Energy Technologies Area Lawrence Berkeley National Laboratory

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

Department of Energy Annual Merit Review
for Fuel Cell Research

Washington, D.C.
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Project ID #
TA021

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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 — National Renewable Energy Laboratory

INL — Idaho National Laboratory

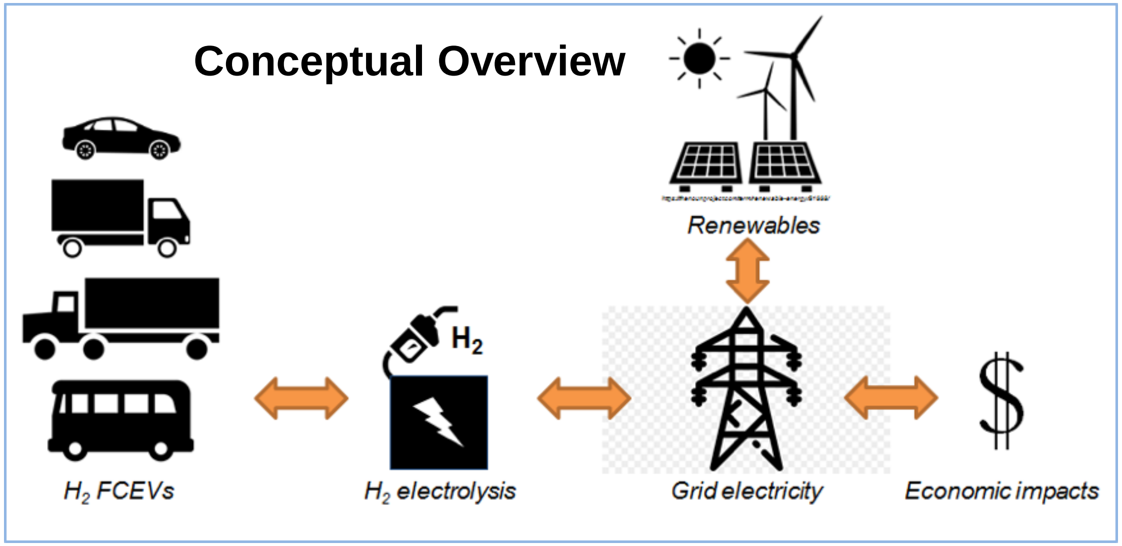
Emerging Futures

Relevance:
Integrated H_2 Systems for Transportation and Grid Support

BERKELEY LAB

Project objectives:

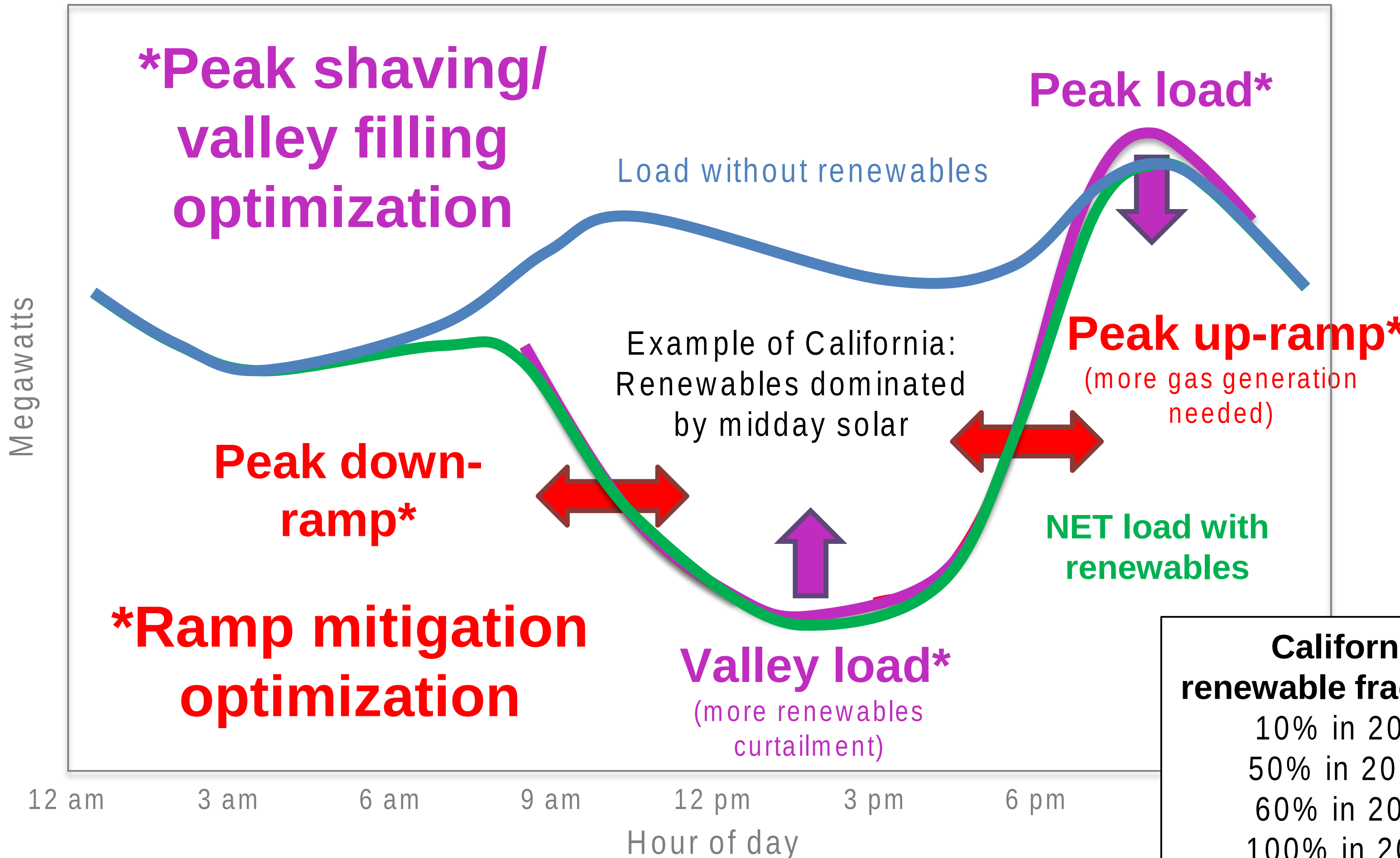
- **Develop an integrated modeling capability ("H2VGI Model")** to quantify the interactions between stationary H_2 generation, fuel cell vehicles, and grid support resources
- **Quantify potential grid support** from flexible H_2 production
- **Optimize the system configuration** and operating strategy for grid-integrated H_2 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



We have developed end-to-end modeling across H_2 FCEV mobility demand, hydrogen production, grid integration with renewables, and economic impacts/opportunities

Relevance: Renewable Integration Challenge in California

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



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

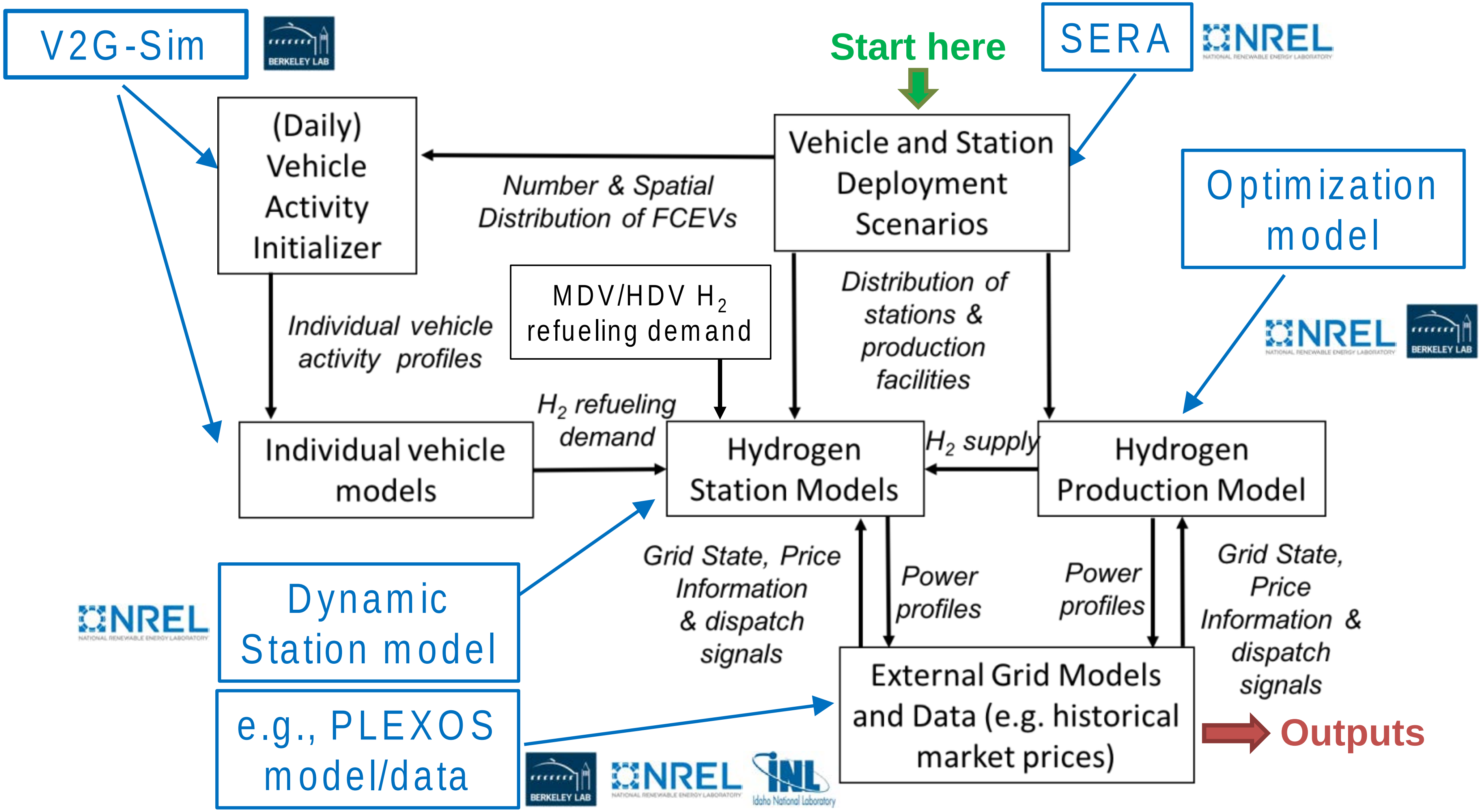
*50% by 2020 on track in 3 IOUs—several yrs. ahead!

Relevance: Stakeholders Benefits

Stakeholder	Benefits explored in this project	H2VGI role
Policy makers	Understand co-benefits of investment in H_2 and grid infrastructure	Support decision making
Automotive	Assess opportunities for system integration and low-cost fuel	Support value proposition
Researchers	Open-source toolset	Tool to explore case studies
H_2 station owners	Design of grid-integrated H_2 refueling stations	Quantify value of H_2 (additional revenues)

The proposed H2VGI model provides techno-economic analysis and decision-making support that benefits multiple industry groups and policy-making stakeholders

Approach: H2VGI Model Structure



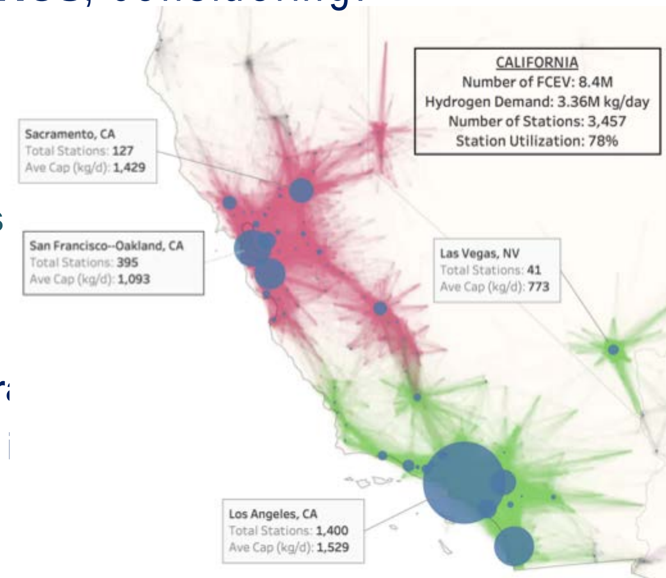
The H2VGI model integrates multiple operational and deployment models for FCEVs and H_2 generation resources with external grid models across various time scales

Approach: SERA model for H_2 refueling station deployment and exploration of central vs. distributed H_2 production

*SERA: Scenario Evaluation, Regionalization & Analysis

The SERA* model is used to generate **self-consistent FCEV adoption and H_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**

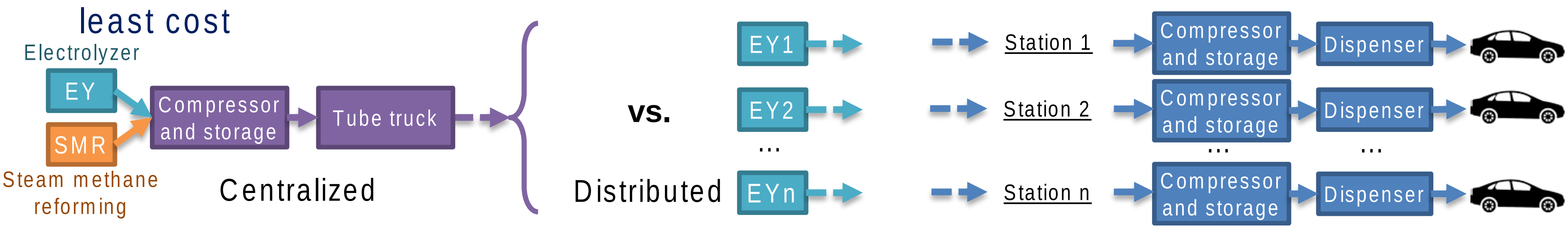


Stations are sized and placed geographically to maximize covera

Distributions of fueling stations evolve over time as H_2 demand

Central vs. distributed H_2 production

- Scenario analysis in SERA used to examine alternative approaches for H_2 production at least cost

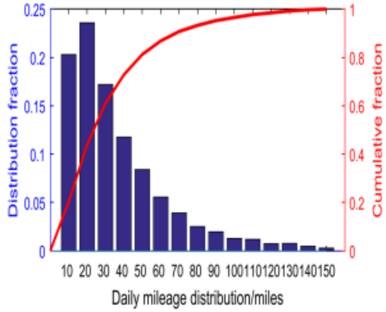


SERA provides annual FCEV adoption, H_2 demand scenarios, and strategic fueling station placement

Approach: V2G-Sim and hydrogen demand (LDV example)

17,000 CA vehicles

NHTS data



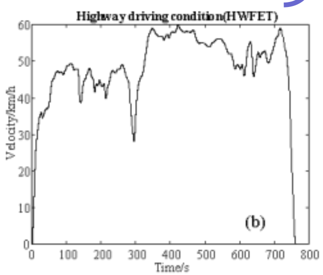
Vehicle ID	State	Start time (	End time (h	Distance (m	Nothing	P_max (W)	Location	NHTS HH Wt
1	Charging	0	12.08333	-1		1440	Home	208.5930918
1	Driving	12.08333	12.41667	2		-1	-1	208.5930918
1	Parked	12.41667	14	-1		-1	Shopping/E	208.5930918
1	Driving	14	14.33333	2		-1	-1	208.5930918
1	Charging	14.33333	24	-1		1440	Home	208.5930918
2	Charging	0	7.3	-1		1440	Home	229.8390097
2	Driving	7.3	7.483333	11		-1	-1	229.8390097
2	Parked	7.483333	7.5	-1		-1	School/Chu	229.8390097
2	Driving	7.5	7.75	11		-1	-1	229.8390097
2	Charging	7.75	9	-1		1440	Home	229.8390097
2	Driving	9	9.25	15		-1	-1	229.8390097
2	Parked	9.25	9.333333	-1		-1	School/Chu	229.8390097
2	Driving	9.333333	9.833333	20		-1	-1	229.8390097
2	Parked	9.833333	10.5	-1		-1	Medical/De	229.8390097

UDDS

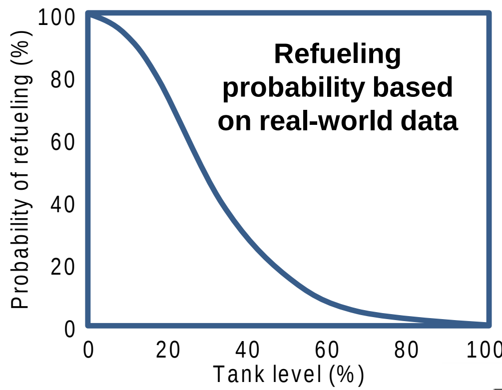
US06

HWFET

Typical Cycles



Vehicle Model

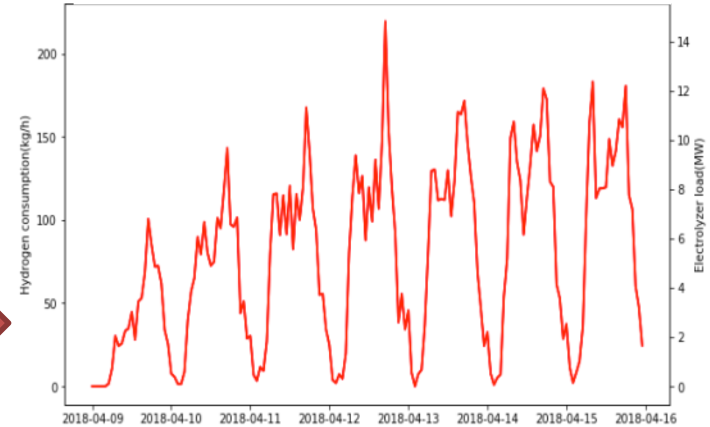


(from National Fuel Cell Technology Evaluation Center)

H_2 consumption array (from SERA)

PLEXOS input for LDVs

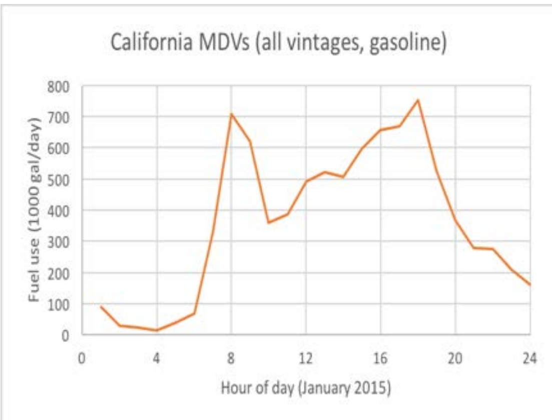
Simulated H_2 refueling profile over 7 days



Approach: Algorithm for MDV/HDV sectors

1. Hydrogen fuel demands

(Non-LDV data from EMFAC)



Generate probabilistic simulations from aggregate data

2. HFCV scenarios

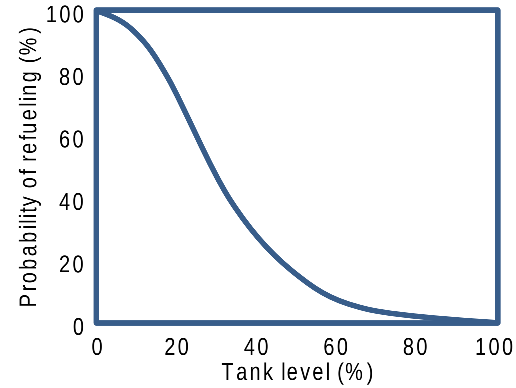
(Synthesis from CA modelers)

Number of FCEVs (fraction of total stock)
5.0 million LDVs (18%)
180,000 MDVs (15%)
22,000 HDVs (6%)
12,750 buses (17%)

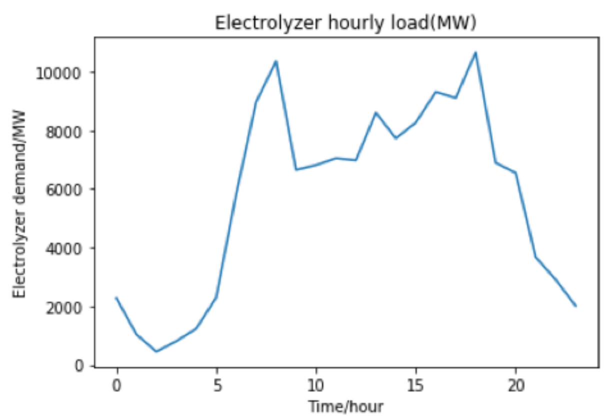
For 2030 reference year

3. Refueling algorithms

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



4. H_2 electrolyzer demand



PLEXOS inputs for MDVs/HDVs

Approach: Integrate Flexible H_2 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 H_2 generation**

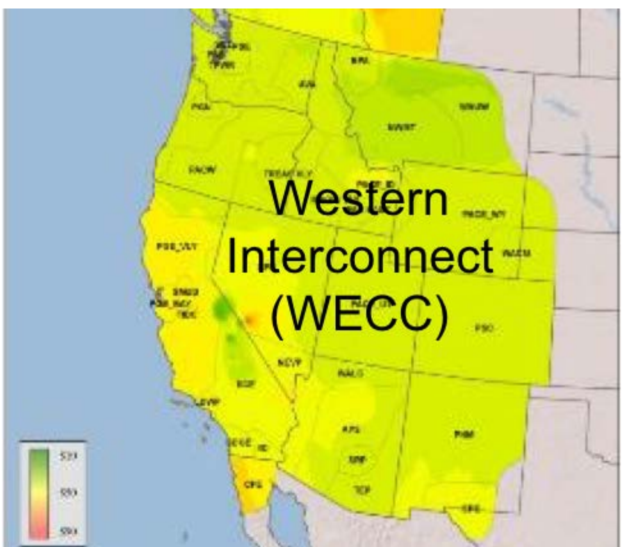
Inputs:

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

→ **Production Cost Model** →

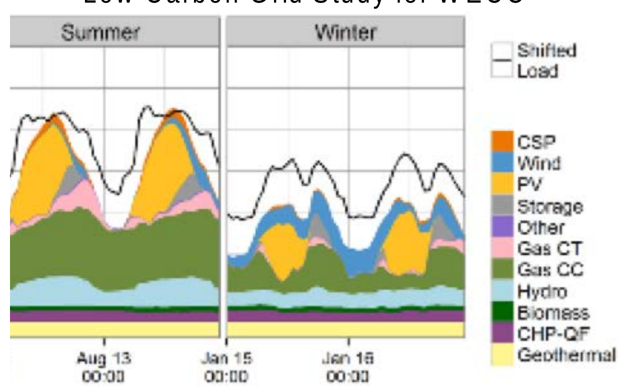
Outputs:

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



(other U.S. regions as well as international grids also available)

Low Carbon Grid Study for WECC



<u>Key Features</u>:

- Unit commitment and economic dispatch at multiple nodes/zones
- DC power flow modeling
- Time step of ≥5 minutes
- Models variety of ancillary services, market horizons, and forecast windows
- Stochastic optimization 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 (H_2-California Duck Curve study)?

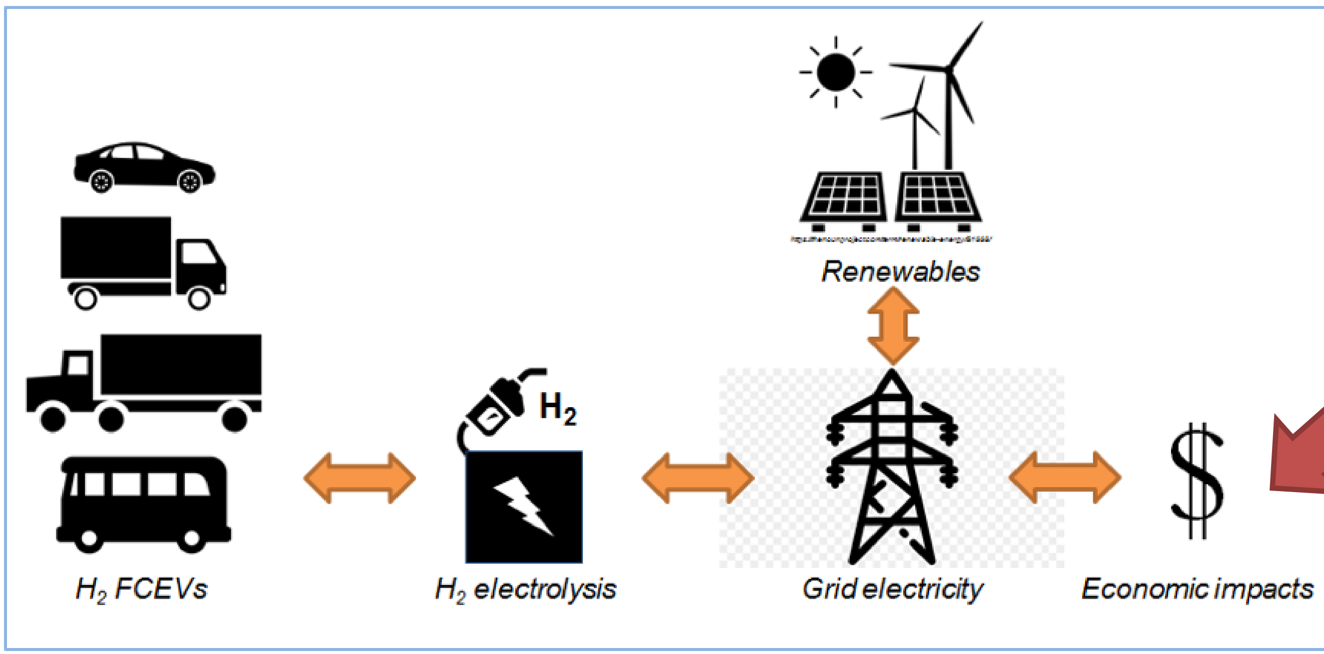
3. What is the **economic potential** of hydrogen systems to provide grid support (PLEXOS production cost model with load-balancing, ramping, flexibility)

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?

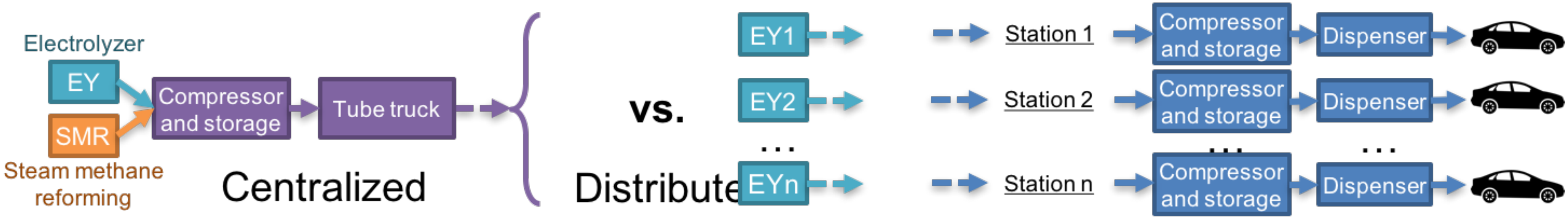
Accomplishments and Progress: FY19 Milestones

Q1	• Develop California scenarios of light-, medium- and heavy-duty FCEV penetrations in 2030
Q2	• Estimate H_2 demand and production loads for light-, medium- and heavy-duty FCEVs • Implement scenarios in PLEXOS to quantify economic opportunities for grid services
Q3	• Generate results across a range of parameter sensitivity scenarios, including higher fractions of intermittent renewables • Compare the relative economic benefits and renewables integration opportunities across the FCEV adoption scenarios
Q4	• Synthesize and disseminate results

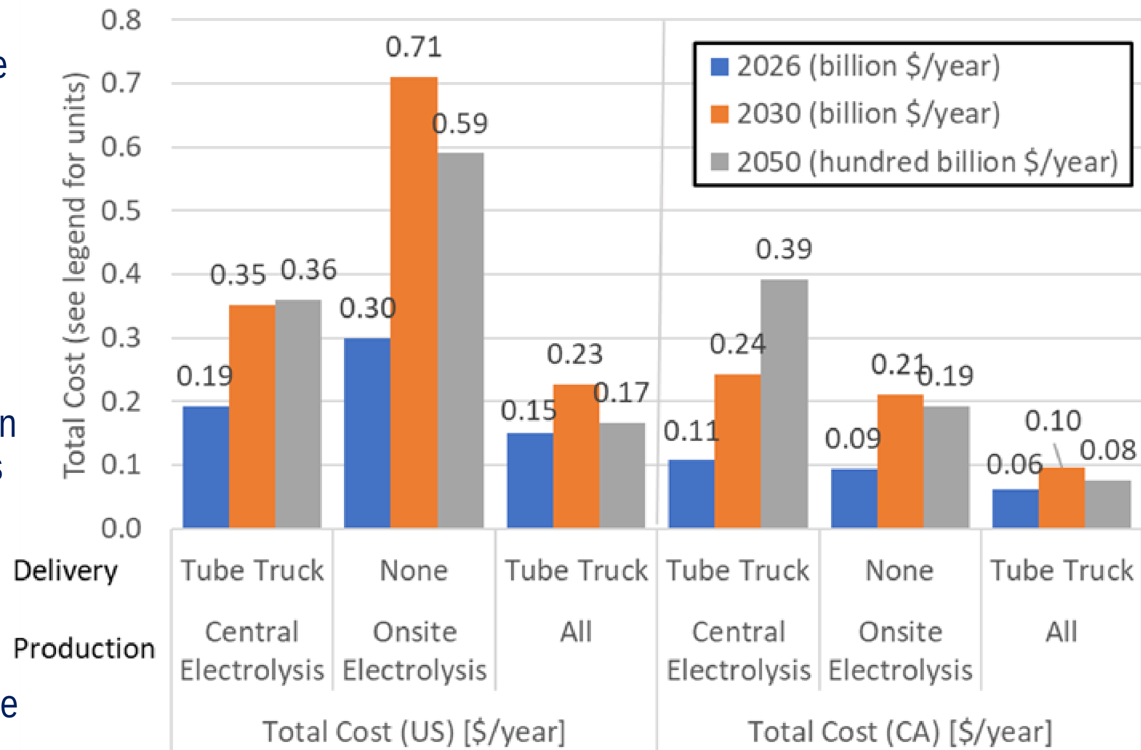


We are here

Accomplishments and Progress: Central vs. distributed H_2 comparison

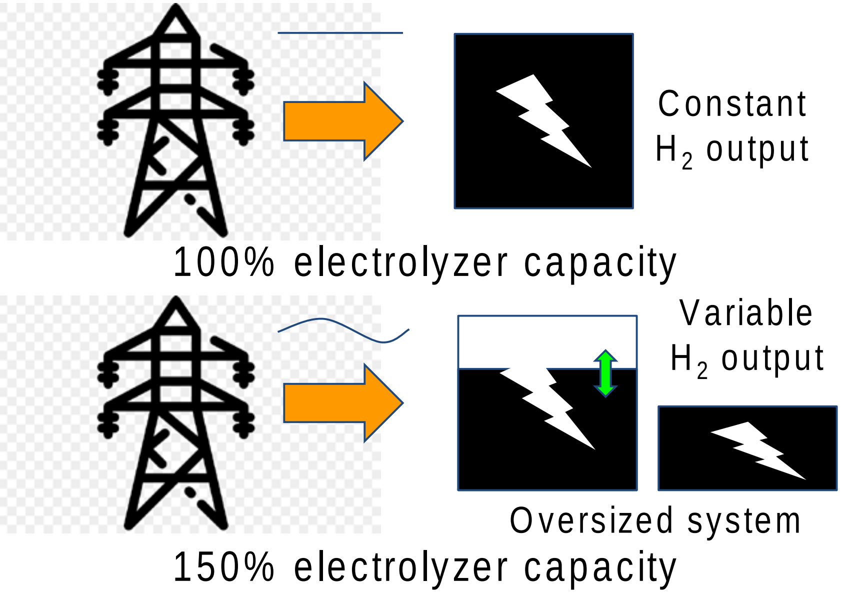


- Hydrogen infrastructure scenarios are compared for California and the U.S. using the SERA model
- Technology Scenarios include
  - Central Electrolysis
  - Onsite Electrolysis
  - All production technologies: central and onsite electrolysis; central, onsite and existing natural gas reforming)
- Allowing "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

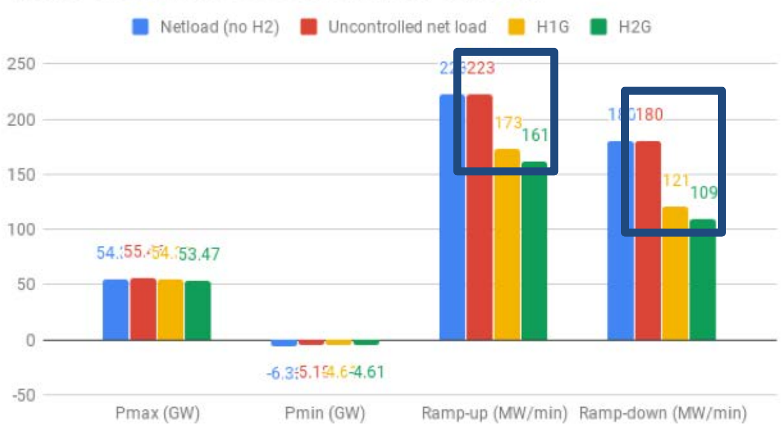


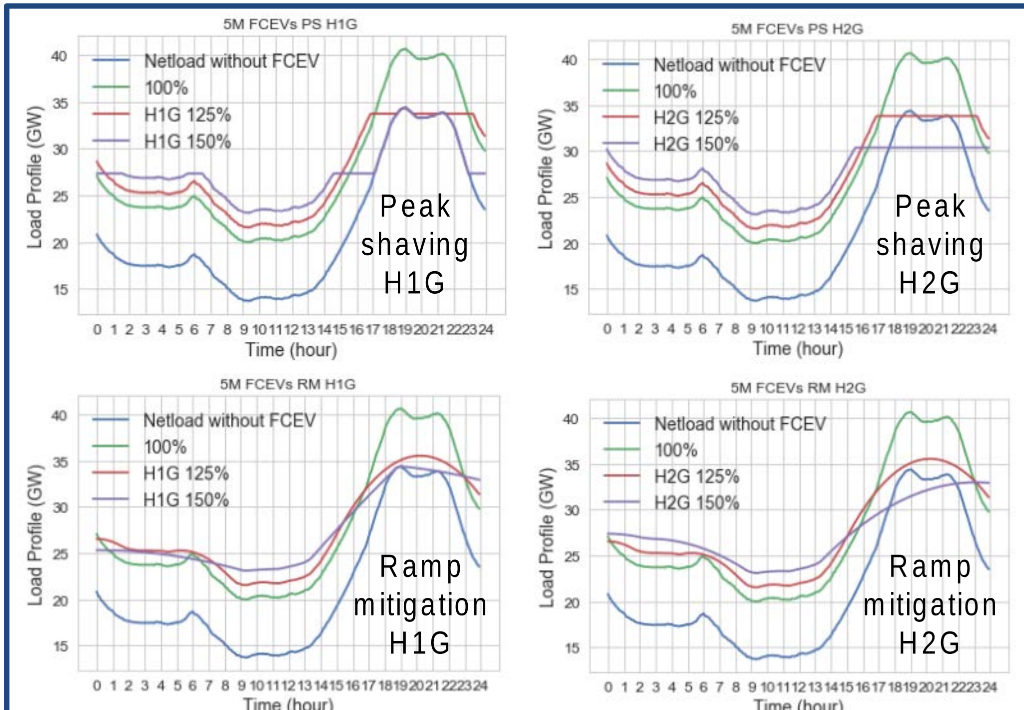
Accomplishments and Progress: Electrolyzer H_2 generation can support greater renewable integration by reducing ramp rates

2025 California Net Load Impact for 5 FCEV Scenarios - Ramp Up Rates are restored to 2014 levels with Flexible Electrolyzer Generation for 0.8-1.5M FCEVs



1.5M FCEVs with 150% electrolyzer capacity



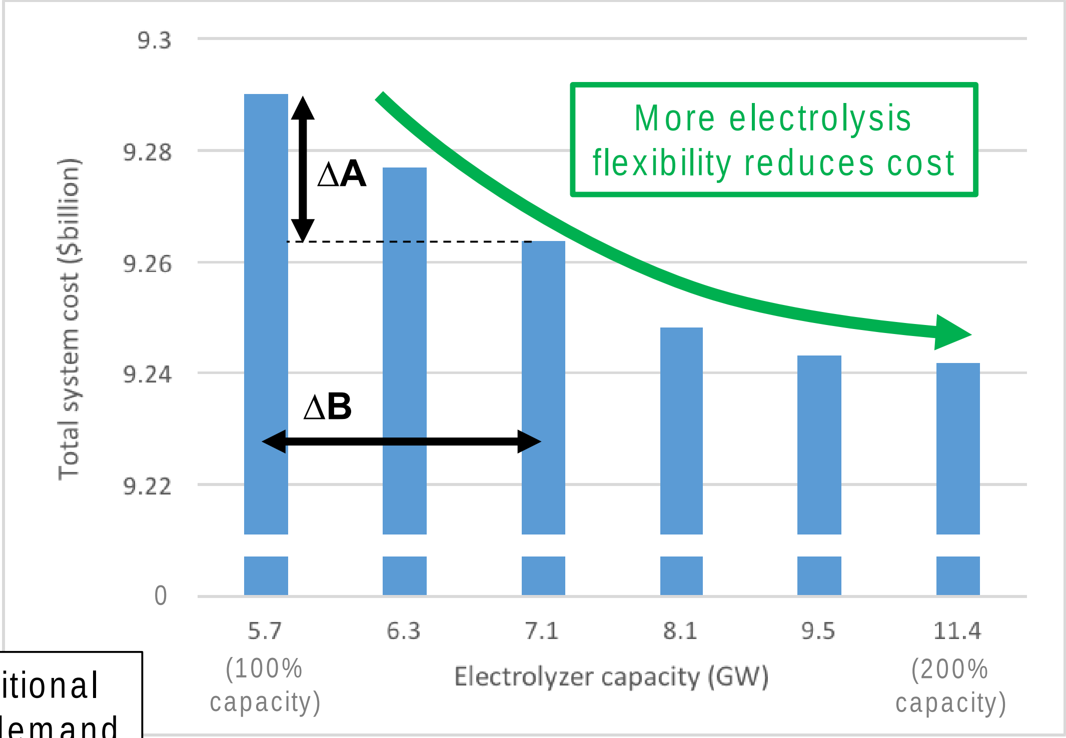


Results for 5M FCEVs

<u>Summary results</u>

- 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



$$\frac{\Delta A}{\Delta B} = \frac{\text{cost savings}}{\text{amt. of flexibility}}$$

LDVs + limited number of MDVs/HDVs

3.1% additional electricity demand due to H_2

Expanded FCEV scenario for California

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

(work in progress)

Key takeaways:

- While differences in cost are small, we observe a clear trend of decreasing electricity cost with increasing H_2 electrolyzer capacity, due to time-of-day flexibility in when electrolyzer can run
- We expect this decrease to be more pronounced with greater H_2 demand, and increased amounts of renewables on the grid; *we are currently working on modeling these scenarios*

Accomplishments and Progress: Responses to Previous Year Reviewers' Comments

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_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_2 electrolysis on grid operations, including addition of MDVs/HDVs (especially buses)

Collaborations

Partner	Type	Role	Project Roles
NREL NATIONAL RENEWABLE ENERGY LABORATORY	National Lab	Sub (Within FCTO)	**Lead hydrogen vehicle and station deployment scenarios and station modeling; co-lead model integration, and case study modeling; support grid services valuation**
INL Idaho National Laboratory	National Lab	Sub (Within FCTO)	**Co-lead dispatch controller development for grid services; and tie-in to FCTO-TV031 project below**
EMERGING FUTURES	Industry/ Research	Sub (Outside FCTO)	**Provide strategic direction; contribute to research, writing, data analysis, simulation and modeling**

Related Projects

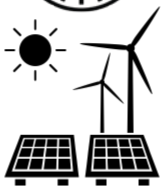
1. Dynamic Modeling and Validation of Electrolyzers in Real Time Grid Simulation (FCTO-TV031, INL lead)

Challenges and Barriers

- Currently **low adoption rates of FCEVs** will reduce the potential grid benefits of dispatchable H_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_2 refueling
- **Cost, performance and reliability of H_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_2 resource participation** will limit the overall value of flexible H_2 production
  - The market for ancillary services is expected to grow as renewable generation shares increase, allowing greater H_2 resource participation

Proposed Future Work

Remainder of FY19



https://thenounproject.com/term/renewable-energy/81668

- 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 H_2 demand, H_2 refueling, siting of H_2 stations (stationary vs. distributed), simulation of H_2 electrolysis in external grid model PLEXOS, and economic calculations of flexible H_2 electrolysis completed

Case study results:

- H_2 electrolysis driven by FCEV demands can play a substantial role in mitigating California "duck curve"
- Flexible H_2 electrolysis reduces power generation cost
- Distributed H_2 lowers cost of delivery and storage

Year 3 (FY18-19): Model development

- PLEXOS economic grid simulations of two-way (H2G) flexible H_2 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

Technical Back-up Slides

Key assumptions for H_2 net load study

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

[1] Electrolyzer capacity = percentage of rated capacity relative to capacity with constant operation (oversizing)
[2] Hydrogen component validation, https://www.hydrogen.energy.gov/pdfs/review17/tv019_terlip_2017_p.pdf
[3] VMT based on NHTS California dataset
[4] 2016 Mirai Product Information, https://pressroom.toyota.com/releases/2016+toyota+mirai+fuel+cell+product.download

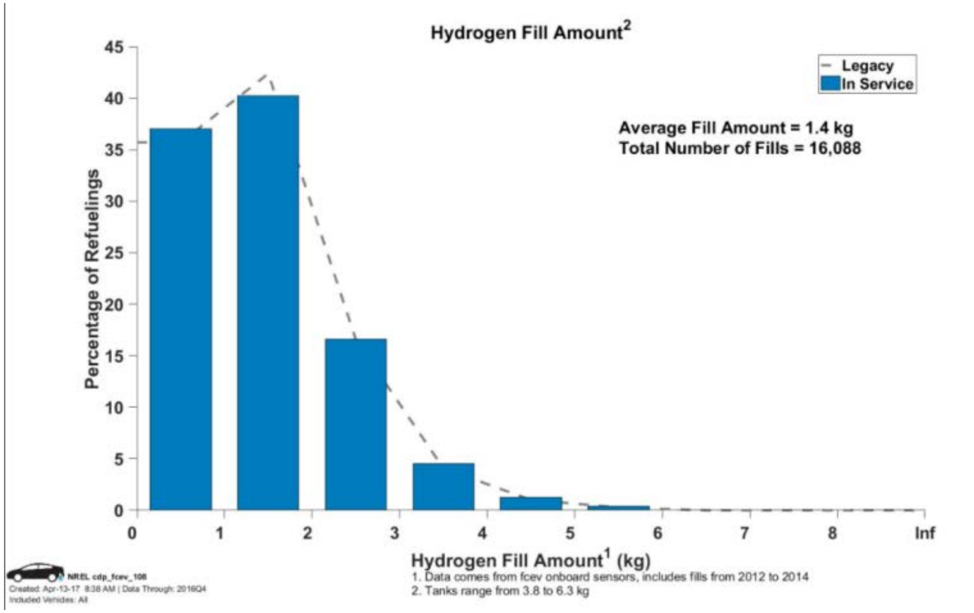
FCEV Adoption Scenario	Number of FCEVs in 2025	H_2 Production (ton/yr)	Electrolyzer Capacity (MW)		
			100%	125%	150%
1	200,000	40,150	304	380	456
2	800,000	160,600	1216	1520	1834
3	1,500,000	301,125	2280	2,848	3,418
4	5,000,000	1,003,750	7,600	9,500	11,400
5	10,000,000	2,007,500	15,200	19,000	22,800

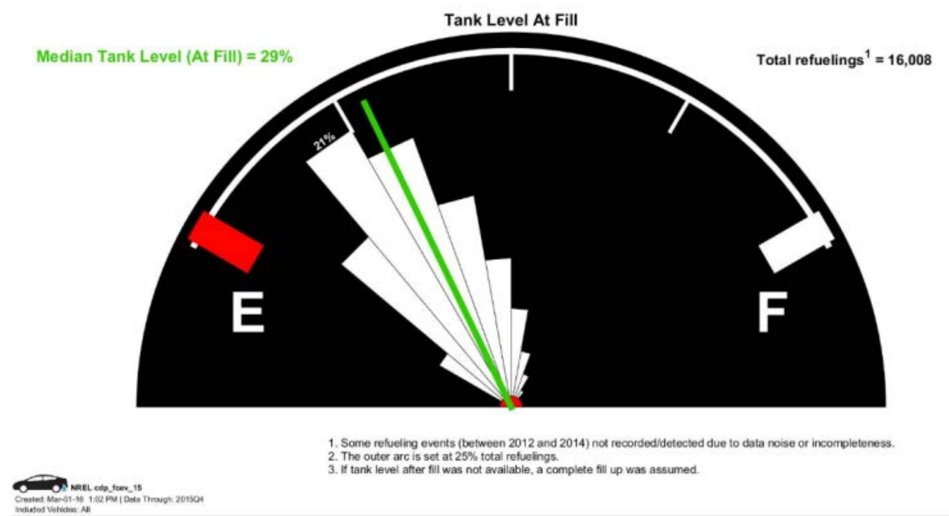
H1G: Uni-directional energy flow to electrolyzer
H2G: Reversible electrolyzer which can feed power back to grid

Amount of oversizing capacity

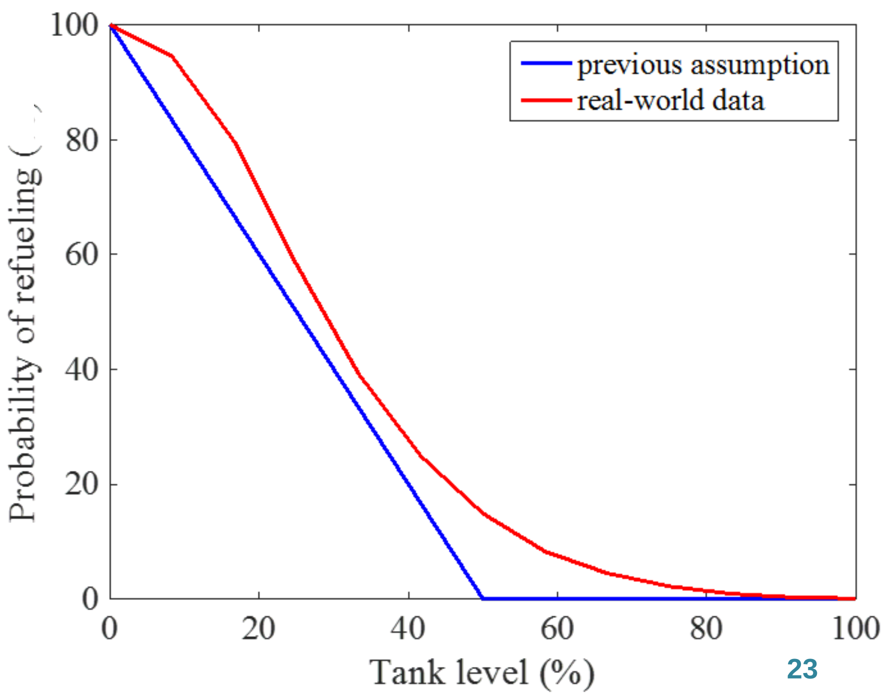
Target number of zero-emission vehicles in 2025 (scenario 3)
Target number of zero-emission vehicles in 2030 (scenario 4)

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

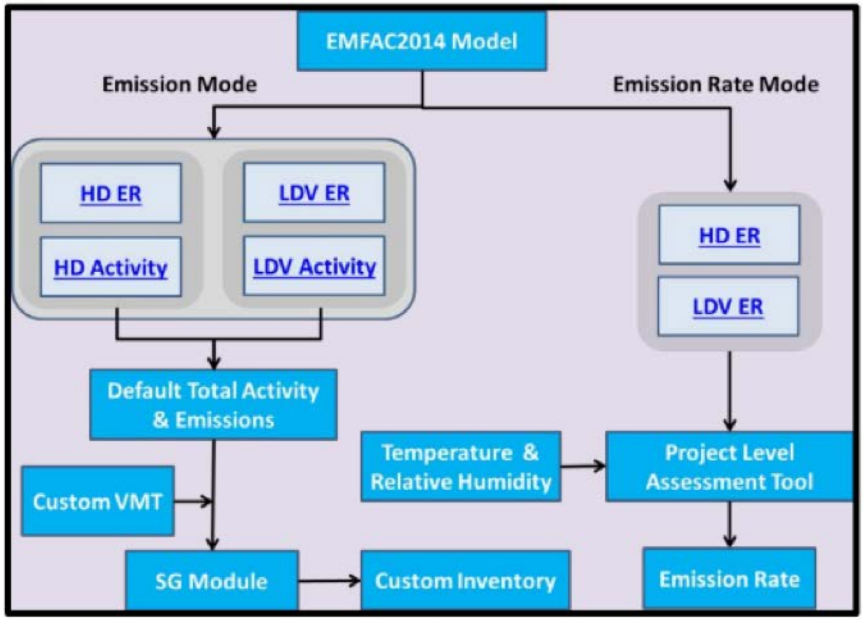


EMFAC2014 background

- **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

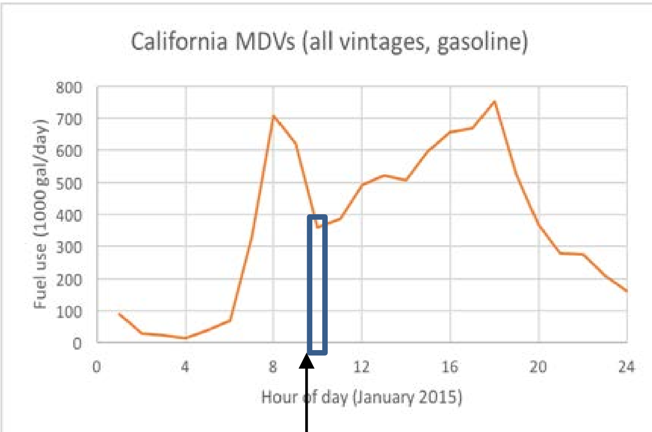


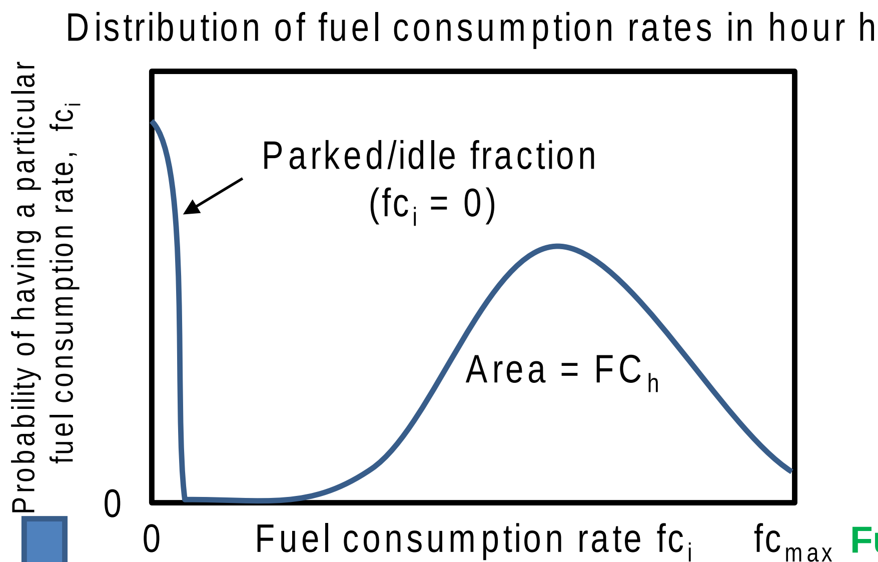
OUTPUTS

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

[1] https://www.federalregister.gov/documents/2015/12/14/2015-31307/official-release-of-emfac2014-motor-vehicle-emission-factor-model-for-use-in-the-state-of-california; [2] https://www.arb.ca.gov/msei/emfac2014_nov_2014_final_w_o_notes.pdf

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





Total fuel consumption in hour h = $FCh = \sum_{i=1}^{\#veh} fc_i$