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Impact of Hydrogen Vehicles on U.S. Greenhouse Gas Emissions and Petroleum Use

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Our research makes quantitative assessments of the impact of fuel cell technologies

Key Metrics:

Petroleum consumption, emissions, and transportation cost

Example assessments:

What are the potential reductions of CO_2 emissions and gasoline consumption due to HFCV adoption?

What is the value of HFCV in comparison to battery electric vehicles or advanced ICE vehicles?

What effect does stationary FC H_2 co-production have on HFCV penetration?

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Which options lead to lower emissions? How do improvements in alternative technologies change our outlook?

Nissan Leaf EV

Honda Clarity HFCV

Ford Fusion Hybrid

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We use a system dynamics approach to model vehicle and stationary H_2 applications

- Meaningful analysis of the impact of H_2 technologies should:
  - Consider competing technologies
  - Allow for sensitivity analysis of unknown/ unknowable parameters
  - Account for different time scales
- Powersim software allows quick generation of code and interfaces and can solve system of ODEs. It allows insight into the dynamic behavior of complex systems.

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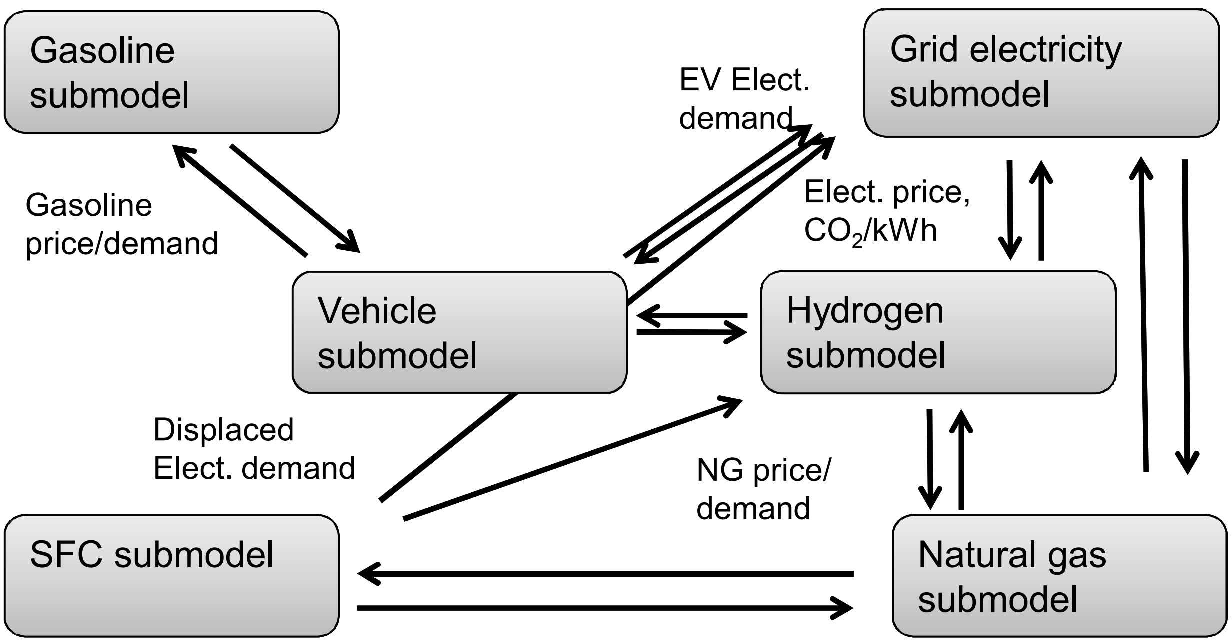
Model competes vehicle options using performance and cost information

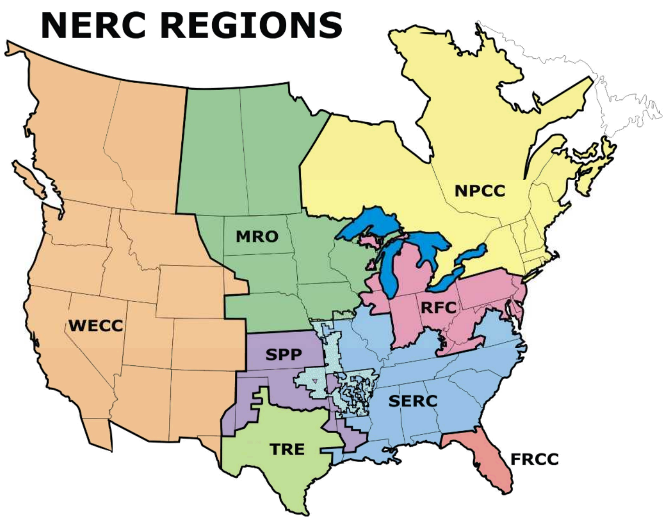
- Vehicle sales divided between PHEV10, PHEV40, BEV, HFCV, and improved conventional vehicles using multinomial logit function.
- Vehicle costs and performance evolve over time
- Fuel prices change with fuel demand and technology improvements.
- Stationary FCs modeled using fixed penetration model. SFCs can be assigned to produce both electricity and hydrogen for vehicles .



Geographic and vehicle segments are used to reflect inhomogeneity of key parameters.

- We model 15 vehicle powertrain & size combinations
- 8 geographic regions used to account for differences in electricity source and renewable potential.

<u>Powertrains:</u> Conventional ICE, HFCV, PHEV10, PHEV40, BEV	<u>Vehicle size/class:</u> Small Car, Large Car, Truck
<u>Energy sources:</u> Coal, Natural gas, Oil, Wind	<u>Fuels:</u> Gasoline, Hydrogen, Electricity



North American Electric Reliability Corporation regions are not geographic regions; our regions approximate NERC regions.

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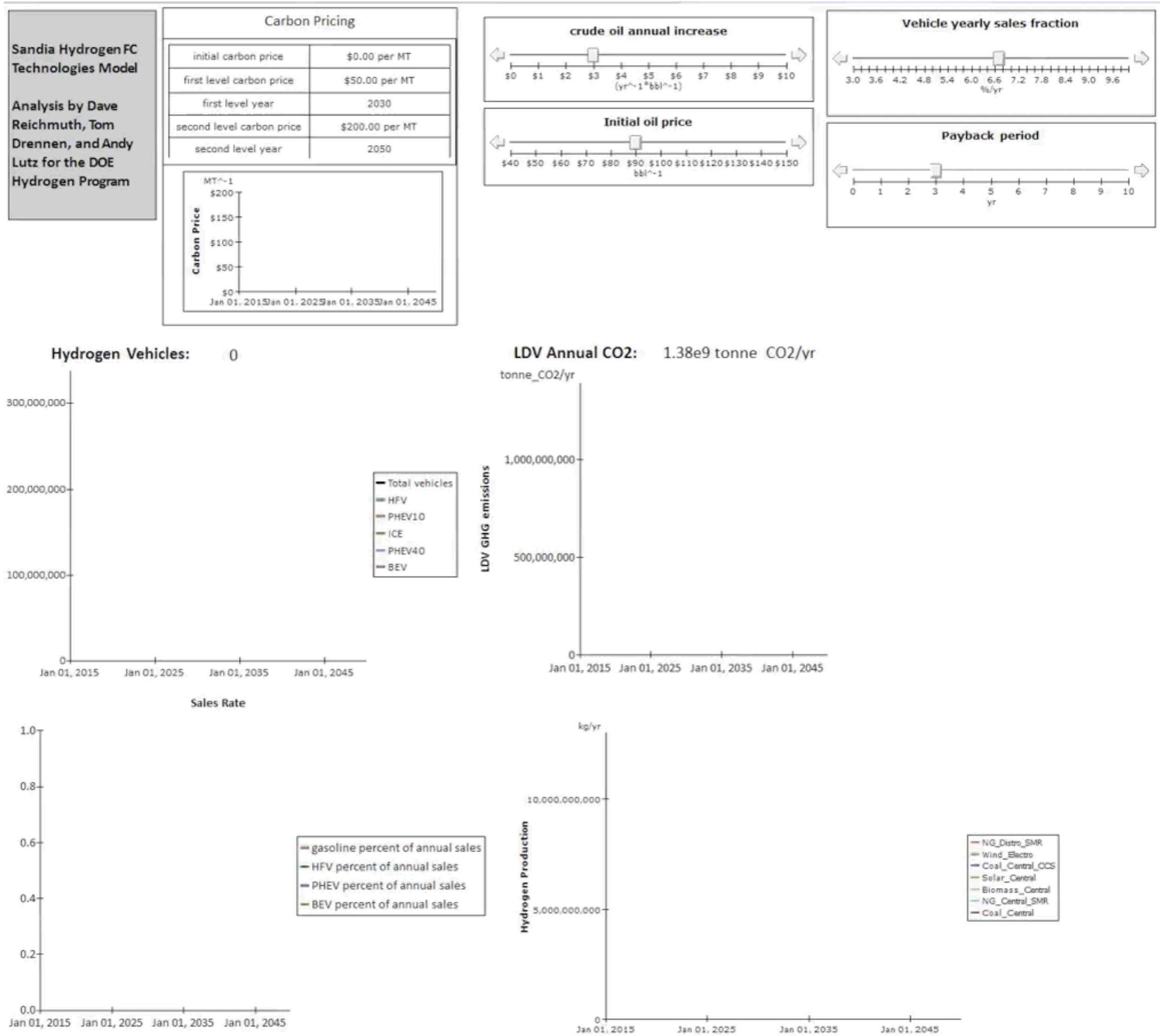
Vehicle Fuel Economy Assumptions

MPGe in 2010/2016/ 2035	Gasoline ICE	HFCV	PHEV10 Gas (77%) Elect (23%)	PHEV40 Gas (37%) Elect (63%)	BEV
Small Car	36/42/45	69/71/76	41/45/56 84/102/136	30/34/47 94/110/148	99/110/148
Large Car	18/30/39	69/71/76	35/39/47 72/87/116	25/29/40 80/94/126	N/A
Truck	18/30/39	69/71/76	20/23/28 42/51/68	N/A	N/A

- Vehicle fuel economy interpolated between points and is fixed at the last value after 2035
- Used EPA vehicle class definitions (not CAFE) - SUVs classified as “large cars”
- Some powertrain/size combinations assumed to be unlikely
- Gasoline internal combustion engine (ICE) powertrain includes hybrids
- Current HFCV values based on Toyota Highlander FCHV-adv report (Wipke *et al*)

Model allows interactive analysis using user interface and automated sensitivity analysis

- Allows sensitivity analysis using Latin hypercube sampling
- Results are displayed on-screen as well as sent to Excel spreadsheet



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Model provides a tool for examining a range of scenarios

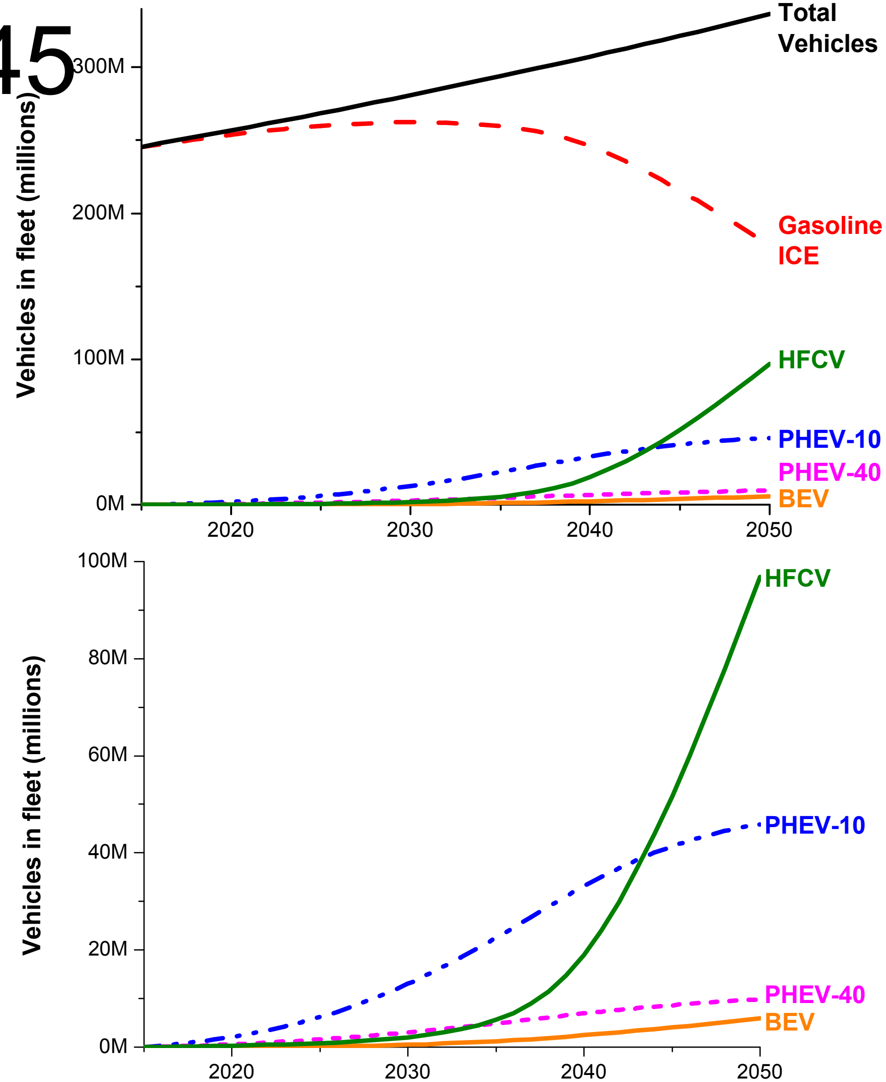
- Key input parameters
  - Vehicles:
    - Fuel economy as a function of time; cost of alternative technologies, learning curve for vehicle cost; sales/discard rates, payback period for additional purchase cost, availability of powertrain options
  - Electricity:
    - Changes in marginal electric mix, rate of change of marginal electric mix, non-transport demand for electricity
  - Energy Sources:
    - NG price elasticity, Supply curves for zero-carbon energy sources, Availability of inter-regional transport, Crude oil initial price and rate of increase
  - SFC:
    - Electric efficiency; H_2 co-production efficiency, fixed & variable costs of H_2 production; penetration rate of SFC units
  - Other: carbon price

Base case: HFCV dominate alternative vehicle fleet by 2045

- With moderate increases in petroleum price ($3/bbl/yr) and without carbon price, gasoline ICE vehicles are the majority for the first half of this century

- PHEV-40 and BEV are hampered by costs and market segment limitations

- Smaller batteries in PHEV-10 reduce vehicle cost, allowing earlier penetration



- Hydrogen-fueled vehicles are the dominant alternative vehicle after 2045
- Fleet is half alternative vehicles at 2050
- Hydrogen-fueled vehicles reach 1 million vehicles by 2026

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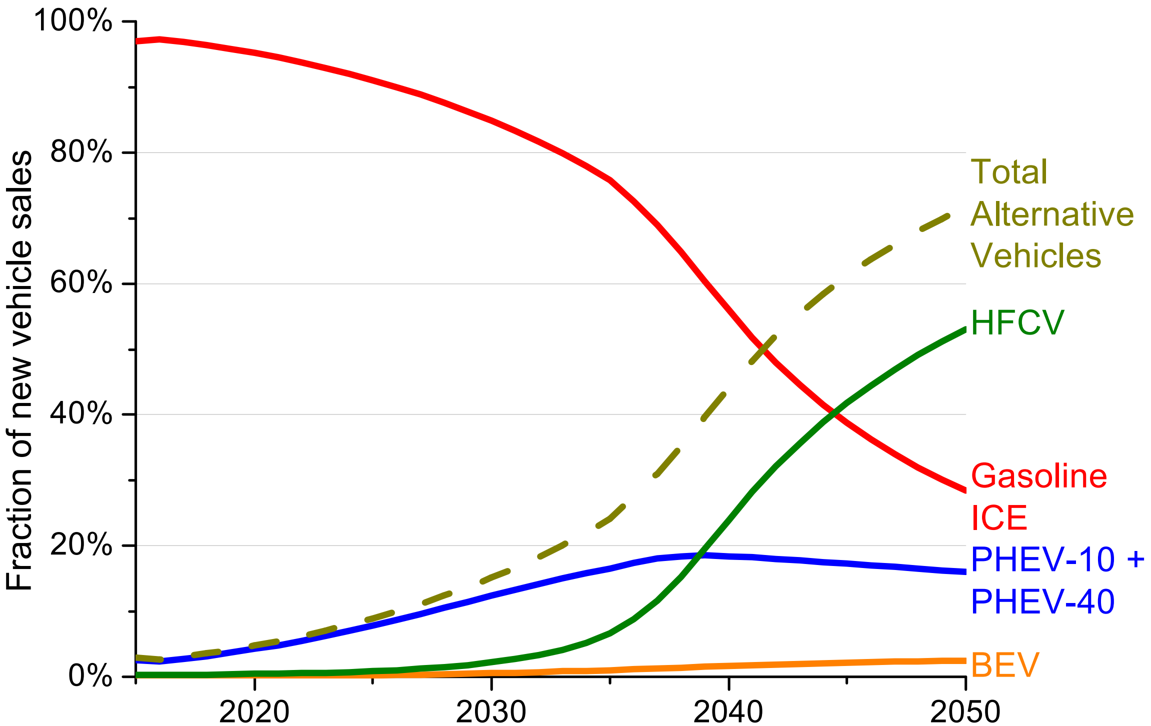
Base case: Alternative fuel vehicle sales accelerate after 2030

Assumptions:

- Improvements in fuel economy for all vehicles
- Reductions in the cost of alternative vehicles
- Carbon policy not considered

Shape and timing of HFCV sales rate is consistent with HyTrans results (Greene *et al*, ORNL 2008)



- Gasoline ICE sales fall below 50% in 2040
- Alternative vehicles make up 75% of new vehicle sales at mid-century (~17 M vehicles/year)

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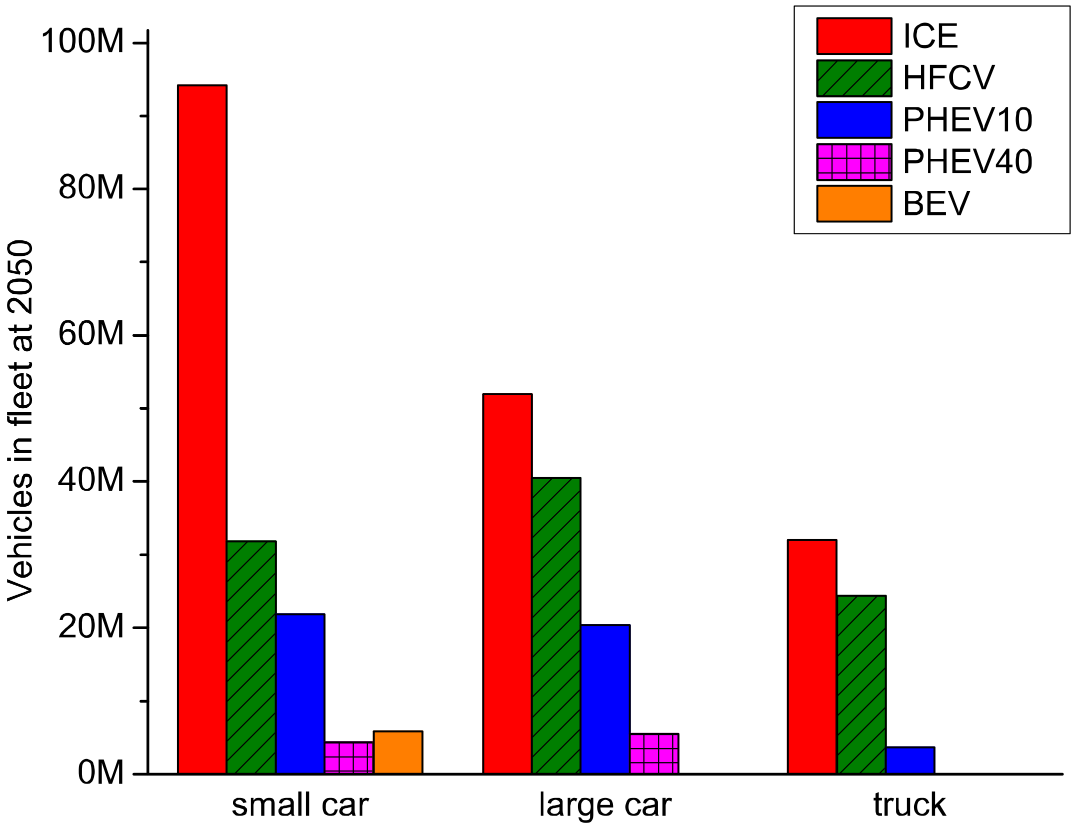
Base case: Powertrain choice varies with size of vehicle

- Large car segment
  - Higher proportion of alternative vehicles due to larger difference in fuel consumption
- Small car segment
  - Small ICEs already efficient
  - Fuel savings of alternative vehicles is small compared to additional purchase costs
- Changing vehicle cost or gasoline price assumptions changes both the penetration and distribution of hydrogen vehicles



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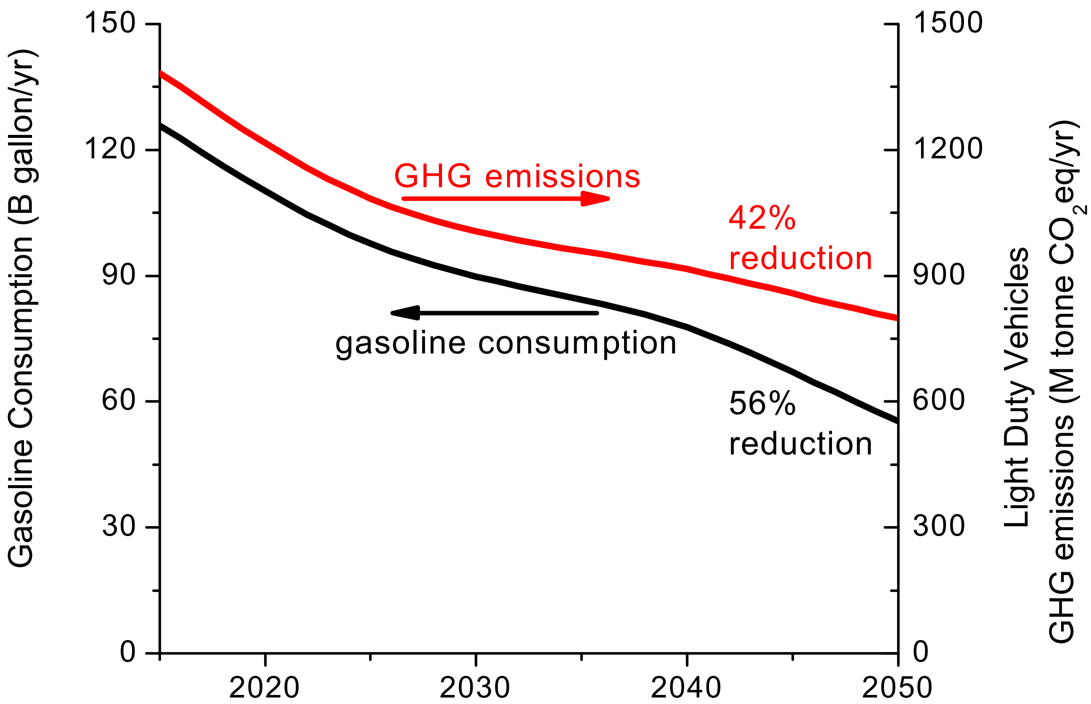
Base case: Large reductions in both gasoline use and GHG emissions from new vehicle technologies

- Significant gasoline use reduction, despite increase in population & vehicles
  - Increases 0.9% per year, total increase 37% from 2015 to 2050
- Gasoline demand in 2050 is within the technical limit of domestic biofuel production
  - About 60 B gallon gasoline equivalent (GGE) per year
- Gasoline ICE improvements alone would achieve 25% reduction in GHG emissions and gasoline use (relative to 2015)



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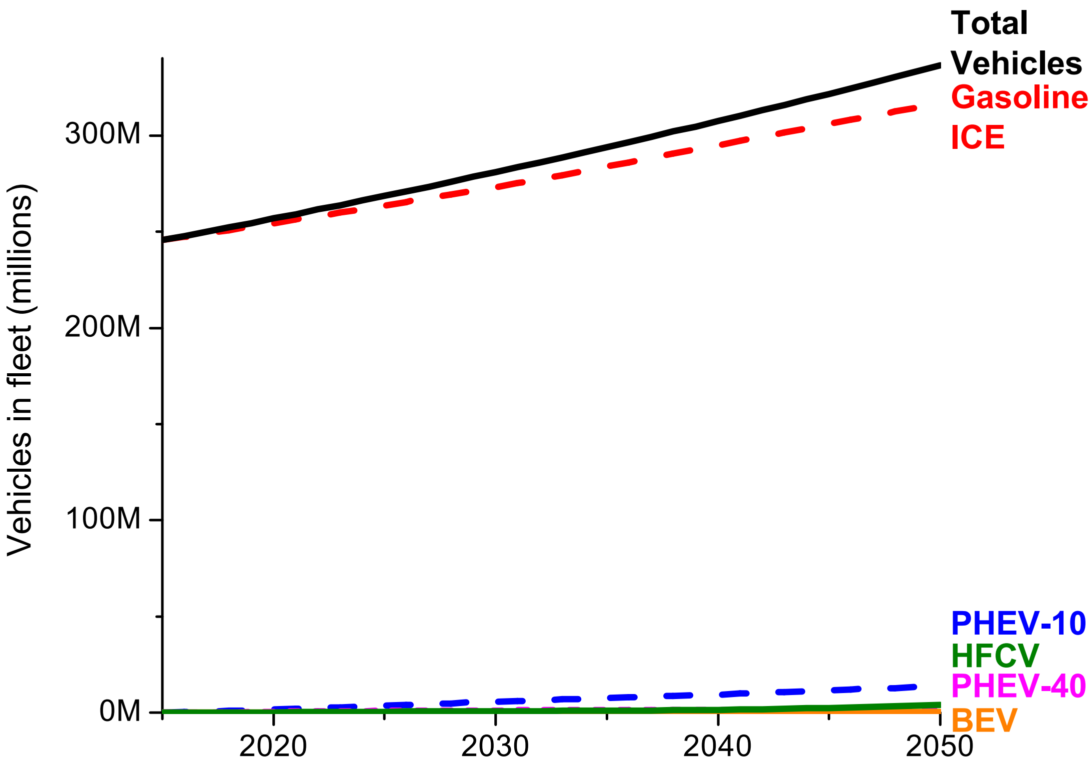
Without higher gasoline costs, alternative vehicles are minor portion of fleet

- Oil price constant at $90/bbl
- No carbon price
- Gasoline ICE continue to improve
- Fuel savings is not sufficient to support purchase of alternative-fueled vehicles
- Model does not presuppose success of alternative vehicles



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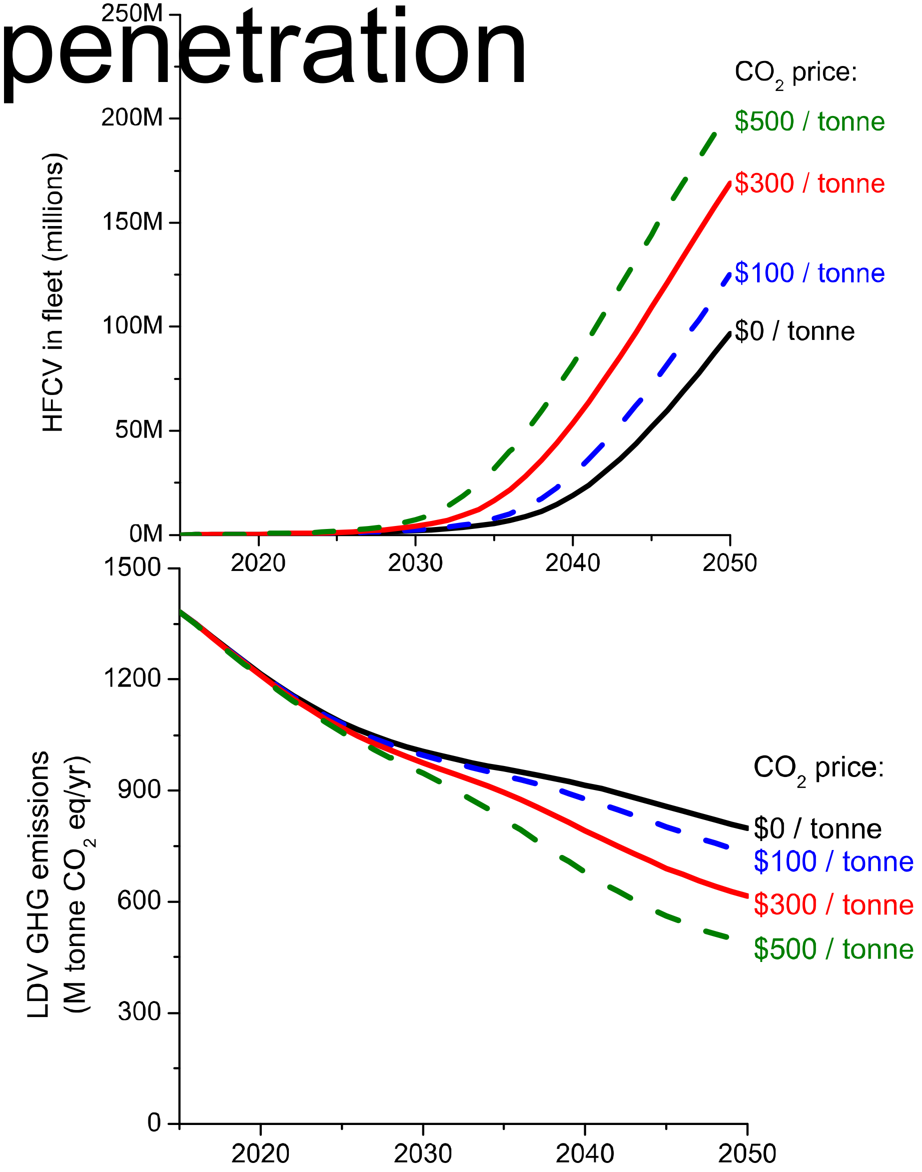
High carbon price increases hydrogen vehicle penetration

- Model allows hydrogen production from natural gas or wind electricity
- Carbon price increases the total number of HFCV and causes earlier introduction
- However, significant carbon price is required to have large impact on hydrogen vehicle sales



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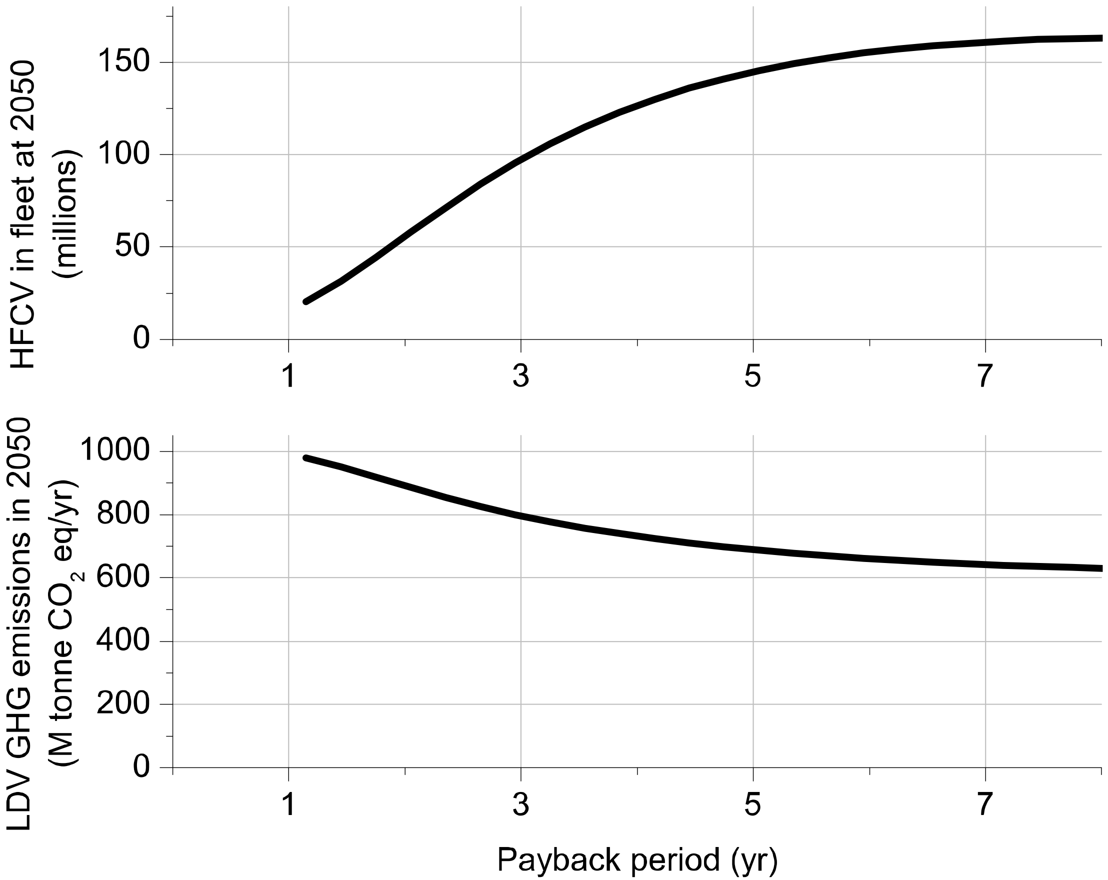
Payback period is a critical parameter for HFCV sales and GHG emissions

- Greene reports consumers use 1.5 to 2.5 year payback period
- Baseline assumption: 3 year period for consumer choice
- Changing from 3 to 5 years to recoup purchase price increases HFCV by 50% and saves >100 M tonne CO_2/year
- Achieving the same reduction with carbon price requires $175/tonne price.



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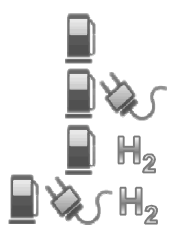
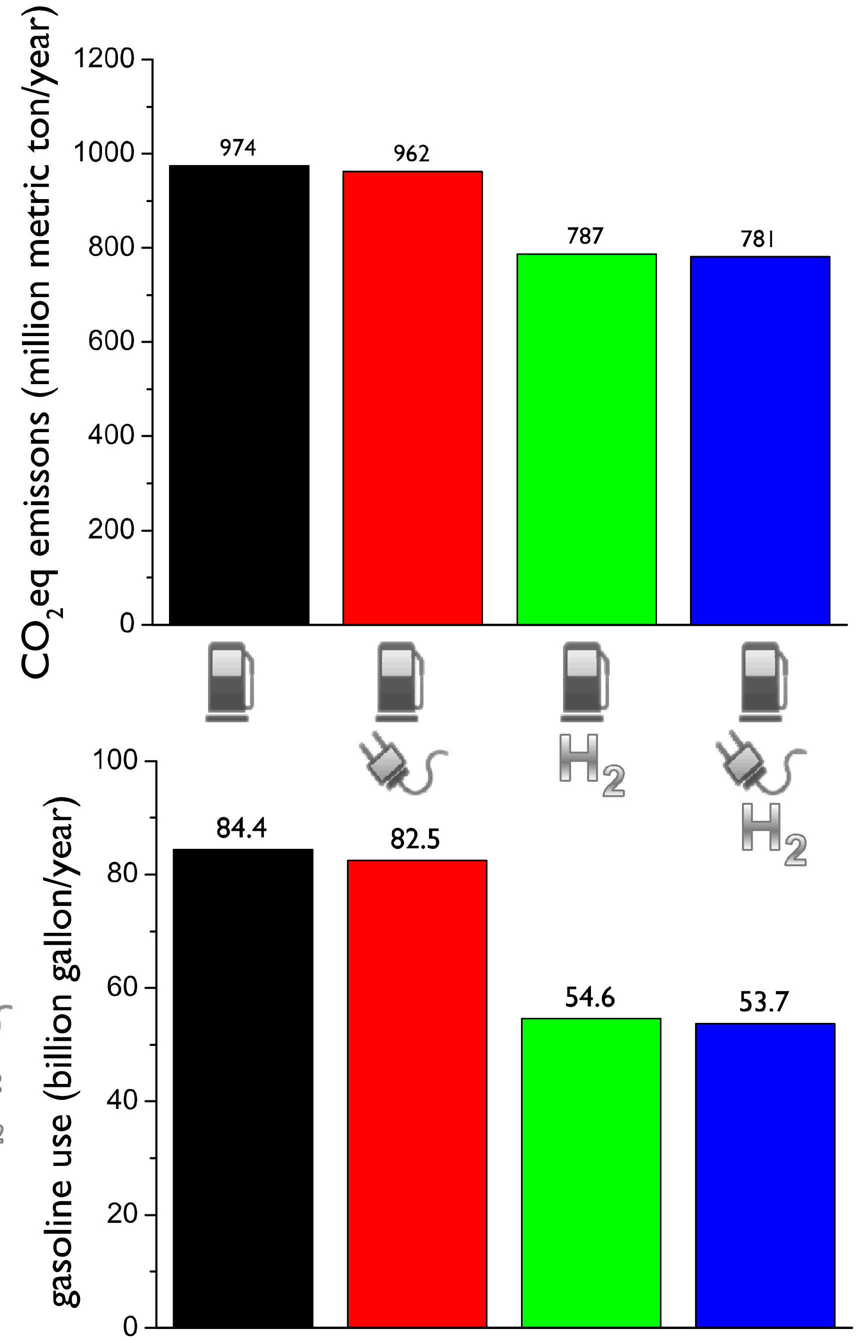
Hydrogen vehicles can have a larger impact on emissions & oil use than battery electric vehicles

- Large-scale use of hydrogen or battery electric vehicles will require infrastructure investment and R&D progress.
- However, the impact of these technologies is not equal.
- Consider 4 scenarios for powertrain availability:
  - Gasoline ICE + PHEV only
  - Gasoline ICE + PHEV + BEV
  - Gasoline ICE + PHEV + HFCV
  - Gasoline ICE + PHEV + BEV + HFCV



- Assumes hydrogen/ fuel cell and battery technologies reach current DOE goals.



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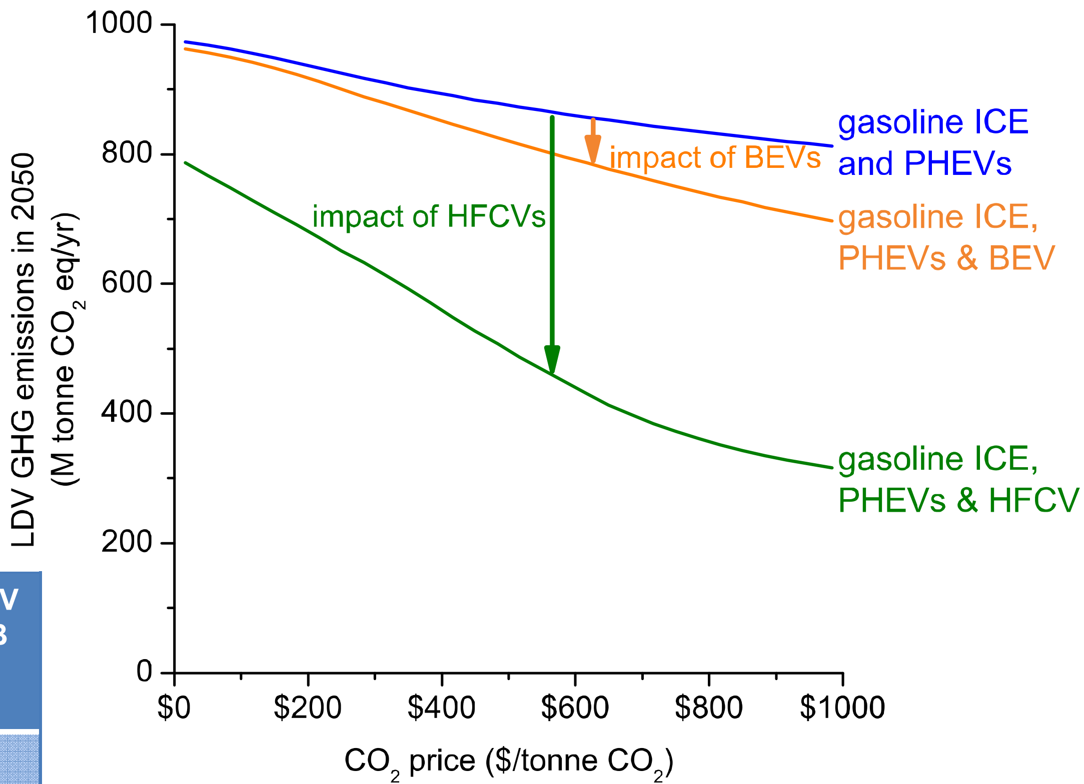

Gasoline use

Oil Price	ICE+PHEV	ICE+PHEV+BEV	ICE+PHEV+HFCV	ICE+PHEV+HFCV+BEV
$90/bbl, no increase	92.7 B gal/yr	92.6 B gal/yr	91.4 B gal/yr	91.3 B gal/yr
$90/bbl → $195/bbl	84.5 B gal/yr	82.6 B gal/yr	56.2 B gal/yr	55.3 B gal/yr
$90/bbl → $265/bbl	79.6 B gal/yr	75.6 B gal/yr	40.5 B gal/yr	39.2 B gal/yr

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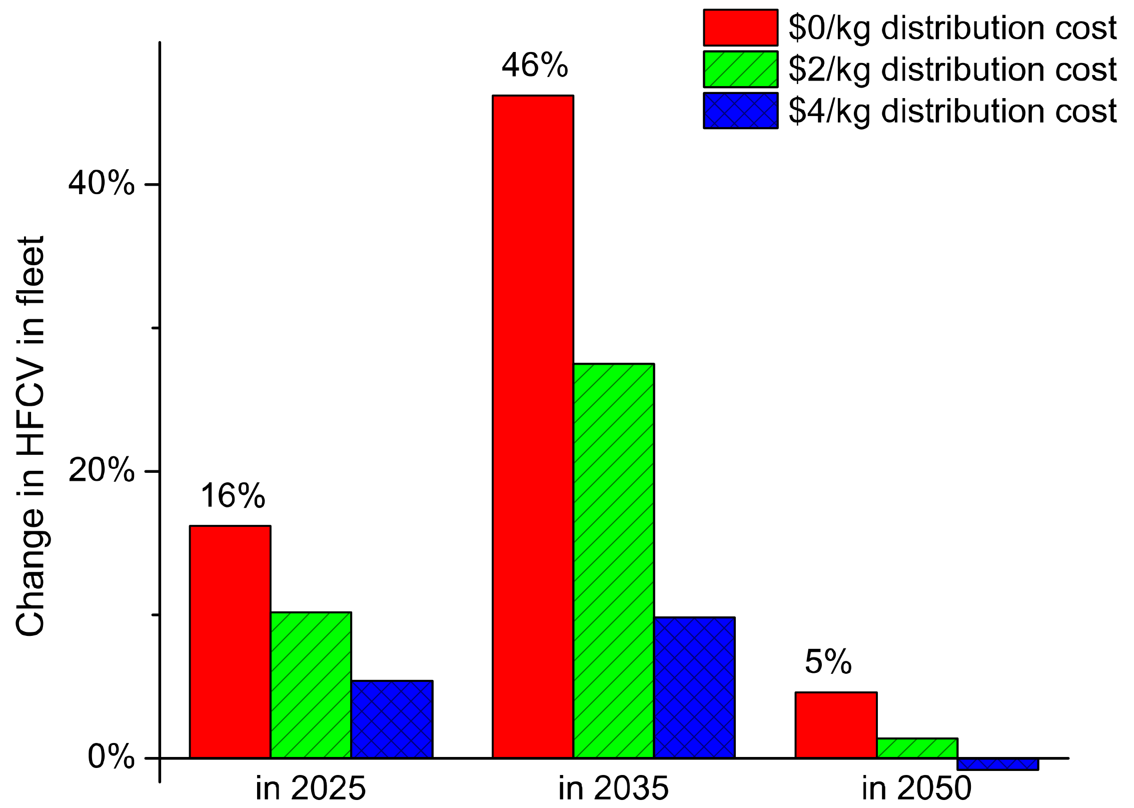
SFC hydrogen availability could change early adoption behavior

- SFC hydrogen co-production increases initial HFCV penetration
- Effect is significant if filling station capital and maintenance costs are subsidized or otherwise reduced



Baseline: 0.84M 5.6M 96.7M

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Summary

- Increasing oil prices and/or policies that give a price to carbon are needed for significant numbers of HFCV to penetrate the light duty vehicle fleet.
  - At moderate oil price increases, our analysis predicts 50% hydrogen and electric vehicles by 2050.
- Hydrogen vehicles would allow significant GHG emission and gasoline use reductions.
  - Over 50% decrease in gasoline use in 2050 (relative to 2015 levels)
  - Hydrogen vehicles are predicted to have much larger effect than battery electric vehicles.
  - Our model shows a high sensitivity to the payback period used for consumer vehicle choice. Policies that address the consumer's view of fuel saving and purchase price could have significant effect on emissions.
- H_2 co-produced from SFC could have impact on early vehicle adoption rates.
  - Up to 46% increase in H_2 vehicles in 2035

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Thank you for your interest