Integrated Systems Modeling of the Interactions between Stationary Hydrogen, Vehicles, and Grid Resources

Department of Energy Annual Merit Review for Fuel Cell Research

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INL: Anudeep Medam

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Overview

Timeline

- Project Start Date: June 1, 2016
- Project End Date: Sept. 30, 2019
- Percent complete: 85%

Budget

- FY18 DOE funding received: $0k
- Planned FY19 DOE funding: $325k
- Total funding received to date: $1,650k

Barriers Addressed

- The extent to which hydrogen ($H_2$) can simultaneously provide sustainable mobility solutions and support the electric grid remains unclear.
- The role of $H_2$ production plants in facilitating renewable energy integration remain unclear.

Partners

- NREL
- INL
- Emerging Futures
We have developed end-to-end modeling across H₂ FCEV mobility demand, hydrogen production, grid integration with renewables, and economic impacts/opportunities.

Relevance: Integrated H₂ Systems for Transportation and Grid Support

Project objectives:
• Develop an integrated modeling capability (“H2VGI Model”) to quantify the interactions between stationary H₂ generation, fuel cell vehicles, and grid support resources
• Quantify potential grid support from flexible H₂ production
• Optimize the system configuration and operating strategy for grid-integrated H₂ systems
• Assess ability to support integration of renewable generation
• In FY19, focus on economic grid benefits by exploring the value of adding medium- and heavy-duty HFCVs and more renewables

Conceptual Overview

H₂ FCEVs  H₂ electrolysis  Grid electricity  Economic impacts

Renewables
Relevance: Renewable Integration Challenge in California

Four important problems highlighted by the daily load or “Duck” curve:

*Peak shaving/valley filling optimization

*Peak down-ramp*

*Ramp mitigation optimization

Example of California: Renewables dominated by midday solar

Load without renewables

Valley load* (more renewables curtailment)

Peak load*

Peak up-ramp* (more gas generation needed)

NET load with renewables

California renewable fractions:
- 10% in 2014
- 50% in 2026*
- 60% in 2030
- 100% in 2045

*50% by 2020 on track in 3 IOUs—several yrs. ahead!
The proposed H2VGI model provides techno-economic analysis and decision-making support that benefits multiple industry groups and policy-making stakeholders.

### Relevance: Stakeholders Benefits

<table>
<thead>
<tr>
<th>Stakeholder</th>
<th>Benefits explored in this project</th>
<th>H2VGI role</th>
</tr>
</thead>
<tbody>
<tr>
<td>Policy makers</td>
<td>Understand co-benefits of investment in H₂ and grid infrastructure</td>
<td>Support decision making</td>
</tr>
<tr>
<td>Automotive</td>
<td>Assess opportunities for system integration and low-cost fuel</td>
<td>Support value proposition</td>
</tr>
<tr>
<td>Researchers</td>
<td>Open-source toolset</td>
<td>Tool to explore case studies</td>
</tr>
<tr>
<td>H₂ station owners</td>
<td>Design of grid-integrated H₂ refueling stations</td>
<td>Quantify value of H₂ (additional revenues)</td>
</tr>
</tbody>
</table>

The proposed H2VGI model provides techno-economic analysis and decision-making support that benefits multiple industry groups and policy-making stakeholders.
The H2VGI model integrates multiple operational and deployment models for FCEVs and H₂ generation resources with external grid models across various time scales.

Approach: H2VGI Model Structure

- **V2G-Sim**
- **SERA**
- **Optimization model**
- **(Daily) Vehicle Activity Initiator**
  - Individual vehicle activity profiles
  - MDV/HDV H₂ refueling demand
- **Vehicle and Station Deployment Scenarios**
  - Number & Spatial Distribution of FCEVs
  - Distribution of stations & production facilities
- **Hydrogen Station Models**
  - Individual vehicle models
  - Hydrogen refueling demand
  - Grid State, Price Information & dispatch signals
  - Power profiles
- **Hydrogen Production Model**
  - External Grid Models and Data (e.g. historical market prices)
  - H₂ supply
- **Outputs**

Dynamic Station model
- e.g., PLEXOS model/data

The H2VGI model integrates multiple operational and deployment models for FCEVs and H₂ generation resources with external grid models across various time scales.
Approach: SERA model for H\textsubscript{2} refueling station deployment and exploration of central vs. distributed H\textsubscript{2} production

The SERA* model is used to generate **self-consistent FCEV adoption and H\textsubscript{2} demand scenarios**, considering:

- Geospatially and temporally resolved vehicle adoption in each Urban Area in California based on demographics and early adopters metrics
- Annual empirically-based vehicle miles
- FCEV fuel economy improvement
- Vehicle stock turnover

Stations are sized and placed geographically to maximize coverage.
Distributions of fueling stations evolve over time as H\textsubscript{2} demand increases.

Central vs. distributed H\textsubscript{2} production

- Scenario analysis in SERA used to examine alternative approaches for H\textsubscript{2} production at least cost

SERA provides annual FCEV adoption, H\textsubscript{2} demand scenarios, and strategic fueling station placement
**Approach: V2G-Sim and hydrogen demand (LDV example)**

- **NHTS data**
  - UDDS
  - US06
  - HWFET

- **Typical Cycles**
- **Vehicle Model**

- **H₂ consumption array (from SERA)**

- **PLEXOS input for LDVs**

- **Simulated H₂ refueling profile over 7 days**

- **Refueling probability based on real-world data**

- **H₂ consumption array (from SERA)**

- **PLEXOS input for LDVs**

- **Simulated H₂ refueling profile over 7 days**

- **17,000 CA vehicles**
1. Hydrogen fuel demands
(Non-LDV data from EMFAC)

Generate probabilistic simulations from aggregate data

2. HFCV scenarios
(Synthesis from CA modelers)

Number of FCEVs
(fraction of total stock)

- 5.0 million LDVs (18%)
- 180,000 MDVs (15%)
- 22,000 HDVs (6%)
- 12,750 buses (17%)

For 2030 reference year

3. Refueling algorithms

- MDVs and buses: End of shift
- HDVs: refueling probability similar to LDVs (fuel tank level)

4. H₂ electrolysers demand

Electrolyzer hourly load (MW)

PLEXOS inputs for MDVs/HDVs
Approach: Integrate Flexible H₂ Generation into the PLEXOS Integrated Energy Production Cost Model

- PLEXOS is a commercially-available, electricity system economic simulation tool that can help researchers understand issues associated with intermittent renewables integration, and novel storage technologies such as H₂ generation

- Transmission Network (electric and gas)
- Generator properties (coal, gas, nuclear, renewables, electric storage, etc.)
- Load requirements
- Reliability requirements
- Other System Constraints

 illegally obtained.

Key Features:
- Generator operation
- Production cost
- Fuel use
- Emissions
- Imports & Exports
- Load served
- Energy and AS Prices

Production Cost Model

- Western Interconnect (WECC)

(Other U.S. regions as well as international grids also available)
Accomplishments and Progress: Key Research Activities & Questions

1. How do centralized vs. distributed hydrogen production costs compare?

2. What is the technical potential for renewables integration with hydrogen mobility at the system level (H2-California Duck Curve study)?

3. What is the economic potential of hydrogen systems to provide grid support (PLEXOS production cost model with load-balancing, ramping, flexibility)

4. How does increased demand for hydrogen from medium- and heavy-duty vehicles (including buses) change the economic benefits?

5. How do higher renewable penetrations affect the economic benefits?
## Accomplishments and Progress: FY19 Milestones

<table>
<thead>
<tr>
<th>Q1</th>
<th>Develop California scenarios of light-, medium- and heavy-duty FCEV penetrations in 2030</th>
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<tbody>
<tr>
<td>Q2</td>
<td>Estimate H₂ demand and production loads for light-, medium- and heavy-duty FCEVs</td>
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<tr>
<td></td>
<td>Implement scenarios in PLEXOS to quantify economic opportunities for grid services</td>
</tr>
<tr>
<td>Q3</td>
<td>Generate results across a range of parameter sensitivity scenarios, including higher</td>
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<tr>
<td></td>
<td>fractions of intermittent renewables</td>
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<td></td>
<td>Compare the relative economic benefits and renewables integration opportunities across</td>
</tr>
<tr>
<td></td>
<td>the FCEV adoption scenarios</td>
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<tr>
<td>Q4</td>
<td>Synthesize and disseminate results</td>
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</table>

![Diagram of renewable energy and economic impacts](image)
Hydrogen infrastructure scenarios are compared for California and the U.S. using the SERA model.

Technology Scenarios include:
- Central Electrolysis
- Onsite Electrolysis
- All production technologies: central and onsite electrolysis; central, onsite and existing natural gas reforming.

Allowing “All” technologies results in the lowest cost, driven by low costs for natural gas reforming.

For electrolysis cases, central is preferred for the U.S., while onsite is preferred for CA.

Electrolysis results are driven by the delivery costs.

Accomplishments and Progress: Central vs. distributed H₂ comparison
Summary results

- FCEVs can provide peak shaving/valley filling and ramp mitigation benefits, but ramp mitigation benefits have much larger proportional reductions.
- Ramp-up rates in 2025 can be reduced to 2014 levels at 800k-1.5M FCEVs and 125-150% electrolyzer capacity.
- Ramp-up rates can be reduced to ~zero at 10M FCEVs and 150% capacity.
- H1G alone can deliver sizable benefits, though H2G enhances impacts.
Accomplishments and Progress: Economic benefits of hydrogen electrolysis on California grids

Key takeaways:

• While differences in cost are small, we observe a clear trend of decreasing electricity cost with increasing H₂ electrolyzer capacity, due to time-of-day flexibility in when electrolyzer can run.

• We expect this decrease to be more pronounced with greater H₂ demand, and increased amounts of renewables on the grid; we are currently working on modeling these scenarios.

 Expanded FCEV scenario for California

<table>
<thead>
<tr>
<th>Type</th>
<th>Quantity</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDVs</td>
<td>5.0 million</td>
<td>18%</td>
</tr>
<tr>
<td>MDVs</td>
<td>180,000</td>
<td>15%</td>
</tr>
<tr>
<td>HDVs</td>
<td>22,000</td>
<td>6%</td>
</tr>
<tr>
<td>Buses</td>
<td>12,750</td>
<td>17%</td>
</tr>
</tbody>
</table>

(work in progress)
Summary feedback:

- Provide more impact and validation of assumptions
  - Updated net load study to technical potential levels with higher FCEV adoption
- Too much focus on modeling
  - We have placed more emphasis on results for this AMR
- Insufficient vetting by industry
  - We held two stakeholder webinars in FY18 to solicit feedback from industry on approach and results, which, among other things, motivated us to consider vehicles beyond light-duty
- More sensitivity analysis of electrolyzer capital cost vs. capacity
  - We have completed most of the work for this, and our final report will convert electrolyzer capacities into capital costs to arrive at total cost impacts of refueling H\textsubscript{2} FCEVs
- Case studies could be more targeted to real-world problems
  - We have developed a set of potential future FCEV scenarios that reflect the realistic impacts of flexible H\textsubscript{2} electrolysis on grid operations, including addition of MDVs/HDVs (especially buses)
## Collaborations

<table>
<thead>
<tr>
<th>Partner</th>
<th>Type</th>
<th>Role</th>
<th>Project Roles</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="NREL" /></td>
<td>National Lab</td>
<td>Sub (Within FCTO)</td>
<td>Lead hydrogen vehicle and station deployment scenarios and station modeling; co-lead model integration, and case study modeling; support grid services valuation</td>
</tr>
<tr>
<td><img src="image" alt="INL" /></td>
<td>National Lab</td>
<td>Sub (Within FCTO)</td>
<td>Co-lead dispatch controller development for grid services; and tie-in to FCTO-TV031 project below</td>
</tr>
<tr>
<td><img src="image" alt="Emerging Futures" /></td>
<td>Industry/Research</td>
<td>Sub (Outside FCTO)</td>
<td>Provide strategic direction; contribute to research, writing, data analysis, simulation and modeling</td>
</tr>
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## Related Projects

1. Dynamic Modeling and Validation of Electrolyzers in Real Time Grid Simulation (FCTO-TV031, INL lead)
Challenges and Barriers

- **Currently low adoption rates of FCEVs** will reduce the potential grid benefits of dispatchable H\textsubscript{2} electrolysis
  - We included MDV/HDV FCEVs that have higher near-term adoption rates; as nascent FCEV markets grow, costs will fall, stimulating greater adoption
- The **lack of detailed data on refueling of MDVs/ HDVs** (unlike LDVs) hampers our ability to accurately estimate hydrogen refueling demand
  - We will continue to search for new data sources of MDV/HDV H\textsubscript{2} refueling
- **Cost, performance and reliability of H\textsubscript{2} electrolyzers** and other components may diminish adoption and grid benefits
  - Electrolyzer costs and performance are expected to improve as higher volumes of this equipment are deployed globally
- **Grid markets that do not permit H\textsubscript{2} resource participation** will limit the overall value of flexible H\textsubscript{2} production
  - The market for ancillary services is expected to grow as renewable generation shares increase, allowing greater H\textsubscript{2} resource participation
Proposed Future Work

Remainder of FY19

- Perform sensitivity analyses on MDV/HDV refueling simulations, and continue to search for MDV/HDV diesel/gasoline/hydrogen refueling data.
- Integrate higher renewable generation scenario of Western Interconnection into PLEXOS and run complete set of economic analyses.
- Perform an economic case-study analysis of FCEV LDV+MDV+HDV scenarios in California at higher renewable penetration levels, for each of several FCEV and hydrogen electrolysis capacity levels. Compare relative economic benefits and renewable integration opportunities.
- Synthesize and disseminate results on economic opportunities for FCEVs to provide grid services within the larger AFV opportunity space. Target high-quality peer-reviewed journal publications to summarize results.

Beyond FY19 funding

- Apply capabilities across additional scenarios, regions, BEVs, renewables, etc.

Any proposed future work is subject to change based on funding levels.
Summary

Objective
Provide an integrated modeling capability to quantify the interactions between stationary hydrogen generation, fuel cell vehicles, and grid support resources

Relevance
Hydrogen technologies can offer a unique ability to simultaneously support both electric and transportation sectors

Approach/Next Steps
Addition of MDV/HDV/bus hydrogen vehicles and higher renewables to model; PLEXOS economic case studies

Technical Accomplishments

Years 1-2 (FY16-18)
Model development: Full end-to-end integration of individual FCEV H₂ demand, H₂ refueling, siting of H₂ stations (stationary vs. distributed), simulation of H₂ electrolysis in external grid model PLEXOS, and economic calculations of flexible H₂ electrolysis completed

Case study results:
• H₂ electrolysis driven by FCEV demands can play a substantial role in mitigating California “duck curve”
• Flexible H₂ electrolysis reduces power generation cost
• Distributed H₂ lowers cost of delivery and storage

Year 3 (FY18-19): Model development
• PLEXOS economic grid simulations of two-way (H₂G) flexible H₂ electrolysis cases were completed
• MDV/HDV hydrogen vehicle penetration scenarios and methodology for estimating hydrogen refueling demand have been developed
• Integration of higher renewable penetration PLEXOS model with rest of modeling framework is in progress

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## Key assumptions for H₂ net load study

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of fuel cell electric vehicles (FCEVs)</td>
<td>200,000 – 10,000,000</td>
</tr>
<tr>
<td>Interaction modes</td>
<td>H1G, H2G</td>
</tr>
<tr>
<td>Net load</td>
<td>2016, 2025</td>
</tr>
<tr>
<td>Electrolyzer capacity</td>
<td>100%, 125%, 150%</td>
</tr>
<tr>
<td>Current electrolyzer conversion efficiency</td>
<td>67.3 kWh per kg [2]</td>
</tr>
<tr>
<td>VMT for FCEVs [3]</td>
<td>10,950 miles per year</td>
</tr>
<tr>
<td>MPGe for FCEVs</td>
<td>67 MPGe [4]</td>
</tr>
</tbody>
</table>

[1] Electrolyzer capacity = percentage of rated capacity relative to capacity with constant operation (oversizing)
[3] VMT based on NHTS California dataset

### Table

<table>
<thead>
<tr>
<th>FCEV Adoption Scenario</th>
<th>Number of FCEVs in 2025</th>
<th>H₂ Production (ton/yr)</th>
<th>Electrolyzer Capacity (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>100%</td>
<td>125%</td>
</tr>
<tr>
<td>1</td>
<td>200,000</td>
<td>40,150</td>
<td>304</td>
</tr>
<tr>
<td>2</td>
<td>800,000</td>
<td>160,600</td>
<td>1216</td>
</tr>
<tr>
<td>3</td>
<td>1,500,000</td>
<td>301,125</td>
<td>2280</td>
</tr>
<tr>
<td>4</td>
<td>5,000,000</td>
<td>1,003,750</td>
<td>7,600</td>
</tr>
<tr>
<td>5</td>
<td>10,000,000</td>
<td>2,007,500</td>
<td>15,200</td>
</tr>
</tbody>
</table>

**H1G**: Uni-directional energy flow to electrolyzer

**H2G**: Reversible electrolyzer which can feed power back to grid

Amount of oversizing capacity

Target number of zero-emission vehicles in 2025

Target number of zero-emission vehicles in 2030
Approach: LDV refueling model

- Refine the refueling behavior model in H2VGI using the real-world data from NREL.
- A preliminary refueling sub-model, which governs when individual vehicles are refueled within their travel itineraries.
EMFAC2014 background

- **EMFAC2014** is the EPA-approved regulatory model for CA criteria pollutant emissions [1] freely available at https://www.arb.ca.gov/emfac/
- EMFAC2014 has been used for state implementation plan (SIP) development and transportation conformity in California
- Continually refined inputs to EMFAC since late ‘90s
  - Provides VMT temporal distribution for light and heavy duty vehicles from data from metropolitan transportation organizations (MPOs) and vehicle activity data for HDV/MDV.
  - Tracks 42 vehicle types spanning light-, medium- and heavy-duty vehicles

**INPUTS**
Vehicle sales by type
Fuel sales by type
Regional VMT data
Vehicle activity logs
Veh. emissions models and testing
Fuel Efficiency/Emissions policies

**OUTPUTS**
Vehicle sales projections
VMT projections by veh. type
Emissions by veh. type and region
Fuel consumption profiles by veh. type and region

Approach for MDVs/HDVs: Modeling distributions of fuel consumption by vehicle type

Total fuel consumption = $F_{Ch} = \sum_{i=1}^{\#veh} f_{ci}$ in hour $h$

Cumulative distribution

- Distribution of fuel consumption rates in hour $h$
- Probability of having a particular fuel consumption rate, $f_{ci}$
- Parked/idle fraction ($f_{ci} = 0$)
- Area = $F_{Ch}$

Cumulative probability

Fuel consumption by vehicle:

- $f_{c1}$
- $f_{c2}$
- $f_{c3}$
- $f_{cn}$