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Designing Networks of Cogenerative Fuel Cell Systems for Reducing Greenhouse Gas Emissions, Energy Costs, and Barriers-to-Entry for Manufacturers

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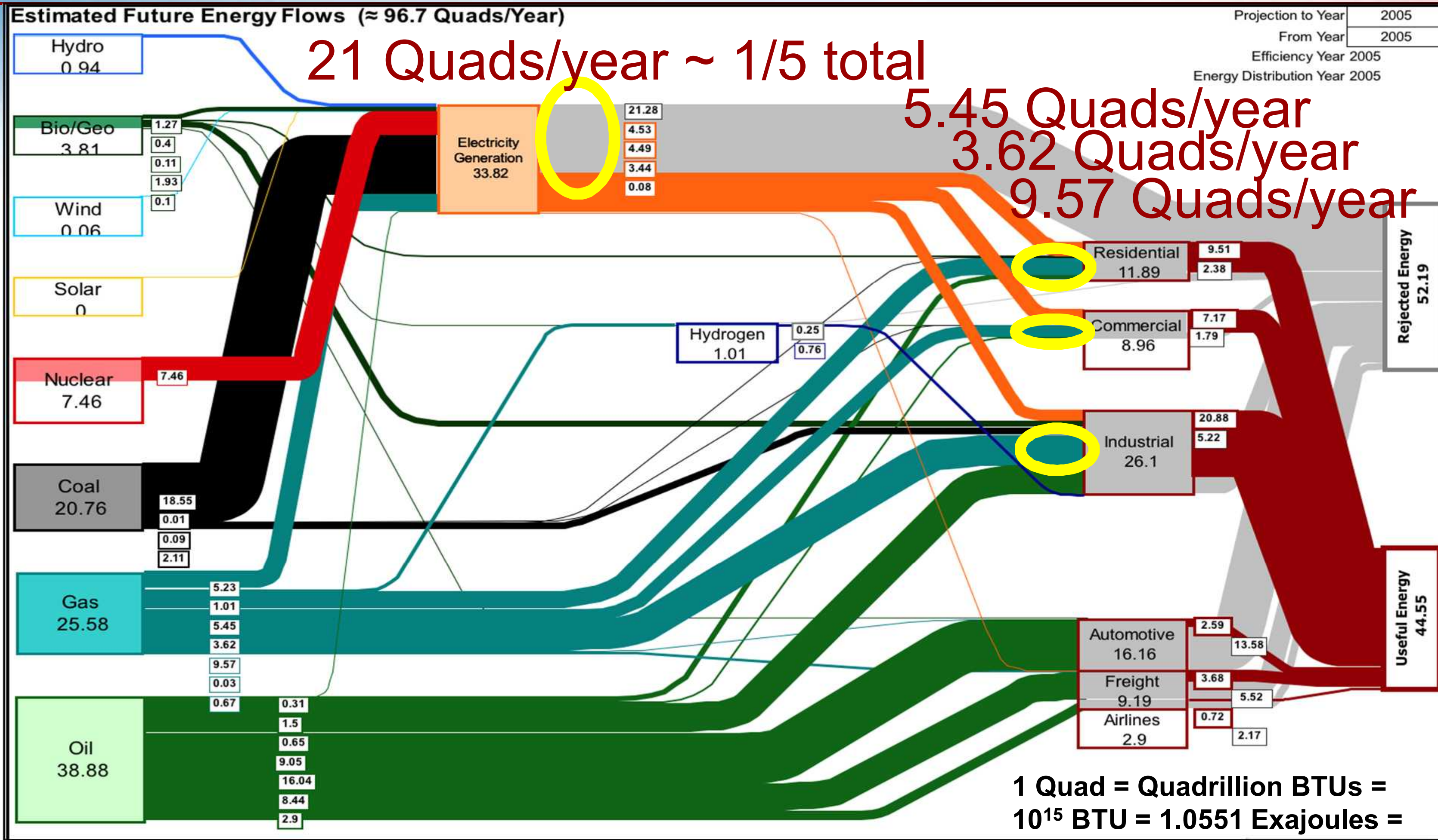
Motivation

Potential Energy Savings of Fuel Cells: 1/5th of Consumption in USA



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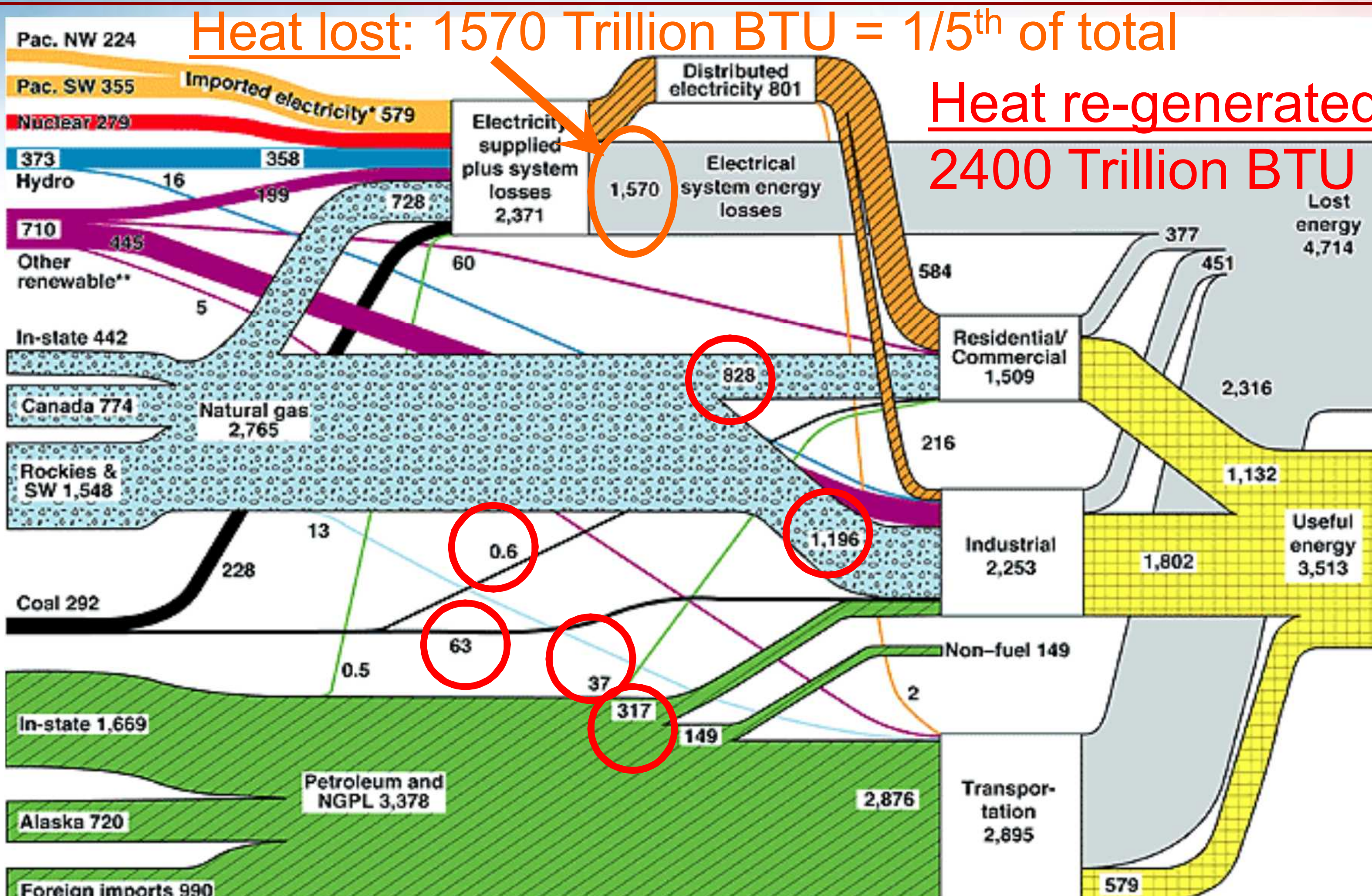
California Energy Flow Figure by Lawrence Livermore National Lab

Potential Energy Savings of Fuel Cells: 1/5th of Consumption in California



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California Energy Flow Figure by Lawrence Livermore National Lab

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Cogen or Combined Heat and Power (CHP)

Conservation of Energy (1st Law of Thermodynamics)

$$\Delta U = W_{elec} + Q_{lost} + Q_{recov},$$

ΔU = total internal energy of the fuel consumed at the power plant

W_{elec} = electric power output of the plant

Q_{lost} = heat losses from the plant

Q_{recov} = heat that is usefully consumed in an end-use application, such as heating an industrial process in a chemical plant, providing space heating for a building, or providing hot water heating.

Cogenerative Fuel Cell Systems Fueled by Natural Gas Make 1/3rd the CO_2 as Conventional Systems

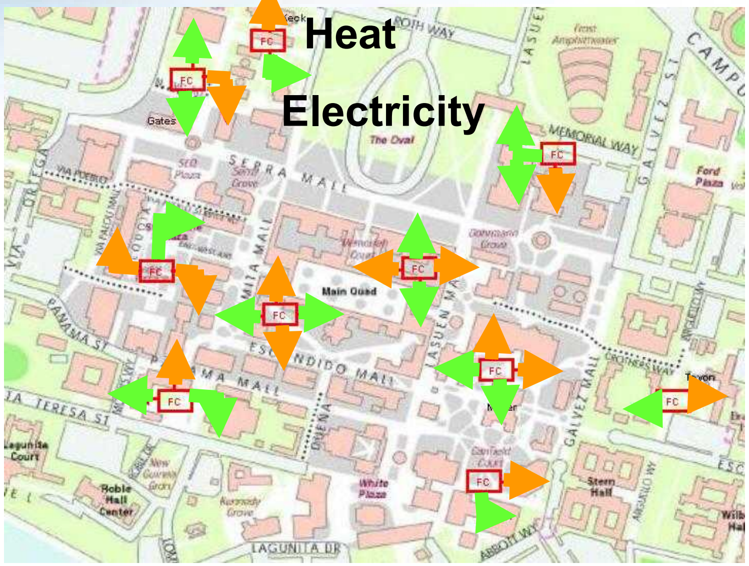
	Source of Electricity or Heat	CO_2 Emission Factor (g/kWh_e or g/kWh_heat)	Electricity Production (MWhr)	Heat Production (MWhr)	CO_2 Emissions (kg)
Case 1: Conventional System	Coal Power Plant with Steam Turbine	860	2	0	1720
	Coal Fired Boiler / Furnace	410	0	1	410
	Total		2	1	**2130**
Case 2: Average System	Mix of 1999 US Electric Generation Plant	600	2	0	1200
	Boiler / Furnace (72% efficient)	280	0	1	280
	Total		2	1	**1479**
Case 3: Advanced System	Cogenerative Combined Cycle Gas Turbine	380	2	0.71	760
	Boiler / Furnace (92% efficient)	219	0	0.29	64
	Total		2	1	**824**
Case 4: Fuel Cell System fueled by natural gas	Cogenerative Molten Carbonate Fuel Cell	373	2	1	**746**
Case 5: Fuel Cell System fueled by renewable hydrogen	Cogenerative Molten Carbonate Fuel Cell	0	2	1	**0**

Greenhouse gas emissions can be greatly reduced with fuel cell systems designed to recover heat.

Background

Non-Networked vs. Networked

Non-Networked / Stand Alone

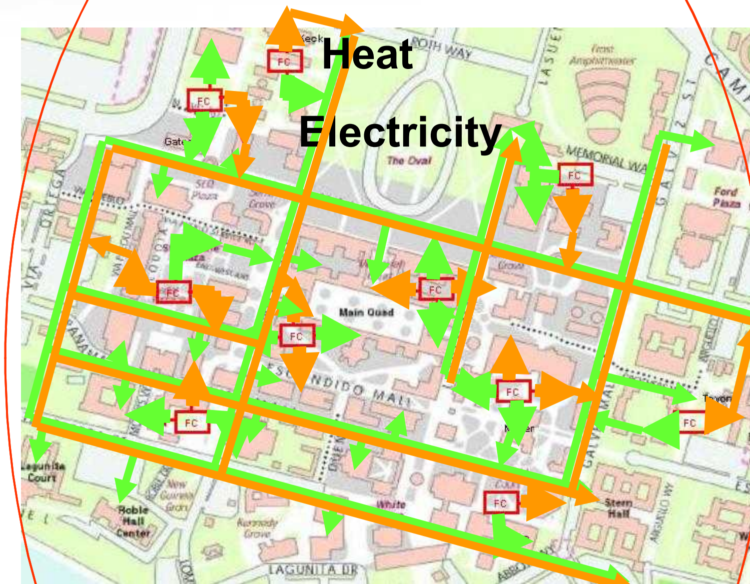


Fuel cells can NOT convey excess heat or electricity into the distribution grid to reach other buildings.

Electricity

Heat

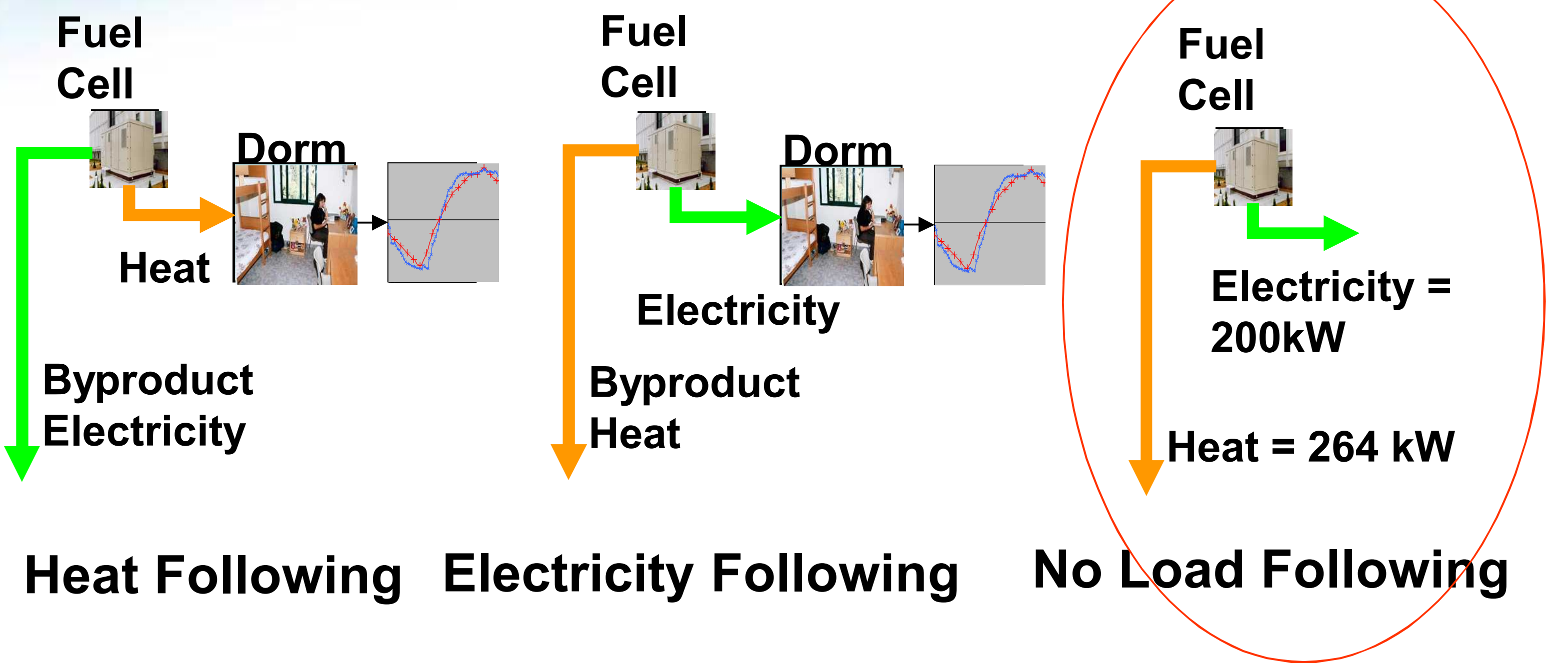
Networked



Fuel cells CAN convey excess heat or electricity into the distribution grid to reach other buildings. Transmission Loss: Electrical ~0%, Thermal ~8%

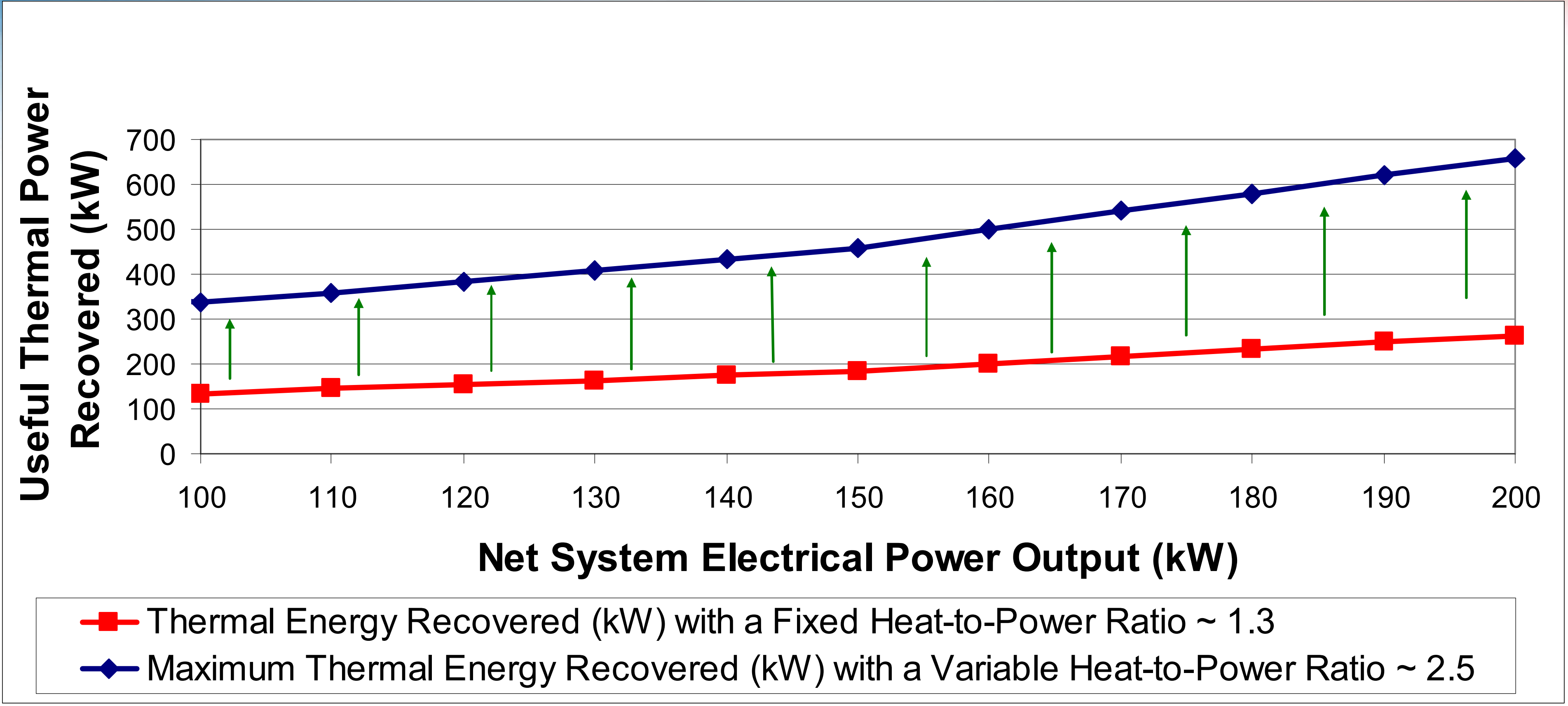
Networks have energy distribution channels

Load following heat vs. electricity vs. constant output



Load following the electrical demand results in byproduct heat, and vice versa. No load following is constant output.

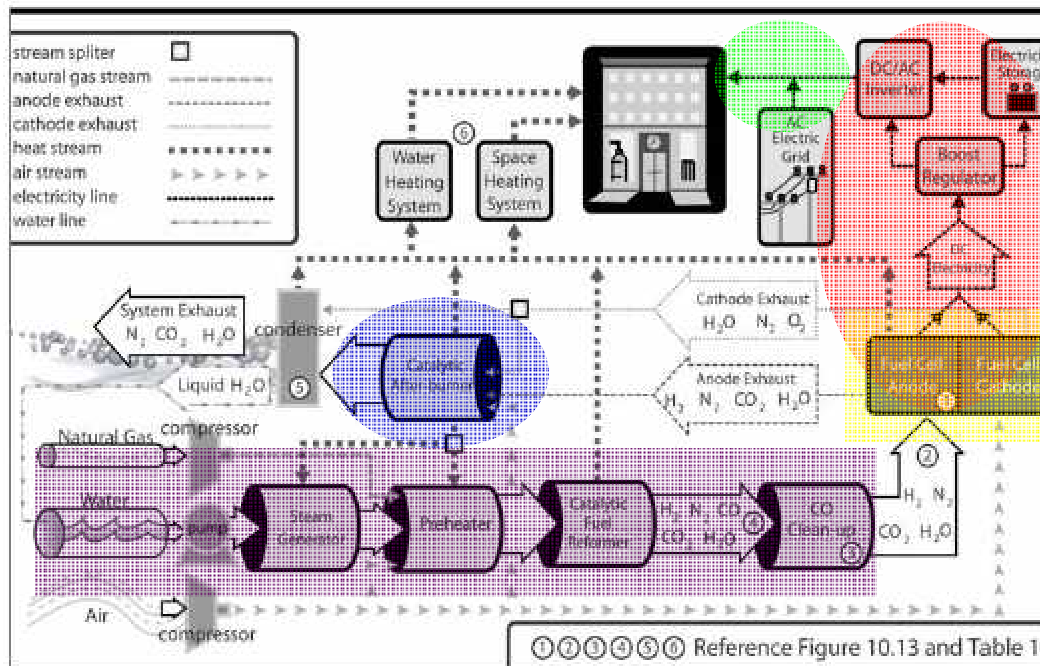
Fixed vs. Variable Heat-to-Power Ratio



Variable ratio increases system operating range

Methods to Achieve a Rapidly Variable Heat-to-Power Ratio; Colella, JPS, 2002

I Vary the ratio of reactants, the temperature, and/or the pressure in the fuel processing sub-system to alter the energy consumed or released by the fuel reforming reactions, and to alter the amount of fuel flowing to the fuel cell, and the heat it releases. (Exp. – operate reformer as SR, POX, or AR by changing S/C)



II Vary the fuel flow rate to the anode off-gas burner

III Vary the system's electrical configuration

IV Change the shape and/or position of the polarization curve during operation

V Use resistance heater but potentially with decreased cell lifetime and increased cell degradation

MTU (Daimler Benz) design – Options I and II: Bypass fuel flowing to fuel cell to combust in reformer

What are California's baseline CO_2 emissions from electric power?

Federal and State CO_2 Estimates Differ by 34%

Row	CO_2 Emissions from In-state Electricity Generation ($MMTCO_2$/yr)	1990	2000	2004	Average	Total
A	Department of Energy (DOE) Data	**53.1**	**66.8**	**60.7**	***56.5***	***848***
B	California Energy Commission (CEC) Data	**36.5**	**51.9**	**47.1**	***42.4***	***636***
	Discrepancy (CEC - DOE Data) as a Percent of CO_2 Emissions from					
C	In-State Electricity Generation	***-45%***	***-29%***	***-29%***	***-34%***	
D	Total CO_2 Emissions in CA	***-6%***	***-4%***	***-4%***	***-4%***	

Federal CO_2 emission data series differ from state data series by 34% for the California in-state electricity sector.

Million Metric Tonnes of Carbon Dioxide per year ($MMTCO_2$/yr)

Normal font shows reported data; italic font shows calculated data.

DOE-EIA and CEC-LBNL Historical CO_2 Data Series Differ by 34% for Electricity in California

Row	CO_2 Emissions from In-state Electricity Generation ($MMTCO_2$/yr)	1990	2000	2004	Average	Total
A	Department of Energy (DOE) Data	**53.1**	**66.8**	**60.7**	***56.5***	***848***
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D	Total CO_2 Emissions in CA	***-6%***	***-4%***	***-4%***	***-4%***

- Data series by DOE's Energy Information Administration (EIA) differs from data series by California Energy Commission (CEC) and Lawrence Berkeley National Laboratories (LBNL)

Million Metric Tonnes of Carbon Dioxide per year ($MMTCO_2$/yr)
Normal font shows reported data; italic font shows calculated data.

DOE and CEC CO_2 Data Series Use the Same Methods and Data Sources

- Both calculate CO_2 emissions (m_{CO_2}) according to:

$$m_F \gamma_{F\text{-}CO_2} = m_{CO_2}$$

where

m_F = fuel consumption from power plants of one fuel type

$\gamma_{F\text{-}CO_2}$ = the average annual emission factor per unit of fuel (constant all years)

- Both rely on data from the DOE's EIA for all values of m_F

Discrepancy in data series surprising given that the same methods and data sources were applied

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CEC-LBNL reported CO_2 Emissions exclude fuel for cogenerative heating, some fuel sources

Fuel Type	m_F Annual Fuel Consumption (Trillion BTUs - 10^12 /yr)	$\bar{\gamma}_{F\text{-}CO_2}$ Average Annual CO_2 Emission Factor per Unit of Fuel Consumption ($MMTCO_2$ / Trillion BTU of Fuel)	m_{CO_2} CO_2 Emissions ($MMTCO_2$ /yr)
Natural Gas (NG)	1,061	0.0528	56.00
Coal (BIT)	0.9740	0.0935	0.0911
Total			56.09

$$m_F \bar{\gamma}_{F\text{-}CO_2} = m_{CO_2}$$

DOE-EIA reported CO_2 emissions – include fuel for cogenerative heating

Fuel Type	m_F **Annual Fuel Consumption (Trillion BTUs - 10^12 /yr)**	$\bar{\gamma}_{F\text{-}CO_2}$ **Average Annual CO_2 Emission Factor per Unit of Fuel Consumption ($MMTCO_2$ / Trillion BTU of Fuel)**	m_{CO_2} **CO_2 Emissions ($MMTCO_2$ /yr)**
Natural Gas (NG)	1,197	0.0531	63.58
Coal (BIT)	41.12	0.0931	3.829
Petroleum Coke (PC)	28.66	0.1021	2.927
Distillate Fuel Oil (DFO)	8.061	0.0732	0.5901
Municipal Solid Waste (MSW)	8.080	0.0417	0.3368
Geothermal (Steam) (GEO)	256.0	0.0012	0.3099
Residual Fuel Oil (RFO)	3.089	0.0789	0.2437
Waste/Other Oil (WO)	1.724	0.0953	0.1642
Tire-derived Fuels (TDF)	0.0091	0.0860	0.0008
Gaseous Propane (PG)	0.0089	0.0631	0.0006
Jet Fuel (JF)	0.0076	0.0709	0.0005
Total			71.98

$$m_F \bar{\gamma}_{F\text{-}CO_2} = m_{CO_2}$$

DOE-EIA CO_2 Emissions – not reported – excludes fuel for cogenerative heating

Fuel Type	m_F Annual Fuel Consumption (Trillion BTUs - 10^12 /yr)	$\bar{\gamma}_{F\text{-}CO_2}$ Average Annual CO_2 Emission Factor per Unit of Fuel Consumption ($MMTCO_2$ / Trillion BTU of Fuel)	m_{CO_2} CO_2 Emissions ($MMTCO_2$ /yr)
Natural Gas (NG)	1051	0.0531	55.81
Petroleum Coke (PC)	22.4	0.1021	2.287
Coal (BIT)	22.8	0.0931	2.121
Distillate Fuel Oil (DFO)	8.1	0.0732	0.5901
Municipal Solid Waste (MSW)	8.1	0.0417	0.3368
Geothermal (Steam) (GEO)	256.0	0.0012	0.3099
Residual Fuel Oil (RFO)	3.1	0.0789	0.2437
Waste/Other Oil (WO)	0.8	0.0953	0.0780
Tire-derived Fuels (TDF)	0.00875	0.0860	0.0008
Jet Fuel (JF)	0.00764	0.0709	0.0005
Gaseous Propane (PG)	0.00856	0.0631	0.0005
Total			**61.77**

Discrepancy partly, but not solely, from difference in cogen heating

Sources of Discrepancy between DOE and CEC Data Series

CEC-LBNL data series excludes

- a portion of fuel/CO_2 from coal power plants

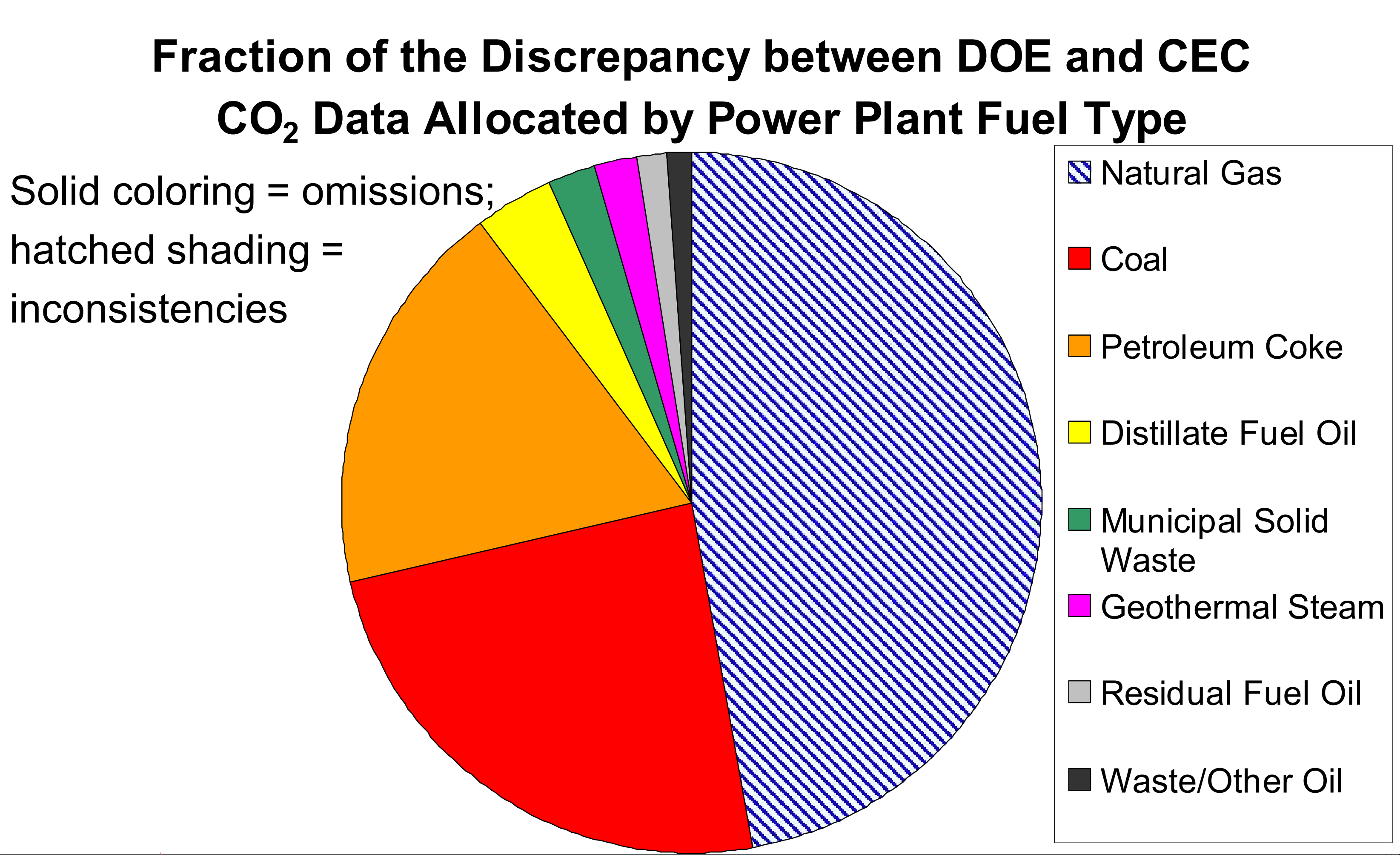
  Reason => math error

- all fuel/CO_2 from plants not fueled by natural gas or coal
  - fuel/CO_2 from petroleum coke, oil
  - fuel/CO_2 from non-fossil fuel power plants

  Reasons => math error; use of truncated EIA data set

- fuel/CO_2 for cogen heating from natural gas/other plants
  - Omitted for years 1990 to 1997 for natural gas
  - Re-allocated to "Industrial Sector" 1998-2004 for natural gas
  - Methods for other fuels unconfirmed; no answer to inquiries.

State data excludes CO_2 from coal, coke, oil, non-fossil fuels; re-allocates or omits cogen heating



We conclude Federal data is a more complete baseline.

Omissions or Inconsistencies?

Discrepancy between DOE and CEC data series is due to

- data omissions from 1990-1998, and
- omissions (53%) and inconsistencies (47%) from 1999-2004.

CEC: Arbitrary Segmentation of Heat Losses

$$\Delta U = X + Y$$

X = a portion of the total internal energy of the fuel consumed at the power plant that operators choose to associate with electricity production

Y = fuel consumption that operators choose to align with heat production

γ_{elec} = fraction of Q_{lost} that operators choose to align with electricity

$$X = W_{elec} + \gamma_{elec} Q_{lost}$$

$$Y = Q_{recov} + (1-\gamma_{elec}) Q_{lost}$$

Electrical efficiency of power plants according to DOE method(η_D)

$$\eta_D = W_{elec} / \Delta U$$

Electrical efficiency of power plants according to CEC method(η_C)

$$\eta_C = W_{elec} / X$$

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2001 Monthly Data Plotted

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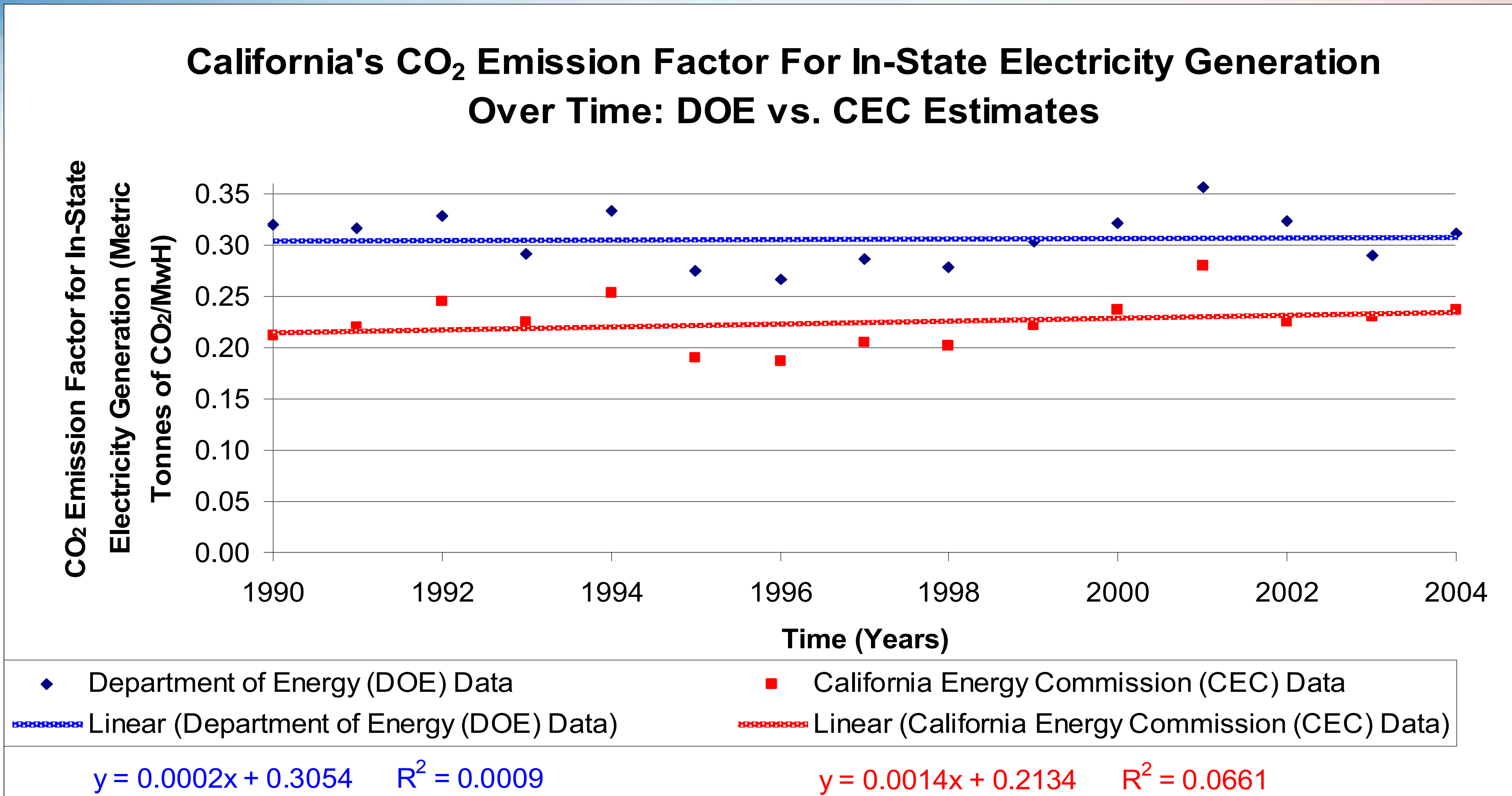
CEC reports lower magnitude, higher rate of increase



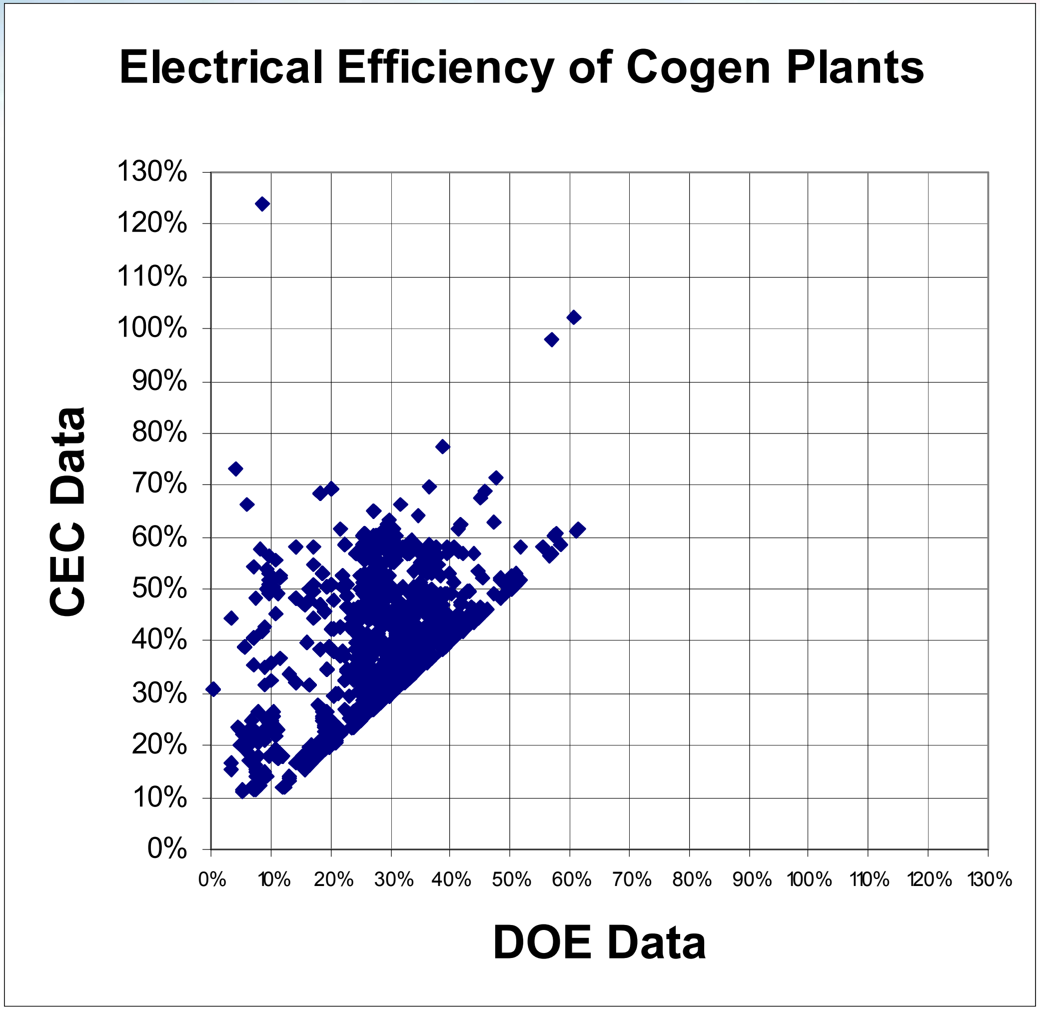
Results: Concerns with CEC Approach

1) Omitted Data for CHP Plants 1990-1997
2) Unverified Reallocation of Emissions
4) Diverse Method Applied for Imported Electricity
3) Arbitrary Segmentation of Heat Losses
5) Thermodynamic Consistency
6) Violation of International Standards on CO2 Accounting

Recommendations

- California Air Resources Board (CARB) should consider using original DOE-EIA data.
- National labs could act as a third-party reviewer of the state's CO_2 monitoring and reporting.
  - National lab assets: "honest broker," technically competent, no direct vested interests.

CEC Data Over-Estimates Power Plant Efficiency



2001 Monthly Data Plotted

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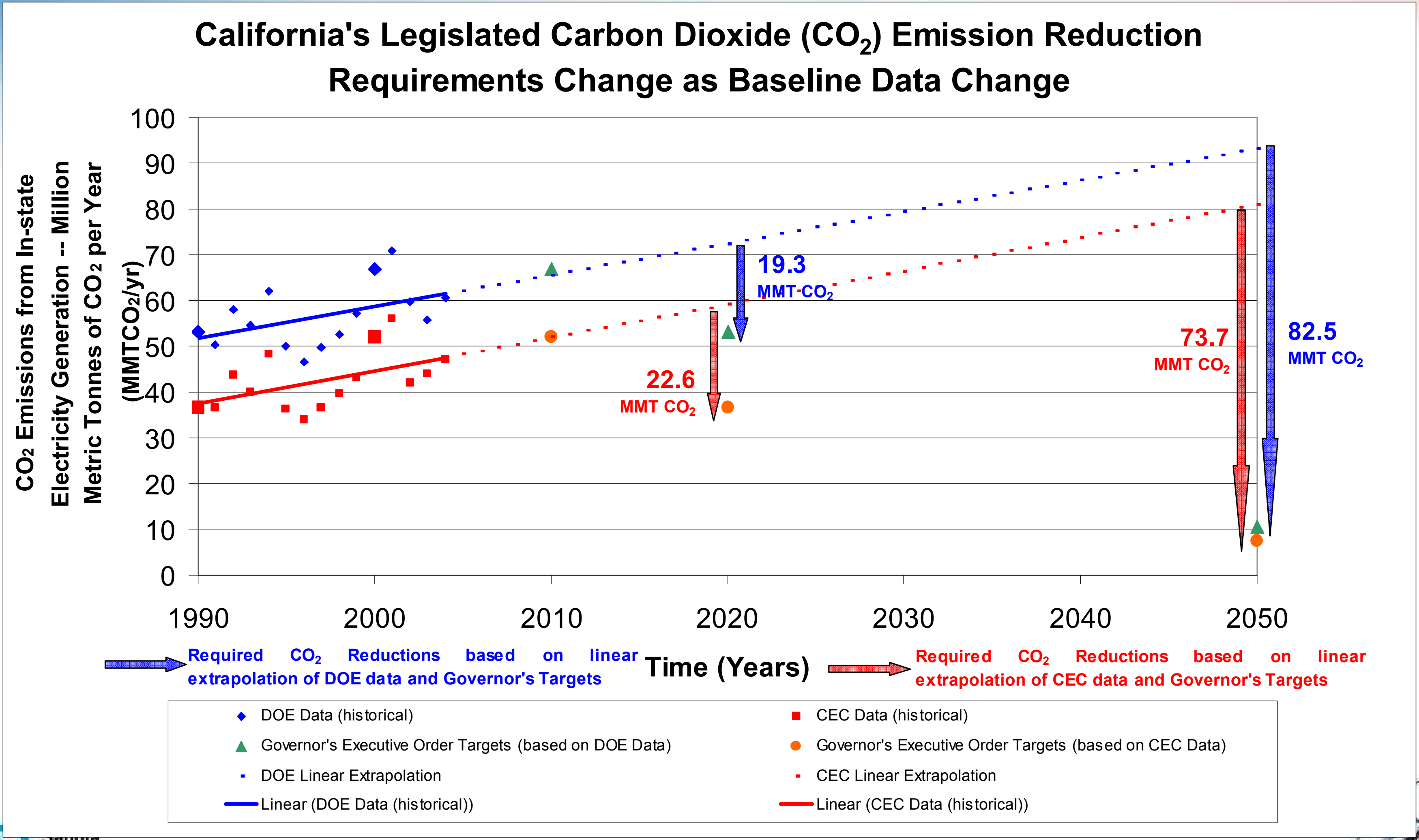
What is the impact of the corrected CO_2 emission baseline on policy?

CA Legislated Goals Change



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Results

- Differences between data series due to omissions in 1990-1999.
- Baseline emissions should be adjusted upwards.
- 2050 Total Targeted Reduction
  - CEC Baseline: 73.7 $MMTCO_2$
  - DOE Baseline: 82.5 $MMTCO_2$

How do CO_2 emissions from fuel cell systems compare with California power generation

(using the correct baseline emissions)?

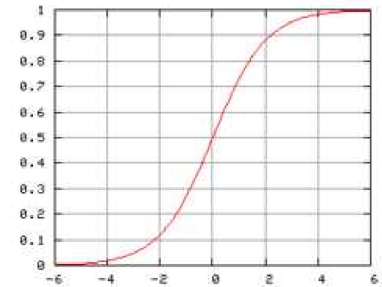
12 Scenarios: Change in CO_2 with Fuel Cell Systems

Fuel Cell Systems Replace Either 1) All Electric Generation, 2) All In-State Generation, or 3) All Electricity Imports in CA from 1990-2004

Non-Cogenerative FCS Consuming Natural Gas Fuel

Electrically Networked (ENW) -- Connected to the Distribution Grid Allowing the Inflow and Outflow of Electricity; Fixed Heat-to-Power (FHP) Ratio

Non-Load Following (NLF) at Maximum Electrical Efficiency (η_{e_max})



Four System Types:

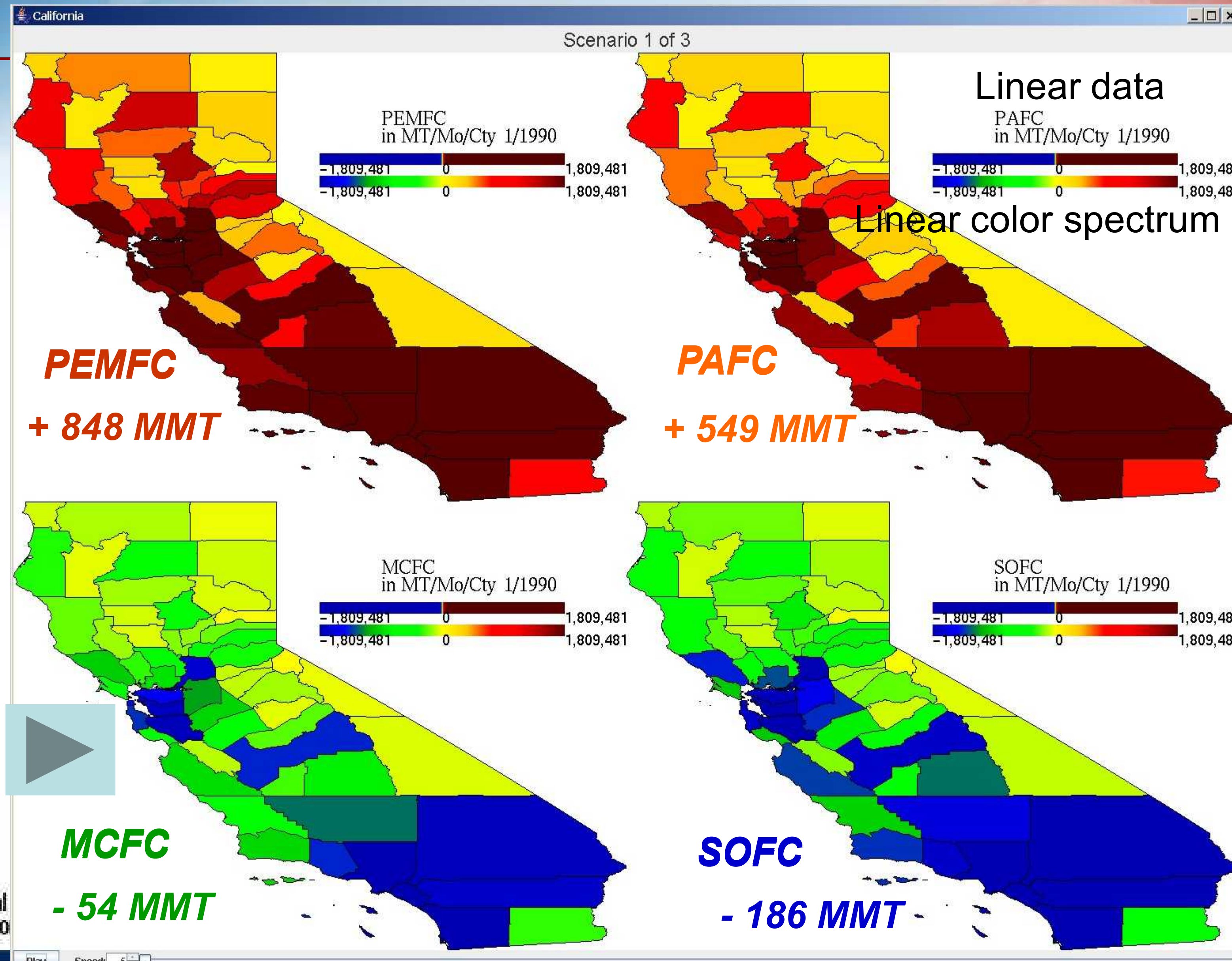
1) Proton Exchange Membrane (PEMFC) $\eta_{e\_max} \approx 32\%$
2) Phosphoric Acid Fuel Cell (PAFC) $\eta_{e\_max} \approx 37\%$
3) Molten Carbonate Fuel Cell (MCFC) hybrid w/ downstream gas turbine $\eta_{e\_max} \approx 54\%$
4) Solid Oxide Fuel Cell (SOFC) pressurized hybrid w/ downstream turbine $\eta_{e\_max} \approx 60\%$

Plots: colors applied sigmoid function to data to highlight small variations in low positive and negative data values.

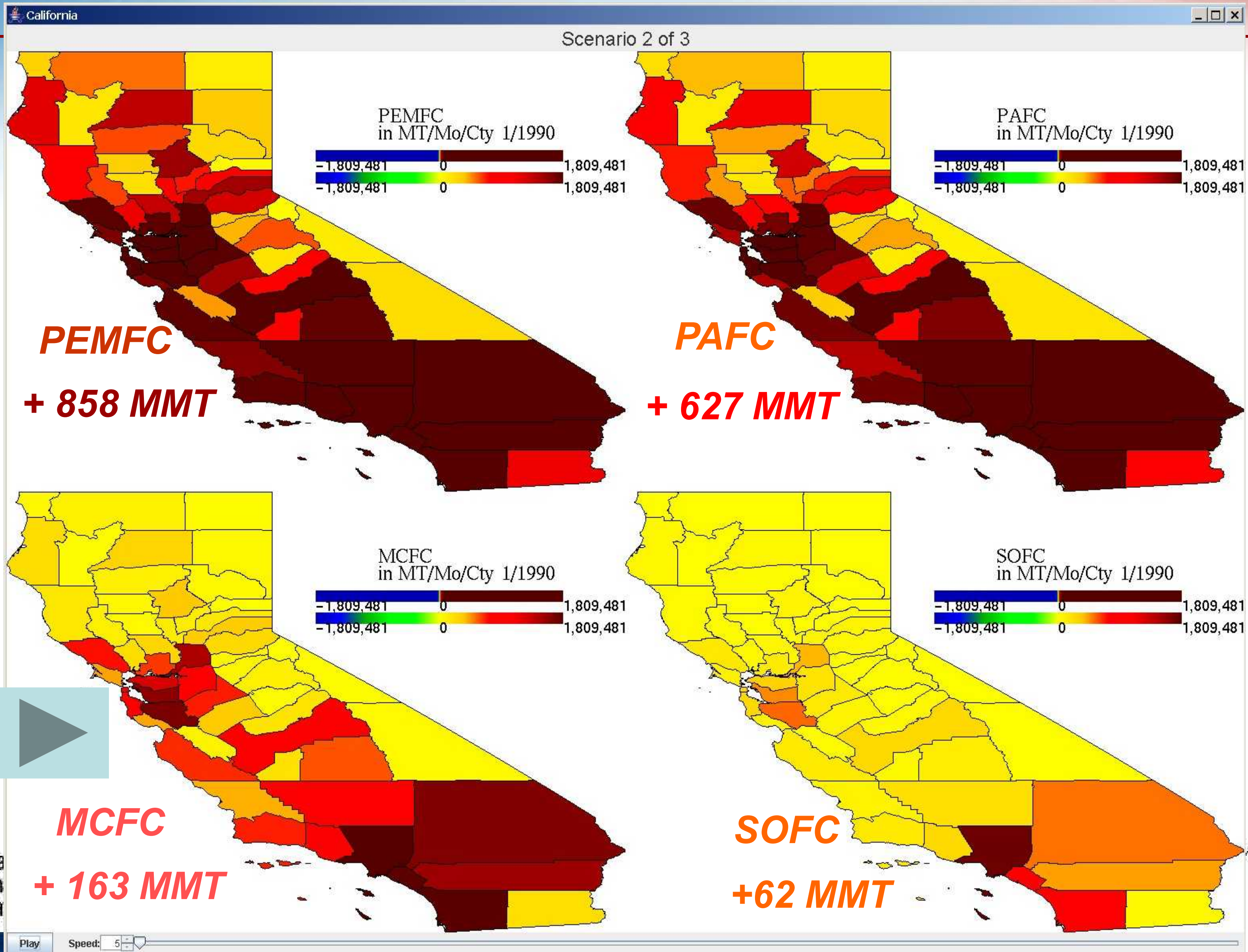
Blue & Green = Good (reduction in CO_2 emissions); Red and Black = Bad (increase in CO_2 emissions)

Cumulative changes in CO_2 over 15 Years (Million Metric Tons - MMT)

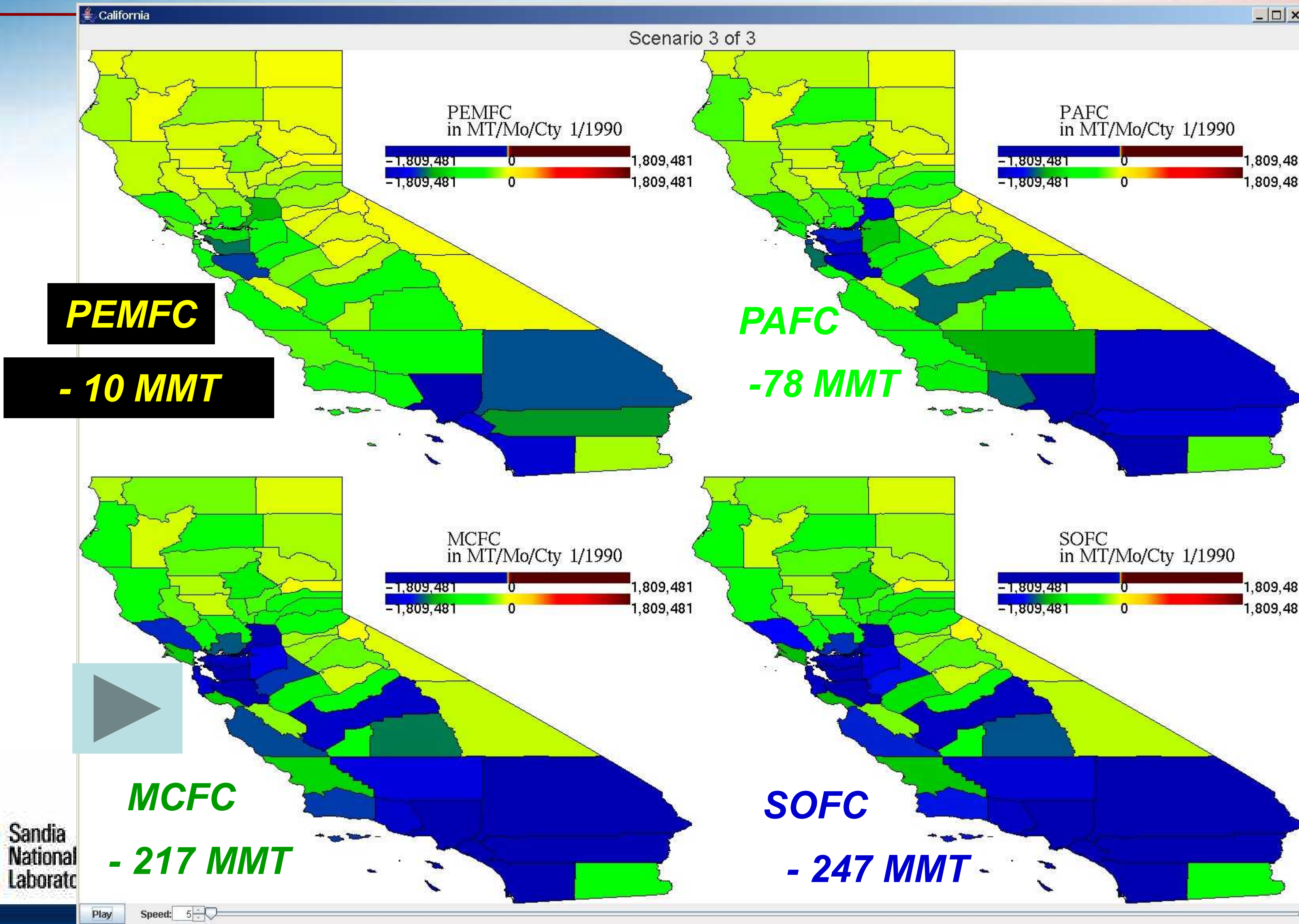
Fuel Cell Systems Replace 100% of Power



Fuel Cell Systems Replace In-State Power Only



Fuel Cell Systems Replace Imported Power Only

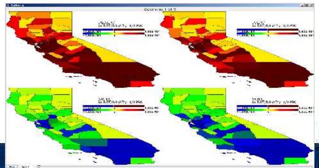


Results

For Non-Cogen FCS, ENW, FHP Ratio, NLF at ηe_max:

Cumulative Change in CO_2 1990-2004 (MMT)				
Replace	**PEM**	**PAFC**	**MCFC**	**SOFC**
All Electricity Consumption	848	549	-54	-186
All In-State Generation	858	627	163	62
All Imports	-10	-78	-217	-247

1. **All fuel cell types reduce CO_2 if replace imports.**
2. **Highest CO_2 reductions if MCFC or SOFC replace imports.**
3. **PEMFC and PAFC must operate cogeneratively with high effective heat recovery to reduce CO_2 effectively.**



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How do we install and operate fuel cell systems to maximize reductions in CO_2 emissions? And maximize financial savings?

➔ Focus on lower temperature systems (PAFC, PEMFC) because they are more tricky to implement for CO_2 reductions.

➔ Develop and apply custom simulation code for maximizing emission reductions and economic savings

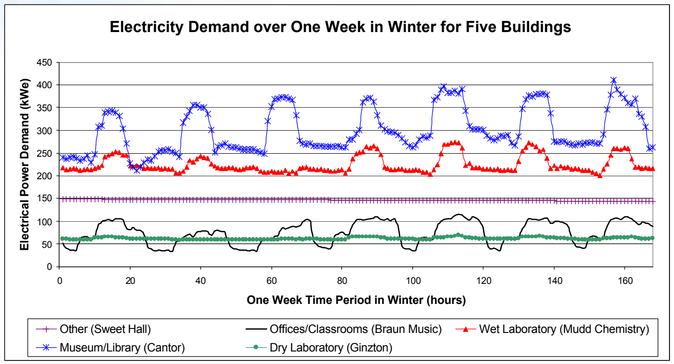
Environmental and Financial Simulation

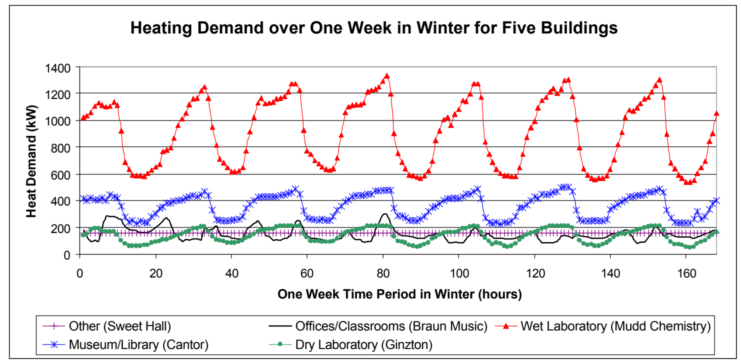
- Model optimizes FCS installation for a particular site, FCS type, and competitive environment.
- Examines game-changing operating strategies not common in commercial industry (HLF, VHP, NW)
- Model allows users to evaluate trade-offs among three competing goals – 1) cost savings to building owners, 2) GHG emission reductions, 3) FCS manufacturer profit
- Optimizes the percentage installation of FCS for minimum CO_2 emissions <u>or</u> maximum cost savings to building owners

Simulation Inputs

User Can Input

- Electricity and heating demand curves for buildings





- Operating and financial data for fuel cell systems and competing generators

Fuel Cell System Costs -- Fixed Cost per year	Amount Borrowed (or Credited) at Time t = zero [P] ($)	Annuity [A] ($)
Capital Costs of 200 kW Fuel Cell System	$ 950,000	$137,869
Installation Costs	$ 250,000	$ 36,281
Commissioning Costs (Start-up, Testing, Tutorials for Operators)	$ 20,000	$ 2,903
Shipping	$ 20,000	$ 2,903
Premium Service Contract (Maintenance and Replacement) -- Annuity Payments		$ 60,000
Fuel Cell System Incentives -- Federal and State		
California Self-Generation Incentive Program (CA SGIP) at $2500/kWe	$ 500,000	$ 72,563
Federal Investment Tax Credit (FITC) at $1000/kWe	$ 200,000	$ 29,025
Fuel Cell System Fixed Costs -- Total Yearly Fixed Costs		**$138,368**

Fuel Cell System Operating Data	Quantity	Units
Maximum Electrical Output	200	kw
Minimum Electrical Output	100	kw
Maximum Heat-to-Electric Power Ratio	2.5	
Minimum Heat-to-Electric Power Ratio	1.3	
Baseline Heat-to-Electric Power Ratio for Fixed Heat-to-Pow	1.3	
Natural Gas Fuel Consumption (in Units of Energy) Per Unit of Electric Power Output	9,222	gas/kwh of electricity
Marginal Increase in Natural Gas Fuel Consumption (in Units of Energy) Per Unit of Additional Heat Demanded (Variable Heat to Power Ratio Scenarios Only)	3,791	BTU natural gas/kwh of electricity
Baseline System Electrical Efficiency	37%	
Baseline System Heat Recovery Efficiency	48%	
Baseline System Heat Losses (Percent)	15%	
Baseline System Combined Electrical and Heat Recovery Ef	85%	
Heat Recovery Efficiency of Burner-Heater for Marginal Heating (Variable Heat to Power Ratio Scenarios Only)	90%	

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Simulation of Operating Strategies

Scenarios Evaluated

- Strategy I: Electrically and Thermally Networked (NW), Electricity Power Load Following (ELF), Variable Heat-to-power ratio (VHP)
- Strategy II: NW, Heat Load Following (HLF), VHP
- Strategy III: NW, Non-Load Following (NLF), Fixed Heat-to-power ratio (FHP)
- Strategy IV: Not Networked/ Stand Alone (SA), HLF, VHP
- Strategy V: SA, NLF, VHP

Example Results Shown for One Case Study

- PAFC vs. cogenerative combined cycle natural gas turbine
- A particular town's buildings and load curves

Scenario A: No state/federal incentives or carbon tax; Strategy I is only economical one

Strategy	Optimal installed fuel cell system capacity as a percent of average power (%)	Annual cost savings (%)	Change in CO_2 compared with base case of no fuel cells (Metric Tonnes of CO_2/yr)
I	17%	3%	-29%
II	0%	0%	0%
III	0%	0%	0%
IV	0%	0%	0%
V	0%	0%	0%

Strategy I [NW, ELF, VHP]: economical with *no subsidies*

17% of average installed capacity, 3% savings, 29% less CO_2

Strategy I = *avant-garde*

Scenario B: State & federal incentives, no carbon tax; Strategy I = most savings, least CO_2 ; III = most profit

Strategy	Optimal installed fuel cell system capacity as a percent of average power (%)	Annual cost savings (%)	Change in CO_2 compared with base case of no fuel cells (%)
I	24%	15%	-31%
II	38%	9%	-12%
III	46%	3%	-27%
IV	13%	1%	-20%
V	32%	2%	-25%

Strategy I: 24% of capacity, 15% savings, 31% less CO_2

Strategy III [NW, NLF, FHP]: 46% of capacity, 3% savings, 27% less CO_2

Dichotomy between optimal financial strategy for building owners and that for fuel cell manufacturers

Scenario B: Best Load Curves Strategies IV and V – Mudd/McCullough most savings; CIS most profit

Strategy IV

Building Type	Load Curve Based on this Building	Optimal Installed Fuel Cell System Capacity as a Percentage of Peak Power Demand throughout Energy Area (%)	Annual Cost Savings (%)
Wet Lab	Mudd (Seeley G) Chemistry	4%	1.5%
Dry Lab	McCullough (Jack A.)	1%	1.0%
Dry Lab	Mechanical Engineering Research La	1%	0.9%
Wet Lab	Center for Integrated Systems (CIS)	4%	0.8%
Dry Lab	Gates Computer Scier	1%	0.7%
Wet Lab	Gordon Moore Materials Research	1%	0.4%

Strategy V

Building Type	Load Curve Based on this Building	Optimal Installed Fuel Cell System Capacity as a Percentage of Average Power Demand throughout Energy Area (%)	Annual Cost Savings (%)
Dry Lab	McCullough (Jack A.)	2%	3.5%
Museum/Library	Cantor Center for Visual Arts	1%	3.2%
Dry Lab	Gates Computer Science	3%	3.2%
Dry Lab	Mechanical Engineering Research La	2%	3.2%
Wet Lab	Mudd (Seeley G) Chemistry	5%	3.1%
Housing	Wilbur Dining Hall	1%	3.0%
Wet Lab	Center for Integrated Systems (CIS)	9%	2.8%
Offices/Classrooms	Packard Electrical Engineering	1%	2.6%
Offices/Classrooms	Tresidder	1%	2.4%
Dry Lab	Ginzton (Edward L.) Labs & Annex	1%	2.4%
Housing	Lagunita Dining	1%	2.4%
Dry Lab	Green Earth Sciences	1%	1.2%

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Wet or dry lab ~ 24-7 industrial facilities = best

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Scenario C: State & federal incentives, $20/tonne CO_2
Strategy I = most savings, least CO_2 ; III = most profit

Strategy	Optimal installed fuel cell system capacity as a percent of average power (%)	Annual cost savings (%)	Change in CO_2 compared with base case of no fuel cells (%)
I	28%	17%	-32%
II	44%	12%	-14%
III	49%	6%	-27%
IV	18%	2%	-25%
V	41%	4%	-31%

Strategy I: 28% of capacity, 17% savings, 32% less CO_2

Strategy III: 49% of capacity, 6% savings, 27% less CO_2

Scenario D: State & federal incentives $100/tonne CO_2
Strategy I=most savings; III=most profit; V=least CO_2

Strategy	Optimal installed fuel cell system capacity as a percent of average power (%)	Annual cost savings (%)	Change in CO_2 compared with base case of no fuel cells (%)
I	36%	25%	-32%
II	50%	20%	-15%
III	60%	13%	-30%
IV	28%	6%	-32%
V	51%	11%	-34%

Strategy I: 36% of capacity, 25% savings, 32% less CO_2

Strategy III: 60% of capacity, 13% savings, 30% less CO_2

Strategy V [SA, NLF, VHP]: 51% of capacity, 11% savings, 34% less CO_2

Three competing goals – 1) cost savings to building owners, 2) GHG emission reductions, 3) FCS manufacturer profit – maximized with three different strategies.

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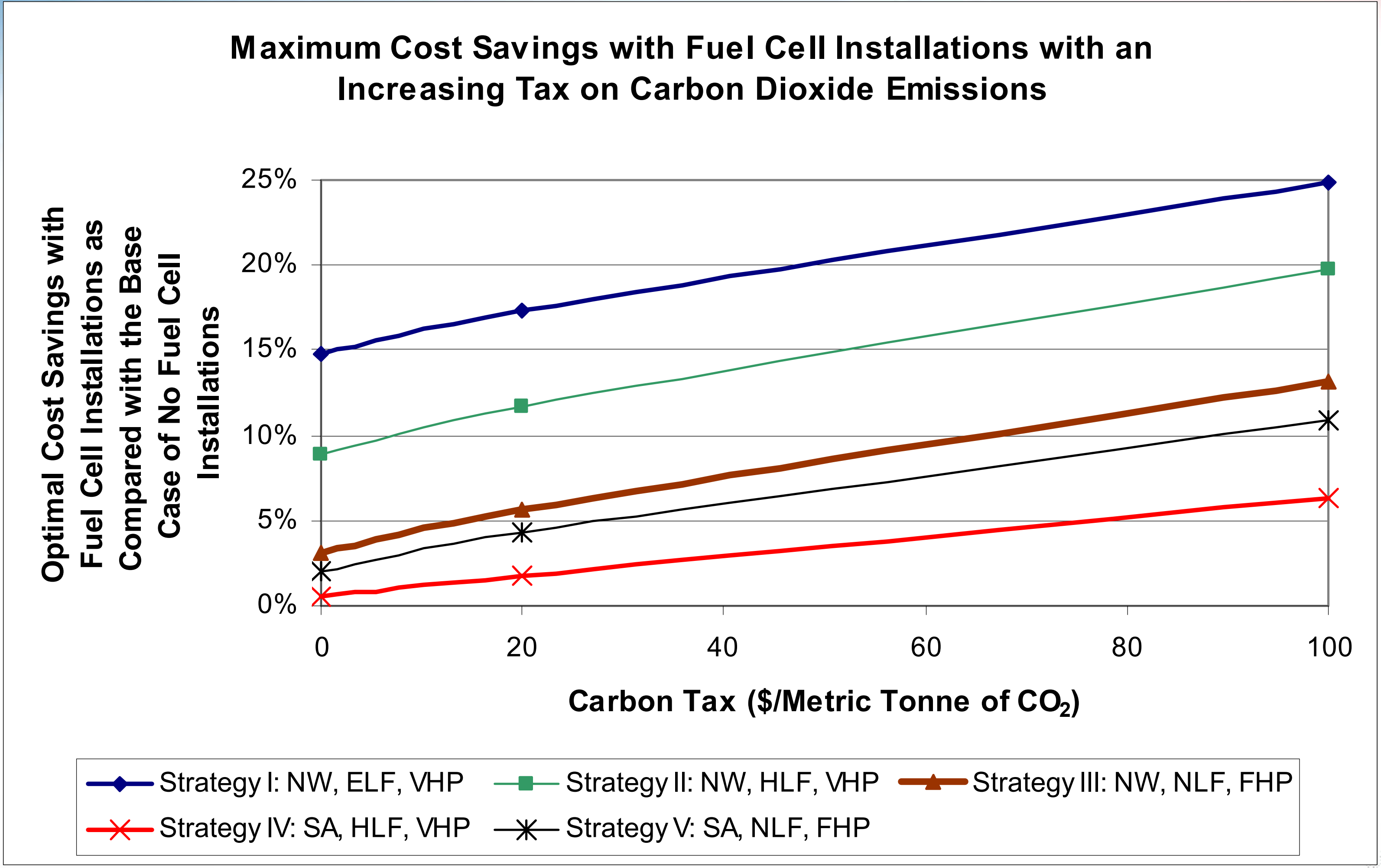
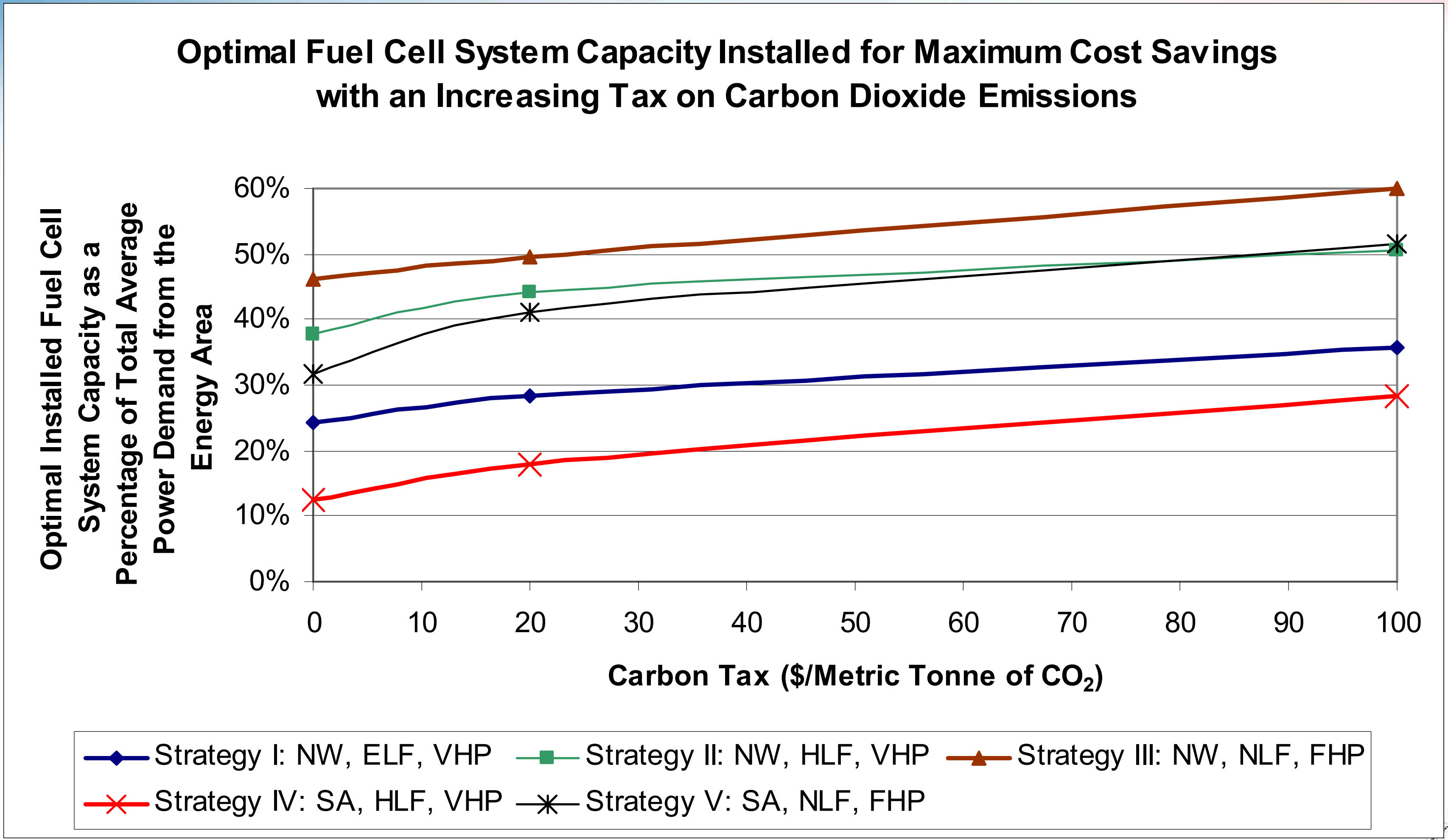
Highest savings for building owners with 1) Strategy I, 2) NW, 3) NW + ELF or HLF



Highest profit for fuel cell makers with Strategy III = *close to status quo*



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Highest CO_2 Reductions with Strategies I, III, V

Strategy	Optimal installed fuel cell system capacity as a percent of average power (%)	Change in CO_2 compared with base case of no fuel cells (%)
I	40%	-32%
II	94%	-16%
III	85%	-32%
IV	57%	-23%
V	68%	-37%

1. **Highest cost savings with Strategy I (avant-garde)**
2. **Highest profitability with Strategy III (status quo)**
3. **Maximum CO_2 reductions with Strategy V (avant-garde) - most economical neither for buildings nor FCS makers - building load curves even more crucial (SA operation) -FCS must manipuate its operation to meet real-time electricity & heating demand w/o back-up**

Highest CO_2 Reductions for Stand-Alone Strategies with Certain Building Load Curves

Wet Laboratory Building Load Curve Has Highest CO_2 Reductions

Building Type	Load Curve Based on this Building	Optimal Number of Fuel Cell System Installations	Optimal Installed Fuel Cell System Capacity (MWe)	Optimal Installed Fuel Cell System Capacity as a Percentage of Peak Power Demand throughout Energy Area	Optimal Installed Fuel Cell System Capacity as a Percentage of Average Power Demand throughout Energy Area	Approximate CO_2 Emissions from Electricity and Heat Provision (metric tonnes CO_2/yr)	Approximate Reduction in CO2 Emissions Compared with Base Case of No Fuel Cells (metric tonnes CO2/yr)	Approximate Annual CO_2 Emission Savings (%)
Wet Lab	Mudd (Seeley G) Chemistry	9	1.8	7%	9%	12,240	5,730	32%
Offices/Classrooms	Braun Music	1	0.2	1%	1%	1,317	563	28%
Dry Lab	Ginzton (Edward L.) Labs & Annex	1	0.2	1%	1%	1,547	634	27%
Offices/Classrooms	Ceras	1	0.2	1%	1%	1,843	635	26%
Museum/Library	Cantor Center for Visual Arts	1	0.2	1%	1%	1,552	560	24%
Housing	Lagunita Dining	2	0.4	1%	2%	2,248	829	24%
Wet Lab	Gordon Moore Materials Research	6	1.2	4%	6%	6,815	2,291	23%
Dry Lab	Gates Computer Science	5	1	4%	5%	5,233	1,928	23%
Offices/Classrooms	Law Crown	3	0.6	2%	3%	4,793	1,401	23%
Offices/Classrooms	Tresidder	2	0.4	1%	2%	2,555	856	22%
Housing	Wilbur Dining Hall	2	0.4	1%	2%	2,021	638	22%
Other Type	Sweet	1	0.2	1%	1%	1,219	399	21%
Other Type	Faculty Club	1	0.2	1%	1%	1,219	399	21%
Wet Lab	Center for Integrated Systems (CIS)	12	2.4	9%	13%	16,918	5,297	21%
Housing	Stern Dining	2	0.4	1%	2%	2,247	605	21%
Offices/Classrooms	Packard Electrical Engineering	2	0.4	1%	2%	2,034	577	20%
Housing	Branner Hall	1	0.2	1%	1%	1,682	468	20%
Library	Green E	1	0.2	1%	1%	1,345	363	20%
Library	Meyer	1	0.2	1%	1%	1,345	363	20%
Offices/Classrooms	Lane History	0	0	0%	0%	891	82	9%
Dry Lab	McCullough (Jack A.)	3	0.6	2%	3%	3,394	0	6%
Housing	Florence Moore Kitchen	1	0.2	1%	1%	897	47	5%
Housing	Moore South	0	0	0%	0%	712	29	4%
Dry Lab	Mechanical Engineering Research Lab	3	0.6	2%	3%	4,154	0	4%
Dry Lab	Green Earth Sciences	3	0.6	2%	3%	3,735	0	3%
Housing	Xanadu	0	0	0%	0%	691	5	1%
Housing	Moore North	0	0	0%	0%	691	0	0%
Offices/Classrooms	Cummings Art	1	0.2	1%	1%	971	0	0%
Offices/Classrooms	TC Seq	0	0	0%	0%	850	0	0%
Dry Lab	Env Fluid Mech	0	0	0%	0%	597	0	0%

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No particular building *type* = best

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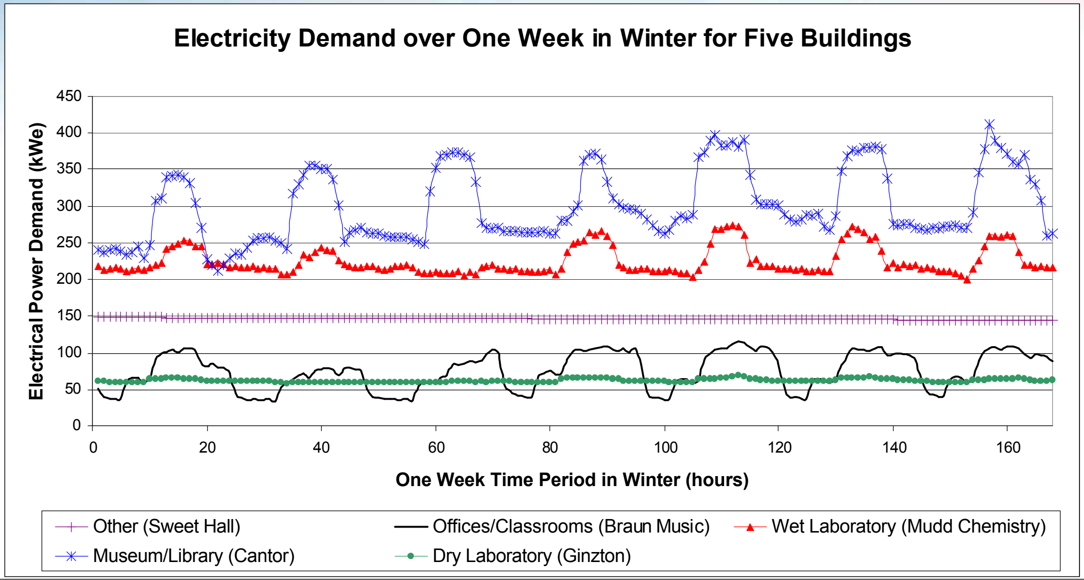
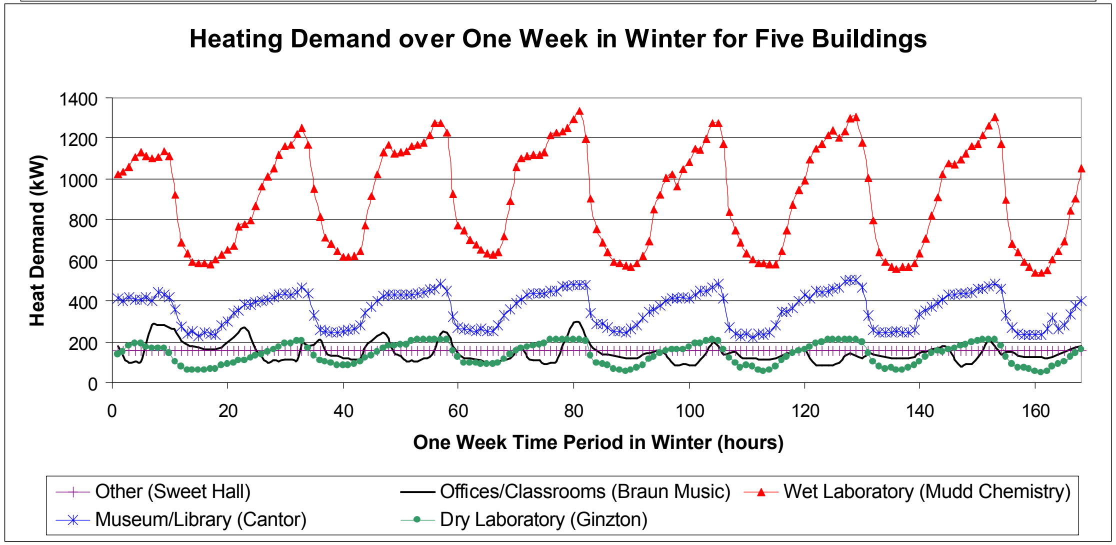
Top three load curves for reduced CO_2 (Mudd - red, Braun -black, Ginzten -green)





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Results

1. **FCS are marginally economical with <u>no subsidies</u> by <u>changing</u> to Strategy I (NW, ELF, VHP) <u>*avant-garde*</u>**
2. **Dichotomy between optimal financial strategy for building owners and that for fuel cell developers.**
3. **Maximum financial savings with particular load curves – wet and dry labs ~ 24-7 industrial facilities**
4. **With full state & federal incentives and a \$100/tonne CO_2 tax, three competing goals – 1) cost savings, 2) GHG emission reductions, 3) FCS maker profit – maximized with three different strategies:**
   Highest cost savings w/ Strategy I (avant-garde)
   <u>Highest</u> CO_2 reductions w/ Strategy V (avant-garde)
   Highest profitability w/ Strategy III (status quo)

Results II

1. **Higher cost savings with NW**
2. **When NW, combining ELF or HLF with VHP has higher savings**
3. **Highest CO_2 reductions with Strategies I, III, V (NW, ELF, VHP and HLF; SA, NLF, VHP)**
4. **Highest CO_2 reductions for stand alone installations V with certain building load curves (a particular wet laboratory's load curve), but not consistently for a building *type* (residence, etc.)**

⇒ Crucial to use simulation to find best buildings

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Conclusions

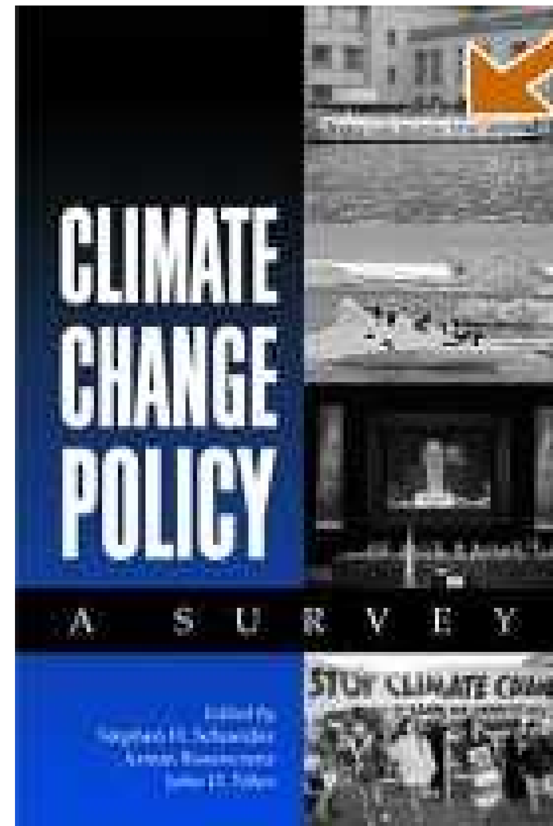
1. **Must apply simulation to find the best installation strategy for a $$ or GHG goal**
   1. **No particular building *type* = best**
   2. **Load curves are crucial**
   3. **Maximum CO_2 reductions with Strategy V (SA)**
      1. **Load curves are even more crucial**
2. ***Avand guard* operating strategies can make FCS more economical and environmentally beneficial.**

Recommendations

1. Create incentives for FCS makers to build VHP
2. Encourage partnerships between FCS makers and energy service companies (ESCO)
3. Focus on installing FCS within pre-existing thermal networks
4. Apply simulations to identify specific building load curves ideal for installation

Educating Policy Makers about Hydrogen

- "Designing Energy Supply Chains Based on Hydrogen [To Mitigate Climate Change]," by W. Colella in Climate Change Science and Policy: Stephen H. Schneider, Armin Rosencranz and Michael D. Mastrandrea, eds. 2008.
- Target audience: engineers & policy makers
- Editors are Stanford University researchers

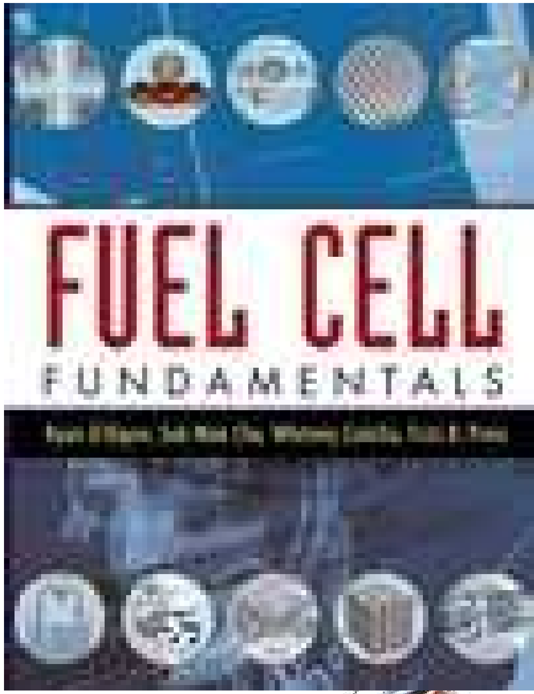


Educating Engineers about Fuel Cells

- 1st Textbook on Fuel Cells: ***Fuel Cell Fundamentals***

  O’hare, Cha, Colella, and Prinz

- Target audience: senior undergraduate or graduate student engineers
- Solved problems in textbox inserts and solutions guide
- Authors were Stanford University researchers



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Extra

Future Work

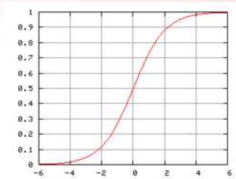
- Develop more detailed fuel cell simulations
  - Quantify impact of seasonal variation in load curve
  - Change the operating strategy during the run – switch between operating strategies over time to minimize emissions or costs – find the mix of best operating strategies over time
  - More sophisticated power plant models (ASPEN chemical engineering / process modeling / system dynamics software)
  - Combine optimization code with more detailed FCS models (ASPEN)
  - Use NISAC's Platts power plant data – hourly supply data from every power plant in the US for electricity output, thermal output, and fuel consumption
  - Analyze the system impacts of high vs. low temperature PEM fuel cell systems for stationary power using Sandia's test data on PEM cells

What are California's CO_2 Emissions from Electricity Consumption?

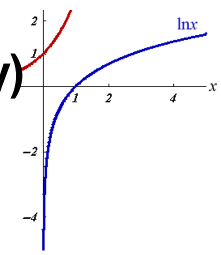
Methodology:

1) EIA Monthly Electricity Sales Data 1990-2004
2) EIA Annual Direct Use Data 1990-2004 -- Monthly Sales Distribution Applied
3) Sales + Direct Use = Total Electricity Consumption
4) EIA Annual Net Generation Data 1990-2004 -- Monthly Sales Distribution Applied
5) Imports = Total Consumption – Net Generation
6) EIA Total CO_2 Emissions from Net Generation/EIA Net Generation = CO_2 Emissions Factor for Net Generation
7) EIA Total CO_2 Emissions from Net Generation (Monthly)
8) CEC Total CO_2 Emissions from Imports/CEC Electricity Imports = CO_2 Emissions Factor for Imports
9) EIA Imports * CO_2 Emissions Factor for Imports = Total CO_2 Emissions from Imports (Monthly)
10) Redistributed by Population

Visualizing CO_2 Emission Changes



- **Custom Geographic Information System (GIS) application**
- **Linear, Logarithmic, Sigmoidal plots**
- **Logarithmic relationship between CO_2 concentrations and radiative forcing (heat trapping effect of global warming).**
- **CO_2 plotted at <u>point of consumption</u>, not generation, to link cause and effect. Environment indifferent to location of emission (unlike air pollution).**



- **Units: Metric Tonnes (MT) per month (Mo) per county (Cty)**
- **Blue & Green = Good; Red and Black = Bad**
- **EIA Logarithmic and Linear Plots:**
  - **EIA Logarithmic Plot: Colors applied logarithmically to the data to highlight variations at the low end. Top legend plots data values linearly. Bottom legend plots color spectrum linearly.**
  - **EIA Linear Plot: Colors applied linearly to the data. The legend shows the color spectrum linearly.**

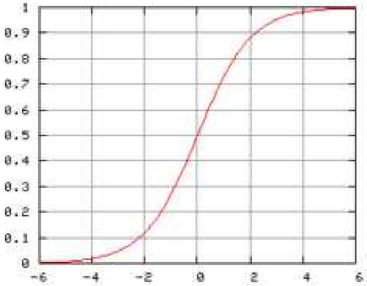
12 Scenarios: Change in CO_2 with FCS

FCS Replace Either 1) All Electric Generation, 2) All In-State Generation, or 3) All Electricity Imports in CA from 1990-2004

Non-Cogenerative FCS Consuming Natural Gas Fuel

Electrically Networked (ENW) -- Connected to the Distribution Grid Allowing the Inflow and Outflow of Electricity; Fixed Heat-to-Power (FHP) Ratio

Non-Load Following (NLF) at Maximum Electrical Efficiency (η_{e_max})



Four System Types:

1) Proton Exchange Membrane (PEMFC) $\eta_{e\_max} \approx 32\%$
2) Phosphoric Acid Fuel Cell (PAFC) $\eta_{e\_max} \approx 37\%$
3) Molten Carbonate Fuel Cell (MCFC) hybrid w/ downstream gas turbine $\eta_{e\_max} \approx 54\%$
4) Solid Oxide Fuel Cell (SOFC) pressurized hybrid w/ downstream turbine $\eta_{e\_max} \approx 60\%$

Proven efficiencies (η), except SOFC only modelled

Plots: colors applied sigmoid function to data to highlight small variations in low positive and negative data values.

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DOE-EIA 906/920 Data Are Complete

- The DOE EIA calculations shown in **Table 2.0** are based on 906/920 databases. LBNL states, "we did not use the [DOE EIA's] 906/920 for CALEB because these data do not include nonutility plants for years prior to 1999…and that would have resulted in a major hole in the data for 1990 to 1998."
- However, by contrast, EIA states that "the 906/920 data set is complete (covers all producing sectors) from 2001 forward."
- Furthermore, in response to the comment from LBNL above, EIA states, "There are no "major holes" in the EIA data series (plural). The analyst from Berkeley is not correct about what data are available from EIA. IF one were to try to use the EIA-906 to get consumption data series from 1989 to 2006, that would not be possible, because that particular Form (the 906/920) was not used prior to 2001. I guess the analyst wasn't aware that the data were collected on other EIA forms. All the data were collected, but under different survey instruments. So no single survey instrument covers the entire time period. But there are no "major holes" because, TAKEN TOGETHER, the surveys collectively provide full coverage over the time period."

LBNL-CEC Methodology

LBNL

- Transposed EIA fuel consumption data into CALEB database,
- Truncated this data (by using fossil fuel only data base), and
- Re-categorized this data (such as CHP-generated electricity and heat), and
- Multiplied some of the fuel consumption categories (excluding geothermal etc.) by emission factors to report CO_2 total emissions (CALEB CO_2).
  - Re-allocated the CO_2 emissions associated with CHP-generated heat and electricity from natural gas power plants into the industrial sector. Removed this data from the electricity sector.
  - *The same procedure applied to other fuels? (LBNL no respond to question.)*
  - Omitted CO_2 emission data from natural gas plant CHP-generated heat between 1990-1999 from the aggregate emission database entirely.

LBNL-CEC Methodology

CEC

- Copied CALEB fuel consumption data (originally EIA fuel consumption data) for natural gas and coal fuel consumption,
- Made a large typo in reporting coal consumption in the process (under-estimated fuel consumption and emissions by 98%),
- Truncated fuel consumption data by only considering two fuels.
- Did not report CO_2 emissions from CHP-generated heat under electricity sector emissions
- Did not report CO_2 emissions from CHP-generated heat under other sectors explicitly, so readers could identify this quantity.

Resulting value-added unclear.

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