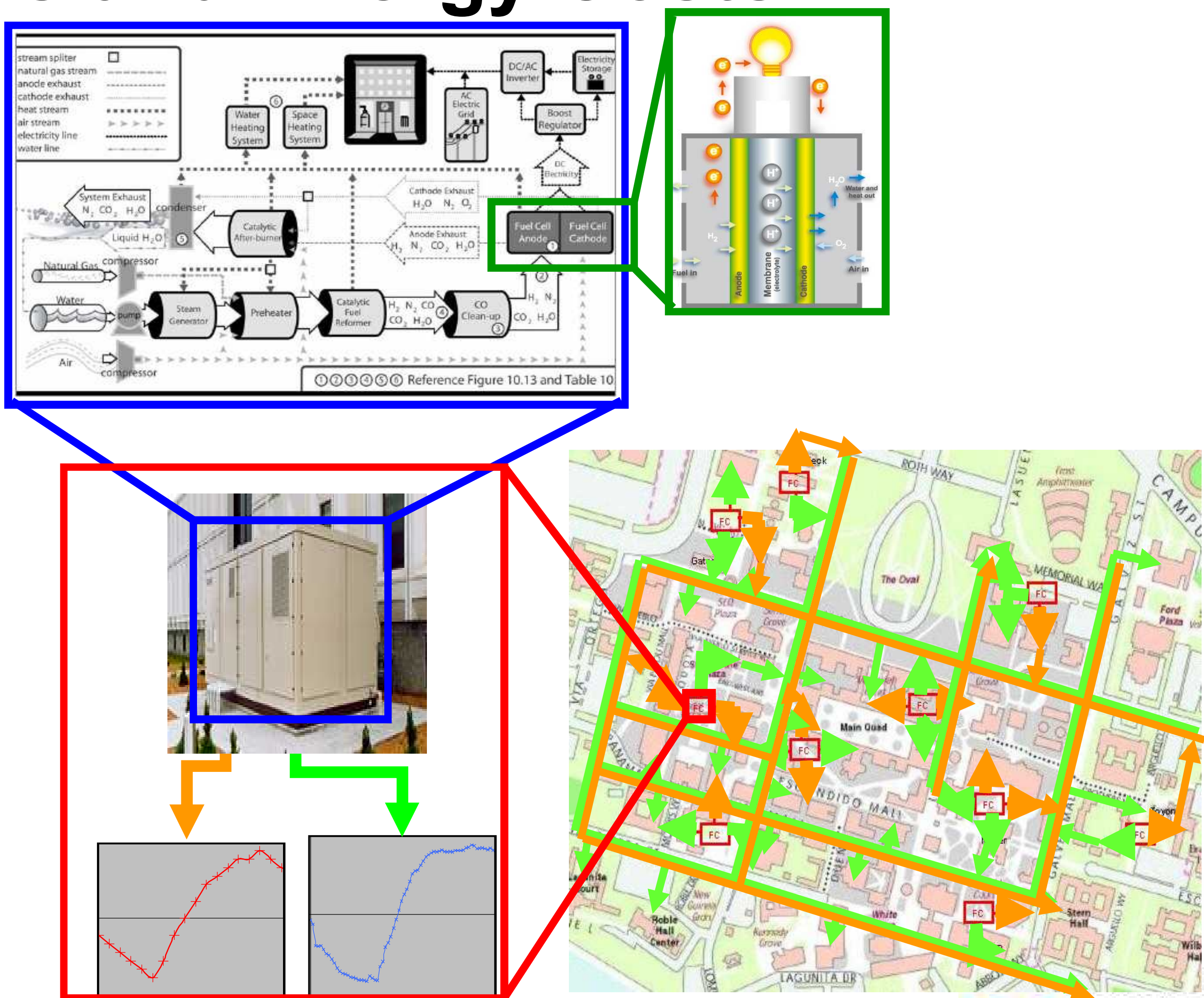
Optimization of Networks of Distributed Combined Heat and Power (CHP) Fuel Cell Systems (FCSs) To Reduce Greenhouse Gas (GHG) Emissions and Energy Costs

SAND2008-1953P



Whitney Colella

Truman Fellow
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March 31, 2008

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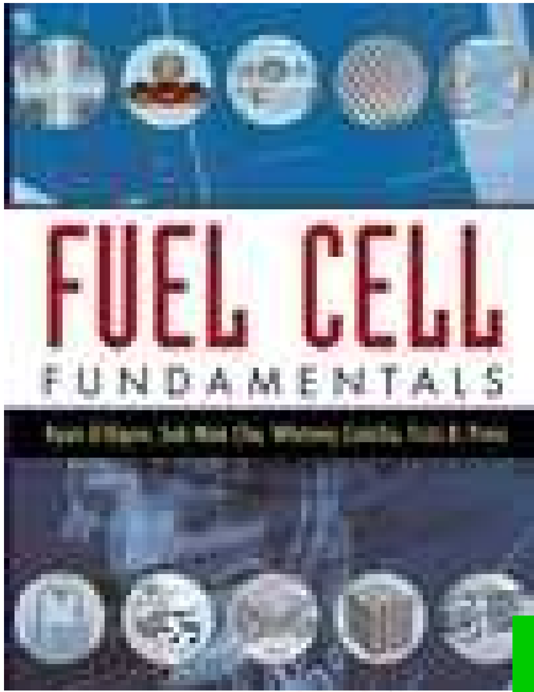
Quiz

Educating Engineers about Fuel Cells

- 1st Textbook on Fuel Cells: ***<u>Fuel Cell Fundamentals</u>***

  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

What fuel cell system operating strategy results in the lowest electricity and heating costs for building owners and a ~30% reduction in CO_2 emissions over a range of financial and environmental scenarios?



Copies available for review at conference

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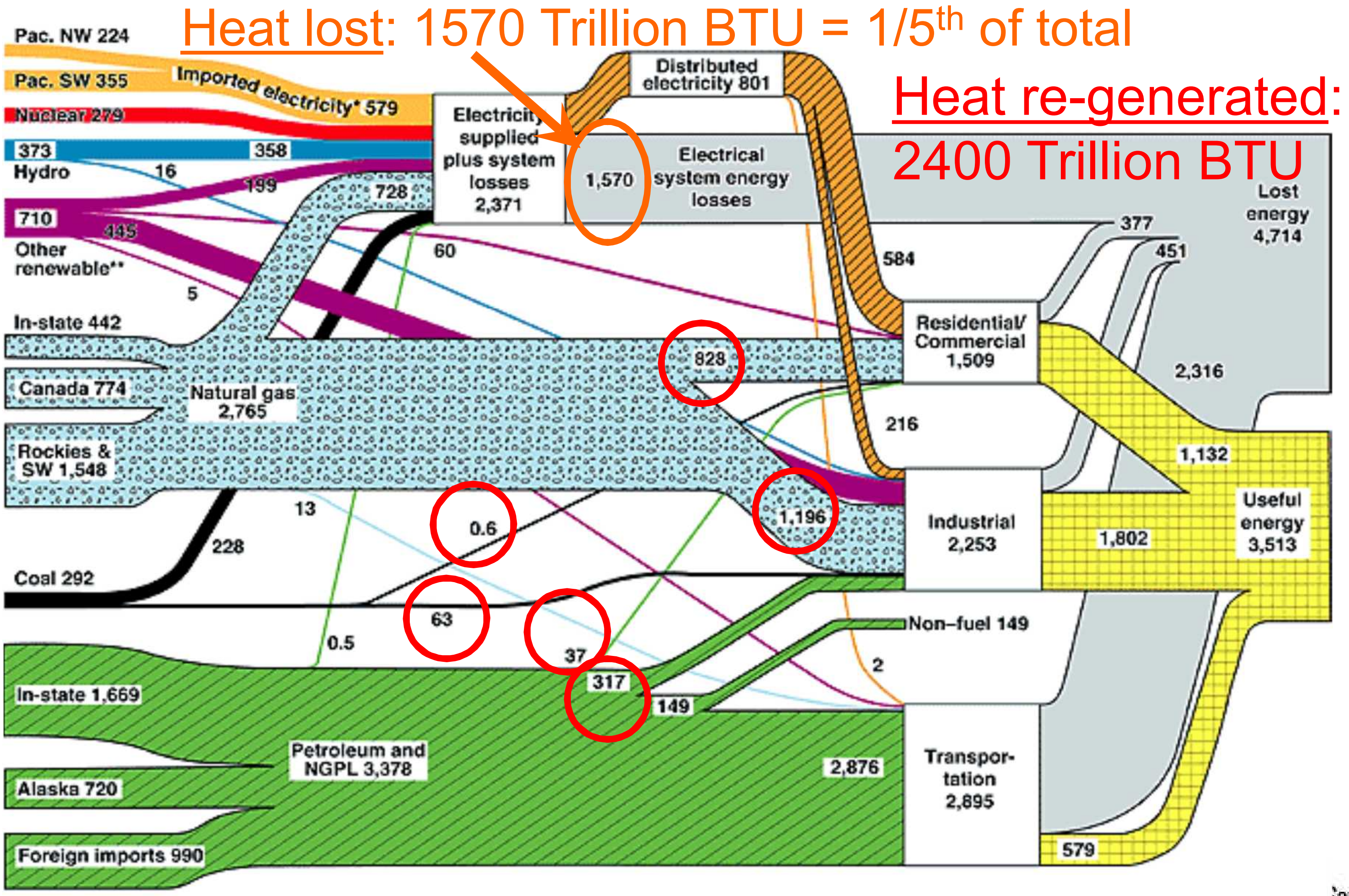
Motivation

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



California Energy Flow Figure by Lawrence Livermore National Lab

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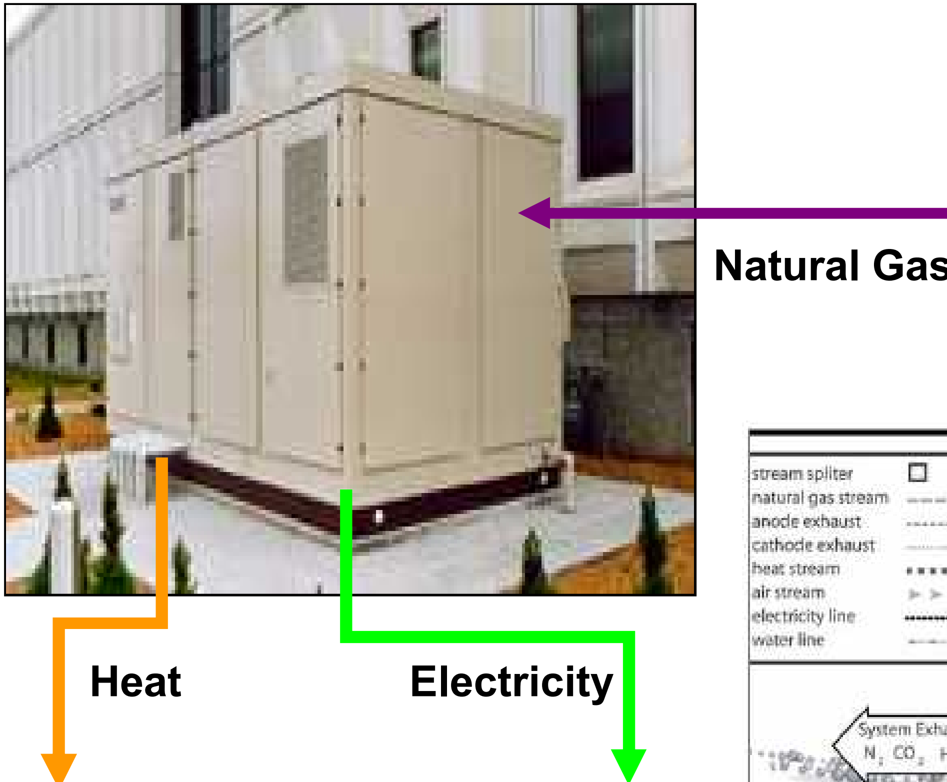
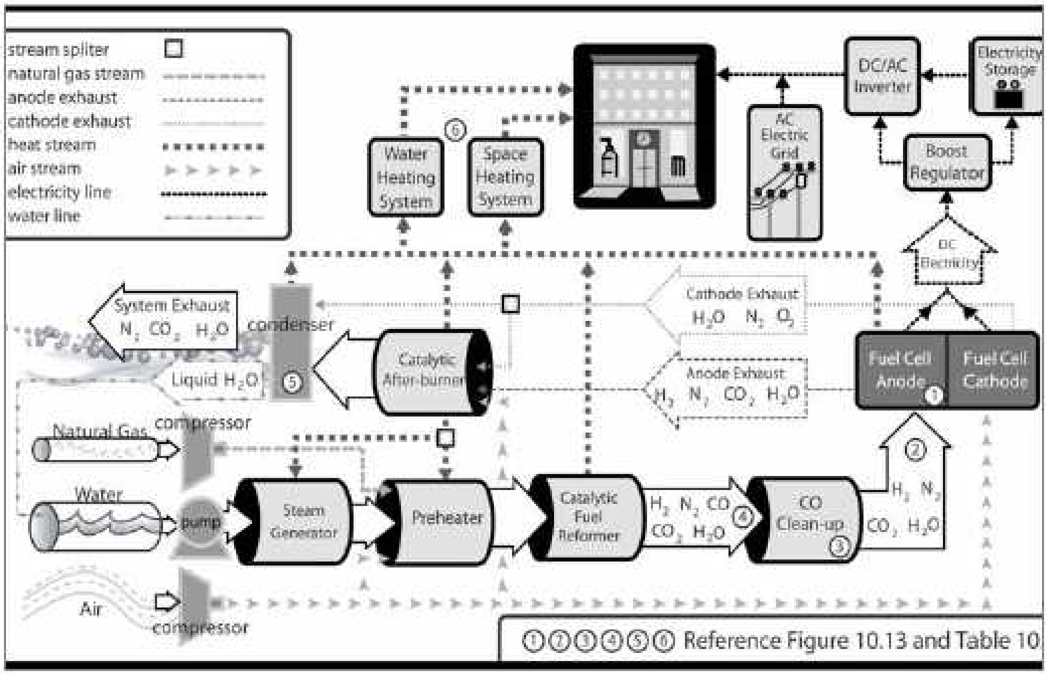
Background

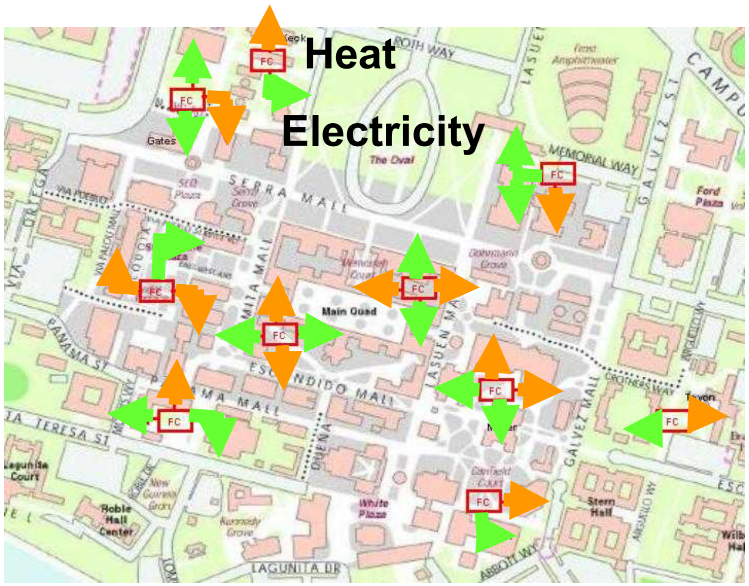
System: Stationary Fuel Cell System





Non-Networked vs. Networked

Non-Networked / Stand Alone

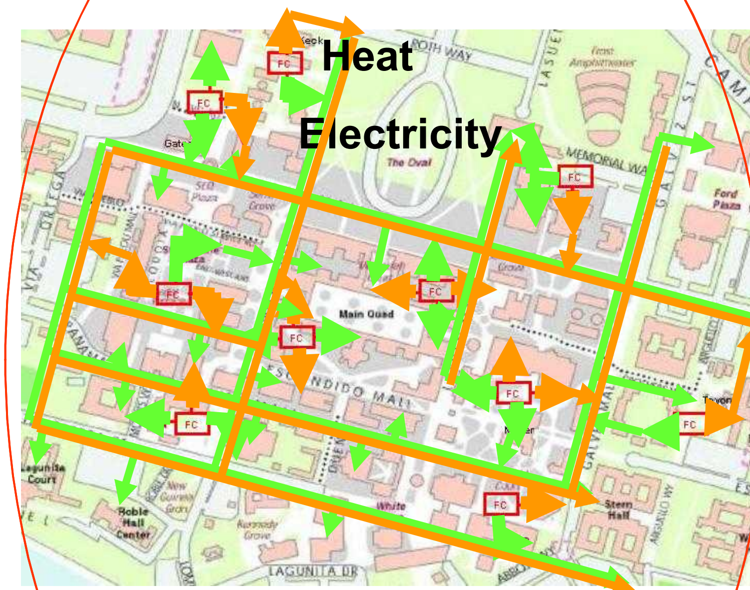


Fuel cells can NOT convey excess heat or electricity into the distribution grid to reach other buildings.

Electricity

Heat

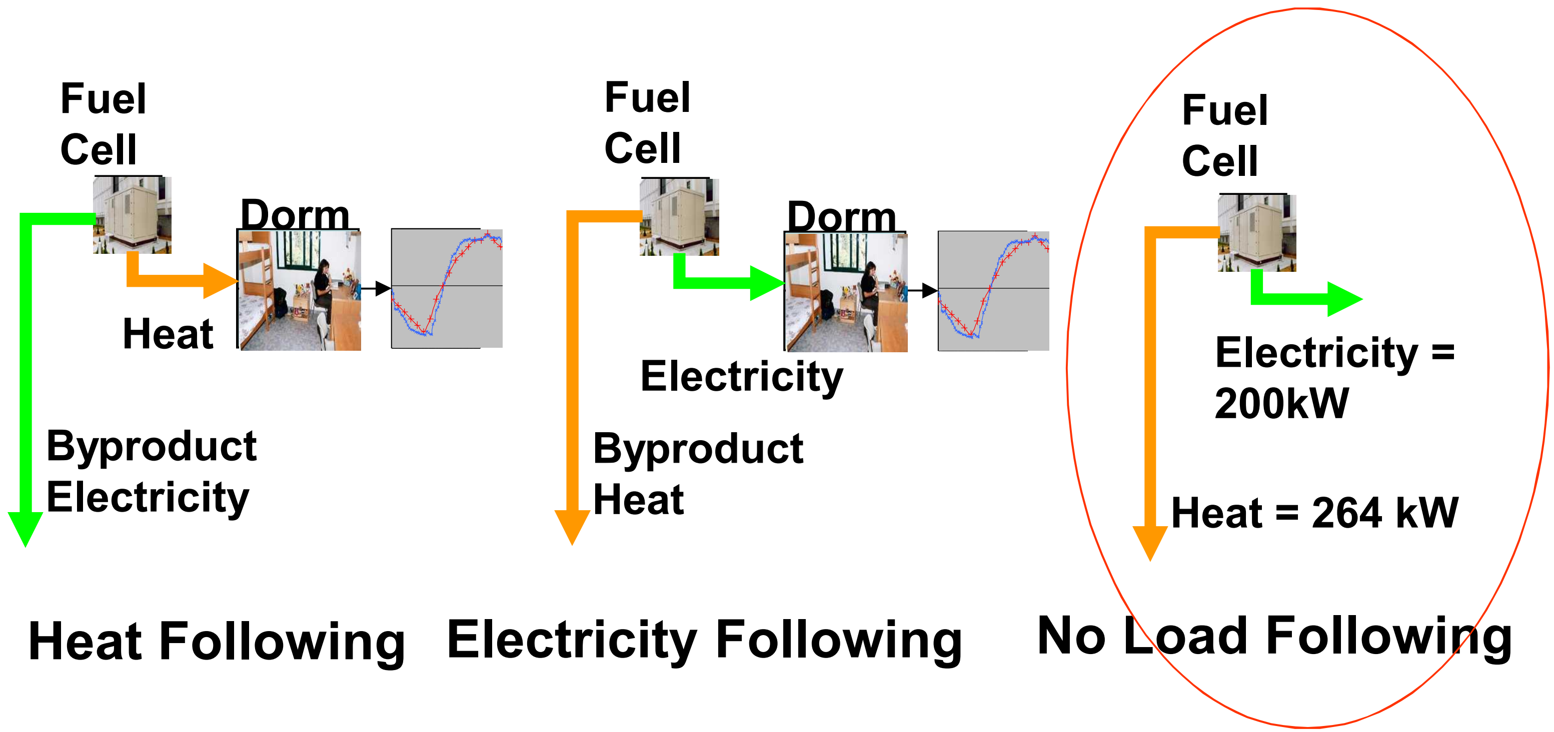
Networked



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

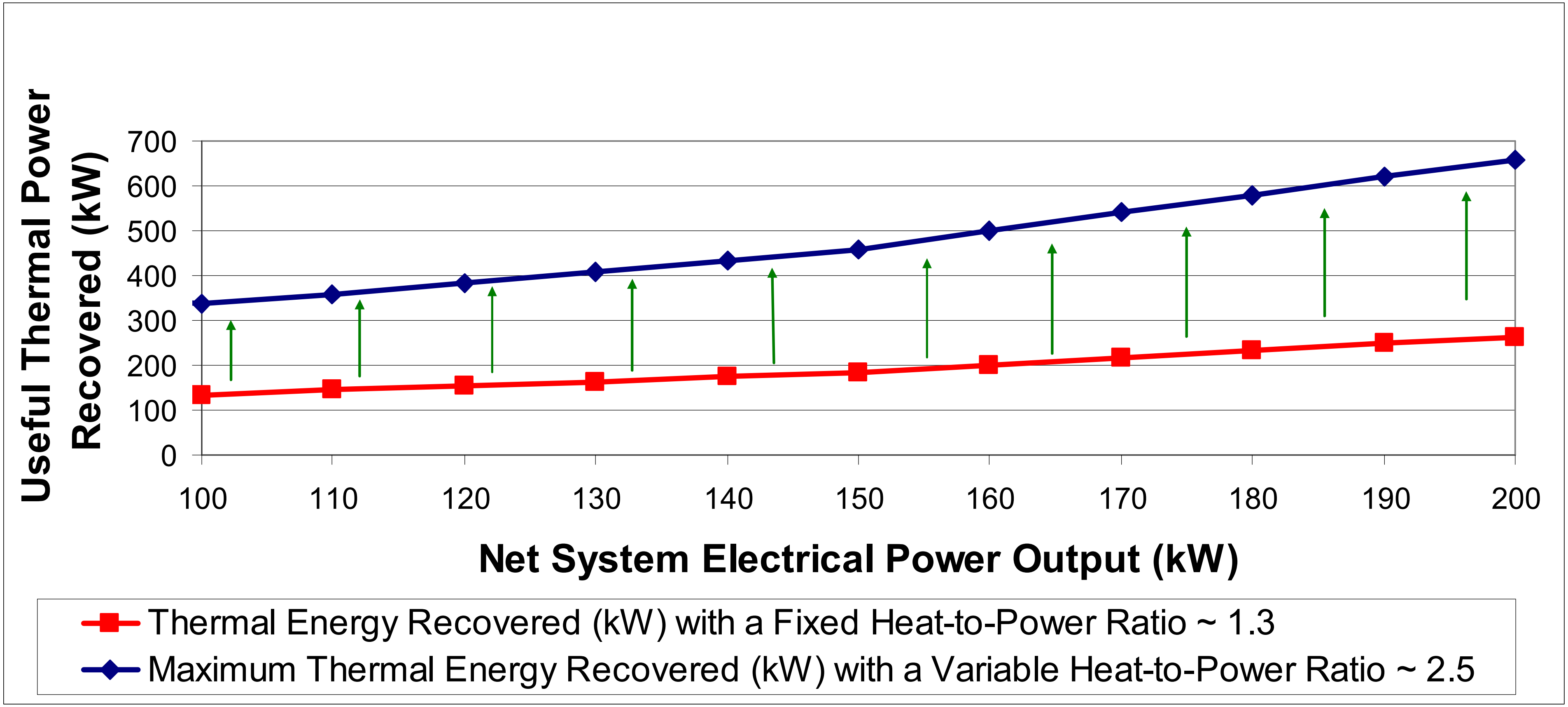
Networks have energy distribution channels

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.

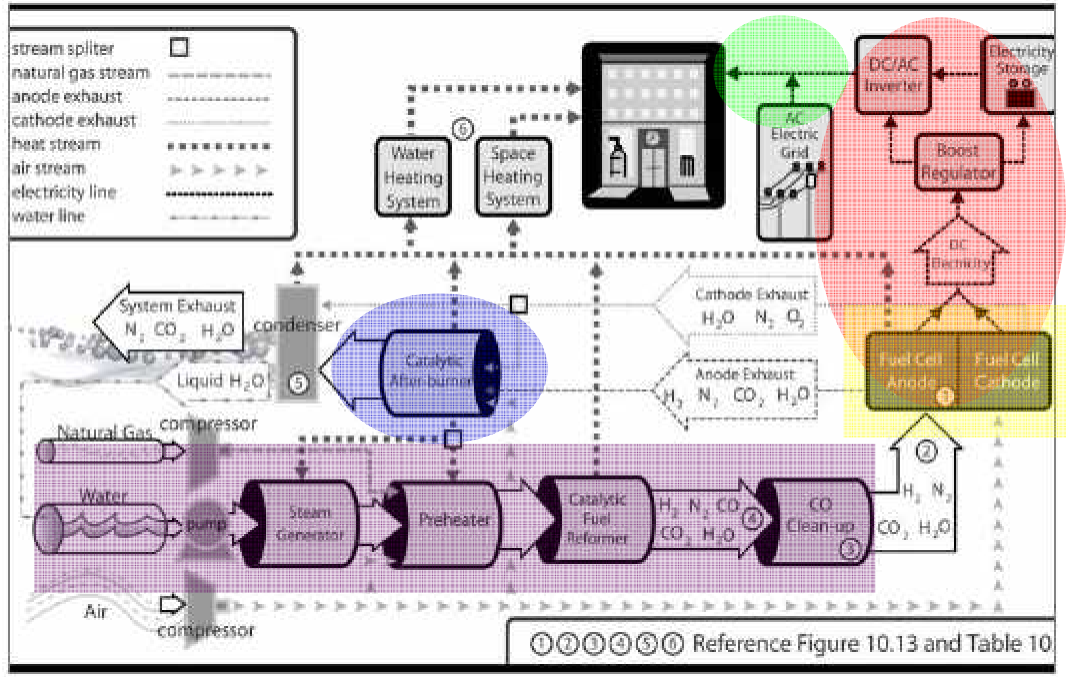
Fixed vs. Variable Heat-to-Power Ratio



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

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

➔ Use *MERESS* Model

Maximizing Emission Reductions and Economic Savings Simulator (*MERESS*)

- 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).
- 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 or maximum cost savings to building owners.

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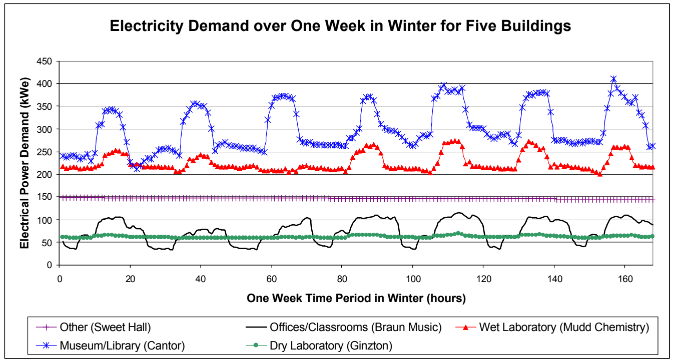
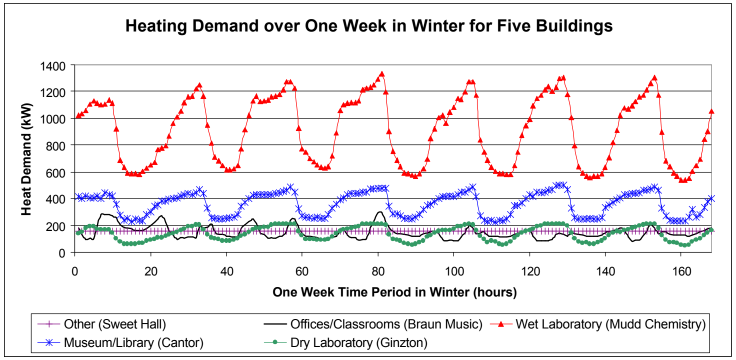
Simulation Inputs

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%	

Five Strategies

Strategy	Electrically and Thermally Networked (NW) or Stand Alone (SA)?	Electricity Power Load Following (ELF), Heat Load Following (HLF), or No Load Following (NLF)?	Variable Heat-to-Power Ratio (VHP) or Fixed Heat-to-Power Ratio (FHP)?
I	NW	ELF	VHP
II	NW	HLF	VHP
III	NW	NLF	FHP
IV	SA	HLF	VHP
V	SA	NLF	FHP

Example Results Shown for One Case Study

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

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Five Scenarios

Input Conditions		
Scenario	Incentives for fuel cells* and for CHP** (N/Y)	Carbon Tax (\$/tonne CO_2)
A	N	0
B	Y	0
C	Y	20
D	Y	100
E	Y	1,000,000

Key Assumptions:

base case = no fuel cells, all CHP combined cycle gas turbine plant

common fuel for fuel cells and turbine = natural gas

base case electricity and heating costs (no fuel cells) = $20 million/yr

cost of capital (r) = 7.42% = educational borrowing rate ≈ bond rate

fuel cell turn-key cost (without incentives) = $6,200/kWe

* fuel cell incentives: $2,500/kWe (state); $1,000/kWe (federal)

free market price of natural gas = $8.95/million BTU

** natural gas price with CHP incentive = $7.45/million BTU

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

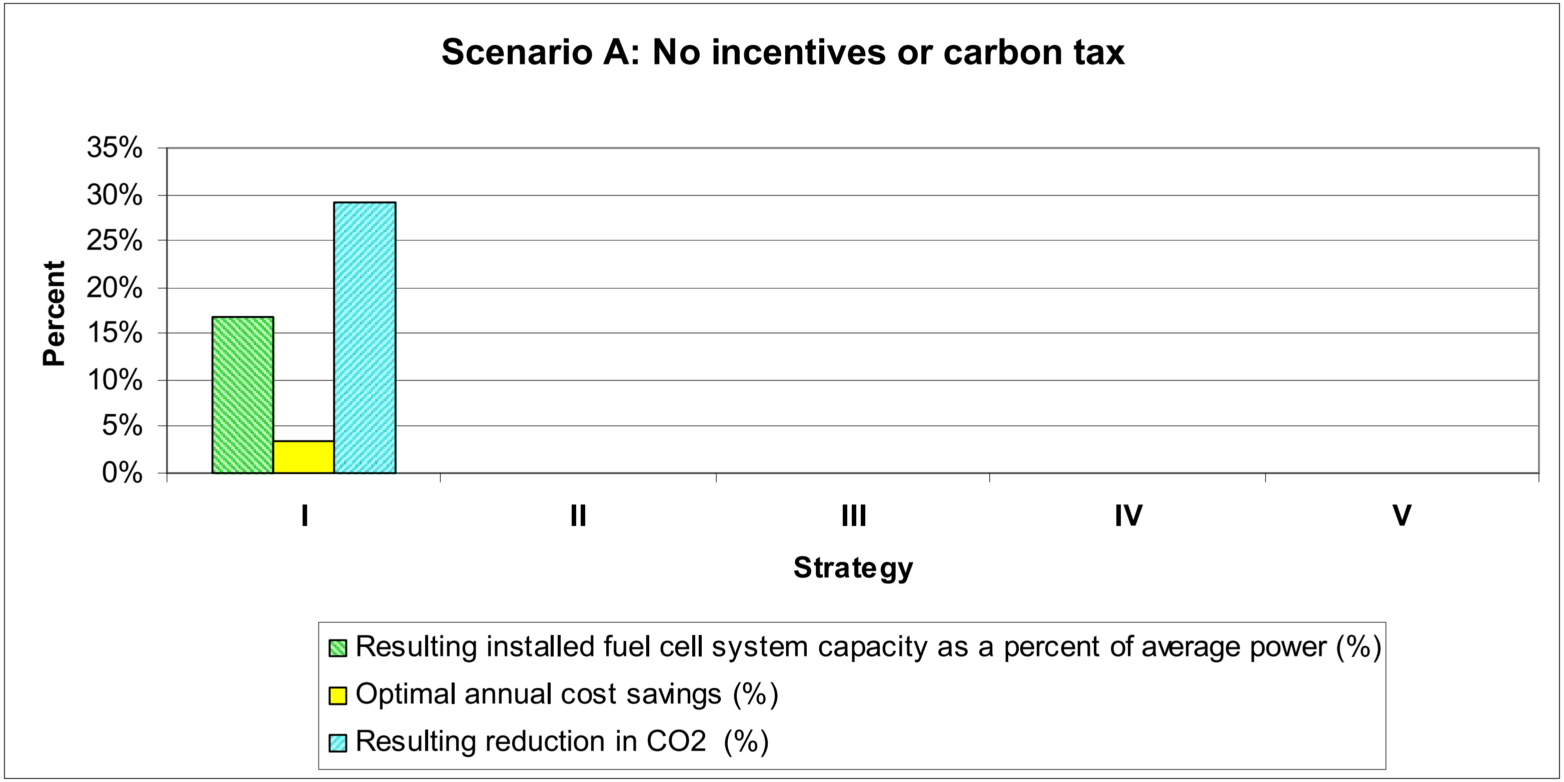
Strategy	Optimal installed fuel cell system capacity as a percent of average power (%)	Annual cost savings (%)	Change in CO_2 compared with base case of no fuel cells (Metric Tonnes of CO_2/yr)
I	17%	3%	-29%
II	0%	0%	0%
III	0%	0%	0%
IV	0%	0%	0%
V	0%	0%	0%

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

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

Strategy I = *avant-garde*

Fuel cell systems can address environmental bottlenecks with avant-garde designs



Systems are economical with no subsidies and achieve the most reduction in CO_2 emissions by changing their operating strategy to Strategy I = avant-garde.

Strategy I = cogenerative, electrically & thermally networked, electricity load following, variable heat-to-power ratio

Scenario B: State & federal incentives, <u>no carbon tax</u>; 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

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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%

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

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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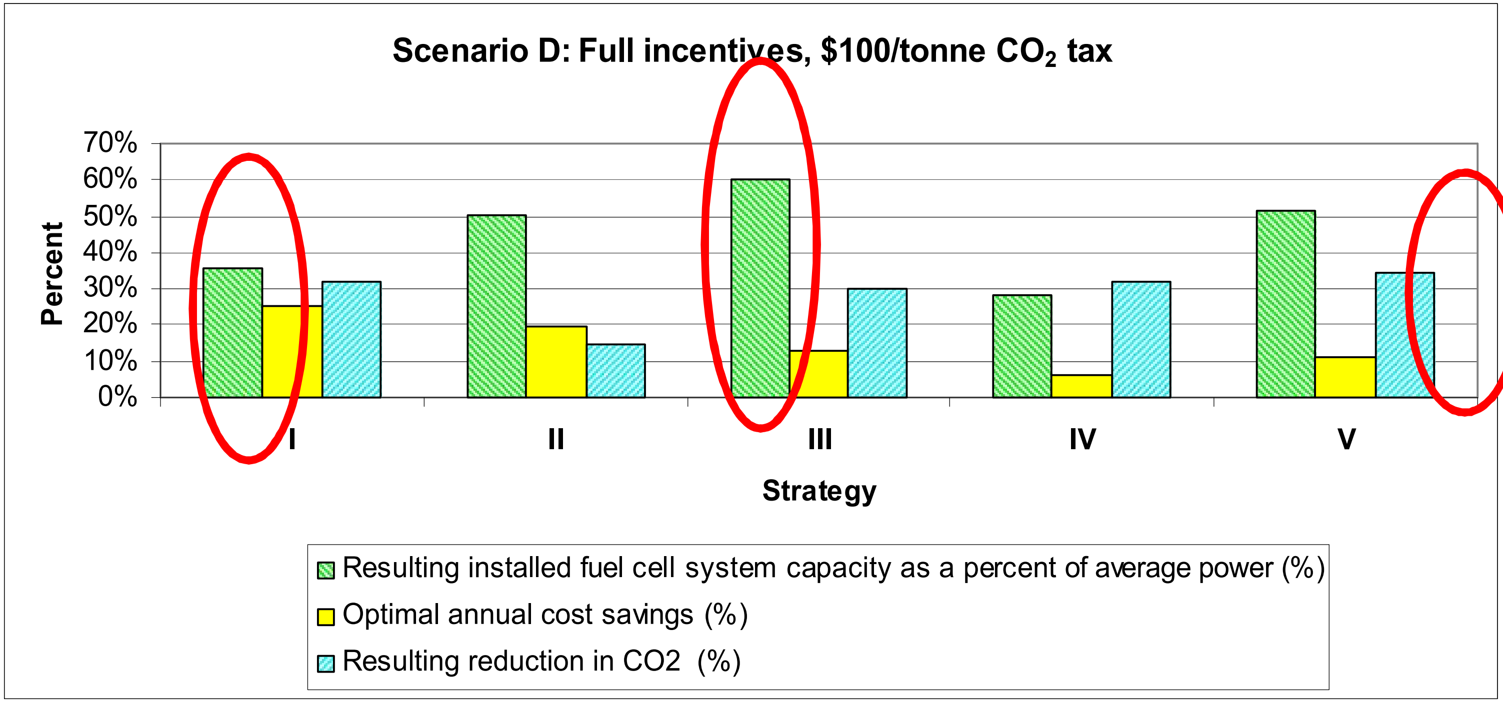
No one networking strategy achieves all economic and environmental goals under all scenarios



Different strategies achieve diverse goals of A) cost savings to building owners, B) high fuel cell manufacturer sales revenue, and C) CO_2 emission reductions

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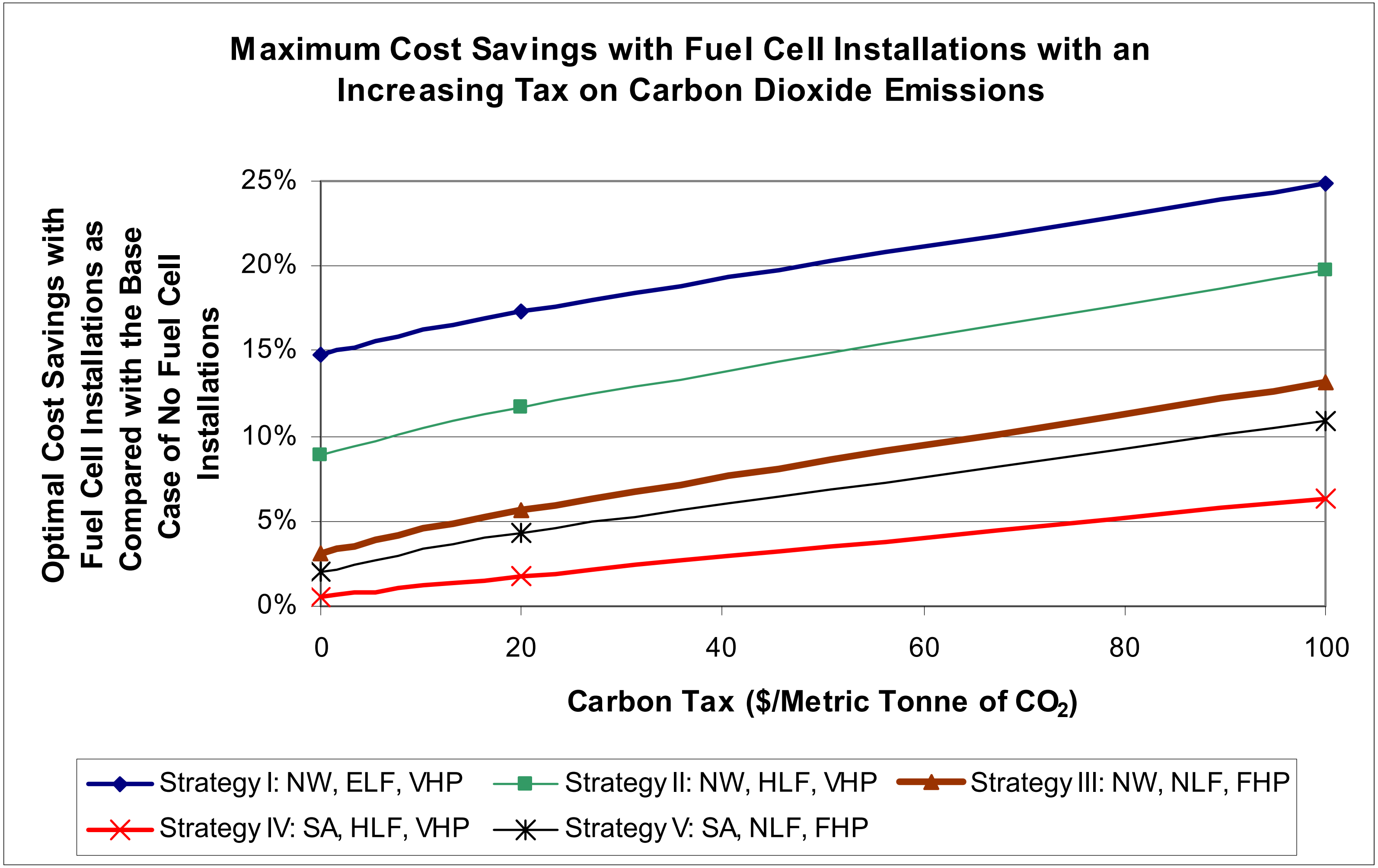
Highest savings for building owners with 1) Strategy I, 2) NW, 3) NW + ELF or HLF



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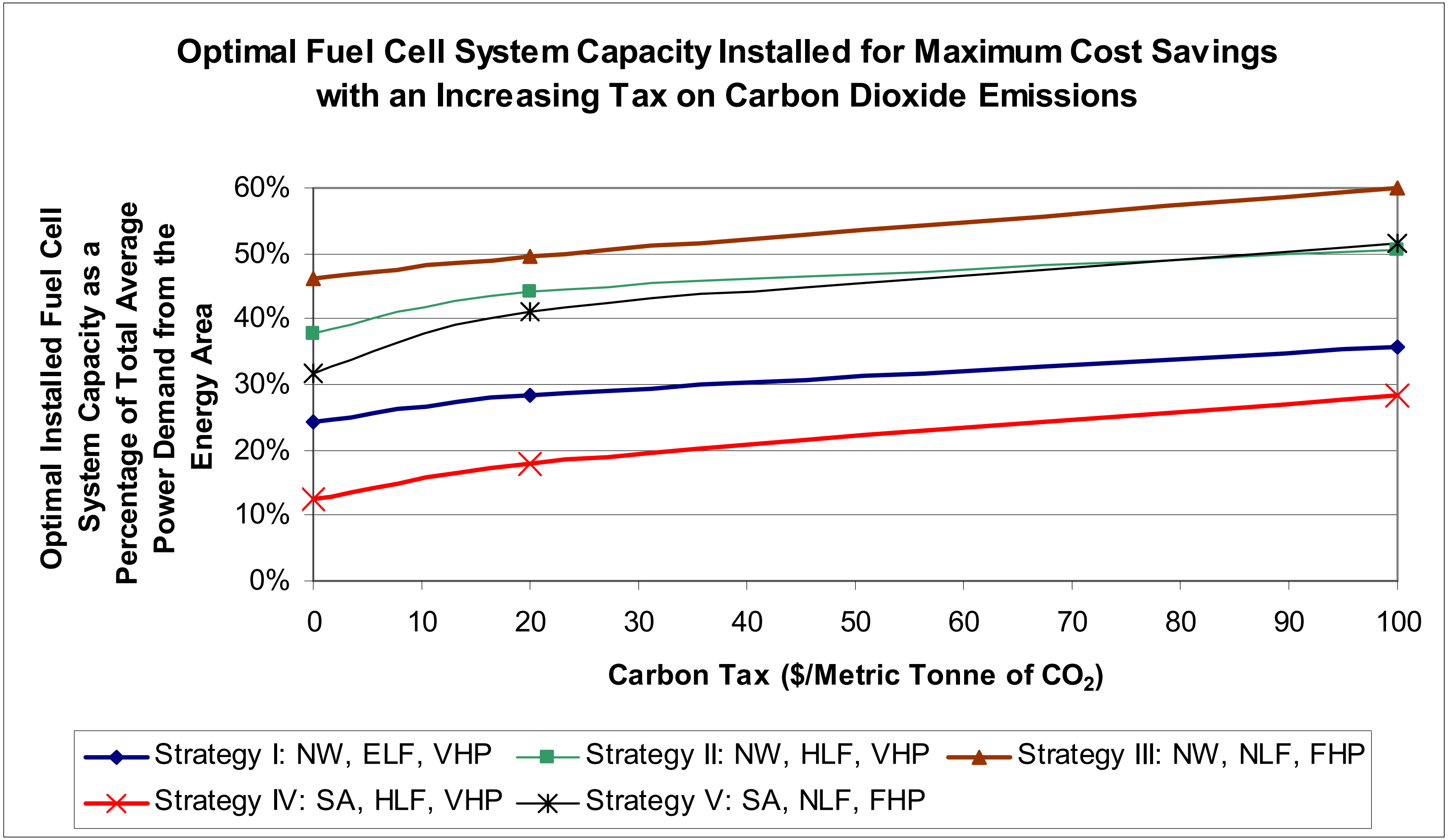
Highest profit for fuel cell makers with Strategy III = *close to status quo*



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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 (status quo) - most economical neither for buildings nor FCS makers**

   - building load curves even more crucial (SA operation)

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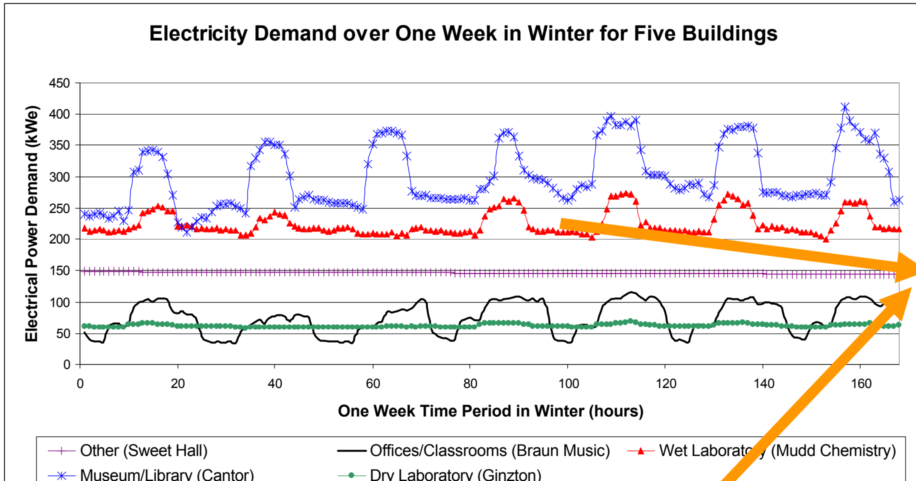
Highest CO_2 Reductions for Stand-Alone Strategies with Certain Building Load Curves

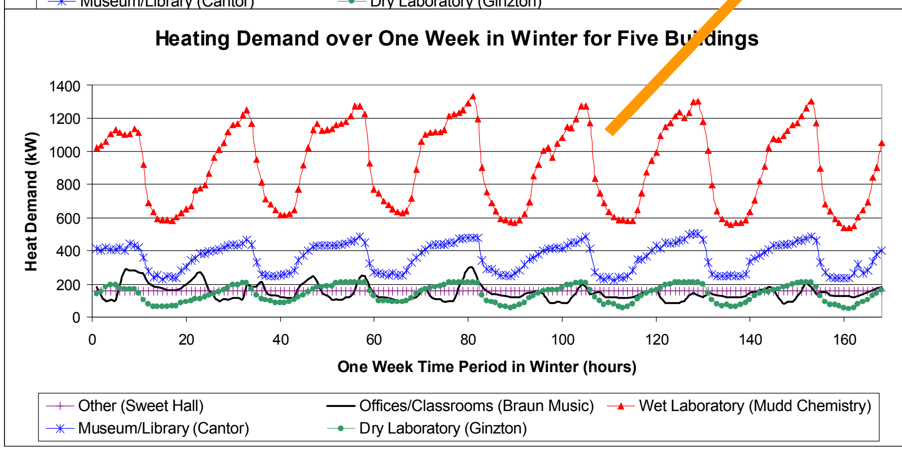
Wet Laboratory Building Load Curve Has Highest CO_2 Reductions

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%

No particular building *type* = best

R&D needs better load curve data from buildings, and supply data.





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Offices/Classrooms	TC Seq	0	0	0%	0%	850	0	0%
Dry Lab	Env Fluid Mech	0	0	0%	0%	597	0	0%

Building load curves strongly influence economics and environmental impacts of system installations

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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)
   Highest CO_2 reductions w/ Strategy V (status quo)
   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;   NW, NLF, FHP;   SA, NLF, FHP)
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

Conclusions

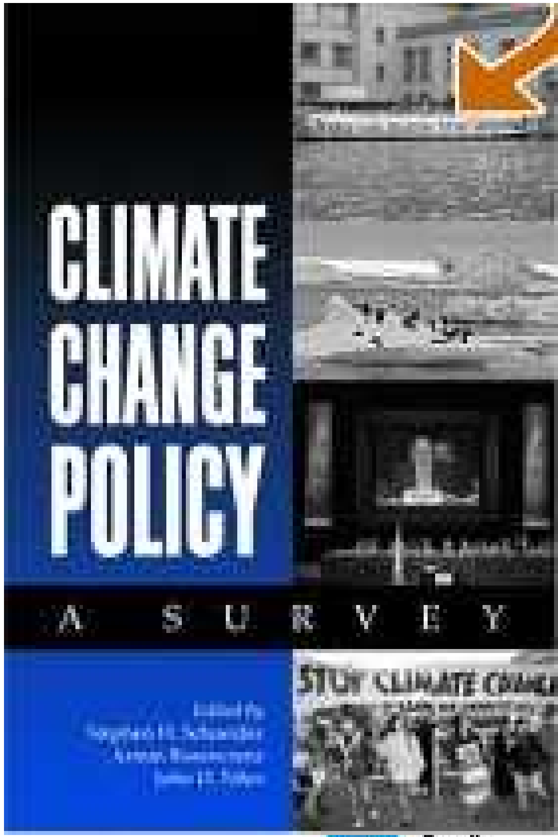
1. **Must apply simulation to find the best installation strategy for a $$ or GHG goal**
    1. **No particular building *type* = best**
    2. **Load curves are crucial**
    3. **Maximum CO_2 reductions with Strategy V (SA)**
        1. **Load curves are even more crucial**
2. ***Avant-garde* operating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

Recommendations

1. Create incentives for FCS makers to build VHP
2. Pursue R&D to enhance VHP capability
   1. Catalysts durable under rapid thermal cycling
   2. One catalyst/reformer design for SR, POX, and AR
3. Spearhead R&D to develop FCS more durable under rapid changes in electrical and thermal load.
   1. Fuel cells coupled to supercapacitors
4. Encourage partnerships between FCS makers and energy service companies (ESCO)
5. Focus on installing FCS within pre-existing thermal networks
6. 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



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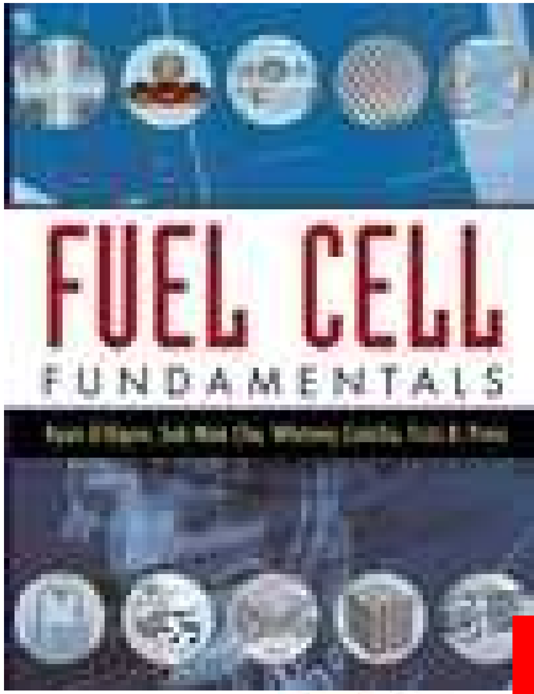
Quiz Results

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



What fuel cell system operating strategy results in the lowest electricity and heating costs for building owners and a ~30% reduction in CO_2 emissions over a range of financial and environmental scenarios?

Copies available for review at conference

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Thank You

Summer internships available for undergraduate, masters, and Ph.D. students.

Extra

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.

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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.

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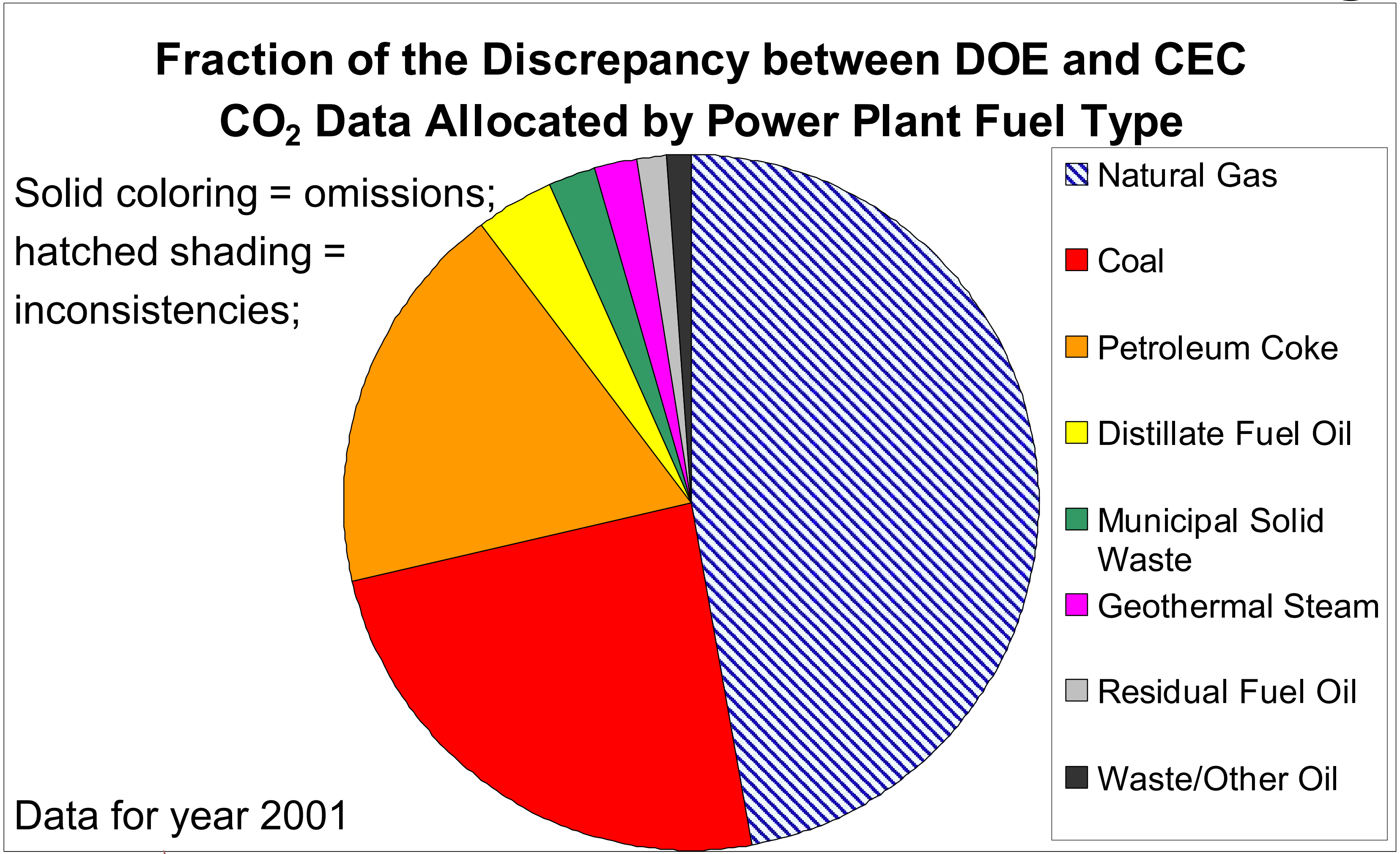
State data excludes CO_2 from coal, coke, oil, non-fossil fuels; re-allocates or omits cogen



We conclude Federal data is a more complete baseline.

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

(using the updated baseline emissions to eliminate discrepancies)?

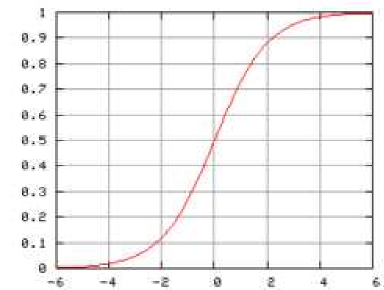
12 Scenarios: Change in CO_2 with Fuel Cell Systems

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)

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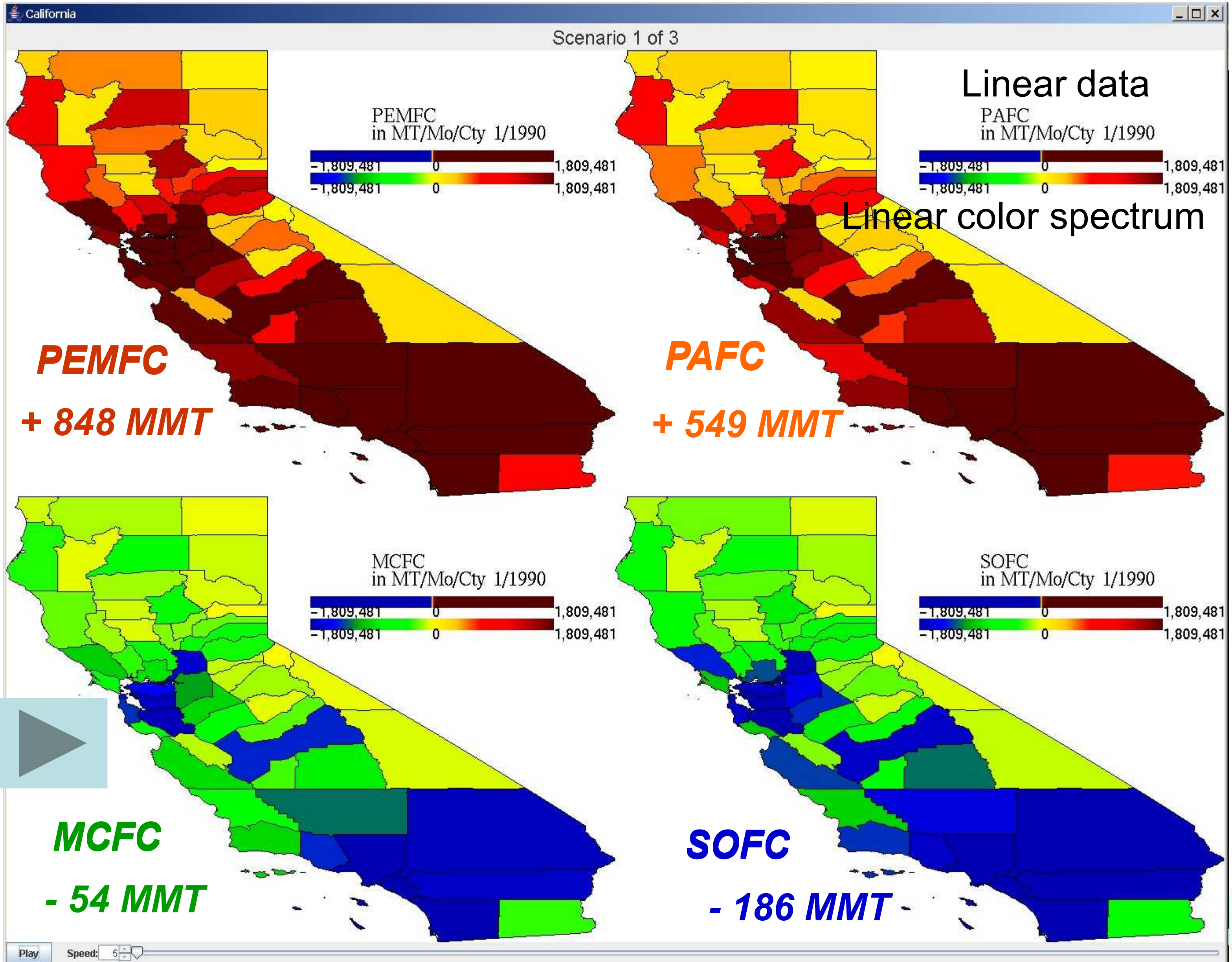
Fuel Cell Systems Replace 100% of Power



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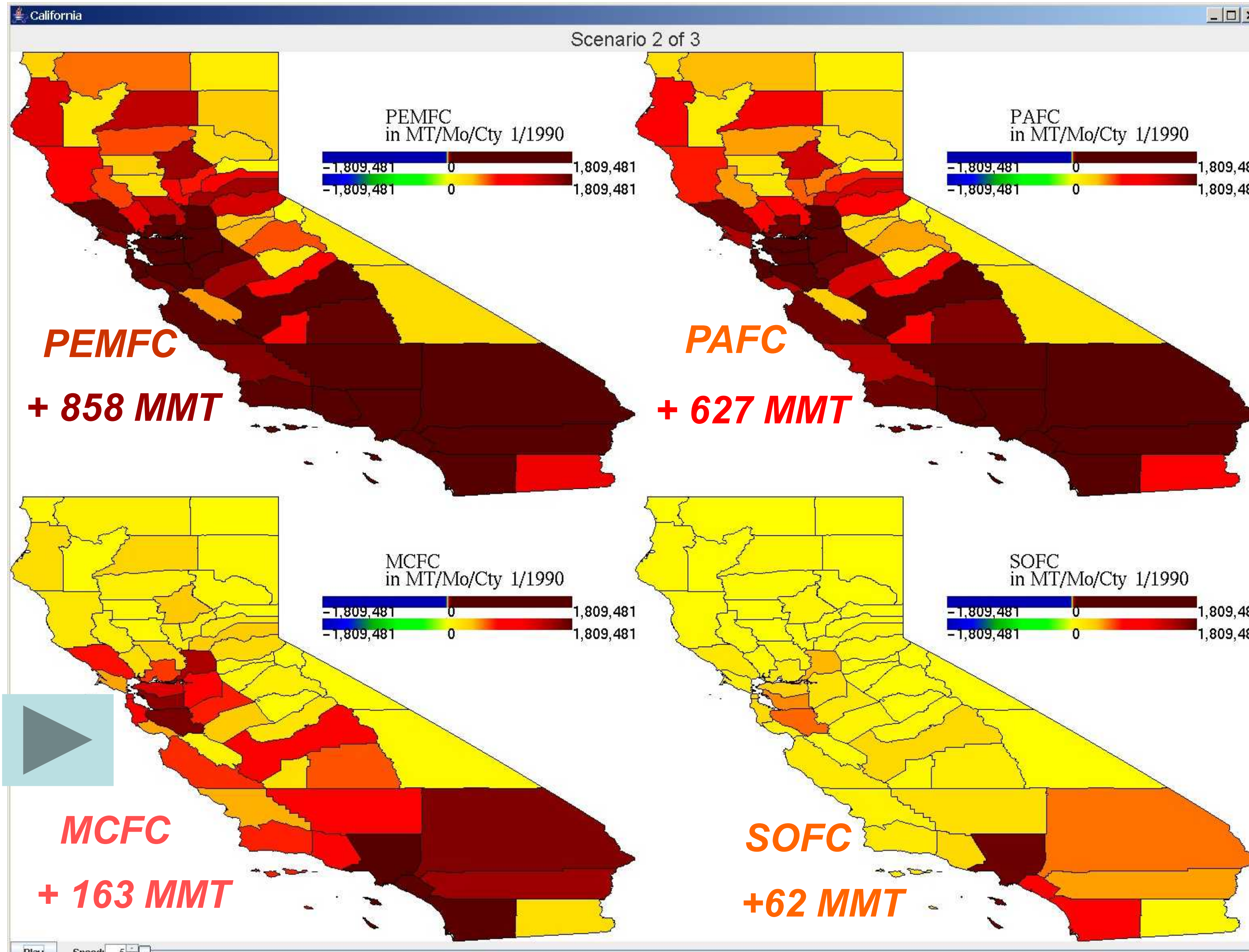
Fuel Cell Systems Replace <u>In-State Power Only</u>



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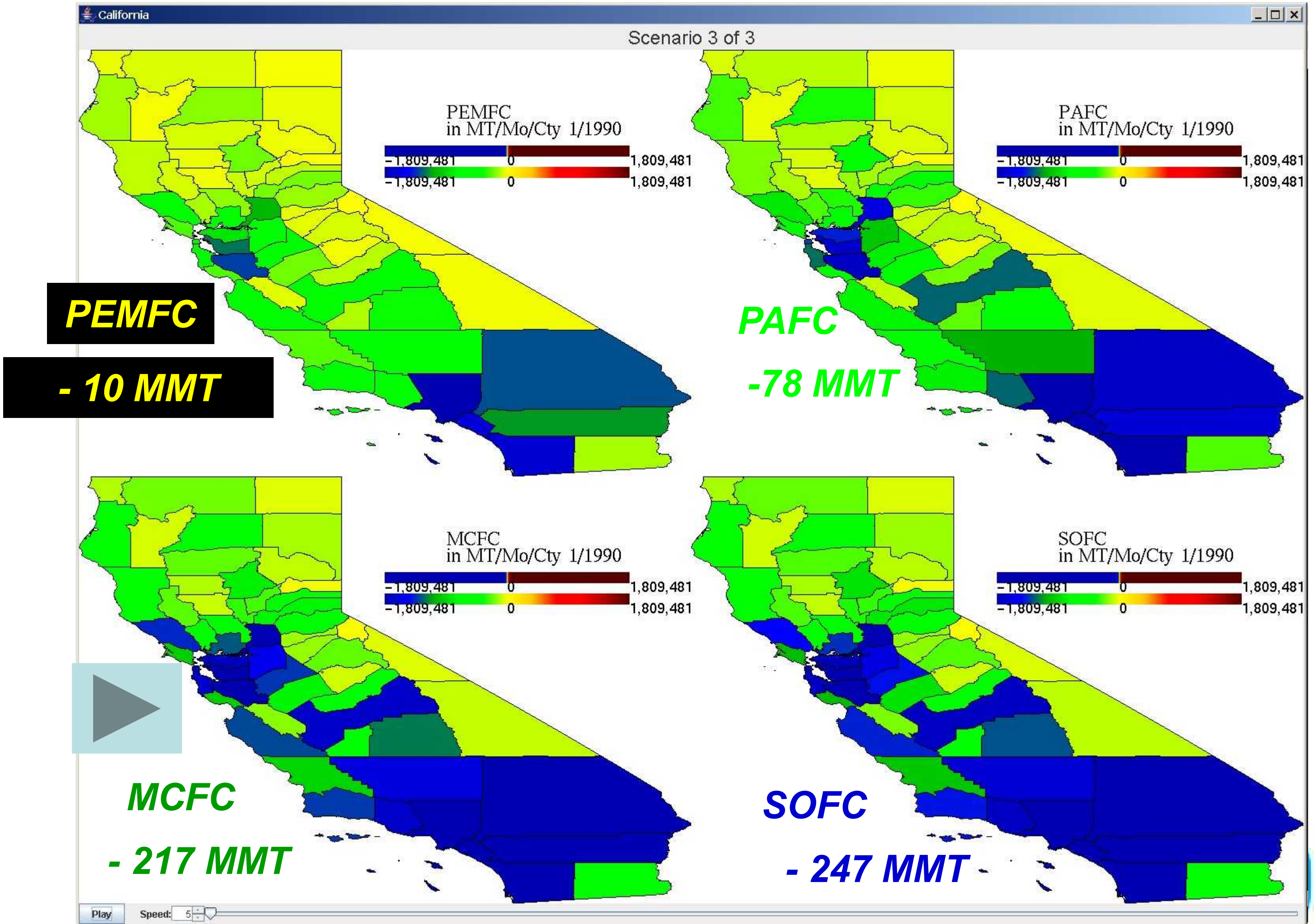
Fuel Cell Systems Replace Imported Power Only



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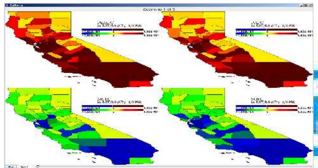
Results

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 <u>imports</u>.**
2. **Highest CO_2 reductions <u>if MCFC or SOFC replace imports.</u>**
3. **PEMFC and PAFC must operate <u>cogeneratively</u> with high <u>effective heat recovery</u> to reduce CO_2 effectively.**



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