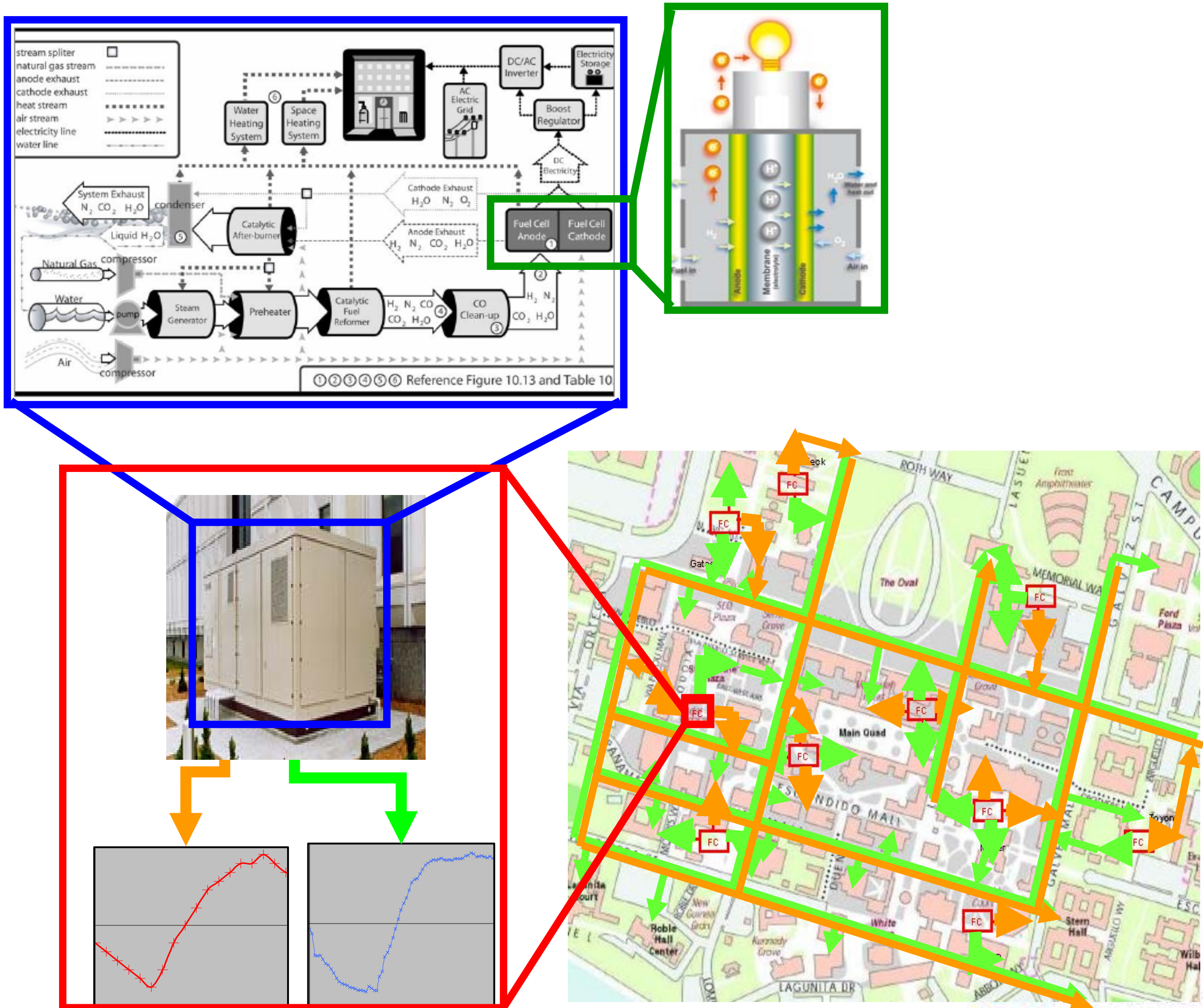
SAND2008-3053P

Optimization of Networks of Distributed Combined Heat and Power Fuel Cell Systems To Reduce Greenhouse Gas Emissions and Energy Costs



Whitney Colella

Truman Fellow
Sandia National Labs

March 31, 2008

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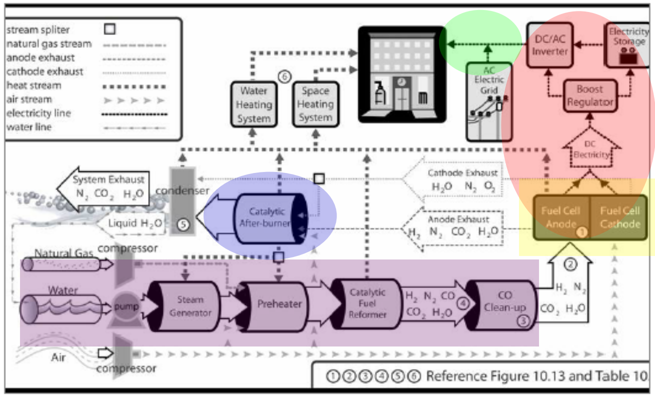
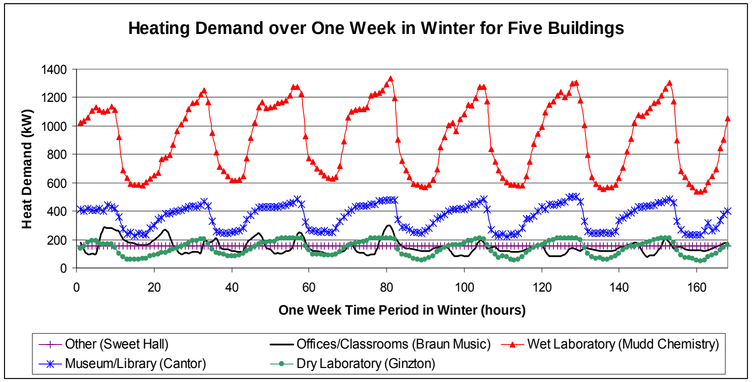
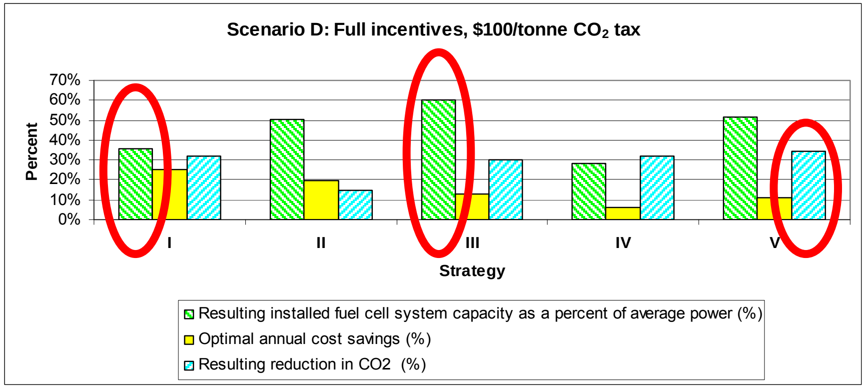
This talk explores financial and economic benefits of using unique operating strategies for fuel cells



Avant-garde operating configurations



Simulation design



Benefits to building owners, manufacturers, and the environment

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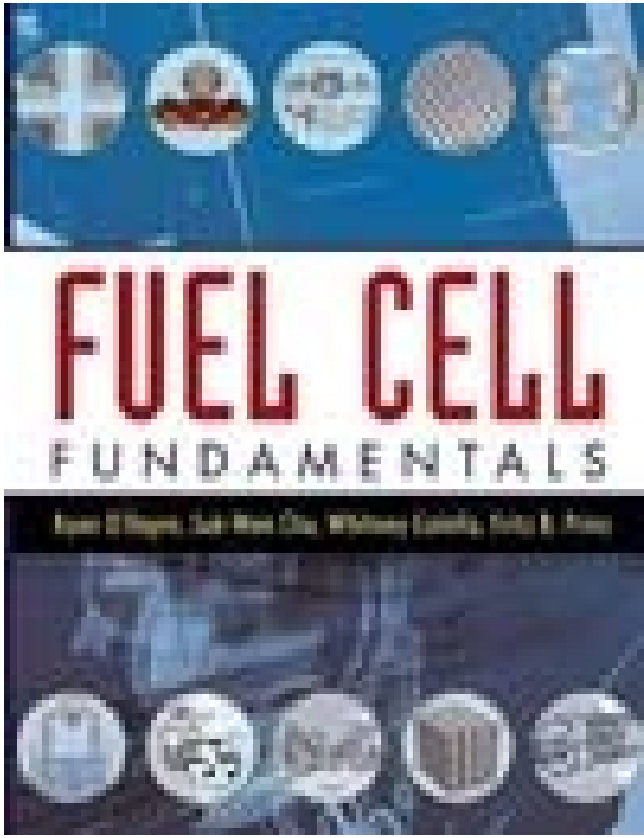
If you answer this quiz question correctly, you can win a copy of this Fuel Cell Fundamentals textbook

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?



Please write your answer on a business card and pass it to our session volunteer Ziv Lang or moderator before the end of the talk

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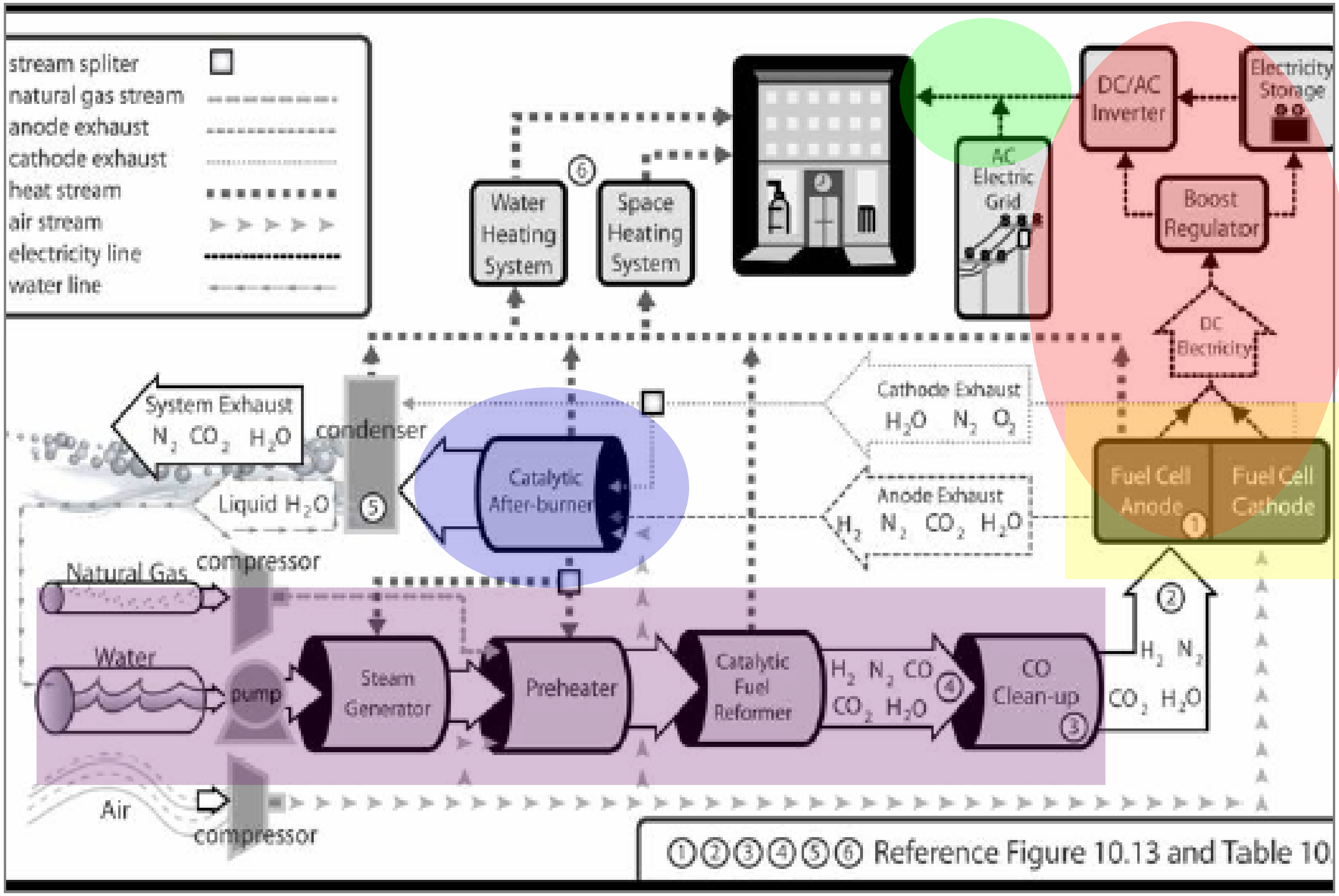


Avant-garde operating configurations

The U.S. loses 1/5th of its energy (21 Quads) as heat at power plants, and then re-generates this same amount downstream to heat buildings and industry

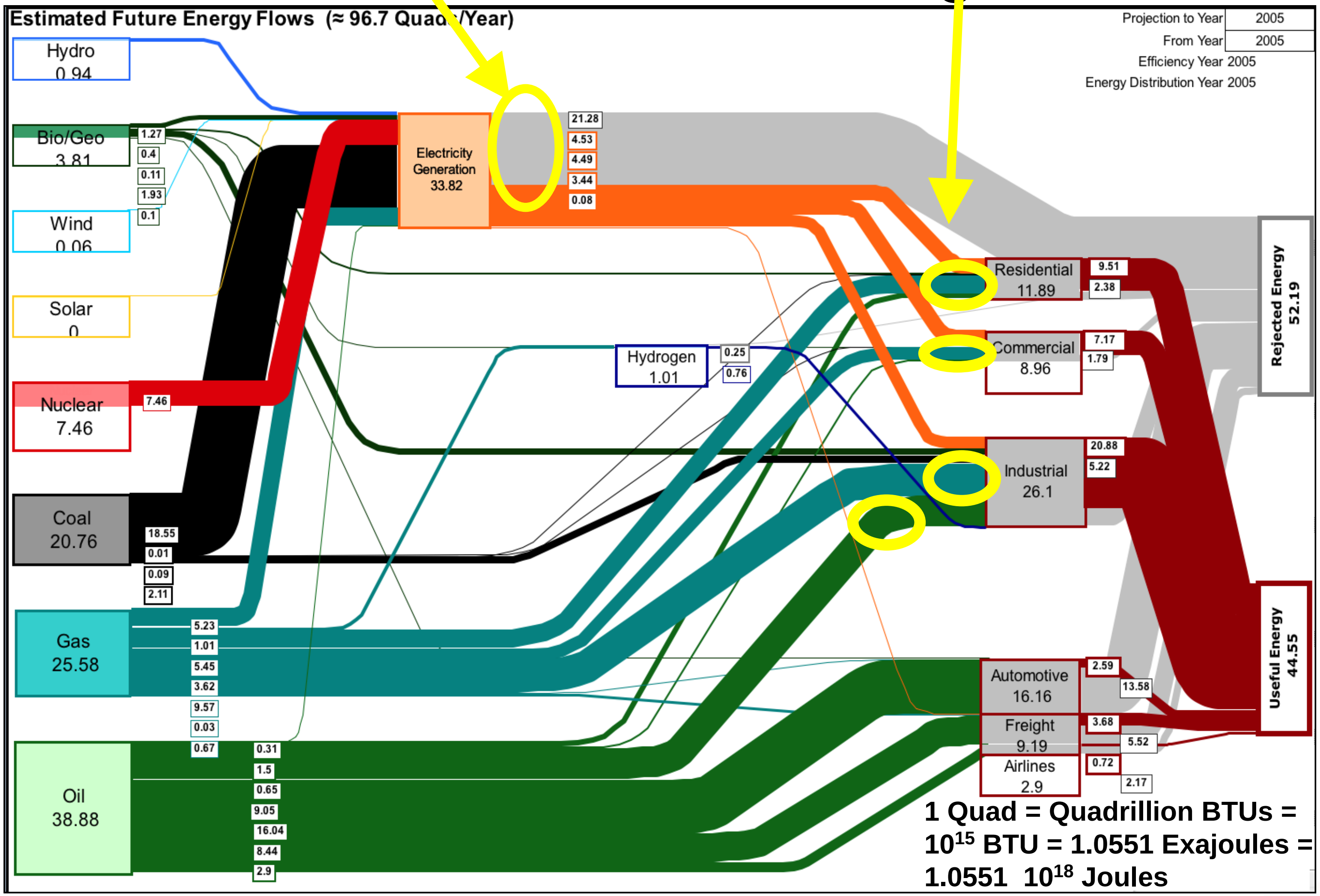
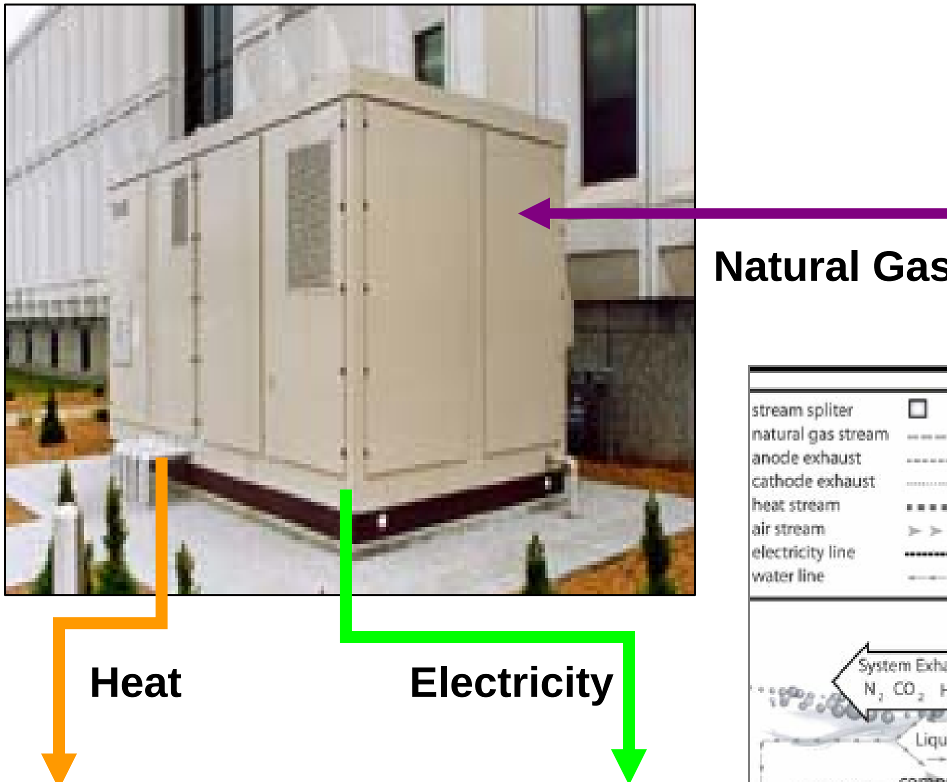
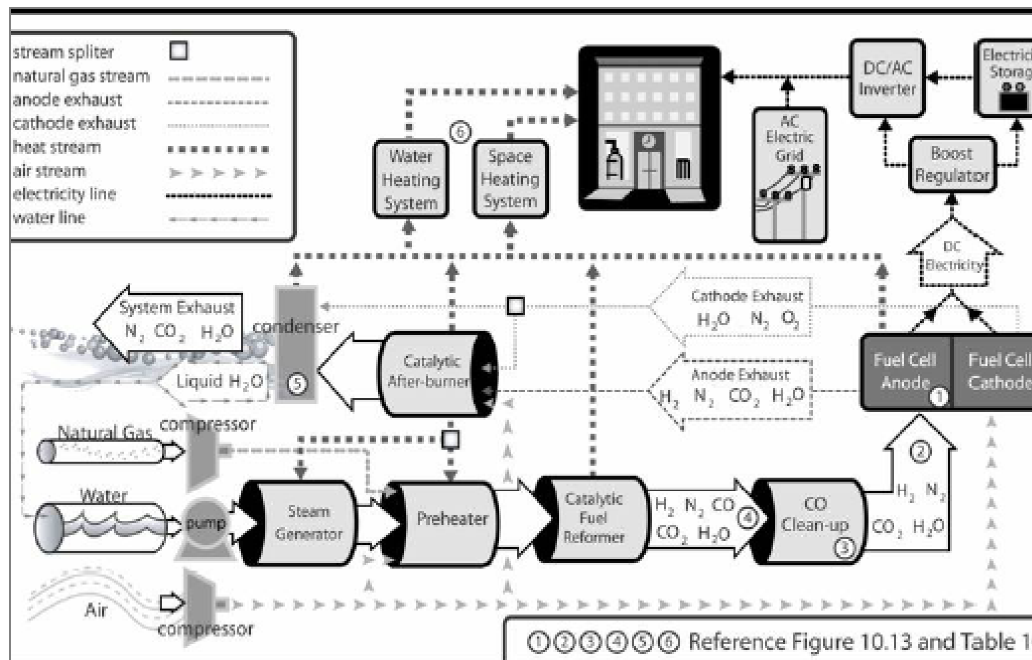


Figure by Gene Berry, Lawrence Livermore National Laboratory

Stationary fuel cell systems can be designed to make both electricity and heat, a process known as cogeneration or combined heat-and-power (CHP)





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Stationary fuel cell systems can provide heat and power to buildings with lower greenhouse gas emissions, *if optimally configured*

	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**

Cogenerative fuel cell systems fueled by natural gas can create 1/3rd the CO_2 as conventional systems, if they are design to recover heat. They make no CO_2 if fueled by hydrogen

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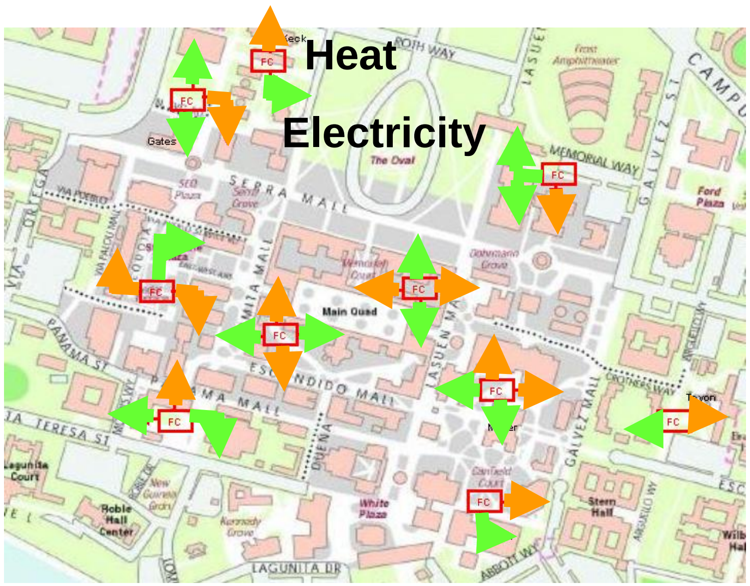
Systems can be configured as stand alone or networked

stand alone vs. networked

stand alone

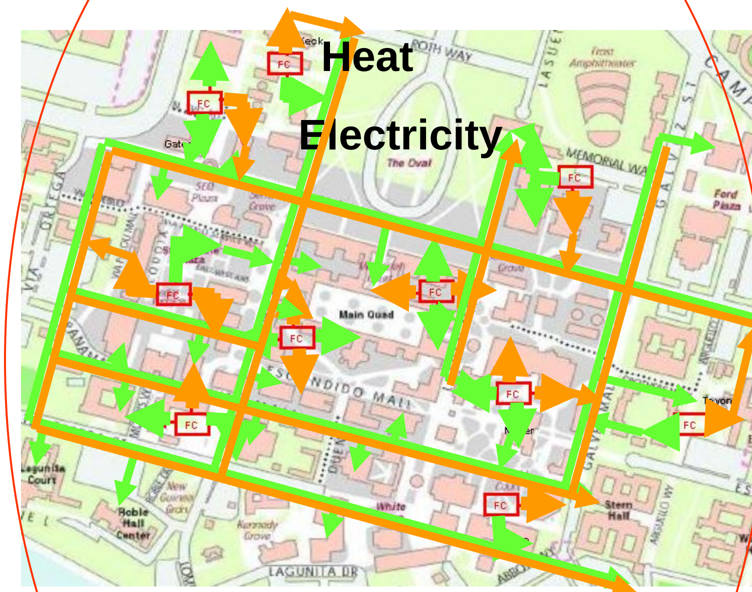


Fuel cells can NOT convey excess heat or electricity into the distribution grid to reach other buildings.

Electricity

Heat

networked



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

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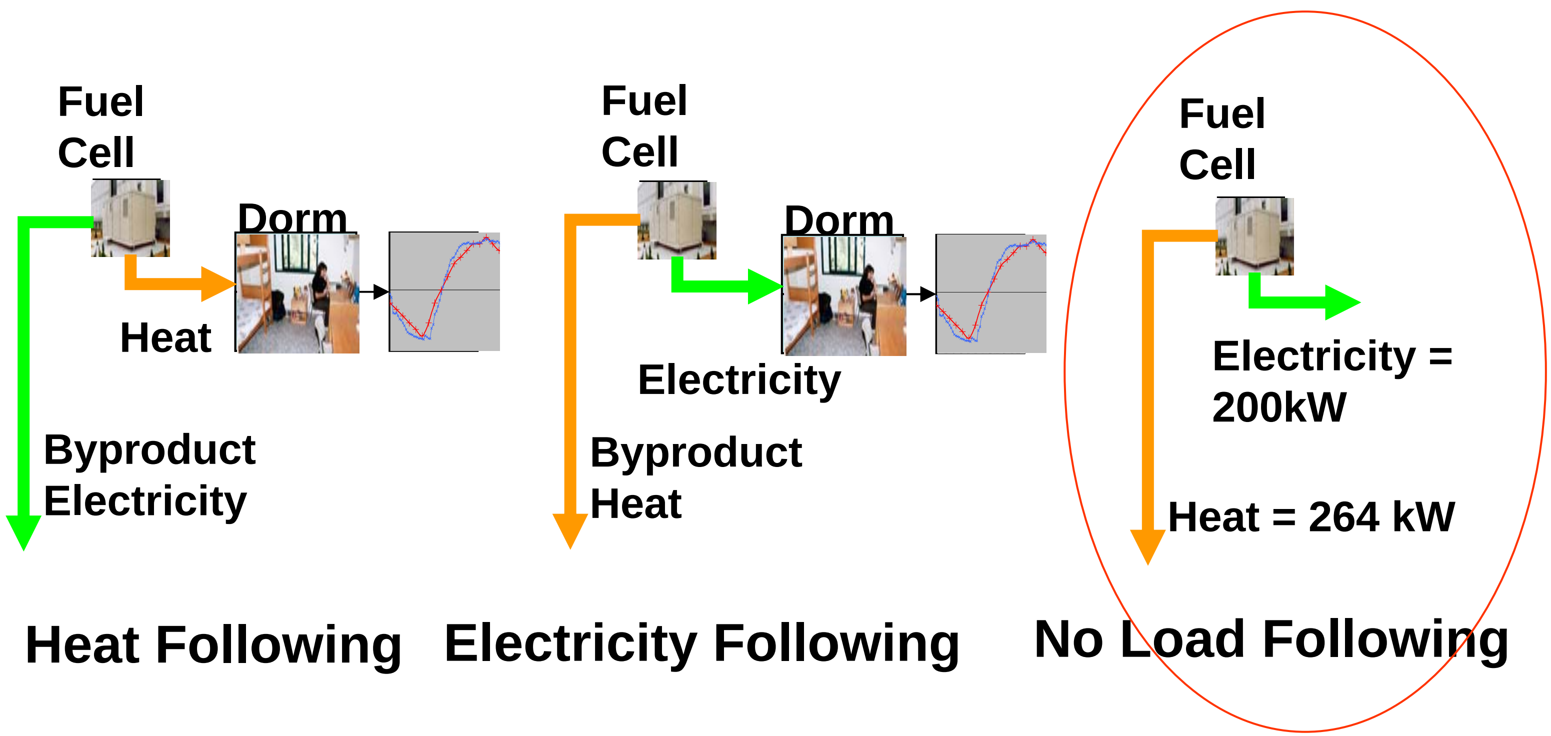
Systems can be configured as heat load following, electricity load following, or no load following



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

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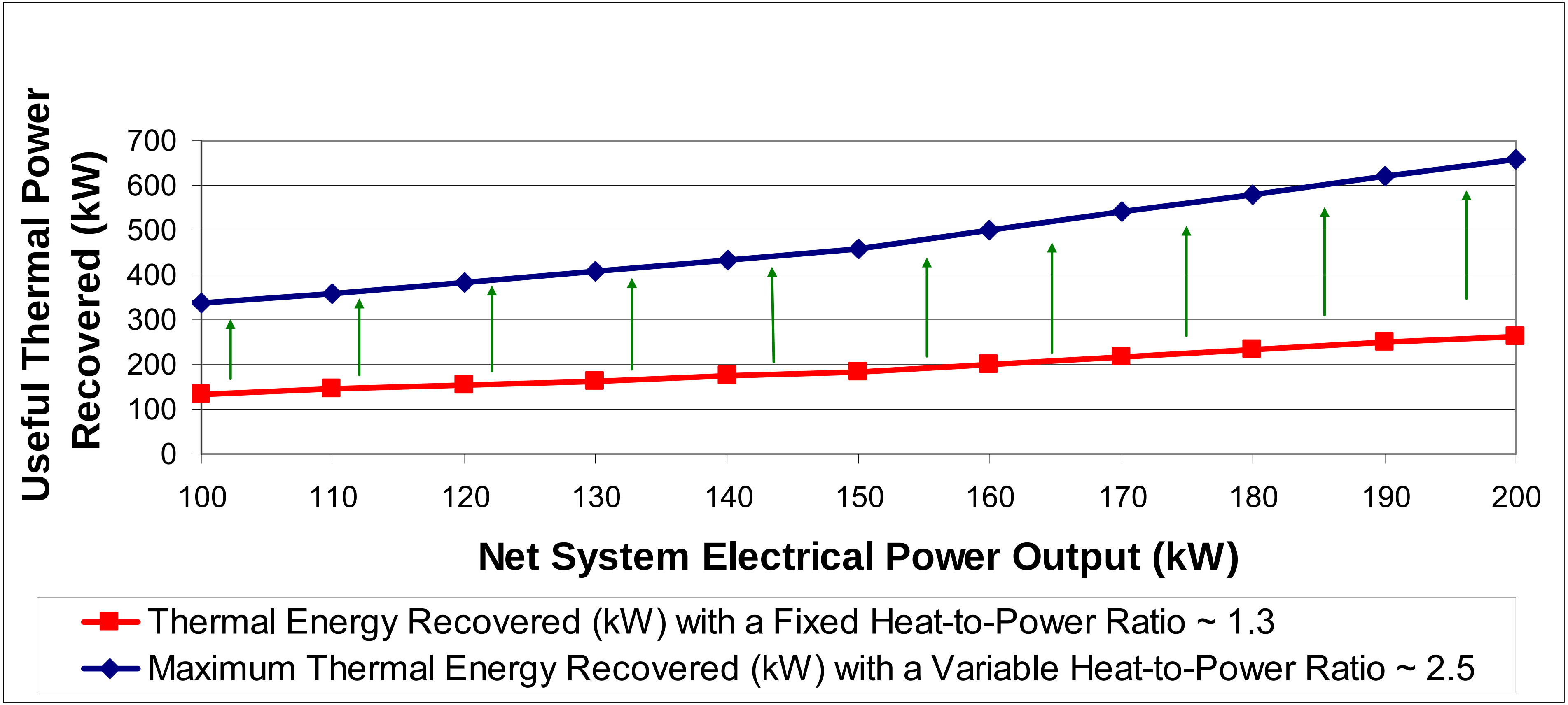
Systems can be configured with a fixed or a variable heat-to-power ratio

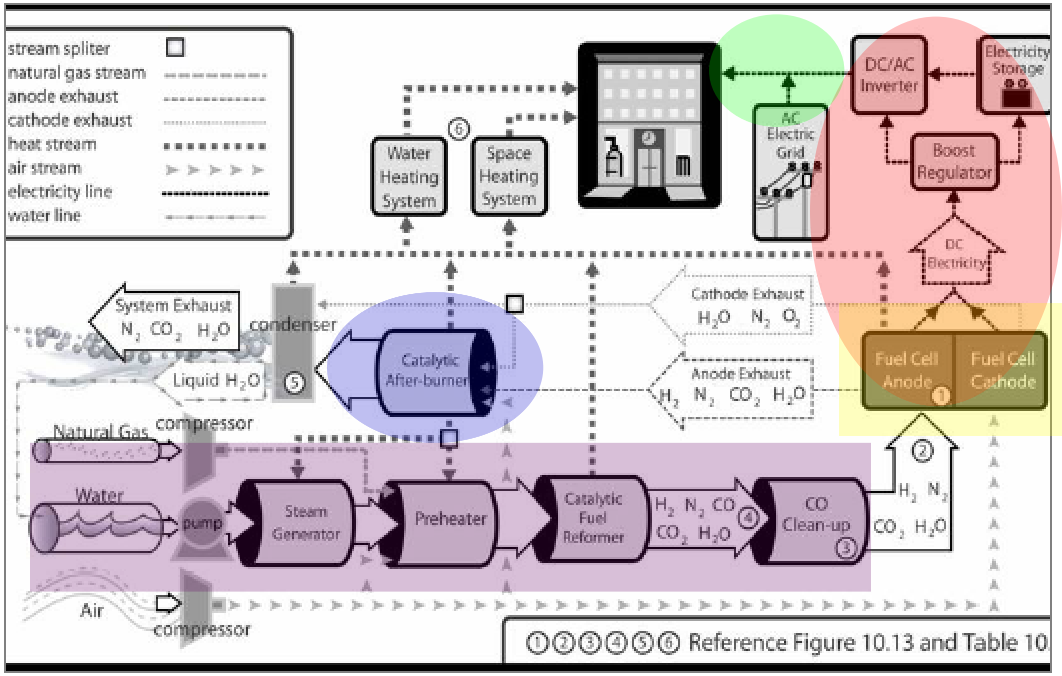
Fixed vs. Variable Heat-to-Power Ratio



Variable heat-to-power ratio increases system operating range

Systems can be configured with a variable heat-to-power ratio using a variety of methods (Colella 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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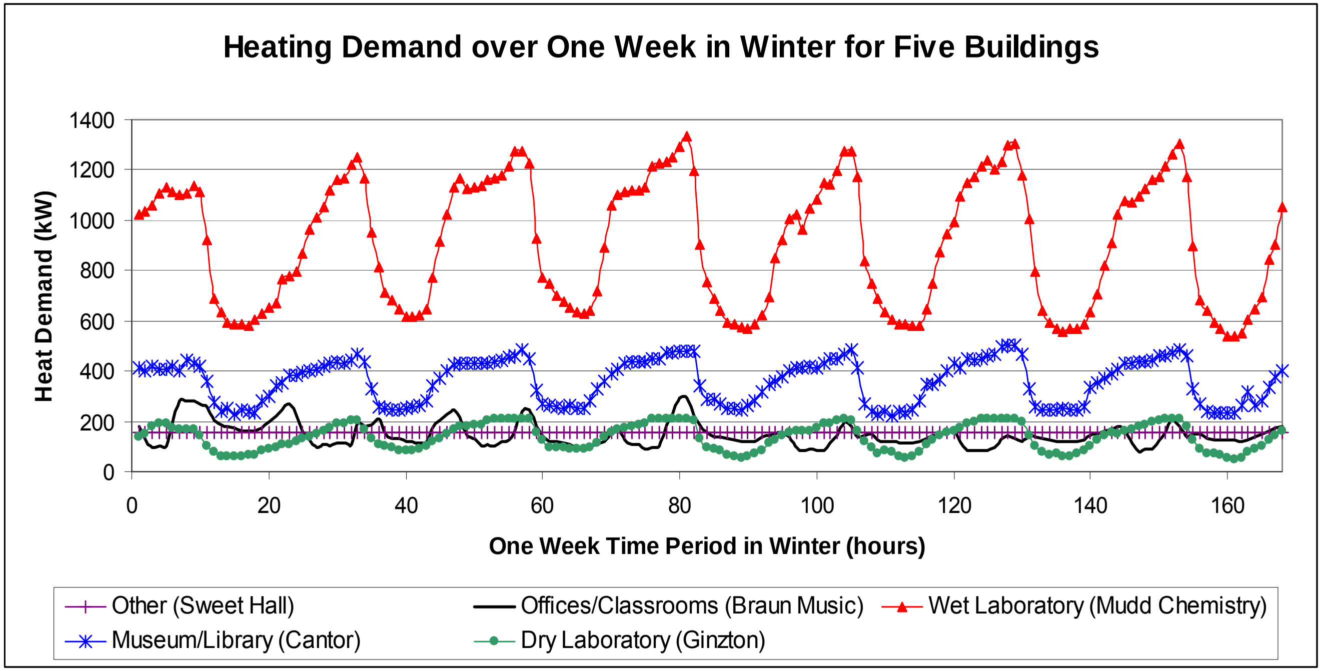

Simulation design

These configurations can be examined using a simulation tool, the Maximizing Emission Reductions and Economic Savings Simulator (*MERESS*) model.

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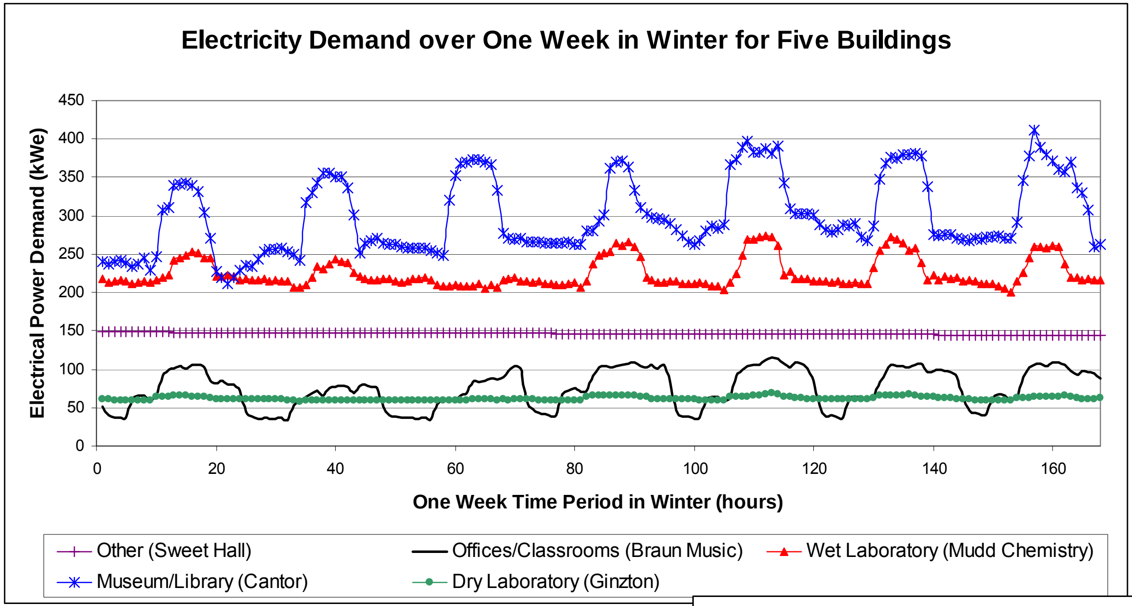
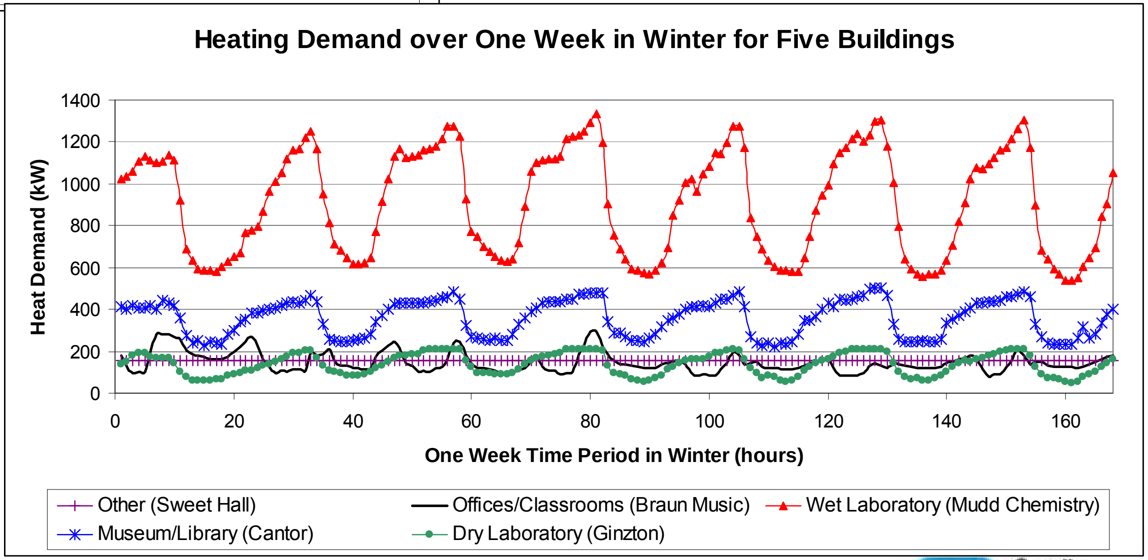
MERESS allows policy makers, building owners, and fuel cell manufacturers to evaluate the environmental and financial impacts of installing FCSs in buildings and towns.

- Optimizes the percentage installation of FCS for minimum CO_2 emissions or maximum cost savings to building owners.
- 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.

A user can input the electricity and heating demand curves of buildings that interest him.





Stanford University building load curves examined here.

A user can input the operating and financial data for fuel cell systems and competing generators

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%	

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**

Phosphoric Acid Fuel Cell (PAFC) system vs. CHP combined cycle gas turbine (CCGT) examined here.

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

Strategy I is *avant-garde* using cogeneration, NW, ELF & VHP

Strategy II is *avant-garde* using cogeneration, NW, HLF & VHP

Strategy III is partly *plain vanilla* using NLF & FHP

Strategy IV is *avant-garde* using cogeneration, HLF & VHP

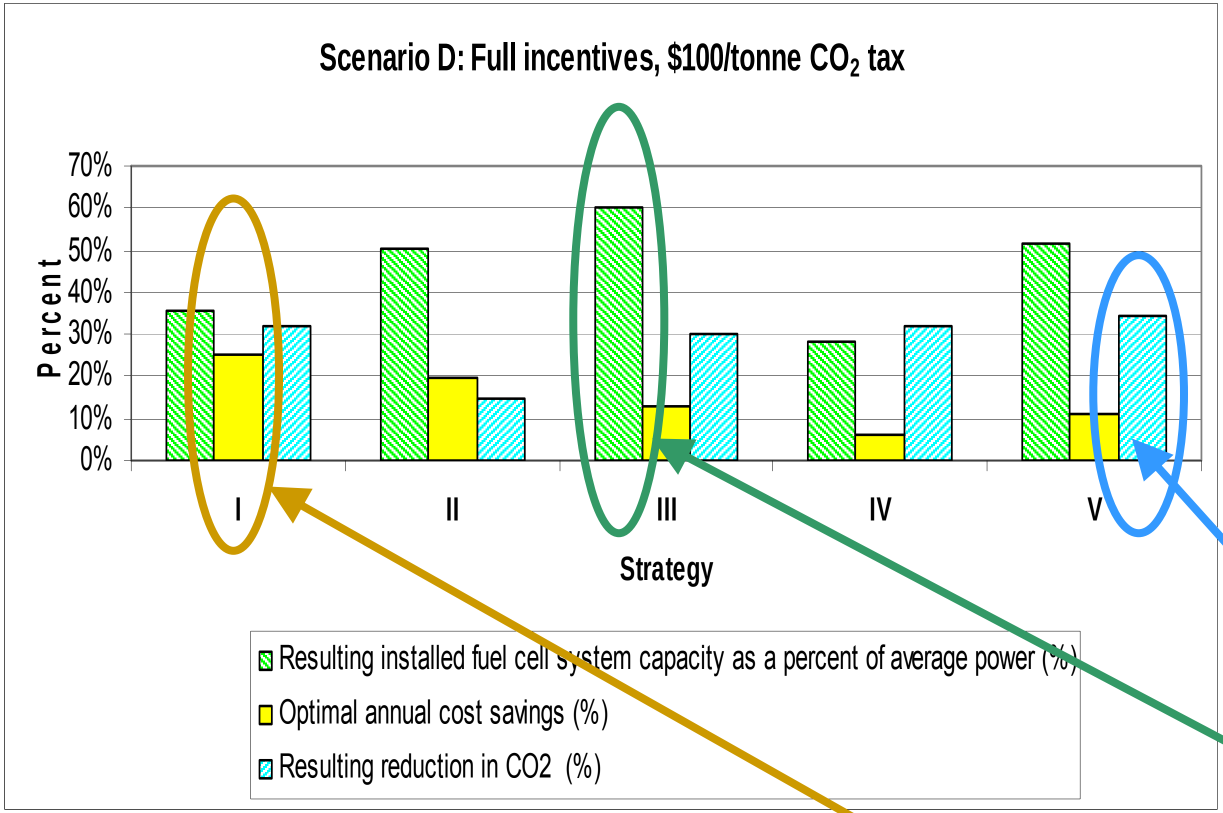
Strategy V is mostly *plain vanilla* using SA, NLF, & FHP

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



Benefits to building owners, manufacturers, and the environment

Blue = "blue skies", lowest CO_2

Green = $$$ money, highest fuel cell manufacturer revenues

Yellow = highest energy cost savings for building owners

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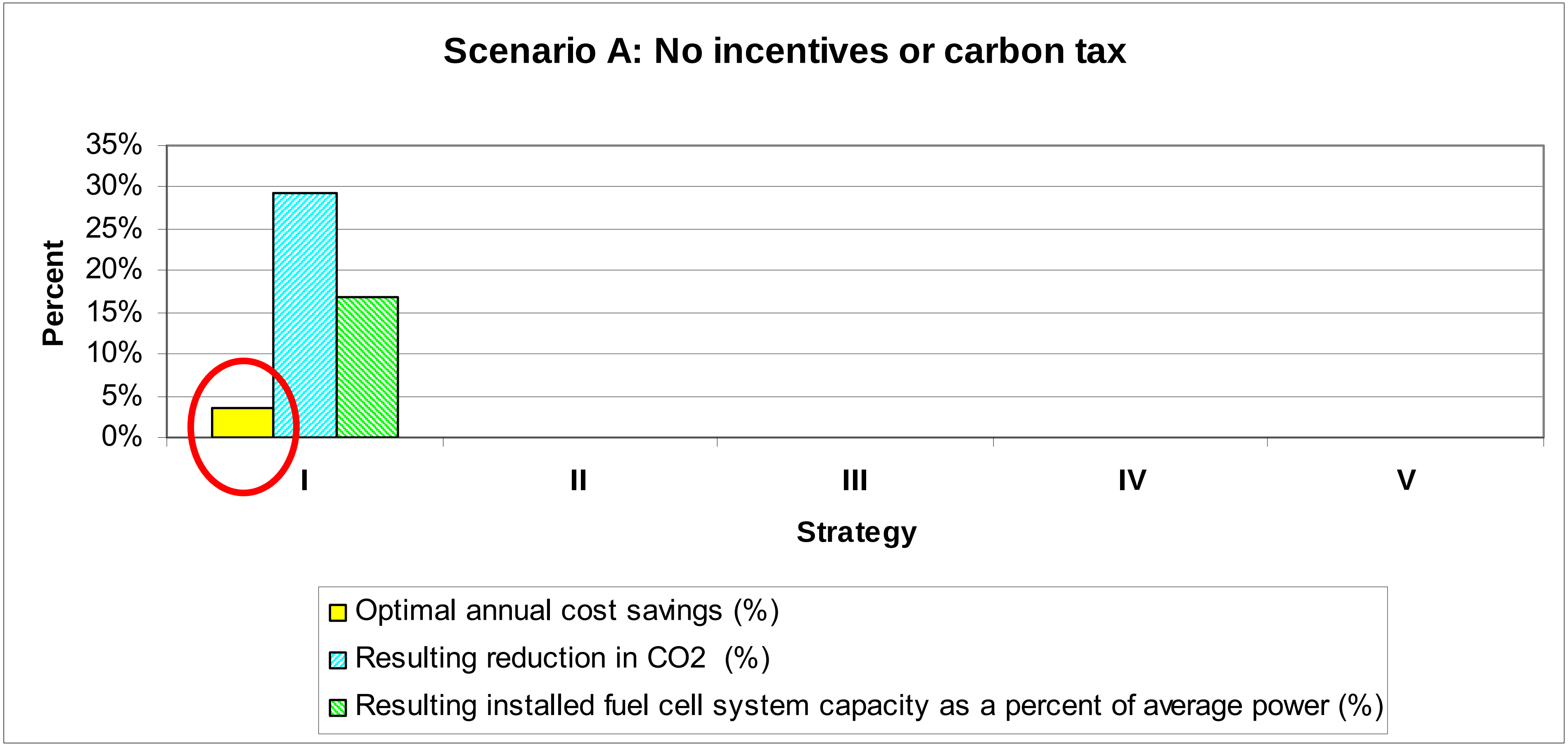
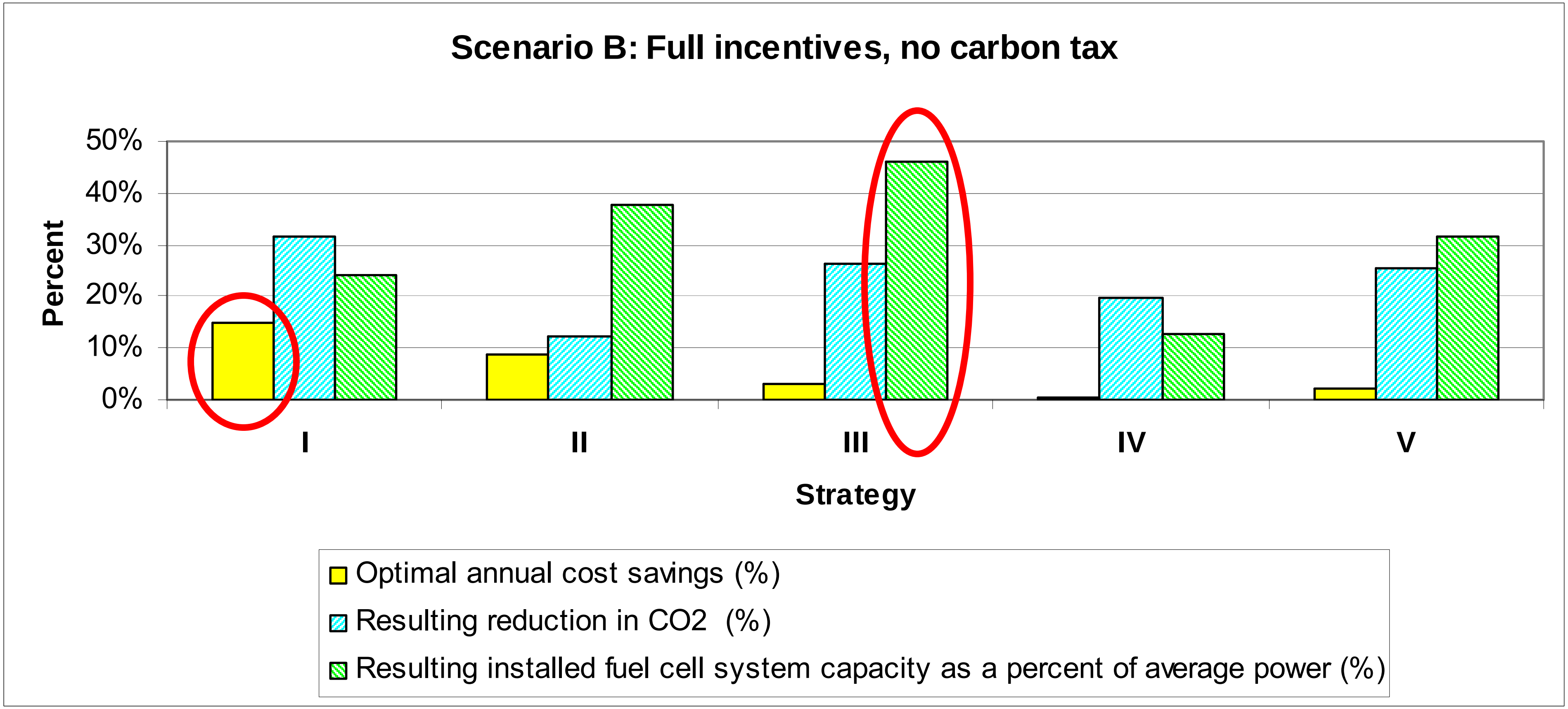
Scenario A: Fuel cell systems are economical with no subsidies if they use avant-garde operating strategies



Strategy I is *avant-garde* using cogeneration, NW, ELF, & VHP

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

Scenario B: Building owners and fuel cell makers profit most from different strategies



Strategy I (*avant-garde*) = most energy cost savings, least CO_2

Strategy III (*plain vanilla)* = [NW, NLF, FHP]
= most revenue for fuel cell makers

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

Strategy IV

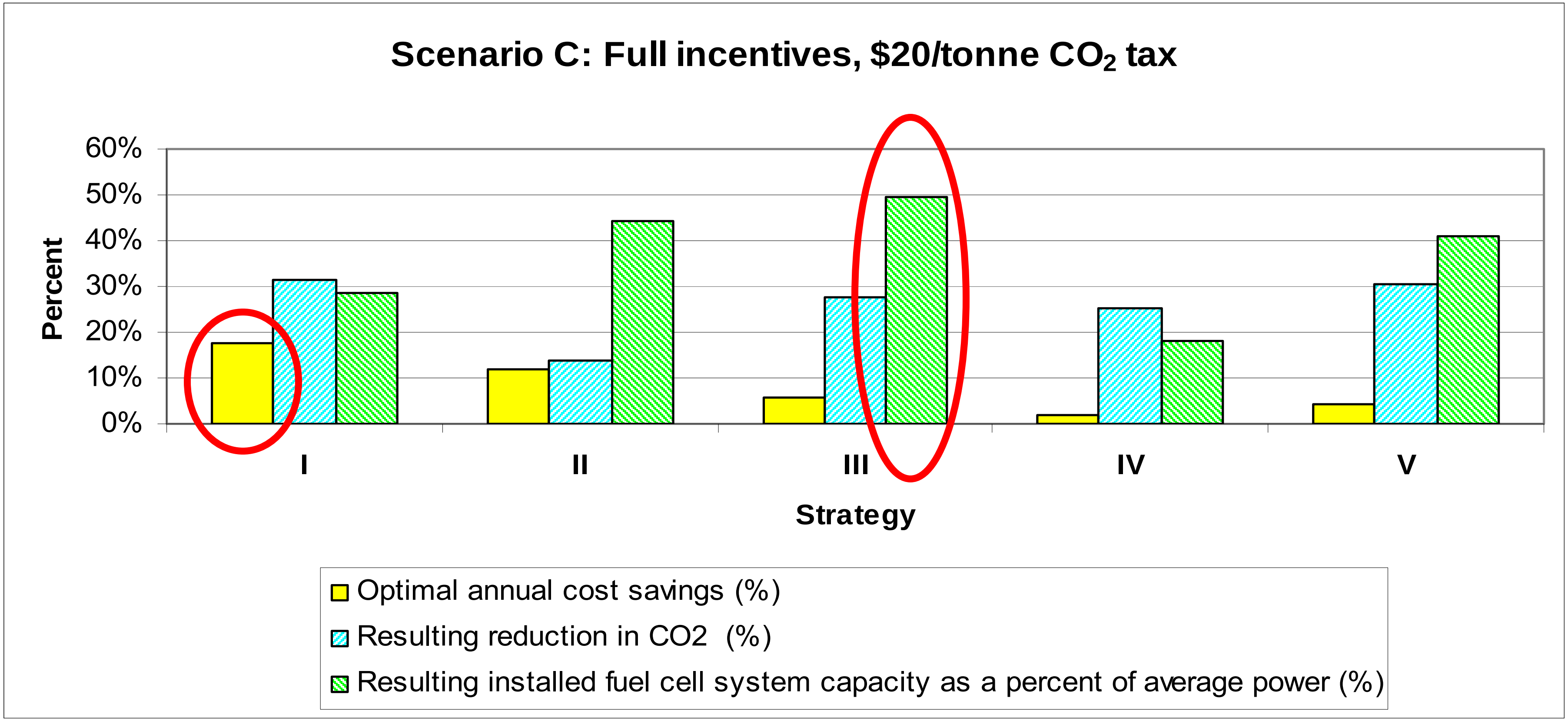
Building Type	Load Curve Based on this Building	Optimal Installed Fuel Cell System Capacity as a Percentage of Peak Power Demand throughout Energy Area (%)	Annual Cost Savings (%)
Wet Lab	Mudd (Seeley G) Chemistry	4%	1.5%
Dry Lab	McCullough (Jack A.)	1%	1.0%
Dry Lab	Mechanical Engineering Research La	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: Building owners and fuel cell makers profit most from different strategies



Strategy I (*avant-garde*) = most energy cost savings, least CO_2

28% of capacity, 17% savings, 32% less CO_2

Strategy III (*plain vanilla*) = [NW, NLF, FHP]

most revenue for fuel cell makers

49% of capacity, 6% savings, 27% less CO_2

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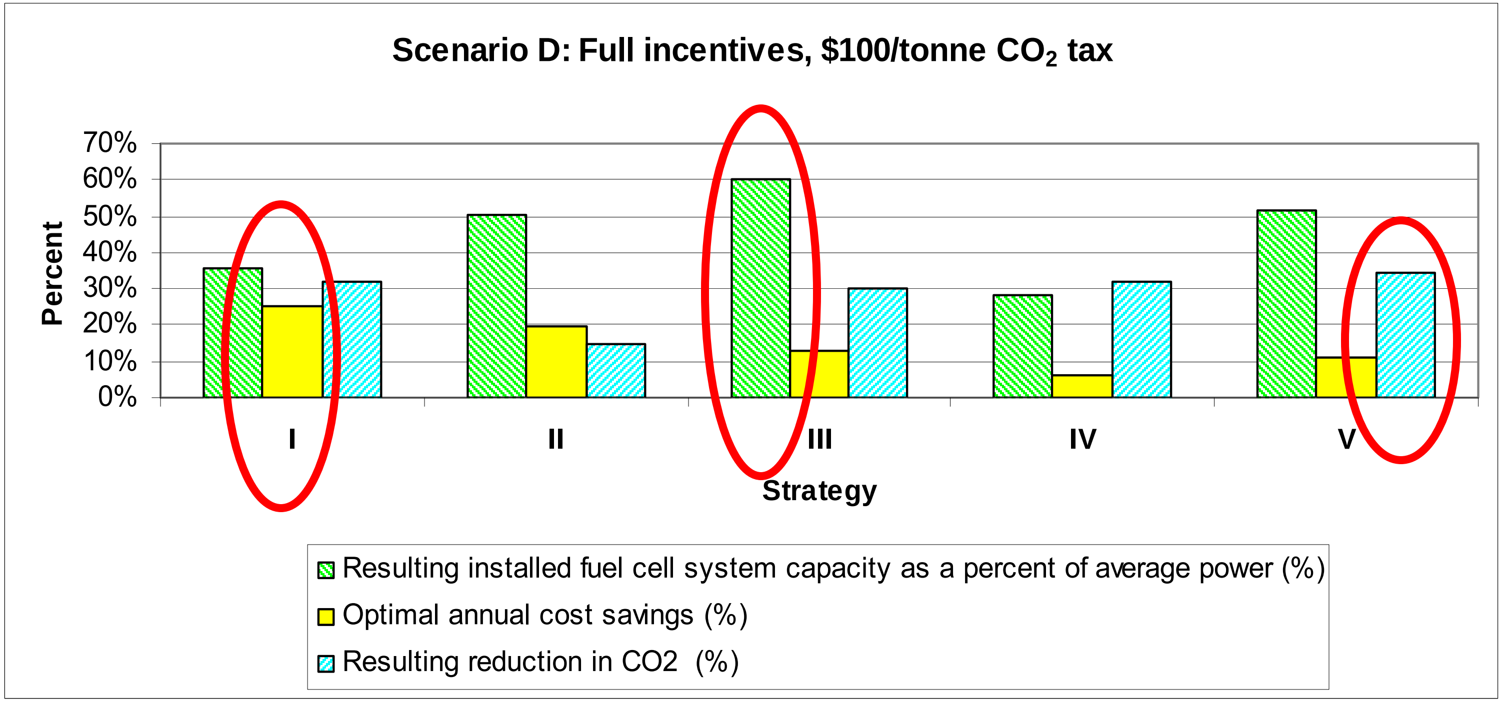
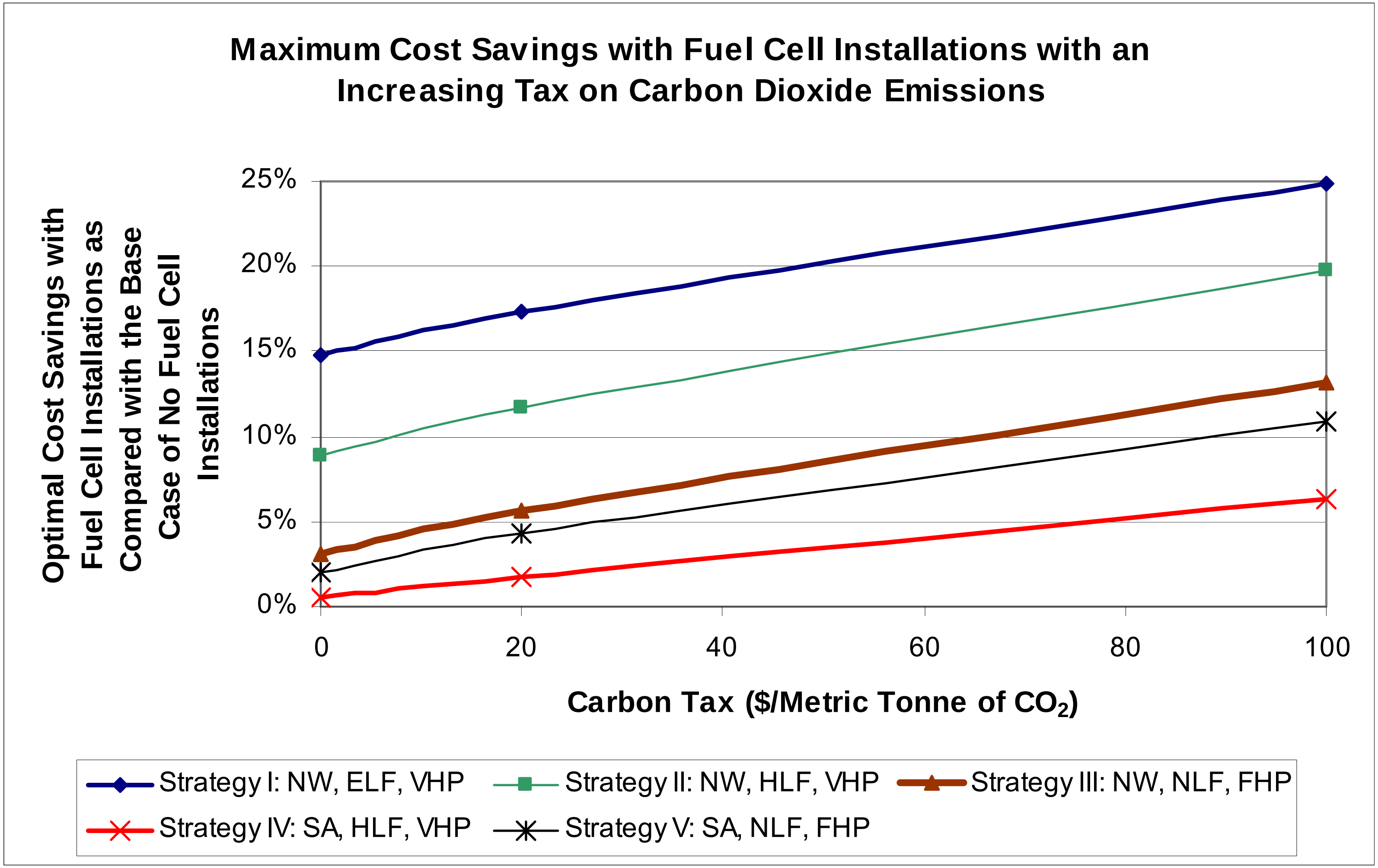
Scenario D: No one strategy achieves all economic and environmental goals under all scenarios



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

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



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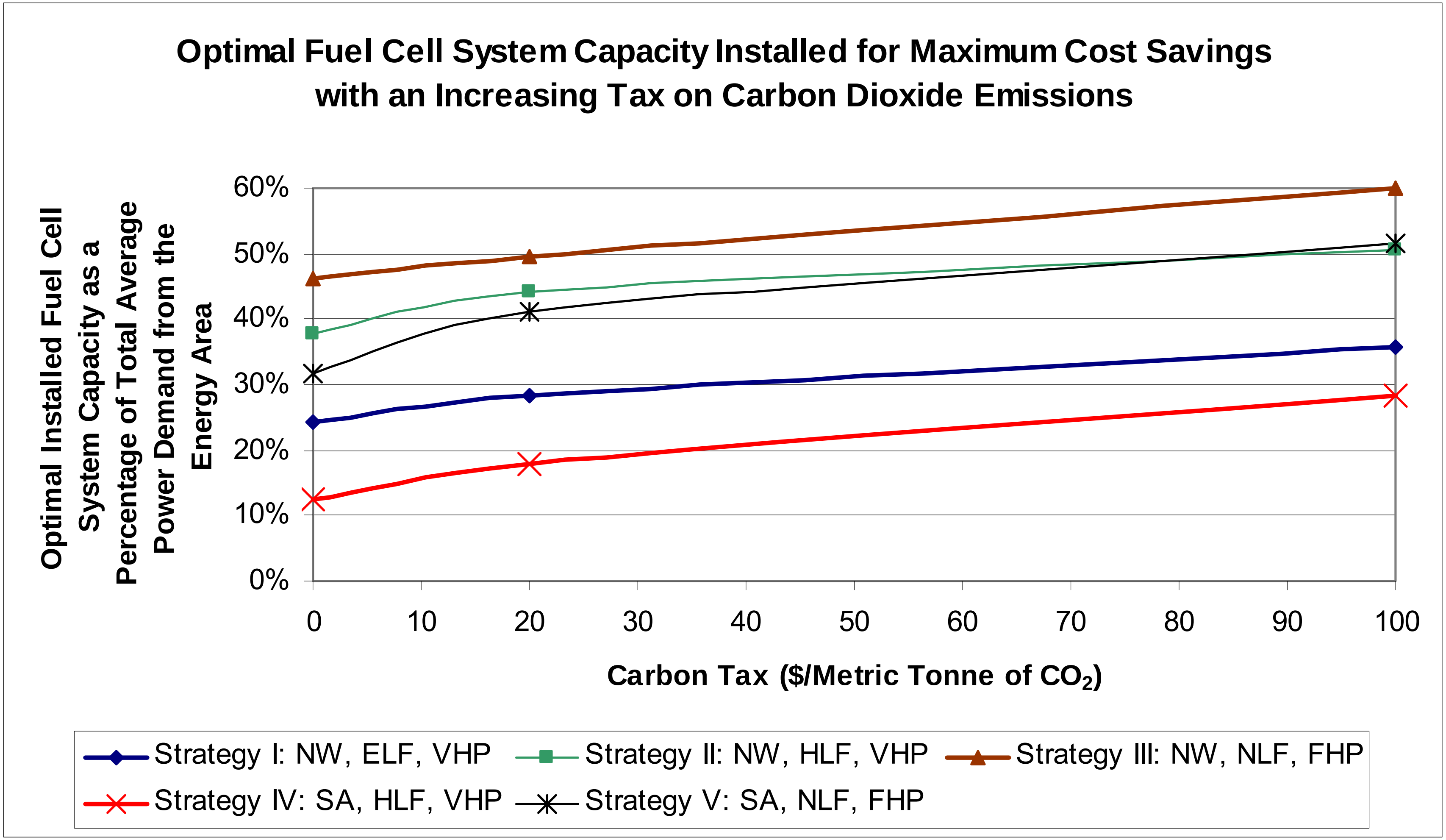
Highest profit for fuel cell makers with Strategy III = *close to status quo*



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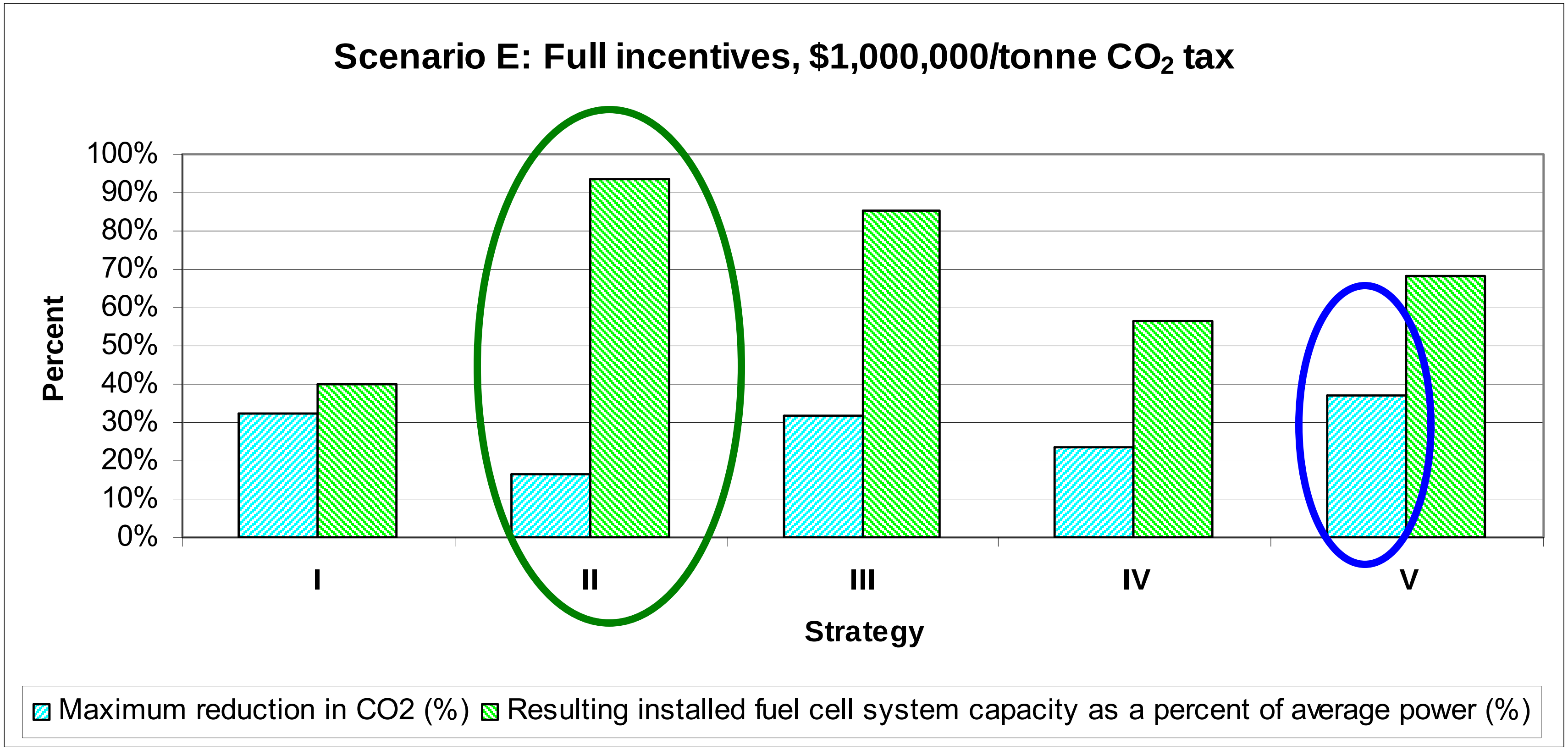
Scenario E: High CO_2 Decrease w/ Strategies I, III, V



1. **Highest manufacturer revenues w/ Strategy II (avant-garde), but highest CO_2 emissions**
2. **<u>Maximum</u> CO_2 reductions with Strategy V (*plain vanilla*)**

   - 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

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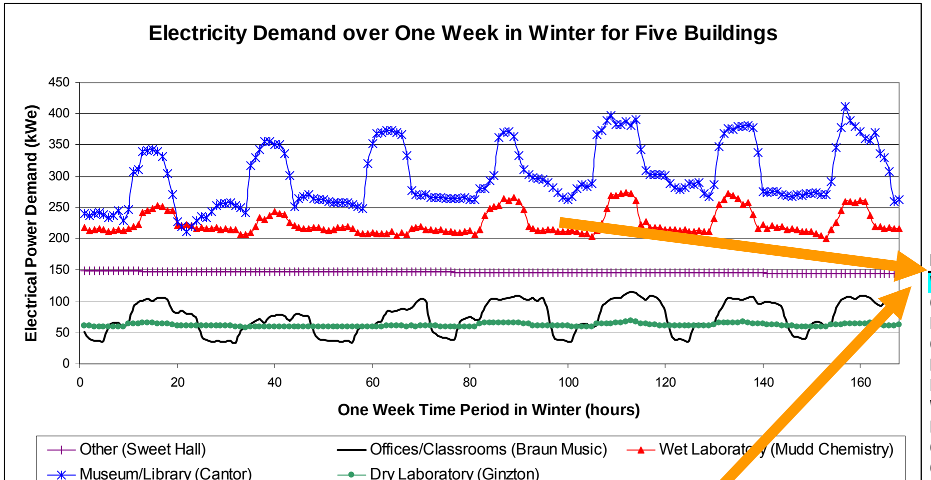
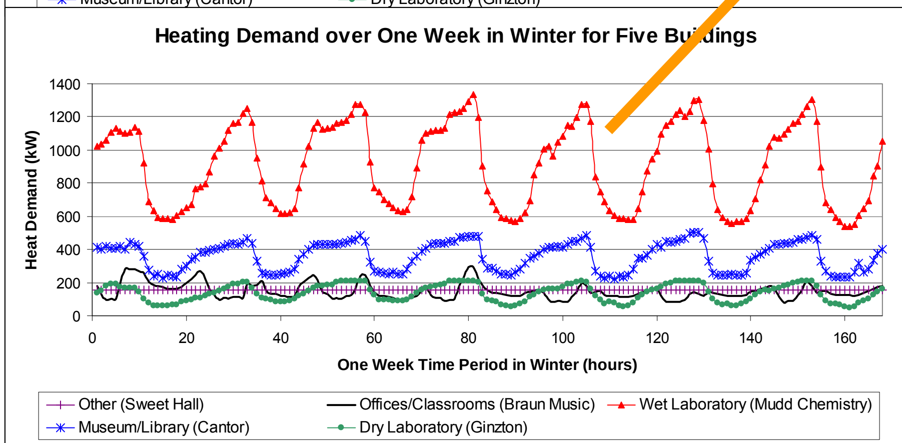
Building load curves strongly influence economics and environmental impacts of system installations





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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%

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

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Results Summary

1. **FCS are marginally economical with <u>no subsidies</u> by <u>changing</u> to Strategy I (NW, ELF, VHP) *avant-garde***
2. **Building owners and fuel cell makers profit most from different strategies**
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 (*plain vanilla*)
   Highest profitability w/ Strategy III (*plain vanilla*)

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.**

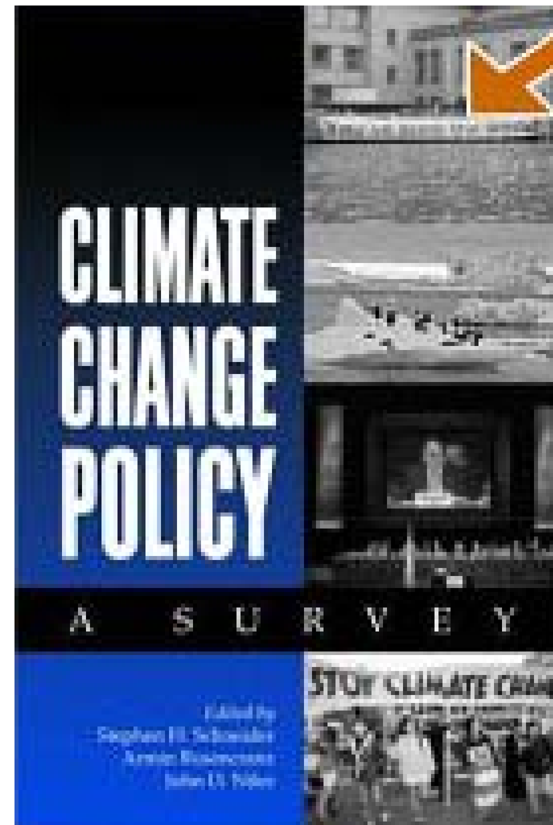
Recommendations

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

Publications

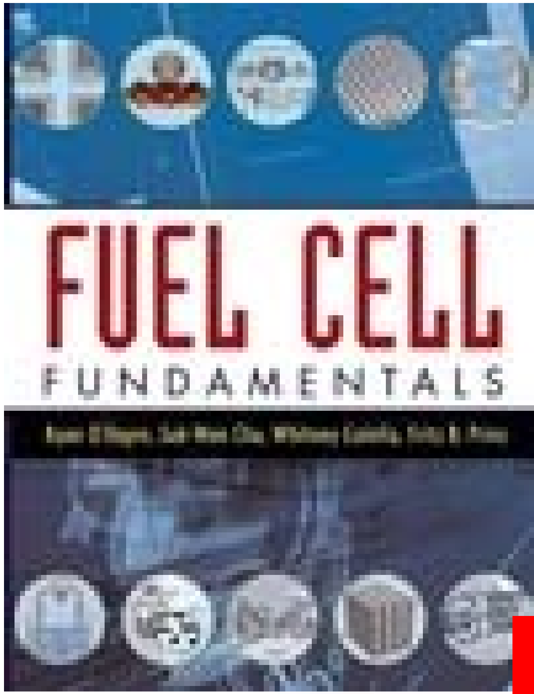
Educating Policy Makers about Hydrogen & Climate

- "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



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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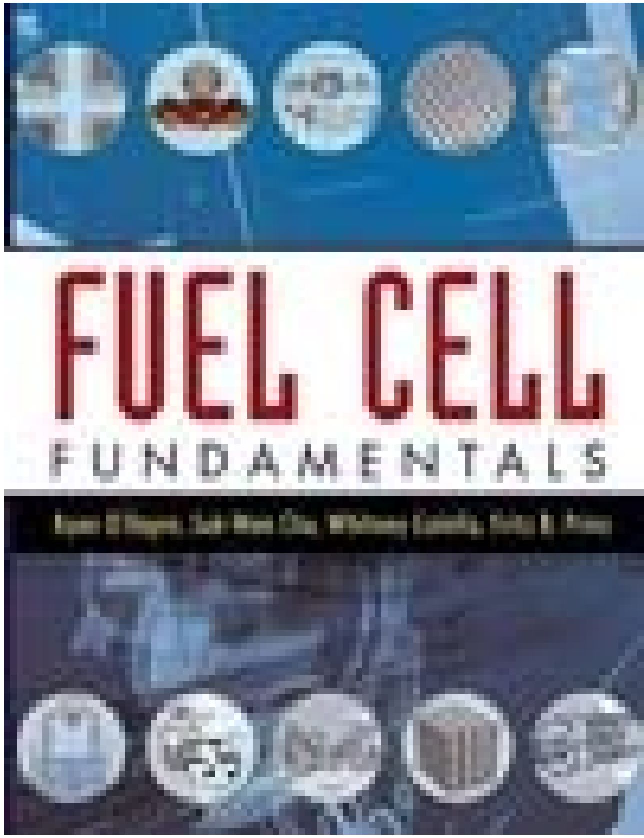
Quiz Results

If you answer this quiz question correctly, you can win a copy of this <u>Fuel Cell Fundamentals</u> textbook.

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?



Please write your answer on a business card and pass it up to the front before the end of the talk.

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Thank You

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