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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Project ID #
TV043

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Overview

Timeline

- Project Start Date: June 1, 2016
- Project End Date: May 30, 2019
- Percent complete: 60%

Budget

- **Total funding: 1.65 Million (DOE)**
- **Funding received in FY17/18: $1,095,000**
- **Planned funding in FY19: $82,000**

Barriers Addressed

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

Partners

NREL NATIONAL RENEWABLE ENERGY LABORATORY

INL Idaho National Laboratory

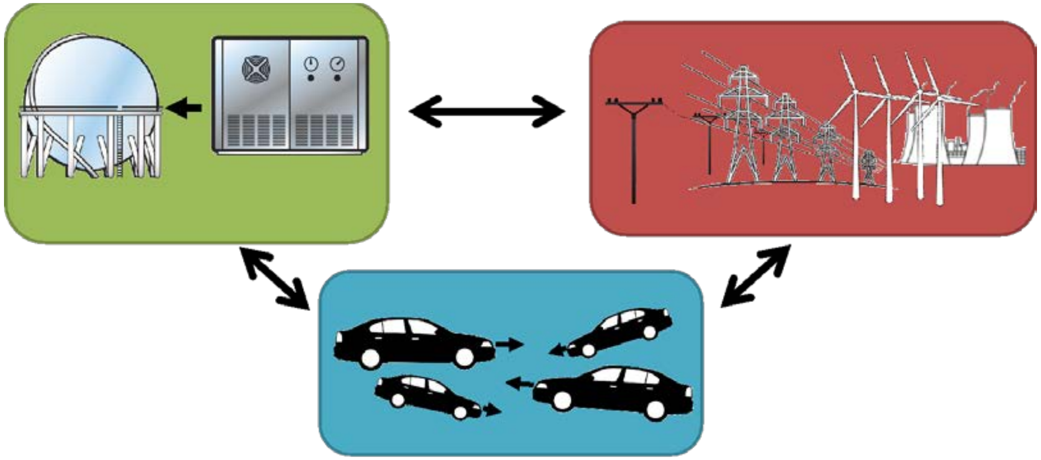
Relevance - Integrated H_2 Systems for Transportation and Grid Support

Hydrogen technologies could creates **synergies** between the electricity and transportation sectors:

- **Electrolytic hydrogen production** can be a flexible load, provide grid services, and support the integration of renewables, including exploiting otherwise-curtailed electricity
- Hydrogen refueling stations can also act as flexible loads, and smart integration with the electric grid may provide cheaper electricity and enable new revenue streams

Project Objectives:

- **Develop an integrated modeling capability ("H2VGI Model")** to quantify the interactions between stationary hydrogen generation, fuel cell vehicles, and grid support resources.
- **Quantify potential grid support** from flexible hydrogen production (e.g., dispatchable production of hydrogen)
- **Optimize the system configuration** and operating strategy for grid-integrated hydrogen systems
- **Assess ability to support integration of renewable** generation (e.g., mitigating the Duck curve)

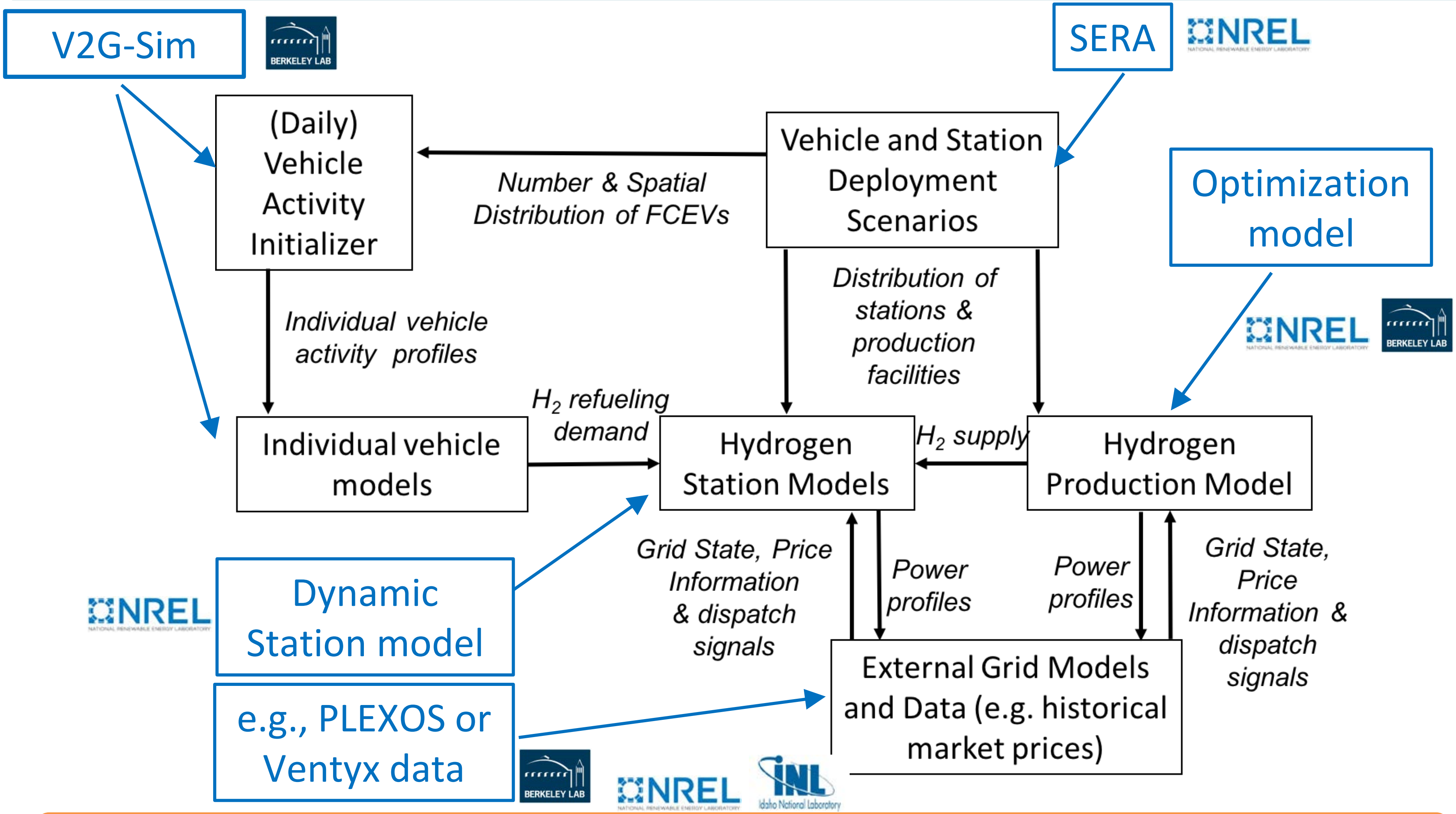


Relevance - Stakeholders Benefits

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 H2 generation resources with external grid models across various time scales

Approach – Overall hydrogen calculation diagram

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NHTS data

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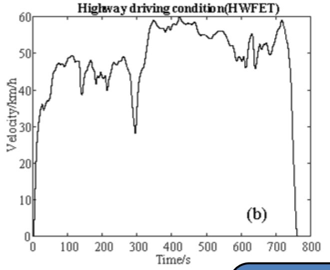
Typical Cycles

- UDDS
- US06
- HWFET



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Vehicle Model

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Hydrogen consumption array

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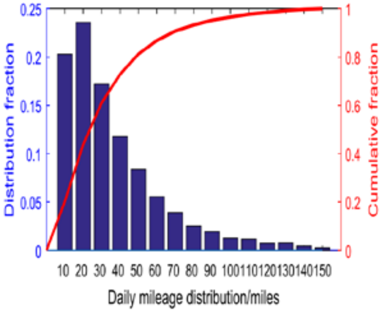
Scaling to SERA output

PLEXOS input



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

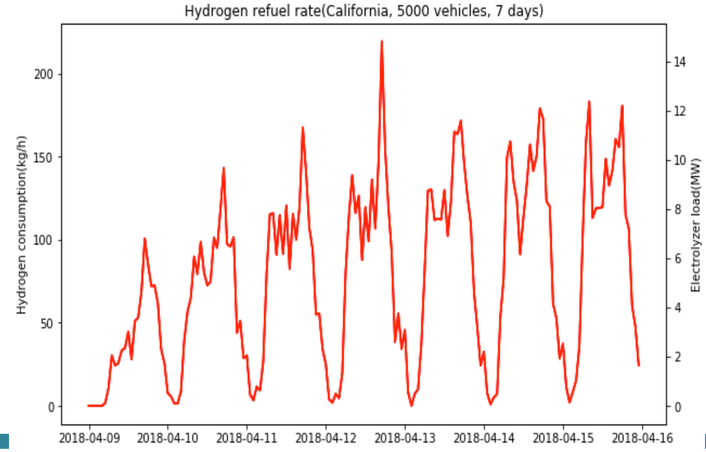
$P_{trac,i} = [(ma_iv_i) + (A + Bv_i + Cv_i^2) + mg\sin(\theta_i)]v$ [kW], $P_{trac,i} \geq 0$

Propulsion :

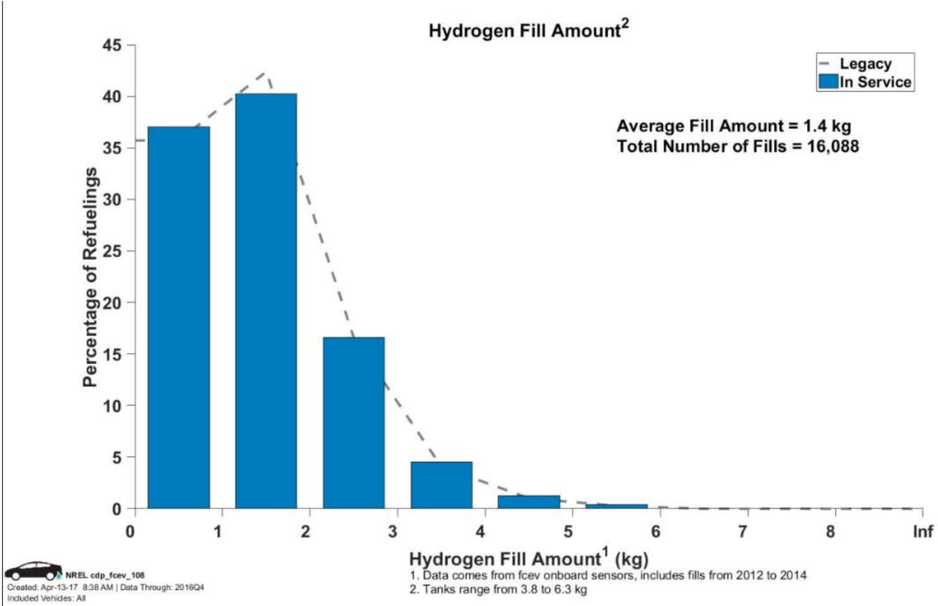
$FC_i = F(P_{trac,})$, $P_{trac,i} \geq 0$

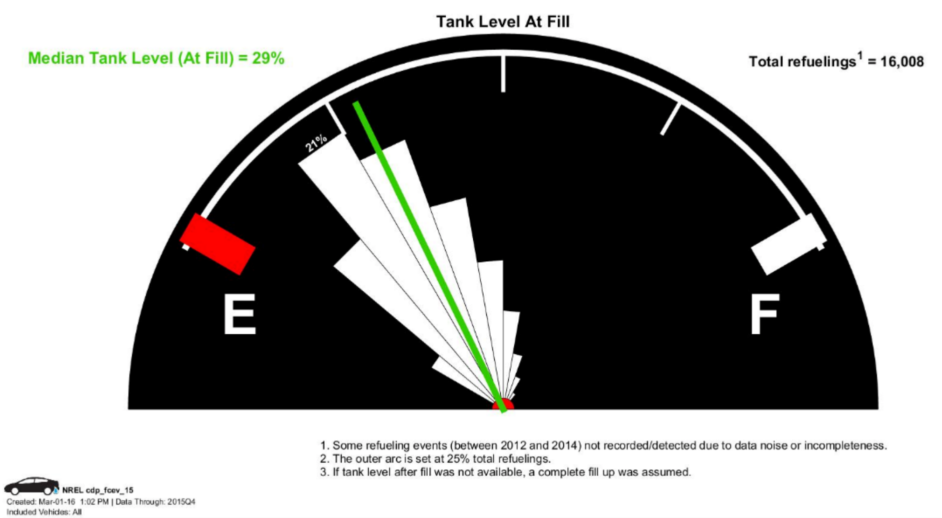
Regeneration:

$FC_i = G(P_{trac,})$, $P_{trac,i} < 0$

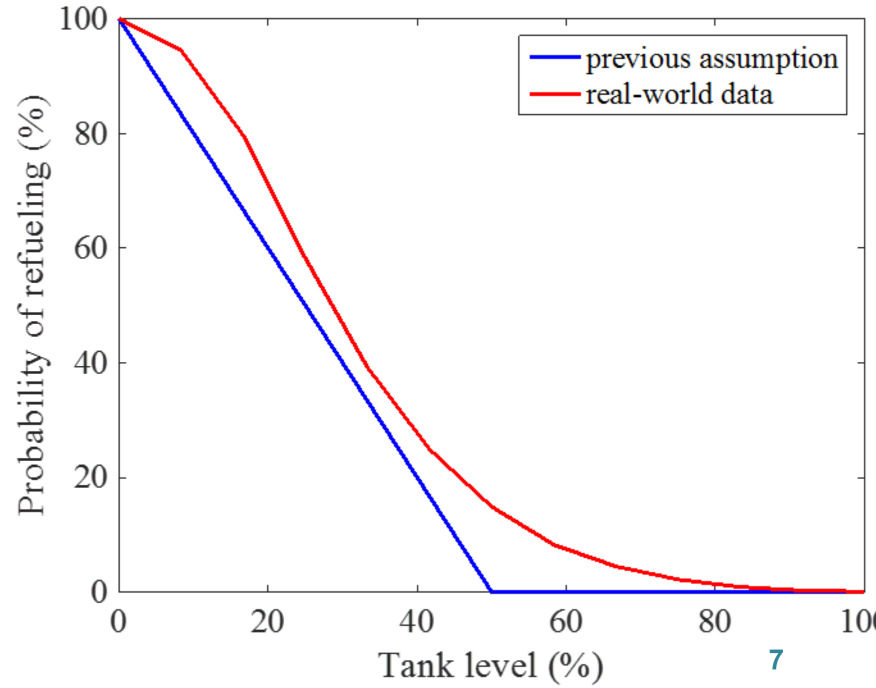


Approach – Refueling model





- 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



Key Research Activities & Questions

1. Determine the **flexibility** available from hydrogen-mobility-grid systems

2. Determine how grid services could affect the **cost competitiveness of hydrogen**

3. Quantify the capacity of hydrogen systems **to provide grid services** (e.g. load-balancing, ramping, flexibility, frequency reserve, operating reserves, etc.)

4. Quantify **value of grid services** provided.

5. Compare **centralized vs. distributed** hydrogen production

6. Assess the overall capability of the hydrogen refueling network to **provide energy storage**

2018 AOP

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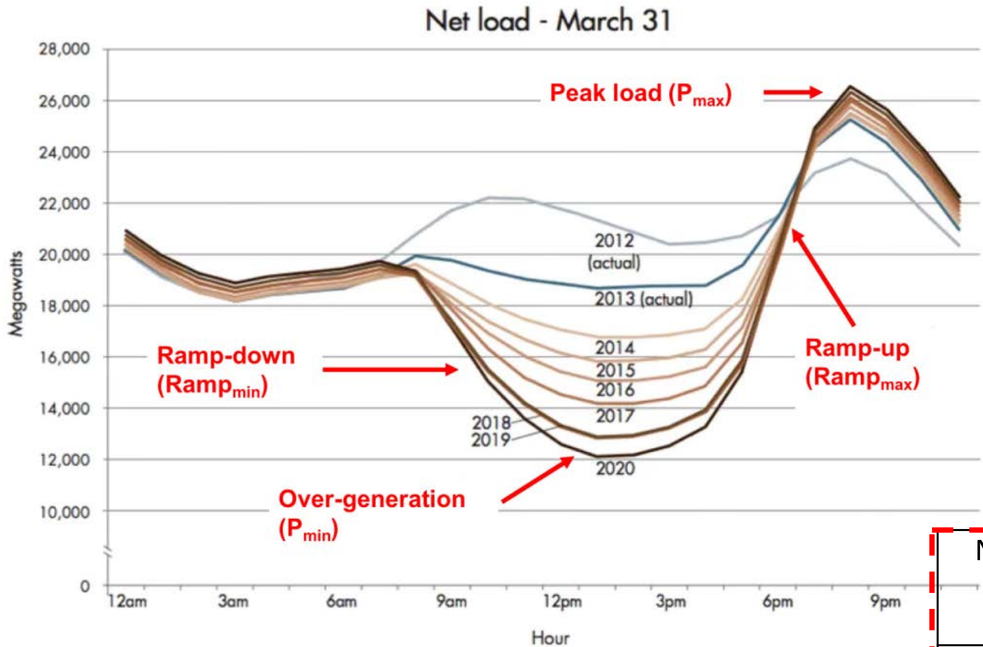
Qtr	Milestones/Deliverables Description	Status
Q1	Realistic integration of H2 resources into grid models to capture potential benefits and impacts for H2 technologies.	Project "Go" decision by FCTO
Q2	Refine input values into economic models for H2 resources from available data; Garner industry feedback for project modeling	Updated electrolyzer and fueling station costs and fueling station behavior from NREL H2 data; Garnered industry feedback from two webinars
Q3	Economic case study quantifying the scale of the opportunity from hydrogen-vehicle-grid integration for both central and distributed electrolyzer operation and station configuration/storage sizing.	Several utility regions in the Western Interconnect assessed with grid benefits of H2 VGI quantified
Q4	Q4 – 2018 – Draft short report on testing and validation of H2VGI economic modeling case study	Ongoing

Accomplishments and Progress
Renewable Integration in California



Four important problems indicated by "Duck Curve":

- Over-generation
- High evening peak load
- Sharp mid-morning down-ramps
- Substantial evening up-ramps

Calculated storage capacity: <8 hours

2025 Scenarios:

Number of FCEVs	Million Metric Tons H2/year	Number of Fueling Stations	Pct of Calif. refinery H2 production
200,000	0.04	350	4%
800,000	0.14	700	15%
1,500,000	0.27	1000	29%

Objective functions to tackle problem:

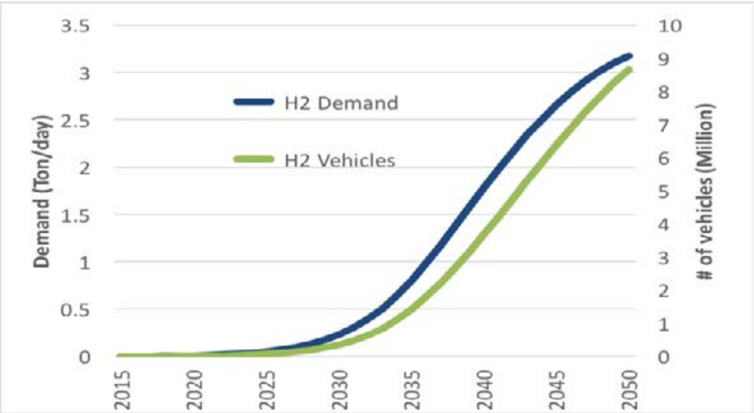
Peak-valley control: $\min \sum_{t=0}^{T}(N(t) + P(t))^2$

Ramp control: $\min \sum_{t=1}^{T}(N(t) + P(t) - N(t-1) - P(t-1))^2$

Subject to: Aggregate power and energy constraints

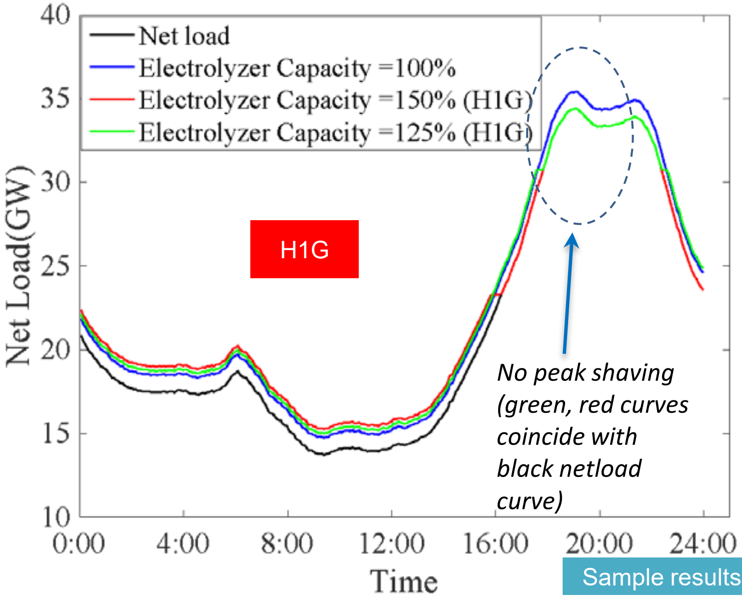
N(t): net load at time t;
P(t): electrolyzer power at time t. (decision variable)

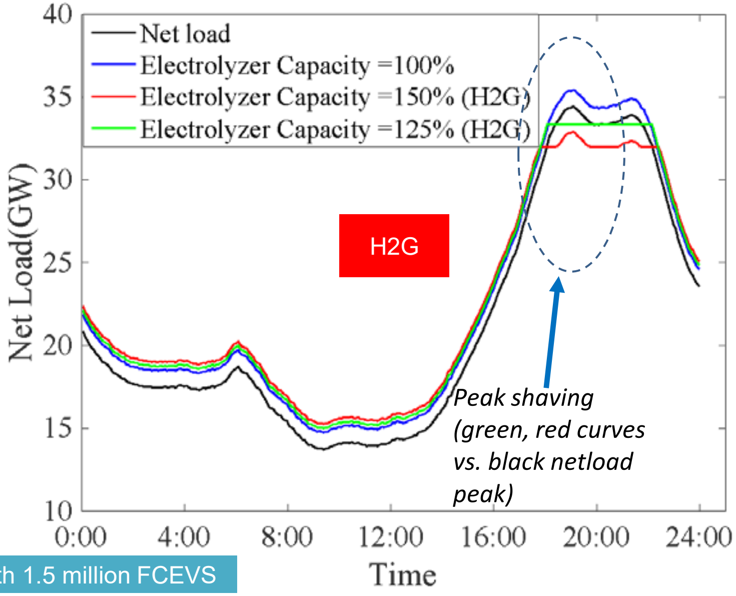
Accomplishments and Progress
Optimal hydrogen production



We simulate a set of scenarios that look at different levels of hydrogen demand (Ton/day), size of the electrolyzer (MW), number of FCEVs on the road, and two hydrogen configurations.

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





Sample results: 2025 netload with 1.5 million FCEVS

The technical potential for centralized electrolysis to provide grid peak shaving and valley filling support for California in 2025 has been modeled for the first time.

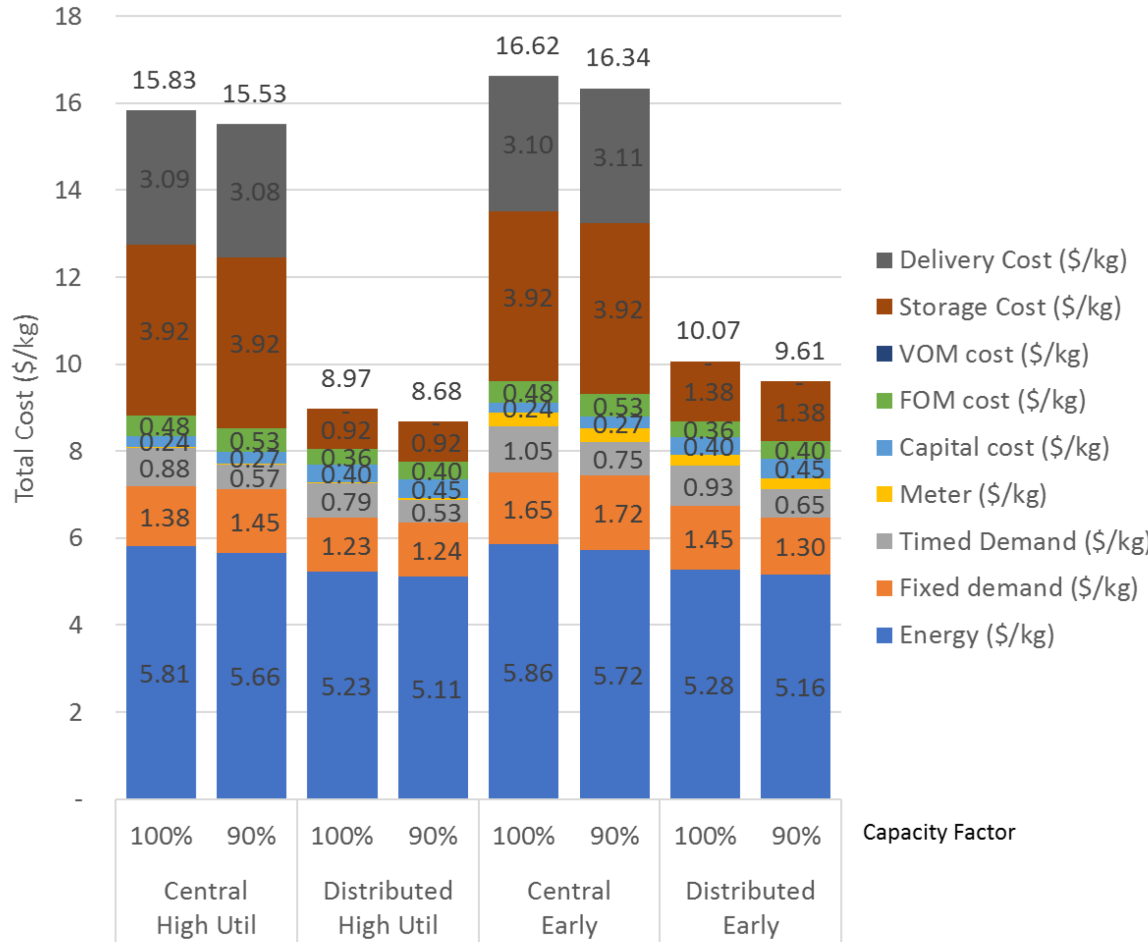
Paper submitted Journal of Power Sources February 2018

Accomplishments and Progress

Central vs. Distributed H2 Cases @ 90%, 100% Cap Factors

- Use current & planned H2 facilities in Northern California
- Iterating station model refines energy consumption for station.

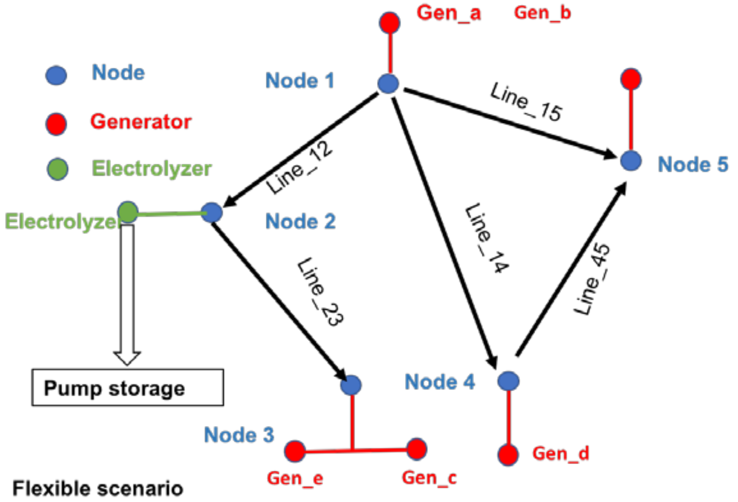
Assumptions	High Utilization	Early Market
H_2 Dispensed (kg/day)	1,085	120
Gaseous Truck deliveries (per day)	4 (central)	1
Electrolyzer power (MW) (Northern California Only)	74-81	7.9-8.8
Capital Cost ($million/MW) (H2A current, central)	1.3	1.3
Fixed O&M Cost ($thousand/MW-yr)	58-63	58-63
Storage Cost ($/kg)	1,000	1,000
Lifetime (years) (H2A)	20-40	20-40
Discount rate	7%	7%
Delivery Costs (SERA/HDSAM)	$0.00115/kg/mile $0.58/kg	$0.00115/kg/mile $0.58/kg
Utility Rates (PG&E, SMUD)	Large industrial	Large industrial

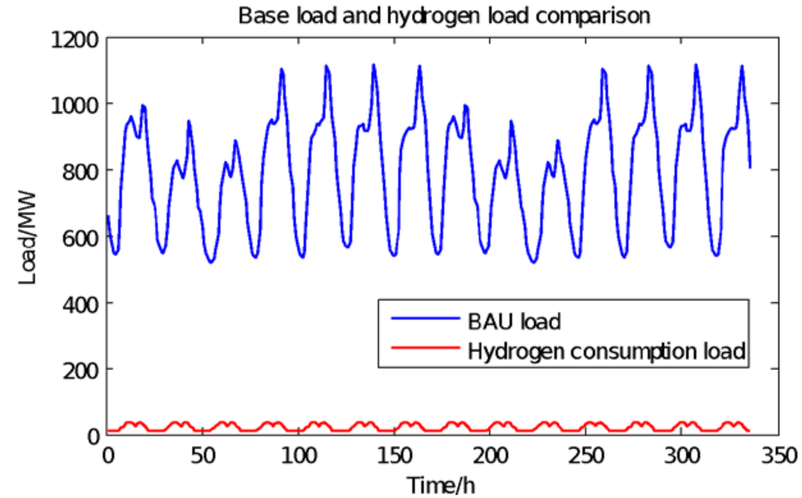


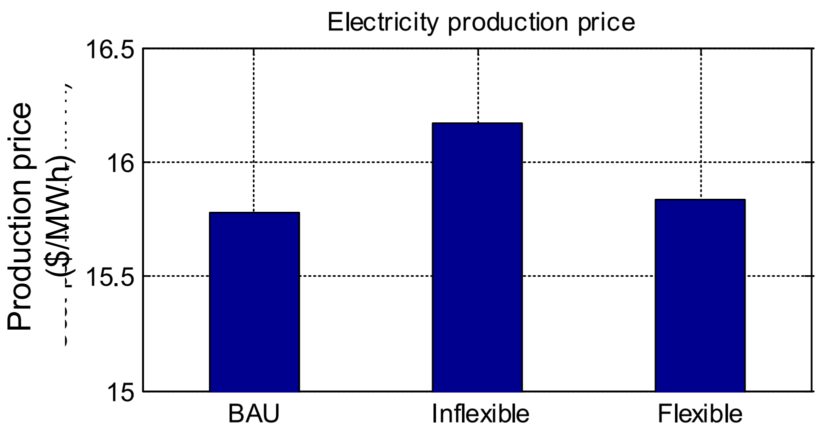
Distributed H2 fueling stations are found to be 40% lower total cost in ($/kg) than Central fueling stations for both early market and high volume scenarios

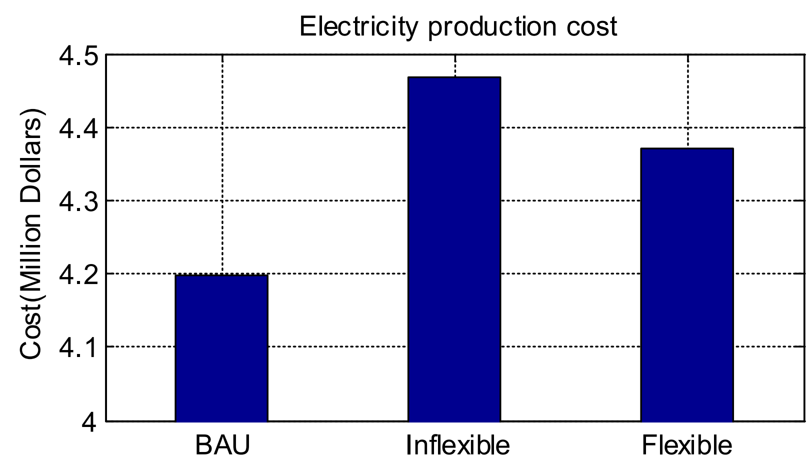
Accomplishments and Progress

Grid modeling result in H1G









BAU: base load without hydrogen electrolyzers

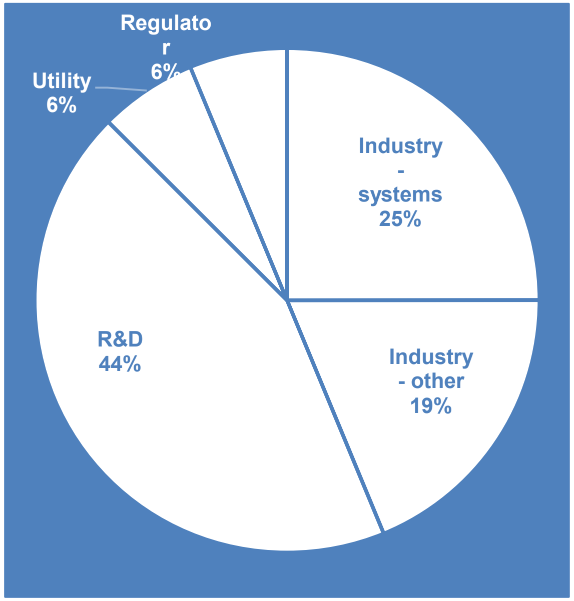
Inflexible: electrolyzer load is added, but the load is not controllable.

Flexible: the hydrogen production load is flexible.

Demonstration that flexible H2 generation case reduces the overall cost of electricity production close to the BAU case

Accomplishments and Progress
Stakeholder Outreach

- Invited ~40 experts in hydrogen production, hydrogen vehicles and grid operations to attend one of two webinars in March 2018. About 20 people participated in total from industry, academia, private research and government



Breakdown of webinar participants

Overall, participants found our methodology sound, but offered several suggestions:

- Include **heavy-duty** and possibly **industrial hydrogen demand**, in addition to light-duty vehicle demand - and also larger quantities of hydrogen (e.g., 4-5 kg) per light-duty vehicle fill
- **Moderate assumptions for FCEV** adoption; more electric vehicles
- Model **other regions besides California** that may have different grid mix, rate structures and geography, and disaggregate by Independent System Operator (ISO) or region to better capture differences
- Include **liquid hydrogen production/distribution**, as likely trend in next few years
- Most value to planners: projecting where, when and how much hydrogen production is needed
- Provided some **revised estimates** for efficiency, operations/maintenance and other cost assumptions, and lead times for building hydrogen production facilities
- Consider **hydrogen injection in natural gas grid** when hydrogen tanks are full

Stakeholder outreach has provided valuable inputs on future scenarios and inputs assumptions e.g., methodology is sound but more focus on medium and heavy duty H2 vehicles

Responses to Previous Year Reviewers' Comments

Feedback requested more for stakeholder feedback, spanning a range of areas

- "Provide more validation of assumptions"
  - Integrated real-world data from NREL H2 data collection on fueling behavior
  - Vetted input assumptions for H2 resource technical assumptions, vehicle modeling, fueling behavior
  - These assumptions were not found to be over aggressive
- "Integrate inputs including those from H2 installations"
  - Extensive inputs collected from Hawaii H2 station technical lead Mitch Ewan
  - Integrating inputs from two webinar on technical assumptions.
- "Include information/inputs on how to catalyze greater electrolysis adoption"

  Responses elicited from two webinars:
  - Ensuring reliable flexible demand
  - Assurance of supply chain manufacturing scale-up
  - Address environmental impacts and environmental justice (at least in California)

Collaborations

Partner	Role	Project Roles
NREL NATIONAL RENEWABLE ENERGY LABORATORY	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	Sub; (Within FCTO)	**Co-lead dispatch controller development for grid services; and tie-in to FCTO-TV031 project below**

Related Projects

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

Remaining Challenges and Barriers

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- Integration of case studies & grid models with nearer term FCEV and lower H2 demand scenarios
  - Modeling H2 resources in grid models for potential benefits and revenue
  - External grid models with FC-based vehicles and battery-based vehicles
- Integration of other H2 demands for H2-VGI scenarios e.g.,
  - Buses, medium duty and heavy duty trucks
  - Draw upon demand modeling from H2@Scale project (e.g., HD transportation, Industry, power-to-gas)
- Engage ISO/RTO system operators, utilities, regulators to gather inputs on grid markets and identifying barriers to greater H2 electrolyzer deployment

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

Proposed Future Work

- Remainder of FY 2018
  - Consolidate past 2 years multi-scale modeling capability, frameworks and industry feedback to focus on high impact applications
  - Q3: Economic case study quantifying the scale of the opportunity from hydrogen-vehicle-grid integration for several utility regions in the Western Interconnect vs. electrolyzer operation and station configurations
  - Q4: Journal paper on testing and validation of H2VGI economic modeling case study
- FY 2019
  - Economic case-study analysis of FCEV / FC MDV, HDV / PEV scenarios for several utility regions in the Western Interconnect with higher penetration of renewable electricity
  - Target high-quality peer-reviewed journal publications to summarize findings

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

Economic case studies on PLEXOS grid modeling, electrolyzer operation, and station/storage sizing

FY17-18 Technical Accomplishments

Sub-model development

- Integrated NREL H2 fueling data behavior in H2 consumption model
- Dynamic station model with either centralized or distributed generation
- External grid modeling using PLEXOS has integrated flexible H2 electrolysis generation H1G case

Integration of FCEV H2 consumption sub-models for H2 station modeling and external grid modeling

Case study results:

- H2 electrolysis generation driven by FCEV demands can play a substantial role in mitigating renewables integration challenges (California "duck curve" mitigation here)
- Centralized vs distributed H2 generation comparison finds distributed case lower cost from delivery and storage cost savings
- External grid model demonstrates reduced power cost with flexible electrolysis production vs inflexible case

Thank you

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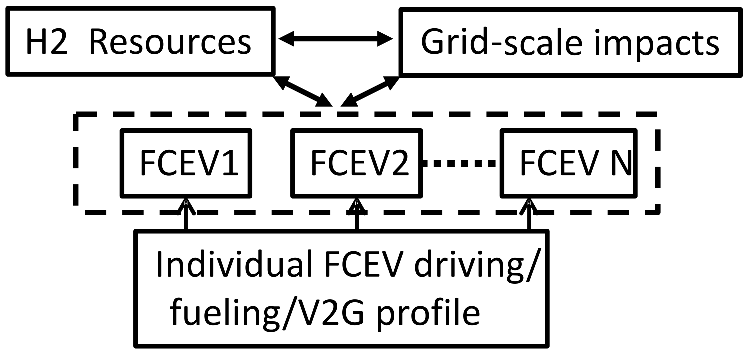
Technical Back-up Slides

Individual FCEV Modeling

V2G-Sim was updated for FCEVs

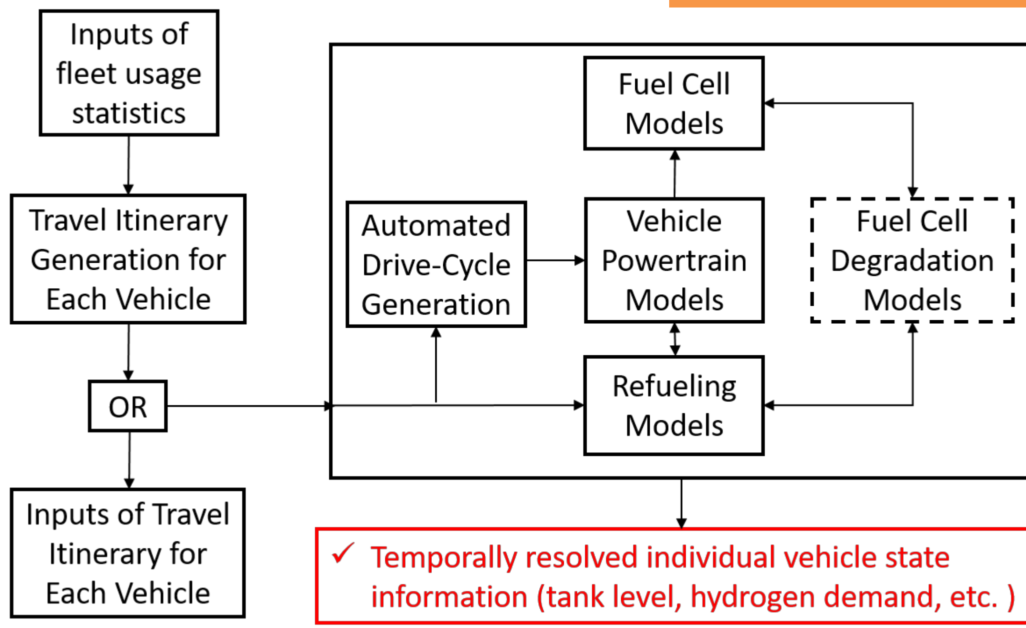
Bottom-up Approach



Includes libraries of models of varying complexity & computing time

Core objective: a platform to develop and test any user-defined fueling control approach and co-simulate with complementary models (e.g. distribution, transmission, market, etc.)

FCEV Model Architecture



V2G-Sim models the driving and fueling of many individual FC vehicles to temporally and spatially predict H_2 demands and how H_2 resources can benefit the electricity grid

2015 R&D 100 WINNER

FCEV adoption and hydrogen refueling station deployment

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

The SERA* model has been used to generate **self-consistent FCEV adoption and hydrogen demand scenarios** relevant to early market transition, considering:

- **Geospatially and temporally resolved vehicle adoption in each Urban Area in California based on demographics and early adopters metrics**
- **Annual vehicle mileage based on empirical evidence**
- **FCEV fuel economy improvement over time**
- **Vehicle stock turnover**

*SERA: Scenario Evaluation, Regionalization & Analysis

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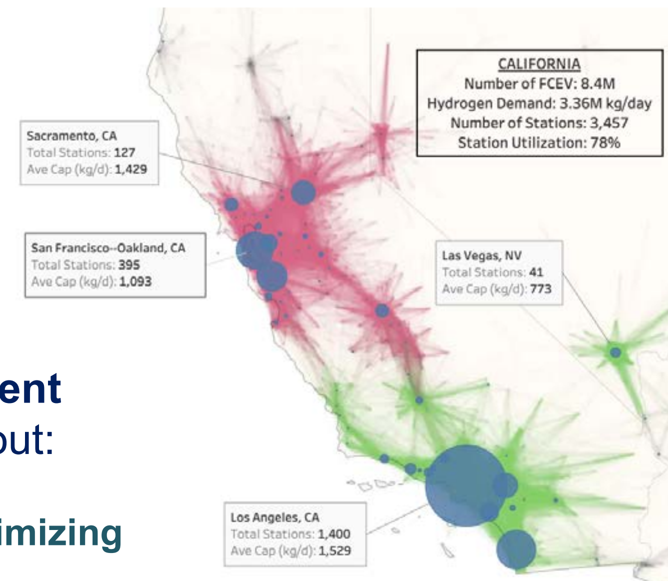


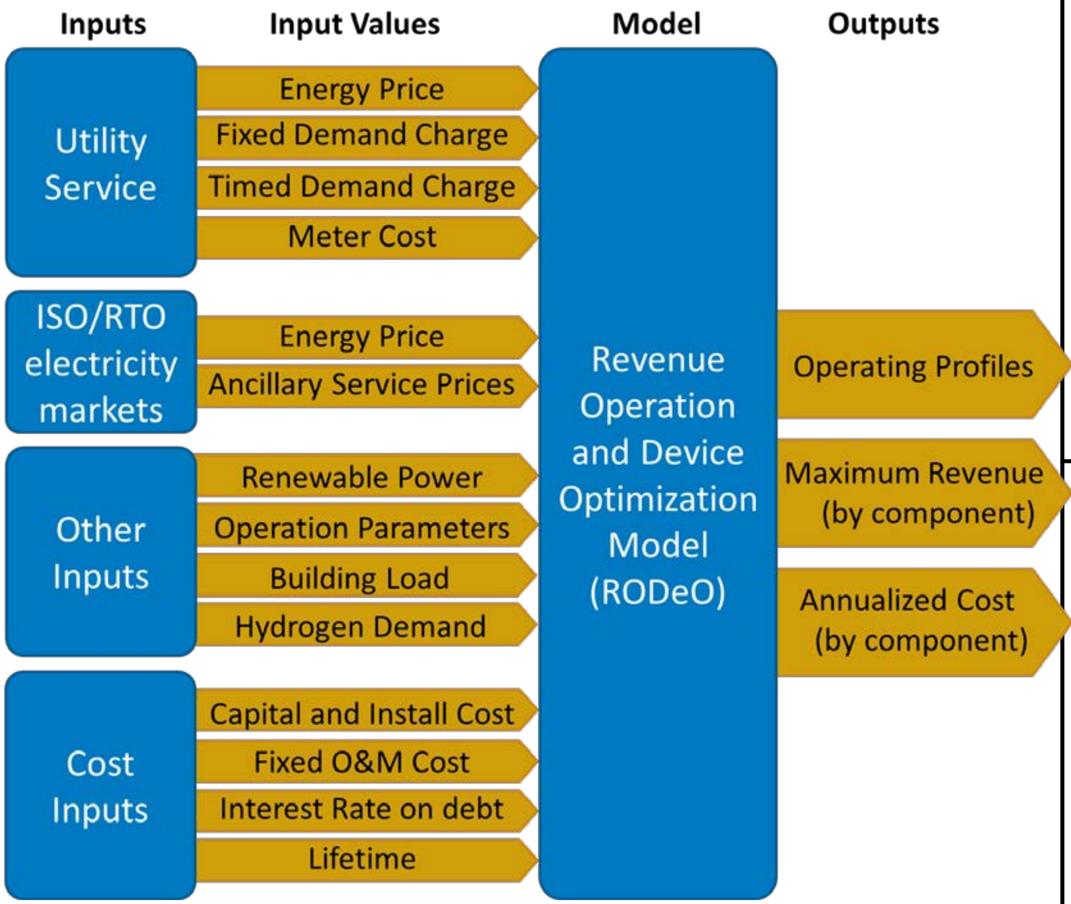
SERA determines optimal **regional infrastructure development patterns** focusing on detailed hydrogen refueling stations rollout:

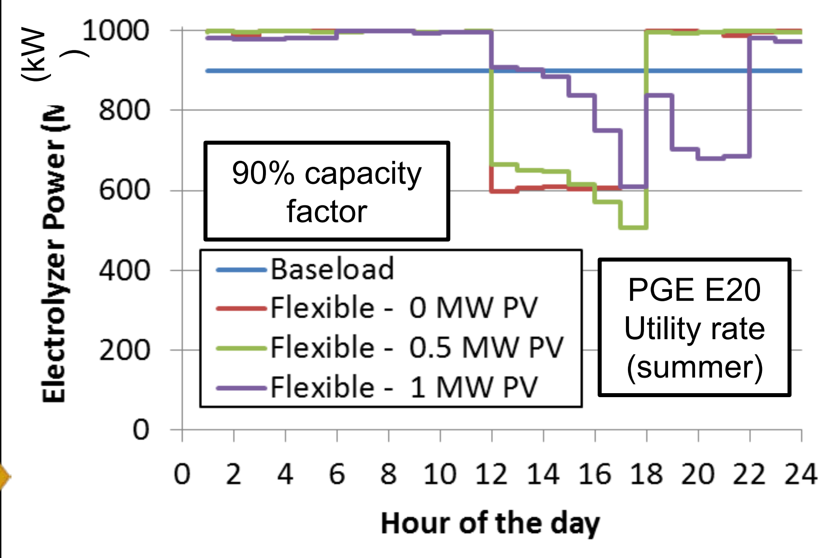
- **Stations are sized and geographically placed strategically, maximizing overall coverage**
- **The distribution of fueling stations (in both capacity and space) will evolve over time as the demand for hydrogen increases**

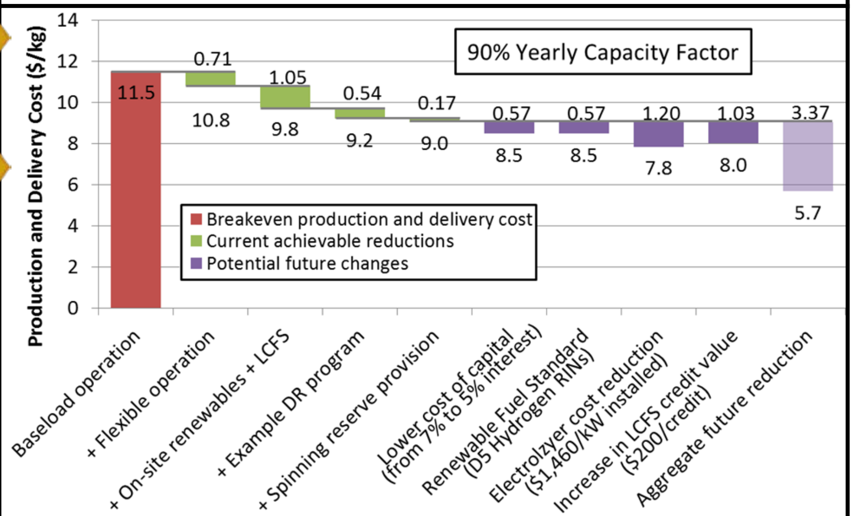
SERA provides annual FCEV adoption and H_2 demand scenarios and strategic placement of fueling stations

Device Optimization for grid integration using RODeO

RODeO models the individual hydrogen production facility and economic competitiveness







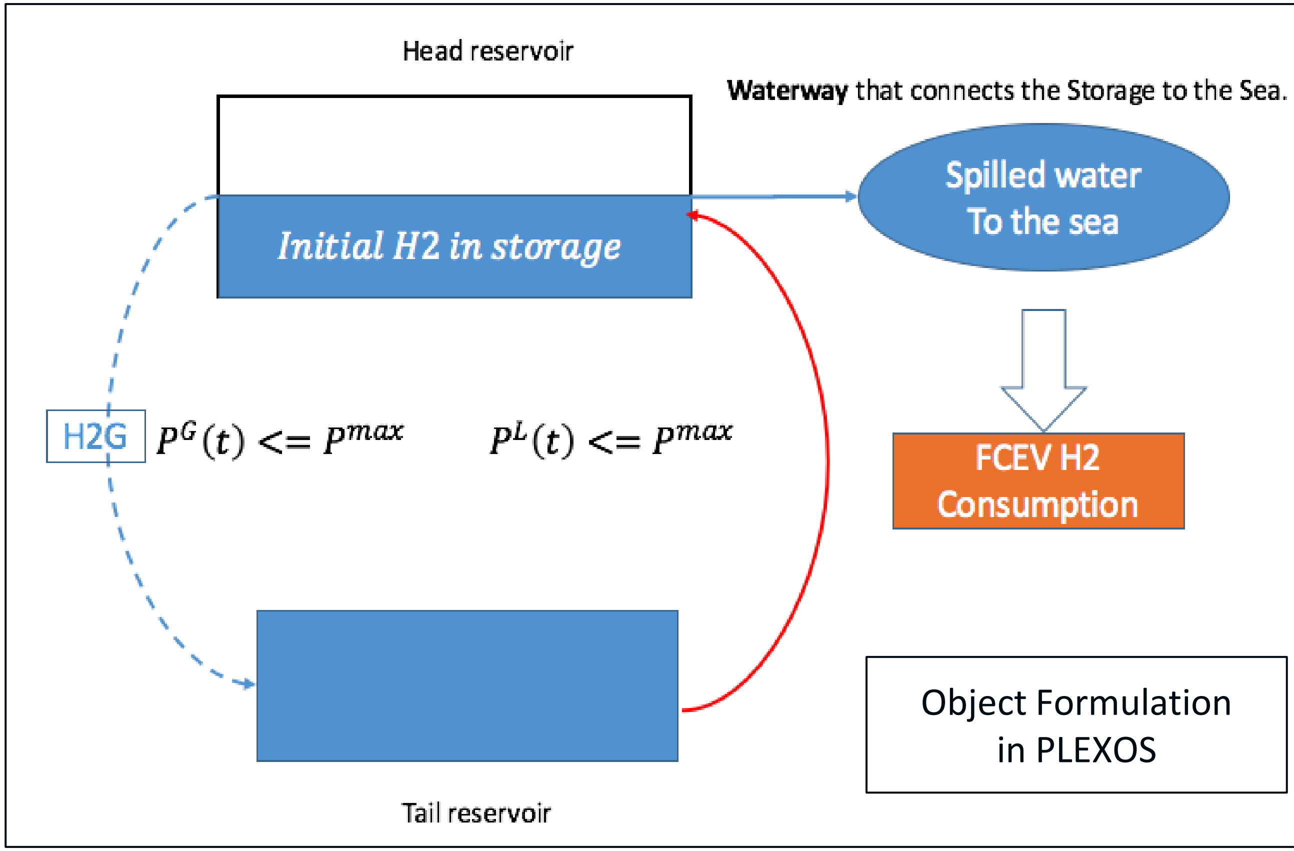
Example result (www.nrel.gov/docs/fy17osti/67384.pdf)

RODeO (Revenue Operation and Device Optimization Model) optimizes uses mixed-integer linear programming to maximize revenue and optimize equipment operation

Accomplishments and Progress- Grid Modeling

PLEXOS Outputs

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



Pumped-storage hydroelectric (PSH) power station object is used to model hydrogen production and storage devices.