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Hydrogen Analysis with the Sandia ParaChoice Model

Project ID#: SA055

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Sandia National Laboratories

DOE Annual Merit Review, June 8, 2016

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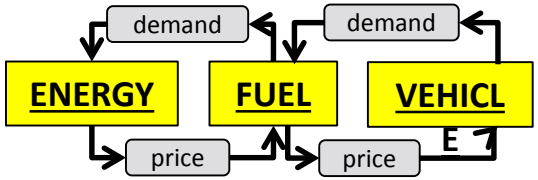
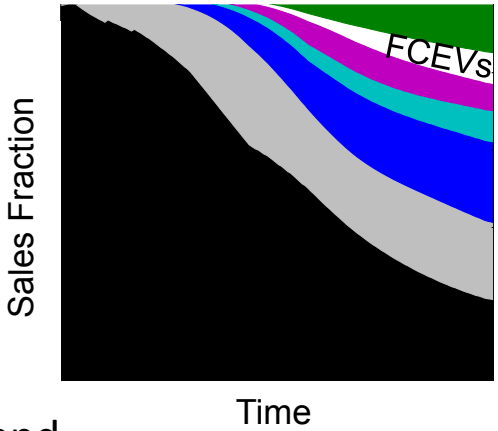
Outline

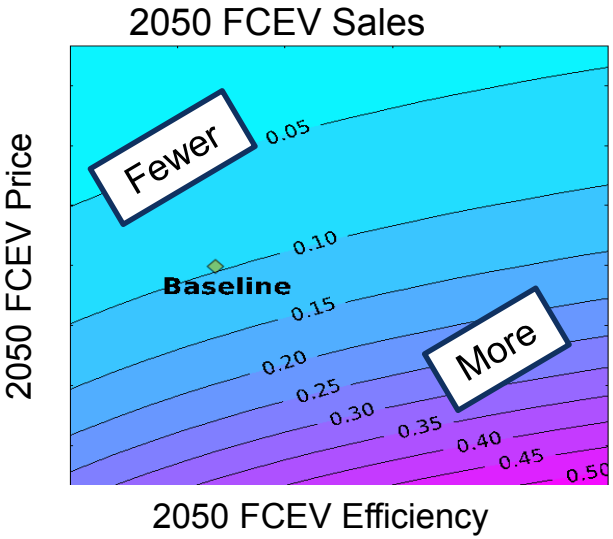
- **Front matter**
  - Overview- context
  - Project relevance & objective



- **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 ways to increase sales and lower GHG emissions with FCEVs



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

Overview

Timeline and Budget

- Start date: FY15 Q1
- End date: Project continuation determined annually
- FY16 project budget $100k
- FY16 DOE funds spent*: $62k

*as of 3/31/2016

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
- ANL, ORNL, NREL, LBNL, Energetics
  - Biweekly lab and analysis calls hosted by VTO to discuss timely updates including model comparison work led by Tom Stephens (ANL).

Overview- How ParaChoice fits into DOE analysis framework

Analysis of FCEV fleet penetration and fuel use through 2050

Analysis Framework
- Energy prices from AEO 2015
- Fleet segmentation from NHTS
- Technology price projections from Autonomie
- Fuel and vehicle emissions from GREET
- H_2 prices and pathways from Macro-System Model (aggregates H_2A, HDSam, & more)
- 2010-2015 fueling stations from AFDC

Models & Tools
- Sandia Pathways ParaChoice Model

Validated model (barrier B). Paper accepted SAE. Cross funded by VTO.

In tandem with analyses for VTO

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

Sub-programs
DOE Offices
Internal &
External Reviews

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

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- *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

- *Recap- Pre-April 2015*: Added FCEVs & H_2 production pathways to ParaChoice, conducted preliminary analyses
- *April 2015-April 2016 FTCO funded goal*: Analysis of drivers & impacts of FCEVs in the LDV stock using FY15 added model capability
  - Business as usual scenario analysis for FCEVs including analysis of
    - Competition for FCEVs
    - H_2 production pathways, costs & emissions
  - Scenarios promoting low carbon production of H_2 & impact on FCEVs
  - Parametric analysis of
    - Oil and natural gas futures
    - Future BEV and FCEV costs
    - Costs for clean H_2
    - FCEV incentives
  - Sensitivity analysis to understand primary drivers of FCEV adoption
  - Analysis of FCEV market competition in scenarios without CNG
  - Parametric analysis of FCEV cost and efficiency

Addresses barrier A

Follow up on 2015 AMR preliminary results

Submitted for publication to Energy Policy

Addresses barrier C

New FY16 Analyses

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

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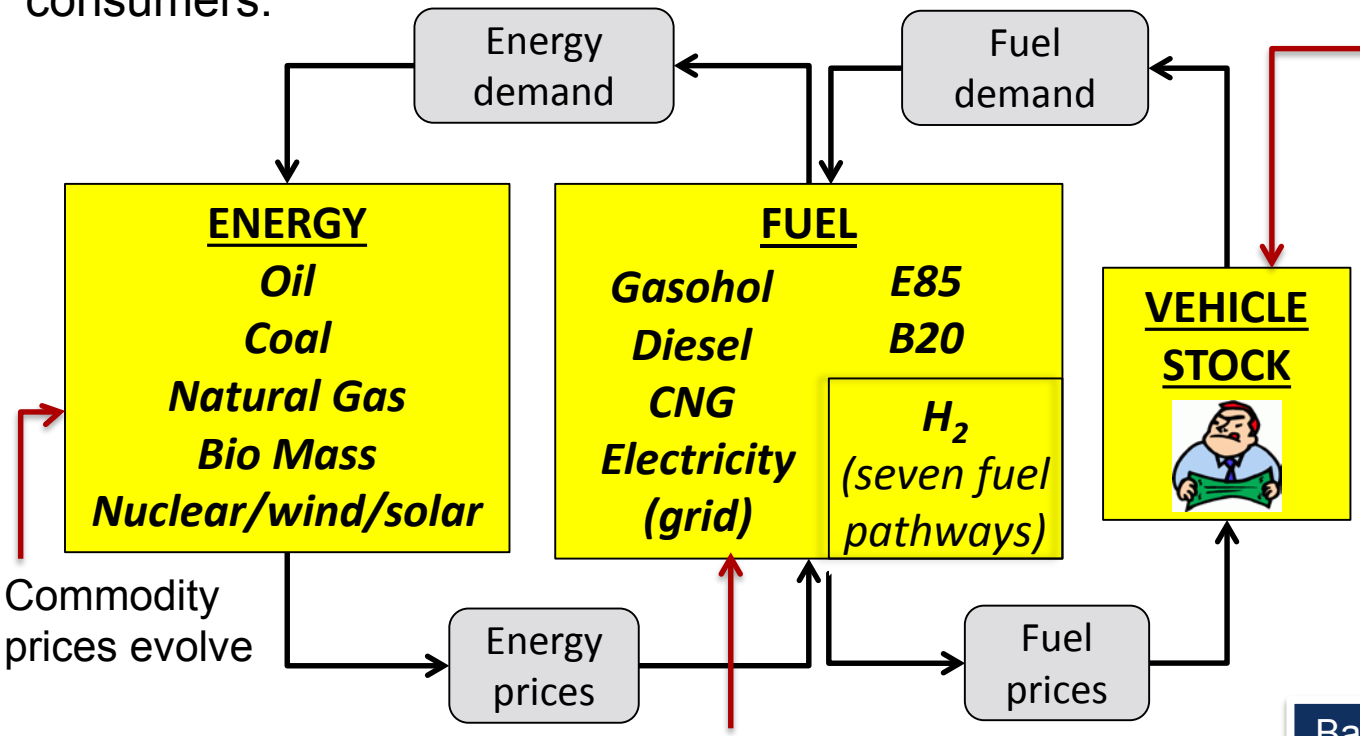
Marches forward from present, when energy, fuel, and vehicle stock states known, to 2050. At each time step, vehicles compete for share in the stock based on value to consumers.



Vehicle costs & efficiencies, infrastructure, stock, and stock emissions vary in time

Red values are endogenously simulated

Commodity prices evolve

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 2015
- H_2 prices and pathways: MSM
- Emissions: GREET
- Fleet segmentation: NHTS
- Vehicle price projections: Autonomie
- 2010-2015 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	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)*

Approach: Seven H_2 production pathways modeled. Availability & pricing scales with demand. Pathways utilized determined endogenously based on economics.

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Uniqueness: from other DOE vehicle models

FUEL

H_2 production pathways in ParaChoice model

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

Simplified model logic for pathway selection (see technical backup or 2015 AMR for detailed logic)

At beginning of simulation

- No pre-existing dedicated H_2 production capacity
- Stations use industrial H_2 at lowest volume pricing (Hydrogen and Fuel Cells US Market Report, 2010; current CA H_2 pricing)

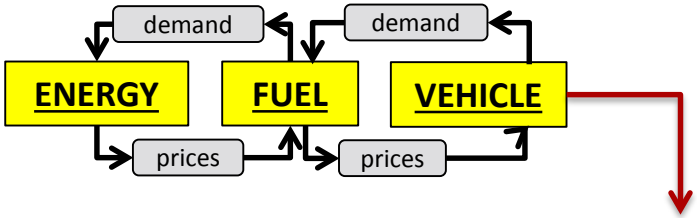
As demand increases due to new FCEV sales in each state, most economical solution selected to meet unmet demand

- Industrial H_2 trucked to stations - chosen at very low demand
- Dedicated distributed production at refueling station
  - Prices are scaled up when usage < capacity
- Dedicated central production
  - Only an option if unmet demand > central production capacity

Production pathways can be influenced by

- Renewable mandates
- Carbon taxes
- Parametric multipliers on costs

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



Geography

Vehicle

Demographics

Understand evolution of H_2 production by region

FY15/16: Parametric analysis of competition between different AEVs for different technology cost futures

Follow up analysis: penetration in different market niches

Understand impact of fueling infrastructure

Vehicle Stock Segmentation

Powertrain

SI
SI Hybrid
SI PHEV10
SI PHEV40
CI
CI Hybrid
CI PHEV10
CI PHEV40

FCEV

E85 FFV
E85 FFV Hybrid
E85 FFV PHEV10
E85 FFV PHEV40
BEV75
BEV100
BEV150
BEV225
CNG
CNG Hybrid
CNG Bi-fuel

Housing type

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

VMT Segmentation

Energy/Fuel Seg.

State

48 CONUS + Washington, DC

Density

Urban
Suburban
Rural

Size

Compact
Midsize
Small SUV
Large SUV
Pickup

Age

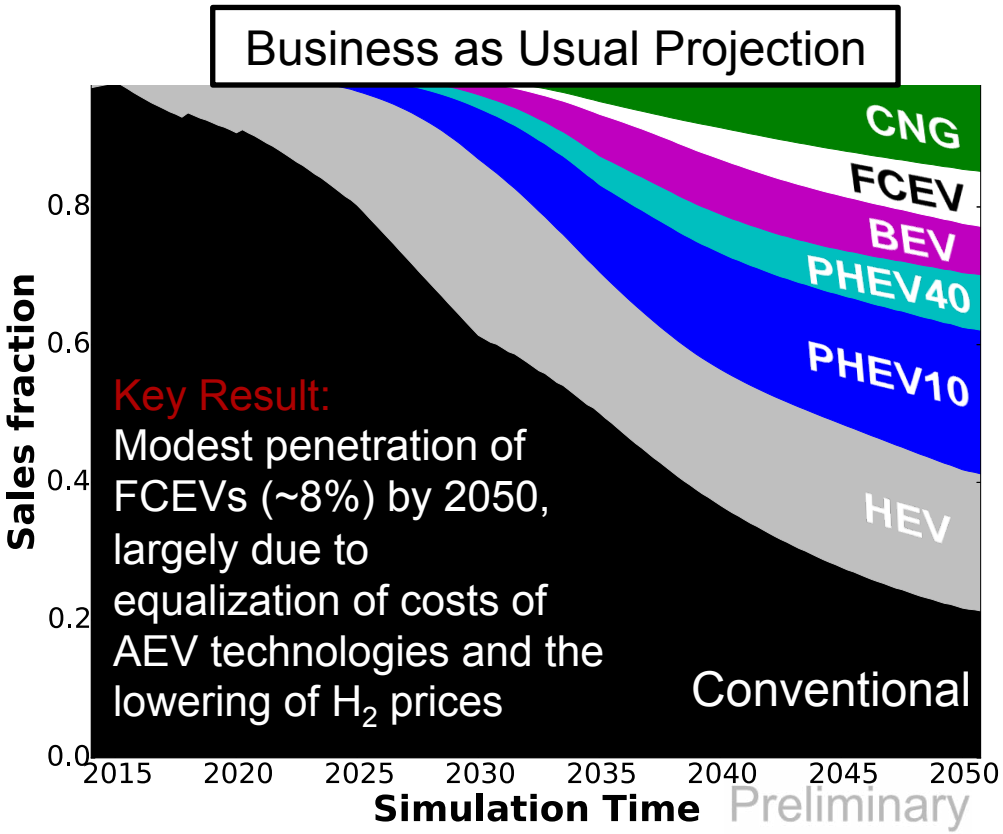
0-46 years

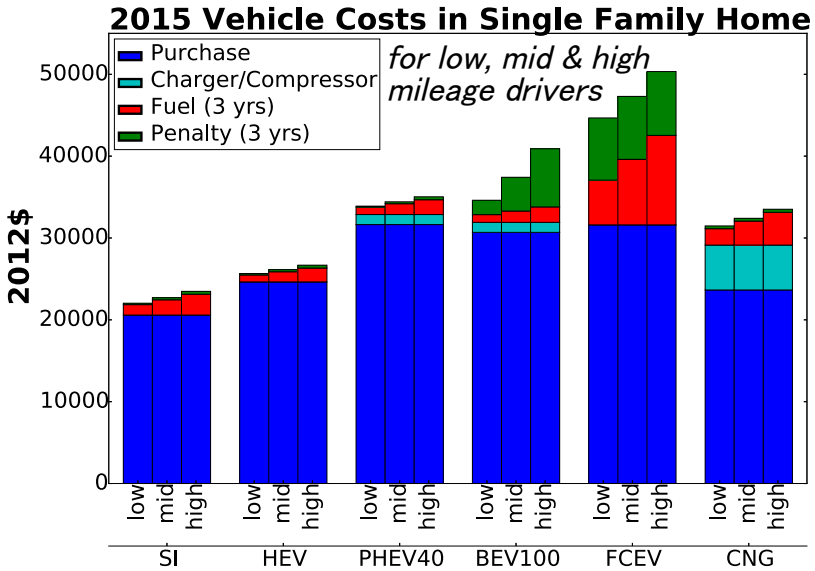
Driver Intensity

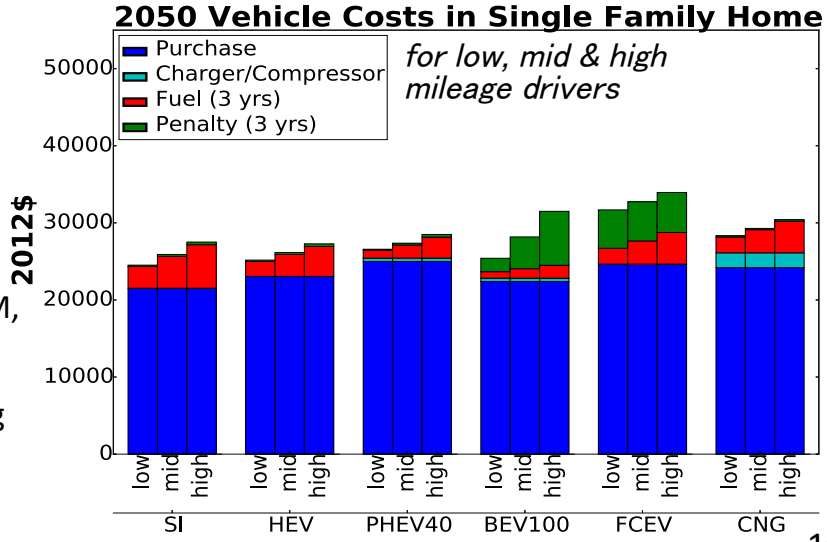
High
Medium
Low

Can use to tease out market niches

Accomplishments & Progress 1: Baseline scenario analyses contributing to "Fuel Cell Electric Vehicles: Drivers and impacts of Adoption"







Data Sources

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

- Purchase (c&p): *Autonomie* 2015
- Compressor (c): CNG California (2012)
- Penalties: adapted, Greene (2001)
- Efficiencies (c&p): *Autonomie* 2015
- Gasohol & CNG fuel (c): AEO 2015
- Electricity (c): EIA 2015
- 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 2015
- Zero Carbon & Biomass energy (c&p): multiple sources

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

A&P 1: Evolution of H_2 costs and production pathways with FCEV demand in baseline scenario.

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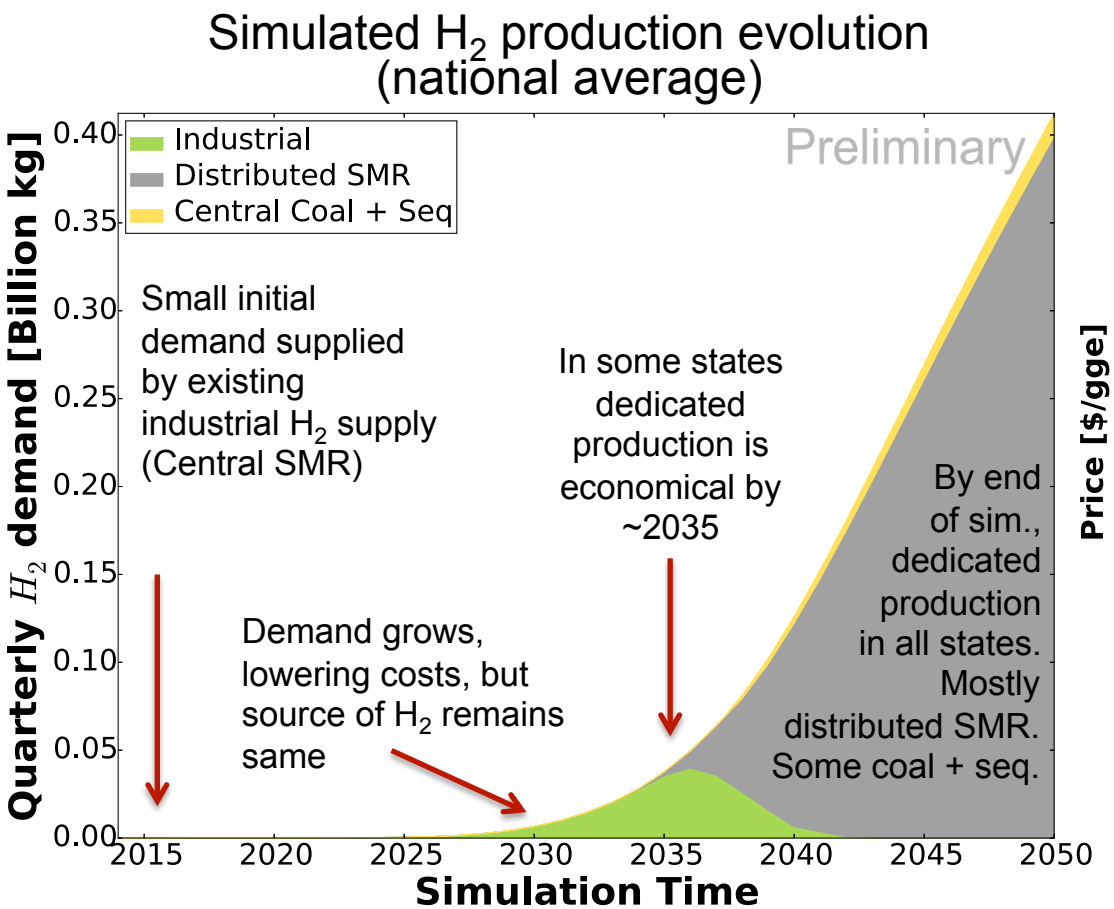
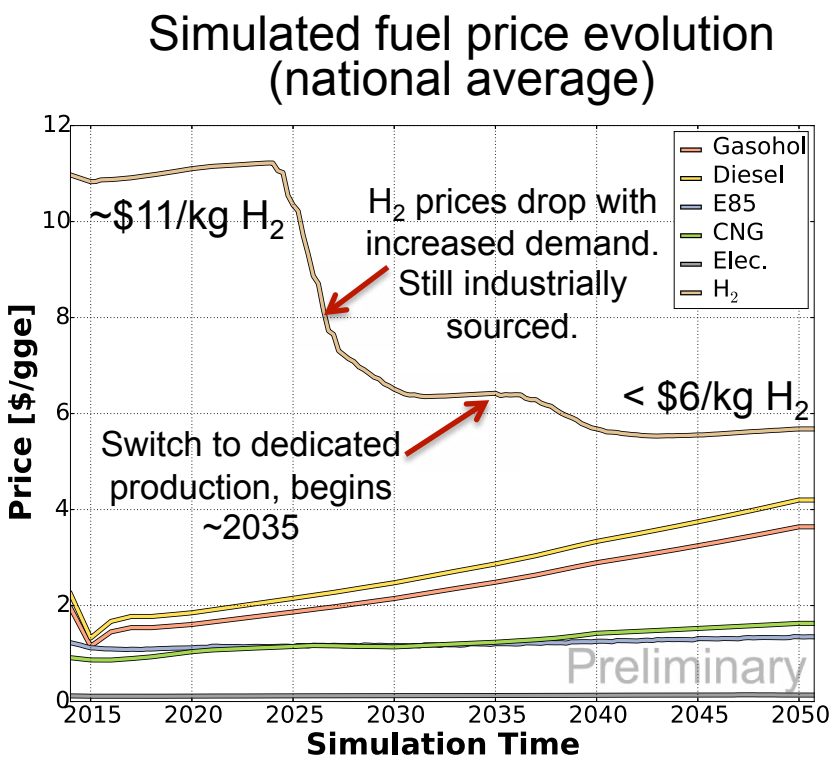
Key Result: Prevalence of distributed SMR H_2 makes FCEVs a GHG neutral addition to the stock.





Confirmation of preliminary finding presented in 2015 AMR, included in "Fuel Cell Electric Vehicles: Drivers and Impacts of Adoption". We additionally explore carbon tax and low cost clean energy electrolysis scenarios, finding them to be effective ways to lower fleet GHG emissions using FCEVs

A&P 1: Key result: FCEVs displace a CNGs disproportionally to other AEVs

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% 2050 sales in scenarios with:

Power-train	**No FCEVs**	**With FCEVs**	*% Change*
Conv.	23.0	21.5	-6.2
HEVs	21.4	20.0	-6.6
PHEVs	30.8	28.8	-6.5
BEVs	7.6	7.1	-6.2
FCEV	0.0	7.9	
CNGs	17.3	14.7	**-15.1**

Roughly equal % changes

outlier

2050 fleet average kg CO_2 equiv. /mi:
No FCEVs: 0.28, With FCEVs: 0.28

Follow up analysis FY16: 'What is FCEV market competition if CNGs aren't part of the vehicle mix? Would the impact of FCEVs on GHG emissions be greater?'

% 2050 sales in scenarios with **No CNGs** and:

Power-train	**No FCEVs**	**With FCEVs**	*% Change*
Conv.	28.4	25.8	-9.3
HEVs	25.9	23.4	-9.7
PHEVs	37.1	33.5	-9.8
BEVs	8.6	7.8	-9.0
FCEV	0.0	9.6	

2050 fleet average kg CO_2 equiv. /mi:
No FCEVs: 0.28, With FCEVs: 0.28

Key result: In absence of competition from CNGs, FCEVs compete fairly equally with all of the other powertrains, though perhaps least so with BEVs. FCEV impact on fleet wide 2050 emissions remains neutral. (new FY16)

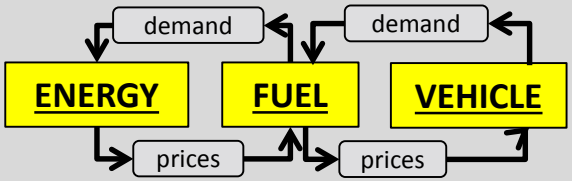
Preliminary

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

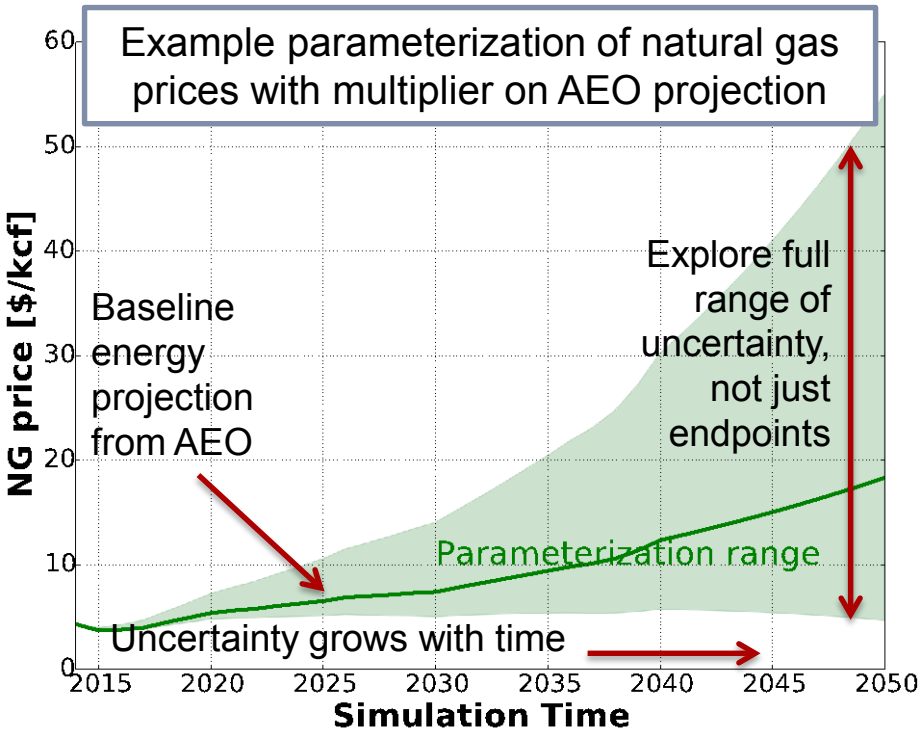
Addresses barrier C

***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.

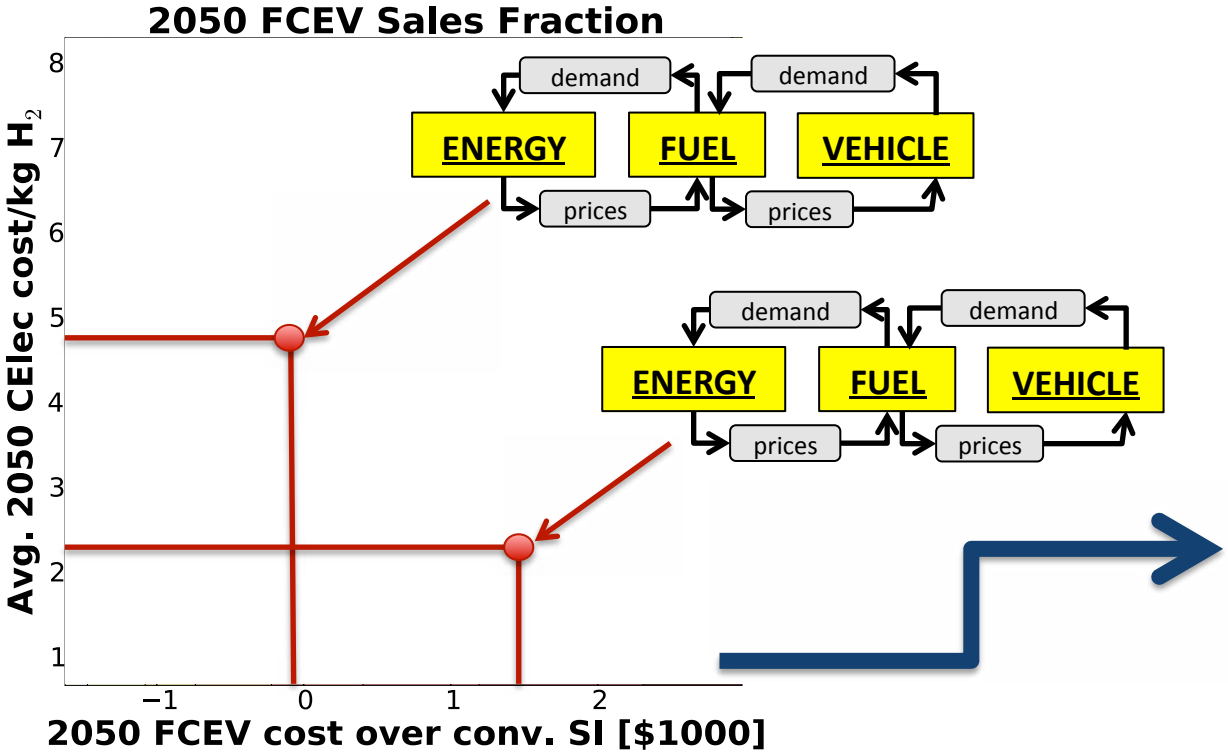


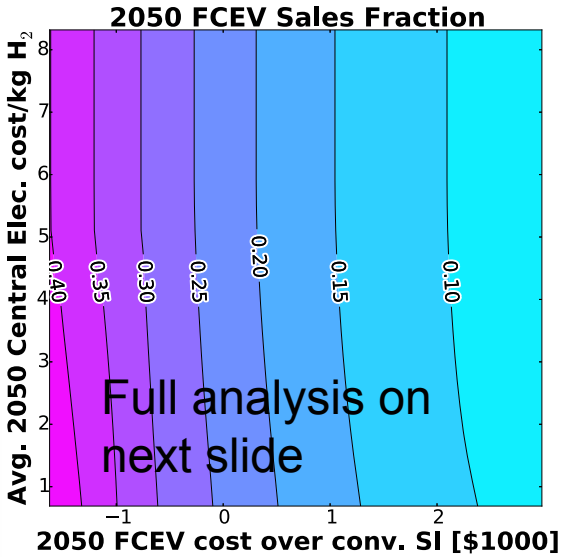
- Simulation is run 1000s of times with varying inputs. This parametric analysis provides:
  - Perspectives in uncertain energy & technology futures
  - Sensitivities and tradeoffs between technology investments, market incentives, and modeling uncertainty
  - The set of conditions that must be true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



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

Approach: Parameterization to explore drivers and impacts of FCEV adoption & H_2 production





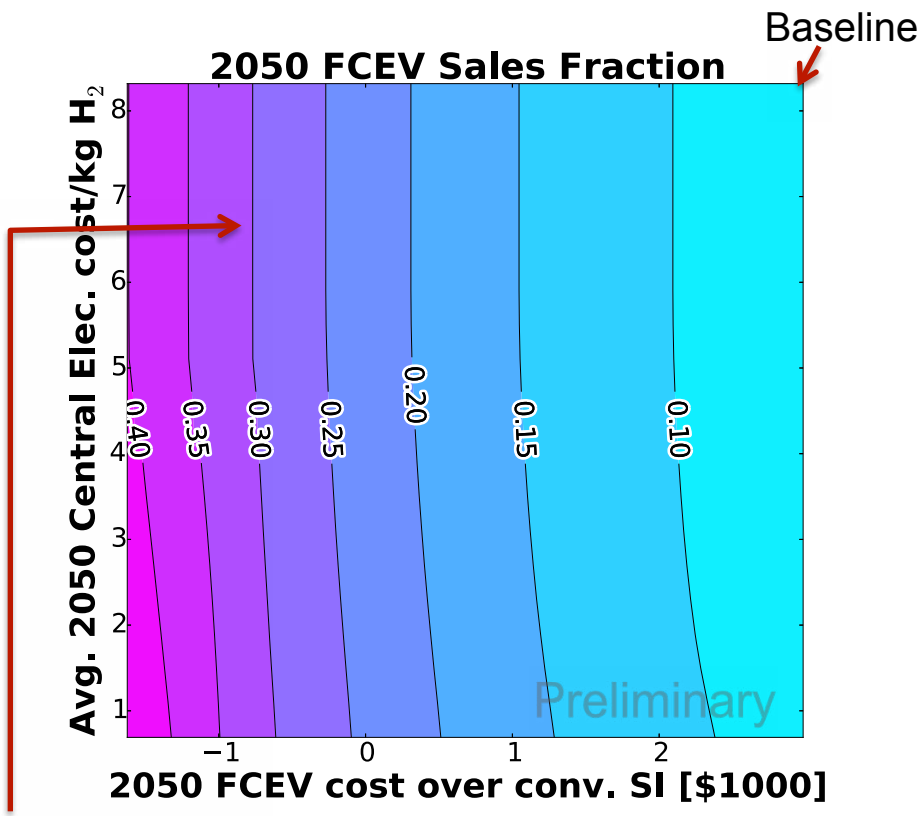
Select parameterized variables relevant to FCEV and H_2

- Multiplier on projected vehicle tech. costs:
  - Battery
  - Fuel cell
  - Other
- Multiplier on projected vehicle efficiencies:
  - BEV
  - FCEV (new FY16)
  - Combustion engine
- Multiplier on projected energy prices:
  - Oil
  - Coal
  - Natural Gas
  - Wind/Nuclear/Solar
  - Biomass
- Multiplier on non-feedstock costs for each H_2 production pathway
- H_2 industrial low volume delivery price markups
- H2 renewable mandate goal
  - Renewable fraction
  - Year achieved
- FCEV federal incentive
  - Purchase discount
  - End year
- Station growth rate (scales with vehicle sales)
- Consumer choice logit exponent
- Vehicle payback period
- Penalty multiplier
- Carbon Price

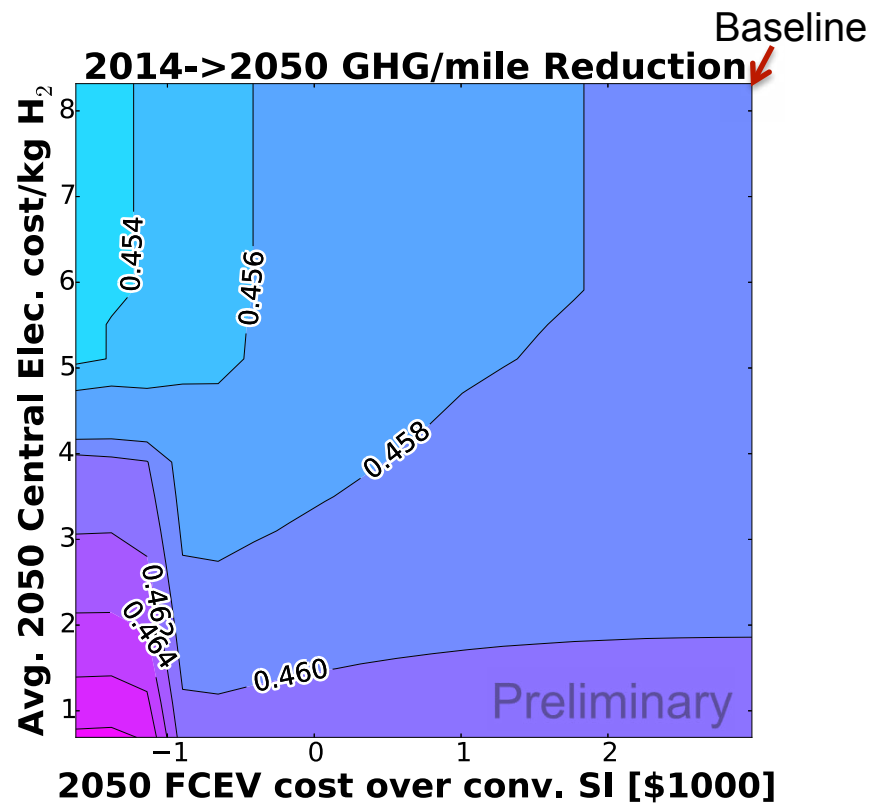
Accomplishments and Progress (A&P) 2: Parametric analyses of clean electrolysis and FCEV sale price contributing to "Fuel Cell Electric Vehicles: Drivers and Impacts of Adoption"

Key results:

Vehicle costs have substantially greater impact on FCEV sales than clean hydrogen costs. FCEV costs alone cannot affect cleaner H_2 production and thus lower GHG emissions.



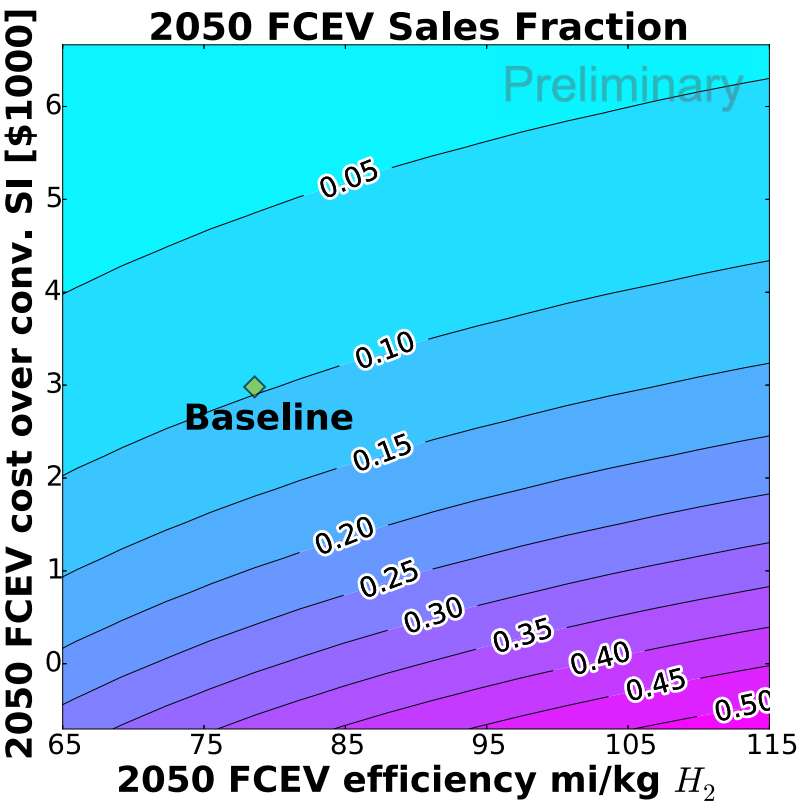
Lower price clean electrolysis has limited impact on FCEV sales and emissions until it is cheaper than other H_2 production technologies (~$6 /kg)

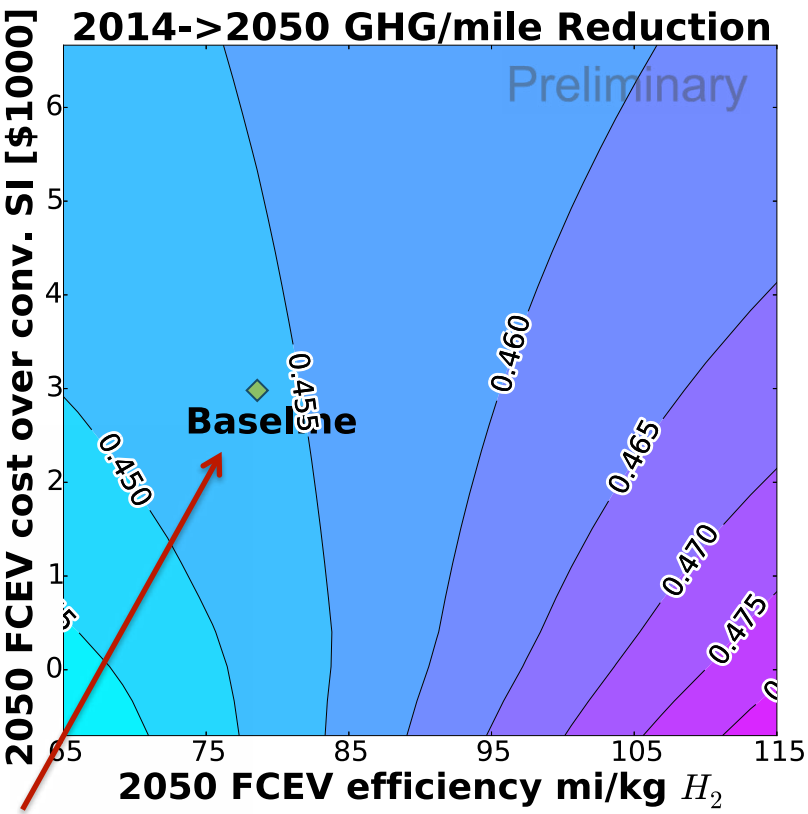


GHG reductions can be achieved with low cost electrolysis alone, but the greatest reductions are seen with in tandem with steep FCEV price cuts

A&P 2: Parametric analysis of efficiency and cost (new FY16)

Key Result: FCEV efficiency gains can motivate sales & improve emissions.





Baseline efficiencies show neutral to detrimental impact of low cost FCEVs on GHG emissions

Key results:

Largest impacts on FCEV sales & fleet average emissions if costs go down as efficiency goes up. But, if efficiency gains necessitate FCEV price increases, fleet average emissions will still improve.

Cross program funded accomplishments & progress: Model validation, inter-lab collaboration, & presentations

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- Conducted model logic validation study. Submitted for publication to *SAE*. "History v. Simulation: An analysis of the drivers of alternative energy vehicle sales". Conclusions relevant to FCEV:
  - The simulation logic is sound, capturing the key elements of consumer response to oil prices and model availability changes, as well as the other underlying drivers that affect AEV sales fractions.
  - Consumer choice is very sensitive to vehicle model availability. Fluctuations in model availability for different AEVs will drive significant changes in sales, possibly reinforcing or potentially countering the effects of oil price shifts or other consumer choice drivers.
  - Consumers are aware of federal and state incentives, and factor these incentives into their purchasing decisions.

Addresses barrier D

- Collaboration on BaSce, a cross-lab model comparison for baseline & DOE program success scenario cases, led by Tom Stephens (ANL)
- Bi-weekly analysis calls with other labs, led by Jake Ward (VTO)

Keeping apprised of current data sets and best modeling practices. Addresses barrier C

- Presentation at UC Davis STEPS Lookback Modeling Workshop December 9, 2015: "Lookback: Sandia ParaChoice Model"
- Invited Talk at Stanford Sustainable Mobility Seminar Series, February 5, 2016 "Vehicle choice modeling with ParaChoice: parameterization and validation"

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 other conference engagements
- The underlying ParaChoice model has been developed using funding from a variety of sources including
  - Sandia Laboratory Directed Research & Development Funds
  - Clean Energy Research Consortium
  - Vehicle Technologies Office
- This work is complemented by modeling and analysis for the VTO. Rebecca Levinson will be presenting poster on VTO-funded ParaChoice analysis (project ID VAN019) Wednesday June 8 at 12:30PM

Proposed Future Work

- Continued analysis of market competition for FCEVs including
  - Deeper dive into market niches for FCEVs in baseline scenario
    - Driver intensity (VMT)
    - Urban/suburban/rural
    - Vehicle class sizes
    - Other?
  - Continued deeper dive into market competition when technology prices change
    - Why does there appear to be less competition with BEVs than with other AEVs?
- Confirm preliminary parametric analyses of FCEV efficiency
- Parametric analysis of H_2 refueling station growth

Milestones:

Draft journal article for peer review by end of FY16 Q4

Review with FCTO and submit for publication by end of FY17 Q1

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:
  - Lowering FCEV purchase costs increases sales, but does not reduce fleet average GHG emissions
  - Lowering clean H_2 production costs has only a modest effect on sales, but can reduce emissions, either alone, or in tandem with lower FCEV purchase costs
  - FCEV efficiency improvements both improve FCEV sales and fleet average GHG emissions. If efficiency gains necessitate FCEV price increases, fleet average emissions still improve.
  - Renewable mandates decrease FCEV sales, but improve fleet average emissions
- Future work will confirm and expand upon present analysis of FCEV fuel & infrastructure dynamics, market competition, and impacts, resulting in journal article publication

Technical Backup Slides (4)

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

- 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		Distributed SMR	Central SMR	Distributed Electrolysis	Central Electrolysis	Central Coal + Seq.	Central SMR + Seq.
Pump price*		$5.09	$5.72	$7.32	$8.31	$5.71	$5.97
kg GHG/ mi	2050 (low^)	0.21	0.19	variable	0.03	0.09	0.11
	2050 (high^)	0.15	0.14	variable	0.02	0.07	0.08

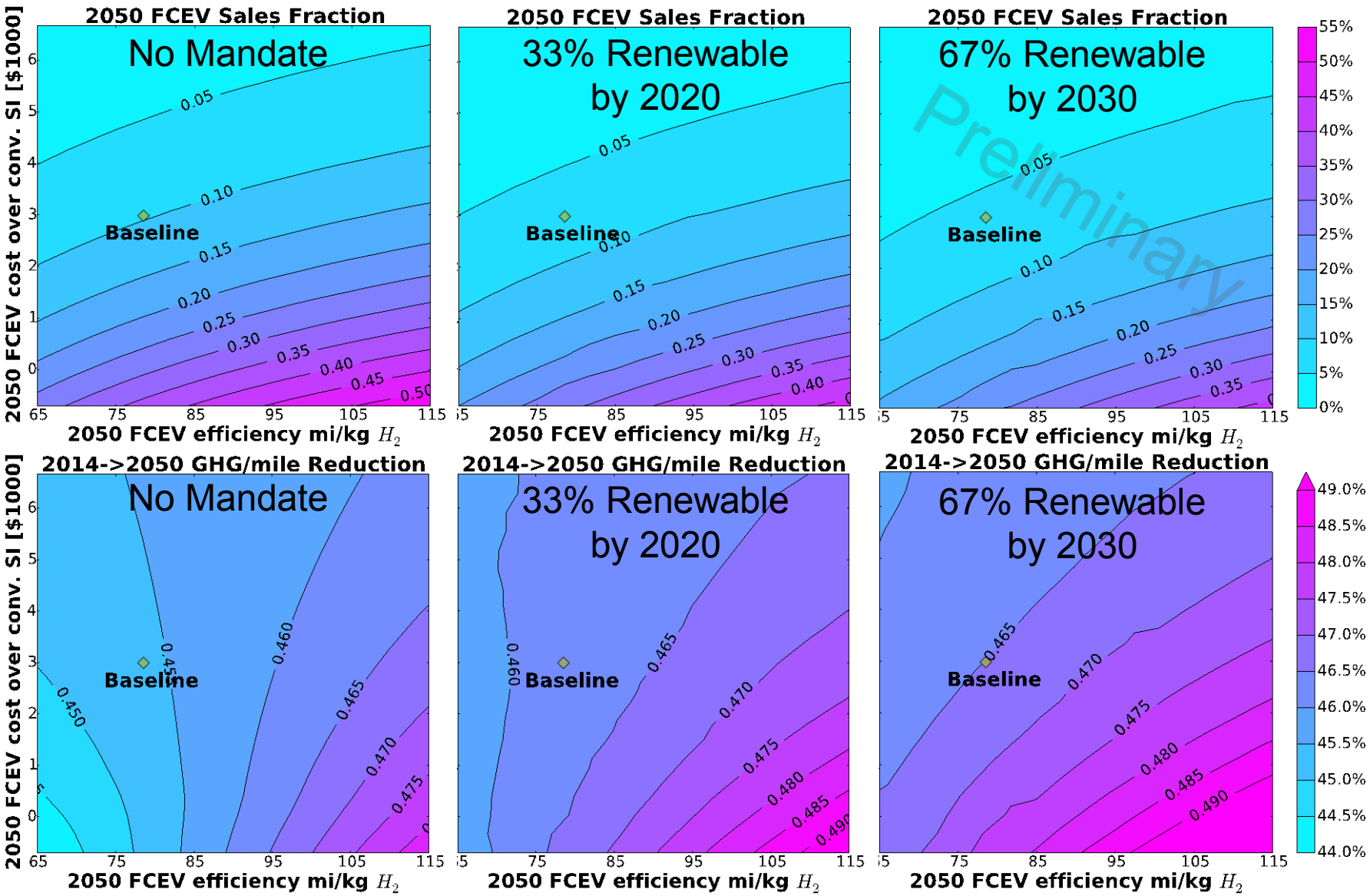
*National avg. pump fuel prices (2012$) for present day commodity prices and full scale production.
^Reflecting *Autonomie* low uncertainty, low program success and high uncertainty, high success vehicle efficiencies

Example sensitivity analysis from "Fuel Cell Electric Vehicles: Drivers and Impacts of Adoption"

Table 7: Baseline, minimum, and maximum values for sensitivity analysis parameters. Also shown are Spearman rank correlation coefficients for outputs (columns) with respect to inputs (rows). Output metrics are measured at simulation end, 2050.

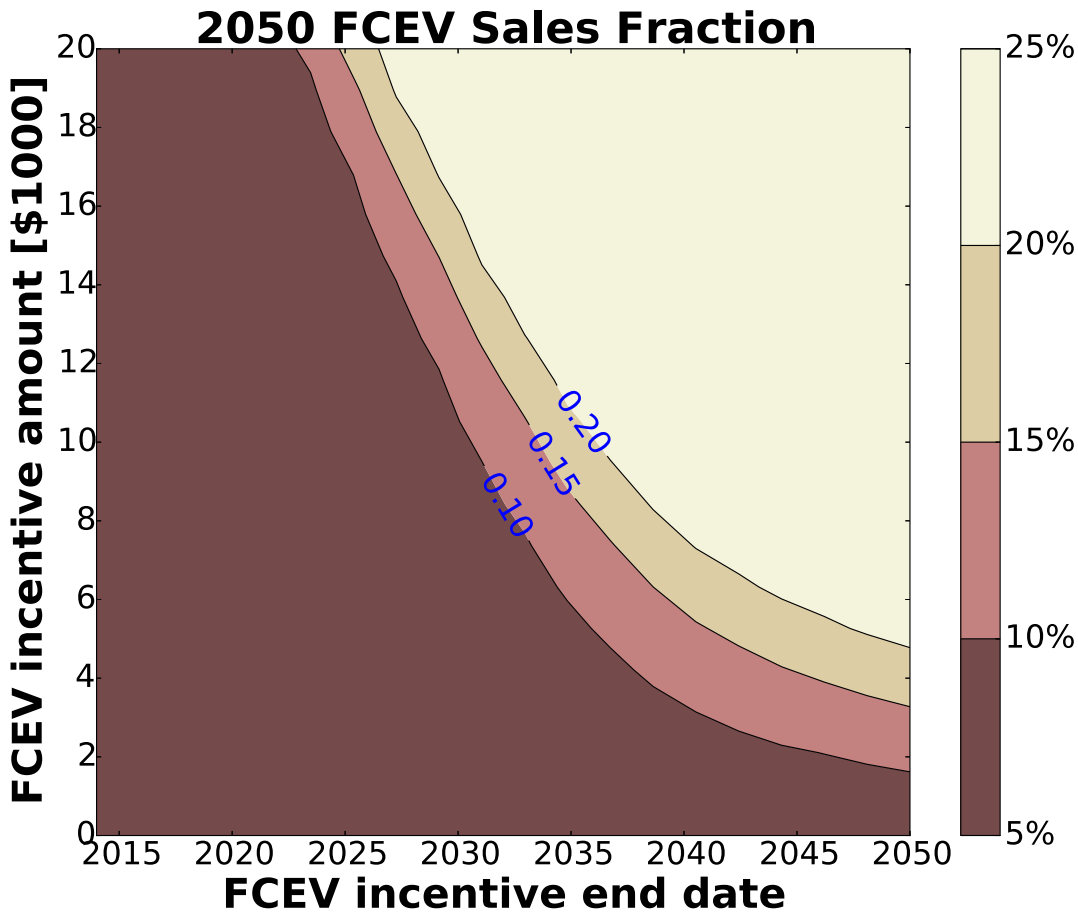
Parameter	Baseline	Min	Max	2050 fleet response FCEV	BEV	ICE
Choice functions						
Vehicle choice logit exponent	[9,12,15]	[6,8,10]	[12,16,20]	-0.35	0.16	-0.14
Fuel choice logit exponent	18	6	20	0.02	-0.03	0.03
Consumer attitudes						
Consumer payback period (years)	3	2	11	-0.18	0.34	-0.36
Penalty mult	1	0	1.5	-0.12	-0.25	0.24
Charging station ratio for 1/2 of pop. to consider public charging	0.1	0.01	0.2	0.13	-0.29	0.14
Bi-fuel usage at \$0.10/gge premium	0.395	0.3	0.49	0.03	0.04	-0.08
Policy						
Carbon price (\$/MT CO_2-equiv)	0	0	500	-0.05	0.41	-0.31
Start year of state mandated H_2 station growth	2015	2015	2040	-0.04	0.03	-0.02
Commodity prices						
Oil price mult	1	0.25	3	0.16	0.18	-0.29
NG price mult	1	0.25	3	-0.14	0.04	0.08
Zero-carbon energy price mult	1	0.25	3	-0.14	-0.02	0.05
Biomass energy price mult	1	0.25	3	-0.04	0.02	-0.03
Coal price mult	1	0.25	3	0.00	0.00	0.01
Vehicle technology						
ICE powertrain eff mult	1	0.6	3	-0.43	-0.41	0.50
Fuel cell cost mult	1	0	2	-0.31	0.03	0.07
ICE vehicle cost mult	1	0.9	1.5	0.30	0.27	-0.22
Battery cost mult	1	0	2	0.20	-0.23	0.10
H_2 technology						
DElec non-feed cost mult	1	0	1	-0.21	0.05	-0.01
DSMR non-feed cost mult	1	0	1	-0.08	0.05	-0.01
CElec non-feed cost mult	1	0.25	3	-0.02	-0.01	0.00
CSMR non-feed cost mult	1	0	1	-0.01	0.01	-0.01
Low demand H_2 price markup mult	0.3	0.01	0.6	-0.02	-0.01	0.02
Other						
Vehicle sales rate (%)	6.7	5	9	0.12	0.12	-0.38
Electricity generator lifespan (years)	40	20	60	-0.09	-0.01	0.02
New stations / 1000 vehicles	0.7	0	1.75	0.00	0.23	-0.16
CNG tech cost reduction rate	0.03	0	0.4	0.00	-0.07	0.04

A&P 2: Parametric analysis of FCEV efficiency & cost given renewable mandates on H_2 production (new FY16)



Key result: Renewable mandates decrease FCEV sales, but improve fleet average emissions

Parametric analysis of incentive impact on FCEV sales



Incentive	Incentive cost billion	FCEVs Sold before 2050 million	inc.	H_2 mileage before 2050 trillion	inc.	2050 H_2 state station frac. range
none		18.6		6.32		0.017 - 0.036
$20k/veh. ends 2025	$289	58.9	217%	24.4	286%	0.047 - 0.140
$9.5k/veh. ends 2035	$236	67.4	262%	28.7	354%	0.057 - 0.151
$4k/veh. ends 2045	$162	58.3	213%	22.0	286%	0.044 - 0.119