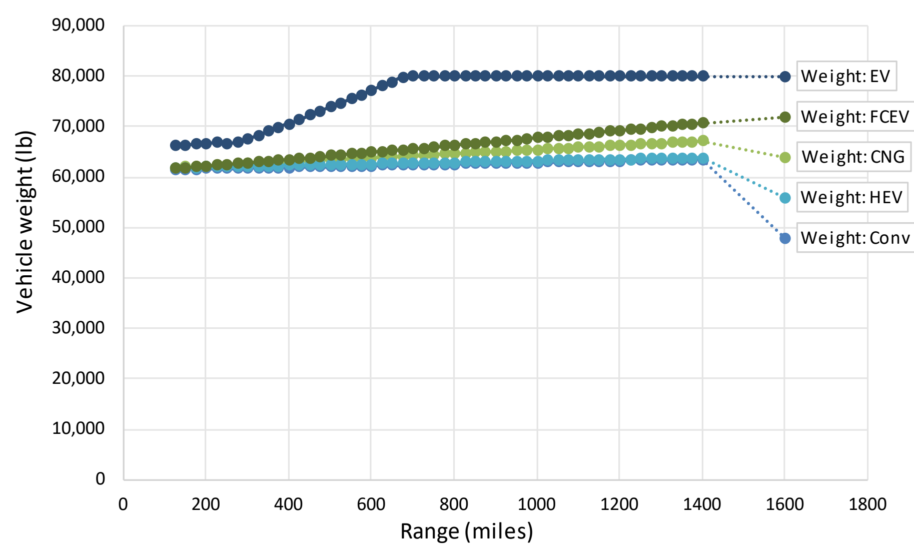




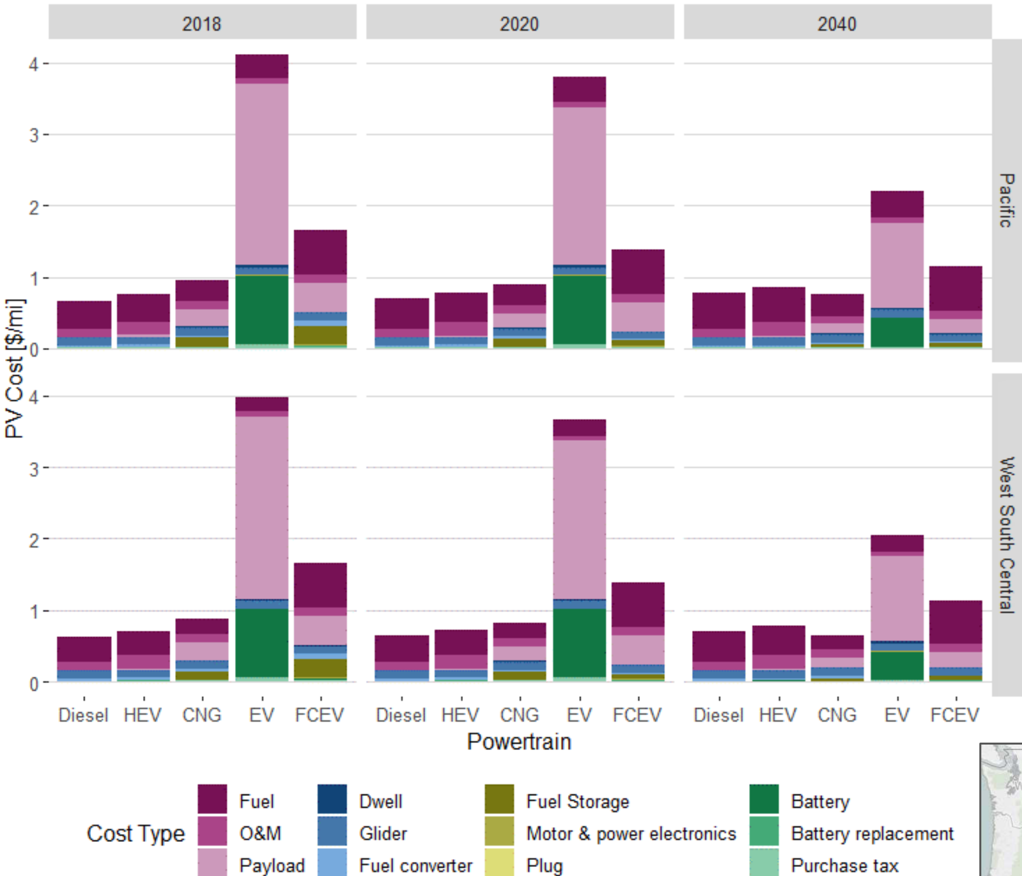
FASTSim

- **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





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