# *Analysis of Energy Infrastructures and Potential Impacts from an Emergent Hydrogen Fueling Infrastructure*

SAND2010-4789P

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# Objectives

- Use dynamic models of infrastructure systems to analyze the impacts of widespread deployment of hydrogen technologies
- Identify potential system-wide deficiencies that would otherwise hinder infrastructure evolution, as well as mitigation strategies to avoid collateral effects on supporting systems
- Analyze the feedback effects of competing alternative transportation options

# We model the dynamics of emergent fuel-vehicle systems

- Our focus is on the feedback and dynamics of future transportation system options.
  - Primary energy source, fueling infrastructure, and vehicles need to be considered together
  - Feedback and competition between transportation and energy alternatives will effect the evolution of transportation systems
  - The differing time scales for change need to be considered

# Which vehicle leads to the lowest emissions? Which is the cost-competitive choice?


Nissan Leaf EV

Honda Clarity HFCV

Ford Fusion Hybrid



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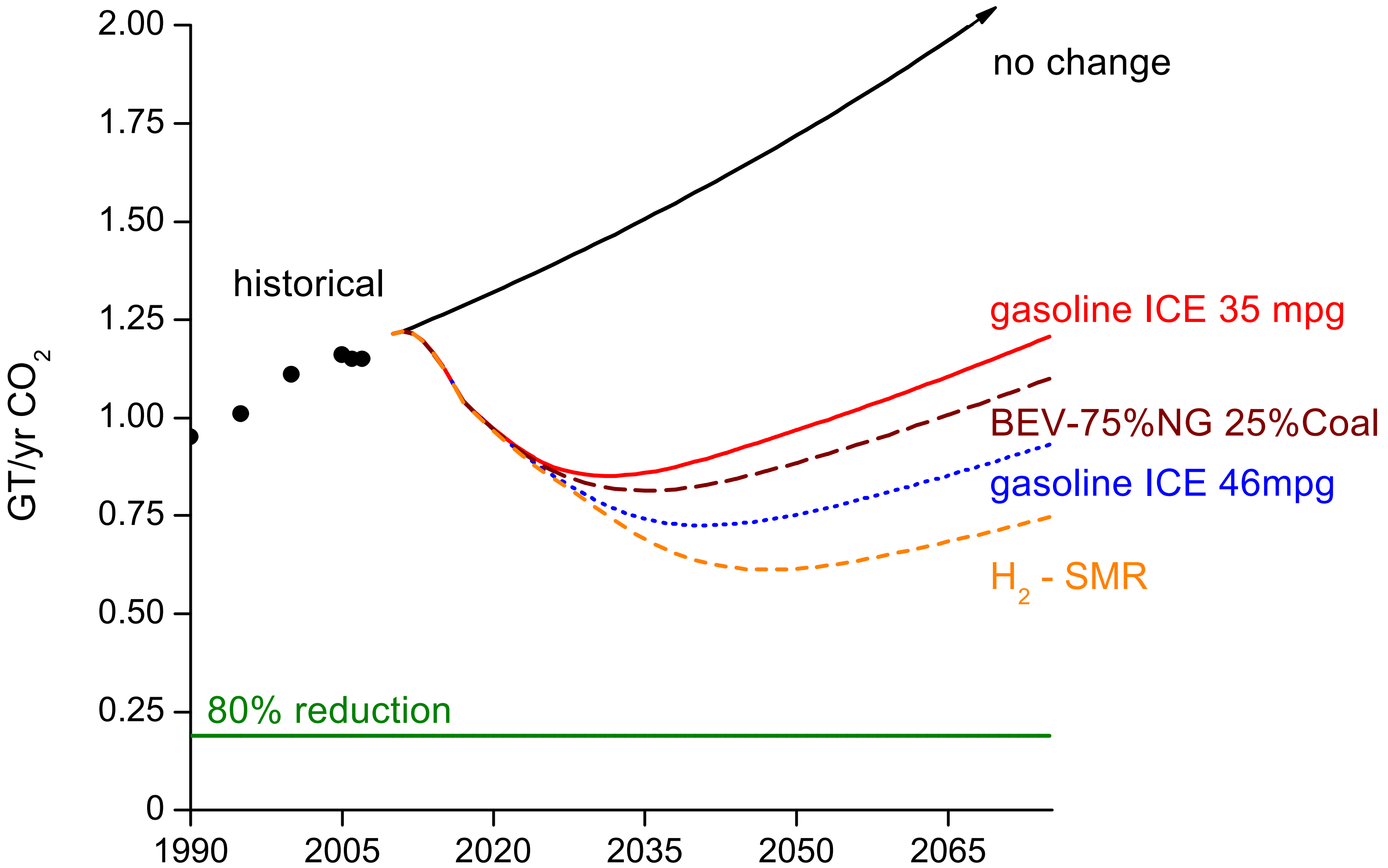
# The answers, of course, are "it depends."

Nissan Leaf EV

Honda Clarity HFCV

Ford Fusion Hybrid

# Using technologies and fuels that exist today, emissions trajectories are similar



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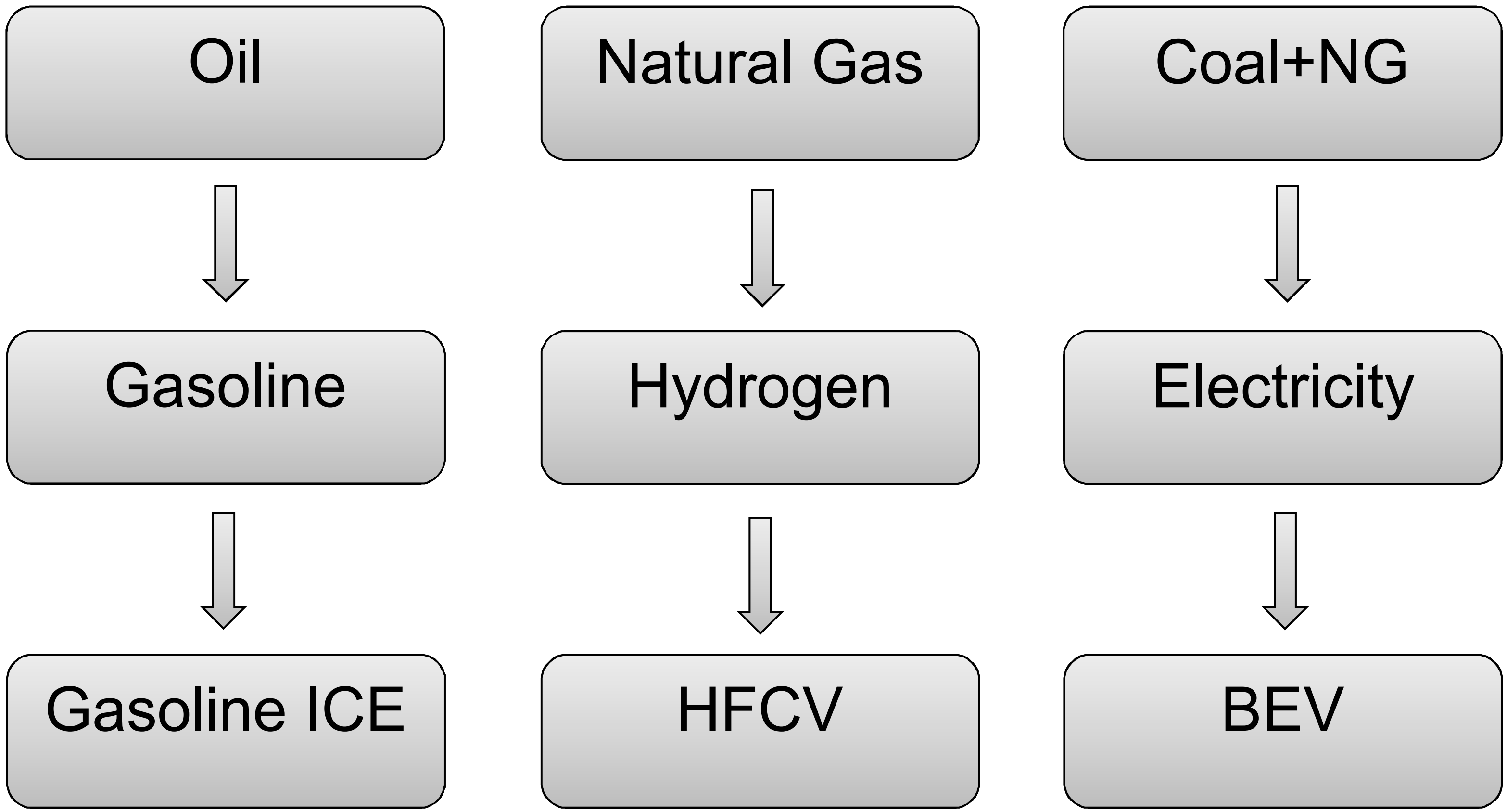
# Alternative fuel pathways will interact



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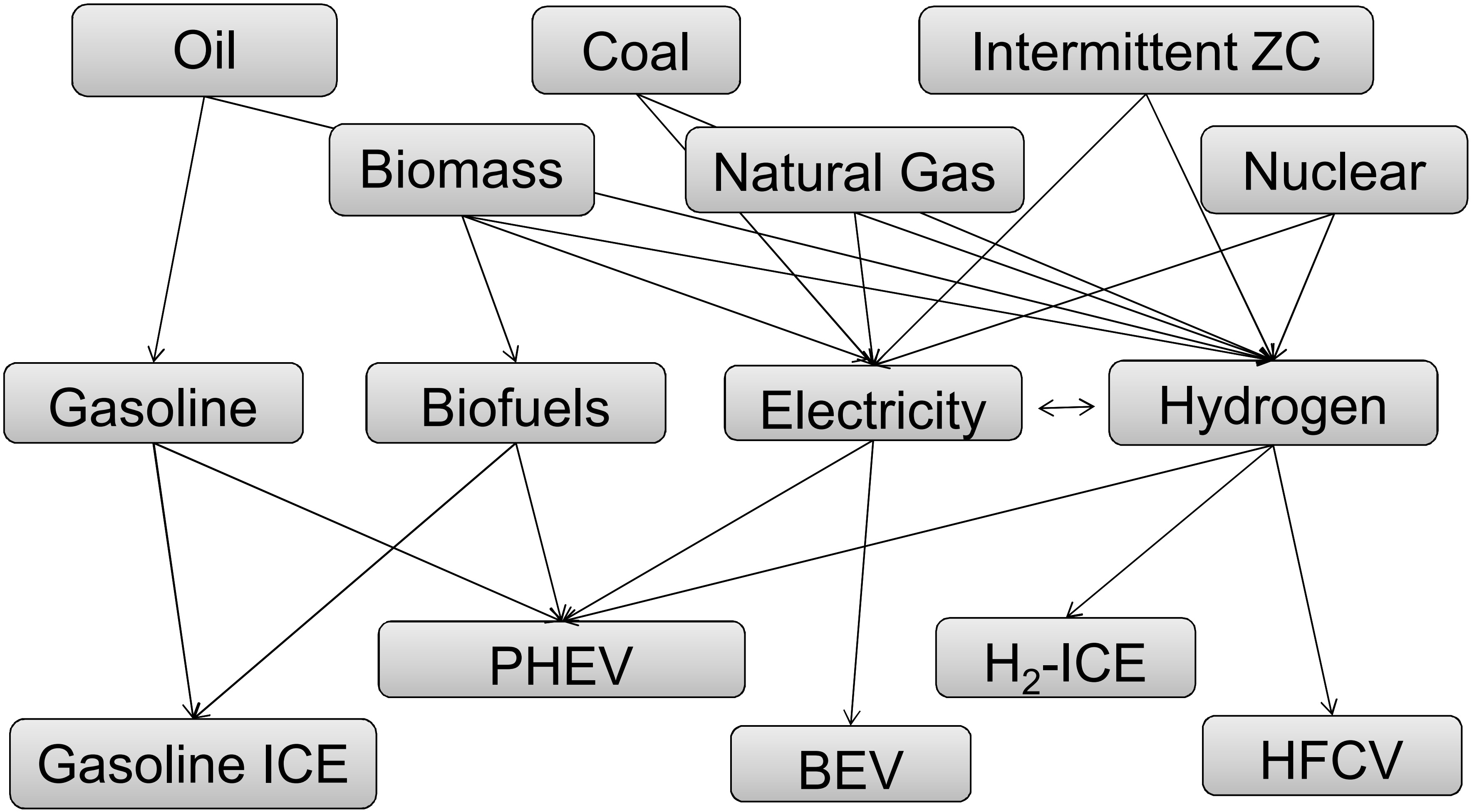

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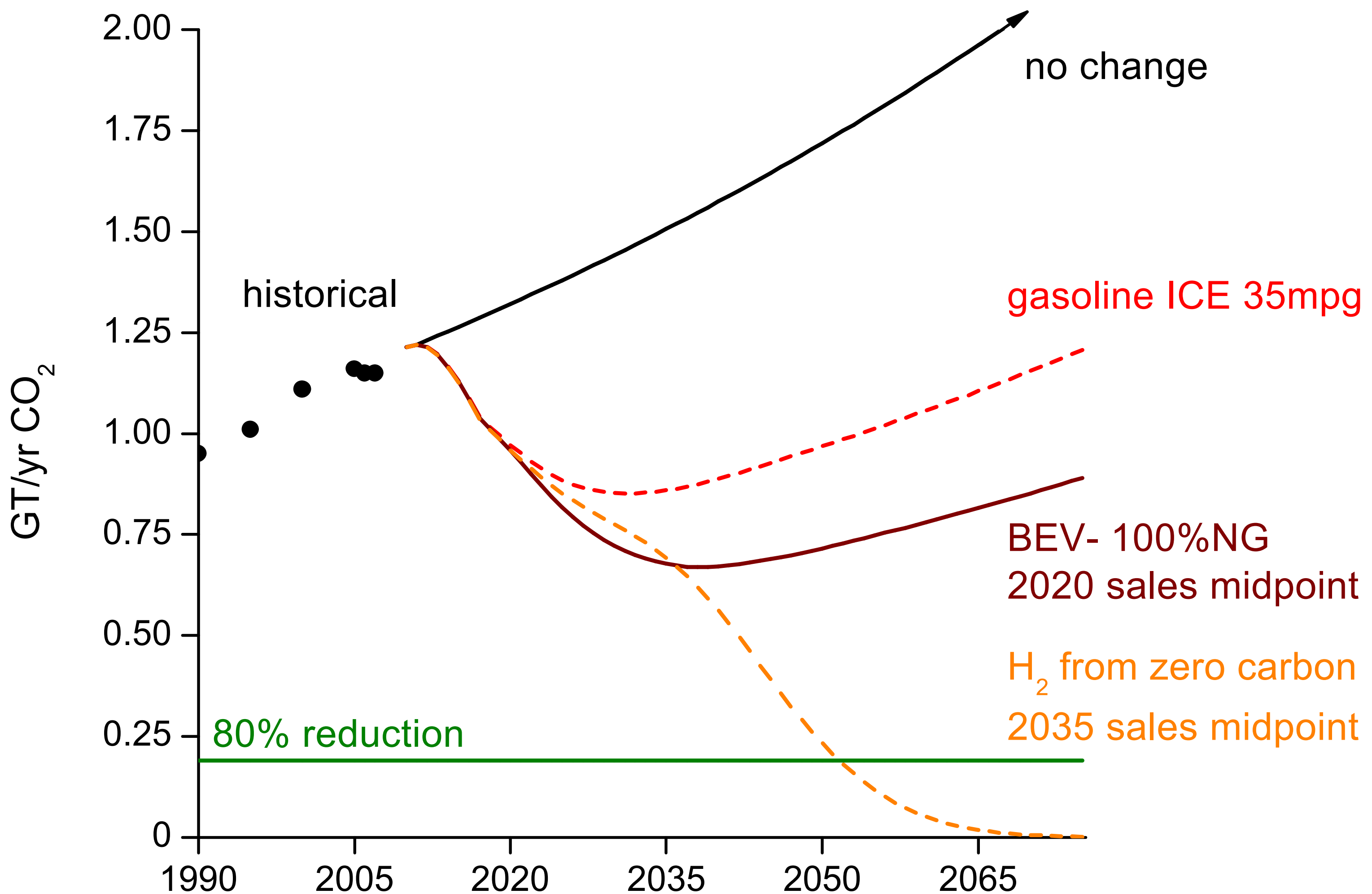
# The type of fuel-vehicle system is more important than the speed of implementation

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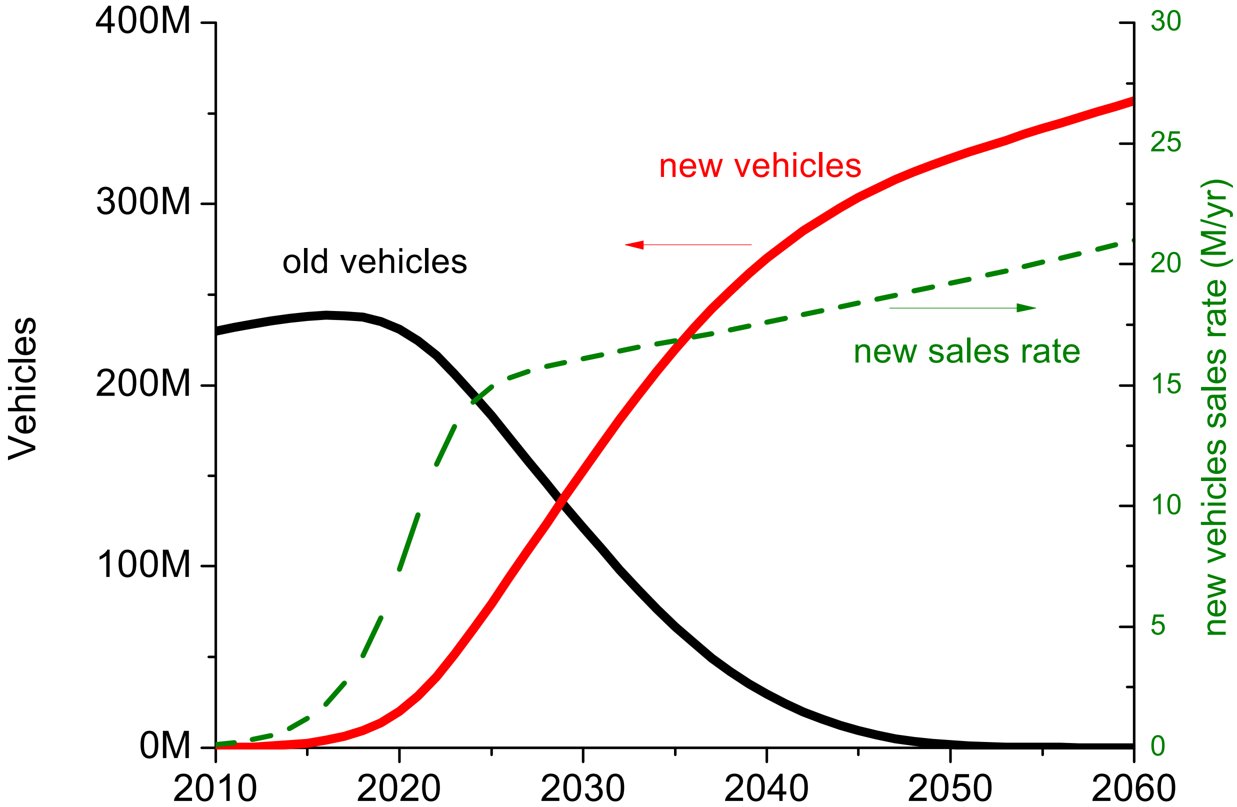
# The turnover rate for the installed vehicle fleet is slow



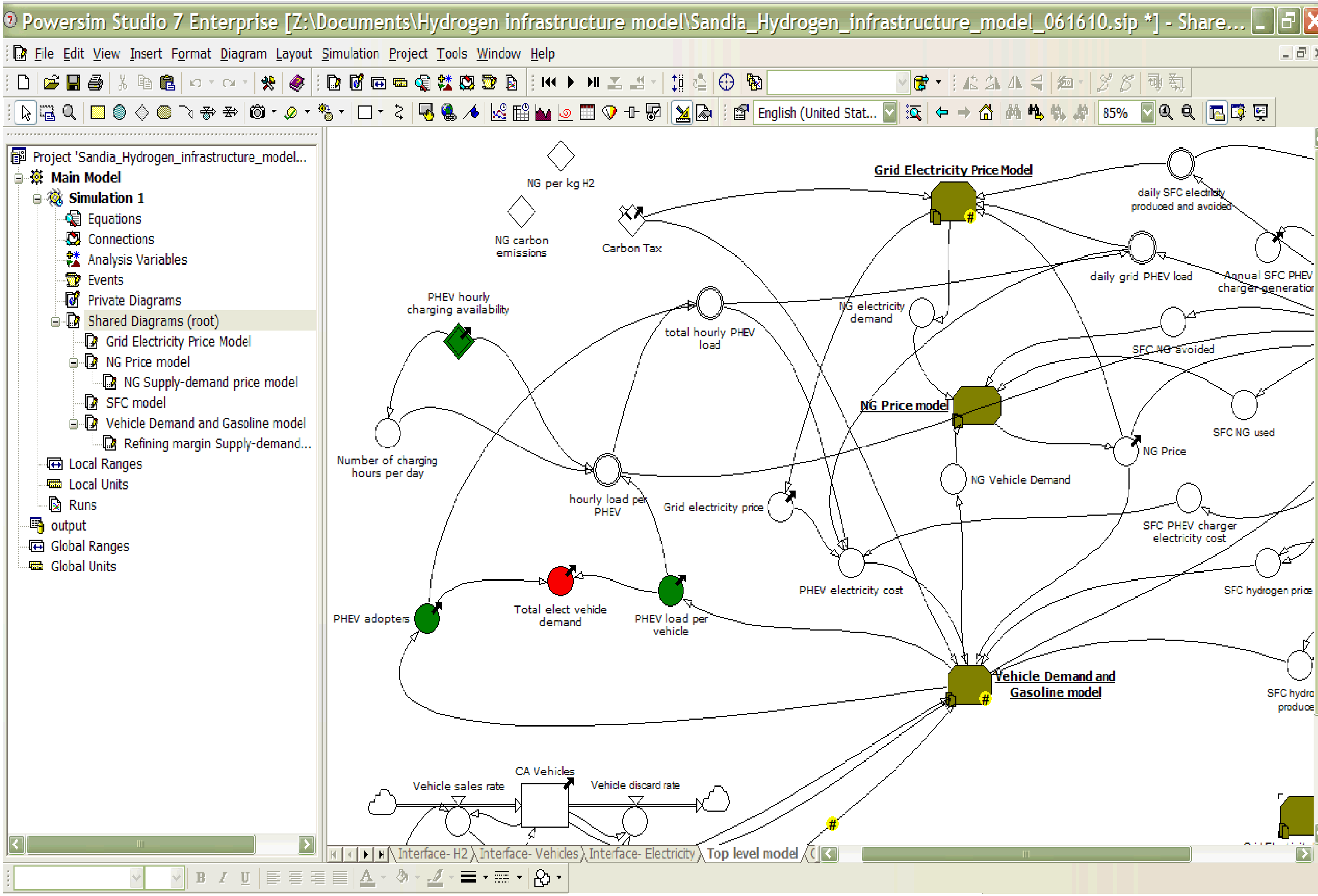

- 50% of sales in 2020 are of "new" type
  - Note: The Prius was introduced in the US in 2001. In 2010 the market share of all hybrids is only 2.2%

(+) Fueling infrastructure capacity only needs to grow with fleet

(-) Difficult to have serial technology transitions

# Approach

- System dynamics: Methodology
  - Choose a region to define the system
    - Selected California (CA) as first application
  - Pose detailed questions
    - What are the impacts of large-scale $H_2$-fueled vehicle market penetration?
    - Can stationary FC systems provide distributed $H_2$ production?
- System dynamics: Analysis
  - Formulate SD models of infrastructure components and interrelations to a sufficient level of detail to see interactions and dependencies
  - 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 by enabling sensitivity analysis.



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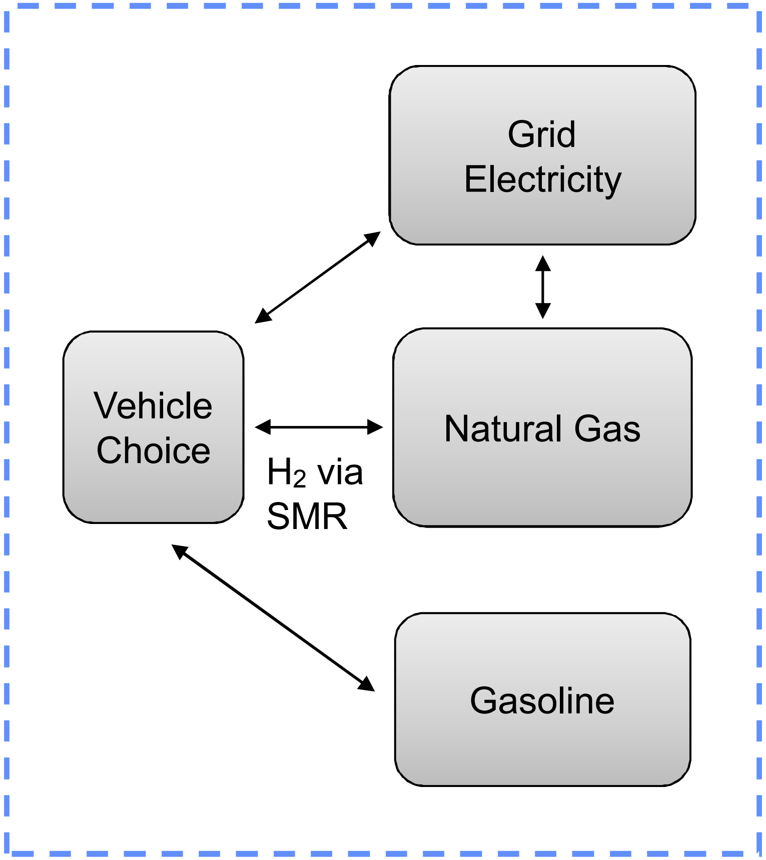
# Transportation model competes alternative vehicles with existing technology

Market Interactions

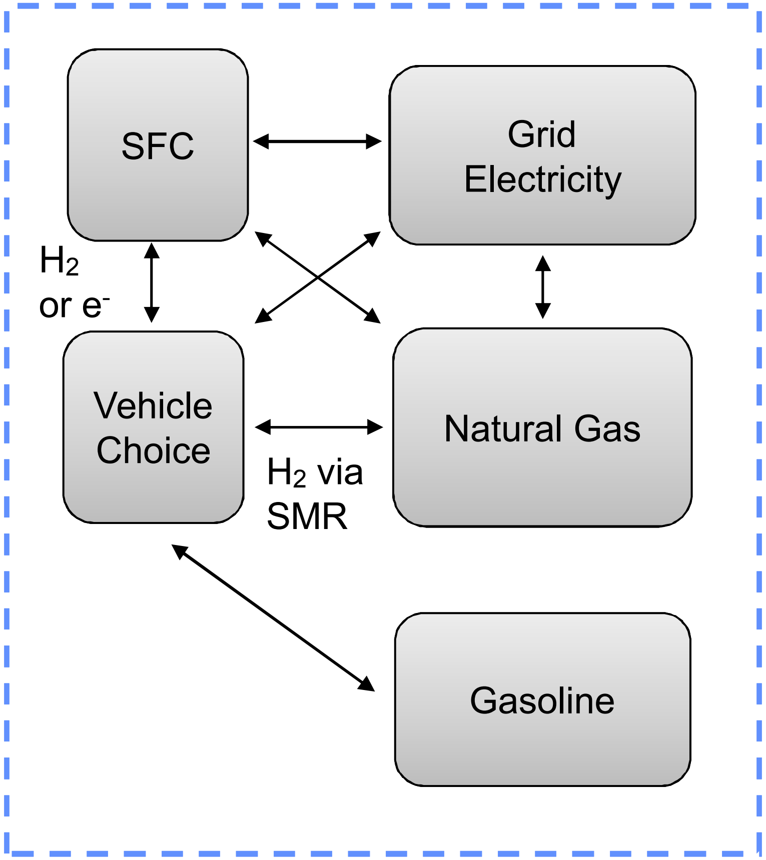
- Competition between PHEVs, HFVs, and future CAFE-compliant vehicles
  - Compete on fuel & vehicle costs
  - Vehicles coupled to electric, natural gas (NG), & gasoline markets
- In California, electricity demand strongly coupled to NG supply infrastructure
- Electric generation for Renewable Portfolio Std (RPS) will alter electricity sector
  - 33% by 2020



# SFC for distributed power generation and interactions with infrastructure

<u>SFC Penetration</u>

- Fixed penetration model
  - Not based on economic choice
    - uncertainty in future technology & costs
  - Use optimistic implementation goals
- SFC could potentially fuel alternative vehicles
  - Distributed hydrogen
  - Dedicated PHEV chargers



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# Assumptions

## Infrastructure Model

- Electric Supply
  - Marginal generation is NG
  - Other generation is "must run"
  - No elasticity in supply/demand
  - BEV/PHEV re-charged at night
- Natural Gas Supply
  - Supply elasticity for CA market
  - Imported and domestic supply
- Gasoline Supply
  - Oil price: linear projection
  - Elasticity for CA refinery supply
- Hydrogen Supply
  - Distributed SMR
  - Hydrogen from Stationary FC
  - Zero-carbon Hydrogen
    - exact path unspecified

## Vehicle Model

- Conventional vehicles
  - Gasoline fueled: 20 m/g today
  - CAFE regulation: 35 m/g by '16
- Plug-in Hybrid Electric Vehicles
  - 48 m/g in gasoline mode
  - 0.35 kWh/m electric mode
  - 1/3$^{rd}$ of miles in gasoline mode
    - 40-mile electric range
- Hydrogen Fuel Cell Vehicles
  - 70 m/kg
- Vehicle adoption
  - Adjusted to Greene *et.al.* (ORNL, '08)
  - 6% yearly sales rate
  - 20 year vehicle lifetime
    - 5% scrap rate

# Assumptions (cont'd)

## Stationary FC Model

- Large Scale: 300 - 500 MW
  - High Temp FC system
  - NG operation with internal reforming
  - 47% NG to electric efficiency
  - 30% NG to heat in CHP mode
  - 10% NG to elect. displaced by chilling
  - 15% to $H_2$ in co-production mode
    - Reduce electric efficiency to 40%
  - Size to meet electric load
    - Use heat or cooling when load exists
- Small scale: 2 - 5 kW
  - Polymer Electrolyte Membrane (PEM)
  - NG operation with integrated reformer
  - 40% NG to electric efficiency
  - 30% NG to heat in CHP mode
- Small scale: 2 kW
  - PEM FC as dedicated PHEV chargers
  - No integration to house electricity

## Stationary FC Applications

- Commercial
  - Hotels, Hospitals, Office
  - Large scale systems
  - Combined heat or $H_2$ and power
- Residential
  - Small scale systems
  - Distributed power
  - Limited to fraction of residences with 2 kW average load
- PHEV charging
  - Overnight charging
  - Avoid local distribution issues for utilities



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# Dynamic model couples energy markets to vehicle adoption model

## Natural Gas

- Supply:
  - Imports & in-state production
- Demand:
  - Electric generation
  - Industrial, commercial, residential, and CNG vehicles (fixed)
  - HFCV demand from SMR
  - Demand from SFC systems
- Price:
  - Market elasticity
    - Long & short term
  - Determines $H_2$ price

## Electricity

- Supply:
  - Imports (31% in 2007)
    - Coal (54% of imports)
  - In-state production
    - Must-run: nuclear, hydro, geo, solar, wind, biomass
    - Variable: NG
  - Distributed production by SFC in large building & homes with CHP
- Demand:
  - Hourly load data (Cal-ISO)
  - Daily PHEV charging
  - Building demands for distributed SFC
- Price:
  - Weighted average of costs
  - SFC electricity priced by fixed & variable costs

## Gasoline

- Supply:
  - Refinery capacity for CA compliant gasoline
- Demand:
  - Conventional and PHEV consumption
- Price:
  - Oil price specified in time
  - Refining margin modeled with market elasticity
    - Short-term elasticity for supply
    - Long-term elasticity identifies major capacity additions



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# Model provides a tool for examining a range of conditions

- Key model input parameters
  - Vehicles:
    - HFV mileage; learning curve; consumer acceptance; battery vs plug-in; daily charging profile; gasoline mileage improvements (CAFE or advanced ICE); $H_2$ production alternatives (low-carbon); sales/discard rates
  - SFC:
    - Electric efficiency; combined heat/cooling factors; matching of heat, cooling, & electric loads with demand; $H_2$ co-production; fixed & variable costs of electricity & $H_2$; penetration rate in building types
  - Grid electricity:
    - Baseload, marginal, & new generation; growth in demand; changes in nuclear, coal, NG, & renewable generation
  - NG:
    - Import capacity; domestic production; demand growth (other than vehicles or electric)
  - Other: carbon tax



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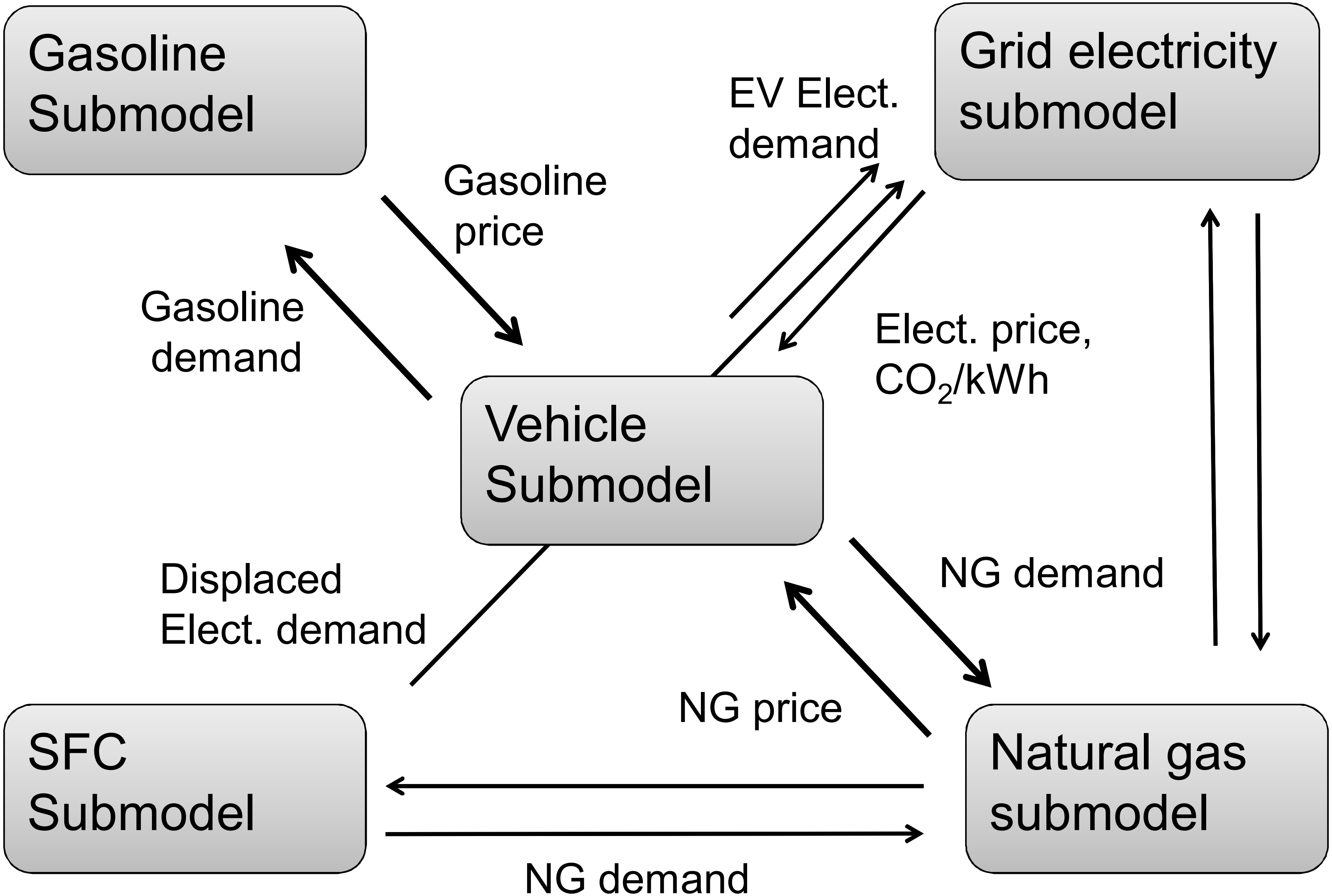
Gasoline Submodel
Grid electricity submodel
EV Elect. demand
Gasoline price
Gasoline demand
Elect. price, $CO_2$/kWh
Vehicle Submodel
Displaced Elect. demand
NG demand
NG price
SFC Submodel
Natural gas submodel
NG demand

# Vehicle adoption model competes PHEV and HFCV with conventional vehicles

- Adoption follows elements of Struben & Sterman model (MIT)
  - Willingness to adopt parameterized by marketing and word-of-mouth
  - Affinity of vehicle choice depends on
    - Fuel cost, vehicle incremental cost, efficiency (mileage)
- Adjusted to penetration Scenario #1 of Greene et al (ORNL) 2008 study
  - On-road HFCV 1% of fleet by 2025
  - Plug-in vehicles replace hybrids
- Vehicle penetrations are sensitive to
  - HFCV:
    - $H_2$ price (from NG price)
    - HFCV mileage: reference=70 miles/kg
  - PHEV:
    - Electricity price

Sales fraction

$$\sigma_H = \frac{W_H \cdot a_H}{\sum W_n \cdot a_n}$$

Affinity:

$$a = e^{(\frac{u}{u_0})\cdot \beta} \qquad u = \frac{\text{miles}}{\$}$$

Willingness to adopt:

$$\frac{dW_H}{dt} = \left( m + (n \cdot W) \cdot (\frac{V_H}{V}) \right) \cdot (1 - W)$$



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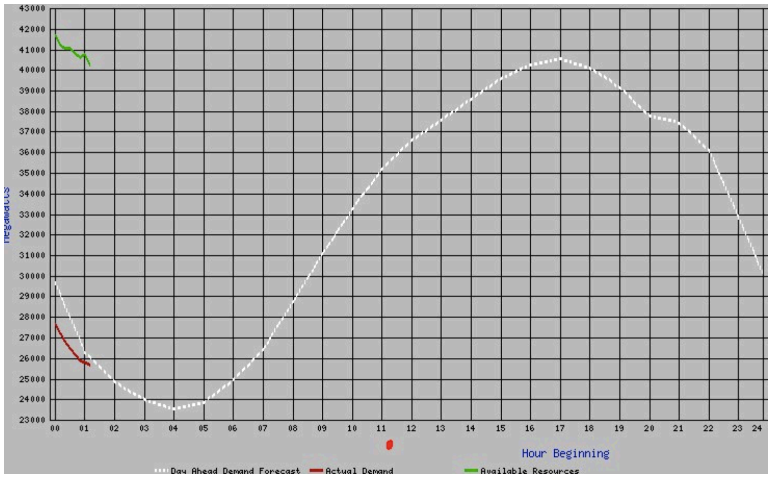
# Electric dispatch model

- Electricity model has two submodules: grid and SFC. SFC has priority over grid power.
- Electric grid model uses three categories of generation: must-run, marginal, and peak. For CA, marginal is modeled as natural gas.
- Generation is allocated to meet demand on an hourly basis. Demand is calculated by adding EV charging profile to existing hourly load data from CA ISO. Generation for intermittent sources is modified on hourly and seasonal basis.

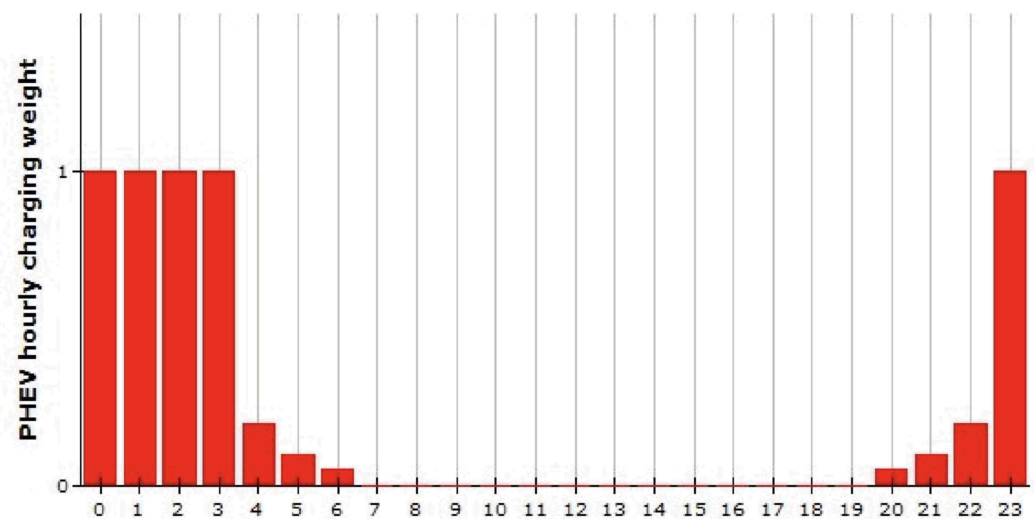
# Electric dispatch model



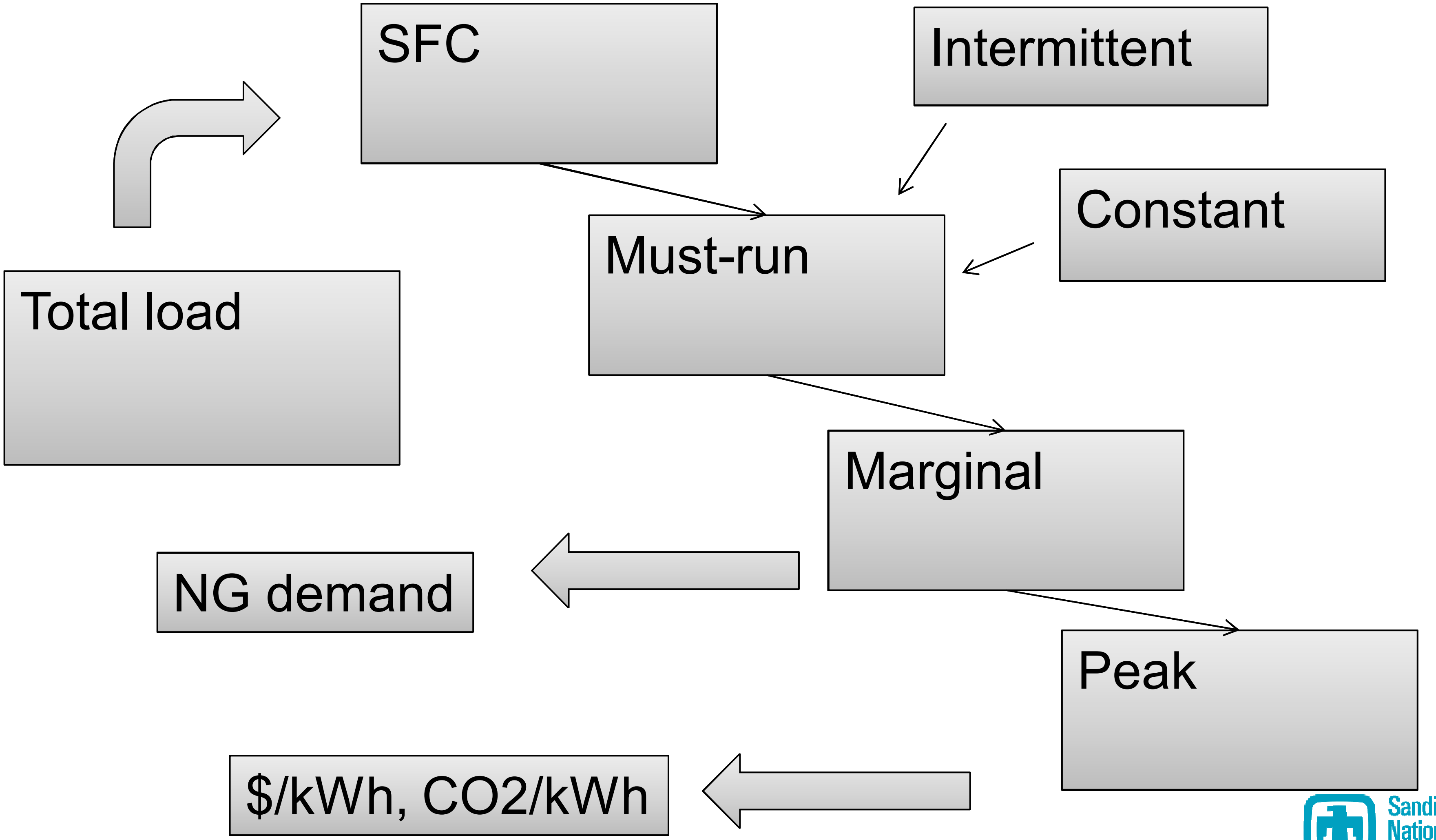

Growth factor

Total load

Number of EV



# Electric dispatch model



# SFC model logic

- Proscribe SFC penetration rate in different building types.
- Currently model large office, large hotel, high-use residential, and dedicated FC for PHEV charging.
- SFC matches electric load.  Heat/Cooling demand (with with hourly and seasonal variation) is matched against heat available.
- SFC heating displaces building NG usage.  SFC cooling reduces building electricity demand.
- If hydrogen production is enabled, electric efficiency is reduced.



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# Fuel supply/demand model

- Natural gas and gasoline use supply/demand models for pricing.
- Long and short run elasticities are used.
- Supply is not explicitly limited, instead feedback loops reduce demand when excess supply is low.

$$\frac{dP}{dt} = \frac{P^* - P}{\tau}, P_{t=0} = P_{ref}$$

$$P^* = P \cdot \left(\frac{D}{S}\right)^{\beta}$$

$$S = S_{ref} \cdot \left(\frac{P}{P_{ref}}\right)^{E_s}$$



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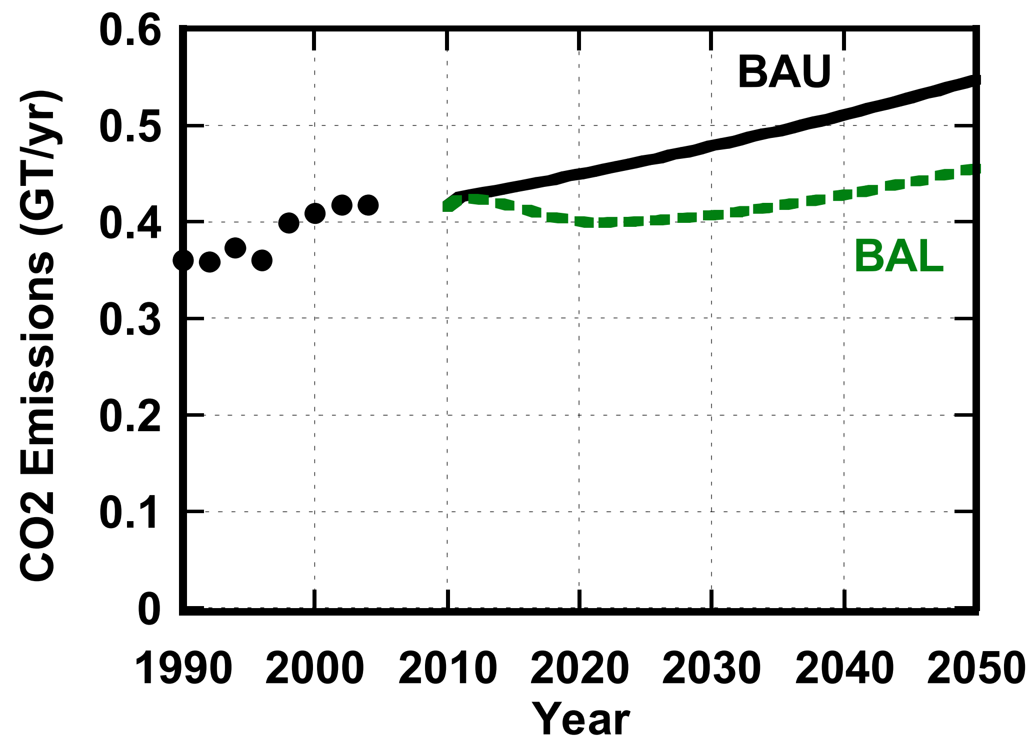
# Baseline scenarios for California's $CO_2$ emissions

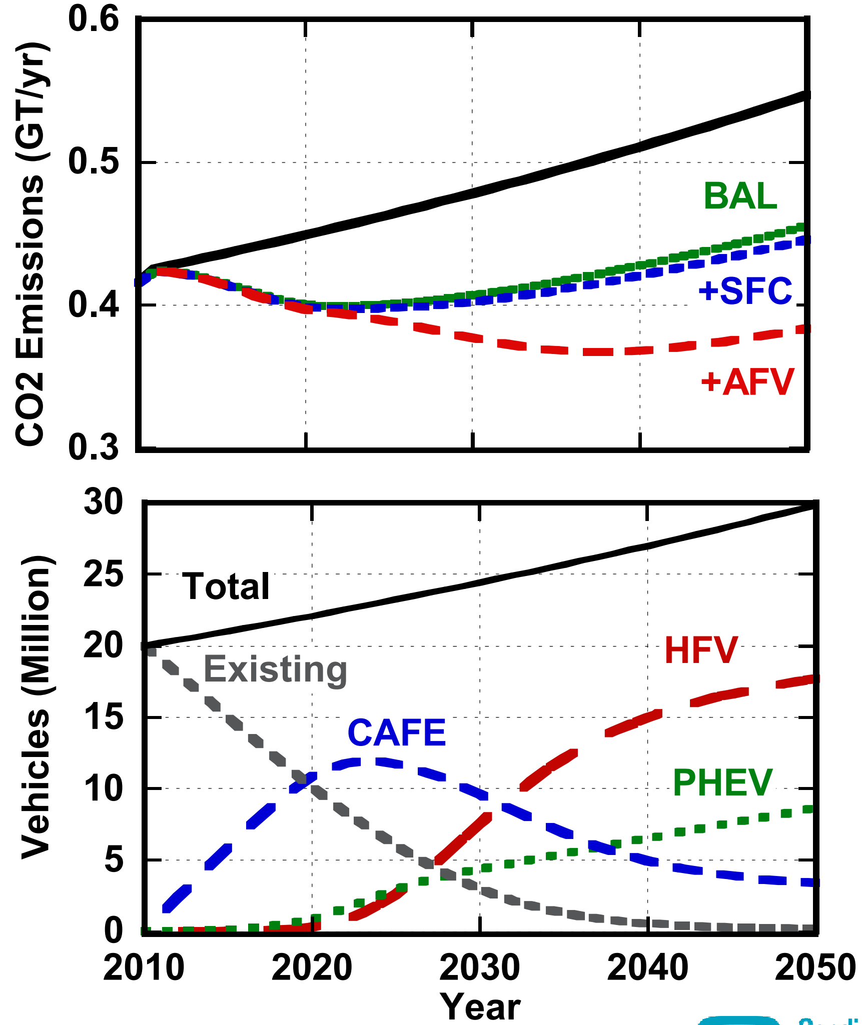
- BAU is 1% / yr growth for:
  - Vehicles
  - Electricity demand
- Data points: CEC
  - Gross $CO_2$ all sectors
- Start with "BAL" scenario
  - Business-as-Legislated
  - CA's Renewable Portfolio Standard
    - 33% by 2020
  - US CAFE regulation on LDV
    - 35.5 mpg by 2016




Existing Legislation to give 18% reduction

# $H_2$ Fueled Vehicles significantly reduce $CO_2$ emissions

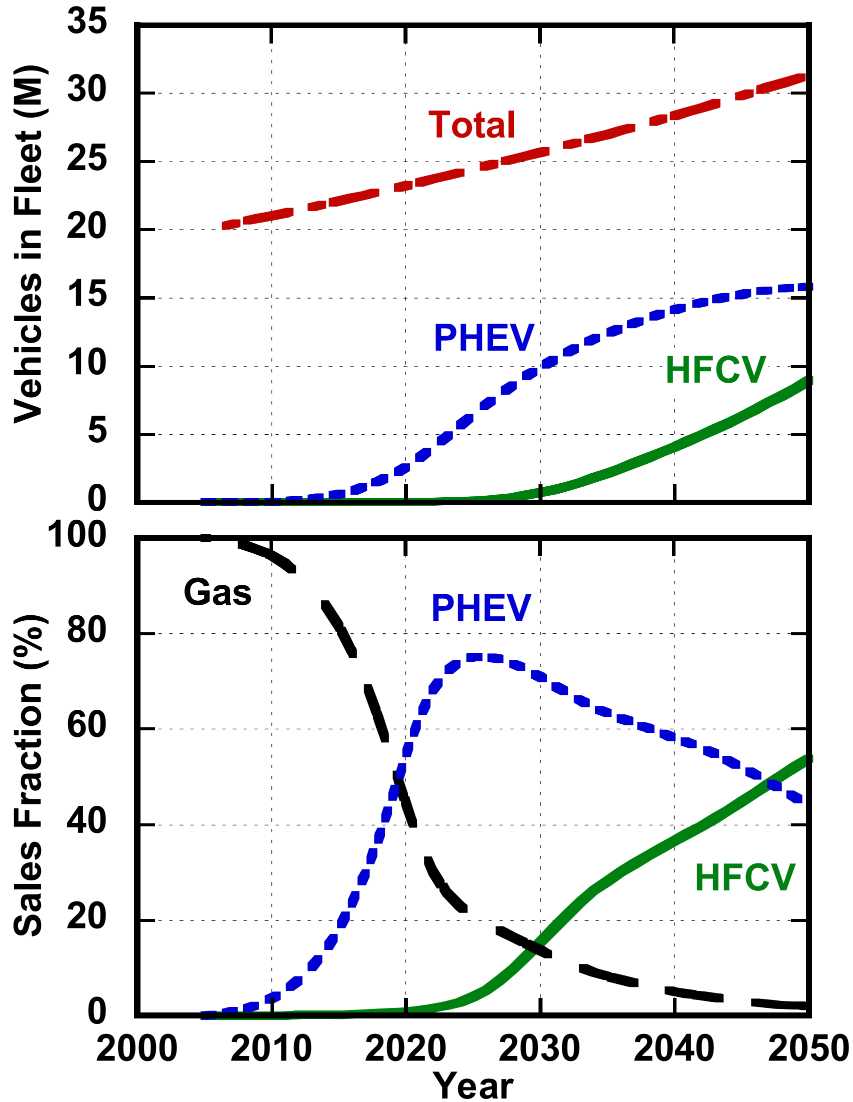
- Use vehicle adoption parameters set to match optimistic Alternative Fuel Vehicle (AFV) scenario
  - AFV includes HFV & PHEV
- Beyond minima at 2040, $CO_2$ emissions increase
  - Continued fleet growth
  - Lack of C-free fuel
- $H_2$ Fueled Vehicles (HFV) make ~ ½ of fleet by 2050
  - Efficiency advantage
    - 70 m/kg $H_2$
  - PHEV suffer from gasoline use
    - $H_2$ @ 4.00 $/kg
    - Gas @ 4.50 $/gal



Tour of model

# HFCVs must achieve high mileage to be cost-effective

- HFCV mileage
  - Reference case: 65 m/kg
  - At 55 m/kg, affinity for HFCV is less than affinity for PHEV
- PHEV mileage
  - 48 m/g in gasoline mode
  - 0.35 kWh/mile electric mode
  - 1/3rd of miles in gasoline mode
    - Based on National Household Travel Survey
    - 40 mile electric range



Model Demo- Vehicle Parameters

- $H_2$ mileage
- ICE miles
- PHEV properties



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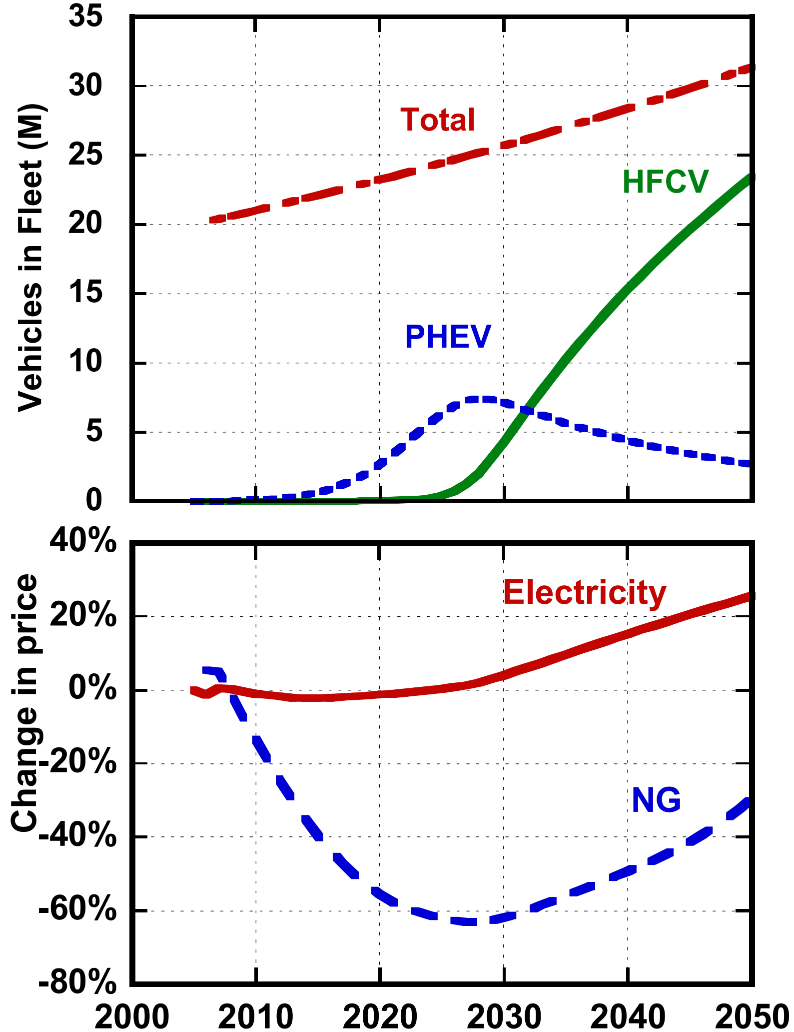
# Aggressive renewable electricity frees NG supply and increases HFCVs

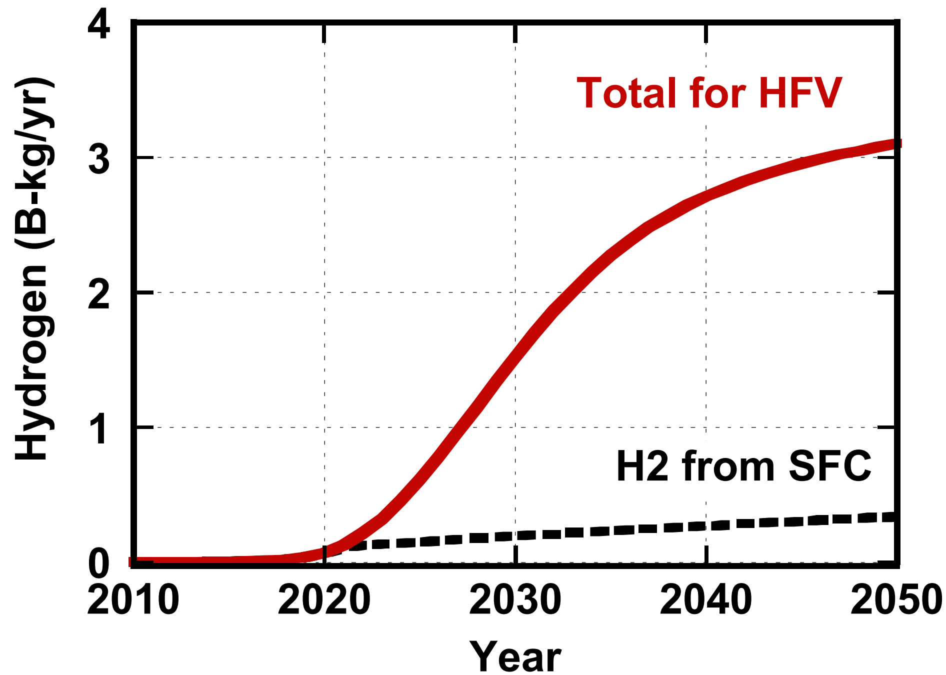
- Increasing renewable power
  - reduces NG demand
  - increases electricity price
  - HFCVs sales rise quickly in response to low NG price
- California's goal of 33% renewable electricity by 2020 requires over 1000 MW/yr of new renewable capacity
  - At linear rate of capacity increase, would result in 78% renewable power in 2050
- Caveat: model does not consider limits to potential for renewable power



# Penetration of SFC systems can provide significant $H_2$ for vehicles

<u>$H_2$ from SFC</u>

- $H_2$ available:
  - Fraction of NG input = 15%
    - Assume 85% $H_2$ utilization in FC
  - Reduced electricity efficiency of FC from 47% to 40%
- SFC provide 11% of $H_2$ demand
  - Supply 2 Million $H_2$ vehicles




<u>SFC dedicated to EV charging</u>

- Cost effectiveness is dependent on SFC capital and maintenance costs
- Effect on $CO_2$ emissions is minimal in regions with NG as marginal supply
- Caveat: utility distribution concerns are not addressed by model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Carbon tax variations

carbon tax

electricity source



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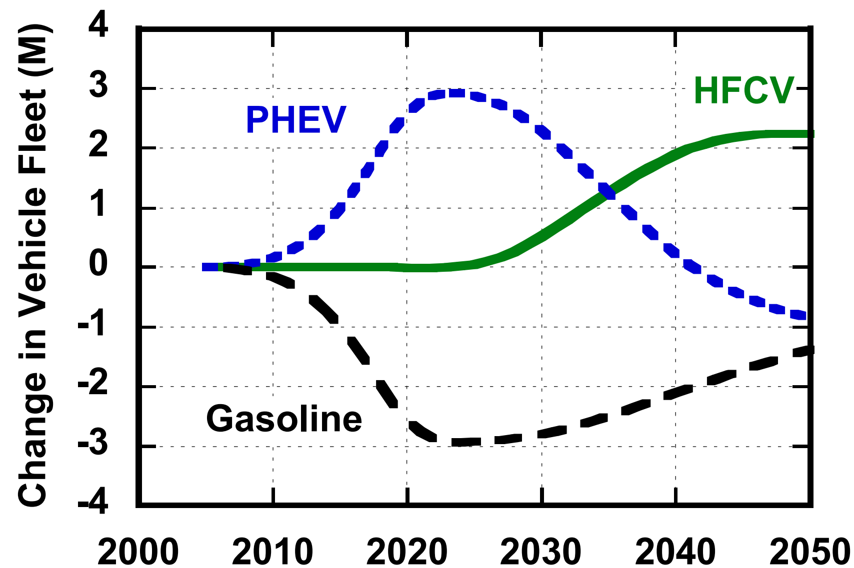
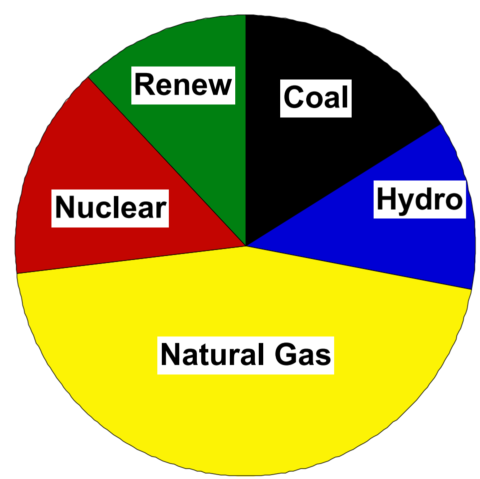
# Carbon tax increases both PHEV and HFCV - at least for CA

- Change in vehicle fleet compared to non-taxed reference case
- Additional CA electricity generated from NG
- Conclusion not likely true for other regions!
- Carbon Tax at 200 $ / tonne
  - 1.76 $/g gasoline
  - 1.85 $/kg $H_2$
  - 0.11 $/kWh electricity
- Tax influence on fuel cost
  - PHEV ~ 4 ¢ / mile tax
  - HFCV ~ 3 ¢ / mile tax
  - Gasoline ~ 9 ¢ / mile tax

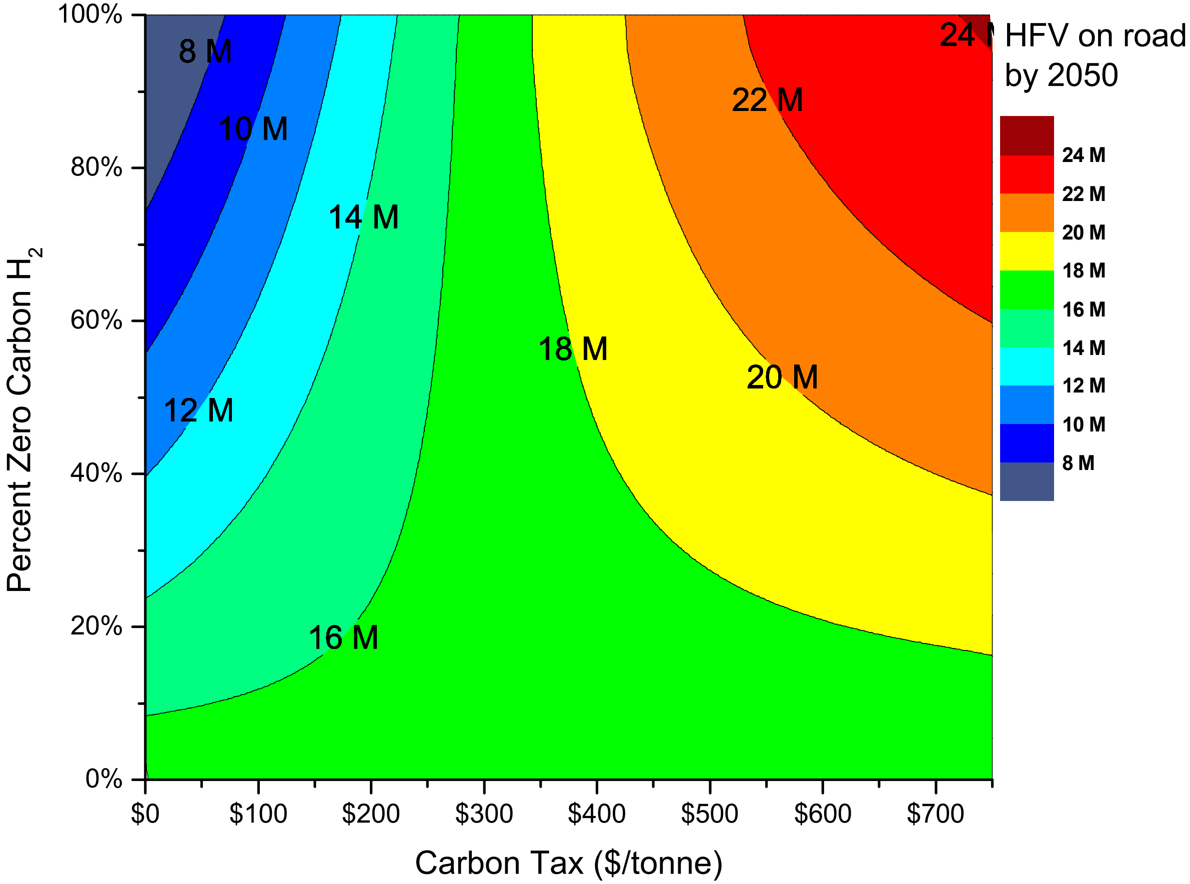



California Electricity



# Higher price of zero-carbon $H_2$ requires a carbon tax to spur HFV sales

- Contours of HFV quantity on road by 2050 based on 1000 simulations
- Hydrogen supply:
  - Zero-carbon $H_2$ at \$6/kg
  - SMR $H_2$ at ~\$4/kg before C-tax
- At low penetration of zero-carbon $H_2$, carbon tax has little impact on HFV sales
- More zero-carbon $H_2$ requires larger carbon tax to motivate HFV sales



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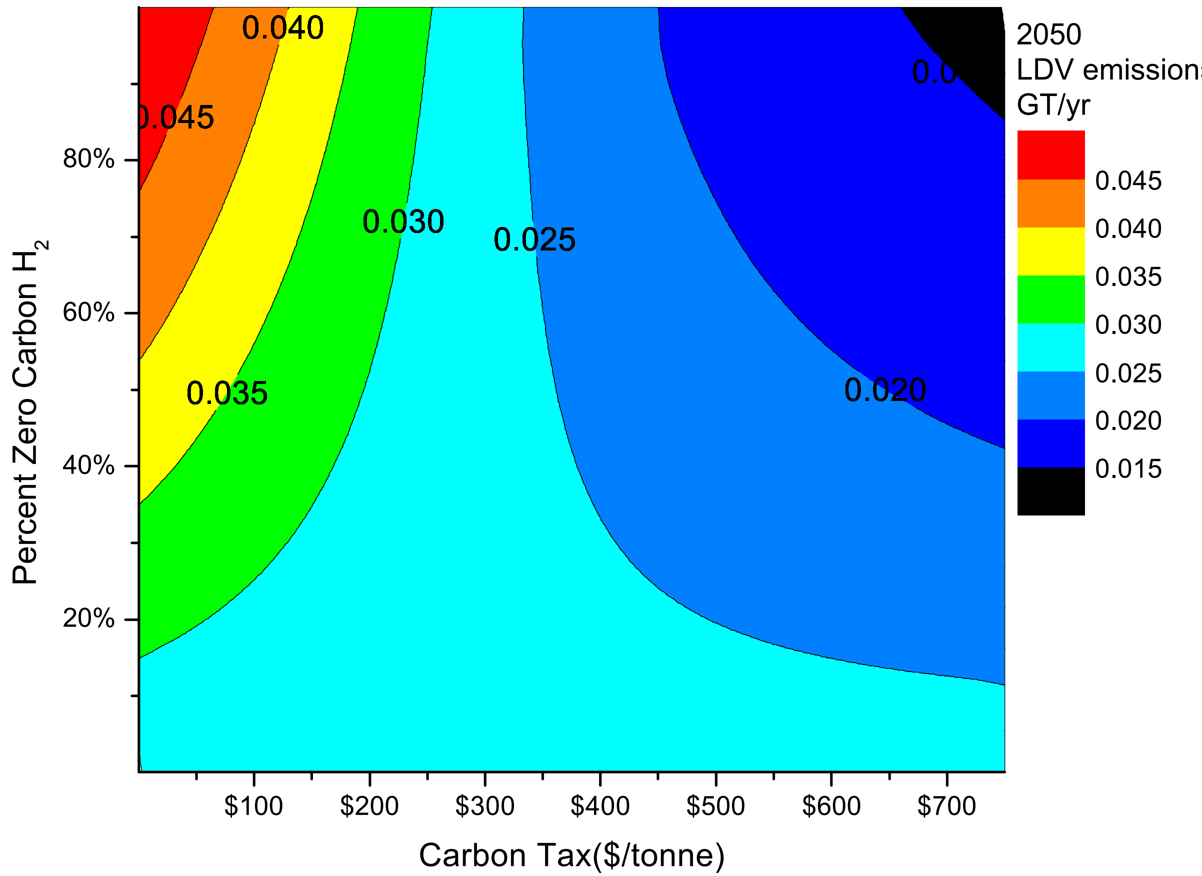
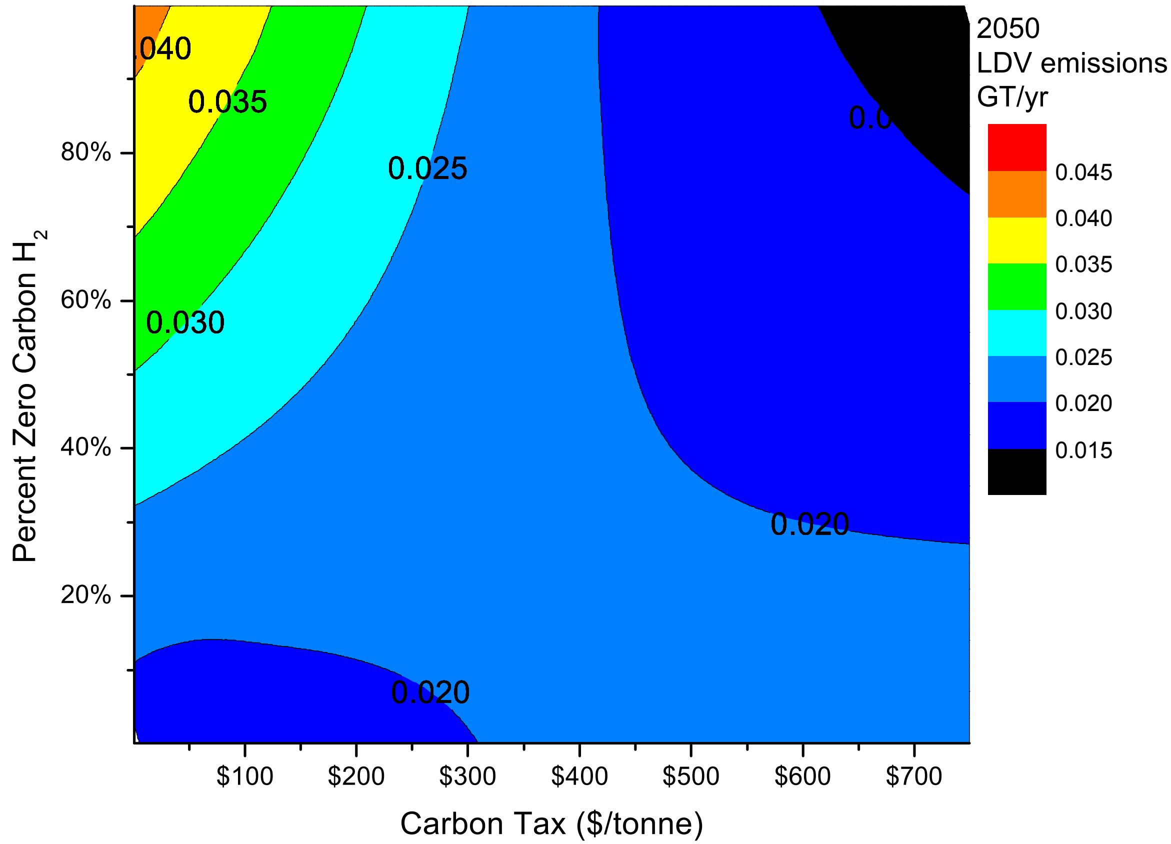



**Carbon tax does not effect emissions without a zero-carbon option.**

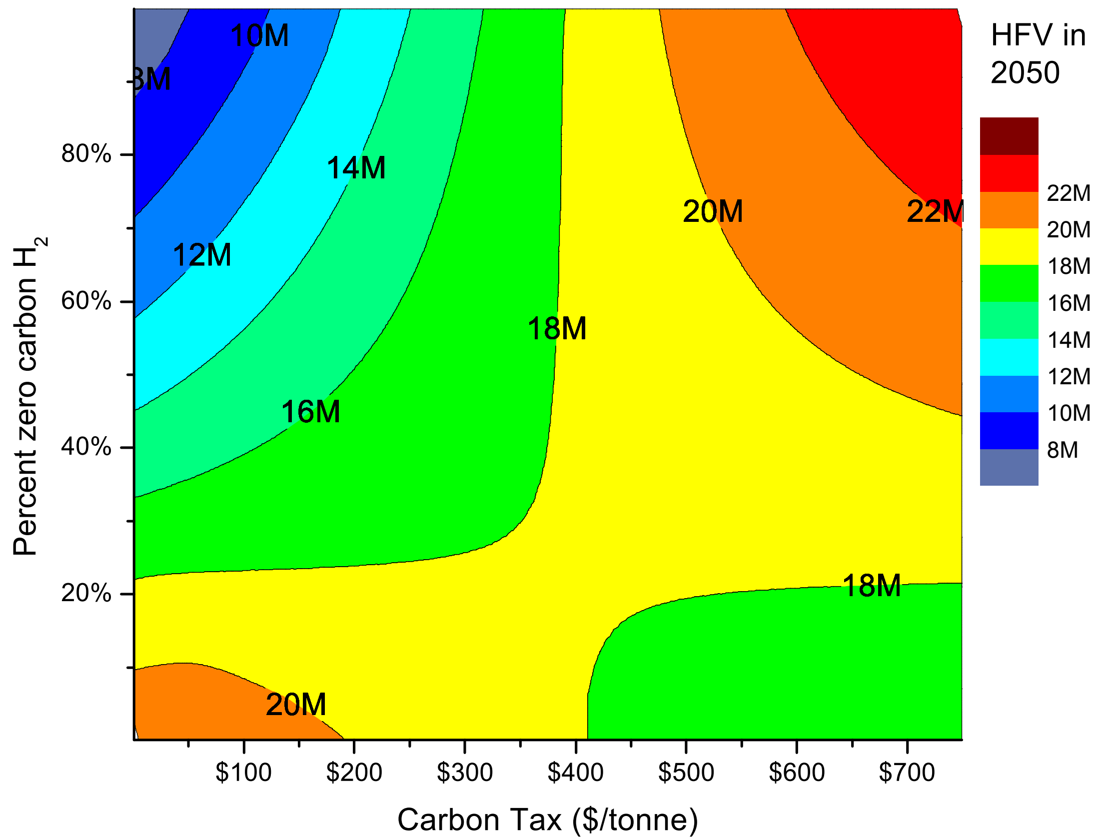
# Adding other sources of zero-carbon fuels gives lower emissions

- Add 3-fold higher zero-carbon electricity than CA RPS default case (33GW by 2020)
- Emissions are lower than the default case
- Emissions at large carbon taxes and no zero-carbon $H_2$ rise slightly due to increasing dependence on natural gas for electricity



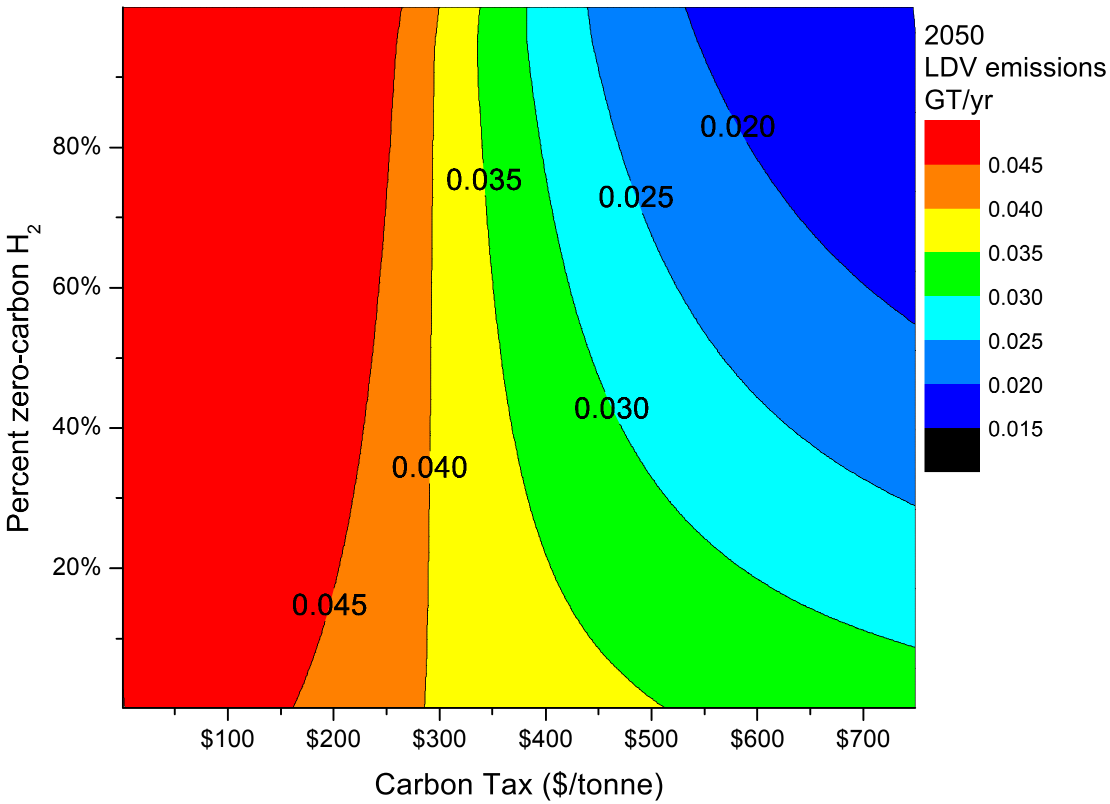
# Adding other sources of zero-carbon fuels gives lower emissions

- Add 3-fold higher zero-carbon electricity than CA RPS default case (33GW by 2020)
- Hydrogen vehicle sales are higher due to cost of zero-carbon electricity.



# Very high carbon tax is required to offset coal-fired power

- Using coal in place of natural gas increases emissions
- High carbon tax is required to achieve the emissions of default case
- Achieving a low emissions target is very difficult



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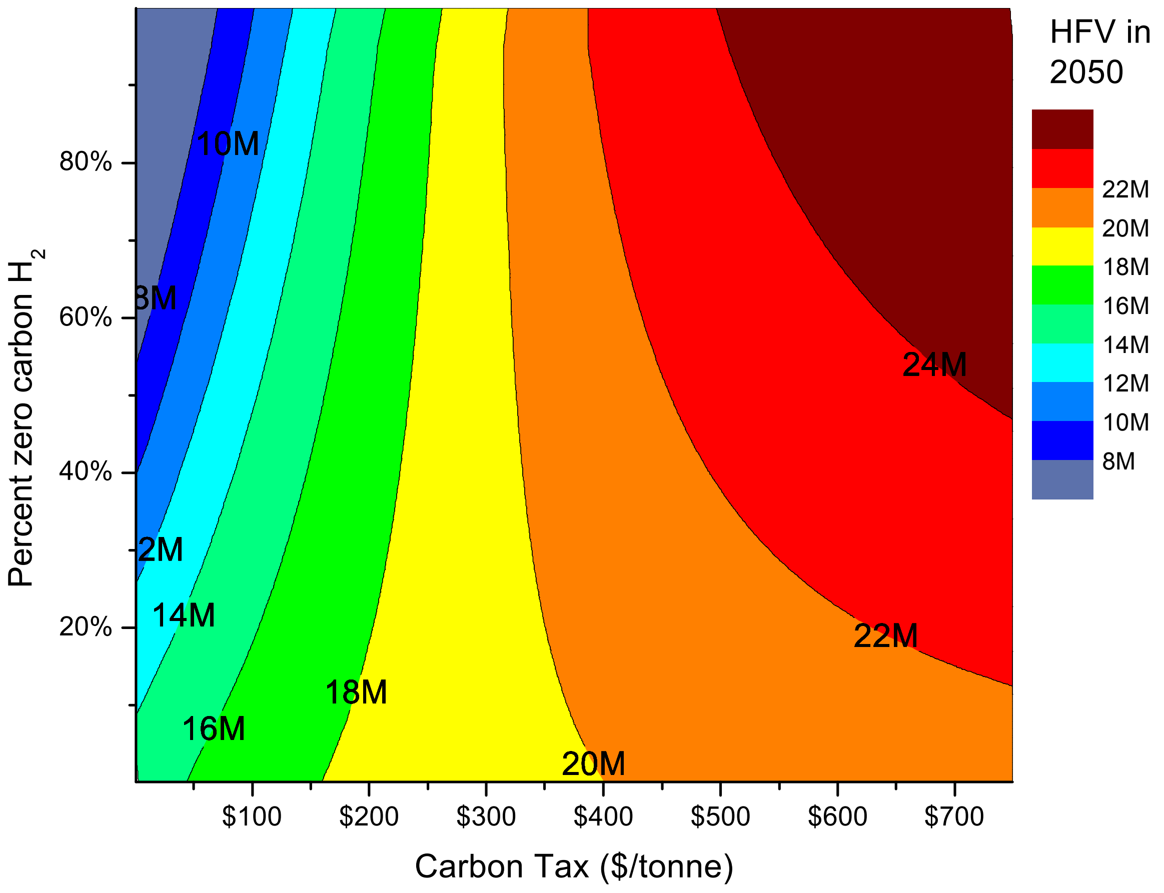
# Regions with coal electricity and zero-carbon hydrogen are very sensitive to carbon pricing

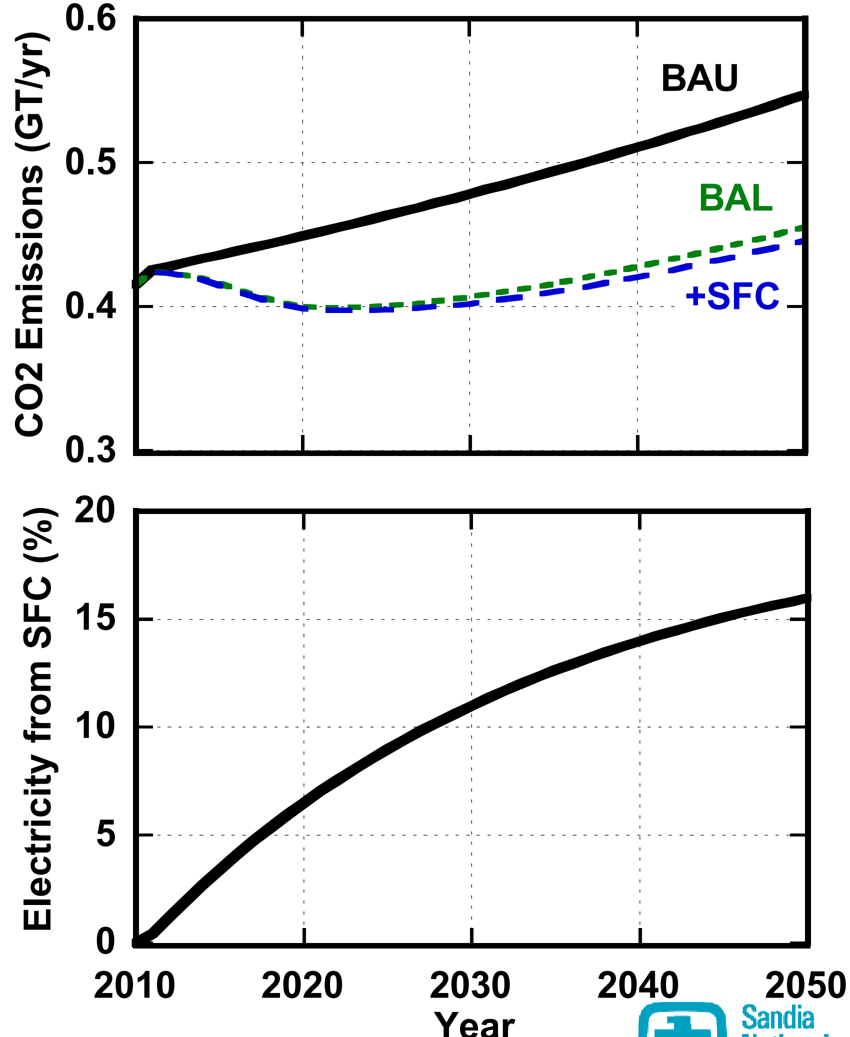
- Hydrogen vehicle penetration is sensitive to carbon tax, especially at high levels of zero-carbon hydrogen



# Optimistic Stationary FC penetration leads to a small effect on $CO_2$ emissions

- Blue scenario is optimistic SFC penetration in:
  - Large buildings (offices, hotels)
  - High-use homes
- By 2050:
  - SFC capacity = 10 GW
    - Matches CEC Assessment (2005) of CHP potential in CA
    - State load varies 30 – 70 GW
  - SFC generation = 67 TWh
    - CA Total = 420 TWh
    - 16% of electric demand
  - SFC reduces $CO_2$ emissions ~2%

| | Units (1000) | Size (kW) | Capacity (GW) |
|---|---|---|---|
| Offices | 7 | 400 | 2.7 |
| Hotels | 8 | 250 | 1.9 |
| Homes | 1300 | 4 | 5.2 |



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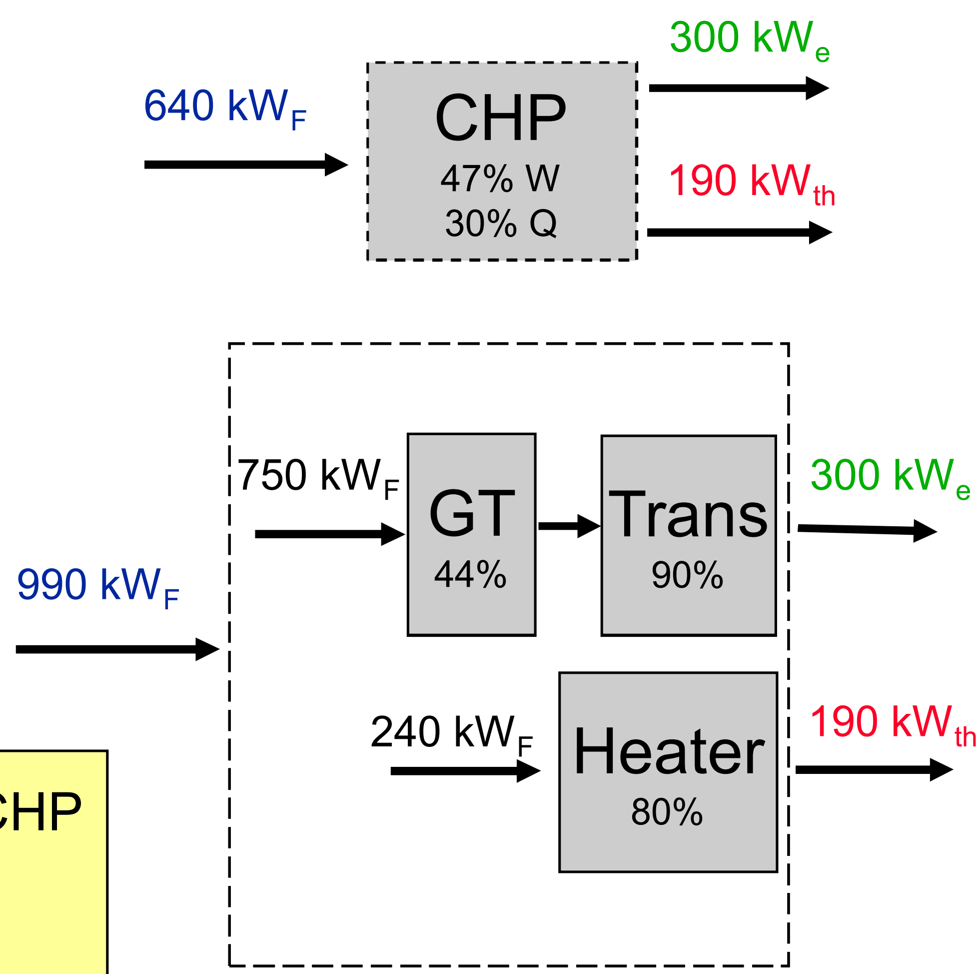
# Why is the impact of SFC on California's $CO_2$ emissions so limited?

- Efficiency improvement, but same marginal fuel
  - Displacing NG generation at 40% by SFC on NG at 40-47% (electrical)
- CHP benefit?
  - Compare to existing infrastructure:
    - Gas Turbine & Heater

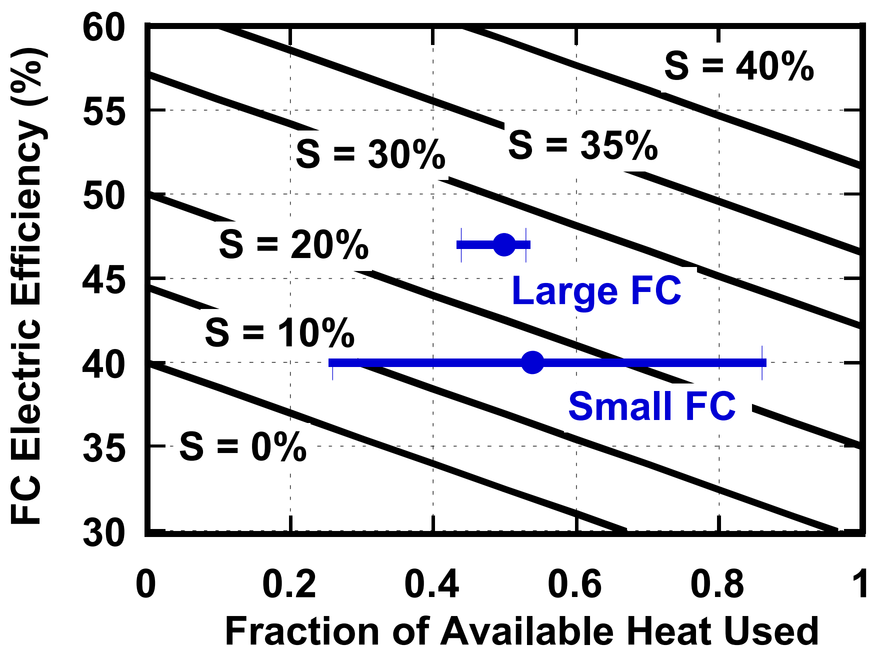



Maximum Fuel Savings by SFC + CHP

$$S = \frac{(990\,kW_F - 640\,kW_F)}{990\,kW_F} = 35\%$$

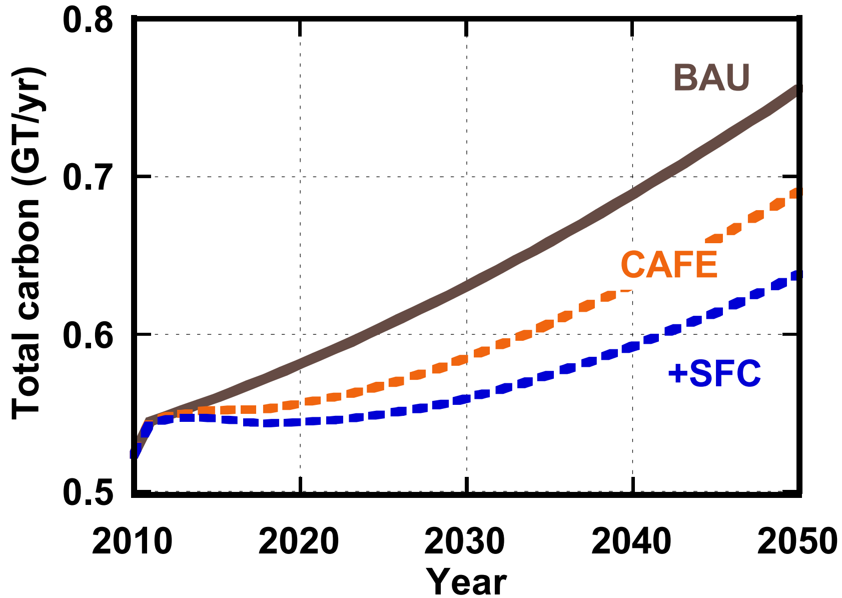
# CHP savings depend on matching of heat load to electric load

- Derived contours of fuel savings parameterized by:
  - Fuel cell electric efficiency
  - Fraction of available heat used
    - Heat provided to building divided by FC heat available
    - Blue points & error bars show average and range of operation
- FC systems sized to achieve an electric capacity factor ~75%



# Model projects a large impact when NG-fired SFC displaces coal

- Analysis of a coal-dominated region is a Future project Milestone (August)
- Using CA regional parameters, but:
  - Adjust generation to reflect US average mix
  - Apply coal as marginal generation
- 8% $CO_2$ reduction by SFC
  - Due to fuel change & improved efficiency




| | CA Mix | US Mix |
|---|---|---|
| NG | 37 % | 18 % |
| Coal | 13 | 50 |
| Nuclear | 21 | 20 |
| Renewable | 29 | 12 |

| | $CO_2$ In Fuel (kg / MJ) | $\eta$ (%) | $CO_2$ per Work (kg / kWh) |
|---|---|---|---|
| Coal | 113 | 33 | 1.23 |
| NG | 54 | 40 | 0.49 |



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# Future directions

- Extend model to multiple regions
- Use competition model in fuel infrastructure model components (e.g. distributed hydrogen stations)
- Consider impact of biofuels on ICE and PHEV emissions



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# Summary

- Existing legislation on transportation and electric sectors is projected to give 18% reduction in $CO_2$ emissions for CA
- Stationary FC systems have a small effect on CA's $CO_2$ emissions
  - Effect of SFC systems with a maximum of 35% relative fuel savings is limited by the potential for CHP systems in CA buildings
  - An optimistic penetration for SFC is 16% of total electricity generation
  - Overall reduction in $CO_2$ is ~2%
- $H_2$ Fueled Vehicles can significantly reduce $CO_2$ emissions
  - Requires large HFV penetration ~50% of CA fleet by 2050
- $H_2$ produced from SFC could potentially supply 11% of HFV fleet demand in 2050
  - Approximately 2 Million vehicles
- Preliminary simulations show that the reduction of $CO_2$ emissions by SFC can be significant when displacing coal generation

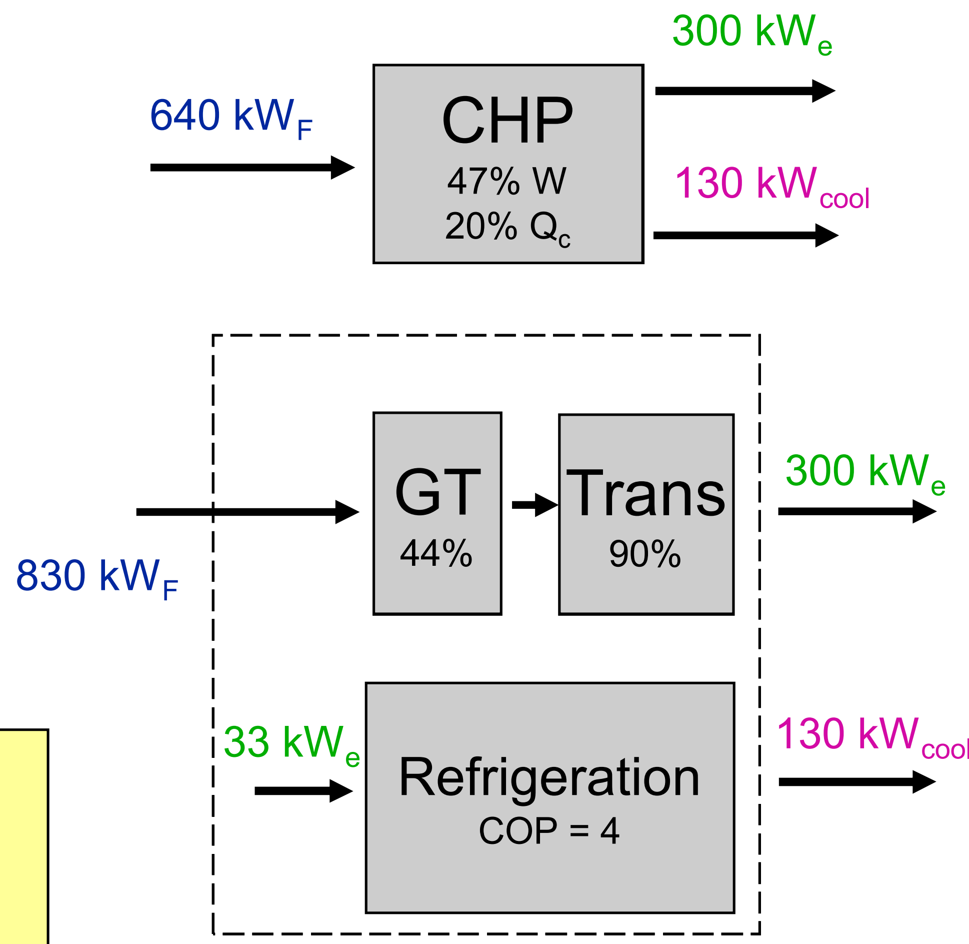
# Supplemental Slides

# Combined cooling and power compared to vapor cooling cycle

- Combined cooling example
  - Traditional "efficiency"
  - Cannot add work and cooling
- Refrigeration efficiency defined by coefficient-of-performance

  $COP = Q / W_e = 4$
- Fuel saving of CCP compared to grid system with refrigeration

  $(830 - 640) / 830 = 23\%$



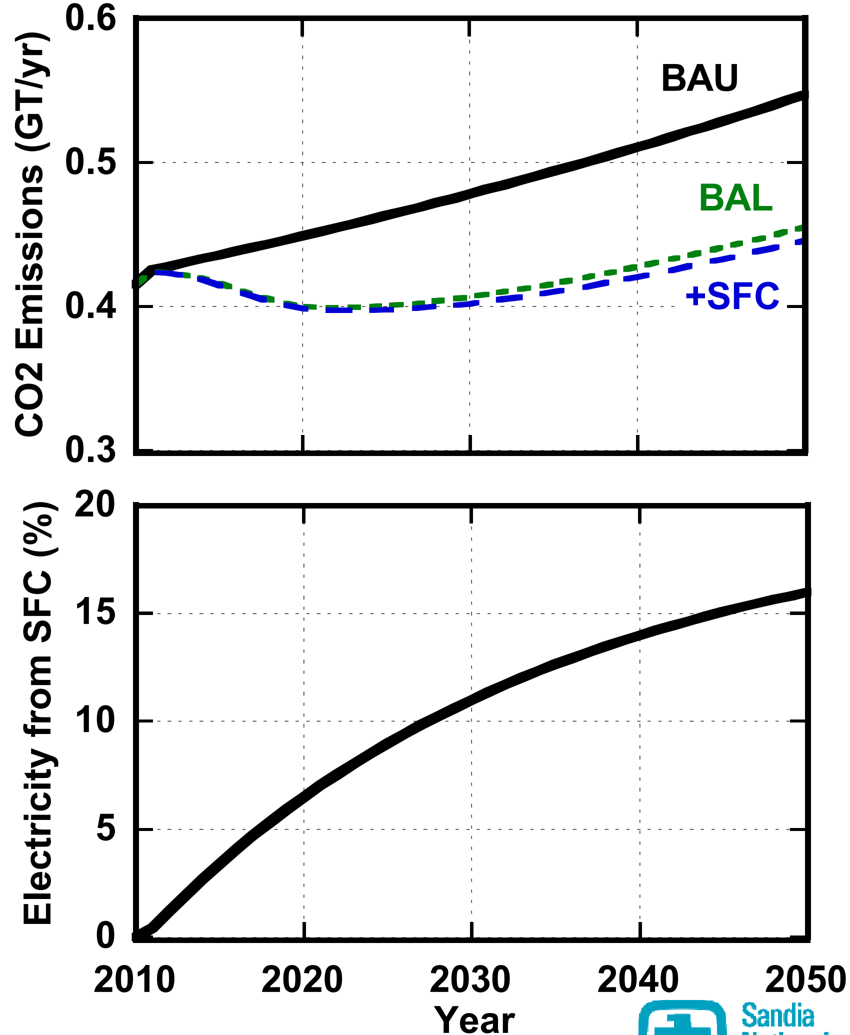

**Efficiency of CCP system**

$$\eta = \frac{(300 + 33)\,kW_e}{640\ kW_F} = 52\%$$

# Optimistic Stationary FC penetration leads to a small effect on $CO_2$ emissions

- Blue scenario is optimistic SFC penetration in:
  - Large buildings (offices, hotels)
  - High-use homes
- By 2050:
  - SFC capacity = 10 GW
    - Matches CEC Assessment (2005) of CHP potential in CA
    - State load varies 30 – 70 GW
  - SFC generation = 67 TWh
    - CA Total = 420 TWh
    - 16% of electric demand
  - SFC reduces CO2 emissions ~2%

| | Units (1000) | Size (kW) | Capacity (GW) |
|---|---|---|---|
| Offices | 7 | 400 | 2.7 |
| Hotels | 8 | 250 | 1.9 |
| Homes | 1300 | 4 | 5.2 |

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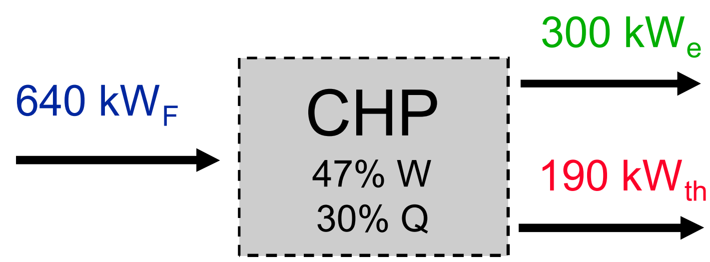
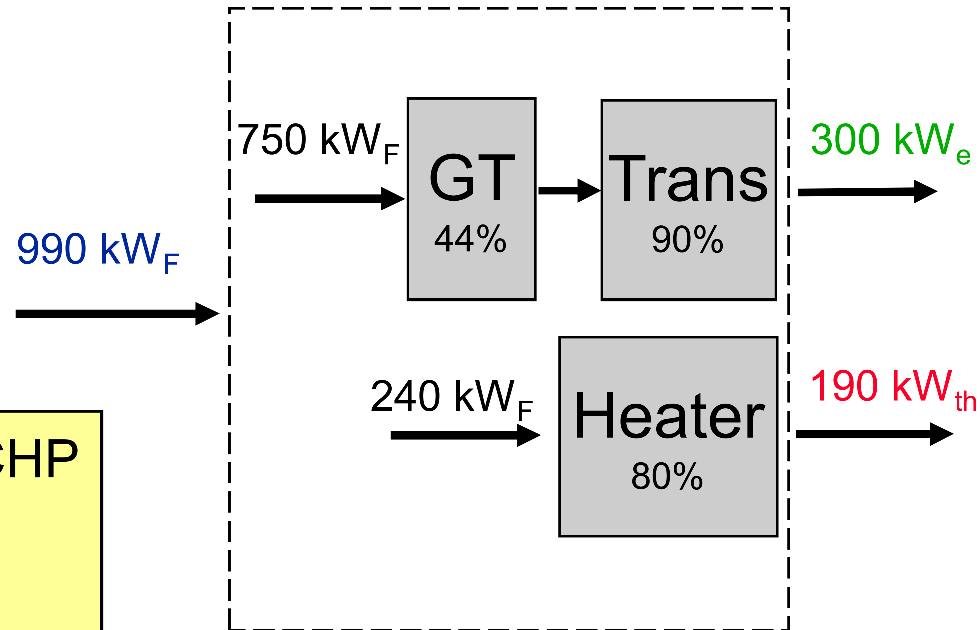
# Why is the impact of SFC on California's $CO_2$ emissions so limited?

- Efficiency improvement, but same marginal fuel
  - Displacing NG generation at 40% by SFC on NG at 40-47% (electrical)




- CHP benefit?
  - Compare to existing infrastructure:
    - Gas Turbine & Heater



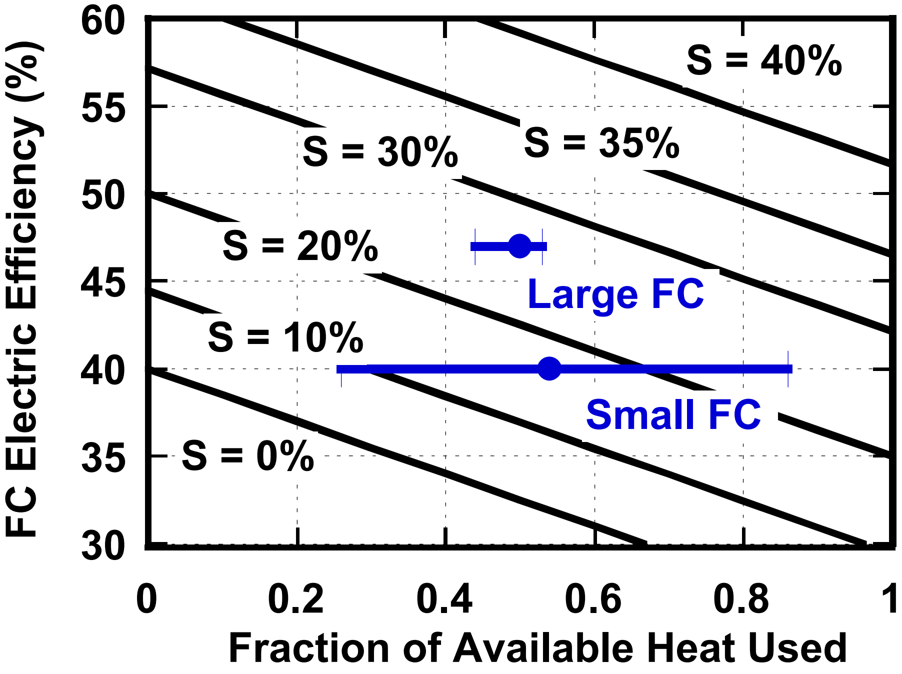

Maximum Fuel Savings by SFC + CHP

$$S = \frac{(990\,kW_F - 640\,kW_F)}{990\,kW_F} = 35\%$$

# CHP savings depend on matching of heat load to electric load

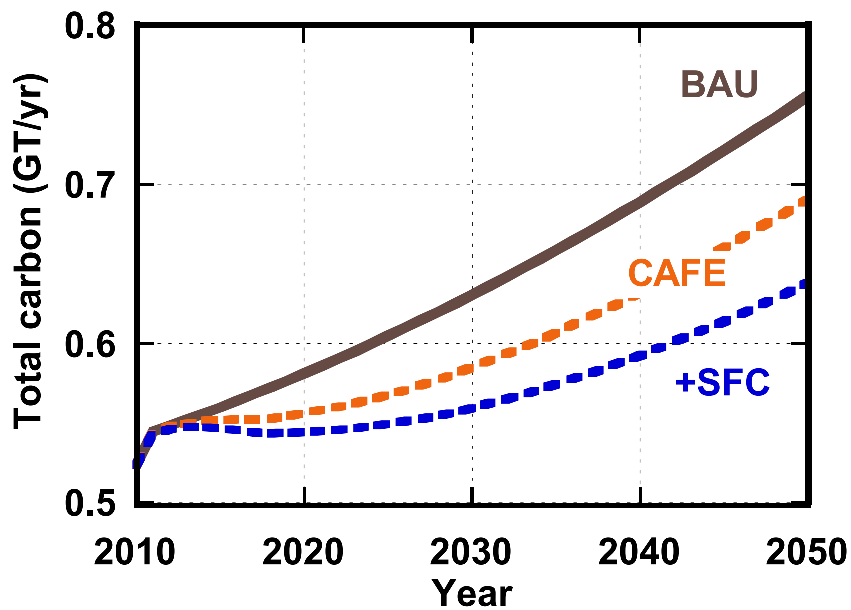
- Derived contours of fuel savings parameterized by:
  - Fuel cell electric efficiency
  - Fraction of available heat used
    - Heat provided to building divided by FC heat available
    - Blue points & error bars show average and range of operation

- FC systems sized to achieve an electric capacity factor ~75%



# Model projects a large impact when NG-fired SFC displaces coal

- Analysis of a coal-dominated region is a Future project milestone (August)
- Using CA regional parameters, but:
  - Adjust generation to reflect US average mix
  - Apply coal as marginal generation
- 8% $CO_2$ reduction by SFC
  - Due to fuel change & improved efficiency




| | CA Mix | US Mix |
|---|---|---|
| NG | 37 % | 18 % |
| Coal | 13 | 50 |
| Nuclear | 21 | 20 |
| Renewable | 29 | 12 |

| | $CO_2$ In Fuel (kg / MJ) | $\eta$ (%) | $CO_2$ per Work (kg / kWh) |
|---|---|---|---|
| Coal | 113 | 33 | 1.23 |
| NG | 54 | 40 | 0.49 |



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# Future Work

- Remainder of FY10:
  - Extend approach to coal-burning region of US
    - Compare SFC effect on carbon emissions due to fuel switching to NG
    - Examine effect of carbon tax
    - Examine SFC dedicated chargers for PHEV
- FY11:
  - Explore a dynamic connection to FC Power model (NREL) for SFC performance parameters and load matching
  - Work with utility partner to consider the equipment trade-off savings potential of SFC dedicated as PHEV charging
  - Couple electricity model to more detailed models of generation and dispatch
  - Consider economics of SFC systems in a penetration model with dynamic feedback
  - Consider coupling of system dynamics tools to Macro-System Model



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