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Hydrogen Analysis with the Sandia ParaChoice Model

Project ID#: SA055

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Sandia National Laboratories

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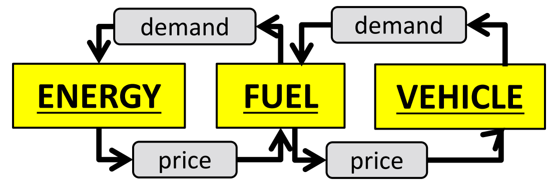
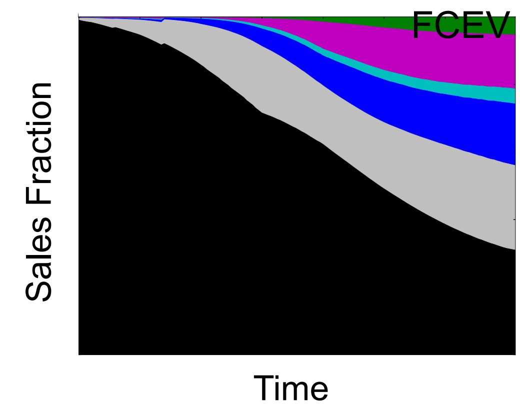
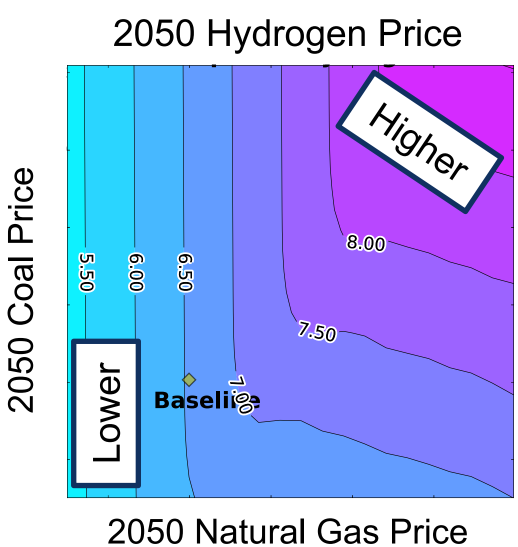
Outline

- **Front matter**
  - Overview- context
  - Project relevance & objective

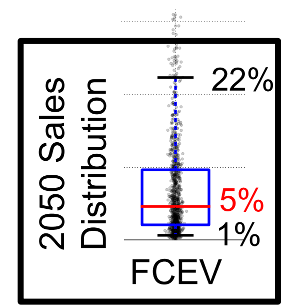


- **Scenario Analysis**
  - Approach – how core model works
  - Accomplishments & Progress – baseline scenario FCEV impact





- **Parametric Analysis**
  - Approach – how we understand uncertainty, analyze trade spaces
  - Accomplishments & Progress – analyses of infrastructure, commodities



- **End matter**
  - Collaboration
  - Proposed future work
  - Summary

Overview

Timeline and Budget

- Start date: FY15 Q1
- End date: Project continuation determined annually
- FY17 project budget $100k
- FY17 DOE funds spent*: $36k

*as of 3/31/2017

Barriers

A. Future Market Behavior

- behavior & drivers of the fuel & vehicle markets
- hydrogen supply infrastructure, vehicle interaction
- various hydrogen fuel and vehicle scenarios

C. Inconsistent Data, Assumptions and Guidelines

- results are strongly influenced by the data sets employed & assumptions
- makes it difficult to put the results and ensuing recommendations in context with other analyses

D. Insufficient Suite of Models and Tools

- model validation is required to ensure credible analytical results are produced from the suite of modeling tools

Partners: Interactions / Collaborations:

- Ford: Real World Driving Cycles
- Toyota
- American Gas Association
- DOT
- UC Davis
- ANL, ORNL, NREL, LBNL, Energetics
  - Biweekly lab and analysis calls hosted by VTO to discuss timely updates including BaSce model comparison work led by Tom Stephens (ANL).

Overview- How ParaChoice fits into DOE analysis framework

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Analysis of FCEV fleet penetration and fuel use through 2050

In tandem with analyses for VTO

Sub-programs
DOE Offices
Internal &
External Reviews

Analysis Framework

- Energy prices from AEO 2016
- Fleet segmentation from NHTS
- Technology price projections from Autonomie 2016
- Fuel and vehicle emissions from GREET
- H_2 prices and pathways from Macro-System Model (aggregates H_2A, HDSam, & more)
- 2010-2016 fueling stations from AFDC

Models & Tools

- Sandia Pathways ParaChoice Model

Validated model (barrier B).
Levinson, Manley, & West (2016)
SAE, Int. J. Alt. Power 5(2)

Studies & Analysis

- Vehicle penetration
- Fuel use & environmental
- Parametric & uncertainty exploration
- Population & vehicle segmentation

Outputs & Deliverables

- Parametric assessments
- Peer-reviewed publications

Addressing barriers (C) by using DOE sanctioned data sources and underlying models where possible.

Parameterizing around them to show the influence and impact of those underlying assumptions

Relevance & Objective: Parametric analysis to understand factors that influence vehicle, fuel, & infrastructure mix

- *Lifetime project goals*: Understand changes to the Light Duty Vehicle (LDV) stock, fuel use, & emissions, including FCEV and H_2
  - System level analysis of dynamic between vehicles, fuels, & infrastructure
  - Use parametric analysis to
    - Identify trade spaces, tipping points & sensitivities
    - Understand & mitigate uncertainty brought in by data sources and assumptions

Addresses barrier A

Addresses barrier C in all studies by the very construct of the analysis

- *FY17 FTCO Milestones and Accomplishments*:

Milestone	Status
Add additional detail to the fuel price model to the ParaChoice model, especially for smaller station sizes.	Complete
Add at home refueling (AHR) to the ParaChoice model.*	Beginning Q3
Complete initial analysis of impact of (AHR) and refined fuel price model on output metrics including FCEV market share and GHG emissions.	Initial fuel price analysis complete. AHR analysis beginning Q3
Complete sensitivity analysis, varying factors including station availability, fuel cost, efficiency, or technology cost.	Prelim. analyses complete. Ongoing
Complete and deliver annual report, including final results of ParaChoice analysis	End of year Milestone
Added task at request of FCTO – Analyze H_2 prices and FCEV sales in various coal and natural gas futures.	Complete

Based on discussion with FCTO, we update our goals throughout the year to ensure their continuing relevancy to FCTO objectives.

* Goal delayed in favor of FCTO request for Coal/NG parametric pricing analysis.

Approach: systems level economic analysis to model dynamic feedback between fuels, vehicles, & infrastructure

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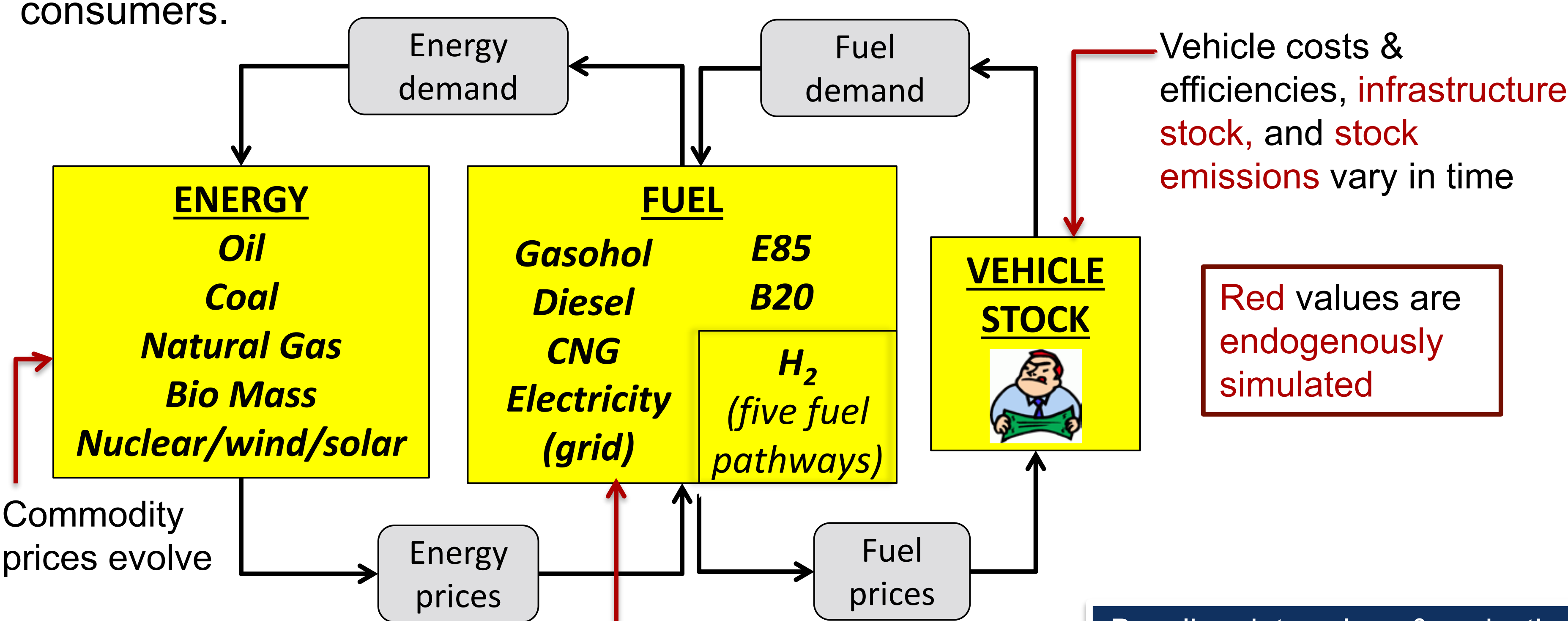
Marches forward from present, when energy, fuel, and vehicle stock states known, to 2050. At each time step, vehicles compete for share in the stock based on value to consumers.



RFS, carbon taxes, H_2 production pathways, electric grid composition, all vary in time

Baseline policies are taken to be current status quo

- No federal renewable H_2 mandate
- No CO_2 tax
- Federal EV, but no FCEV incentive
- State incentives included

Baseline data values & projections taken from trusted sources

- Energy prices: AEO 2016
- H_2 prices and pathways: MSM
- Emissions: GREET 2016
- Fleet segmentation: NHTS
- Vehicle price projections: Autonomie
- 2010-2017 fueling stations: AFDC

Approach: At every time step, simulation assesses generalized vehicle costs for each vehicle. Choice function assigns sales based on these costs and updates stock.

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VEHICLE STOCK

Vehicle		Generalized Vehicle Cost				Percent of Sales
Conv. SI	→	$X /year				A %
FCEV	→	$Y /year	→	Nested Multinomial Logit Function	→	B %
PHEV40	→	$Z /year				C %

… And 17 more

Given:
- Input attribute(s)
- Fixed set of 2+ output choices

Nested Multinomial Logit Function

Outputs:
- Probability distribution

Generalized Vehicle Cost

Upfront Costs Amortized Over "Required Payback Period"
- Purchase price
- One time incentives
- One time penalties *(Infrastructure penalty)*

Recurring Costs
- Fuel cost
- Annual incentives
- Annualized penalties *(Range penalty)*

Modeling Accomplishments & Progress: Revisions based on feedback from FCTO & updates to AEO & MSM models.

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Uniqueness: from other DOE vehicle models

FUEL

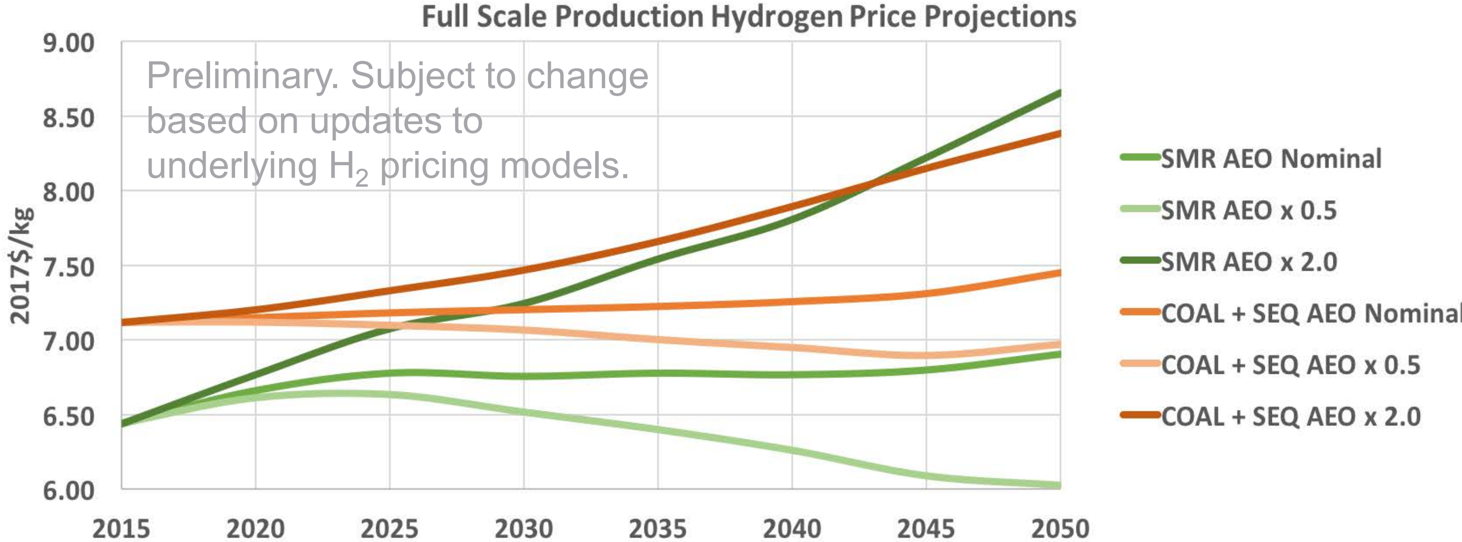
H_2 production pathways in ParaChoice model

- Industrial (Central SMR + $ markup)
- Central SMR
- Central SMR + sequestration
- Central Coal + sequestration
- Central (Clean) Electrolysis

- 2015 H_2 prices (at scale) by MacroSystem Model (MSM) 2017$
- Station sizes:
  - 1,500 kg/day for dedicated production
  - 700 kg/day for industrial (lower demand)

SMR	$6.44
SMR + seq	$6.63
Coal + seq	$7.12
Electrolysis	$9.88

MSM efficiencies and AEO energy price projections are used to estimate future H_2 prices



* Projections do not include FCTO RD&D Plan's hydrogen delivery goals

Key result: For baseline AEO projections, SMR is always less expensive than coal gasification + seq. However, uncertainties in the NG price projection can easily change the outcome.

Approach: Five H_2 production pathways modeled. Pathways utilized determined endogenously based on which option produces the least expensive hydrogen, by state.

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Simplified model logic for pathway selection

(see technical backup for detailed logic)

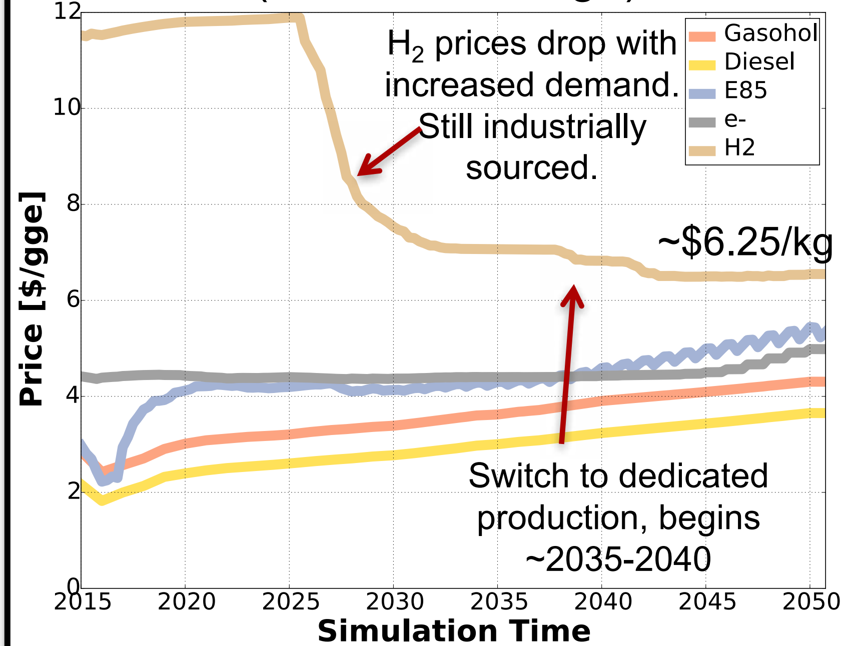
At beginning of simulation

- Stations use industrial H_2 at pricing that decreases with volume of demand (*Hydrogen and Fuel Cells US Market Report*, 2010; current CA H_2 pricing)

As demand increases due to new FCEV sales in each state, the most economical solution is selected to meet unmet demand

- Industrial H_2 trucked to stations
  - Chosen if demand is low compared to 50,000 kg/day
  - Market pricing based on volume of demand
  - Calibrated so national average price in 2015 is ~$12/kg
- Dedicated central production for vehicles
  - Only an option if unmet demand >= central production plant capacity (50,000 kg/day) x number of production plants needed for state's size
  - NG SMR, NG SMR+ seq, coal gasification + seq, or wind electrolysis chosen based on price of delivered H_2
  - H_2 delivered to stations in liquid form by truck

Result: Simulated fuel price evolution (national average)



Production pathways can be influenced by

- Renewable mandates
- Carbon taxes
- Parametric multipliers on resource and/or technology costs (slide 8)

Approach: segment vehicles, fuels, & population to understand competition between powertrains & market niches

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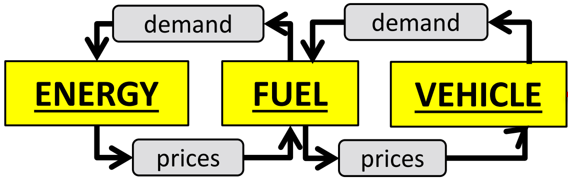

Geography

Vehicle

Demographics

Understand evolution of H_2 production by region

Parametric analysis of competition between different AEVs for different technology cost futures

Understand impact of fueling infrastructure

Vehicle Stock Segmentation

Powertrain

SI	E85 FFV
SI Hybrid	E85 FFV Hybrid
SI PHEV10	E85 FFV PHEV10
SI PHEV40	E85 FFV PHEV40
CI	BEV75
CI Hybrid	BEV100
CI PHEV10	BEV200
CI PHEV40	BEV300
	CNG
	CNG Hybrid
FCEV	CNG Bi-fuel

Housing Type

- Single family home without NG
- Single family home with NG
- No access to home charging/fueling

Workplace Charging Access Yes/No

VMT Segmentation

Energy/Fuel Seg.

State
48 CONUS +
Washington, DC

Density
Urban
Suburban
Rural

Size
Compact
Midsize
Small SUV
Large SUV
Pickup

Age
0-46 years

Driver Intensity
High
Medium
Low

Can use to tease out market niches

Scenario Accomplishments & Progress: Baseline scenario analyses lending insight into FCEV market evolution & competition

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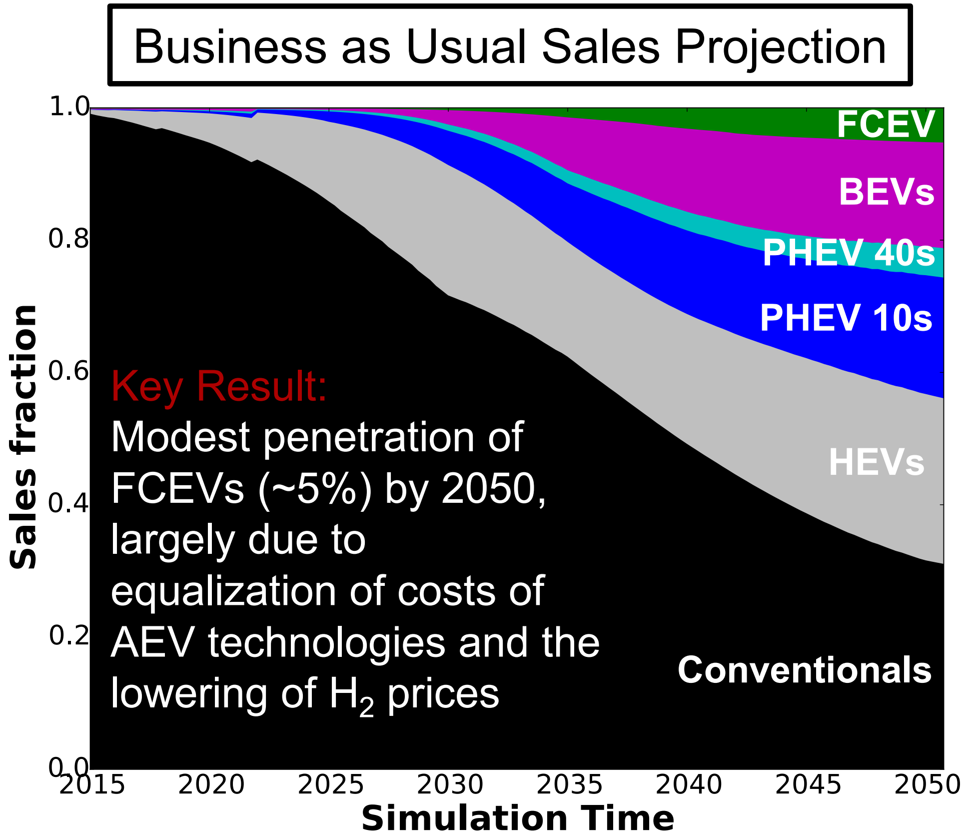
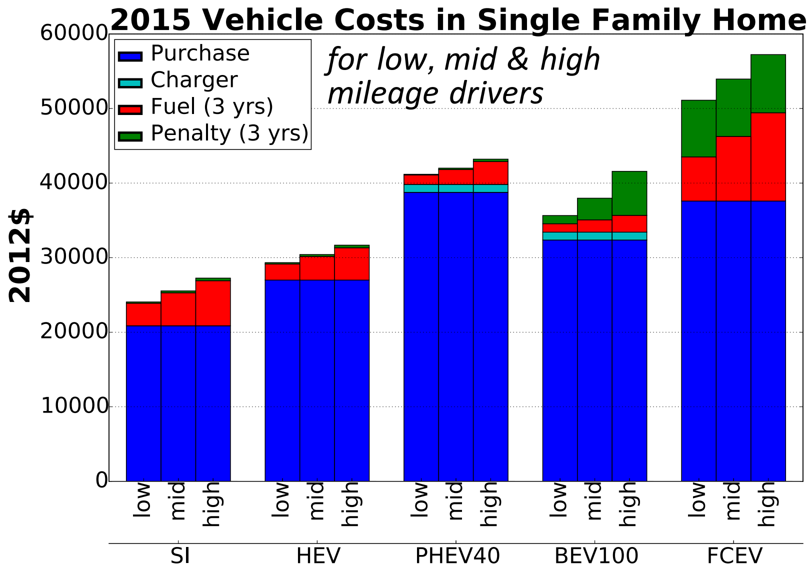
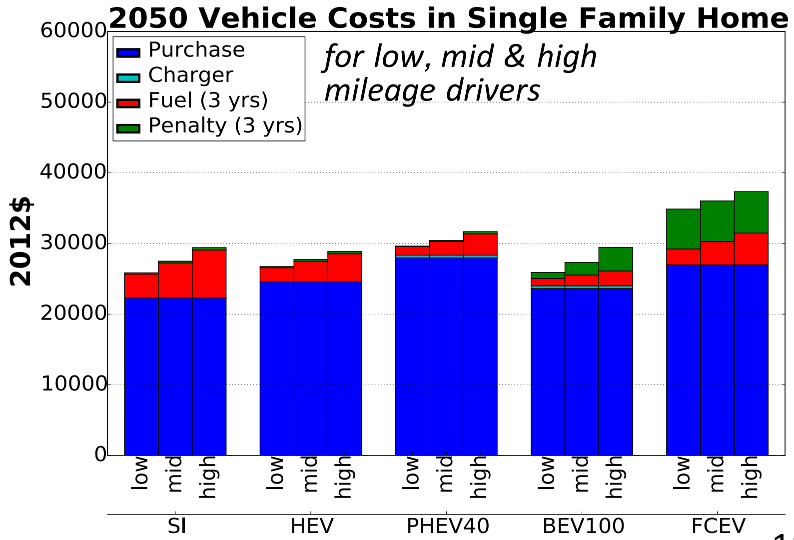






Data Sources

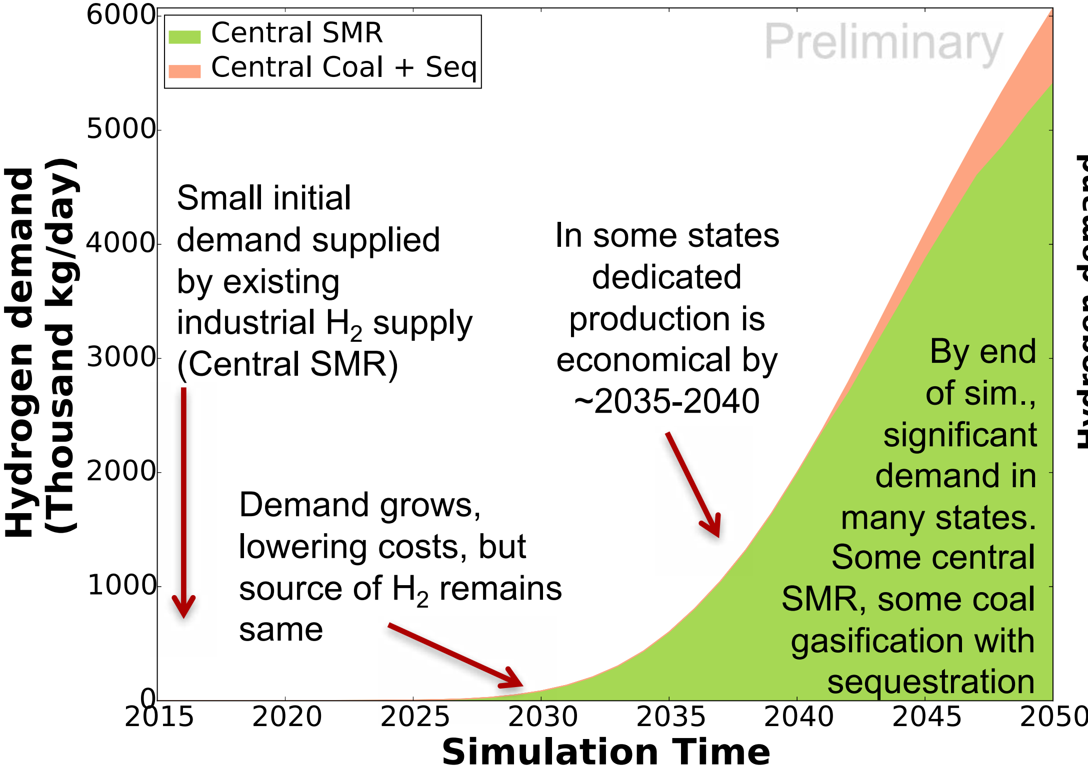
c - current values used; c&p - current & projected

- Purchase $ (c&p): *Autonomie* 2016 + Incentives from AFDC 2016
- Efficiencies (c&p): *Autonomie* 2016
- Gasohol fuel (c): AEO 2016
- Electricity (c): EIA 2016
- H_2 fuel (mult. pathways) (c): MSM, Hydrogen and Fuel Cells: The US Market Report (2010)
- Oil, NG, Coal (c&p) for computing future fuel prices: AEO 2016
- Zero Carbon & Biomass energy (c&p): multiple sources
- Penalties: adapted, Greene (2001)

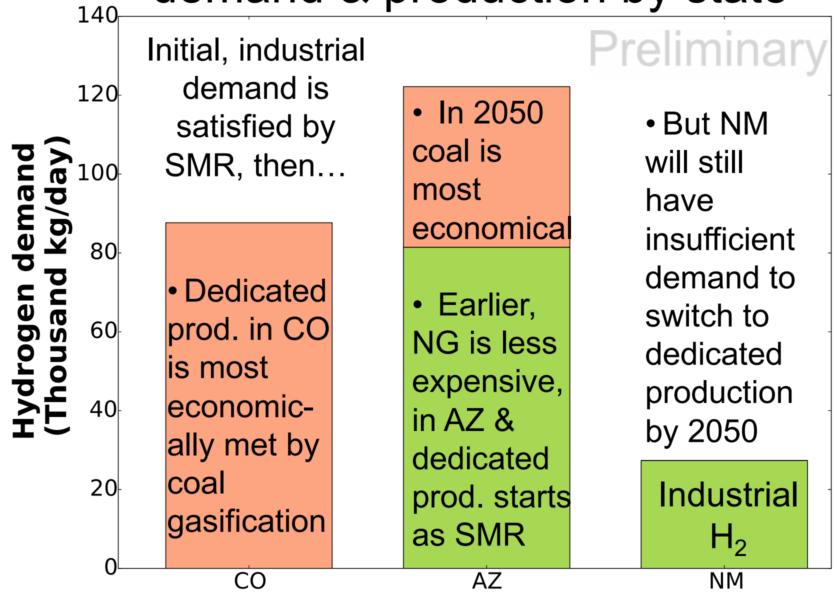
Scenario projections are NOT the goal of the model, but a starting point for understanding market drivers

Scenario A&P: Evolution of H_2 production with demand in scenario with 1.25 x nominal 2050 NG Prices.

Simulated H_2 production evolution (national average)



Simulated 2050 hydrogen yearly demand & production by state



These results are preliminary, subject to review based on update to underlying H_2 pricing models!

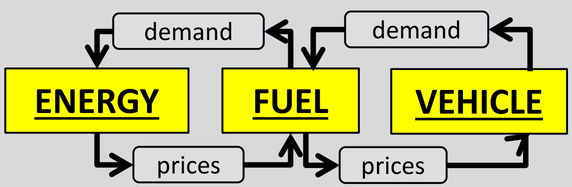
Key result: Hydrogen demand by region, commodity price evolution, and regionally specific electricity and commodity prices determine hydrogen pathway and price within a region. We simulate feedback between hydrogen price and demand to project the co-evolution of FCEVs in the fleet with hydrogen production.

Parametric Approach: Use parameterization to understand & mitigate uncertainty brought in by data sources & assumptions

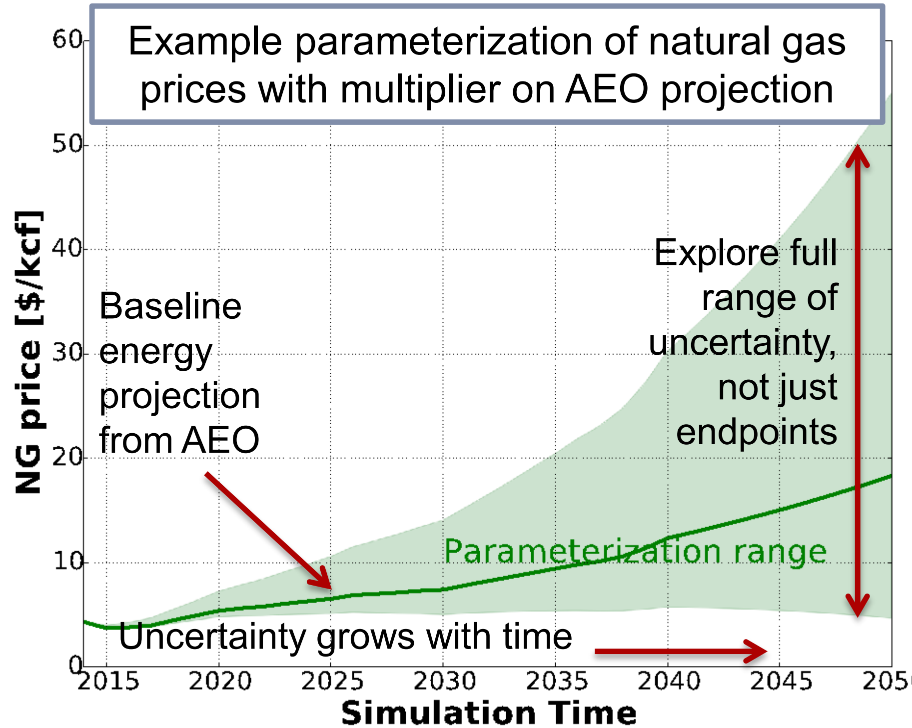
Addresses barrier C

***Uniqueness from other DOE models*:**
ParaChoice is designed to explore uncertainty & trade spaces, easily allowing identification of tipping points & sensitivities

- Core simulation is a system-level analysis of dynamic, economic relationship between energy, fuels, & vehicles with baseline values from trusted DOE sources. Technologies compete in the simulation, are allowed to flourish or fail in the marketplace.



- Simulation is run 1000s of times with varying inputs. This parametric analysis provides:
  - Perspectives in uncertain energy & technology futures
  - Sensitivities and tradeoffs between technology investments, market incentives, and modeling uncertainty
  - The set of conditions that must be true to reach performance goals

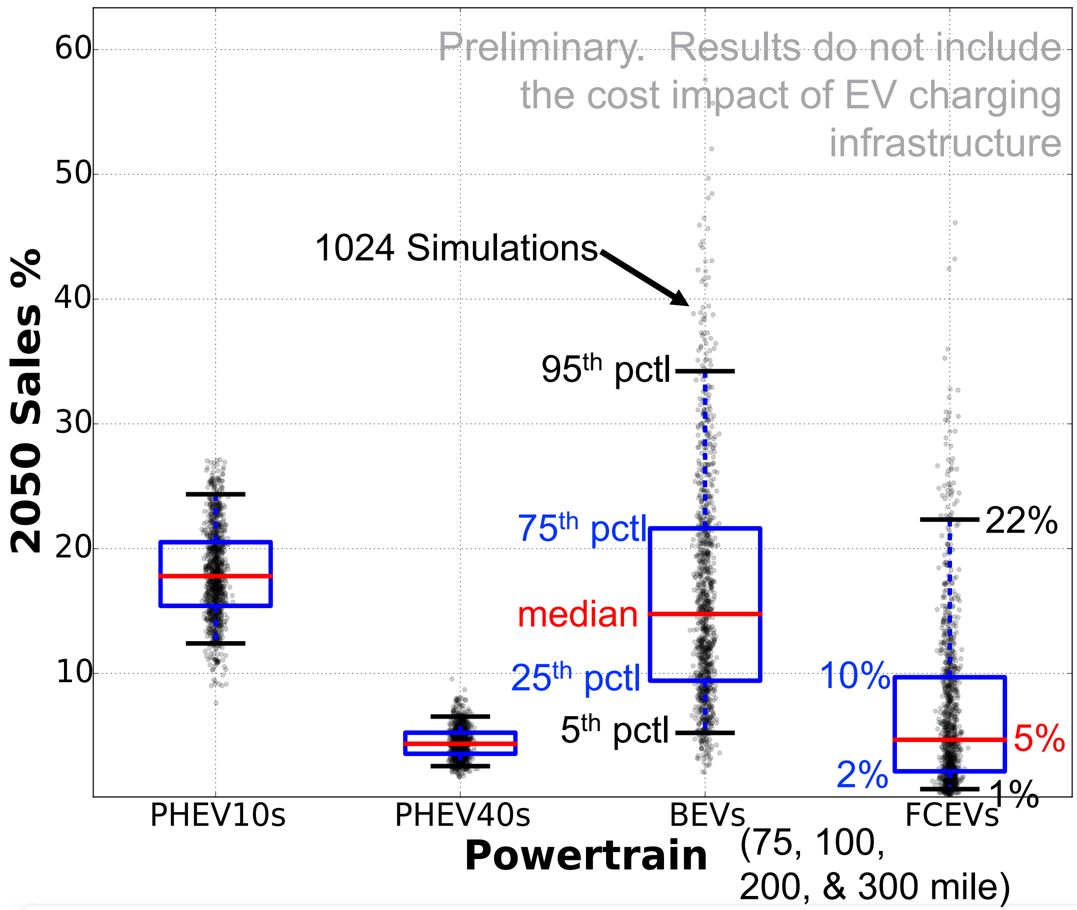


- Vary two parameters at once- trade space analysis (~400 scenarios, uniform distributions)
- Vary many parameters- sensitivity analysis or MC (~3000 scenarios, triangular distributions)
- Parameterization ranges designed to explore plausible AND 'what if' regimes, covering all bases

Parametric A&P: Monte Carlo uncertainty analysis allows us to put confidence intervals on results

Development funded by VTO FY17

Addresses barrier C



Select parameters in MC analysis

Parameter	Baseline	Min	Max
Oil, Coal, NG $	AEO	x0.5	x2.0
Biomass, Zero Carbon Energy $	Multiple sources	x0.5	x2.0
Battery $	Autonomie low tech uncertainty, low cost uncertainty	x0.5	x2.0
Fuel Cell Tech $		x0.5	x2.0
ICEV Tech $		x0.8	x1.25
EV Efficiency		x0.67	x1.5
FCEV Efficiency		x0.67	x1.5
ICEV Efficiency		x0.71	x1.4
Payment Period	3 years	2 yrs	4 yrs
H_2 stations/1k veh	0.7	0.1	1.3

(See backup slides for full list and sensitivity analysis)

Key results: Future FCEV sales are highly dependent on uncertain underlying inputs. In 90% of scenarios, 2050 FCEV sales may be between 1% and 22% of total sales.

Highest FCEV penetration for scenarios with:

Lowest
- fuel cell costs
- consumer price sensitivity
- consumer sensitivity to penalties

Greatest
- oil prices
- FCEV efficiencies
- H_2 station growth in response to sales

Parametric A&P: Analyses of coal and natural gas futures show that H_2 prices will stay low, even with unexpectedly high coal or natural gas prices.

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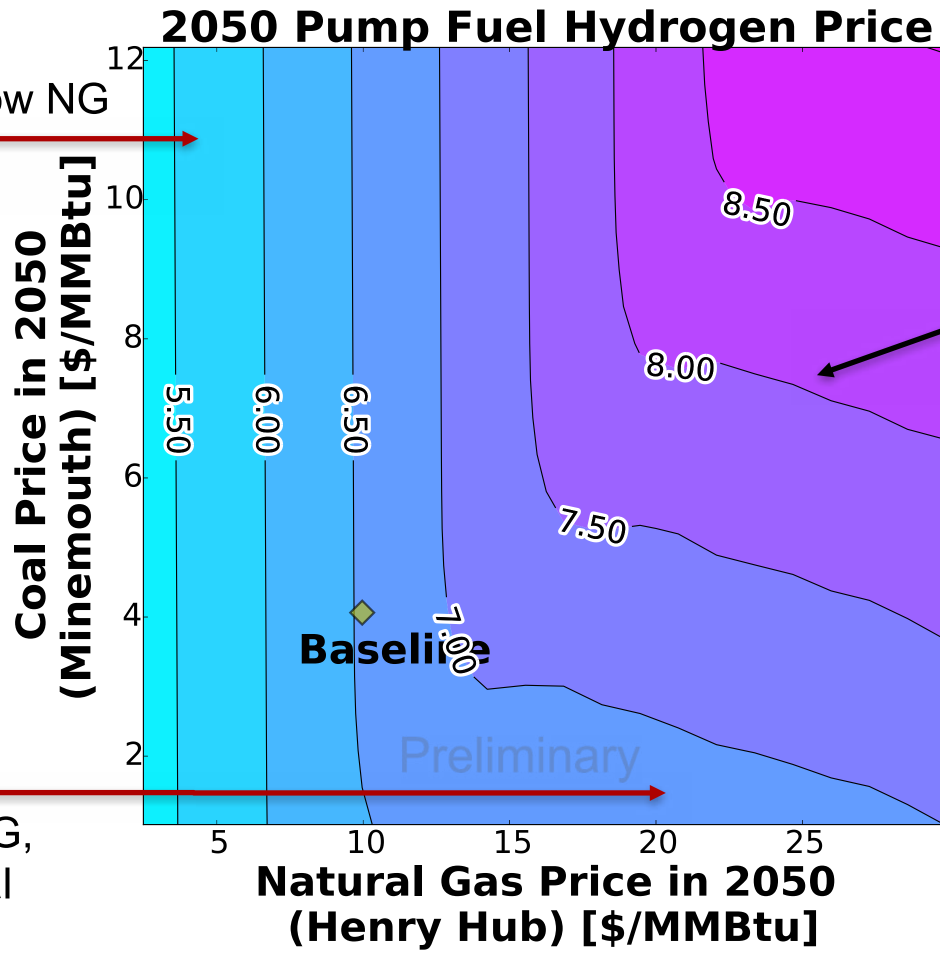
High coal, low NG

Hydrogen prices are mostly protected against high natural gas prices OR coal prices, as production can switch to the lower cost pathway. However, if the price of both is high the price of H_2 must follow.

High NG, low coal



The negative slopes at very high natural gas prices are caused by high industrial H_2 costs which lead to low initial FCEV sales and insufficient H_2 demand in some states to prompt the switch to dedicated H_2 production (with coal).

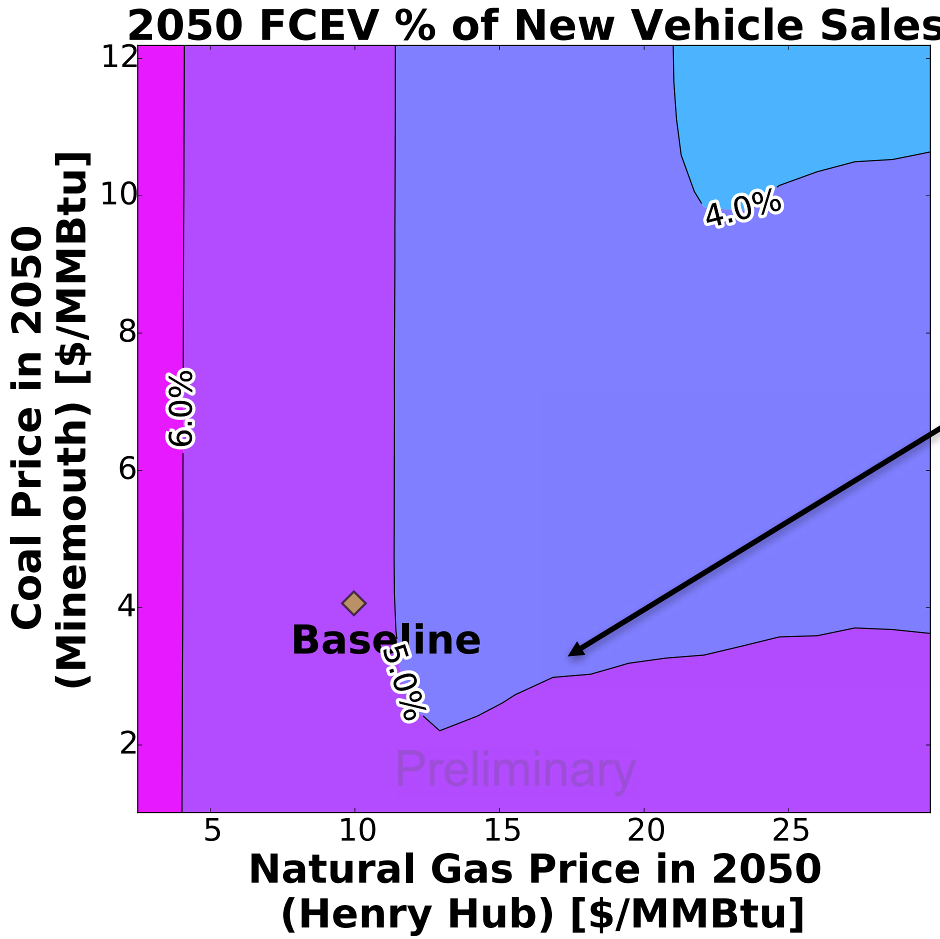
Therefore, even though H_2 could be made more cheaply with coal, H_2 costs in these states remain high due to poor demand and consequently industrial SMR production pathways, driving up the national average price.

Key results:

2050 H_2 will remain under $7/kg if either natural gas prices stay below ~$12/MMBtu or coal prices stay below ~$2/MMBtu in 2050.

H_2 prices are lowest, ~$5.50/kg, for the lowest natural gas price projections.

Parametric A&P: Analyses of coal and natural gas futures show that FCEV sales are only modestly influenced by coal and natural gas prices.



Sales trends largely follow H_2 price trends.

However, natural gas is also used to make gasoline, so very high natural gas prices also increase gasoline prices.

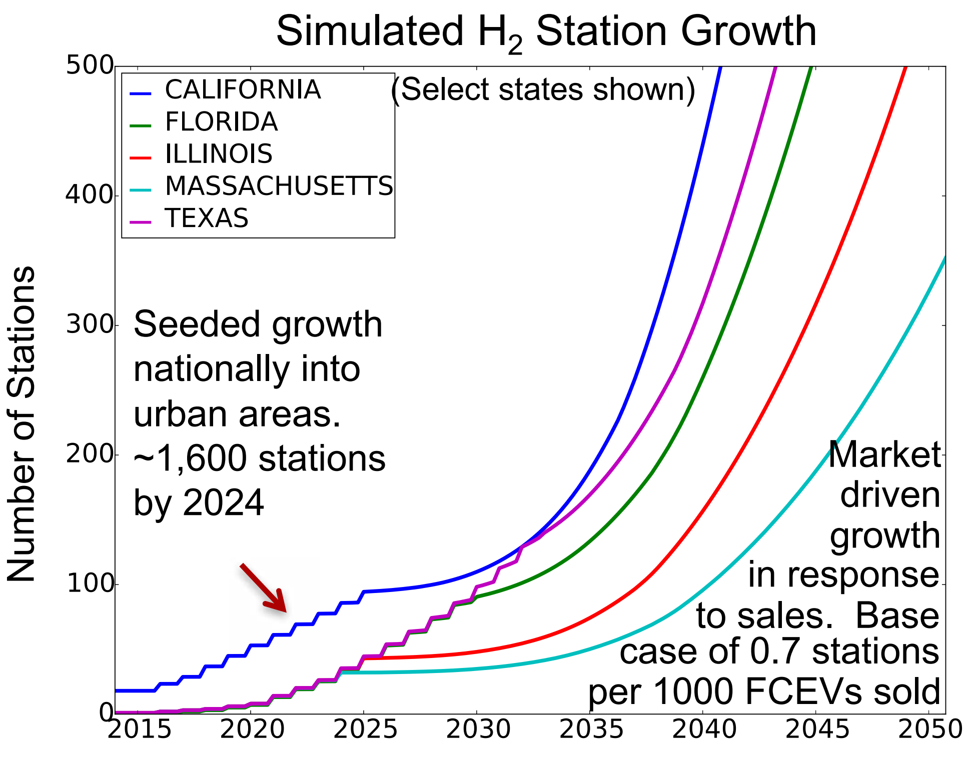
High gasoline prices improve all AEV sales, including FCEV.

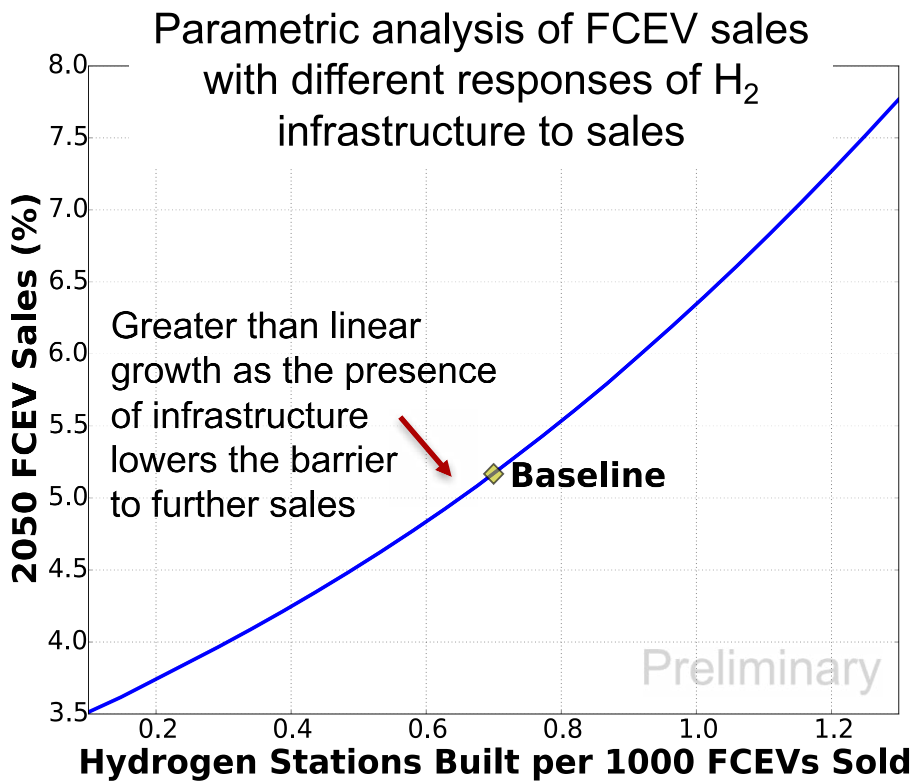
Key results:

2050 FCEV sales are largely robust to coal and natural gas price changes, varying from only 3% of total vehicle sales to 7% of total vehicle sales, even if AEO estimates for coal and NG prices vary from 0.25x to 3x nominal projections in 2050.

Parametric A&P: Analyses of market driven H_2 infrastructure

Key results: Parametric variation of H_2 infrastructure response to sales shows that 2050 FCEV sales may increase by 50% if 1.3 stations are built per 1,000 FCEVs sold rather than the 'business as usual' 0.7





We modified ParaChoice to seed H_2 stations into urban areas first, following CA's lead and H_2USA (H_2USA LRWG *National Hydrogen Scenarios* 2017). We seed 1,600 stations nationally, by 2024 similar to H_2USA's 1,800 by 2025 in their Urban Markets scenario. We then model ways that the FCEV market and H_2 infrastructure may co-evolve, depending on the response of H_2 infrastructure to FCEV sales.

Collaborations

- No funding given to other institutions on behalf of this work
- Technical critiques received from Ford Motor Company, General Electric, American Gas Association, and more
- The underlying ParaChoice model has been developed using funding from a variety of sources including
  - Sandia Laboratory Directed Research & Development (LDRD) Funds
  - Clean Energy Research Consortium (CERC)
  - Vehicle Technologies Office
- This work is complemented by modeling and analysis for the VTO. Brandon Heimer's presentation on the VTO-funded ParaChoice analysis is VAN019

Proposed Future Work

- Add at home refueling option to ParaChoice model (FY 2017 Milestone)
- Complete analysis of impact of at home refueling and refined fuel price model on output metrics including FCEV market share and GHG emissions (FY 2017 Milestone)
- Complete and deliver annual report, including final results of ParaChoice analysis (FY 2017 end of year deliverable)
- FY18: Explore the role and potential impact of fuel cells in the heavy duty vehicle space with our ParaChoice Truck model. This work would build upon our existing VTO studies to determine
  - Where technology advancements might have the greatest impact on efficiency and criteria pollutant reduction for heavy trucks
  - Which technologies have the greatest potential in different heavy trucking segments

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

Summary

- ParaChoice
  - Is a **validated system level analysis model** of dynamic between vehicles, fuels, & infrastructure
    - **Leveraging other DOE models and inputs**
    - Simulating fuel production including **endogenous selection between hydrogen production pathways** that scales with fuel demand
  - Is **designed for parametric analysis** in order to
    - **Understand & mitigate uncertainty** brought in by data sources and assumptions
    - Identify trade spaces, tipping points & sensitivities
  - Helps us understand changes to the LDV stock, fuel use, & emissions, including FCEV and H_2
  - Is NOT simply a tool for creating scenario sales projections
- Analysis key results:
  - Future FCEV sales are highly dependent on uncertain underlying inputs. To 90% confidence, 2050 FCEV sales may be between 1% and 22% of total sales.
  - 2050 H2 prices are robust to uncertainties in either coal or NG prices. H2 will remain under $7/kg if either natural gas prices stay below ~$12/MMBtu or coal prices stay below ~$2/MMBtu in 2050.
  - Parametric variation of H2 infrastructure response to sales shows that 2050 FCEV sales may increase by 50% if 1.3 stations are built per 1,000 FCEVs sold rather than the business as usual 0.7.
- Future work to
  - Complete this years' milestone for at home refueling analyses
  - Explore the potential penetration and impacts of fuel cell technologies in heavy trucks

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

Technical Backup Slides (5)

Full set of parameters varied in Monte Carlo uncertainty analysis. Triangular distributions used, Latin Hypercube sampling.

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Parameter	Baseline	Min	Max
Oil $	AEO projections[1] Costs varied regionally.	x 0.5	x 2.0
Coal $		x 0.5	x 2.0
Natural Gas $		x 0.5	x 2.0
Biomass $	US Billion Ton Update Analysis[2]	x 0.5	x 2.0
Zero Carbon $	ReEDS[3] Model	x 0.5	x 2.0
Battery $	Moawad et al. 2016[4] (*Autonomie)* low technology uncertainty, low cost uncertainty scenario. Max efficiency cases reflect the high/high scenario.	x 0.5	x 2.0
Fuel Cell Tech $		x 0.5	x 2.0
ICEV Tech $		x 0.8	x 1.25
Electric power efficiency		x 0.67	x 1.5
FCEV efficiency		x 0.67	x 1.5
ICEV efficiency		x 0.74	x 1.4
At-home EV charger $ reduction rate	0.03	0.01	0.05
Multinomial logit exponents[5]	[9,12,15]	[6,8,10]	[12,16,20]
Vehicle payback period	3 years	2 years	4 years
Sensitivity to penalties	1	x 0.5	x 2.0
Infrastructure willingness[6]	0.1	0.05	0.15
Total vehicle sales rate	0.067	0.05	0.09
H2 infrastructure growth/ 1k vehicles	0.7	0.1	1.3
Infrastructure growth/ 1k vehicles (other)	0.7	0.1	1.3
Electricity generator lifespan	40 years	20 years	10 years

(1) U.S. EIA. Annual Energy Outlook 2016: with Projections to 2040. U.S. DOE, Aug. 2016a.

(2) U.S. DOE. U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry. ORNL/TM-2011/224. R. D. Perlack and B. J. Stokes (Leads) ORNL, Oak RIdge, TN, 2011a.

(3) W. Short, P. Sullivan, T. Mai, M. Mowers, C. Uriarte, N. Blair, D. Heimiller, and A. Martinez. Regional energy deployment system (ReEDS). Technical Report NREL/TP-6A20-46534, Golden, CO, Nov. 2011.

(4) A. Moawad, N. Kim, N. Shidore, and A. Rousseau. Assessment of Vehicle Sizing, Energy Consumption, and Cost through Large-Scale Simulation of Advanced Vehicle Technologies. ANL, Argonne, IL, Mar. 2016.

(5) Consumer sensitivity to factors not captured in generalized cost; lower = more sensitive

(6) Fraction of DC fast chargers to gasoline pumps that ½ of population will be willing to use public EV infrastructure.

Most sensitive drivers of 2050 FCEV Sales. Spearman correlation coefficients.

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Parameter	Baseline	Min	Max	2050 FCEV Sales Response
Oil $		x 0.5	x 2.0	0.25
Coal $		x 0.5	x 2.0	-0.01
Natural Gas $		x 0.5	x 2.0	-0.05
Biomass $		x 0.5	x 2.0	0.01
Zero Carbon $		x 0.5	x 2.0	0.01
Battery $		x 0.5	x 2.0	0.03
Fuel Cell Tech $		x 0.5	x 2.0	-0.58
ICEV Tech $		x 0.8	x 1.25	0.09
Electric power efficiency		x 0.67	x 1.5	-0.03
FCEV efficiency		x 0.67	x 1.5	0.24
ICEV efficiency		x 0.74	x 1.4	-0.19
At-home EV charger $ reduction rate	0.03	0.01	0.05	-0.01
Multinomial logit exponents[5]	[9,12,15]	[6,8,10]	[12,16,20]	-0.47
Vehicle payback period	3 years	2 years	4 years	0.04
Sensitivity to penalties	1	x 0.5	x 2.0	-0.40
Infrastructure willingness	0.1	0.05	0.15	-0.04
Total vehicle sales rate	0.067	0.05	0.09	0.08
H2 infrastructure growth/ 1k vehicles	0.7	0.1	1.3	0.16
Infrastructure growth/ 1k vehicles (other)	0.7	0.1	1.3	-0.04
Electricity generator lifespan	40 years	20 years	10 years	0.00

Larger absolute values show stronger correlation.

Positive (negative) values indicate positive (negative) correlation.

H_2 production pathway pricing, production, & emissions assumptions & data sources

Sandia National Laboratories

- Energy intensity and efficiency factors for the pathways come from the NREL-Sandia *Macro Systems Model*, which itself aggregates other DOE model inputs (e.g. H_2A, HDSAM)
- Emissions factors for all pathways save distributed electrolysis come from *GREET*
  - Distributed electrolysis emissions are computed from regional electric grid emissions
- H_2 pump fuel costs and GHG emissions by pathway are taken from MSM for 2015 technologies and efficiencies. These costs are divided into:
  - Production/transportation feedstock costs
  - Production electricity costs
  - State and federal taxes and fees
  - All other costs (e.g. fixed, O&M) associated with production, transport, and distribution
- Feedstock and electricity costs evolve throughout the simulation, and H_2 costs by pathway evolve consequentially.
- Technology advancements for the production pathways are modeled as multipliers on the 'other' (fixed and O&M) production costs

Pathway		Central SMR	Central SMR + Seq.	Central Coal + Seq.	Central Electrolysis
Pump price*		$6.44	$6.63	$7.12	$9.88
kg GHG/ mi	2050 (low^)	0.19	0.11	0.09	0.03
	2050 (high^)	0.14	0.08	0.07	0.02

*National avg. pump fuel prices (2017$) for 2015 day commodity prices and full scale production
^Reflecting *Autonomie* low uncertainty, low program success and high uncertainty, high success vehicle efficiencies

Powertrains Modeled

Abbreviation		fuels
SI Conventional	Conventional spark ignition	gasohol
SI HEV	Hybrid spark ignition	gasohol
SI PHEV 10	Plug-in hybrid 10mi electric range spark ignition	electricity, gasohol
SI PHEV 40	Plug-in hybrid 40mi electric range spark ignition	electricity, gasohol
CI Conventional	Compression ignition	diesel OR B20 blend
CI HEV	Hybrid compression ignition	diesel OR B20 blend
CI PHEV 10	Plug-in hybrid 10mi electric range compression ignition	electricity, diesel OR B20 blend
CI PHEV 40	Plug-in hybrid 40mi electric range compression ignition	electricity, diesel OR B20 blend
E85 Conventional	Flex fuel spark ignition	gasohol OR E85
E85 HEV	Hybrid flex fuel spark ignition	gasohol OR E85
E85 PHEV 10	Plug-in hybrid 10mi electric range flex fuel spark ignition	electricity, gasohol OR E85
E85 PHEV40	Plug-in hybrid 40mi electric range flex fuel spark ignition	electricity, gasohol OR E85
BEV 75	Battery electric 75 mi range	electricity
BEV 100	Battery electric 100 mi range	electricity
BEV 200	Battery electric 200 mi range	electricity
BEV 300	Battery electric 300 mi range	electricity
FCEV	Fuel cell electric vehicle	hydrogen
CNG Conventional	Compressed natural gas spark ignition	compressed natural gas
CNG HEV	Compressed natural gas hybrid	compressed natural gas
CNG BI	Compressed natural gas bi-fuel	compressed natural gas OR gasohol

For Vehicle characteristics, please see Moawad et al. 2016, sometimes referred to in this presentation as ‘Autonomie’, based on the model used in that publication. The specific scenario used in our baseline studies is the low technology uncertainty and low price uncertainty scenario.

Acronyms and Abbreviations

- Powertrains/ vehicles
  - AFV/AEV- alternate fuel/energy vehicle
  - BEV/EV- battery electric vehicle
  - CI- compression ignition
  - CNG- ICE with compressed natural gas fuel
  - E85- ICE using either gasohol or 85% ethanol fuel
  - FCEV- fuel cell electric vehicle
  - ICE- internal combustion engine
  - PHEV- plug-in hybrid electric vehicle with 10 or 40 mile all electric range
  - SI- spark ignition
- Fuels and Commodities
  - B20- 20% biodiesel blend
  - CNG- compressed natural gas
  - E85- 83% ethanol blend
  - NG- natural gas
  - Elec.- electricity
- H_2 production
  - Coal- coal gasification
  - Seq.- sequestration of carbon created during production
  - SMR- Steam methane reformation of natural gas
- Other
  - AEO- EIA Annual Energy Outlook
  - AFDC- Alternative Fuel Data Center
  - DOT- Department of Transportation
  - EIA- Energy Information Administration
  - GHG- green house gas
  - GREET- The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (ANL)
  - LDV- light duty vehicle
  - MSM- Macro System Model (NREL)
  - NHTS- National Household Transportation Survey (2010)
  - VMT- annual vehicle miles traveled