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

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Livermore, CA

June 8, 2010

AN002

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Overview

Timeline

- Start – Dec. 2007
- Finish – Sep. 2012
- 50% complete

Budget

- Total project funding
  - DOE $590K
- Funding received in FY2010
  - $250K

Barriers

A. Future Market Behavior

B. Stove-piped/Siloed Analytical Capability

E. Unplanned Studies and Analysis

Targets

Analyze issues and long term impacts related to infrastructure evolution, hydrogen fuel, and vehicles (Task 1)

Relevance / Objectives

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**

Relevance

- **Transition to H2 fueling is expected to rely on distributed steam-methane reforming (SMR) and stationary fuel cells (SFC); we must understand the impact of hydrogen vehicles and stationary fuel cells on the infrastructure**

Milestones

MM / YYYY	Milestone
February / 2010	Develop modules to simulate distributed Combined Heat and Power (CHP) systems for stationary power and distributed hydrogen production
August / 2010	Extend analysis to a coal-burning region; Modify model input and conduct infrastructure assessment

Approach

- **Analysis-driven approach defined by programmatic needs**
  - Provide analysis and insight into the dynamic behavior of complex systems
- **System dynamics: Methodology**
  - Choose a region to define the system
    - Selected California (CA) as first application
  - Pose detailed questions
    - What are the potential reductions of CO_2 emissions by stationary FC systems?
    - What is the effect of stationary FC systems on the existing grid and fuel markets?
    - 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
  - Use Powersim software to quickly generate code

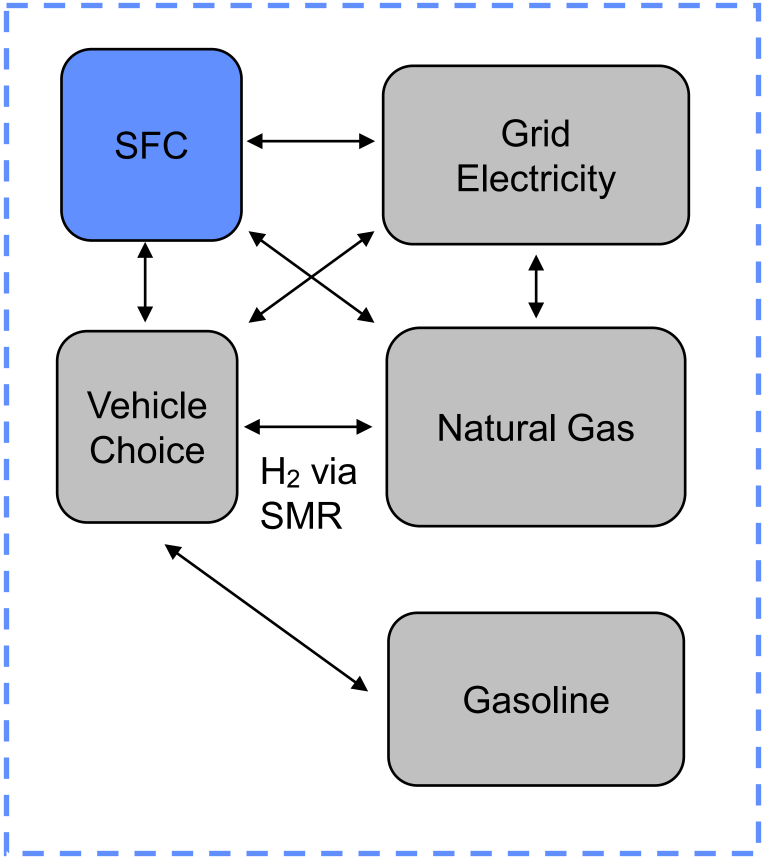
Technical Progress: added SFC for distributed power generation and interactions with infrastructure

SFC Penetration

- **Fixed penetration model**
  - NOT based on economic choice, due to uncertainty in future technology & costs
  - Use optimistic implementation goals

Market Interactions

- **Competition between PHEVs, HFVs, and future CAFE 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)**
  - 33% by 2020



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Assumptions

Infrastructure Model

- **Electric Supply**
  - Marginal generation is NG
  - Other generation is "must run"
  - No elasticity in supply/demand
  - Plug-in vehicles 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
  - Zero-carbon H_2 (exact path unspecified)

Vehicle Model

- **Conventional vehicles**
  - Gasoline fueled: 20 mpg today
  - CAFE regulation: 35 mpg by 2016
- **Plug-in Hybrid Electric Vehicles**
  - 48 mpg in gasoline mode
  - 0.35 kWh/mile electric mode
  - 1/3rd of miles in gasoline mode (40-mile electric range)
- **Hydrogen Fuel Cell Vehicles**
  - 70 mile / kg
- **Vehicle adoption**
  - Adjusted to scenario of Greene *et al* (ORNL, 2008)
  - 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 electricity displaced by chilling
  - 15% to H_2 in co-production mode
    - Reduce electric efficiency to 40%
  - Size to meet electric load with high capacity factor
    - 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 hydrogen 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

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 scenarios

- **Key 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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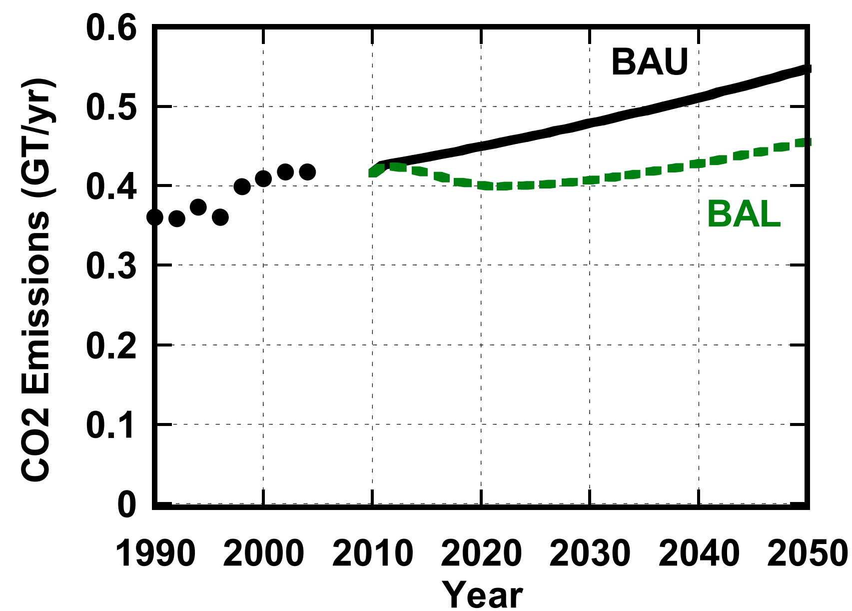
Baseline scenarios for California's CO_2 emissions

- **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

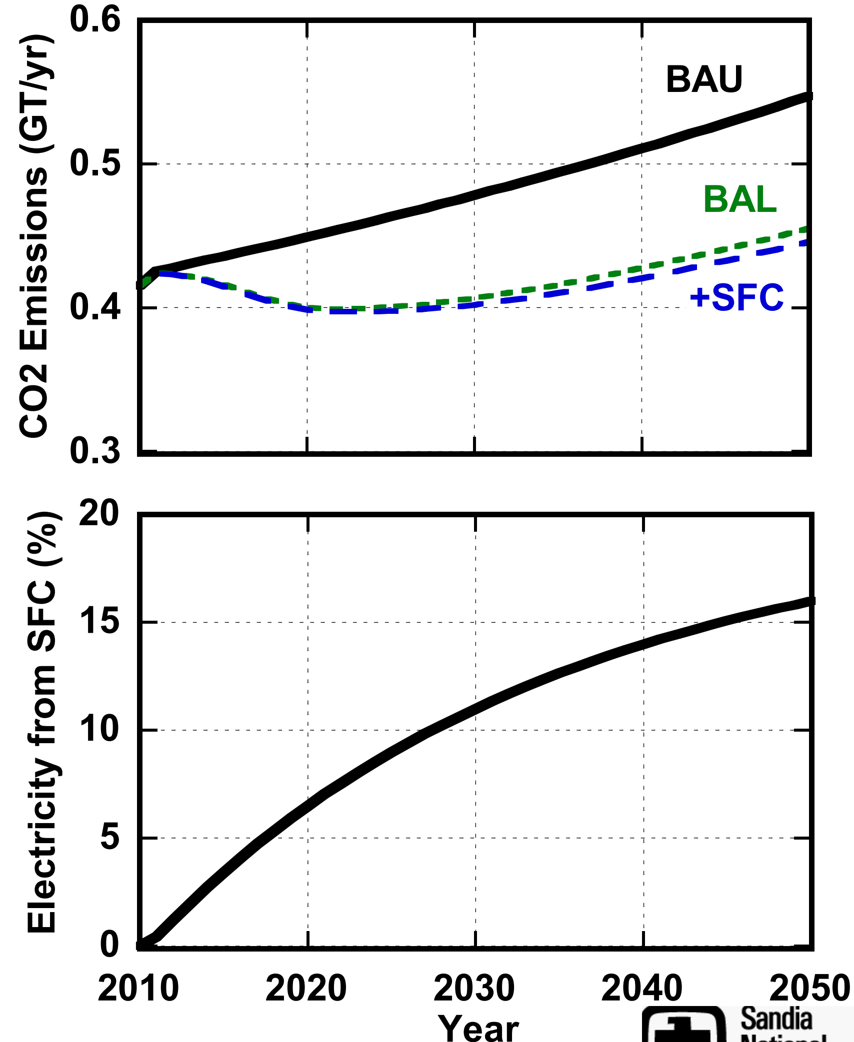


Existing Legislation to give 18% reduction

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

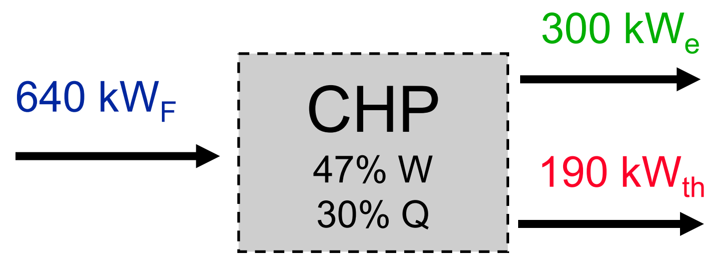
- **Blue scenario is optimistic SFC penetration in:**
  - Large buildings (offices, hotels)
  - High-use homes
- **By 2050:**
  - SFC capacity = 10 GW
    - Matches CEC Assessment (2005) of CHP potential in CA
    - State load varies 30 – 70 GW
  - SFC generation = 67 TWh
    - CA Total = 420 TWh
  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

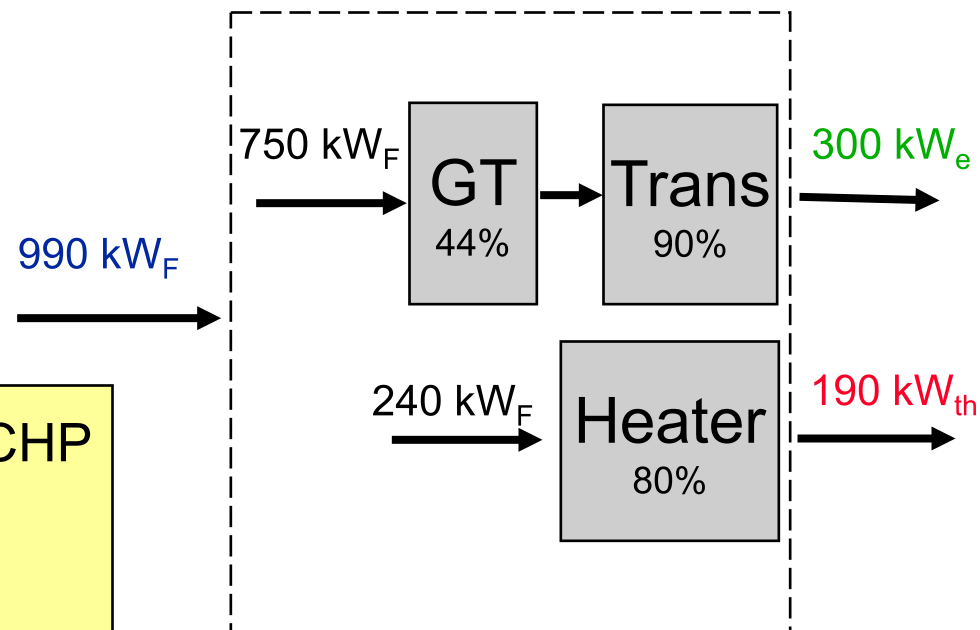
	Units (1000)	Size (kW)	Capacity (GW)
Offices	7	400	2.7
Hotels	8	250	1.9
Homes	1300	4	5.2



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

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

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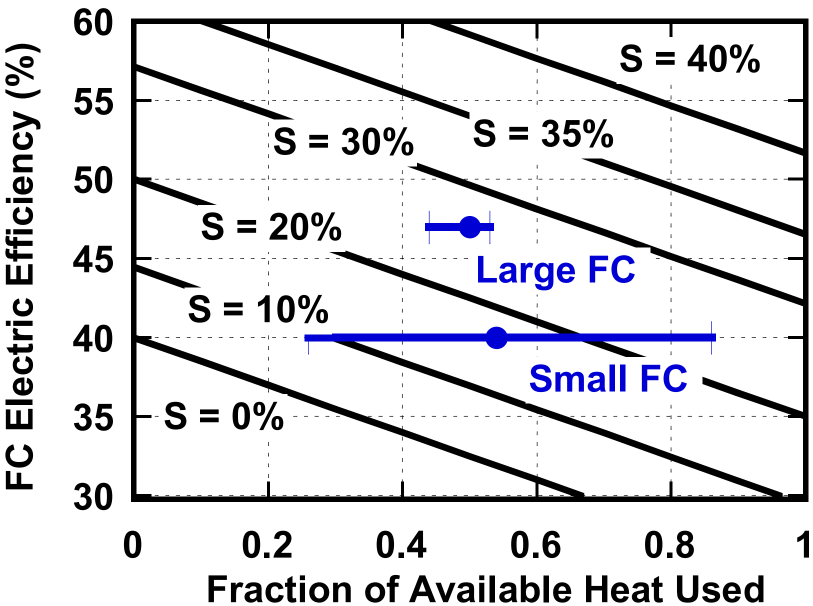
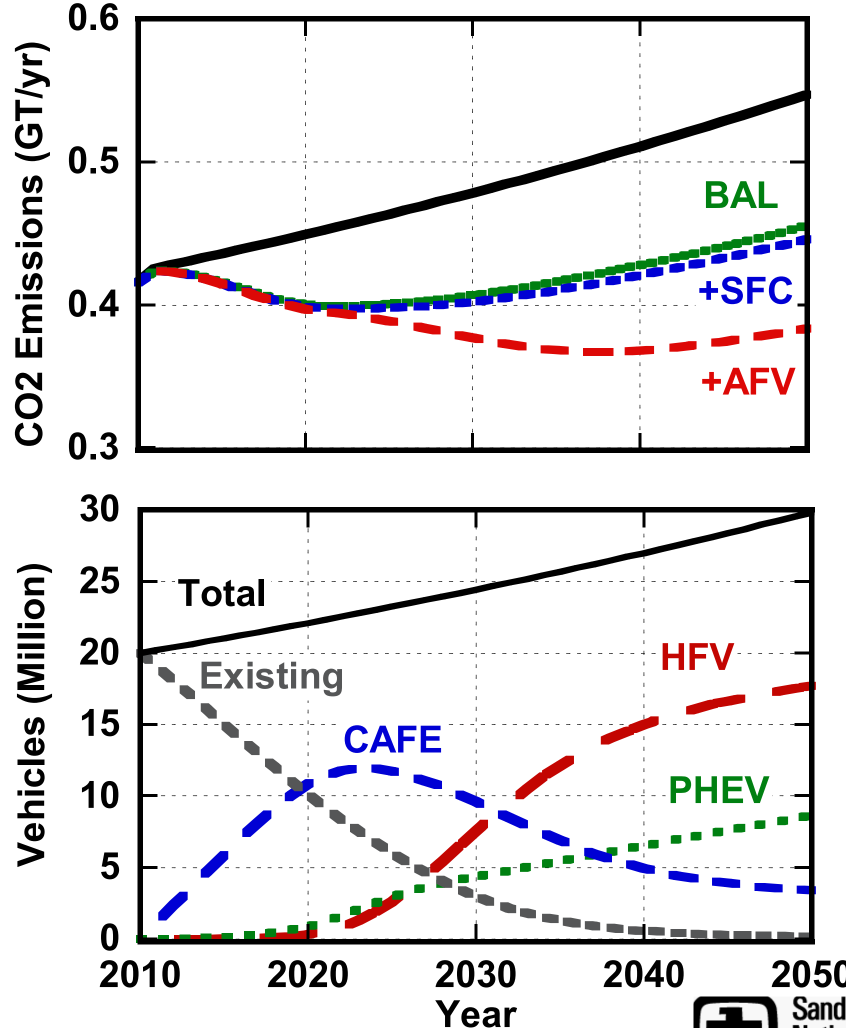
CHP savings depend on matching of heat load to electric load

- **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%**



H_2 Fueled Vehicles significantly reduce CO_2 emissions

- **Use vehicle adoption parameters set to match optimistic Alternative Fuel Vehicle 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 mile/kg H_2
  - PHEV suffer from gasoline use
    - H_2 @ 4.00 $ / kg
    - Gas @ 4.50 $/gal



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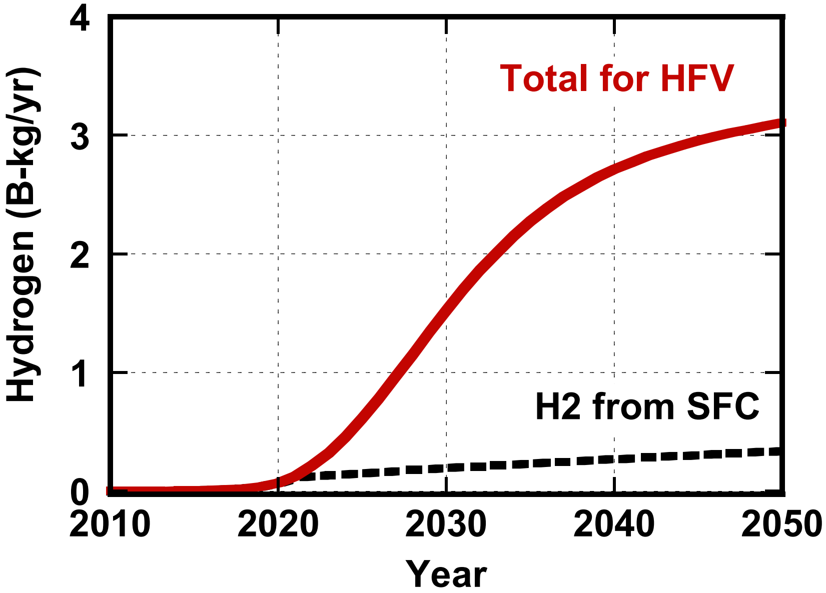
Penetration of SFC systems can provide significant H_2 for vehicles

<u>H2 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

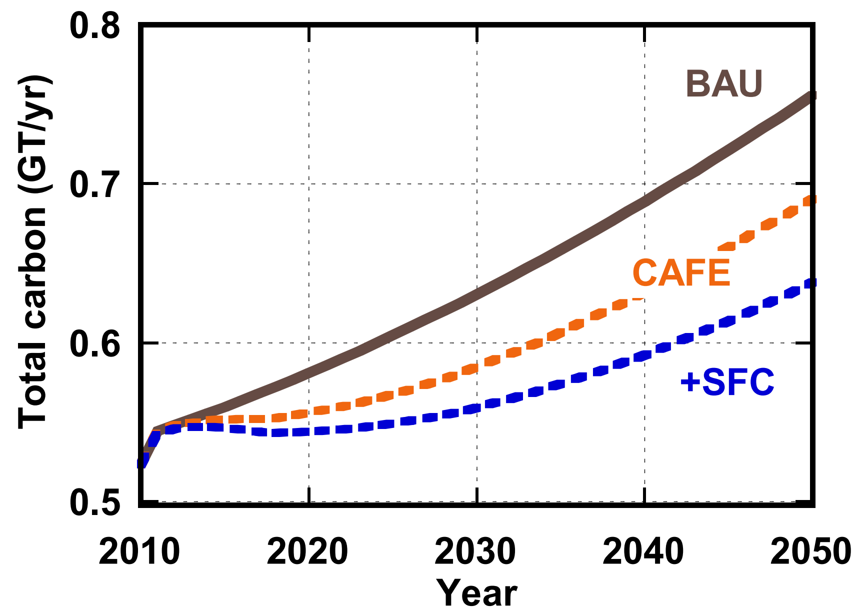


<u>SFC dedicated to EV charging</u>

- **Cost effectiveness is highly 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**

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)	η (%)	CO_2 per Work (kg / kWh)
Coal	113	33	1.23
NG	54	40	0.49

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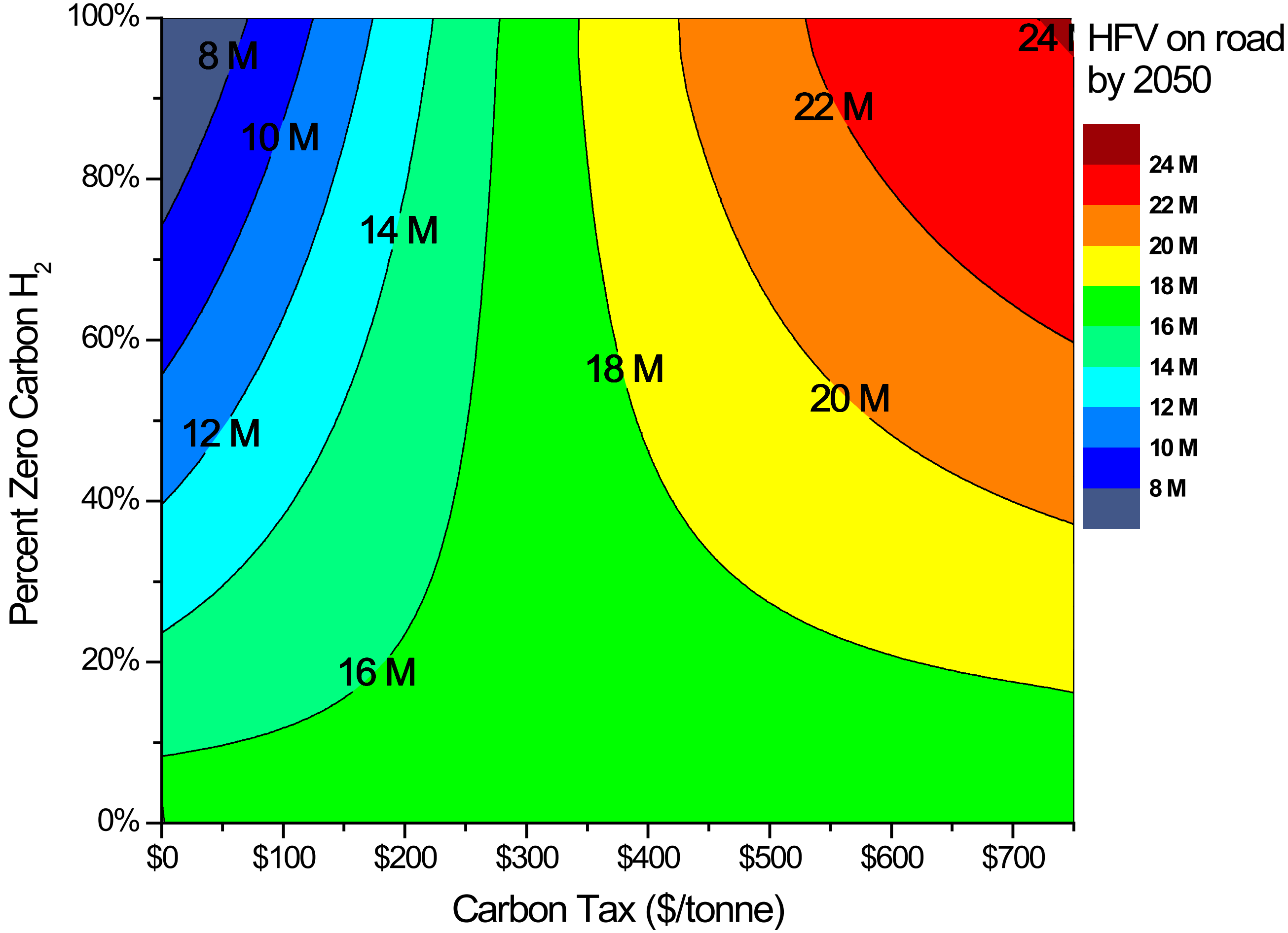
Stochastic sensitivity: Higher price of zero-carbon H_2 requires a carbon tax to spur HFV sales

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



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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**

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

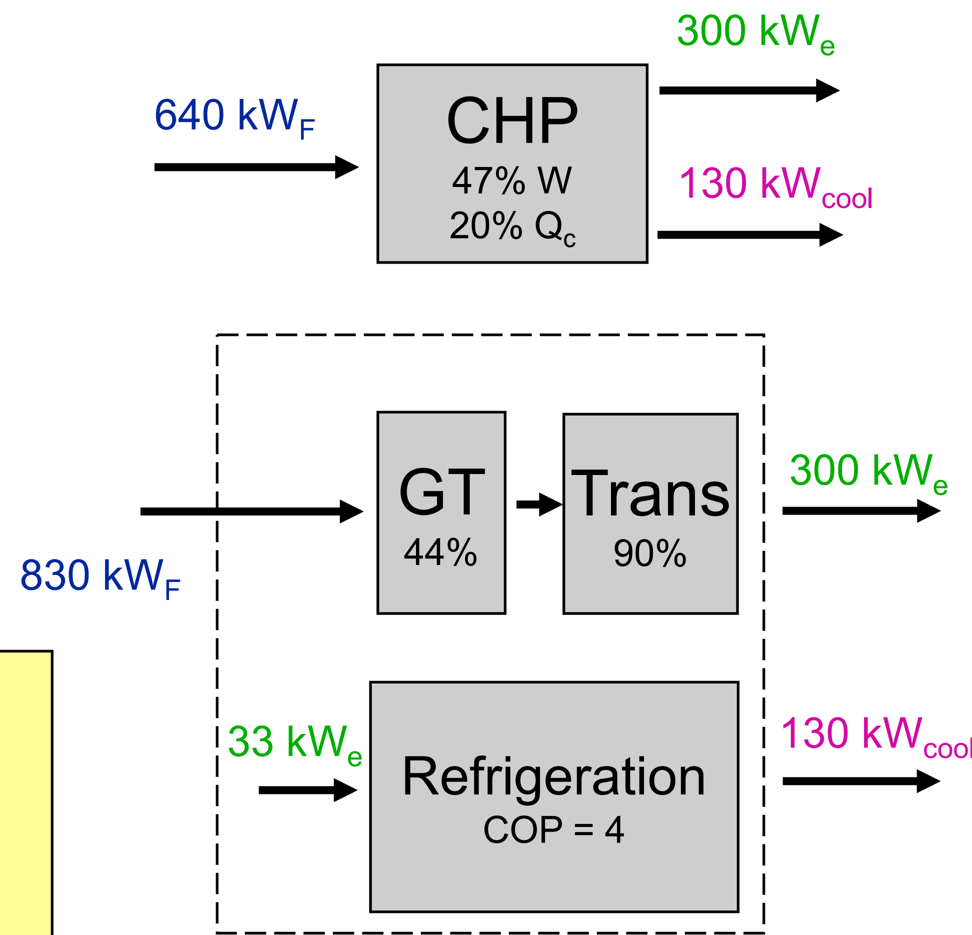
Supplemental Slides

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

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