Light Duty Hydrogen Infrastructure Analysis at NREL

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This presentation does not contain any proprietary, confidential, or otherwise restricted information
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

<table>
<thead>
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<th>Category</th>
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<tr>
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National Light-Duty FCEV Adoption: Different Market Support Scenarios Using the Scenario Evaluation and Regionalization Analysis (SERA) Model

SERA Demand Side Overview

U.S. FCEV Adoption Over Time

Spatial and Temporal Stock Model

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

### National Expansion

- **Denver-Aurora, CO**
  - Total Stations: 244
  - Ave Cap (kg/d): 1,917
- **Kansas City, MO**
  - Total Stations: 9
  - Ave Cap (kg/d): 376
- **Minn.-St. Paul, MN**
  - Total Stations: 163
  - Ave Cap (kg/d): 1,853
- **Chicago, IL**
  - Total Stations: 832
  - Ave Cap (kg/d): 1,960
- **Columbus, OH**
  - Total Stations: 82
  - Ave Cap (kg/d): 1,822

- **Seattle, WA**
  - Total Stations: 440
  - Ave Cap (kg/d): 1,932
- **Portland, OR**
  - Total Stations: 129
  - Ave Cap (kg/d): 1,864
- **Sacramento, CA**
  - Total Stations: 167
  - Ave Cap (kg/d): 1,832
- **Los Angeles, CA**
  - Total Stations: 1,854
  - Ave Cap (kg/d): 1,945
- **Las Vegas, NV**
  - Total Stations: 242
  - Ave Cap (kg/d): 1,718

- **Boston, MA**
  - Total Stations: 455
  - Ave Cap (kg/d): 1,862
- **New York, NY**
  - Total Stations: 1,599
  - Ave Cap (kg/d): 1,970
- **Atlanta, GA**
  - Total Stations: 365
  - Ave Cap (kg/d): 1,830
- **Houston, TX**
  - Total Stations: 439
  - Ave Cap (kg/d): 1,945
- **Miami, FL**
  - Total Stations: 563
  - Ave Cap (kg/d): 1,928

(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

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

Energy Resources

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

Hydrogen Production

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

Storage & Delivery

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

Retail Station Networks

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

Los Angeles
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

**Technology**
- Existing SMR
- NEW SMR
- GH2 Truck
- LH2 Truck
- HyLine

**Capacity (kg/yr)**
- $\leq 1,000,000$
- 20,000,000
- 40,000,000
- 60,000,000
- 80,000,000
- $\geq 100,000,000$
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.

### Graph Description:

- **Capex**: Capital expenditure investment over time for different technologies.
- **Feedstock Opex**: Feedstock operational expenditure over time for different technologies.
- **Utility Cost**: Utility cost investment over time for different technologies.
- **Non-Utility or Feedstock Opex**: Non-utility or feedstock operational expenditure over time for different technologies.

### Financial Model:

- **H2FAST**: A rigorous financial model integrated into SERA.

- **Excel Model**: Available for download.
**SERA Results**: Production, Transmission, and Dispensing Technologies

**Production Mix**
- Central SMR
- Existing Plant
- Onsite SMR

SMR dominates through 2040

**Long-Distance Transmission Mix**
- Conventional Pipeline
- H2Grid
- GH2 Truck
- LH2 Truck

Pipeline transmission has highest economic prevalence

**Delivery & Dispensing Mix**
- Early delivery trucks are replaced by pipeline and onsite SMR production
SERA Results: H2Grid Build-Out In Los Angeles in 2038

PRELIMINARY RESULTS

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

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## 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

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**Regional TCO analyzed using established models and OEM specifications**
### Sample of Current and DOE Target Performance and Cost Data

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

**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

### 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

### 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

*Dwell time = down time for refueling/recharging*
Vehicle Modeling and Benchmarking

**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)
4. Completed FASTSim modeling
5. Benchmarked with Toyota, Hyundai, and Nikola data and Autonomie model

<table>
<thead>
<tr>
<th>Vehicle Class</th>
<th>Vocation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FY18</strong></td>
<td></td>
</tr>
<tr>
<td>Class 4</td>
<td>Parcel Delivery</td>
</tr>
<tr>
<td>Class 5</td>
<td>Van, Basic Enclosed</td>
</tr>
<tr>
<td>Class 6</td>
<td>Parcel Delivery</td>
</tr>
<tr>
<td>Class 7</td>
<td>Truck Tractor</td>
</tr>
<tr>
<td>Class 8</td>
<td>Transit Bus</td>
</tr>
<tr>
<td>Class 8</td>
<td>Refuse, Garbage Pickup</td>
</tr>
<tr>
<td><strong>FY19</strong></td>
<td></td>
</tr>
<tr>
<td>Class 8</td>
<td>Short Haul</td>
</tr>
<tr>
<td>Class 8</td>
<td>Long Haul</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Fuel Economy (mi/gge)</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
</tr>
<tr>
<td>14</td>
</tr>
<tr>
<td>12</td>
</tr>
<tr>
<td>10</td>
</tr>
<tr>
<td>8</td>
</tr>
<tr>
<td>6</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>0</td>
</tr>
</tbody>
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There is a large spread in reported/projected FCET fuel economy and tractor weights. FASTSim estimates are within the spread reported.
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.

Payload opportunity cost is the lost revenue from being not able to load as much cargo as a diesel tractor.
Thank You

www.nrel.gov

Contact: Michael Penev mike.penev@nrel.gov

NREL/PR-5400-73944
**SERA Results:** Percent of Stations Connected to the H2Grid (Scenario B: State Success)

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

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

Available payload weight reduced due to heavier tractor
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**

### Transport

- **LH2 Truck**
- **LH2 Train**
- **GH2 Truck**
- **Pipeline**

### Scale (thousands kg)

- $> 52,000$
- $8,750 - 52,000$
- $1,250 - 8,750$
- $50 - 1,250$
- $0 - 50$

### Scale (millions kg)

- $> 4,000 \times 10^6$
- $1,000 \times 10^6 - 4,000 \times 10^6$
- $500 \times 10^6 - 1,000 \times 10^6$
- $100 \times 10^6 - 500 \times 10^6$
- $0 - 100 \times 10^6$

### Petroleum Displacement

### Net Water Consumption

**H2@Scale Analysis**

Low Cost Electrolysis
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

- **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

![Drive Cycle Data](drive_cycle_data.png)

![Class 8 Sleeper](class_8_sleeper.png)
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