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Hydrogen Analysis with the Sandia ParaChoice model

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Overview

Timeline

- Start date: FY15 Q1
- End date: Project continuation determined annually

Partners

- Interactions / Collaborations:
  - Ford: Real World Driving Cycles
  - Toyota
  - American Gas Association
  - DOT
  - ANL, ORNL, NREL, Energetics

Budget

- FY15 funding: $100K

Barriers

- Availability of alternative fuel and charging infrastructure
- Availability of AFVs and electric drive vehicles
- Constant advances in technology
- Uncertainty in vehicle choice models and projections

Project was **not** reviewed in previous Merit Reviews

ParaChoice Relevance/Objective: parametric analysis across factors that influence the vehicle, fuel, & infrastructure mix

- *Objective*: ParaChoice captures **changes to the Light Duty Vehicle (LDV) stock through 2050** and its dynamic, economic relationship to fuels and energy sources

- *Uniqueness*: The model occupies a **system-level analysis layer with input from other DOE models** to explore the uncertainty and trade space (with **10,000s of model runs**) that is not accessible in individual scenario-focused studies

- *Approach*: Model **dynamics and competition** among LDV powertrains and fuels using **regional-level** feedback loops from vehicle use to energy source
  - Technologies allowed to flourish or fail in the marketplace

- *Targets*: By conducting parametric analyses, we can identify:
  - The set of conditions that must be true to reach performance goals
  - Sensitivities and tradeoffs between technology investments, market incentives, and modeling uncertainty

- *Focus for FY15 FCTO funded work*: Add hydrogen production and fuel cell electric vehicles to existing Sandia ParaChoice model to further the FCTO mission
  - Determine how FCEVs compete in the fleet with conventional and other AEVs
  - Determine effects of FCEV and H_2 adoption on petroleum usage and GHG emissions
  - Evaluate H_2 production and consequences for H_2 pricing, FCEV adoption, and GHG emissions

Analysis Project Overview

Analysis of FCEV fleet penetration through 2050 with the Sandia parachoice model

Analysis Framework

- Energy prices from AEO 2014
- Technology prices from Autonomie 2011
- Fleet segmentation from NHTS
- 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

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Studies & Analysis

- Vehicle penetration analysis
- Environmental analysis

In tandem with analyses for VTO

→

Outputs & Deliverables

- Parametric assessments
- Peer-reviewed publications

Sub-programs DOE Offices Internal & External Reviews

Assumptions: from published DOE or other reputable sources where available

Energy sources

- Oil: Global price from EIA Annual Energy Outlook (2014)
- Coal: National price from EIA Annual Energy Outlook (2014)
- NG: Regional price from EIA Annual Energy Outlook (2014)
  - Also use differential prices for industrial, power, and residential uses
- Biomass: State supply curves from ORNL's Billion Ton Study
  - Price corrected to match current feedstock markets

Fuel conversion and distribution

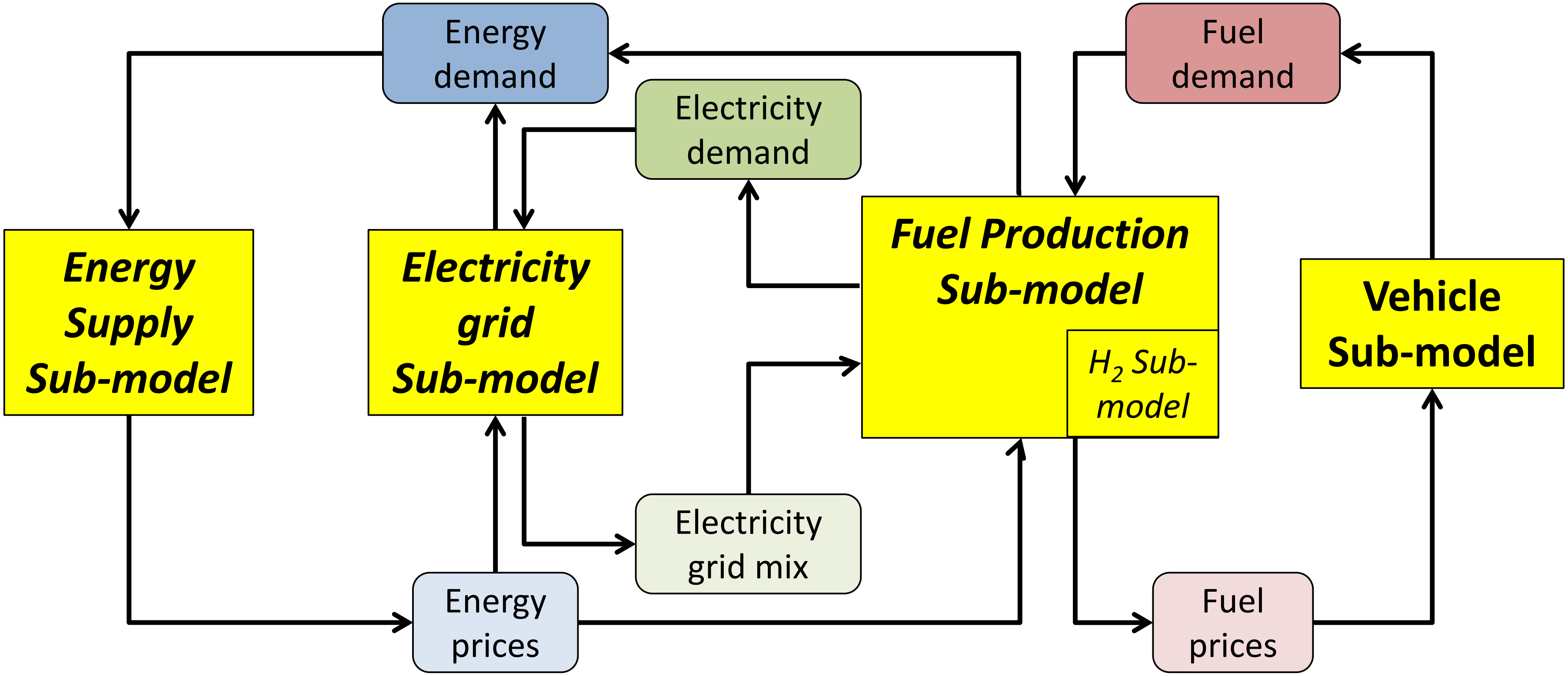
- Conversion costs and GHG emissions derived from ANL GREET model (latest version)
- H_2 production efficiencies, costs, and emissions taken from Macro-System Model which itself incorporates other DOE sources: H_2A, HDSAM, HyDRA, HyPro, GREET
- Electricity grid: EIA, Electric Power Annual (2012)
  - State-based electricity mix, allowed to evolve according to population growth and energy costs
  - EVs and Distributed Electrolysis assumed to be supplied by marginal mix

Vehicle efficiency and price projections

- *Autonomie* 2011

What we don't know, we parameterize.

Modeling Approach: The high-level model diagram depicts the feedback loop of energy supply<-->energy carrier<-->vehicle



Modeling Approach: The model has many segments to capture different niches of LDV consumers

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

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

Geography
Vehicle
Demographics

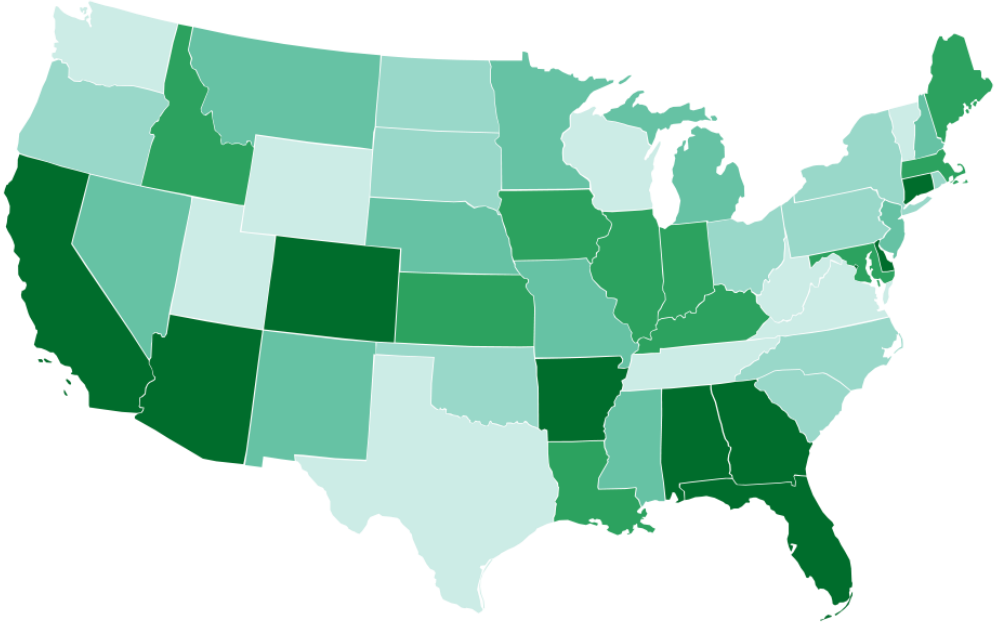
Fuels
Gasoline
Diesel
Biodiesel
Ethanol
Electricity
CNG
Hydrogen

Energy Sources
Petroleum
Natural Gas
Coal
Biomass
Solar/Wind

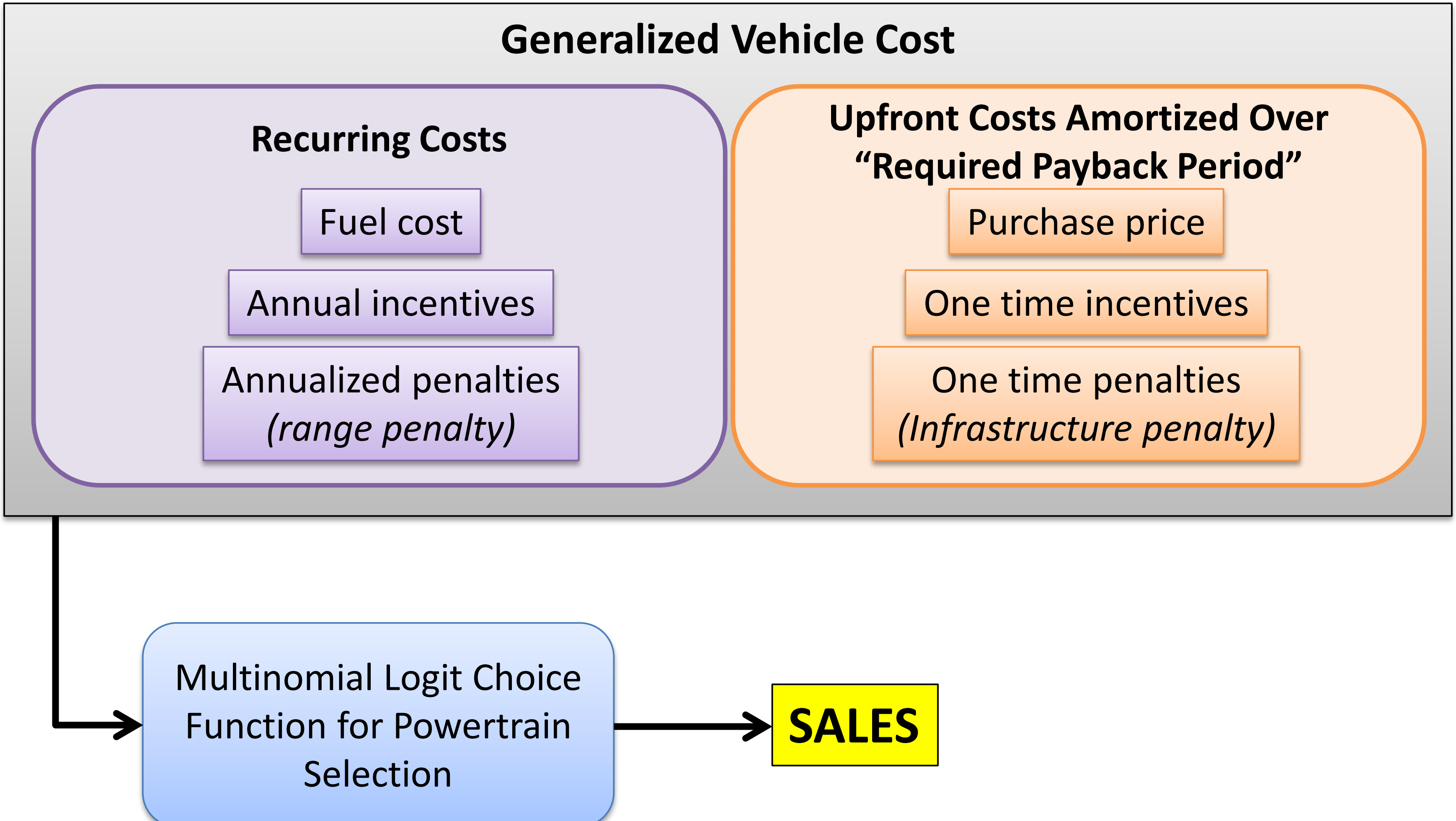
Modeling Approach: Energy supplies, fuels, and vehicle mixes vary by state

State-level Variations

- Vehicles
  - Numbers, sizes, drive-train mixes
- Driver demographics
  - VMT intensity, urban-suburban-rural divisions, single-family home rates
- Fuels
  - Costs, hydrogen production pathways, electricity mix, taxes & fees, alternative fuel infrastructure
- Energy supply curves (as appropriate)
  - Biomass, natural gas
- Policy
  - Consumer subsidies and incentives

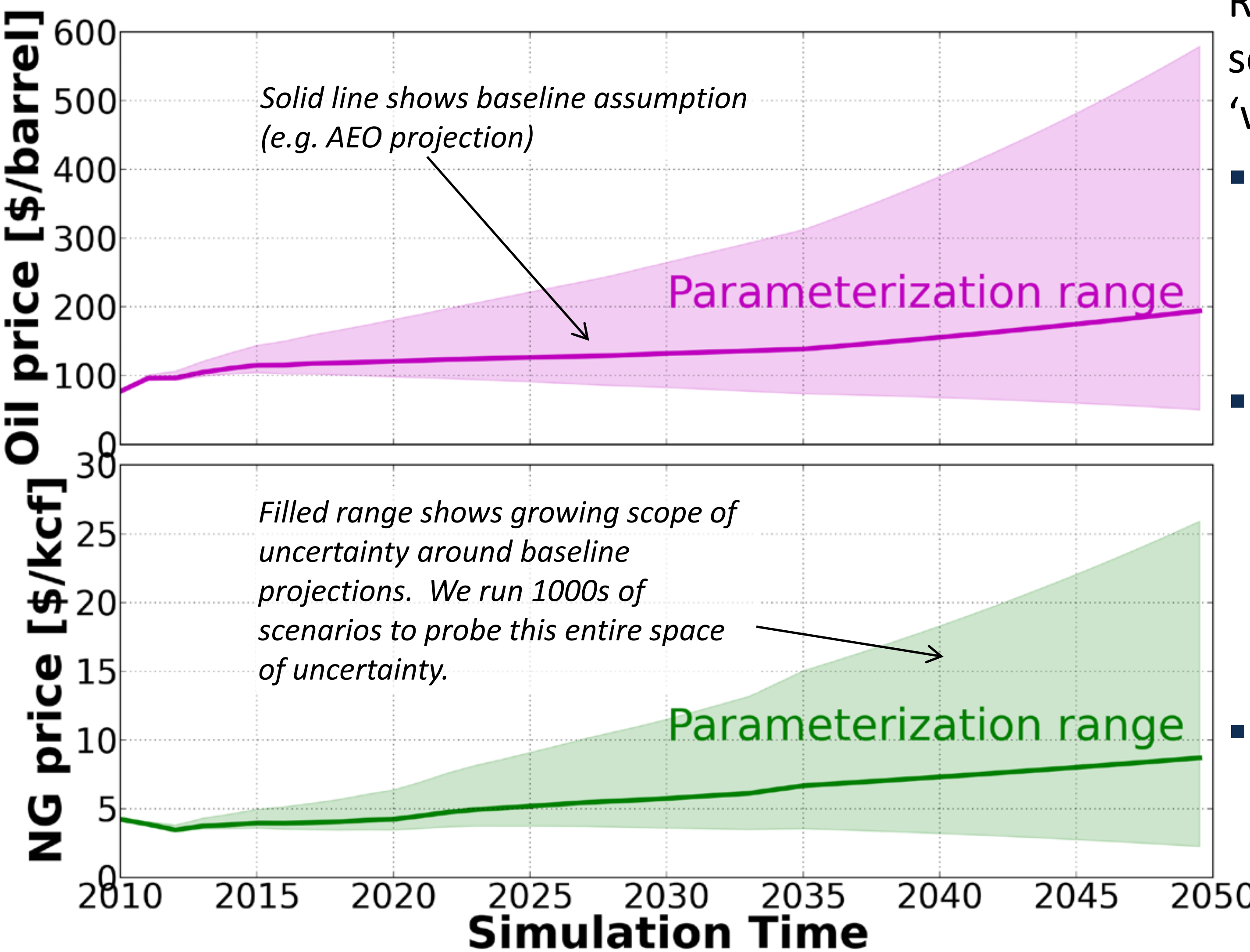


Modeling Approach: A multinomial logit choice function assigns consumer purchase shares based on generalized vehicle cost



FCEV are treated the same as other AEVs

Modeling Approach: Parameterization helps account for uncertainty in commodity prices, technology performance, modeling assumptions, etc.

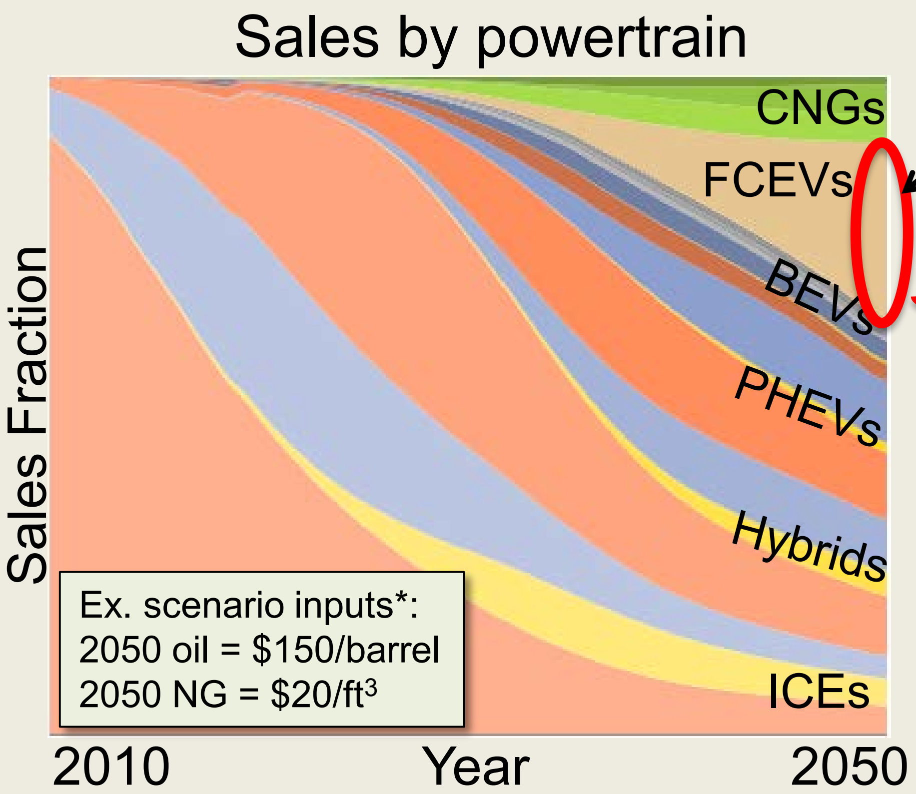


Run 1000s of scenarios to explore 'what if?'

- One baseline set of input variables taken from trusted references
- Then vary input variables to probe scenarios for all probable (and some improbable) model inputs
- 1000s of model results analyzed to test sensitivities of findings to input parameters

Approach: Parametric studies allow us to explore the trade space of uncertain variables by running thousands of scenarios with different input values and comparing the results

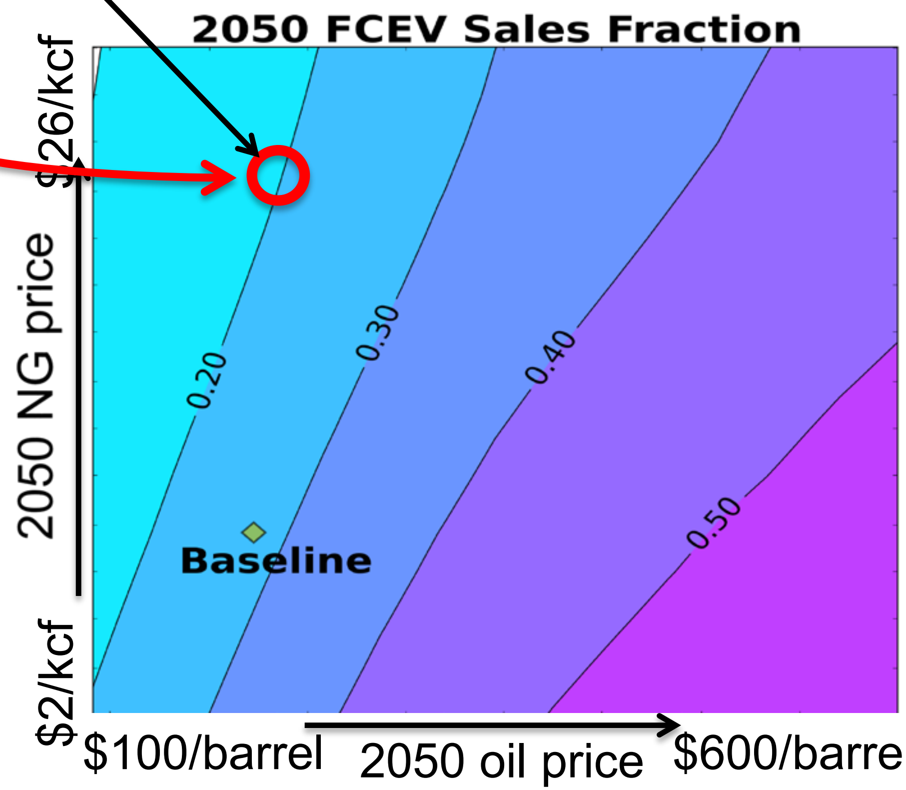
Single scenario projects sales fractions through 2050 for one set of input parameters.



Run model thousands of times, over all plausible scenarios (e.g. many different oil and NG price projections)

Take one output (e.g. FCEV sales fraction) from each scenario and put it on a grid with corresponding input parameters

- *Shows how input assumptions affect results*



Approach: Progress and Milestones

Completed

- Added hydrogen production pathways and refueling to ParaChoice model
  - Industrial
  - Distributed SMR
  - Central SMR
  - Central SMR + sequestration
  - Distributed Electrolysis
  - Central Electrolysis
  - Central Coal + sequestration
- Added FCEVs to vehicle submodel
- Initial verification testing completed, e.g.,
  - Verified that model matches Macro System Model reported costs
  - Compared model outputs to other published or modeled results as appropriate (e.g., GREET)

Ongoing

- Analysis of FCEV adoption, H_2 production pathways, and sensitivity analysis
- ~ 1 month ahead of schedule

Accomplishments and Progress: Summary of H_2 fuel production logic added to the ParaChoice model

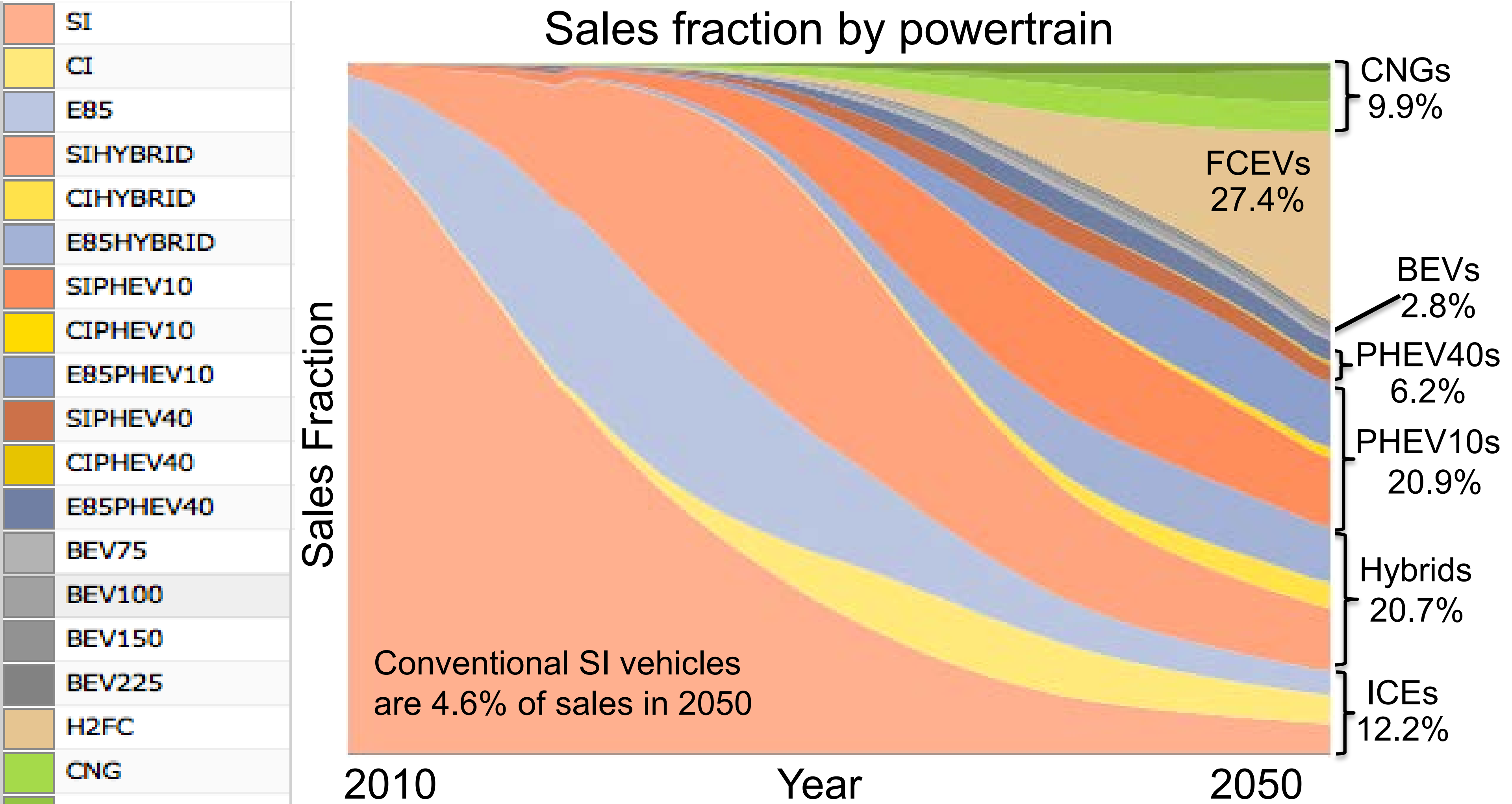
FCEV model introduction in 2015:

- Number of H_2 stations is taken from AFDC (~50 nationally, ~20 in CA)
- 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)
- FCEV technology costs from *Autonomie* 2011

Logic in the ParaChoice model (loop until year = 2050):

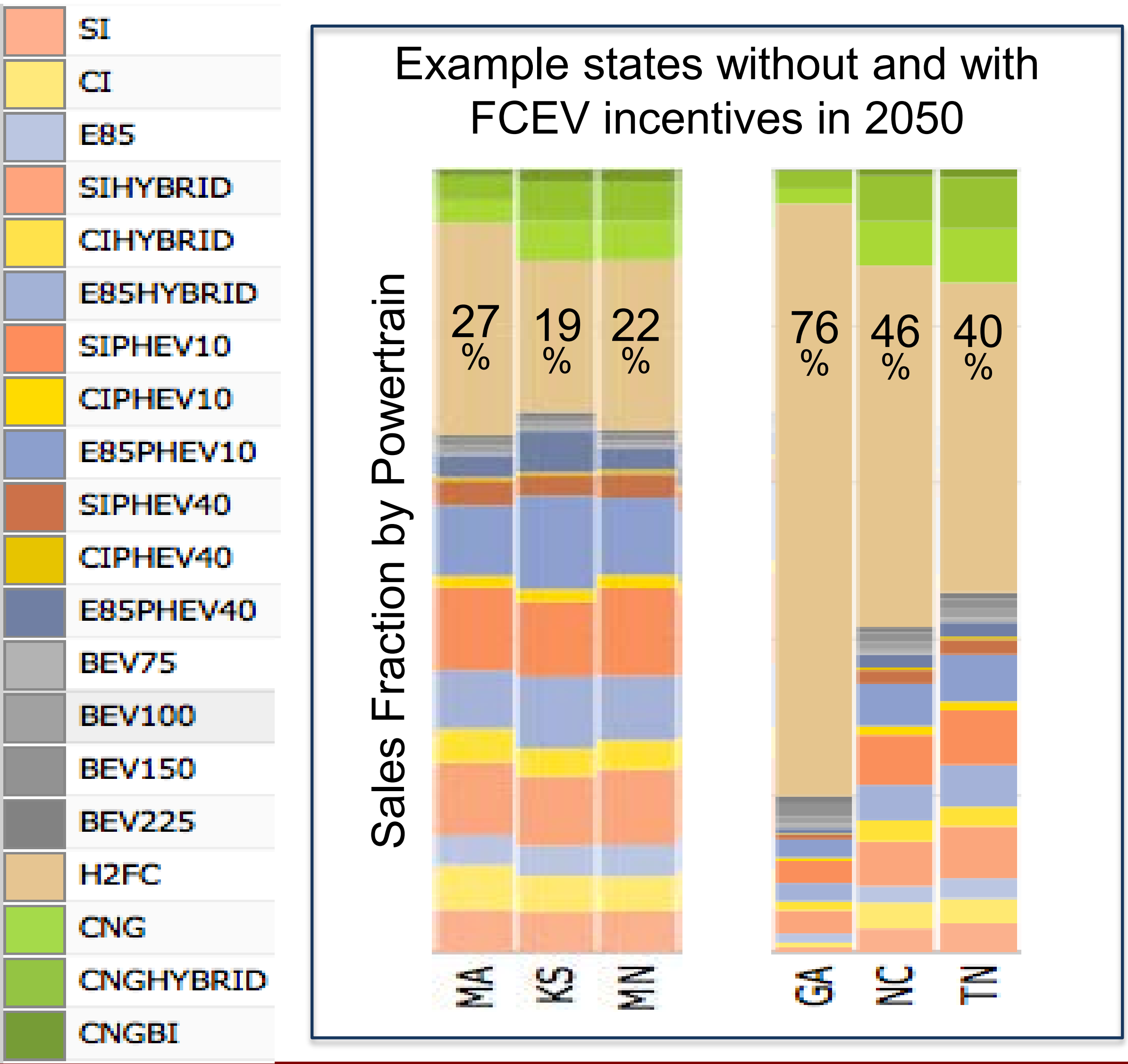
- New H_2 demand determined by FCEV fleet use
- Retire any old production capacity (central > 40 years, distributed > 20 years)
- By state, if H_2 demand > existing production capacity: choose between
  - Industrial H_2- chosen at very low demand
  - Dedicated distributed production at refueling station
    - Production at full scale is 1,500kg/day (H_2A), prices from MSM/ AEO
    - Prices are scaled up when usage < capacity
  - Dedicated central production
    - Production at full scale is 50,000kg/day (H_2A), prices from MSM/ AEO
    - Only an option if unmet demand > 50,000kg/day. No low-volume price scaling.
- New H_2 prices are supplied to vehicle sub-model to compute new FCEV sales
  - Sales also depend on technology costs, penalties, incentives, etc.

Key Results (model outputs): Using baseline input parameters, we find that FCEVs are a significant fraction of fleet sales by 2050.



FCEVs are in competition with all of the powertrains. In a world without FCEVs, ICE vehicle sales are only 4% greater.

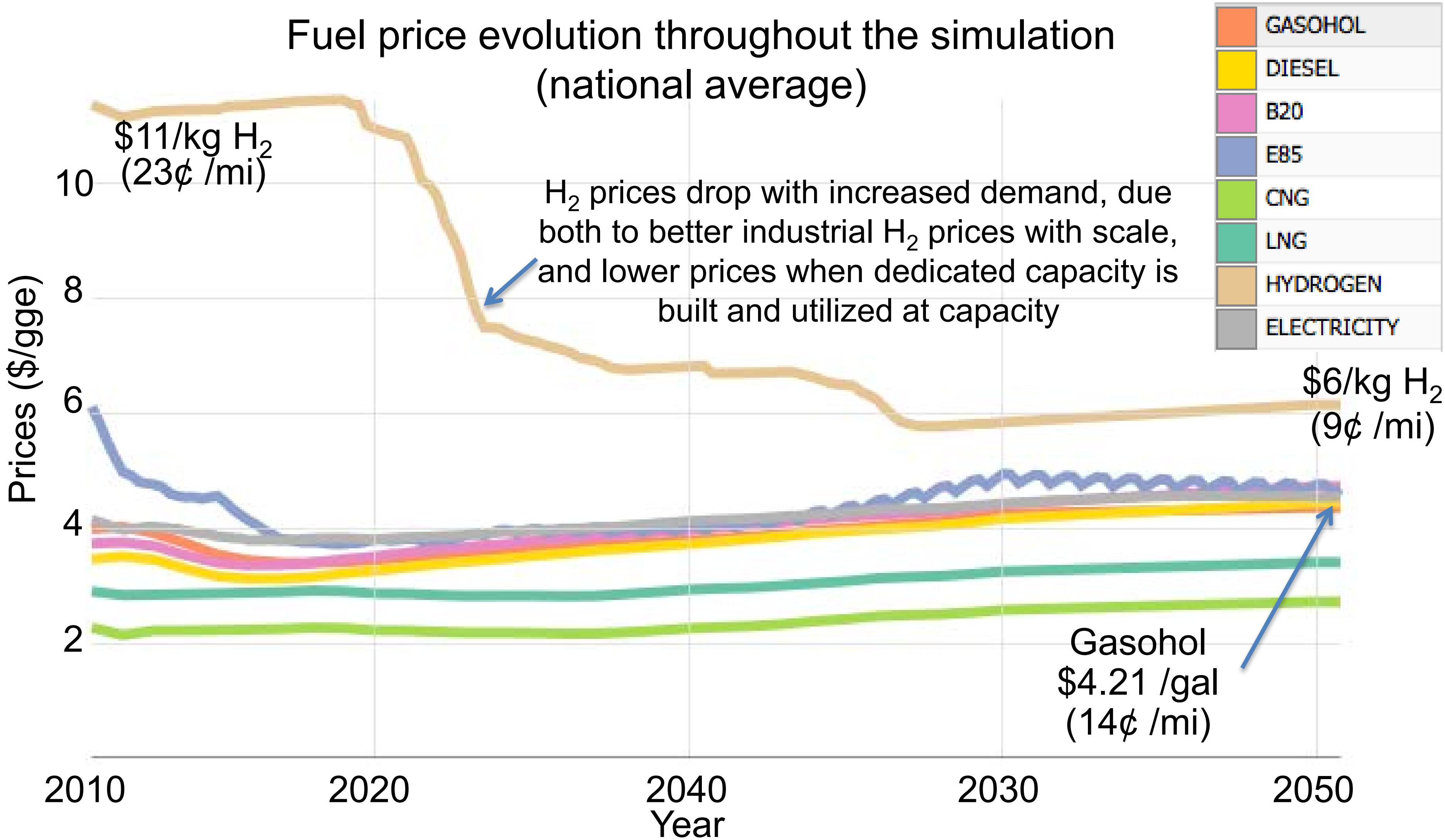
Key Result: Pathways model outputs show the effects of different state incentives on 2050 FCEV sales. Incentives work!



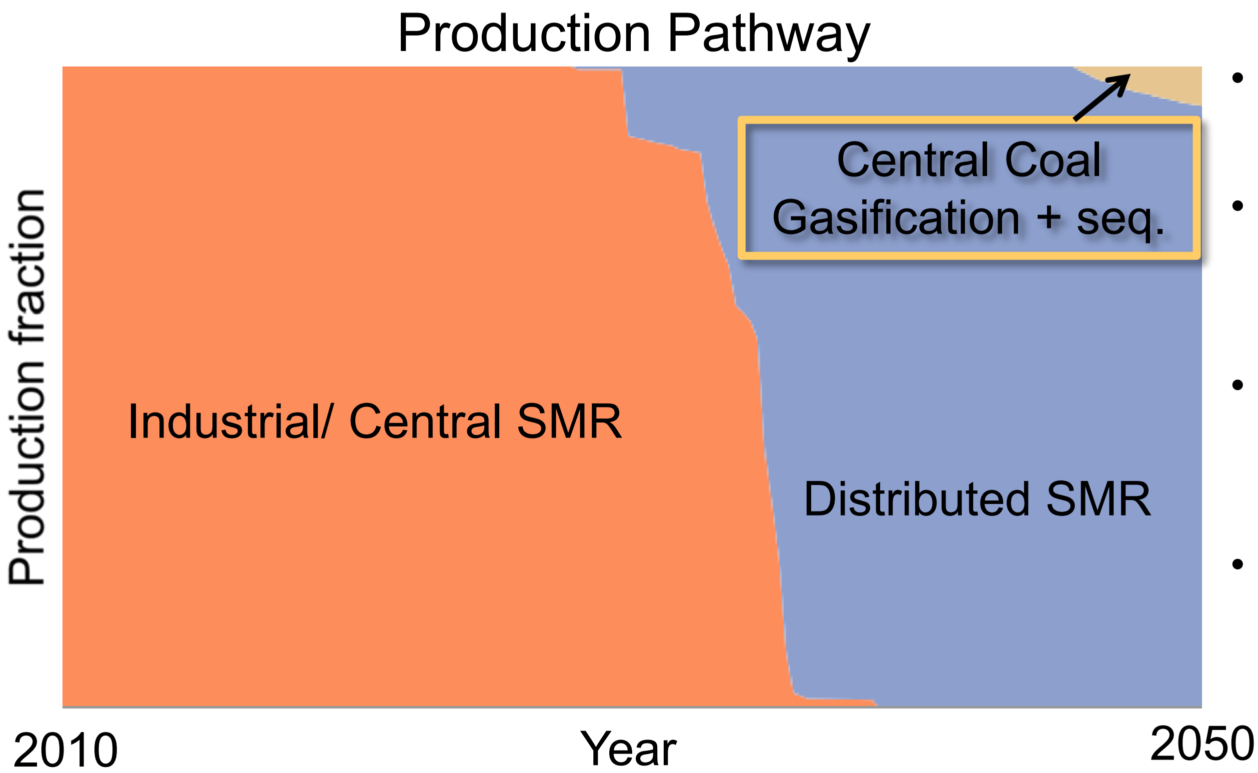
State Incentives and fuel prices drive regional variation in FCEV adoption

- GA: Non-sunsetting $5000 tax credit towards FCEV purchases.
- NC & TN: Grant FCEVs access to high occupancy vehicle lanes. H_2 costs 9¢ per mile in both states by 2034.

Key Result: H_2 pump fuel prices drop with increasing demand, ultimately becoming competitive with gasohol prices on a per mile basis



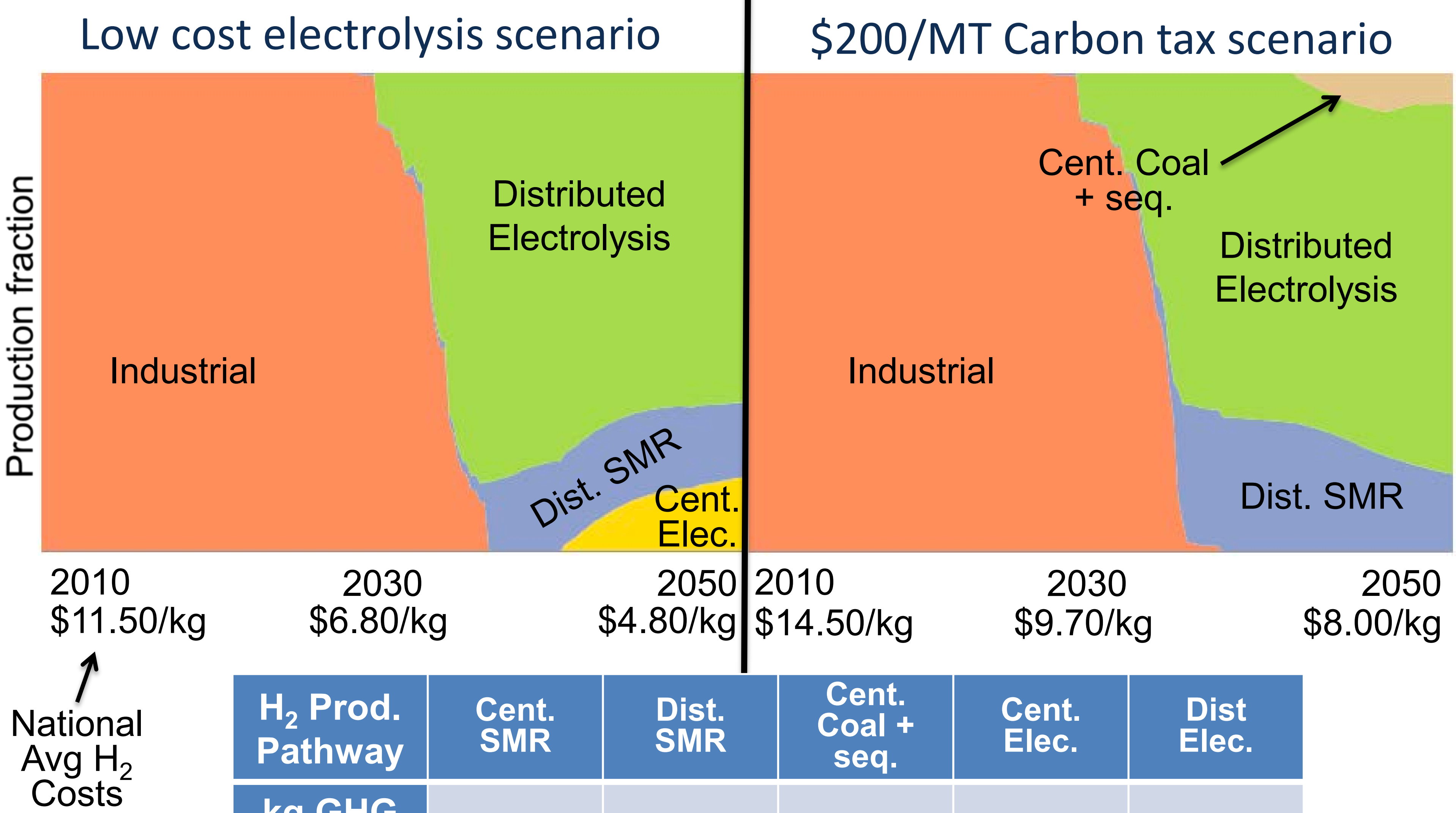
Key Result: For baseline inputs, industrial H_2 gives way to distributed production of H_2 via SMR. Consequently, GHG emissions are not strongly affected by the substantial FCEV adoption.



- Refueling stations start simulation using industrial H_2
- By mid 2030s, H_2 demand sufficient to make dedicated production economical
- Dedicated production via distributed NG reformation initially cheapest
- By 2045, centralized production using coal plus sequestration cheapest for some states

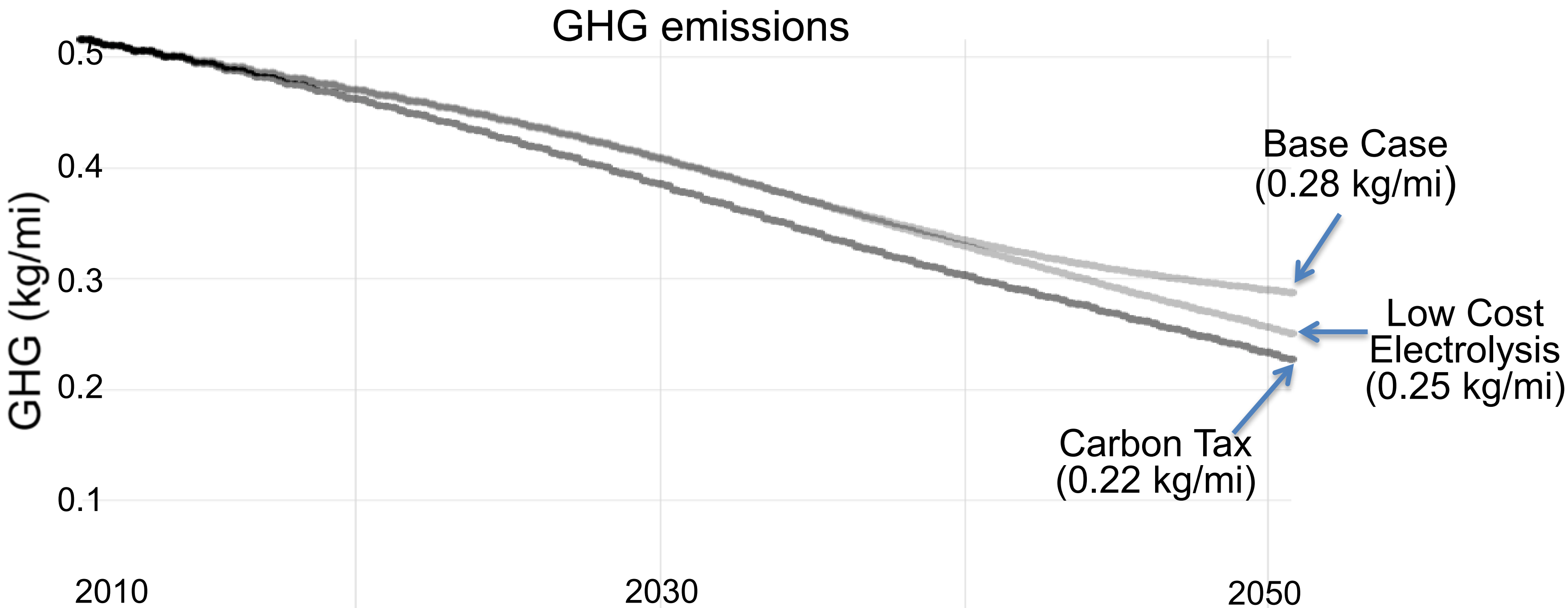
- 2045 GHG emissions of a FCEV are 0.24kg/mi if the H_2 is produced via dist. SMR.
- 2045 GHG emissions of an SI Hybrid are 0.22kg/mi, (GREET/*Autonomie*)
- Model result: National GHG emissions in scenarios with and without FCEVs are effectively the same!

Key Result: Both discounts and fees can incentivize lower carbon H_2 production pathways.



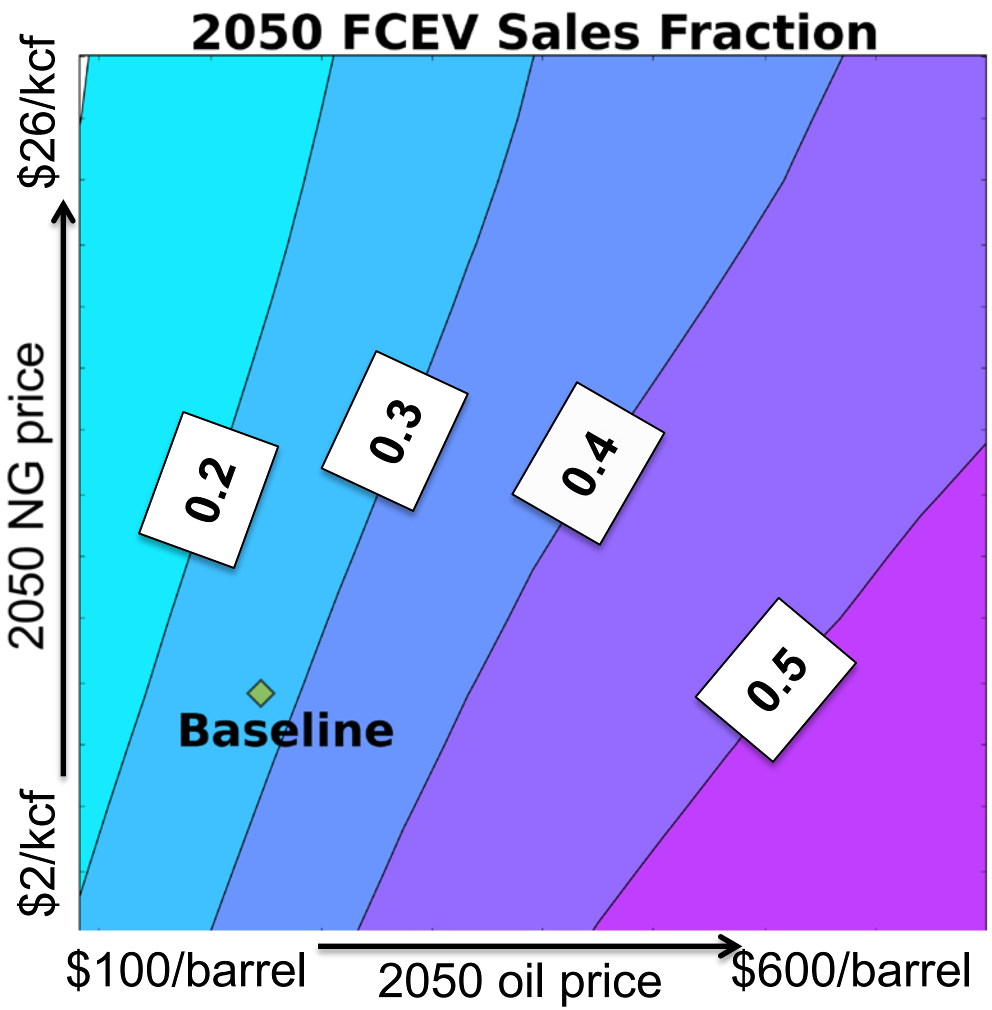
H_2 Prod. Pathway	Cent. SMR	Dist. SMR	Cent. Coal + seq.	Cent. Elec.	Dist Elec.
kg GHG per mi	0.22	0.24	0.11	0.03	variable

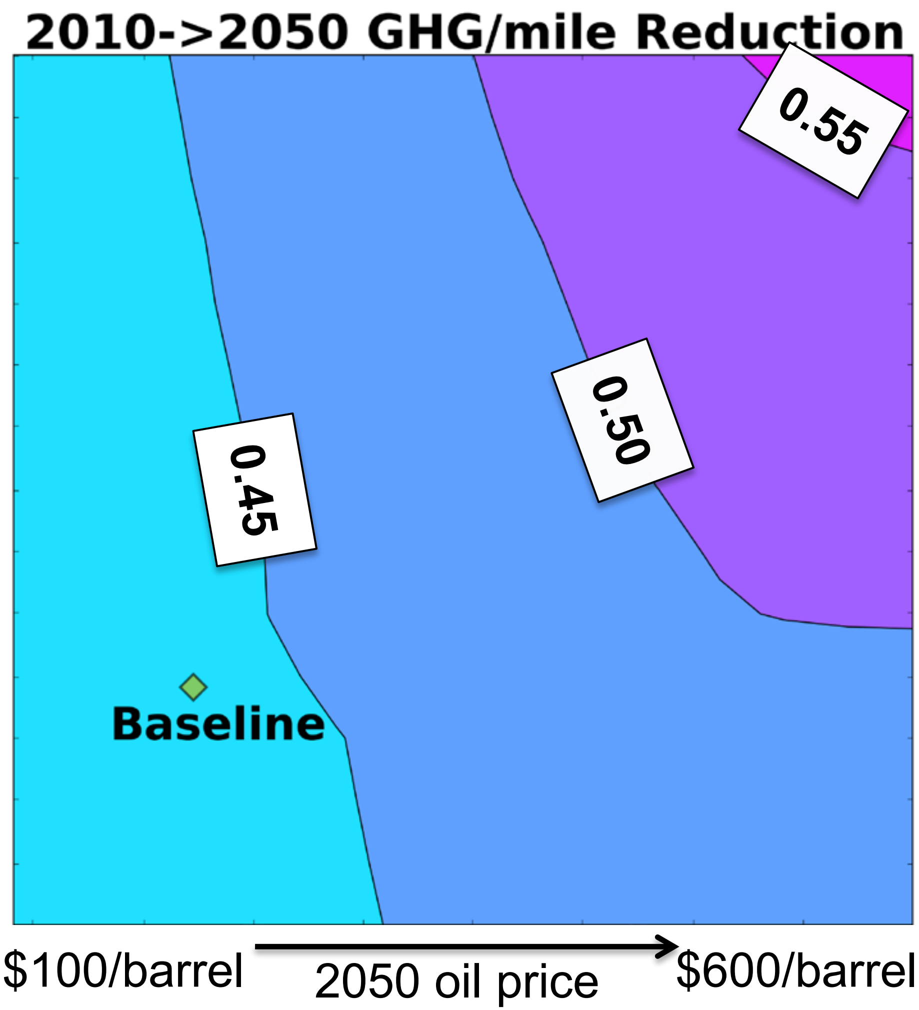
Key Result: Both discounts and fees can incentivize lower carbon H_2 production pathways and thus lower GHG emissions through FCEV use.



- Low cost electrolysis ($4.80/kg by 2050) incentivizes clean H_2 production pathways and increases FCEV adoption, driving down the GHG emissions of the fleet.
- A $200/MT Carbon tax will achieve even lower 2050 GHG emissions
- Carbon taxes can lower emissions rapidly, by incentivizing FCEVs, shifting H_2 production to lower carbon pathways, increasing market shares of other AEVs, and increasing non-petrol usage of all PHEVs and Bi-fuel vehicles

Key Result: Parameterization allows us to understand the sensitivities of FCEV adoption and GHG emissions to underlying commodity prices.





GHG emissions are reduced the most when both oil and NG prices are high, but FCEV adoption benefits from low NG prices, as the cheapest H_2 production pathways rely on NG

Collaboration with other institutions

- 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
- This work is complemented by modeling and analysis for the VTO. Dawn Manley will be presenting VTO-funded ParaChoice analysis (project ID VAN014) on Thursday, June 11 at 11am

Proposed future work

- **Continuing analysis to:**
  - Explore effect of fuel cell cost uncertainties on FCEV market adoption
  - Explore effect of 2015 H_2 price (industrial H_2 price markup) on FCEV adoption
  - Determine which levers have the greatest effect on FCEV adoption
- **Peer review**
- **Deliverables:**
  - Parametric assessments of those factors that affect FCEV adoption, petroleum use reduction, and GHG emissions
  - Publications and conference presentations
  - Scenario comparison

Summary

- FCEVs and H_2 fuel production now part of the Pathways ParaChoice model

- Initial findings:
  - Hydrogen can play a large role in the 2050 fleet
  - If market forces are the only drivers of H_2 production pathways, FCEVs will have a carbon neutral effect on the fleet out through 2050.
  - FCEVs have the potential to reduce GHG emissions if Carbon taxes, technology improvements, or incentives steer H_2 production towards cleaner pathways.

- Parametric approach allows exploration of broad range of scenarios and tradeoffs
  - We are in the process of determining which factors have the greatest impact on FCEV adoption and GHG emissions

- Future work will expand on this analysis of FCEVs in the vehicle fleet and on the pathways used to produce Hydrogen as a vehicle fuel

Technical Backup Slides

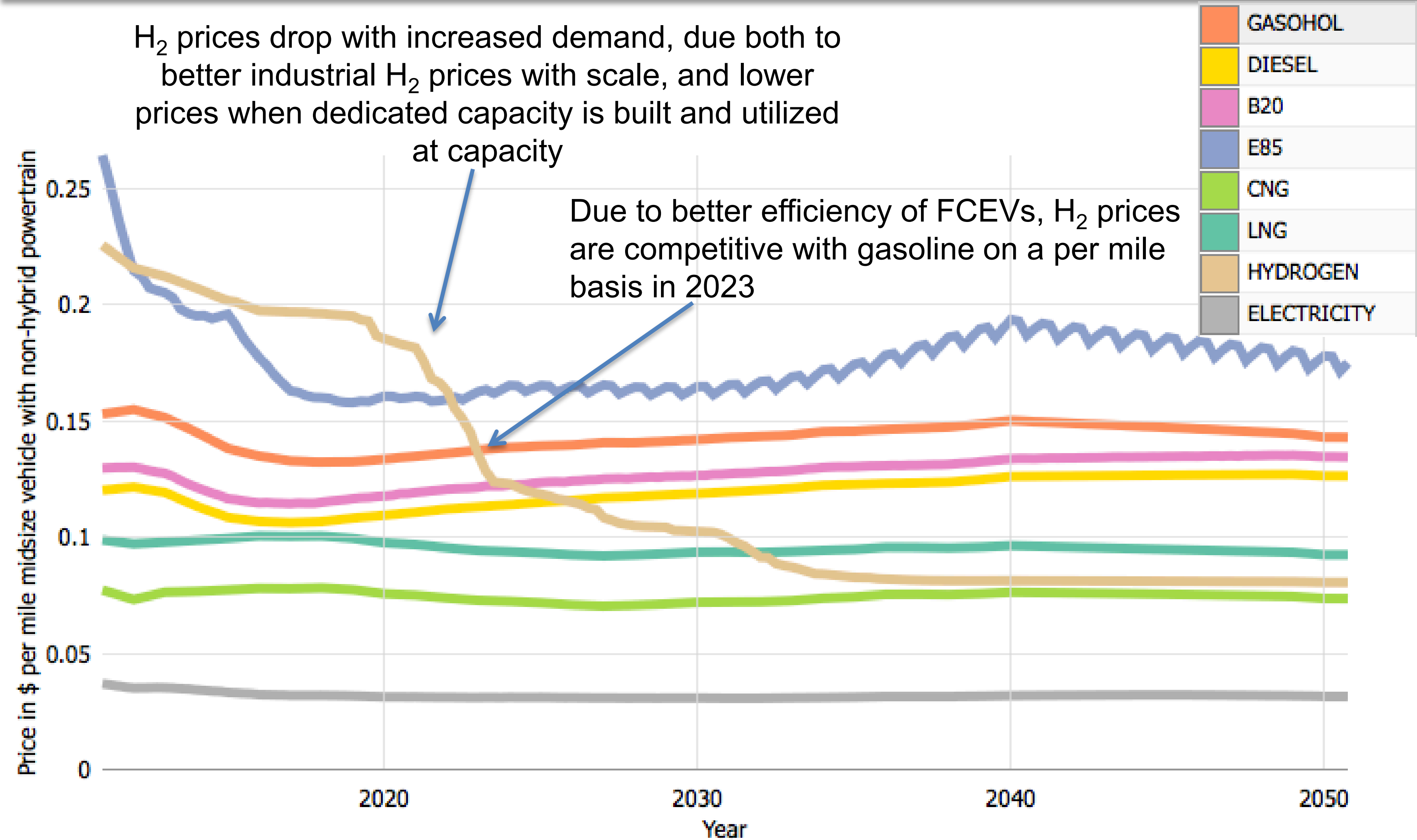
H_2 pricing, production, and emissions assumptions and data sources

- 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 the pathways comes from *GREET* (latest version)
  - Fuel prices can be influenced by carbon taxes
- 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

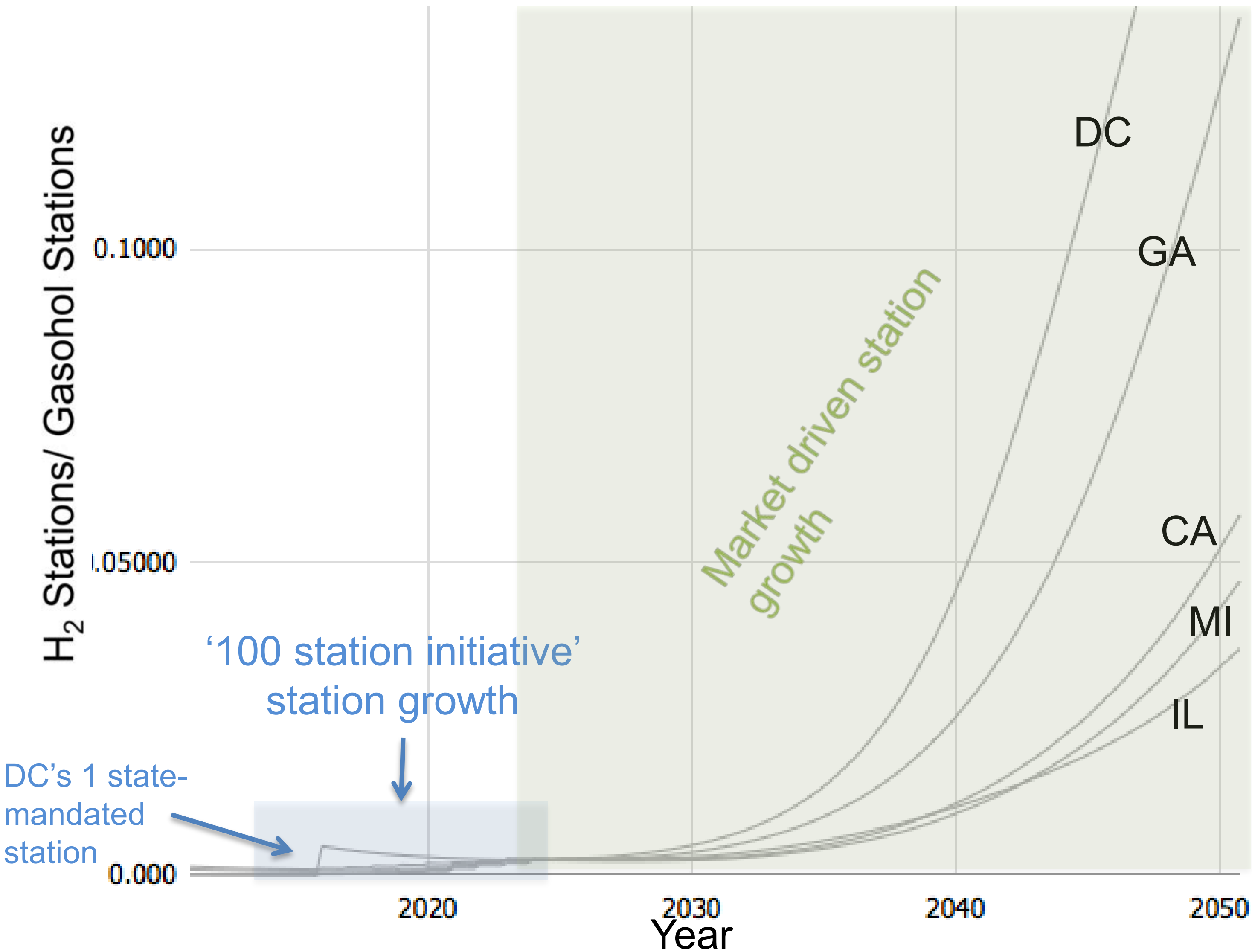
Pathway	Dist. SMR	Dist. Elec	Cent. Coal	Cent. SMR	Cent Elec.	Cent Coal + Seq	Cent SMR + Seq
Cost at scale* (2012$)	5.09	7.32	4.58	5.72	8.31	5.71	5.97

*National average pump fuel prices for present day commodity prices and full scale production.

Key Result: H_2 pump fuel prices drop with increasing demand, ultimately becoming competitive with gasohol prices on a per mile basis



Refueling infrastructure: We pre-seed H_2 infrastructure assuming that each state will have an initiative akin to CA's 100 station initiative.



- State mandated H_2 stations provide a kick-start for station growth, but the majority of growth is market driven, after the initiatives end.
- We are in the process of analyzing the effects of pre-seeding station growth, and preliminary results show the net effect on FCEV market share is small.

- FCEV's hold 37% of vehicle sales by 2050 in the base case, and 14% of all vehicle mileage.
- In the scenario where electrolysis is low cost, FCEV sales increase, but gasohol mileage stays effectively stagnant.
- A carbon tax reduces gasohol use by 10% from the base case.

Powertrain		ICE	Hybrid	PHEV10	PHEV40	BEV	**FCEV**	CNG
% of 2050 sales	World without FCEVs	16.3	27.7	27.8	8.1	4.1	**NA**	16.1
	Base Case	12.2	20.7	20.9	6.2	2.8	**27.4**	9.9
	Low Cost Electrolysis	11.2	19.0	19.1	5.6	2.5	**33.7**	8.8
	Carbon Tax	7.9	19.0	20.1	7.3	4.3	**31.4**	10.0

Pump Fuel		Gasohol	Diesel	E85	NG	**H_2**	Electricity
% of 2050 mileage	World without FCEVs	63.4	10.9	1.6	11.0	**NA**	13.0
	Base Case	55.8	9.4	1.5	8.0	**14.1**	11.1
	Low Cost Electrolysis	54.2	9.1	1.4	7.6	**17.0**	10.7
	Carbon Tax	45.4	7.7	7.8	8.5	**16.1**	14.3

Acronyms and Abbreviations

- Powertrains/ vehicles
  - AFV- alternate fuel vehicle
  - BEV- 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
  - CNG- compressed natural gas
  - E85- 51-83% ethanol blend
  - NG- natural gas
  - Coal- coal gasification
  - Cent.- centralized production, H_2 is delivered to distribution stations
  - Dist.- production at distribution site
  - Elec.- electrolysis
  - Seq.- sequestration of carbon created during production
  - SMR- Steam methane reformation of natural gas
- Other
  - DOT- Department of Transportation
  - EIA- Energy Information Administration
  - GHG- green house gas
  - NHTS- National Household Transportation Survey (2010)
  - VMT- annual vehicle miles traveled
  - kcf- thousand cubic feet