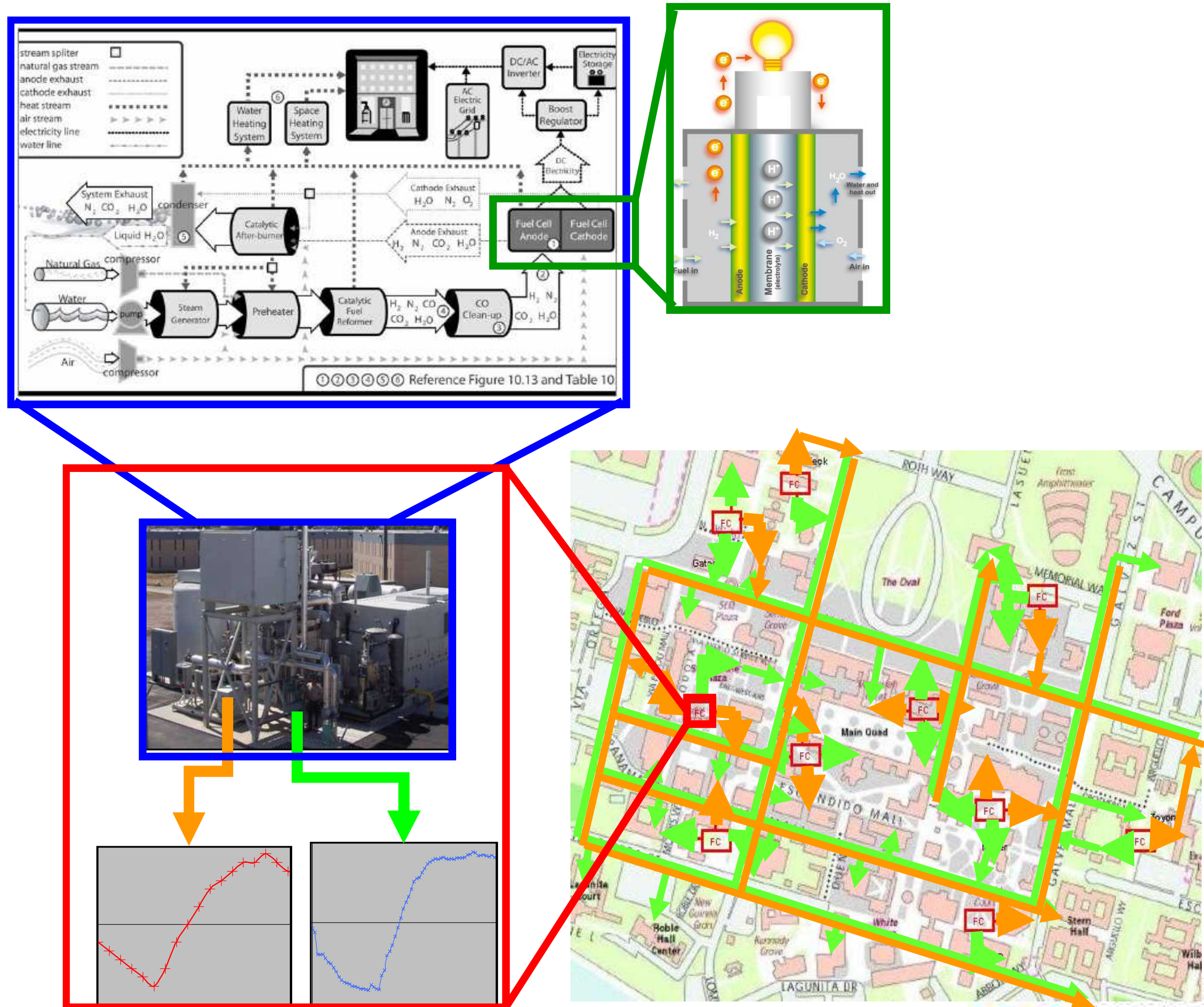
Network design optimization of fuel cell systems and distributed energy devices

SAND2008-5267C



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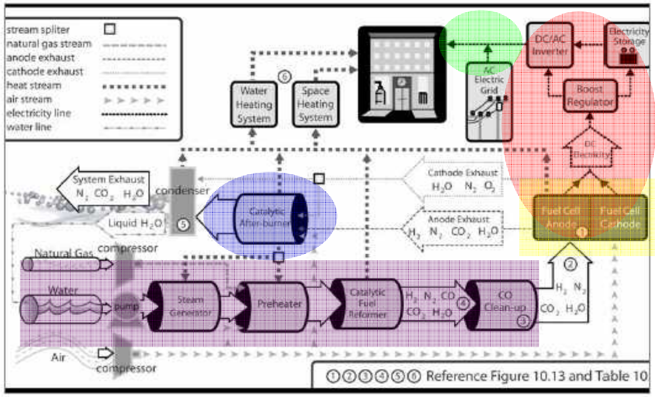
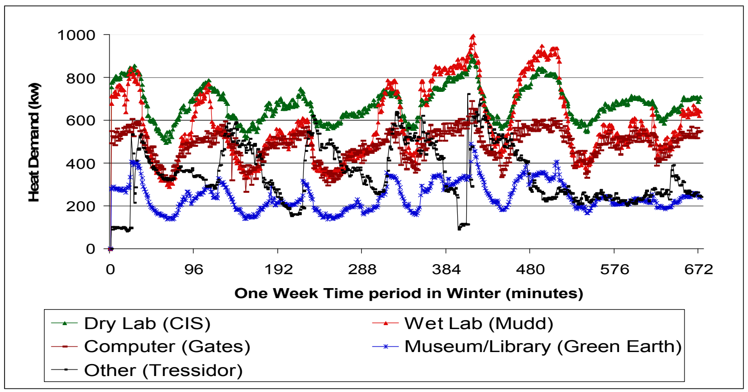
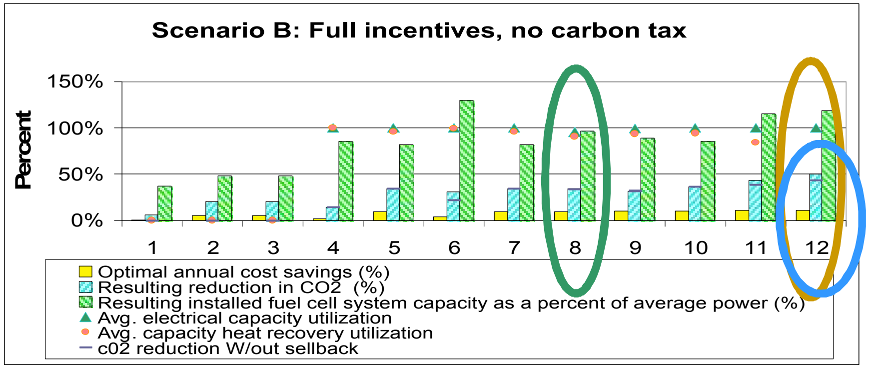
This talk explores financial and economic benefits of using unique operating strategies for fuel cells



Novel operating strategies



Simulation design



Benefits to building owners, manufacturers, and the environment

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Background

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

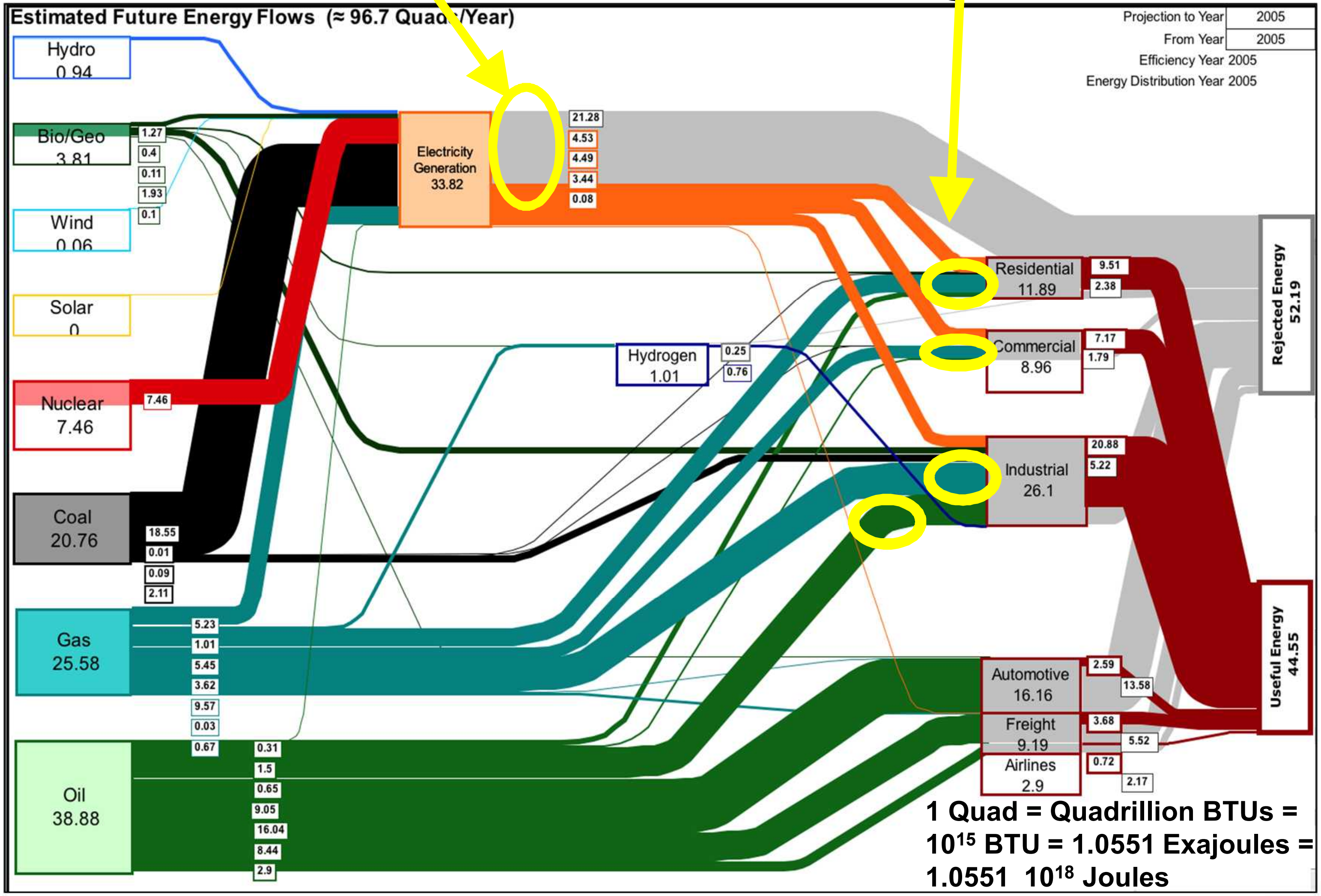

Figure by Gene Berry, Lawrence Livermore National Laboratory

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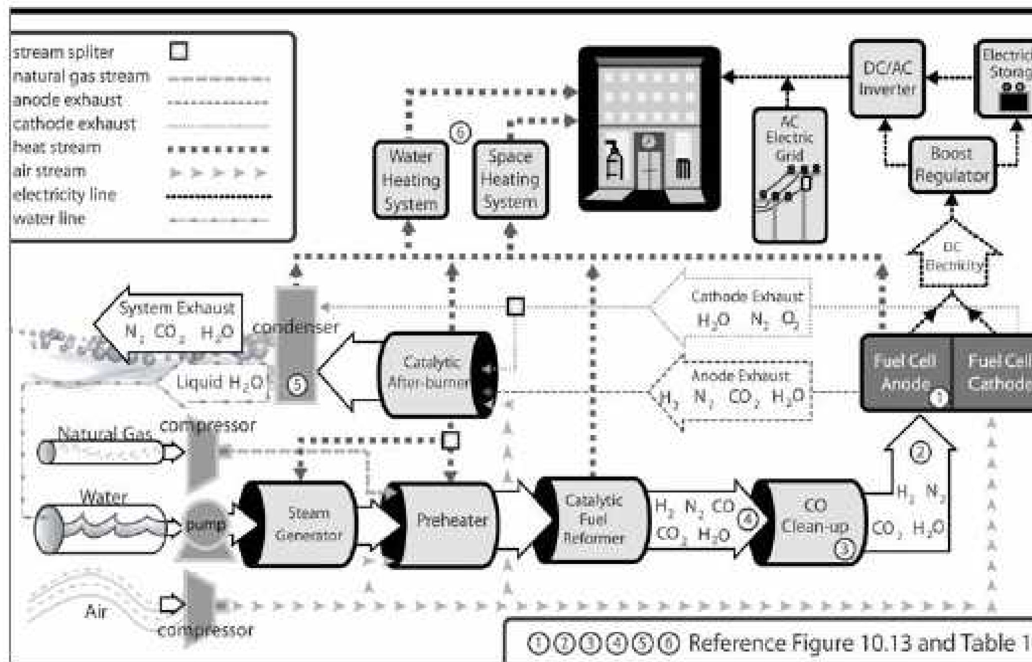
Stationary fuel cell systems can be designed to make both electricity and heat, a process known as cogeneration or combined heat-and-power (CHP)

Natural Gas, Propane, or Biogas

Cooling

Heat

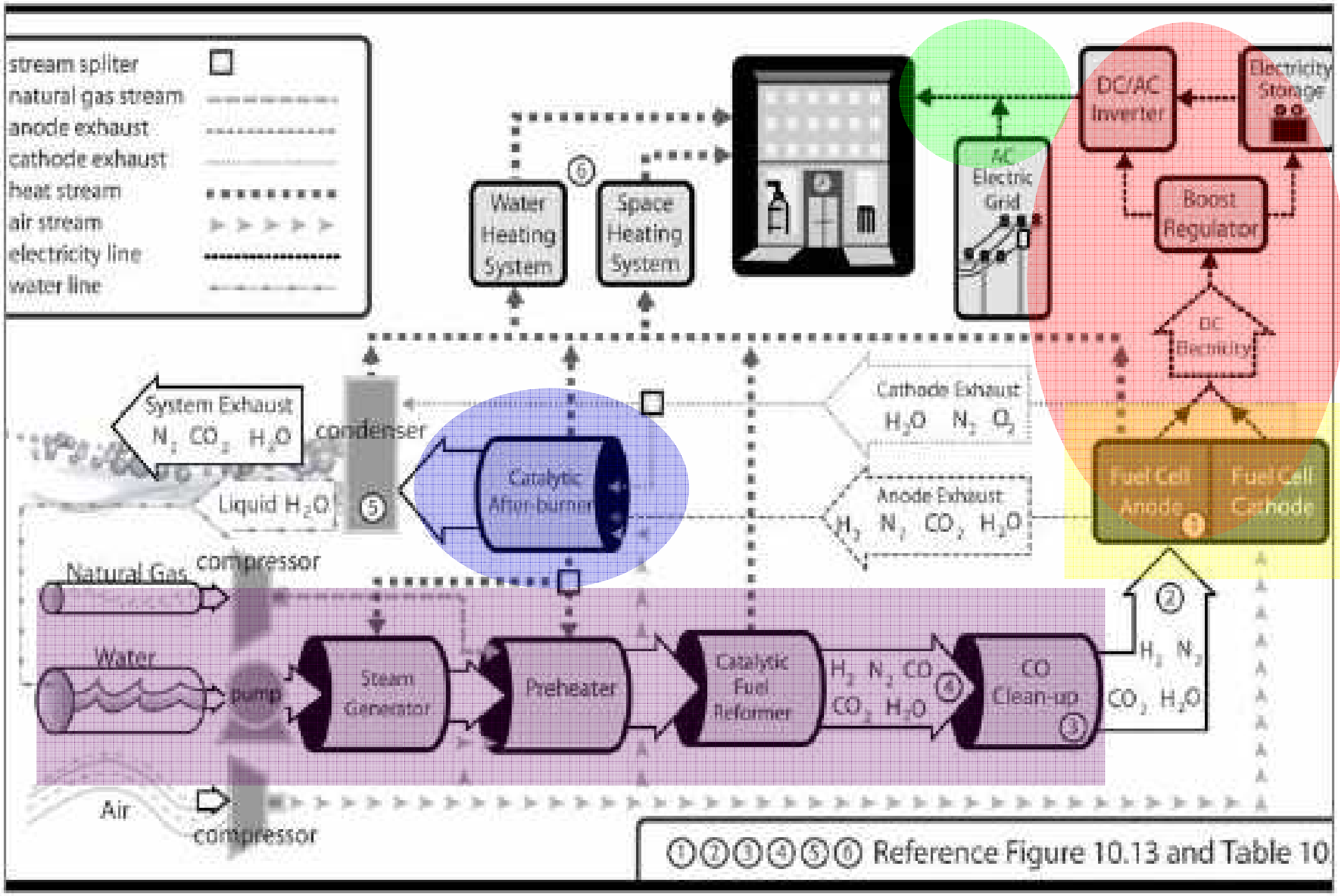
Electricity



Stationary fuel cell systems (FCS) 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 designed to recover heat and with high end-use capacity utilization. They make no CO_2 if fueled by renewable H_2.



Novel operating configurations

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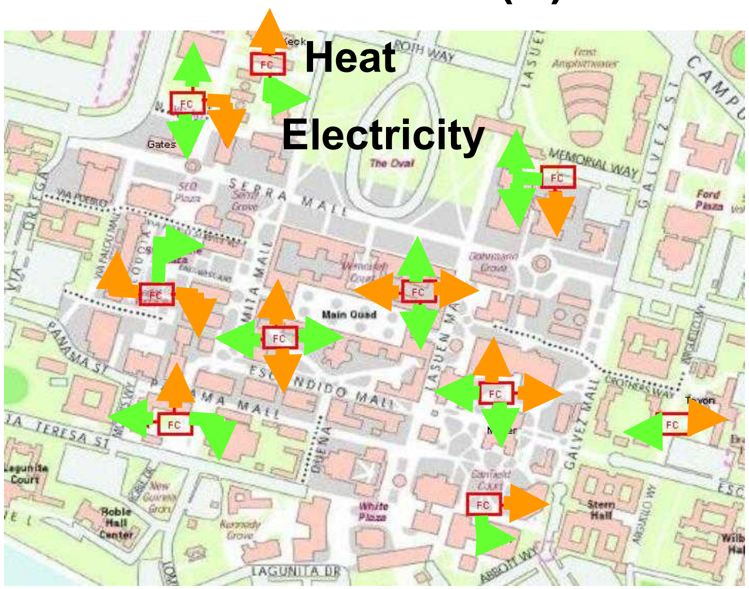
Systems can be installed stand alone or networked

Electricity

Heat

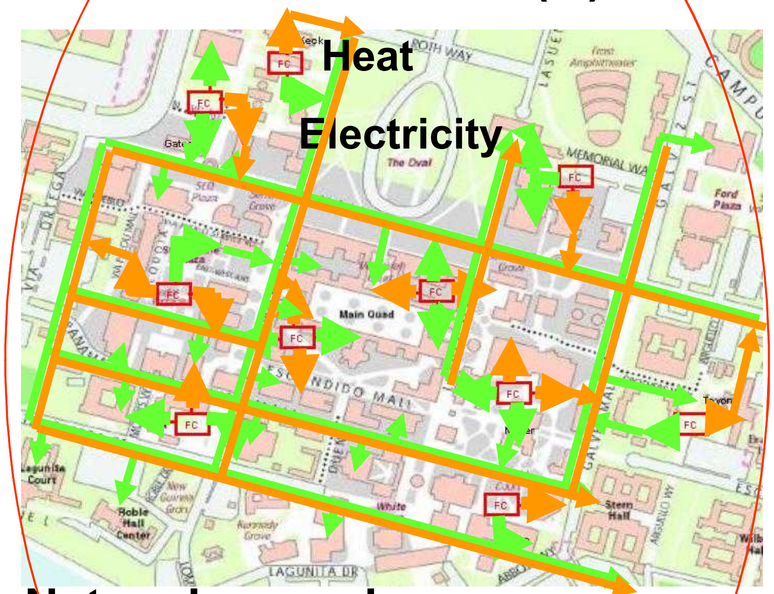
stand alone vs. networked

stand alone (S)



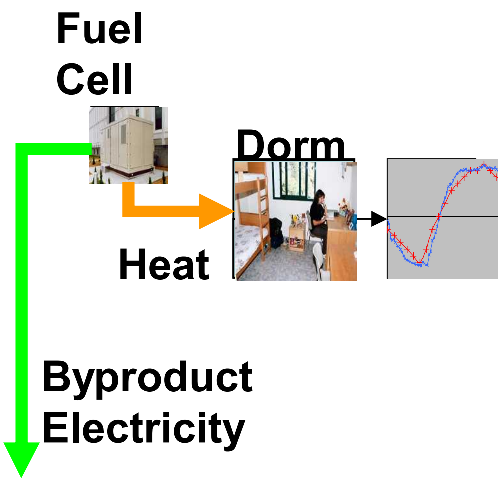
Fuel cells can NOT convey or sell excess heat or electricity into the distribution grid to reach other buildings. One system serves only one building. Buildings can import additional heat and electricity. FuelCell Energy currently installs its units this way.

networked (N)

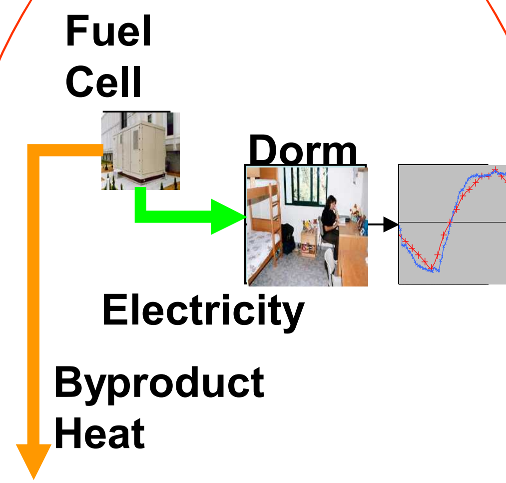


Networks have energy distribution channels. Fuel cells CAN convey excess heat or electricity into the distribution grid to reach other buildings, and sell back electricity to the grid. Transmission Loss: Electrical ~0%, Thermal ~8%.

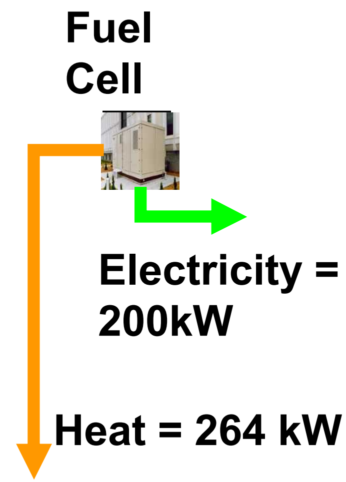
Systems can be configured as heat load following, electricity load following, or no load following



Heat Following (H)



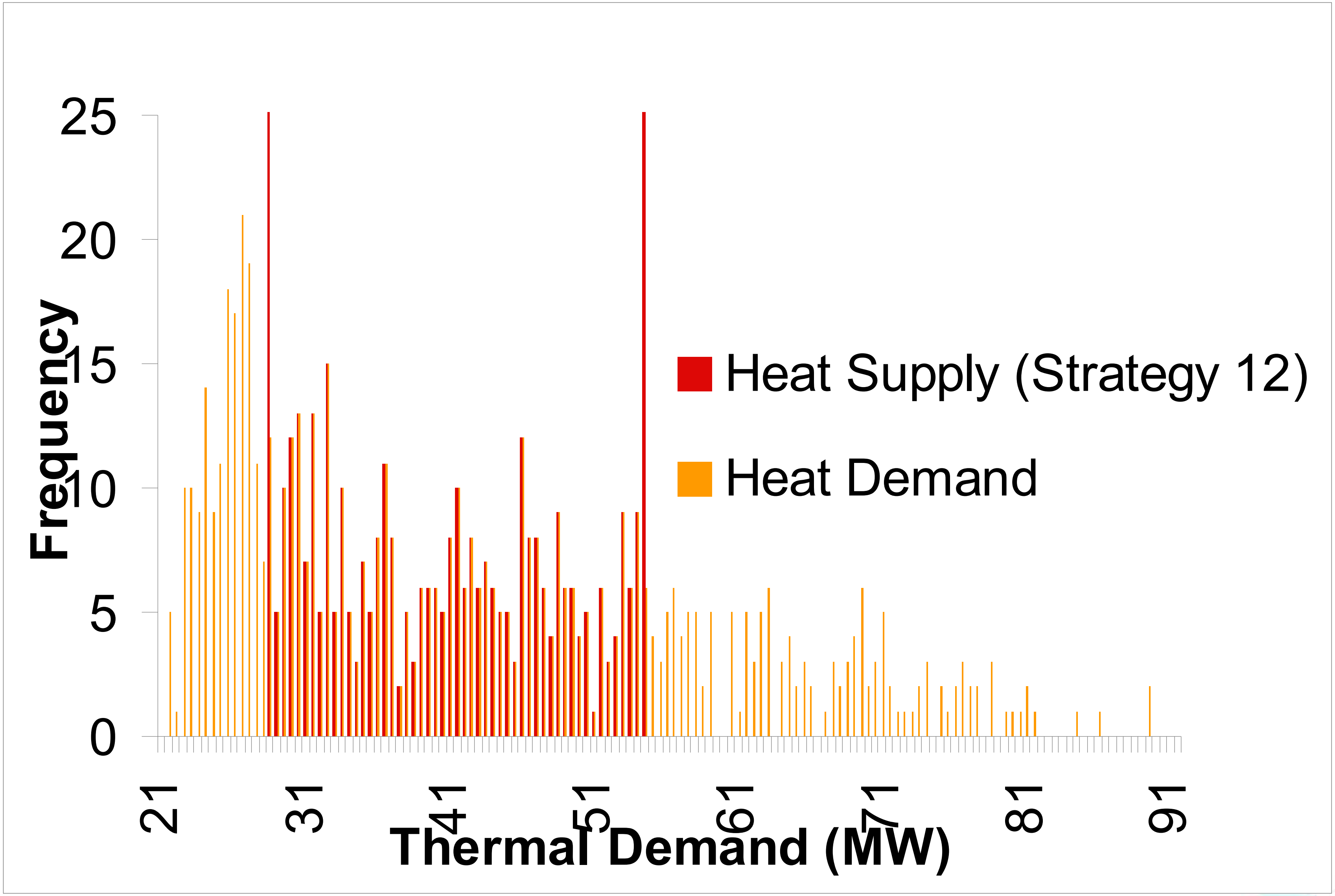
Electricity Following (E)



No Load Following – at Electrical Maximum (EX)

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

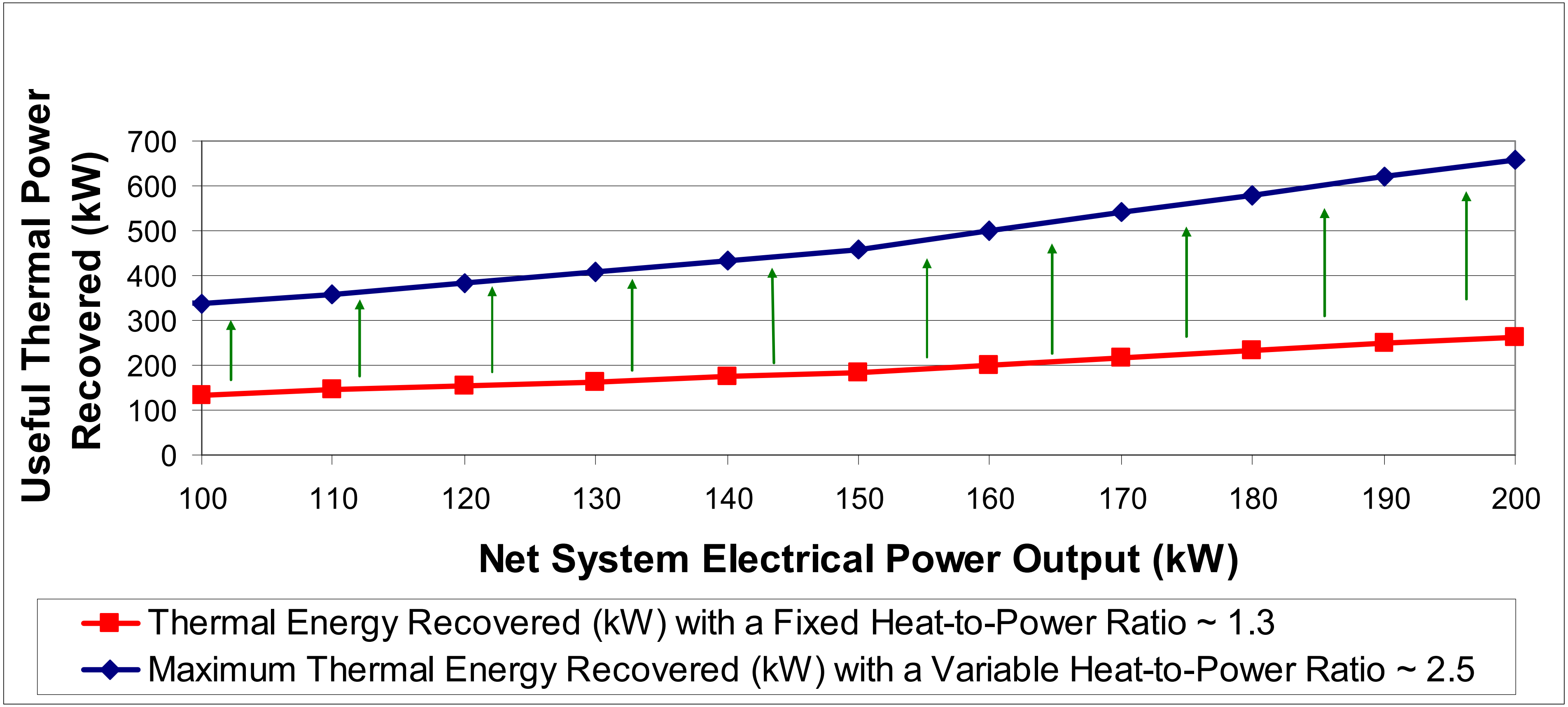
Load following is physically constrained by the system's energy output range and ramp rate.



 Histogram of heat demand vs. supply for load following

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

Fixed (F) vs. Variable (V) Heat-to-Power Ratio



Variable heat-to-power ratio increases system operating range

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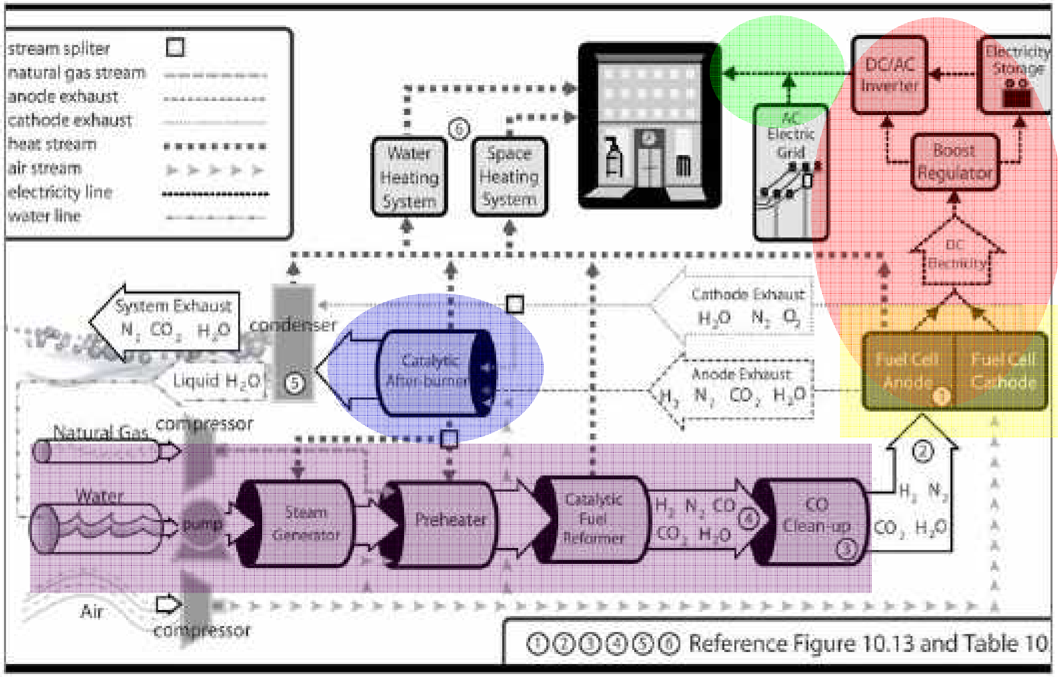
Systems can be configured with a variable heat-to-power ratio using a variety of methods (Colella 2002)

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 with increased cell run time, and potentially increased cell degradation / decreased lifetime

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

FuelCell Energy design – Option V: Resistance heater

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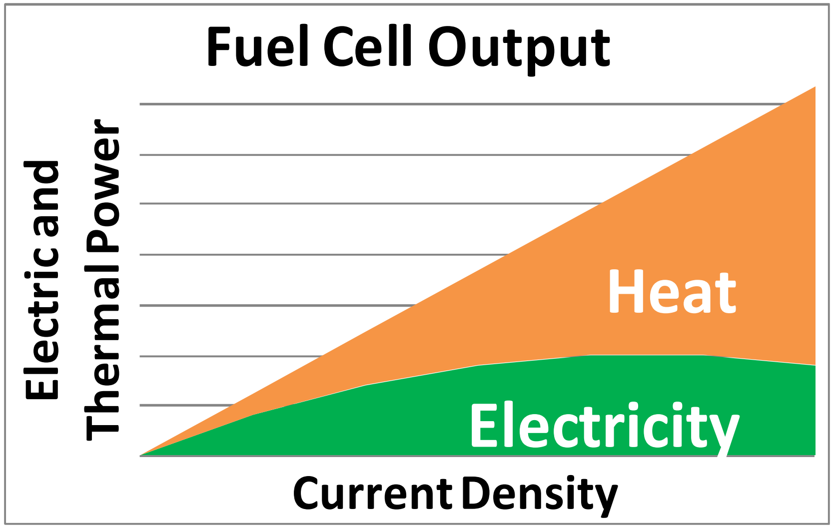
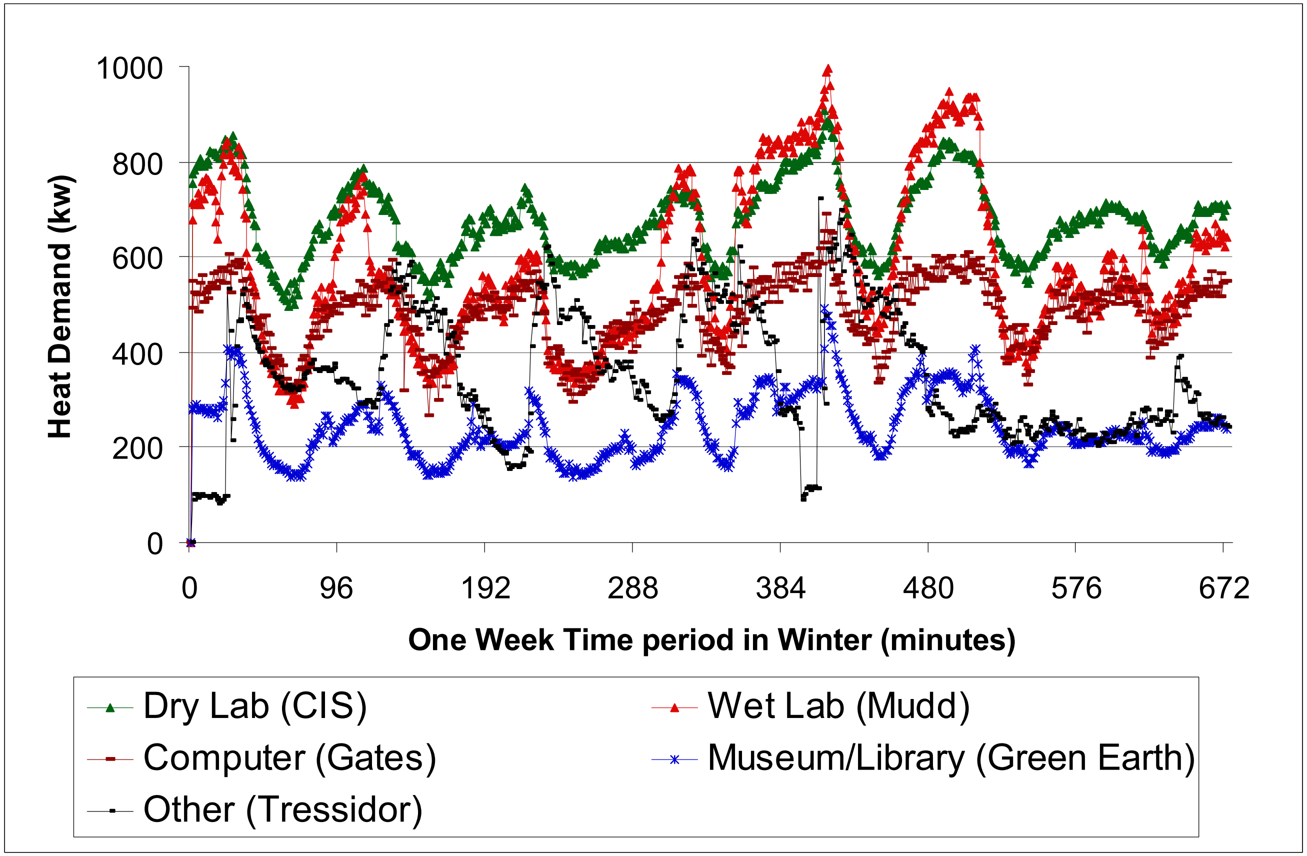
Systems can be configured to convert waste heat into cooling power with an absorptive cooling cycle



Type	COP	Heat Source
Single Effect LiBr/Water	0.5-0.7	80-110°C
Double Effect LiBr/Water	0.8-1.2	120-150°C
Triple Effect LiBr/Water	1.2-1.5	160-190°C

LiBr/water absorptive cooling cycle is the standard for space cooling (5°C), but its coefficient of performance (COP) varies with heat source temperature and other factors.



Simulation design

Novel strategies are examined using a simulation tool.

Model evaluates novel operating strategies for stationary FCSs installed in buildings

- Examines novel operating strategies not common in commercial industry (NVHE).
- Optimizes the percentage installation of FCS for
  - minimum CO_2 emissions
  - minimum CO_2 emissions per unit energy cost, or
  - maximum energy cost savings to building owners.
- Optimizes FCS installation for
  - a particular location
  - climatic region
  - building load curves
  - FCS type, and
  - competitive environment.
- Shows trade-offs among competing goals:
  - cost savings to building owners, CO_2 reductions, FCS installed capacity and manufacturer sales.

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Model includes 2007 real-time measured demand data for electricity, steam, and chilled water from 19 Stanford buildings at 1 hour increments

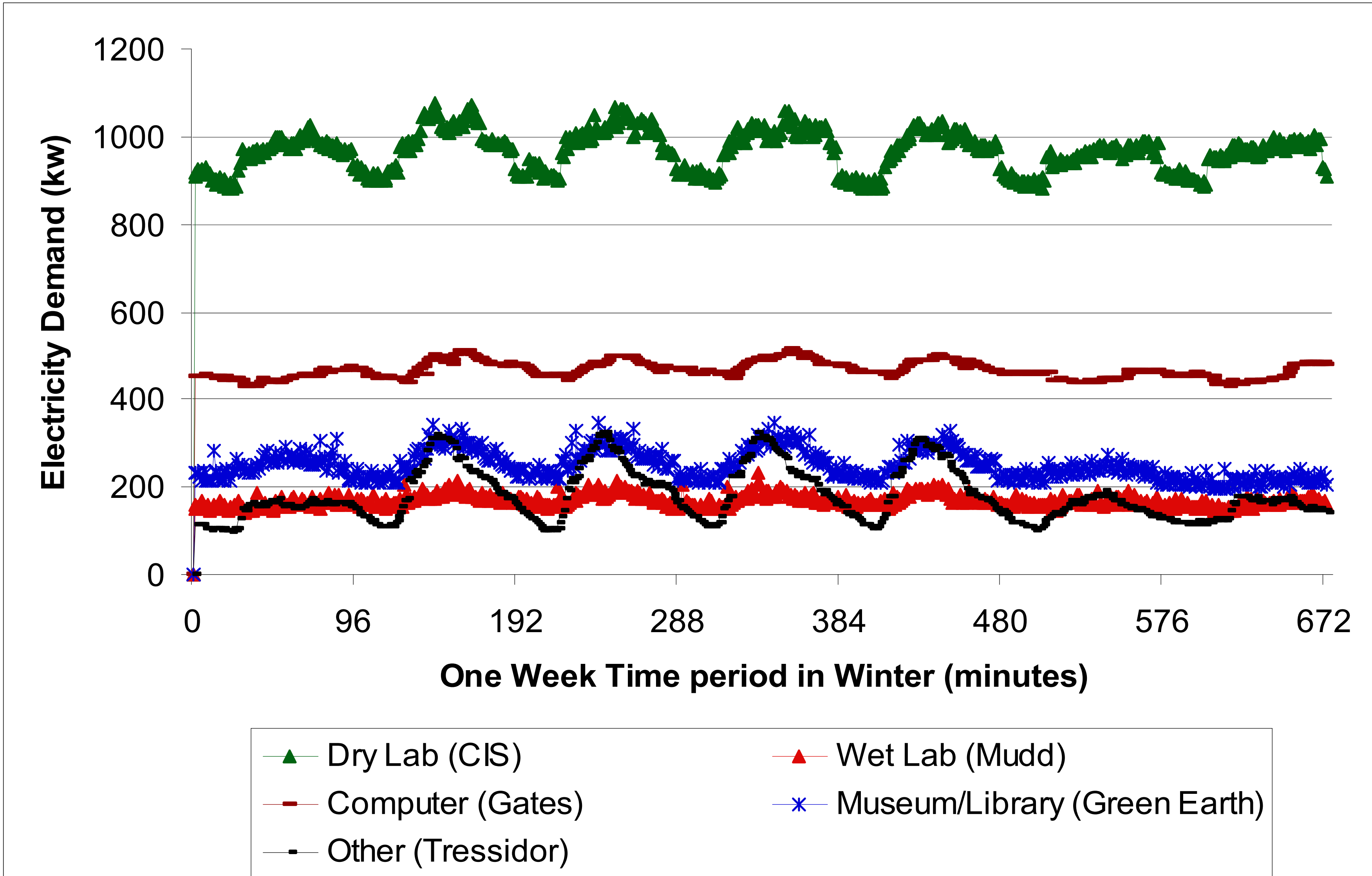
electricity

steam

chilled water

A unique feature of this data set is that the space cooling demand is directly measured and distinguishable from electricity demand (unlike air conditioning systems).

Model describes electricity, heating, & cooling demand, which varies by time of day, day of week, season, & building type



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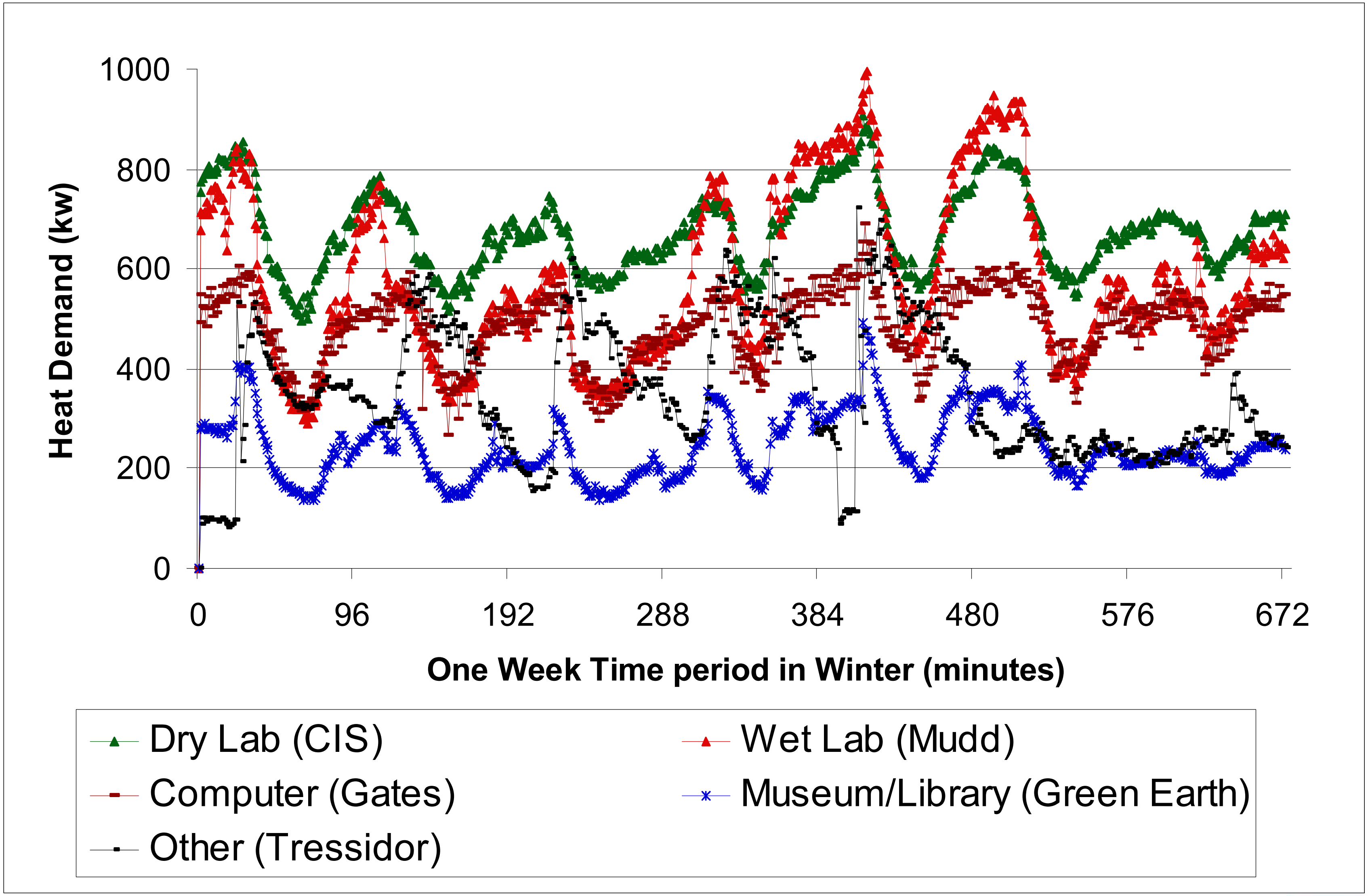
Heating demand varies by time of day, day of week, season and building



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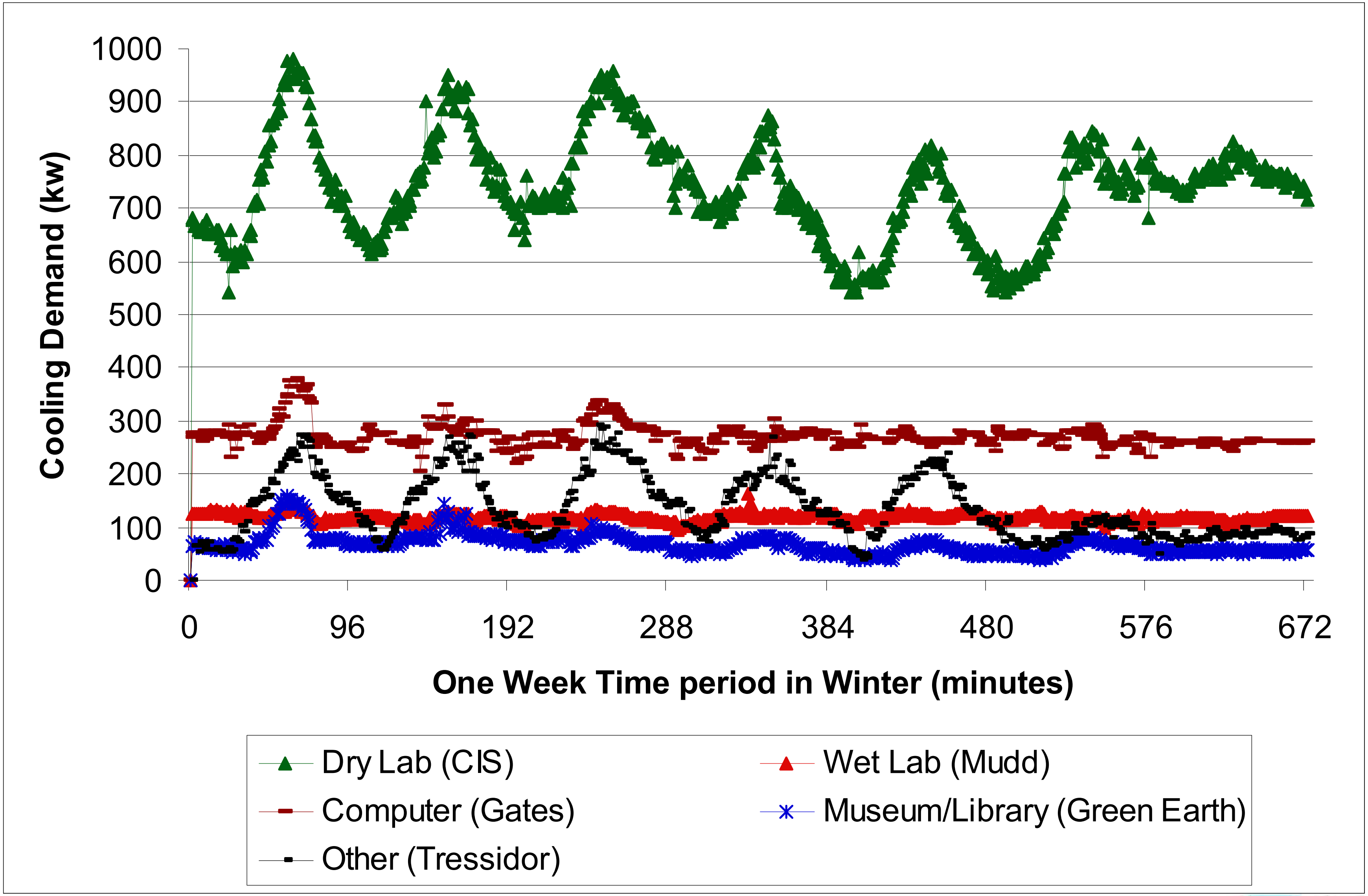
Cooling demand varies by time of day, day of week, season and building



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The four seasons are represented using four weeks of measured data with similar weather conditions to the seasonal averages (avoiding school breaks)

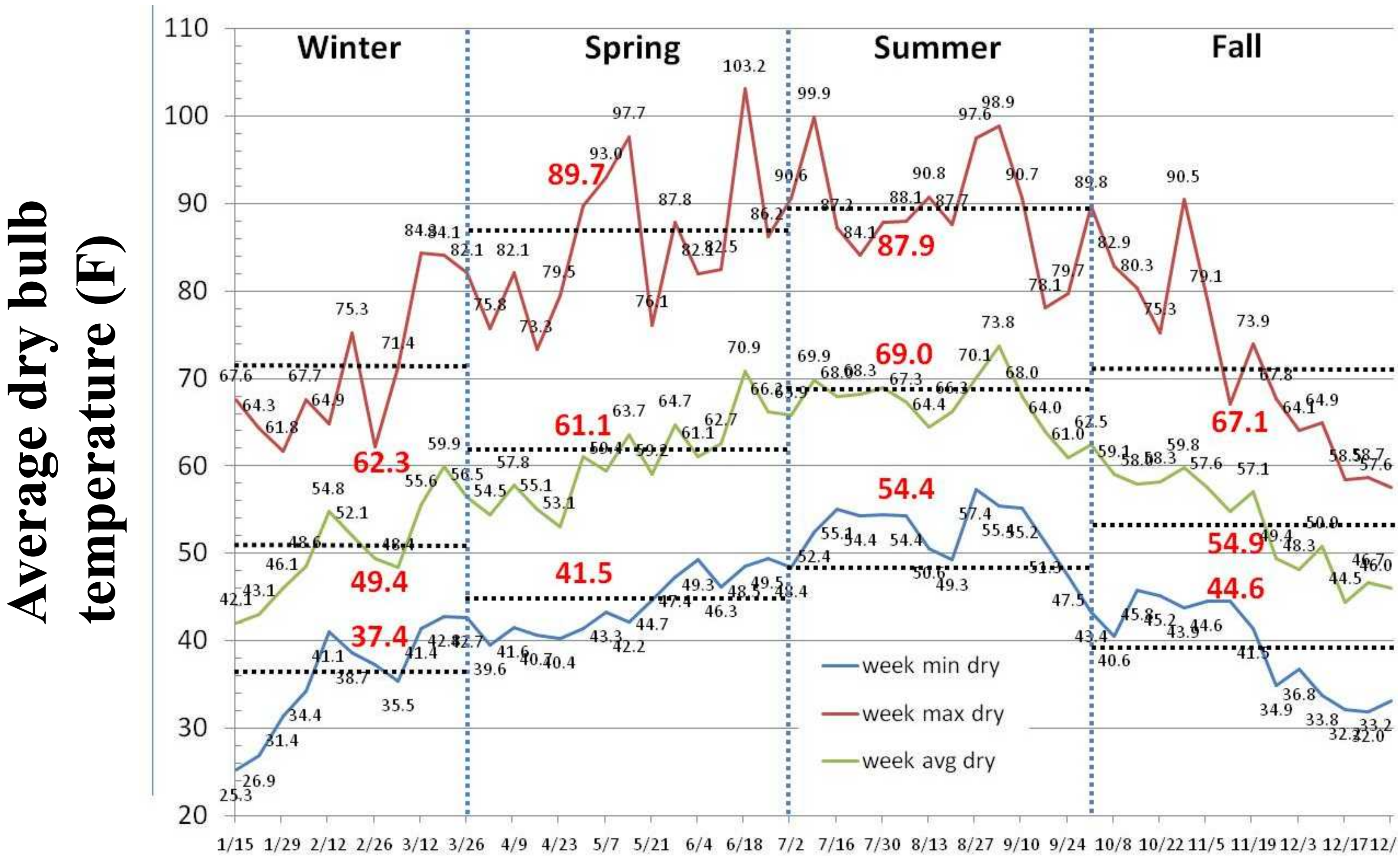
Winter: Jan. thru March 2007

Spring: April thru June 2007

Summer: July thru Sept. 2007

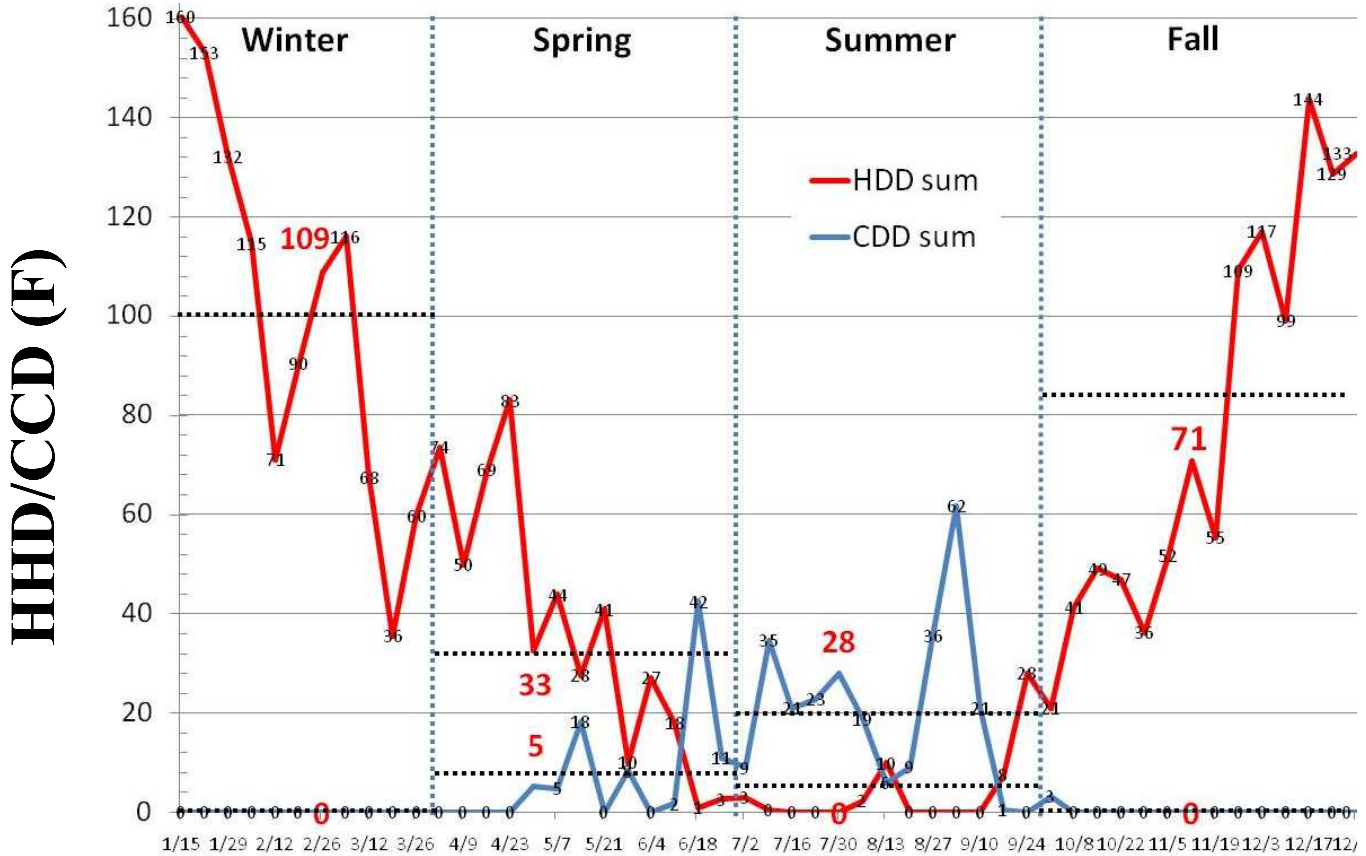
Fall: Oct. thru Dec. 2007

Selected weeks are chosen to have a dry bulb temperature within 0.5 standard deviations of the seasonal average.



Selected weeks shown in red-bold; average seasonal values shown as dotted horizontal lines

Selected weeks are chosen to have heating and cooling degree days (HDD/CDD) within 0.5 standard deviations of the seasonal average.



Heating/Cooling Degree Day (HDD/CDD) is the deviation of average daily temperature from 65°F, and is a measure of the heating or cooling required for a building. Selected weeks are in red-bold, and average seasonal values are represented by dotted horizontal lines

Demand data of 19 buildings in six categories was scaled up to simulate total campus demand

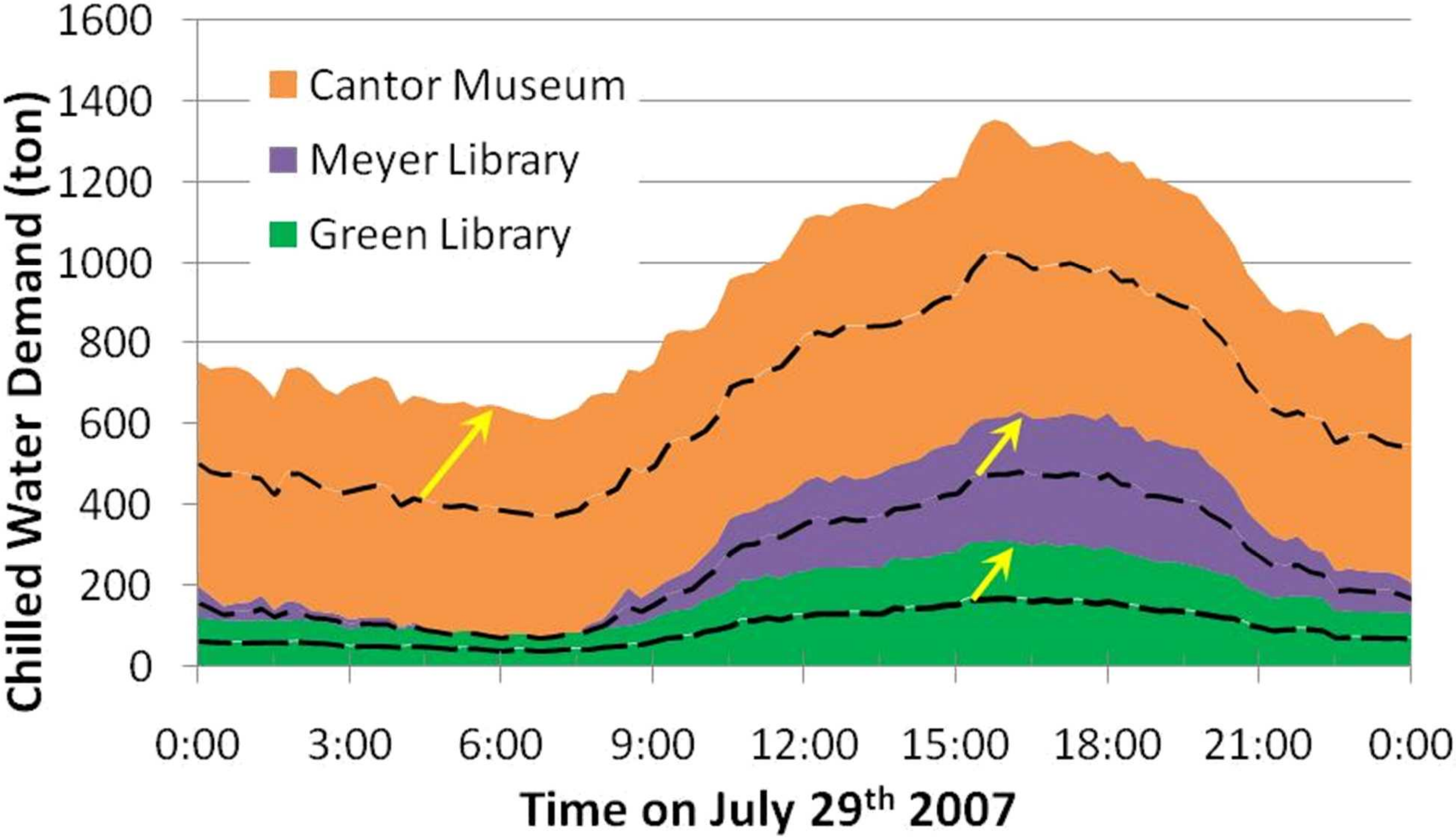
- **Located total campus demand for electricity, steam, and chilled water for each building category**

- **Solved for factors that scale each building's demand data to equal the total demand on each day for chilled water, electricity, and steam from that building's category**

- **Solved for 420 scale factors**
  - 5 categories (buildings within category have same factors)
  - 3 measurements (chilled water, electricity, steam)
  - 28 days (factors for each day of four selected weeks)

Each building within a category has the same scale factor for each measured quantity, and factors are chosen so category daily demand matches actual daily demand

Library/museum chilled water demand scaled to meet total building category demand on July 29th



Scale factors are found for all three demand measurements and all five building categories on all 28 days

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Model describes operating data for fuel cell systems

Fuel Cell System Operating Data	Quantity	Units
Maximum Electrical Output	1000	kw
Minimum Electrical Output	880	kw
Maximum Heat-to-Electric Power Ratio	1.346154	
Minimum Heat-to-Electric Power Ratio	0.7	
Baseline Heat-to-Electric Power Ratio for Fixed Heat-to-Pow	0.7	
Natural Gas Fuel Consumption (in Units of Energy) Per Unit of Electric Power Output	6,824	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	50%	
Baseline System Heat Recovery Efficiency	35%	
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%	

Molten Carbonate Fuel System (MCFC) system vs. CHP combined cycle gas turbine (CCGT) examined here.

Model describes the financial and operating 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 1000 kW Fuel Cell System	$ 3,200,000	$789,157
Installation Costs	$ 1,000,000	$246,611
Commissioning Costs (Start-up, Testing, Tutorials for Operators)		$ -
Shipping	$ 100,000	$ 24,661
Premium Service Contract (Maintenance and Replacement) -- Annuity Payments		$400,000
Fuel Cell System Incentives -- Federal and State		
California Self-Generation Incentive Program (CA SGIP) at $2500/kWe	$ 2,500,000	$616,529
Federal Investment Tax Credit (FITC) at $1000/kWe	$ 1,000,000	$246,611
Fuel Cell System Fixed Costs -- Total Yearly Fixed Costs		**$597,289**

Competing Generator: Natural Gas Combined Cycle Gas Turbine Plant		
Cost of steam for heating	0.056	$/kWh steam
Cost of electricity	0.085	$/kWh electricity
Baseline System Heat Recovery Efficiency	0.22	
Baseline System Electrical Efficiency	0.40	
Baseline System Heat Losses	0.38	

Molten Carbonate Fuel System (MCFC) system vs. CHP combined cycle gas turbine (CCGT) examined here.

Model investigates 12 novel operating strategies.

Strategy	Electrically and Thermally Networked (N) or Stand Alone (S)?	Variable Heat-to-Power Ratio (V) or Fixed Heat-to-Power Ratio (F)?	Primary Control: Electricity Power Load Following (E), Heat Load Following (H), or No Load Following (EX)?	Secondary Control: Electricity Power Load Following (E), Heat Load Following (H), or No Load Following (HN, HX, EN, EX)?
1	S	F	EX	HN
2	S	V	H	E
3	S	V	EX	H
4	N	F	E	HN
5	N	F	E	HX
6	N	F	EX	HN
7	N	F	EX	HX
8	N	V	H	EN
9	N	V	H	E
10	N	V	E	H
11	N	V	H	EX
12	N	V	EX	H

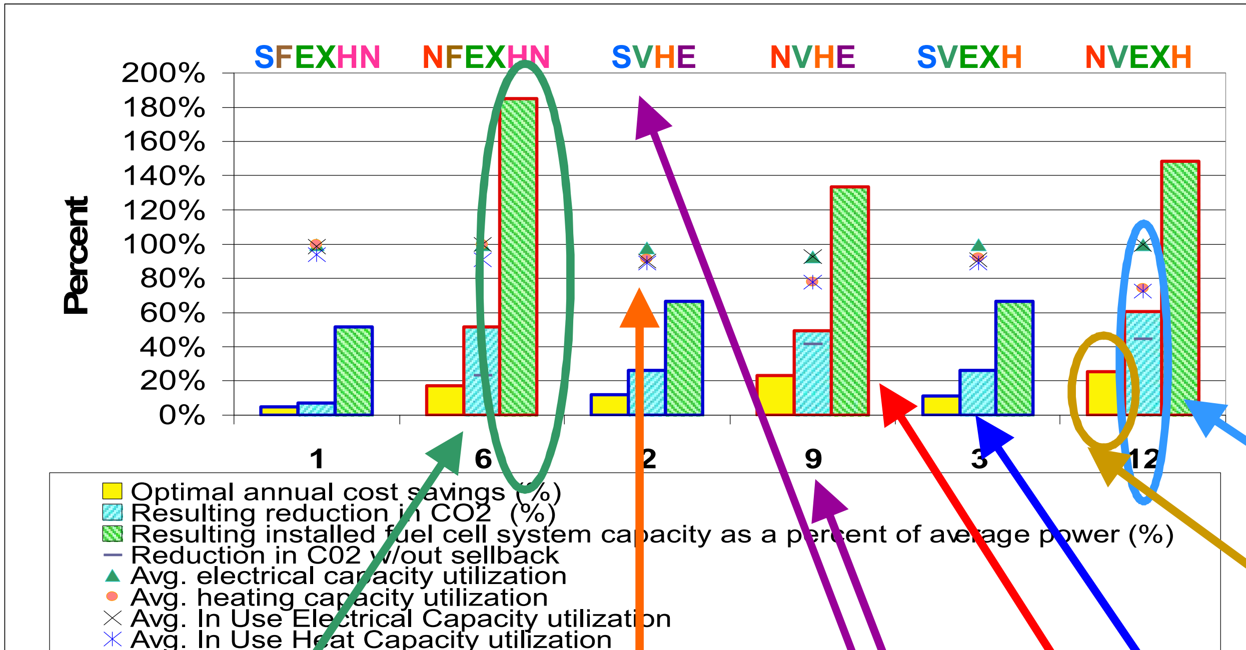
Most FCS are now installed as Strategy 1 [SFEXHN]

Model analyzes a range of incentives & carbon taxes

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

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 & heating costs (no fuel cells) = \$40 million/yr
Networked model is able to sell back to grid at purchase price
Cost of capital ® = 7.42% = educational borrowing rate
Fuel cell turn-key cost (without incentives) = \$4,300/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

Highest Blue = "blue skies", lowest CO_2

Highest yellow = highest energy cost savings for building owners

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

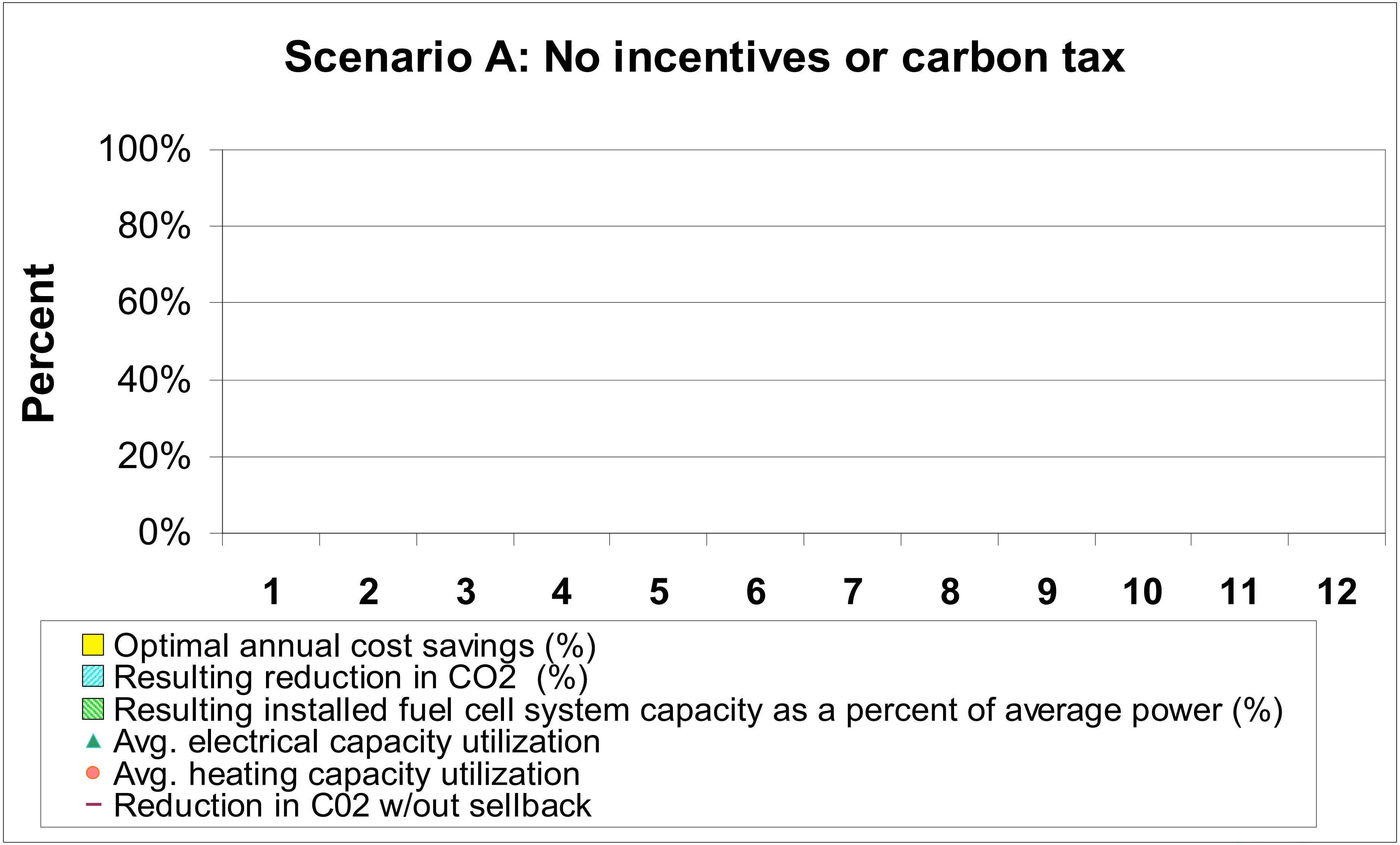
Blue outline is stand alone

Red outline is networked

Strategy name and number

- ● Heat capacity utilization
- ▲ Electrical capacity utilization
- * In use heat capacity utilization
- X In use electrical capacity utilization

Fuel cell systems are not economical without <u>incentives</u> under any strategy



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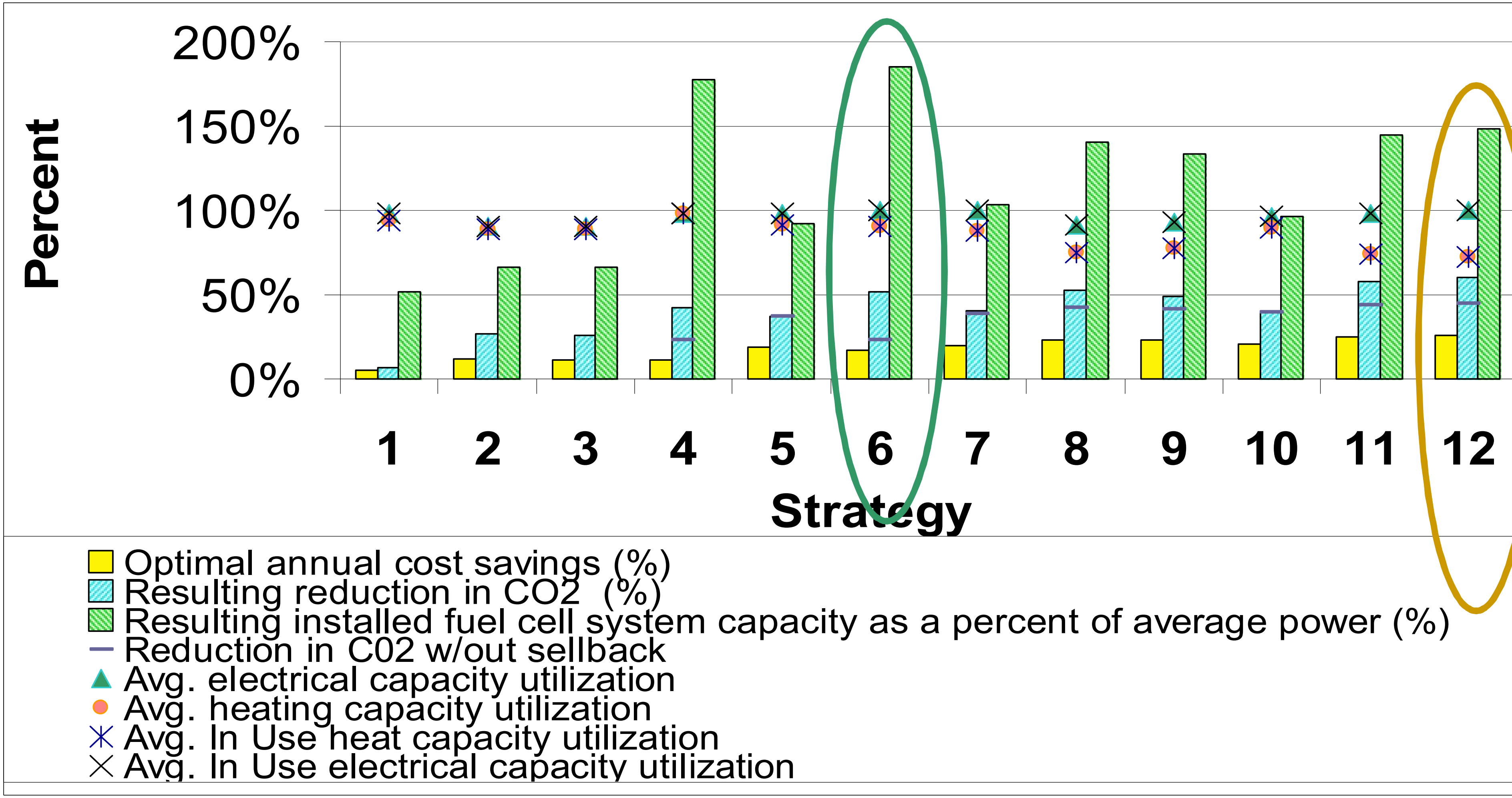
Optimal strategies differ for cost savings and profit



Strategy 12 [NVEXH] = *novel* = most cost savings; **excess thermal capacity, a larger number of units than needed for heat demand**

Strategy 6 [NFEXHN] = *plain vanilla* = most revenue/sales/ profit

Results for Scenario D: full incentives, $\$100/MTCO_2$

Optimal strategies differ for cost and CO_2 savings

Strategy 12 [NVEXH] = *novel* = most cost savings

Strategy 11 [NVHEX] = *novel* = most CO_2 reduction

Results for Scenario D: full incentives, $100/MTCO_2$

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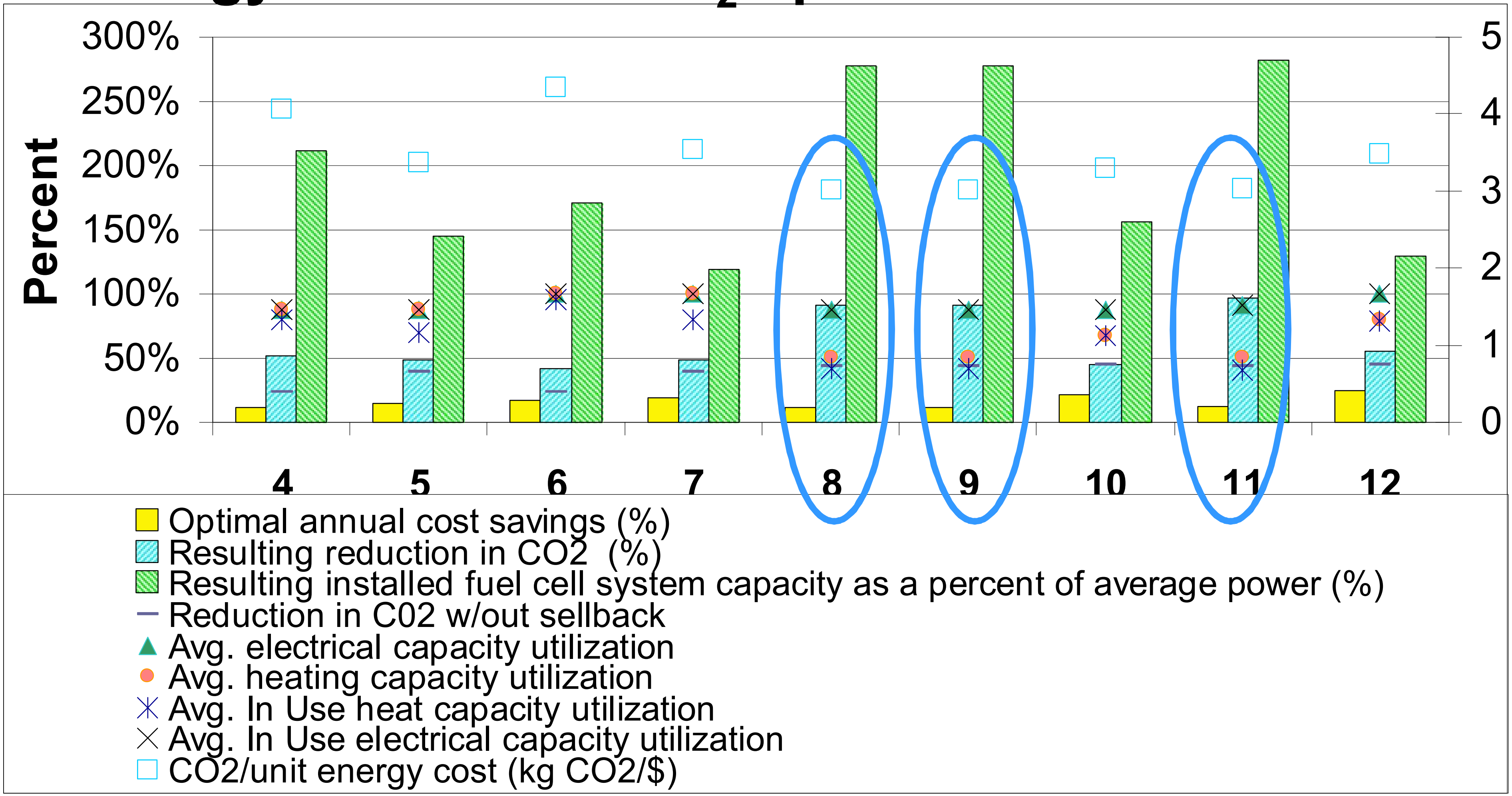
Optimal strategies for minimizing CO2 per unit energy cost mirror CO_2 optimum.



Strategies 11 [NVHEX], 9 [NVHE] and 8 [NVHEN] = *novel* = most CO_2 reduction/unit cost, HLF maximize fuel utilization

Results for Scenario D: full incentives, $100/MTCO_2$

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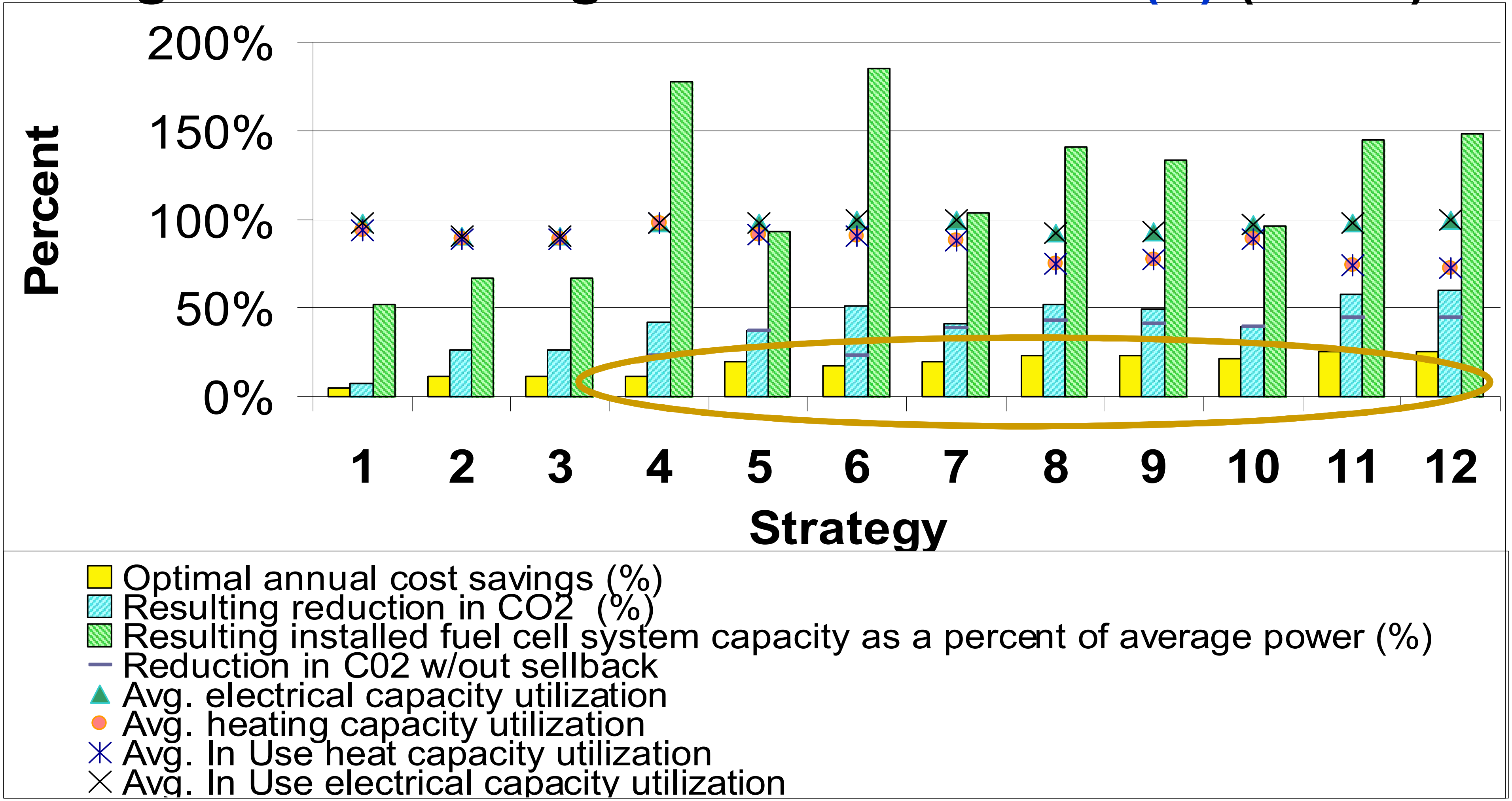
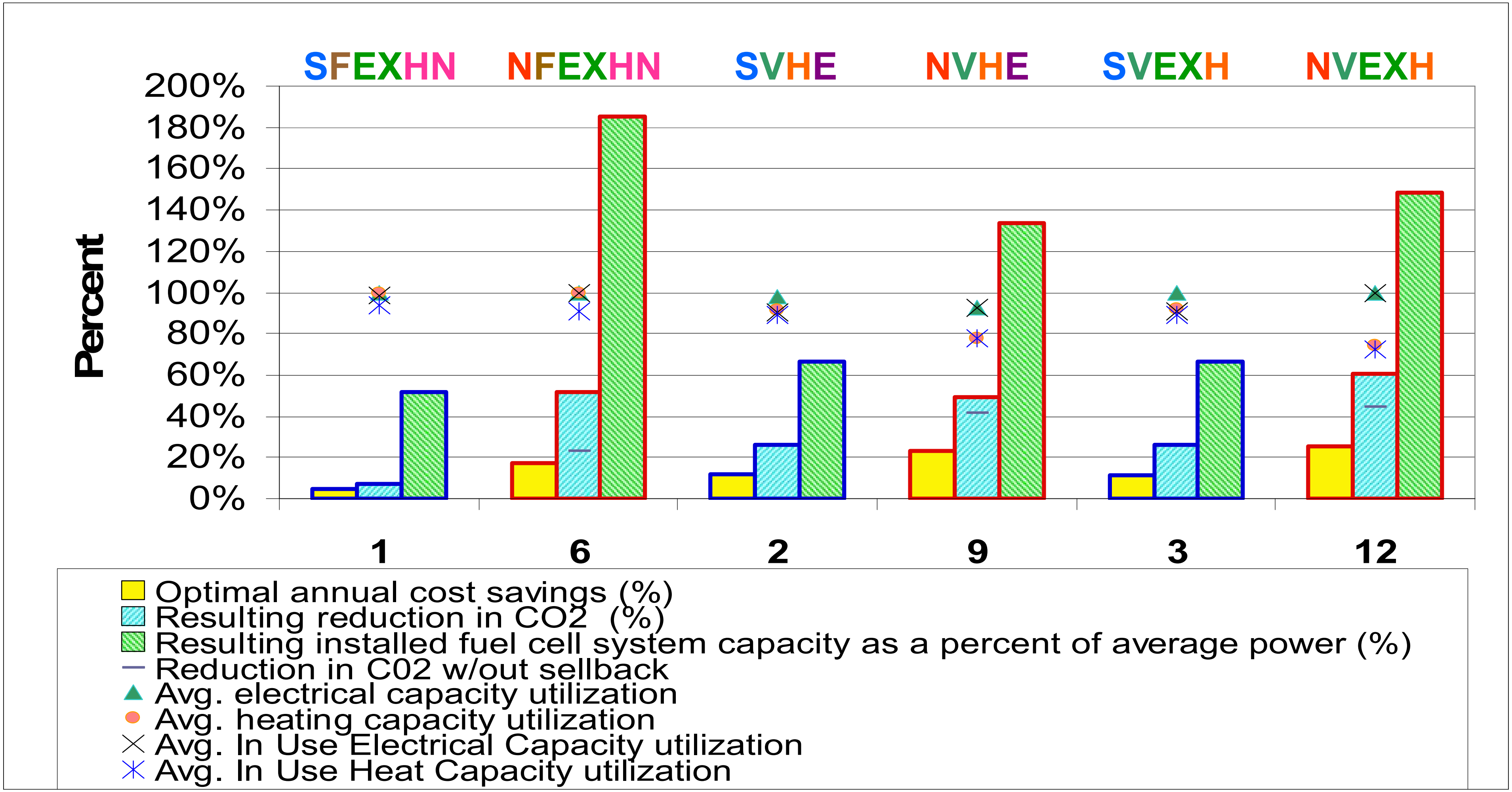
Optimized for cost, networked (N) (4 to 12) shows higher cost savings than stand alone (S) (1 to 3)



Exceptions are at lower incentive levels for Strategies 4 [NFEHN] and 6 [NFEXHN], that are N but F and minimum heat.

Results for Scenario D: full incentives, \$100/MTCO_2

For the same configuration, optimized for cost, networked has higher cost savings than stand alone



Networked can install a larger number of systems while maintaining a high fuel cell system capacity factor.

Results for Scenario D

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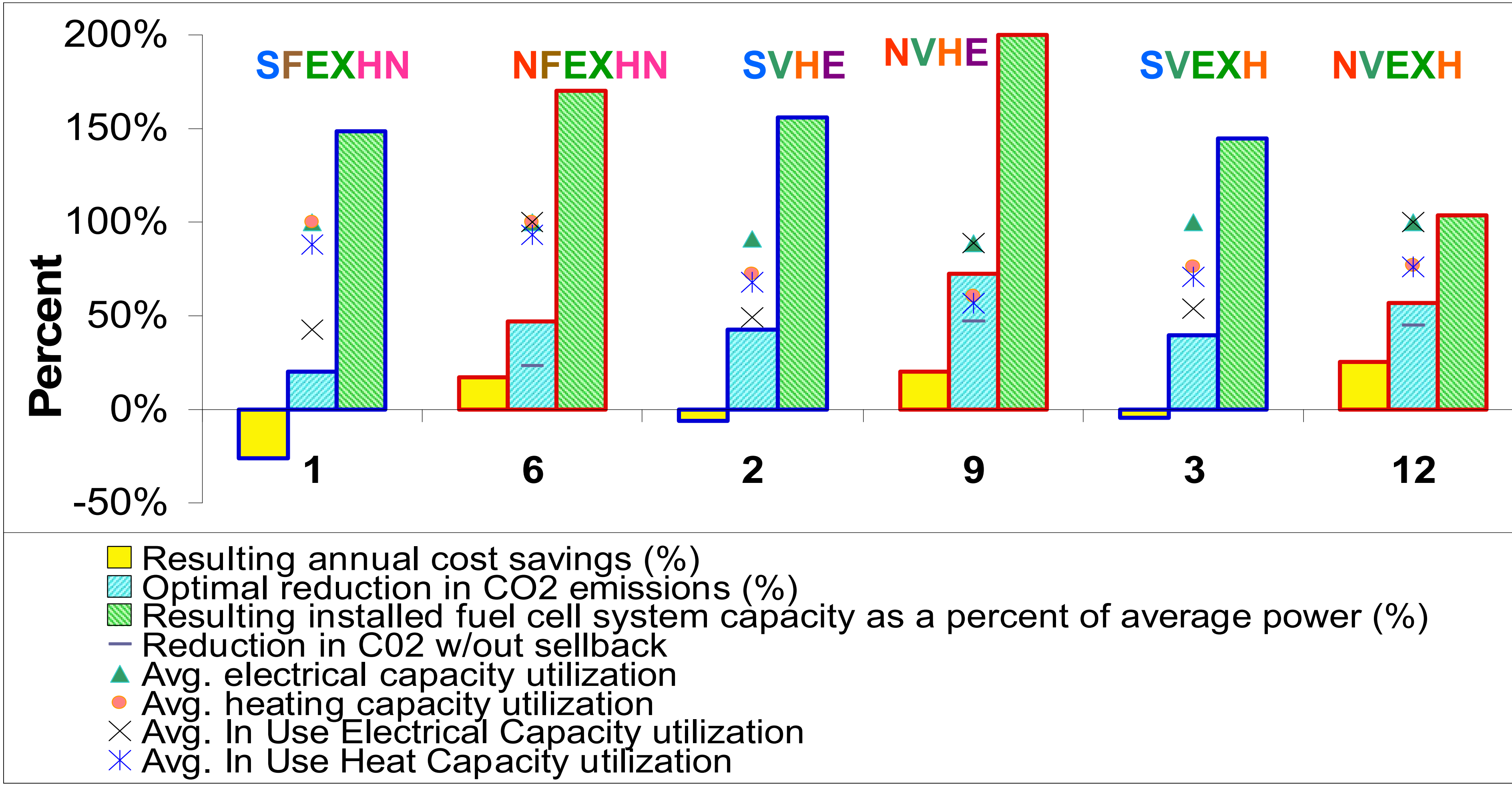
For the same configuration, optimized for CO_2, networked has higher CO_2 savings than stand alone



CO_2 difference between N and S is the displaced CO_2 from selling electricity back to the grid. Ignoring this, N achieves same CO_2 as S at much lower cost.

Results for Scenario D

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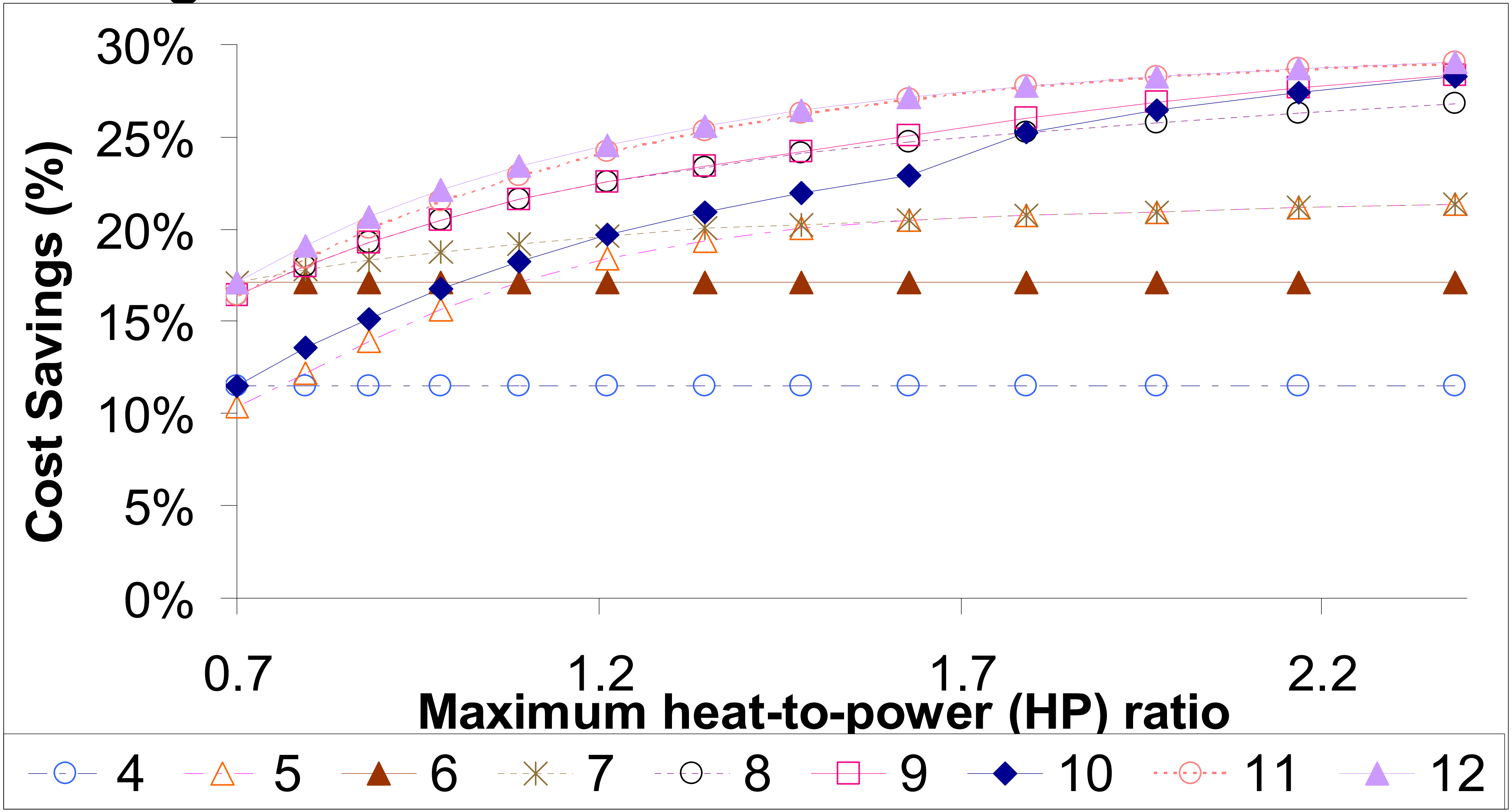
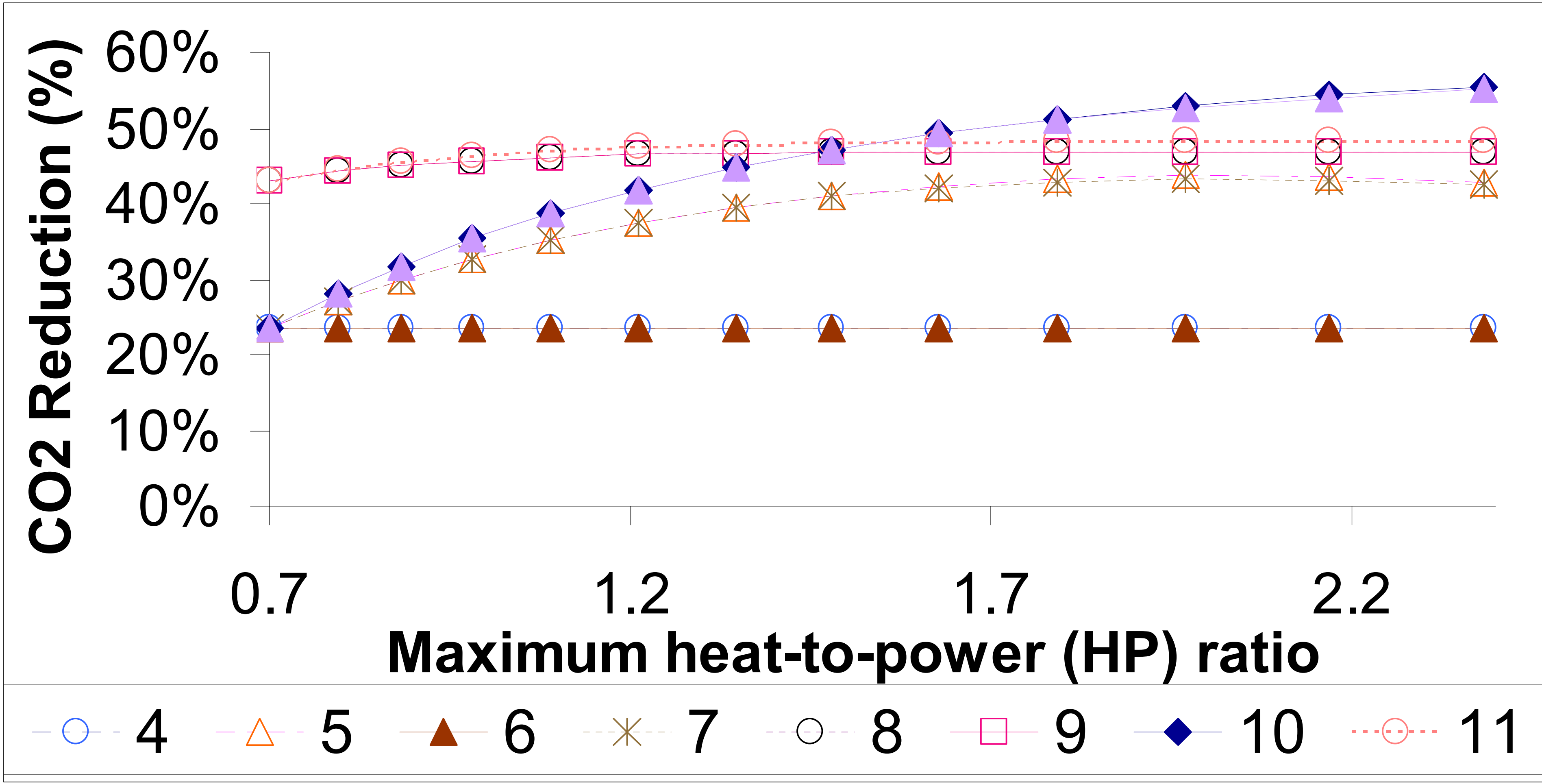
Variable heat-to-power ratio (VHP) has higher cost savings than fixed above a certain maximum VHP



Largest gain in cost savings with initial increase in VHP, as VHP meets a larger percent of heat demand.

Results for Scenario D, cost optimization

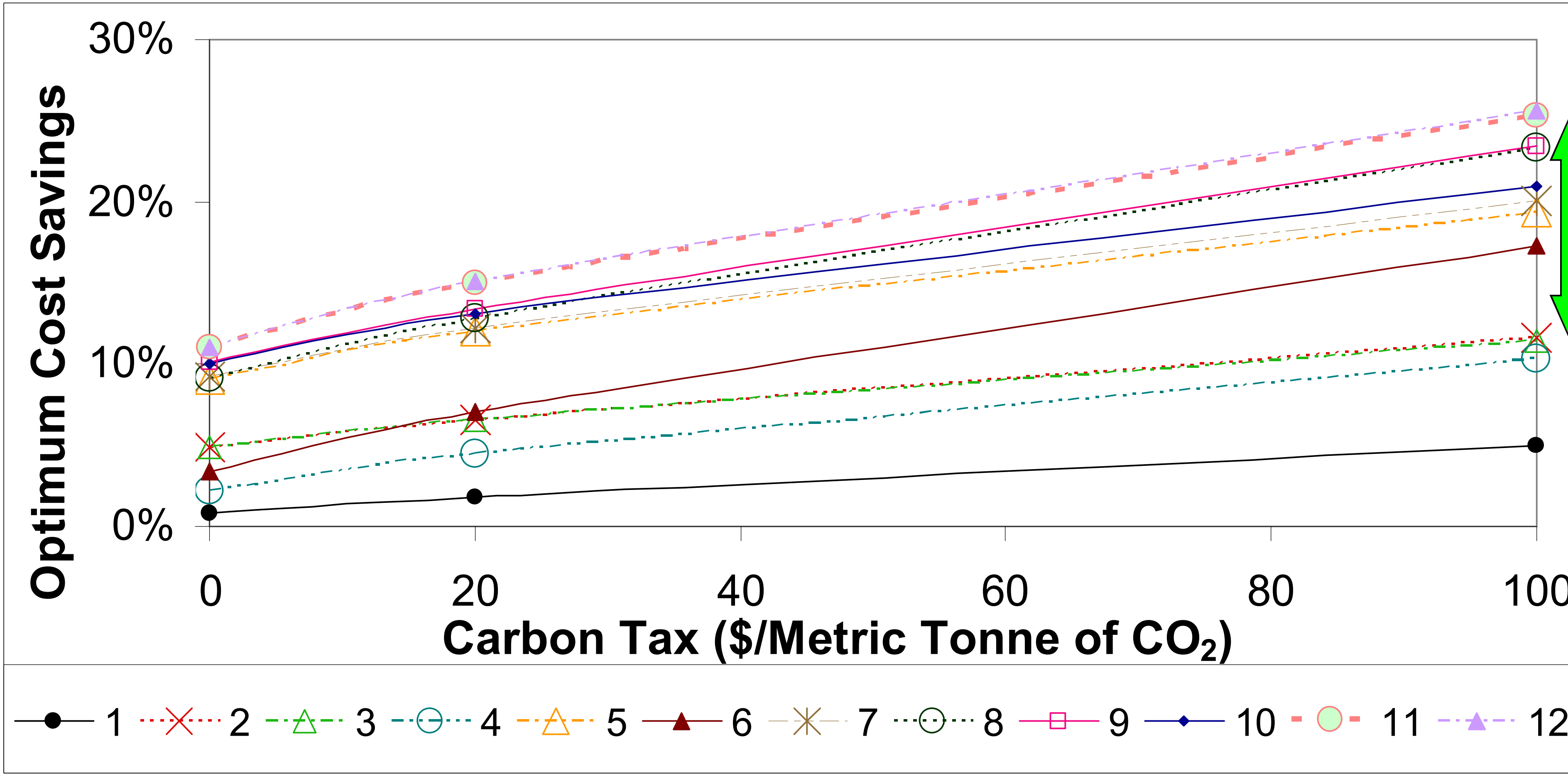
Variable heat-to-power ratio (VHP) has higher CO_2 reduction than fixed



Largest gain in CO_2 reduction with initial increase in VHP, as VHP meets a larger percent of heat demand.

Results for Scenario D, CO_2 optimization

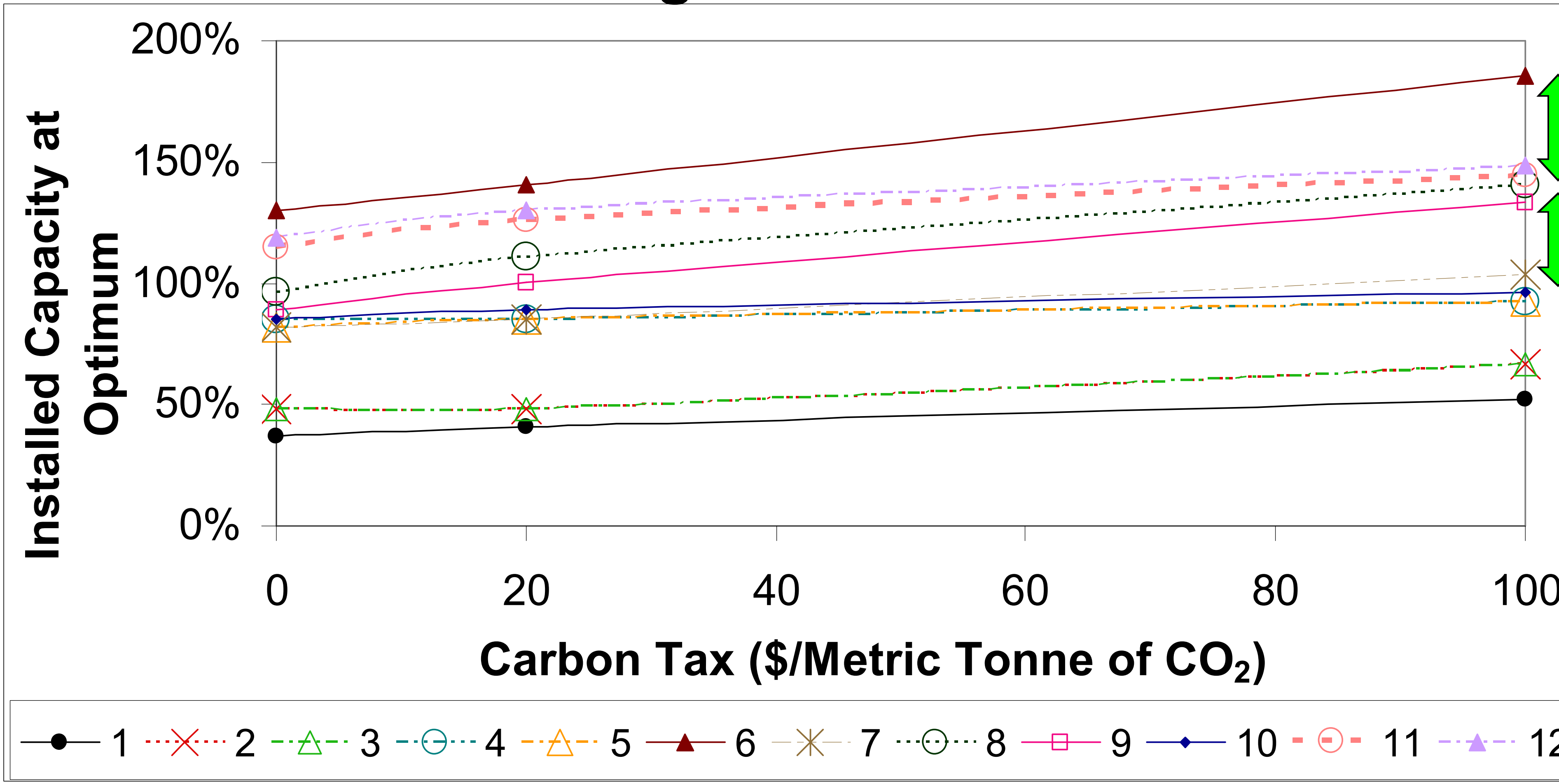
Changing to novel strategies can improve energy cost savings more than increasing the carbon tax.



The marginal increase in cost savings with increasing carbon tax is greater for novel strategies (Strategies 11 [NVHEX] & 12 [NVEXH] = most cost savings)

Results for cost optimization

Changing strategies can increase installed capacity more than increasing carbon tax.



Strategies 6 [NFEXHN], 8 [NVHEN], 9 [NVHE] see greatest increase in installed capacity due to grid sell-back.

Greater installed capacity increases mass-production economies of scale & reduces manufactured cost. Results for cost optimization.

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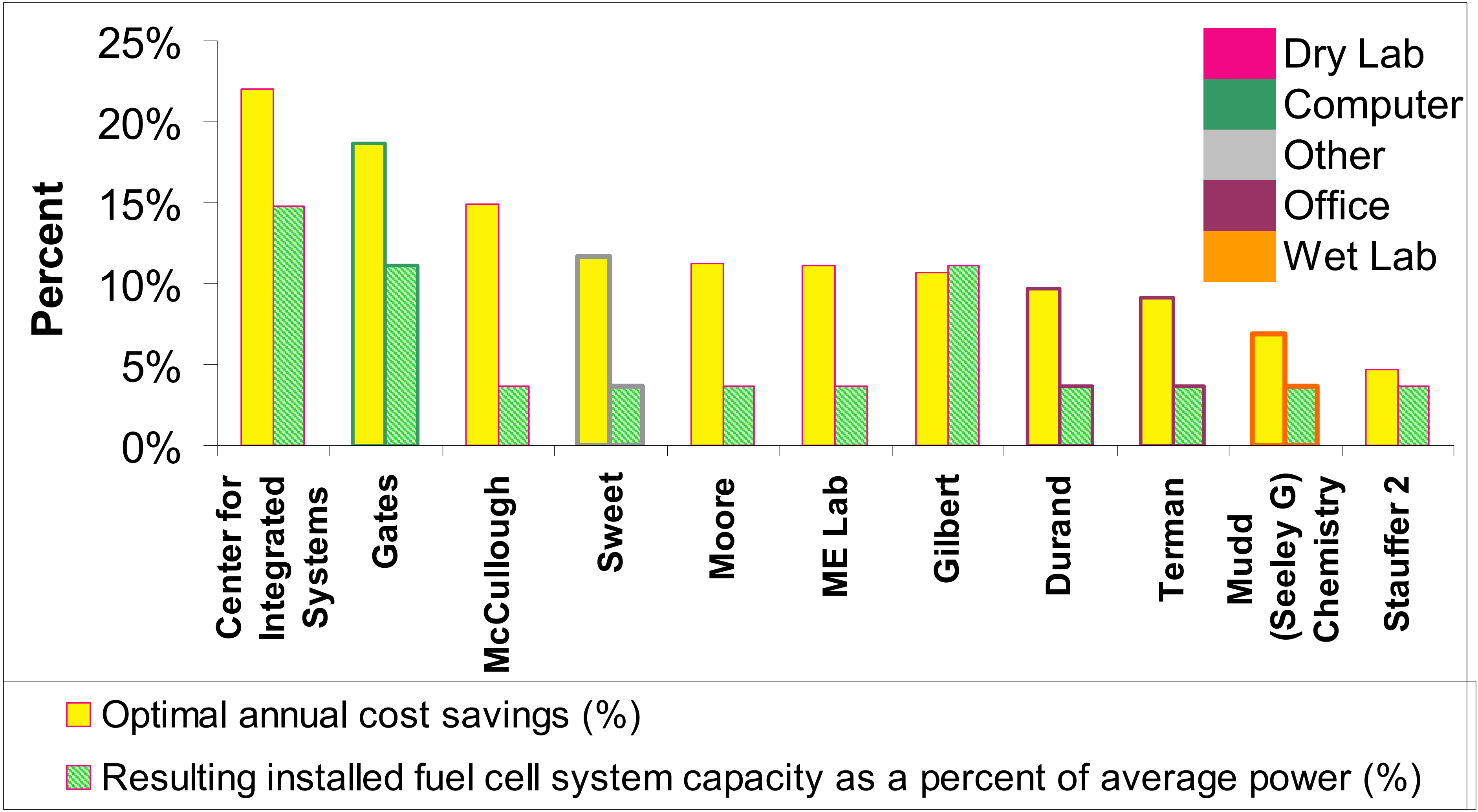
Load curve shape impacts installation economics. Stand alone units are best installed in dry labs.



The building with the most savings, most revenue is CIS. Buildings best for installation may change with strategy & load curve.

 Results for Scenario D, Strategy 2, cost optim (1&3 similar)

Results

1. FCS are not economical without incentives
2. No one strategy achieves all economic and environmental goals under all scenarios
3. Different strategies achieve diverse goals of cost savings to building owners, high fuel cell manufacturer sales, and CO_2 emission reductions
4. The environment sees the highest CO_2 reductions and building owners get the highest energy cost savings by switching to novel strategies:
    1. Switching from stand alone (S) to networked (N).
    2. Followed by going from fixed (F) heat-to-power rato to variable (V).
    3. When already NV, load following has little impact, assuming constant energy prices over time.

Results

1. Changing to novel strategies can improve energy cost savings and installed capacity as much as or more than increasing the carbon tax.
2. The environment sees higher CO2 reductions and building owners get higher energy cost savings by combining a carbon tax with certain novel strategies.
3. Maximum financial savings with particular load curves –dry labs ~ 24-7 industrial facilities

Recommendations for R&D

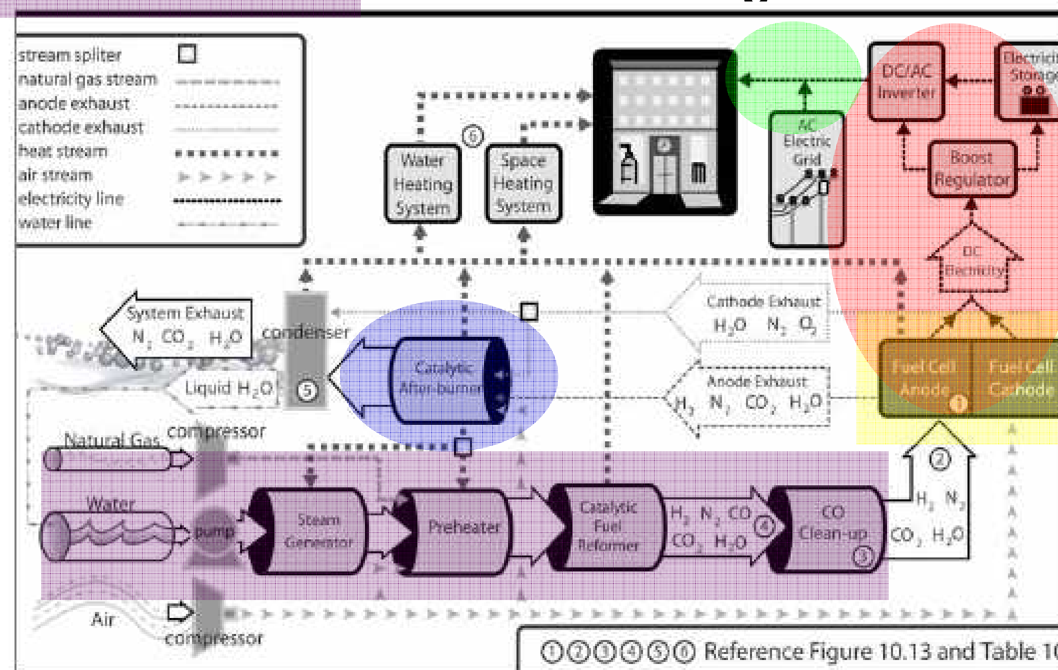
1. Enhance VHP capability
   1. Operate the reformer as SR, POX, and/or AR by changing S/C to change the net heat released
   2. Expand operating range of the anode off-gas burner
2. Develop FCS that are more durable under rapid changes in electrical and thermal load.
   1. Fuel cells coupled to storage devices
   2. Increased cell durability under rapid cycling
3. Further develop and apply simulations of complex energy systems using technical-economic models (Science article: Whitesides, 2007.)
   1. Model the incentives of users, manufacturers, and environment & test methods for aligning them

Variable heat-to-power ratios can be achieved with different component or system-level designs

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.

Operate the reformer as SR, POX, and/or AR by changing S/C to change the net heat released

- **One reformer design capable of SR, POX, and AR**
- **Catalyst combo suitable for all**
- **Catalyst durable under rapid thermal cycling**



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

Expand operating range of the anode off-gas burner

- **Mitigate temperature limitations of catalysts & materials**

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

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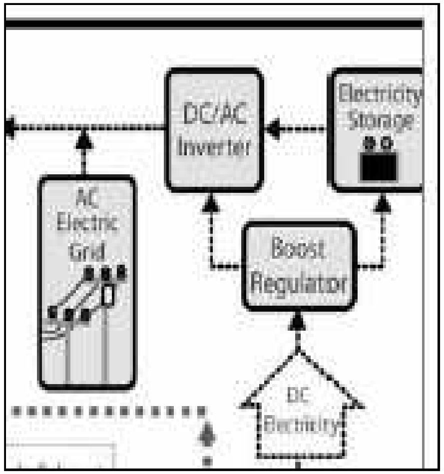
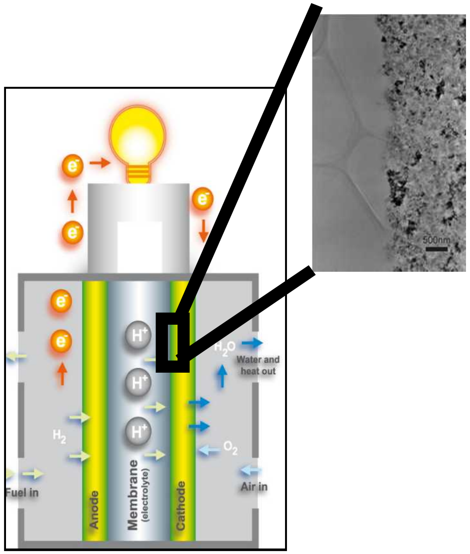
Electricity load following needs 1) hybrid design with electric storage or 2) better understanding of degradation mechanisms in cell under cycling



Hybrid design with batteries and capacitors for electrical storage

Although hybrid designs pass on a more level load to the fuel cell, this approach is improved with an increased understanding of cell cycling limitations



More durable catalysts for load cycling

Better understanding of degradation mechanisms under rapid load cycling leading to shorter lifetimes

Better understanding of the effect of steady vs. dynamic load on cell lifetime

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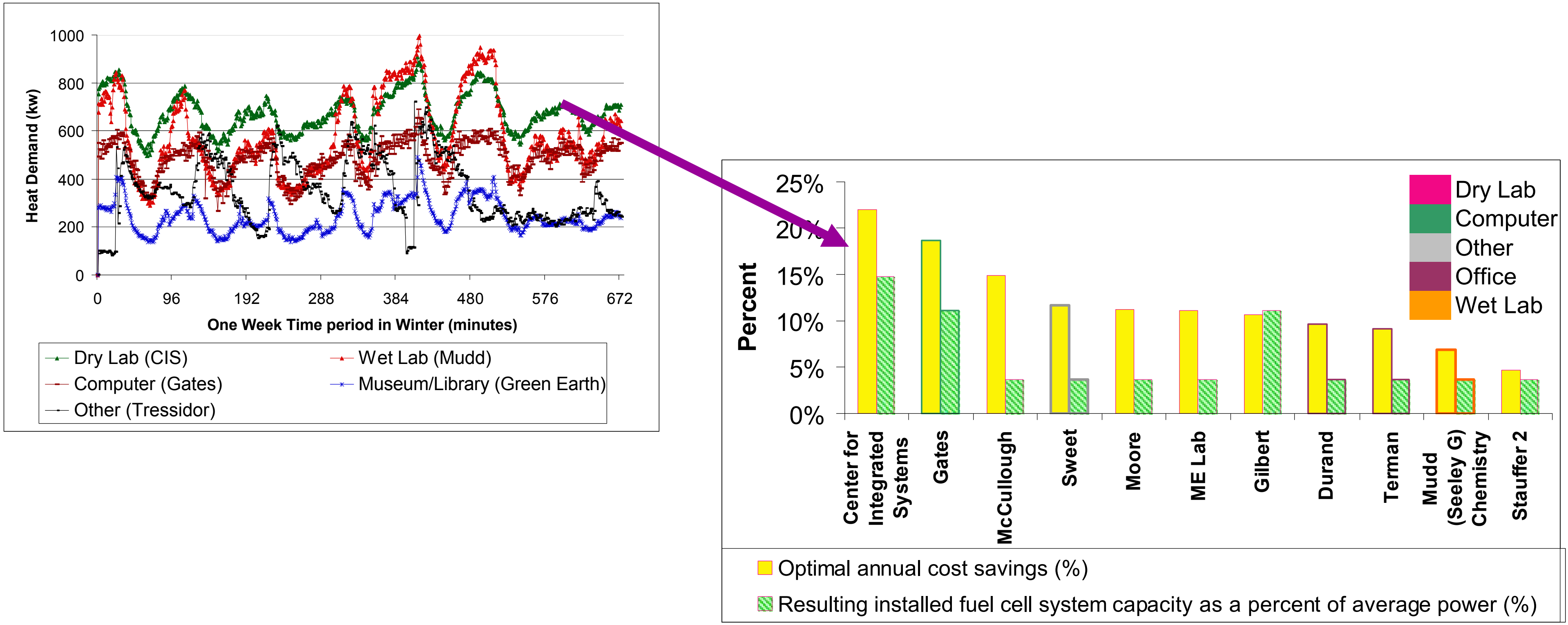
Develop and apply simulations to identify specific building load curves ideal for installation



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

Aerel Rankin and Melahn Parker are university students who contributed to this work.

Aerel Rankin is a senior mechanical engineering student at the University of Washington. His educational focus is on the engineering of sustainable energy devices.

B.S. in Mechanical Engineering (Expected 2009)

Melahn Parker is studying for his engineering PhD at Stanford University. He has five years of academic experience in clean energy. He is the teaching assistant for Fundamentals of Renewable Energy Processes (EE 293).

B.Sc. Aeronautics, B.Sc. Chemical Eng. MIT 2000, M.Eng. Aerospace Eng. MIT 2001, M.Sc. Chemical Eng. Caltech 2003, Ph.D. Aeronautics Stanford (Expected 2009)

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University of California at Berkeley

- Professor Daniel M. Kammen

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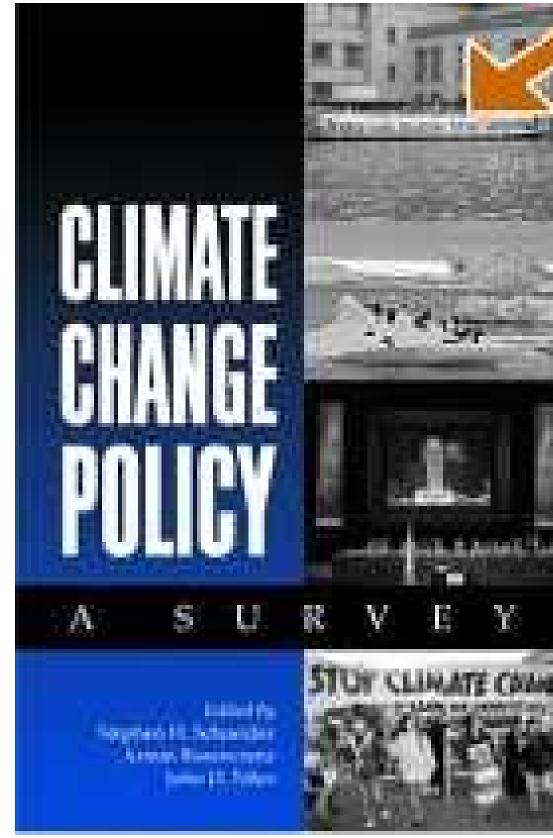
Publications

Climate Change Science and Policy educates policy makers and engineers on hydrogen and climate



"**Designing Energy Supply Chains Based on Hydrogen** [To Mitigate Climate Change]," by W. Colella

Editors are Stanford University researchers: Stephen H. Schneider, Armin Rosencranz and Michael D. Mastrandrea

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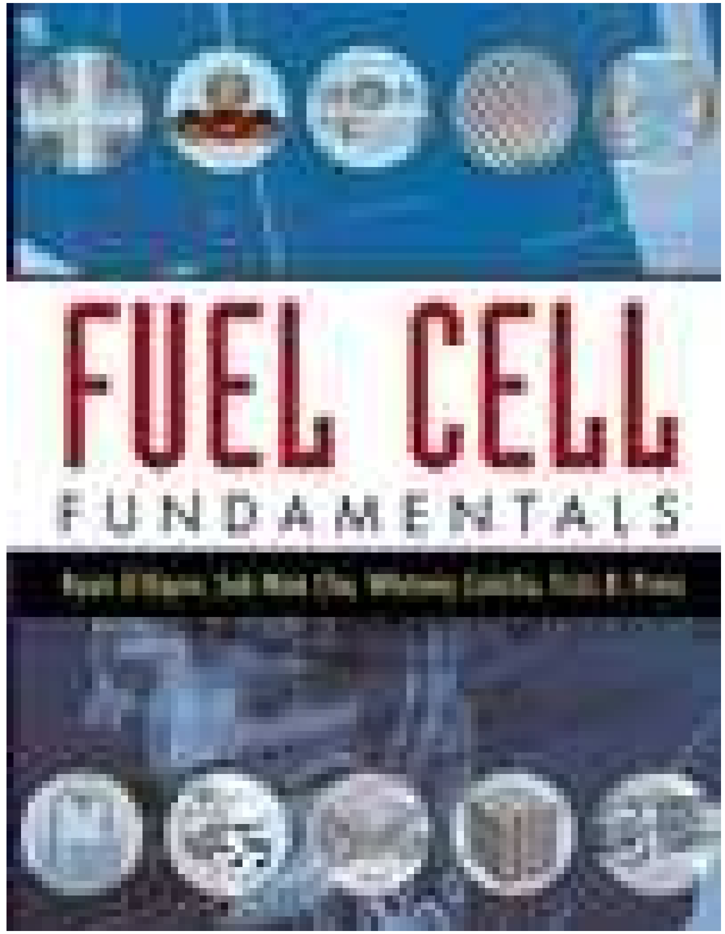
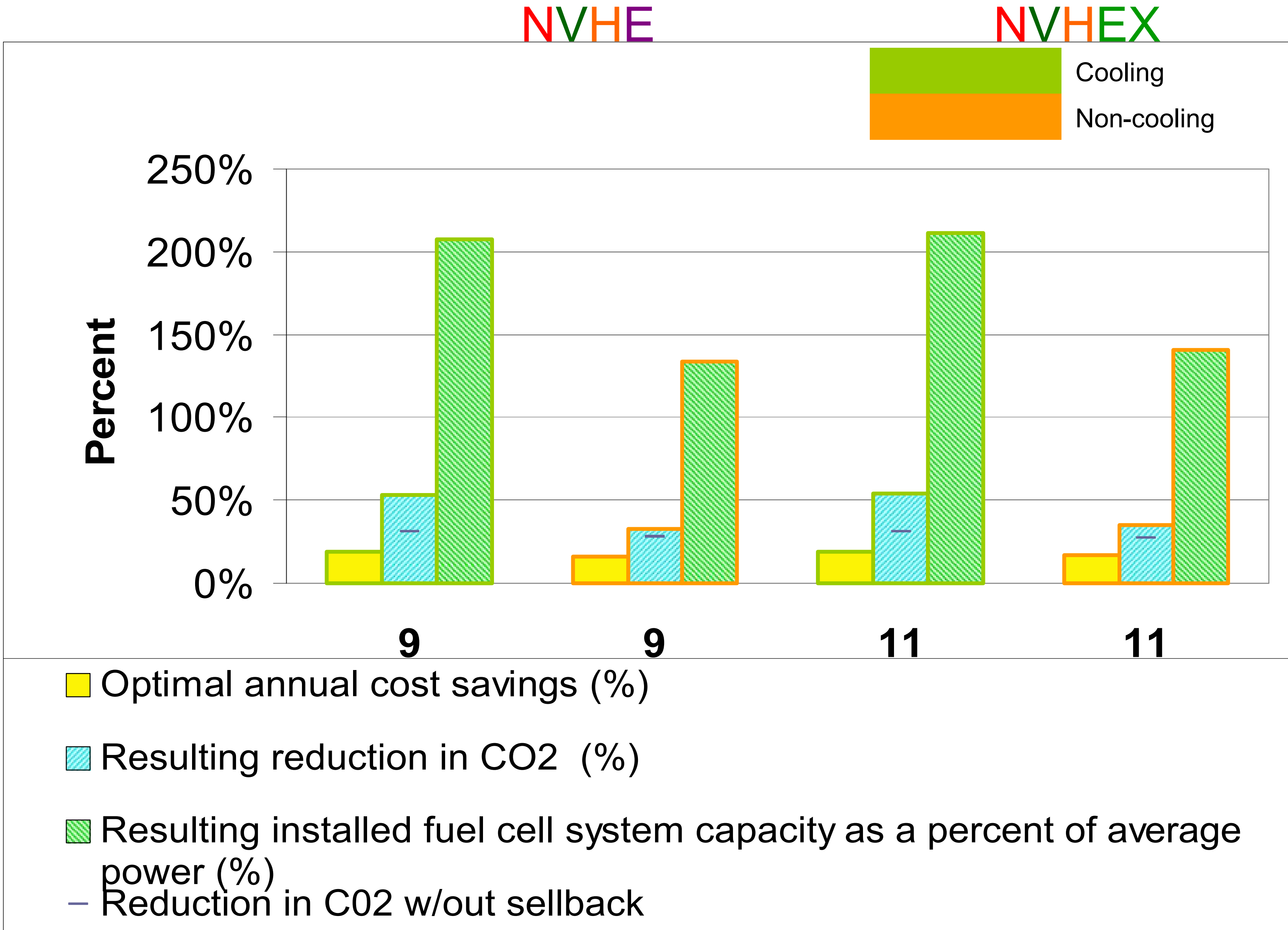
Fuel Cell Fundamentals educates engineers about fuel cells



This book is the first textbook on fuel cells, and includes solved problems and a solutions guide. The authors were Stanford researchers. The target audience is engineering students, senior undergraduates or graduate students.

Next Steps

For the same operating configuration, cooling has higher energy cost savings and CO_2 reduction



Thank You

Extra Slides

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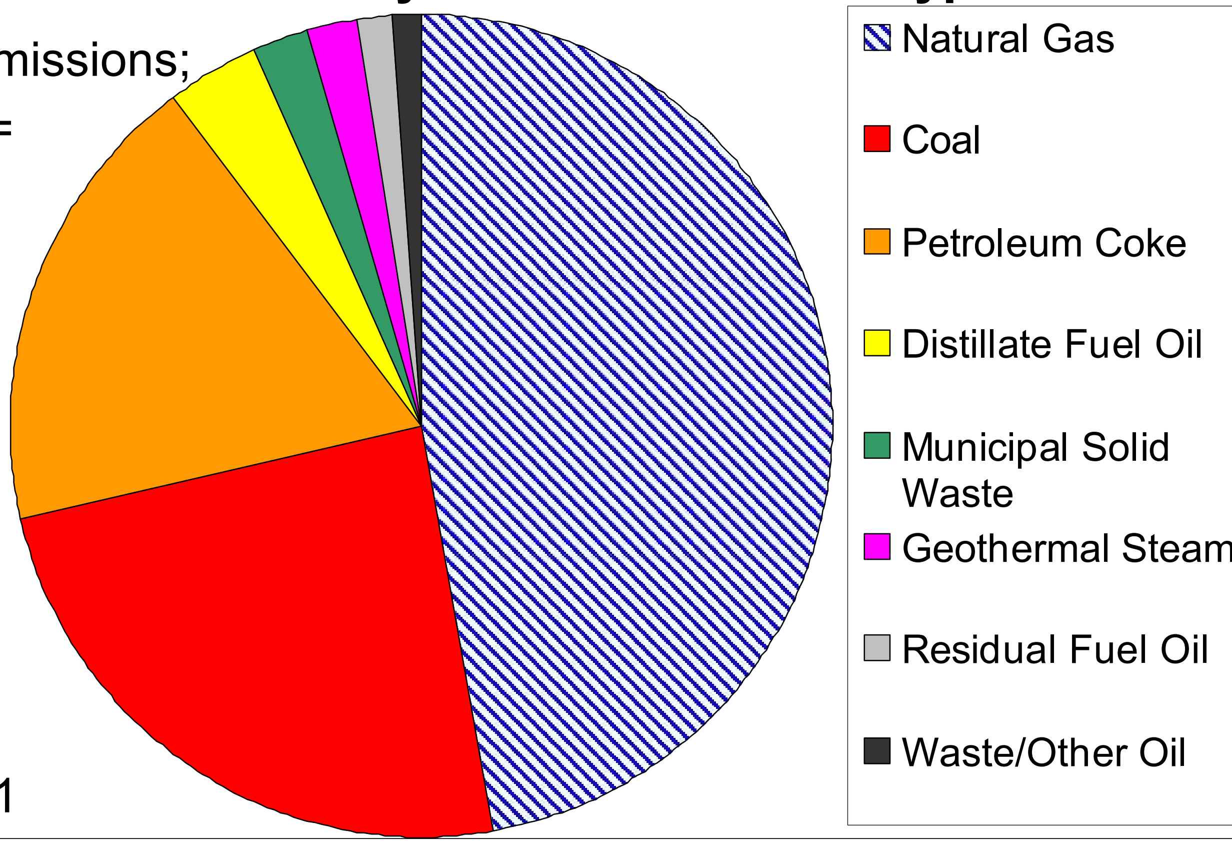
State data excludes CO_2 from coal, coke, oil, non-fossil fuels; re-allocates or omits cogen

Fraction of the Discrepancy between DOE and CEC CO_2 Data Allocated by Power Plant Fuel Type

Solid coloring = omissions; hatched shading = inconsistencies;



Data for year 2001

We conclude Federal data is a more complete baseline.

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

(using the updated baseline emissions to eliminate discrepancies)?

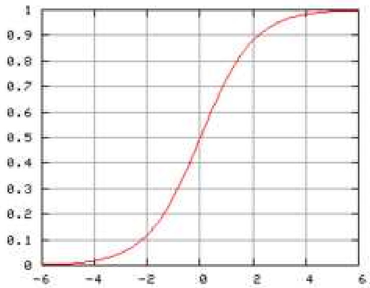
12 Scenarios: Change in CO_2 with Fuel Cell Systems

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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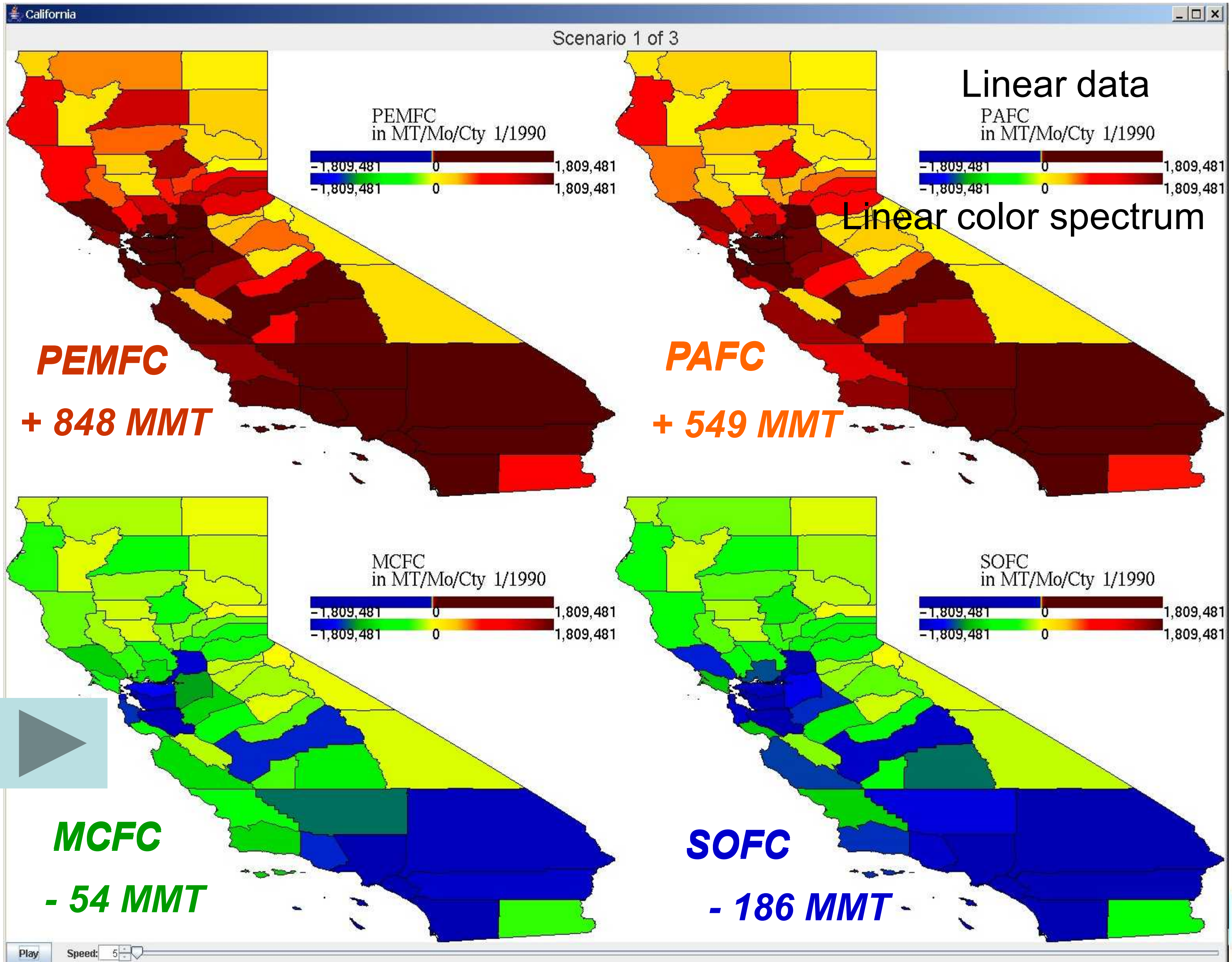
Fuel Cell Systems Replace 100% of Power



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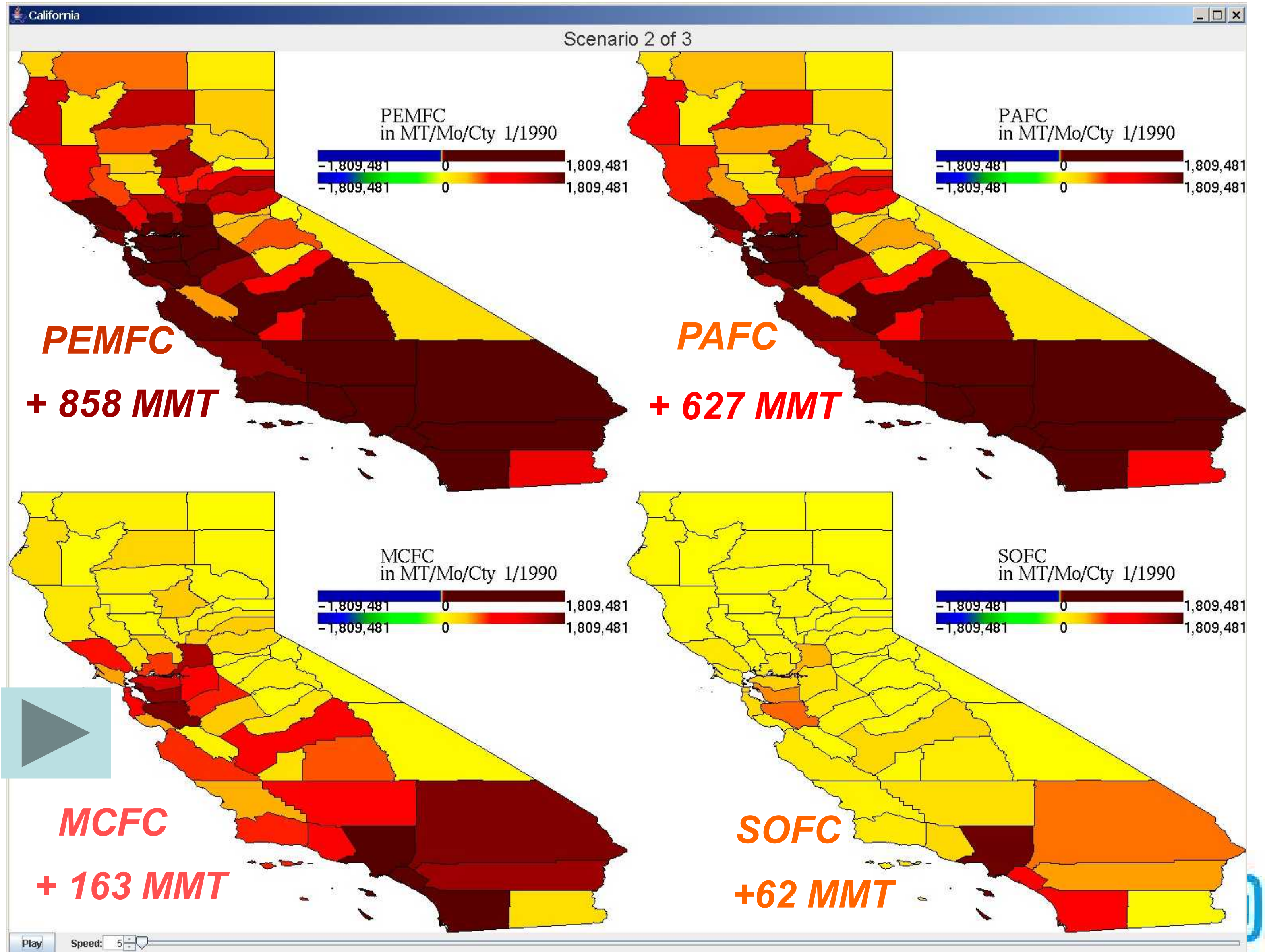
Fuel Cell Systems Replace In-State Power Only



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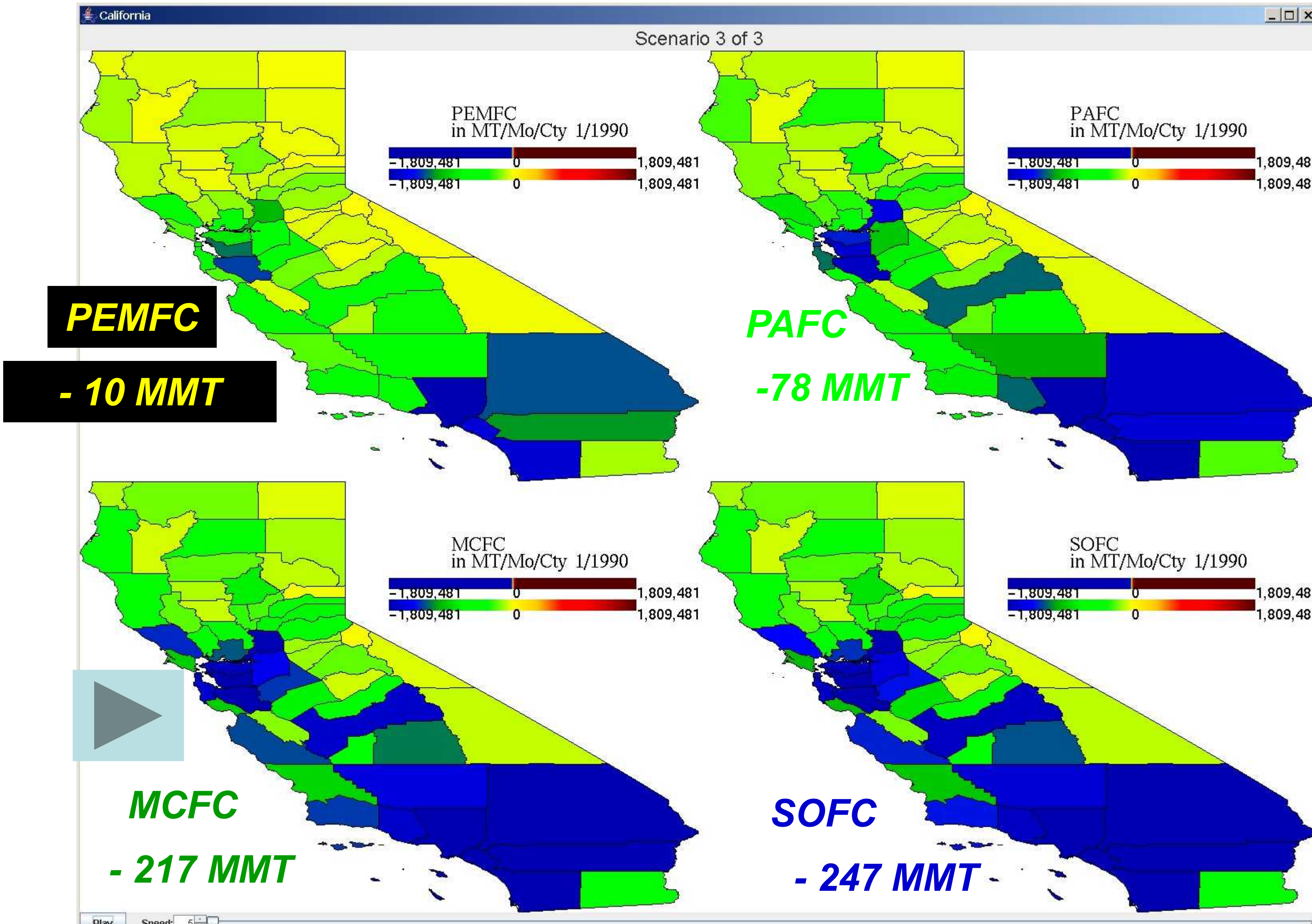
Fuel Cell Systems Replace Imported Power Only



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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**

Future Add cooling to analysis

Cogenerative fuel cell systems fueled by natural gas can create 1/3rd the CO_2 as conventional systems, if they are designed to recover heat and with high end-use capacity utilization. They make no CO_2 if fueled by renewable H_2.

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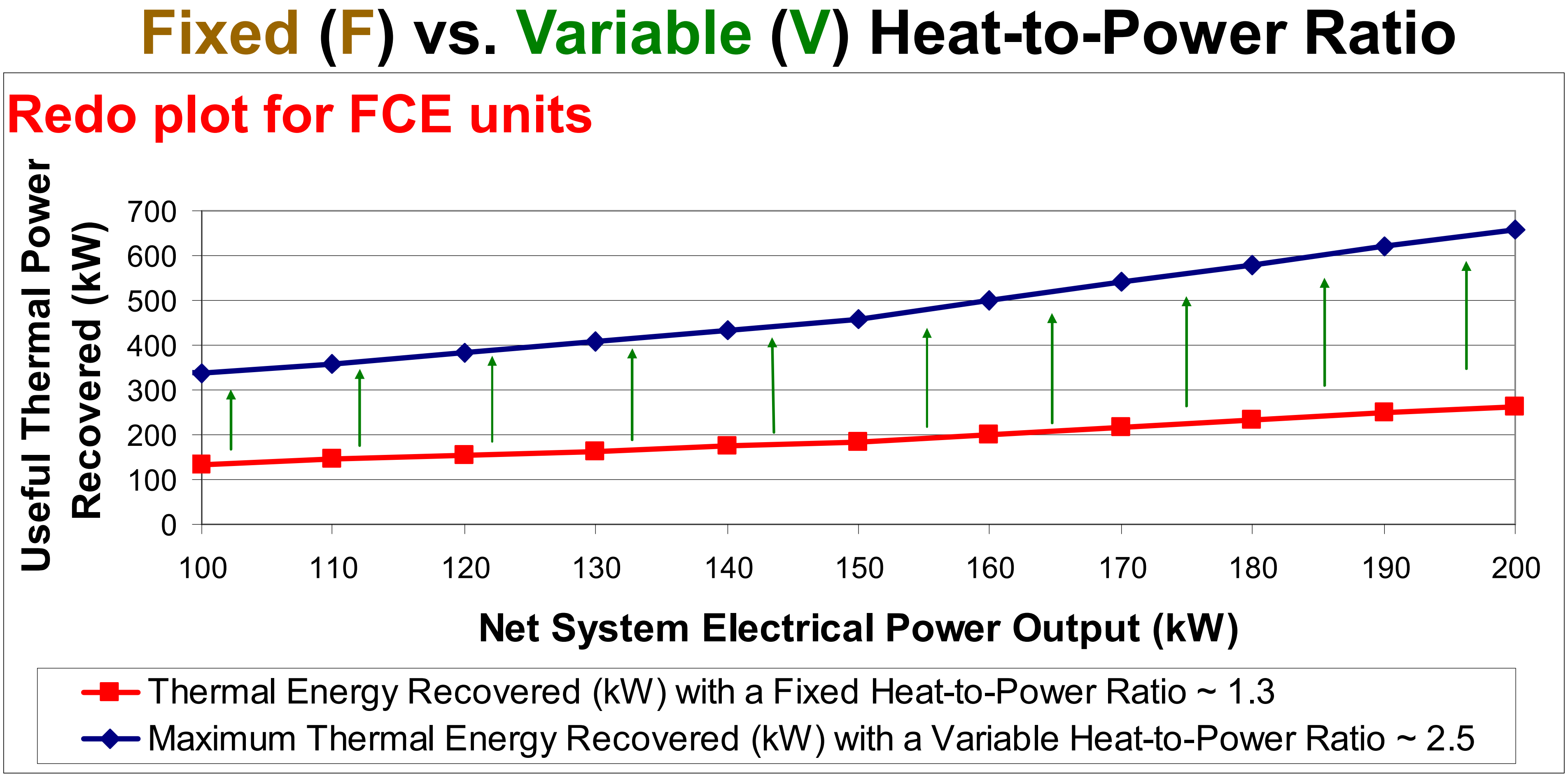
Systems can be configured with a fixed or a variable heat-to-power ratio



Variable heat-to-power ratio increases system operating range

Systems can be installed stand alone or networked

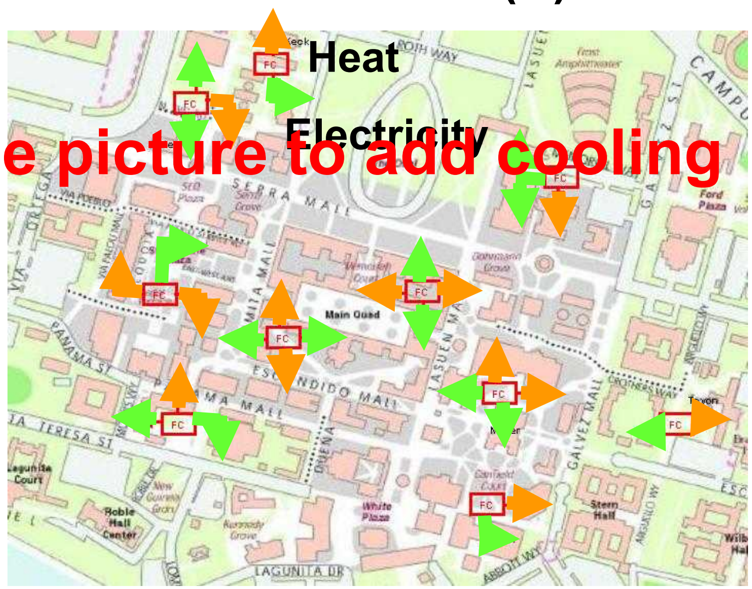
Electricity

Heat

stand alone vs. networked

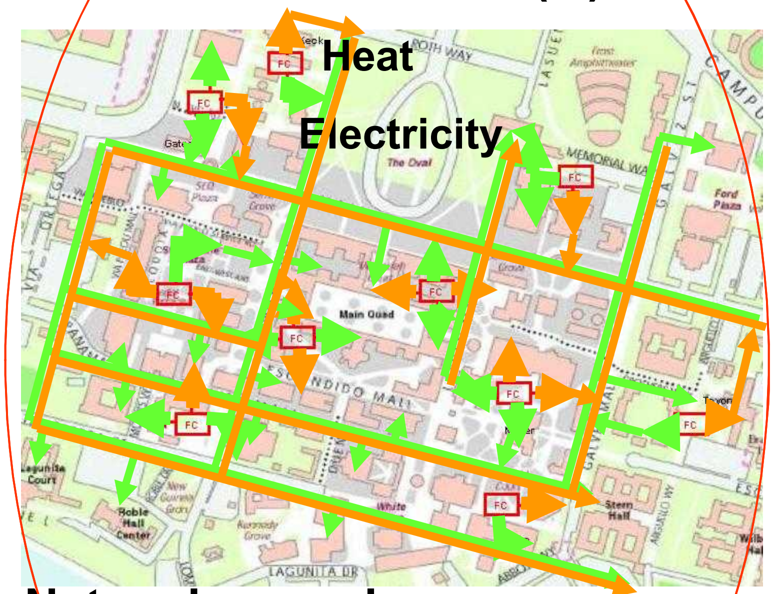
Change picture to add cooling

stand alone (S)



Fuel cells can NOT convey or sell excess heat or electricity into the distribution grid to reach other buildings. One system serves only one building. Buildings can import additional heat and electricity. FuelCell Energy currently installs its units this way.

networked (N)



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

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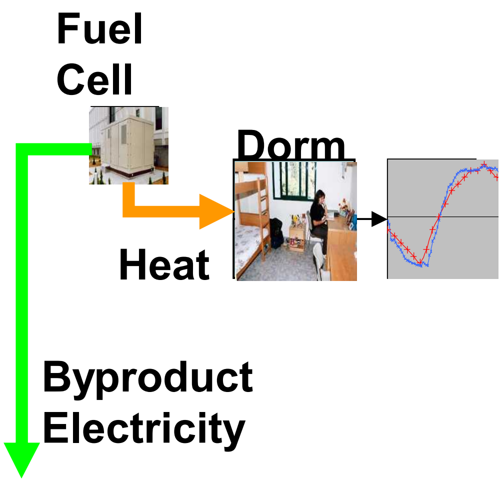
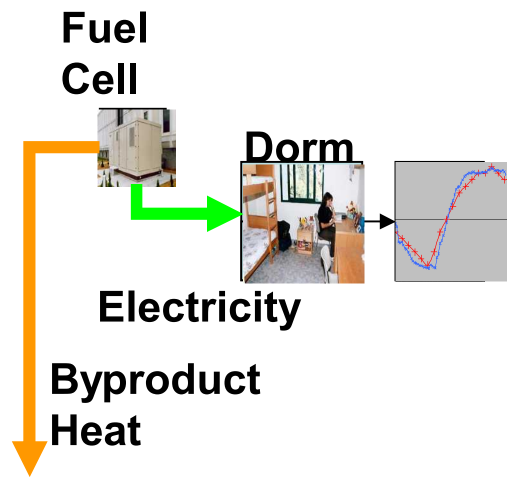
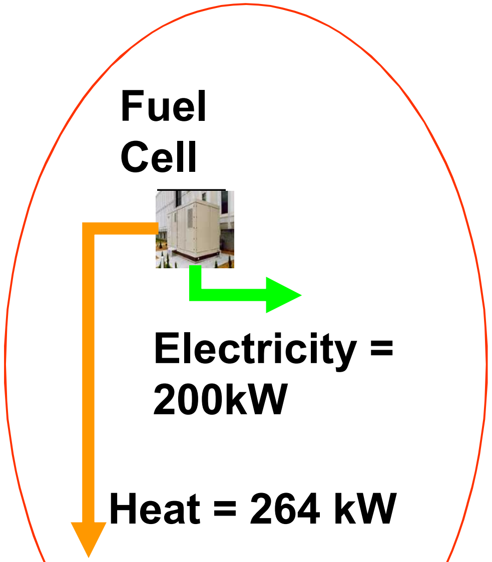
Systems can be configured as heat load following, electricity load following, or no load following

Change picture to add cooling







Heat Following (H)

Electricity Following (E)

No Load Following – at Electrical Maximum (EX)

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

Model describes operating data for fuel cell systems

Fuel Cell System Operating Data	Quantity	Units
Maximum Electrical Output	1000	kw
Minimum Electrical Output	880	kw
Maximum Heat-to-Electric Power Ratio	1.346154	
Minimum Heat-to-Electric Power Ratio	0.7	
Baseline Heat-to-Electric Power Ratio for Fixed Heat-to-Pow	0.7	
Natural Gas Fuel Consumption (in Units of Energy) Per Unit of Electric Power Output	6,824	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	50%	
Baseline System Heat Recovery Efficiency	35%	
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%	

Expand to include more data

Molten Carbonate Fuel System (MCFC) system vs. CHP combined cycle gas turbine (CCGT) examined here.

Model describes the financial and operating data for fuel cell systems and competing generators

Expand to include more data

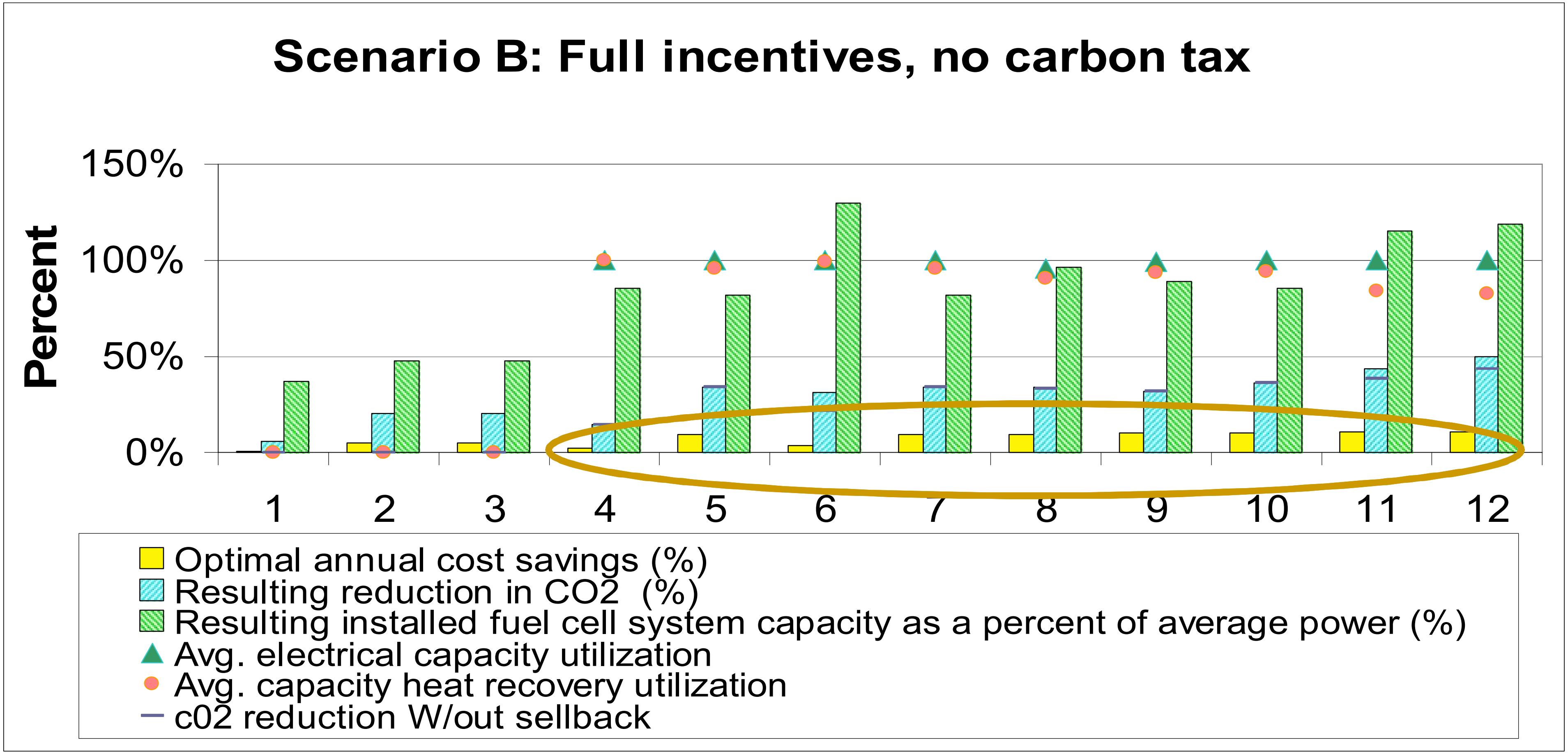
Fuel Cell System Costs -- Fixed Cost per year	Amount Borrowed (or Credited) at Time t = zero [P] ($)	Annuity [A] ($)
Capital Costs of 1000 kW Fuel Cell System	$ 3,200,000	$789,157
Installation Costs	$ 1,000,000	$246,611
Commissioning Costs (Start-up, Testing, Tutorials for Operators)		$ -
Shipping	$ 100,000	$ 24,661
Premium Service Contract (Maintenance and Replacement) -- Annuity Payments		$400,000
Fuel Cell System Incentives -- Federal and State		
California Self-Generation Incentive Program (CA SGIP) at $2500/kWe	$ 2,500,000	$616,529
Federal Investment Tax Credit (FITC) at $1000/kWe	$ 1,000,000	$246,611
Fuel Cell System Fixed Costs -- Total Yearly Fixed Costs		**$597,289**

Add summary cooling data for competing generator

Competing Generator: Natural Gas Combined Cycle Gas Turbine Plant		
Cost of steam for heating	0.056	$/kWh steam
Cost of electricity	0.085	$/kWh electricity
Baseline System Heat Recovery Efficiency	0.22	
Baseline System Electrical Efficiency	0.40	
Baseline System Heat Losses	0.38	

Molten Carbonate Fuel System (MCFC) system vs. CHP combined cycle gas turbine (CCGT) examined here.

Networked (4 to 12) is more economical than stand alone (1 to 3) with two exceptions



Exceptions are Strategies 4 [NFEHN] and 6 [NFEXHN] that are networked but fixed heat-to-power and minimum heat.

Results for Scenario D: full incentives, \$100/MTCO$_2$

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Stand alone units are best installed in dry labs; the building with the most savings, most revenue is CIS

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 (%)	Total Costs of Electricity and Heat Provision ($/yr)	Total Savings for Electricity and Heat Provision Compared with Base Case of No Fuel Cells ($/yr)	Annual Cost Savings (%)
Dry Lab	Center for Integrated Systems (CIS)	4	4	11%	15%	$ 8,771,370	$ 2,469,650	22.0%
Computer	Gates	3	3	8%	11%	7911386.573	$ 1,816,555	18.7%
Dry Lab	McCullough	1	1	3%	4%	$ 2,334,145	$ 408,774	14.9%
Other	Sweet	1	1	3%	4%	1876703.383	$ 249,142	11.7%
Dry Lab	Moore	1	1	3%	4%	$ 3,175,480	$ 399,816	11.2%
Dry Lab	ME Lab	1	1	3%	4%	$ 4,144,566	$ 517,612	11.1%
Dry Lab	Gilbert	3	3	8%	11%	$11,535,125	$ 1,369,340	10.6%
Office	Durand	1	1	3%	4%	1448977.113	$ 155,874	9.7%
Office	Terman	1	1	3%	4%	1481632.555	$ 149,115	9.1%
Wet Lab	Mudd (Seeley G) Chemistry	1	1	3%	4%	$ 1,897,398	$ 140,866	6.9%
Dry Lab	Stauffer 2	1	1	3%	4%	$ 2,183,860	$ 106,626	4.7%

Best buildings for installation may change with strategy & load curve
Results here are similar for Scenario D, Strategies 1, 2 (above), & 3.

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Constrained week to be Monday → Sunday and analyzed seasonal weekly average weather

Season	Avg. Weekly Temp (F)	Avg. Min Weekly Temp (F)	Avg. Max Weekly Temp (F)	Avg. Weekly Heating Degree Days (F*day)	Avg. Weekly Cooling Degree Days (F*day)
Winter	50.9	36.4	71.8	100.0	0.0
Spring	61.6	44.9	86.5	32.1	7.8
Summer	67.1	52.4	89.3	5.4	20.0
Fall	53.1	39.2	70.8	84.0	0.0

Above are average weekly values for each season

Heating/Cooling Degree Day (HDD/CDD) is the deviation of average daily temperature from 65°F, and is a measure of the heating or cooling required for a building.

Four example weeks are selected that have weather similar to the seasonal averages*

Season	Dates Selected	Avg. Temp (F)	Avg. Min Temp (F)	Avg. Max Temp (F)	HDD (F*day)	CDD (F*day)
Winter	Feb 19-25 2007	49.4	37.4	62.3	108.9	0.0
Spring	April 23-29 2007	61.1	41.5	89.7	32.6	5.3
Summer	July 23-29 2007	69.0	54.4	87.9	0.0	28.0
Fall	Nov 5-11 2007	54.9	44.6	67.1	70.9	0.0

Above are average weekly values for selected weeks

Major assumption is that picking weeks with mean weather conditions for each season will represent typical electricity, heating and cooling demand during these seasons.

*** weeks must not include holiday recess weeks**

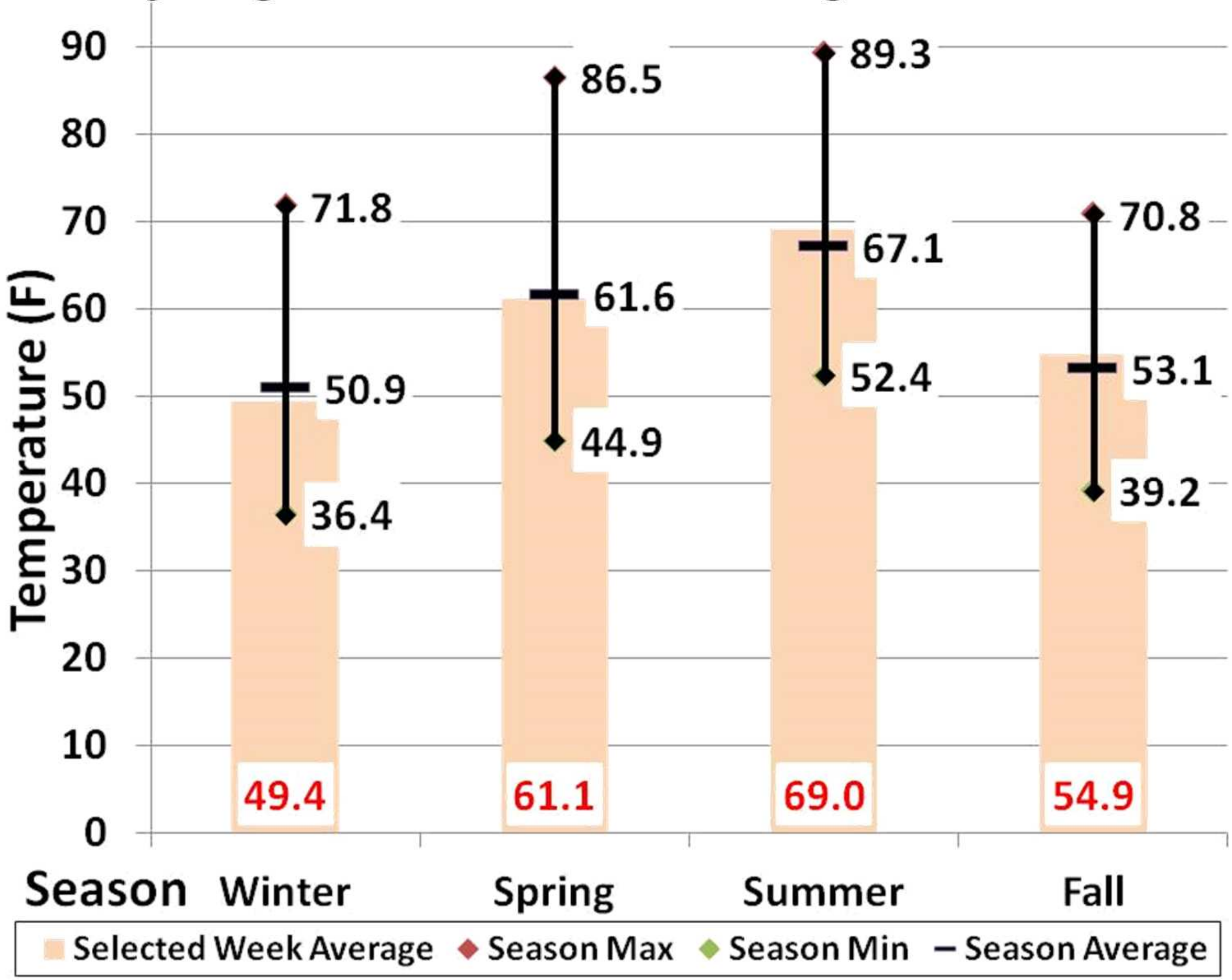
The selected weeks are representative of the average weather found during each season

Standard Deviation from Average			
Season	**Avg. Temp**	**HDD**	**CDD**
Winter	0.3	0.2	0.0
Spring	0.1	0.0	0.1
Summer	0.5	0.5	0.4
Fall	0.3	0.3	0.0

The weather conditions in all selected weeks are within 0.5 standard deviations of the average seasonal value.

The sample data represents the underlying data well

The sample data from the selected weeks represent the underlying seasonal average weather data



The temperature of all selected weeks are within 0.5 standard deviations of the average seasonal value.

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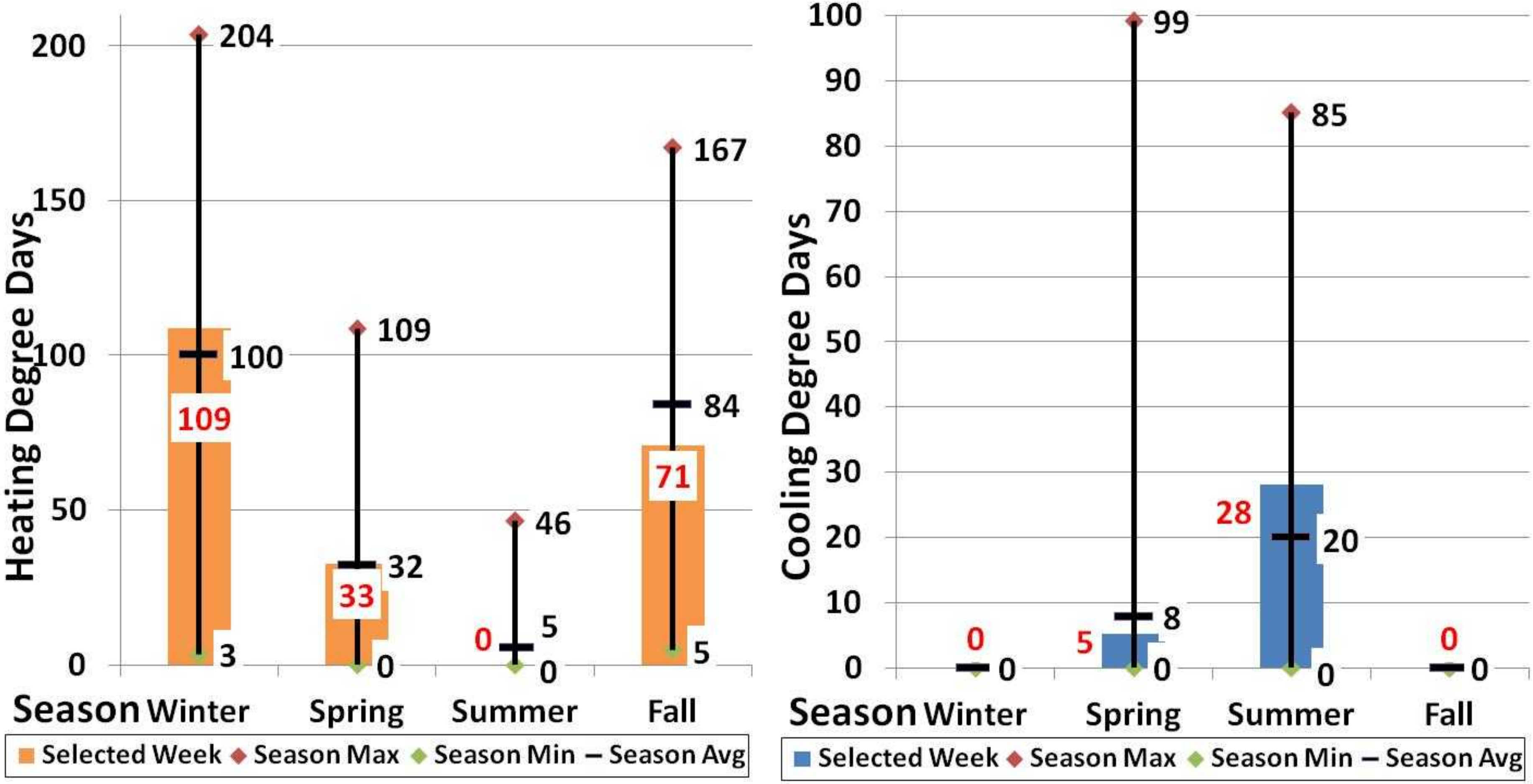
The sample data from the selected weeks represent the underlying seasonal average weather data



Heating and Cooling Degree Days in all selected weeks are within ½ a standard deviation of the seasonal average

Collect data from nineteen buildings that represent five out of six representative building types

Nineteen buildings are classified into five groups

- 7 dry labs
- 5 wet labs
- 3 computer facilities/classrooms
- 3 libraries/museum
- 1 other/dining

Data is collected for instantaneous chilled water, electric, and steam demand in 15 min intervals for selected weeks

Stanford campus demand data is unique for having cooling data separate from electrical demand

Fractional use of total chilled water, electricity, and steam demand for each building type

Percent of Total Campus Demand (%)				Number of Buildings
Building Type	Chilled Water	Electricity	Steam	
Dry Labs	13.2	22	12	7
Wet Labs	53.8	41	49	5
Library/Museum	5.5	5	5	3
Computer/Office	24.2	17	22	3
Other	3.3	3	3	1
Housing	0	12	9	0

Nineteen buildings are classified into five of these groups

No housing buildings are included because they only use electricity and steam, and they are not instrumented for data collection at 15 minute intervals

Scale the nineteen buildings data to total campus demand

1) Find total campus chilled water, electric, and steam demand for each building category
2) Solve for factors that scale each building's demand data to equal the total demand on each day for chilled water, electricity, and steam from that building's category

Currently there are 420 scale factors

- **5 categories** (buildings within category have same factors)
- **3 measurements** (chilled water, electricity, steam)
- **28 days** (factors for each day of four selected weeks)

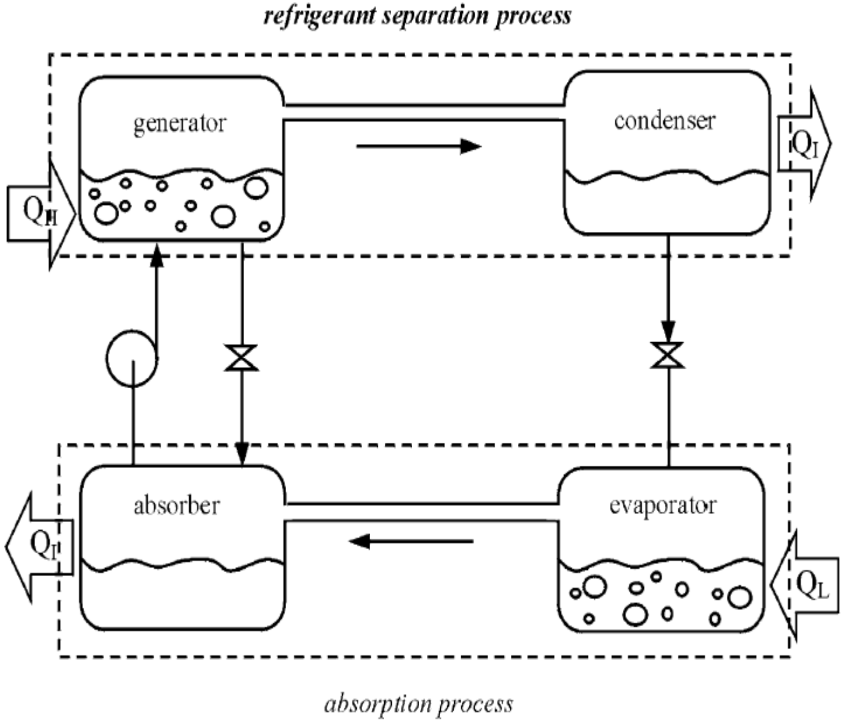
Each building within a category has the same scale factor for each measured quantity, and factors are chosen so category daily demand matches actual daily demand

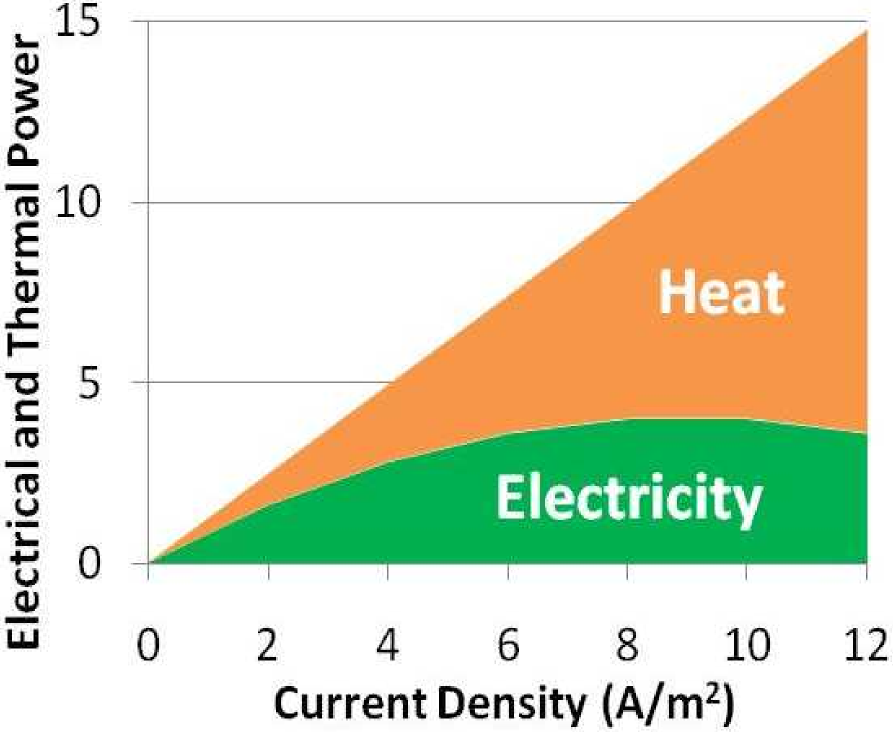
Average total campus demand over four selected weeks

Season	Dates Selected	Chilled Water (MW)	Electricity (MW)	Steam (MW)
Winter	Feb 19-25 2007	15.8	26.3	41.3
Spring	April 23-29 2007	26.9	25.0	31.1
Summer	July 23-29 2007	33.8	21.5	20.7
Fall	Nov 5-11 2007	14.9	22.4	54.8

Scaling the buildings allows a more detailed analysis of the entire campus demand with detailed data from only nineteen buildings

Fuel cells produce a lot of heat (right) that can be used to power an absorptive cooling cycle (left)





1) Heat is used to boil refrigerant out of solution
2) Refrigerant is condensed
3) Refrigerant absorbs heat when evaporated
4) Refrigerant is reabsorbed into solution

Left image: *A Review of Absorption Refrigeration Technologies*, P. Srikhirin, S. Aphornratana, S. Chungpaibulpatana, Renewable & Sustainable Energy Reviews, Vol 5 (2001) pp 343-372

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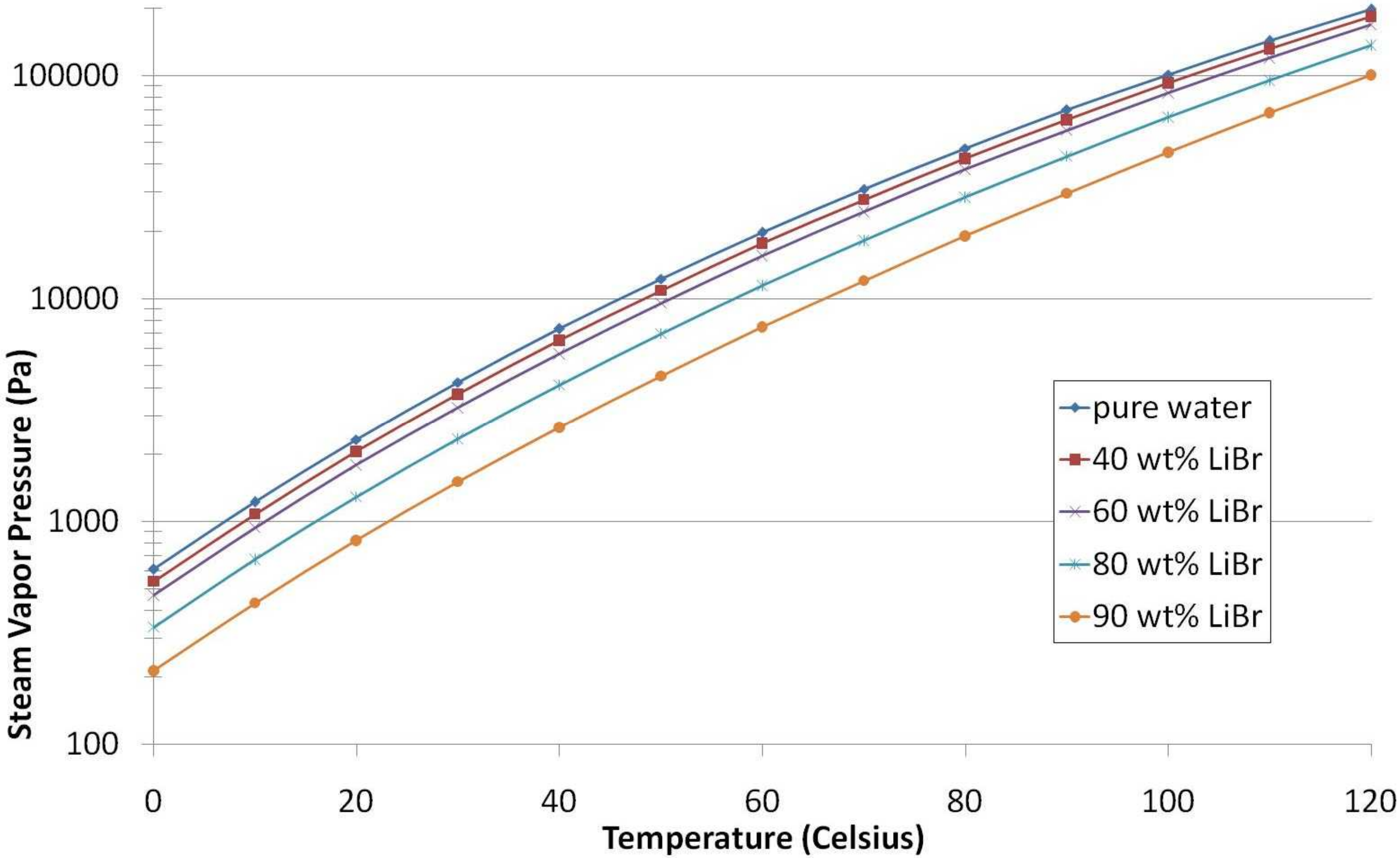
Steam partial pressure over concentrated LiBr is less than partial pressure over pure water

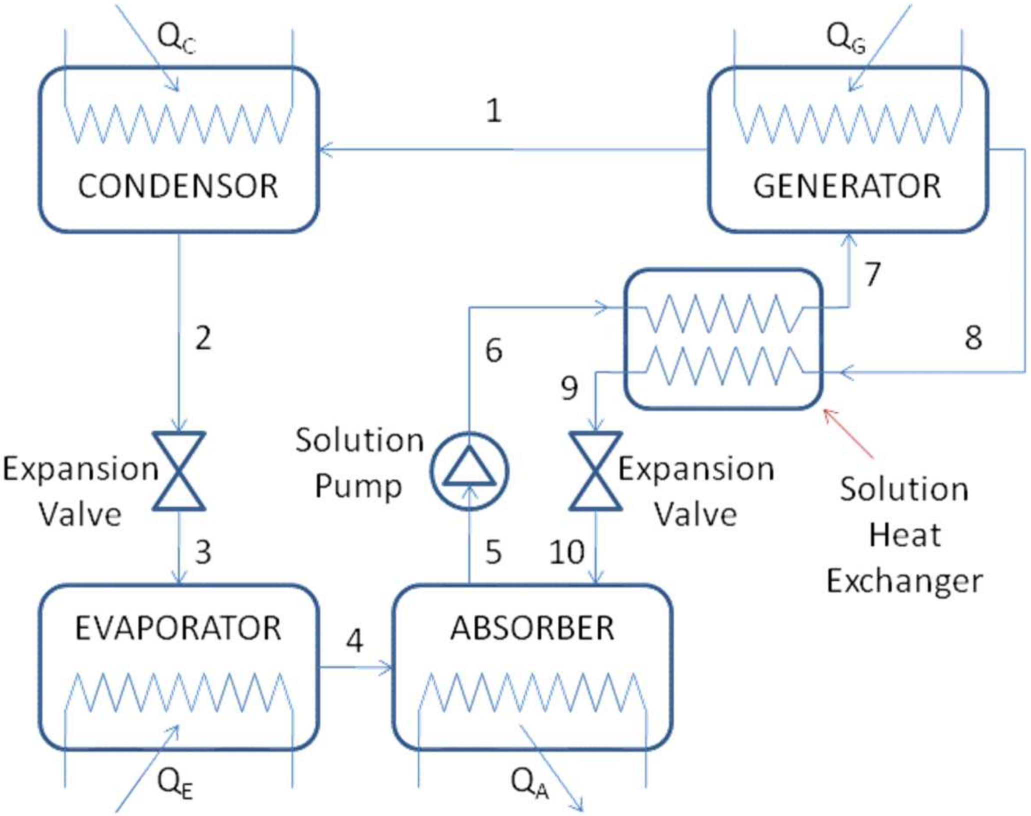


1) At high T & P: refrigerant boiled out of solution
2) At low T & P: refrigerant absorbed into solution

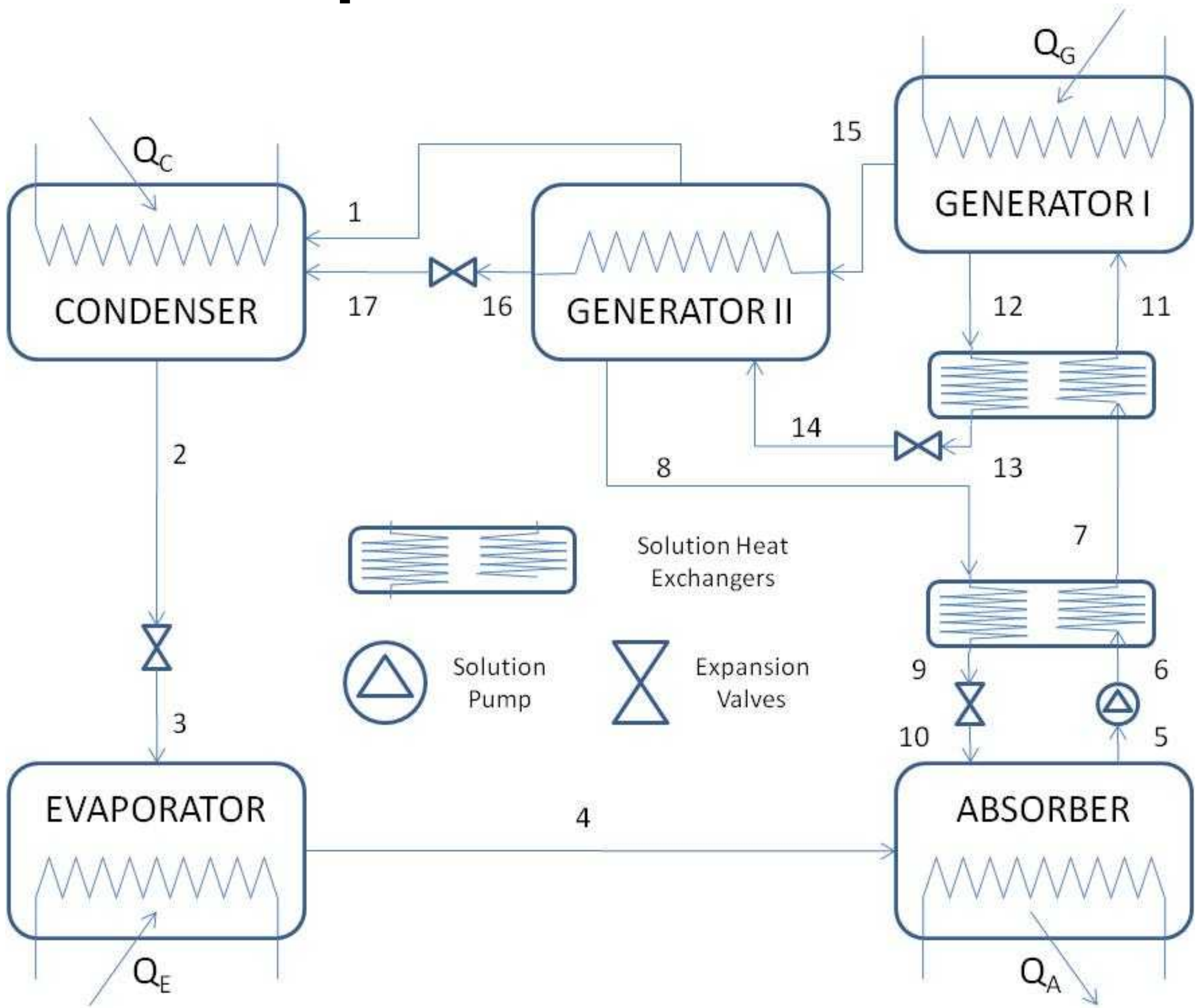
The model considers single-, double-, and triple-effect LiBr/water cycles, and calculates heat/cooling fluxes based on temperatures, concentrations, and pressures

Input: Temperature of evaporator, condenser, generator, absorber, and refrigerant flow rate

Output: COP, cooling of evaporator, heat flux from condenser, generator, absorber, and pressures

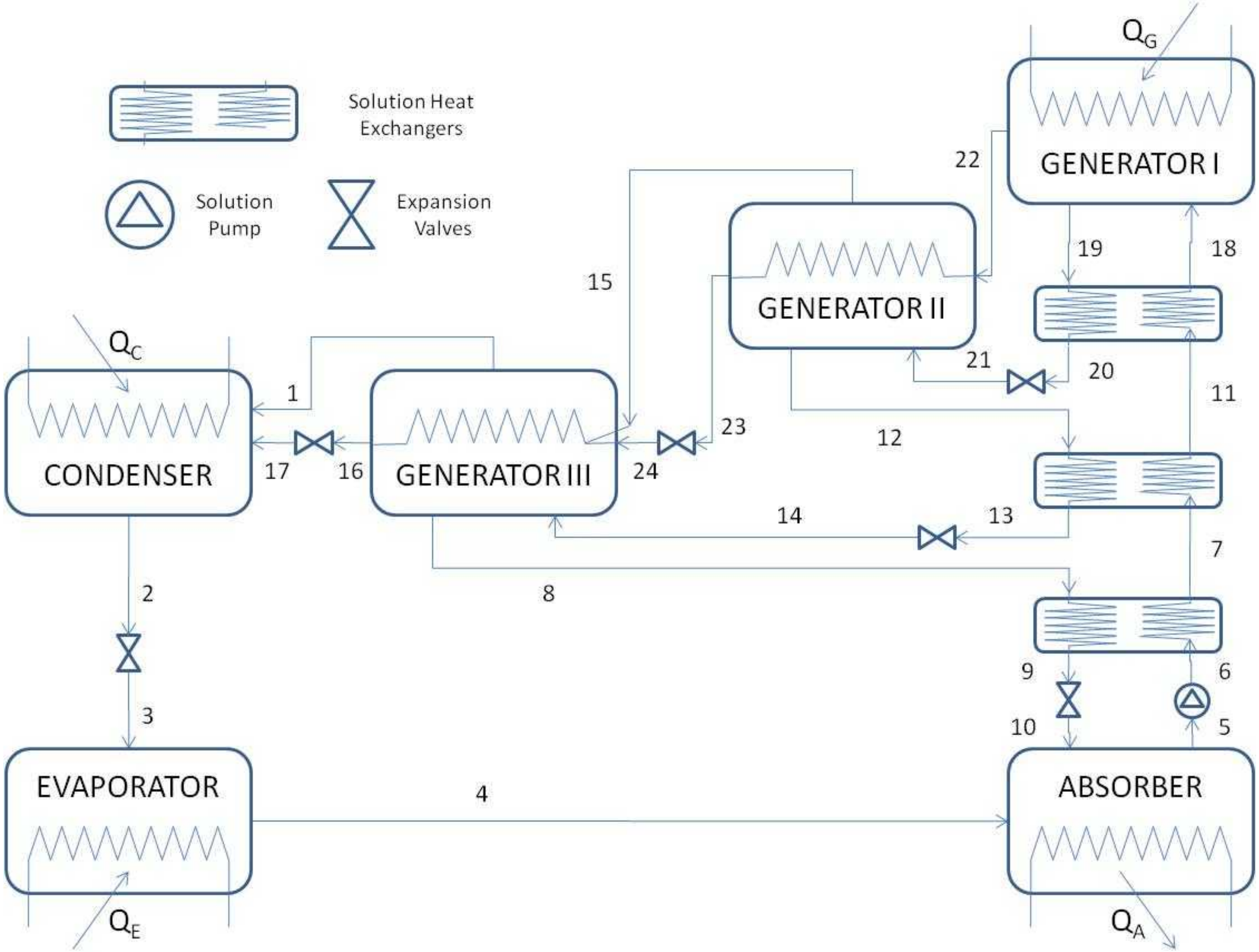


Double-effect model uses similar relations to single-effect, but includes extra temperatures, heat fluxes and pressures



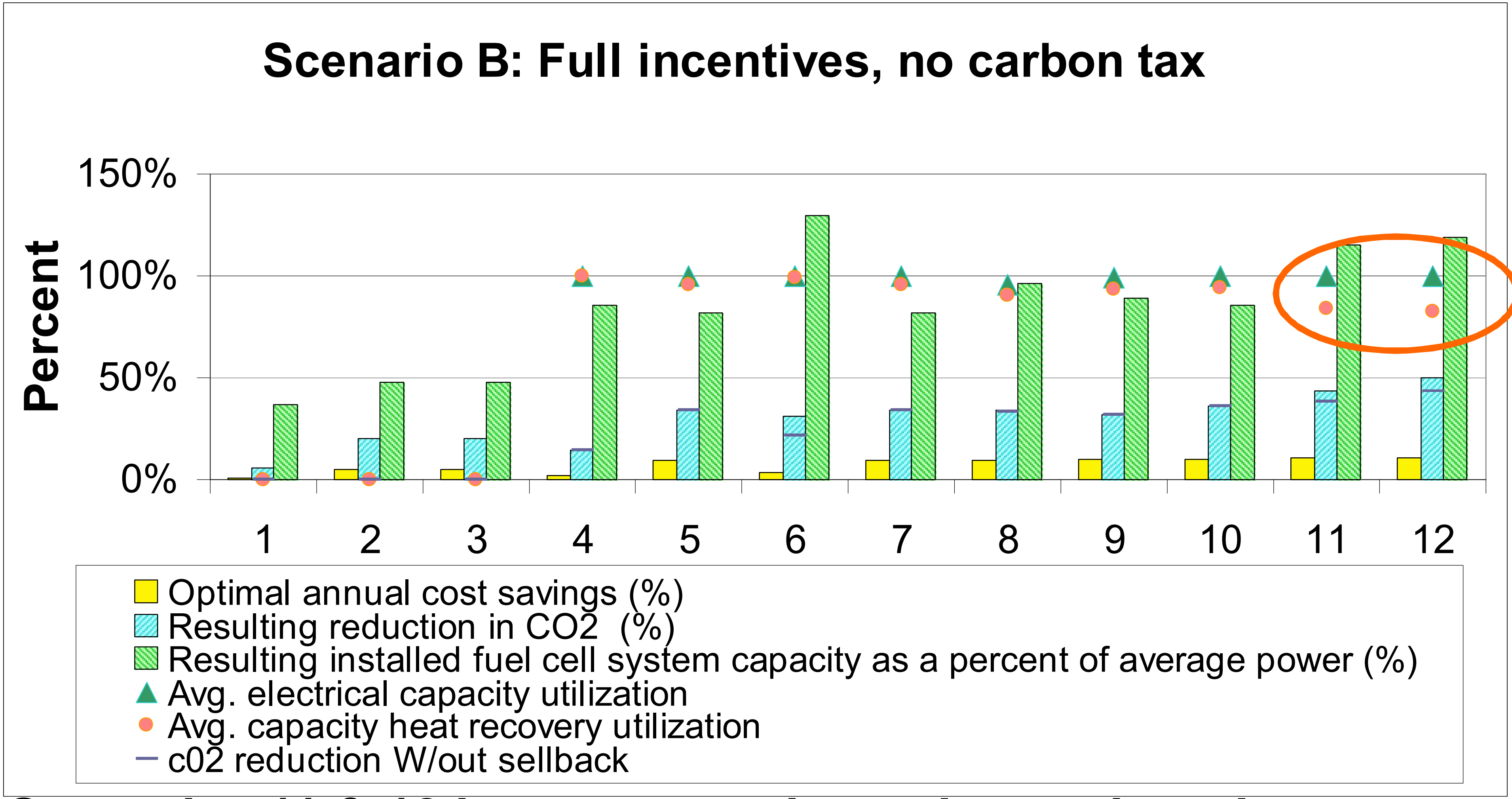
Double-effect Absorption Cooling Cycle

Triple-effect model uses similar relations to single-effect, but includes extra temperatures, heat fluxes and pressures



Triple-effect Absorption Cooling Cycle

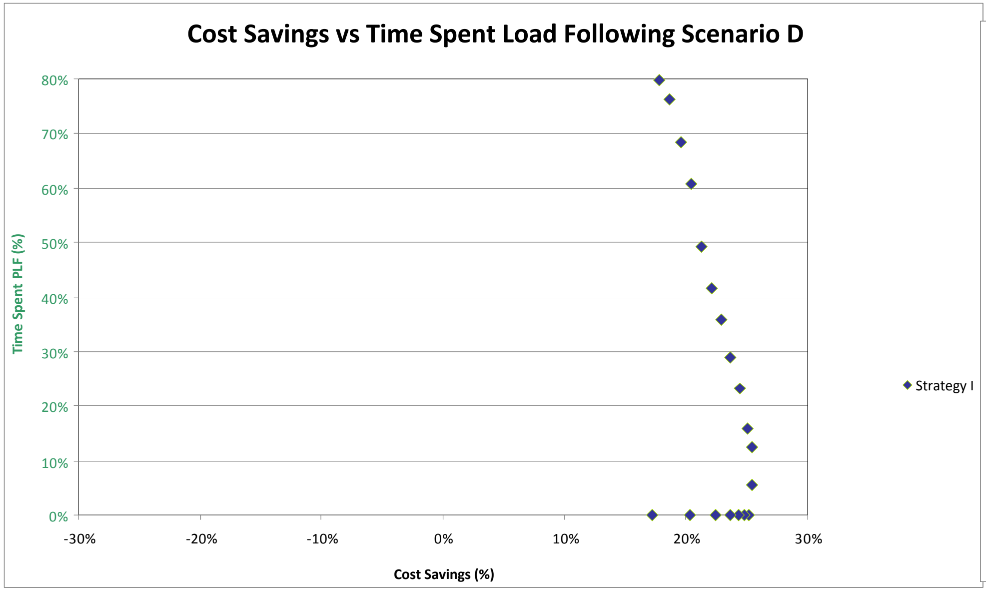
Thermal capacity utilization is lower for most economical strategies.



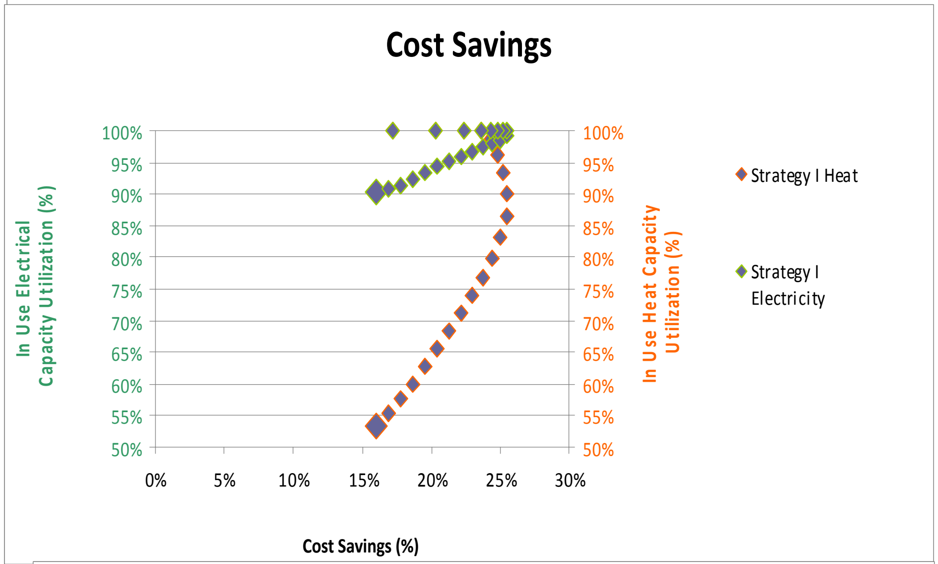
Strategies 11 & 12 have excess thermal capacity, a larger number of installations than needed for heat demand.

Results for Scenario B: full incentives, $0/MTCO$_2$

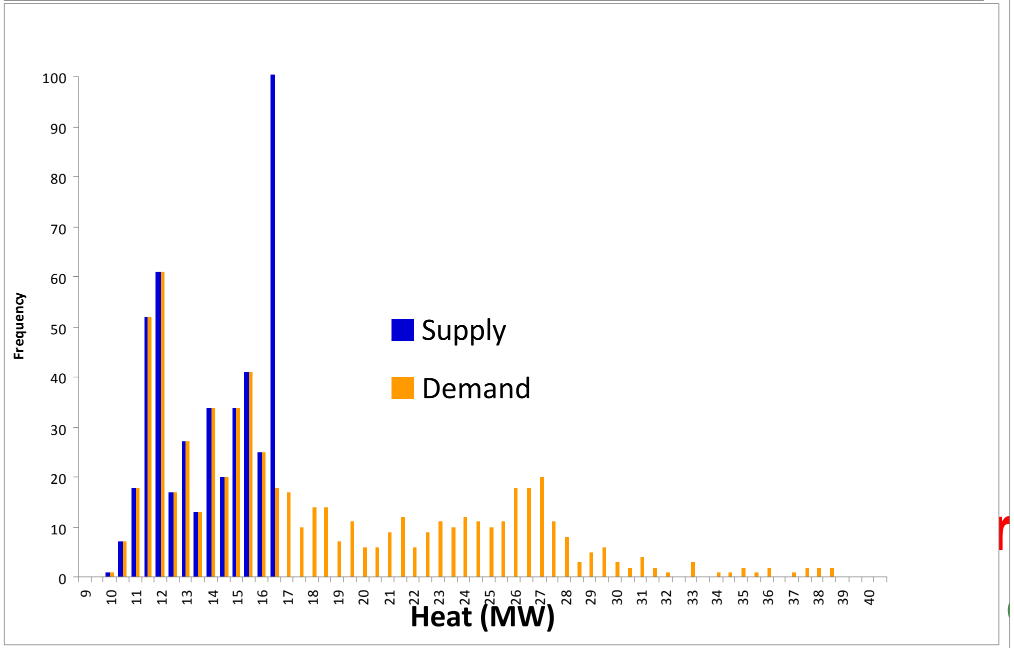
Strategy I (D):



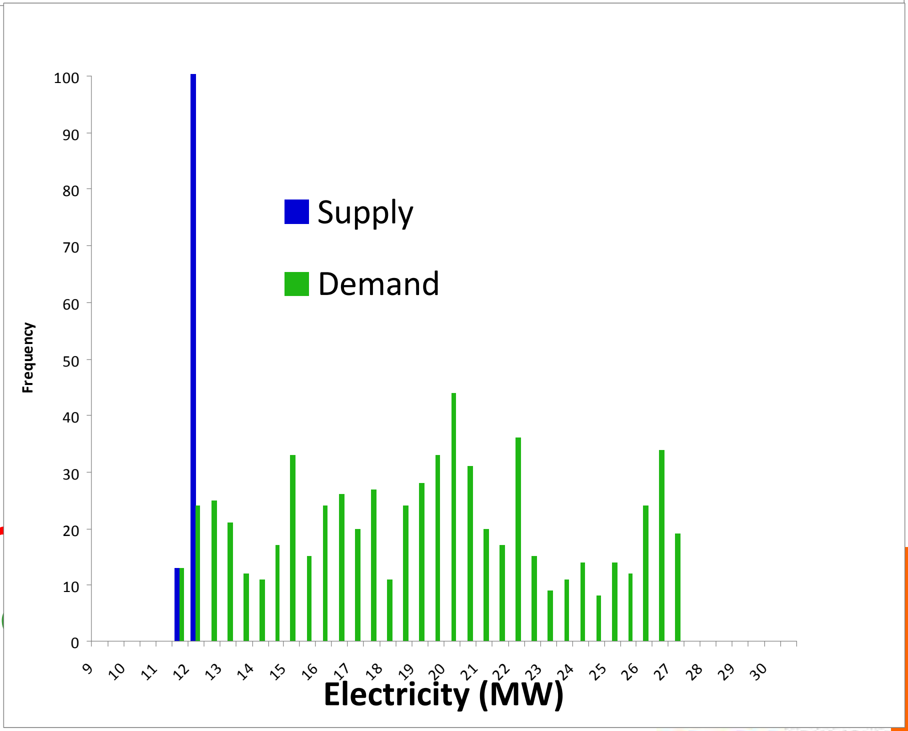
Cost Savings vs Time Spent Load Following Scenario D
Time Spent PLF (%)
80%
70%
60%
50%
40%
30%
20%
10%
0%
-30%
-20%
-10%
0%
10%
20%
30%
Cost Savings (%)
Strategy I



Cost Savings
In Use Electrical Capacity Utilization (%)
In Use Heat Capacity Utilization (%)
100%
95%
90%
85%
80%
75%
70%
65%
60%
55%
50%
0%
5%
10%
15%
20%
25%
30%
Cost Savings (%)
Strategy I Heat
Strategy I Electricity



Frequency
100
90
80
70
60
50
40
30
20
10
0
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
Supply
Demand
Heat (MW)



Frequency
100
90
80
70
60
50
40
30
20
10
0
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
Supply
Demand
Electricity (MW)

CO_2 emissions decrease the most with Strategies I, III, V

1. Highest manufacturer revenues w/ Strategy II (novel), but highest CO_2 emissions
2. Maximum 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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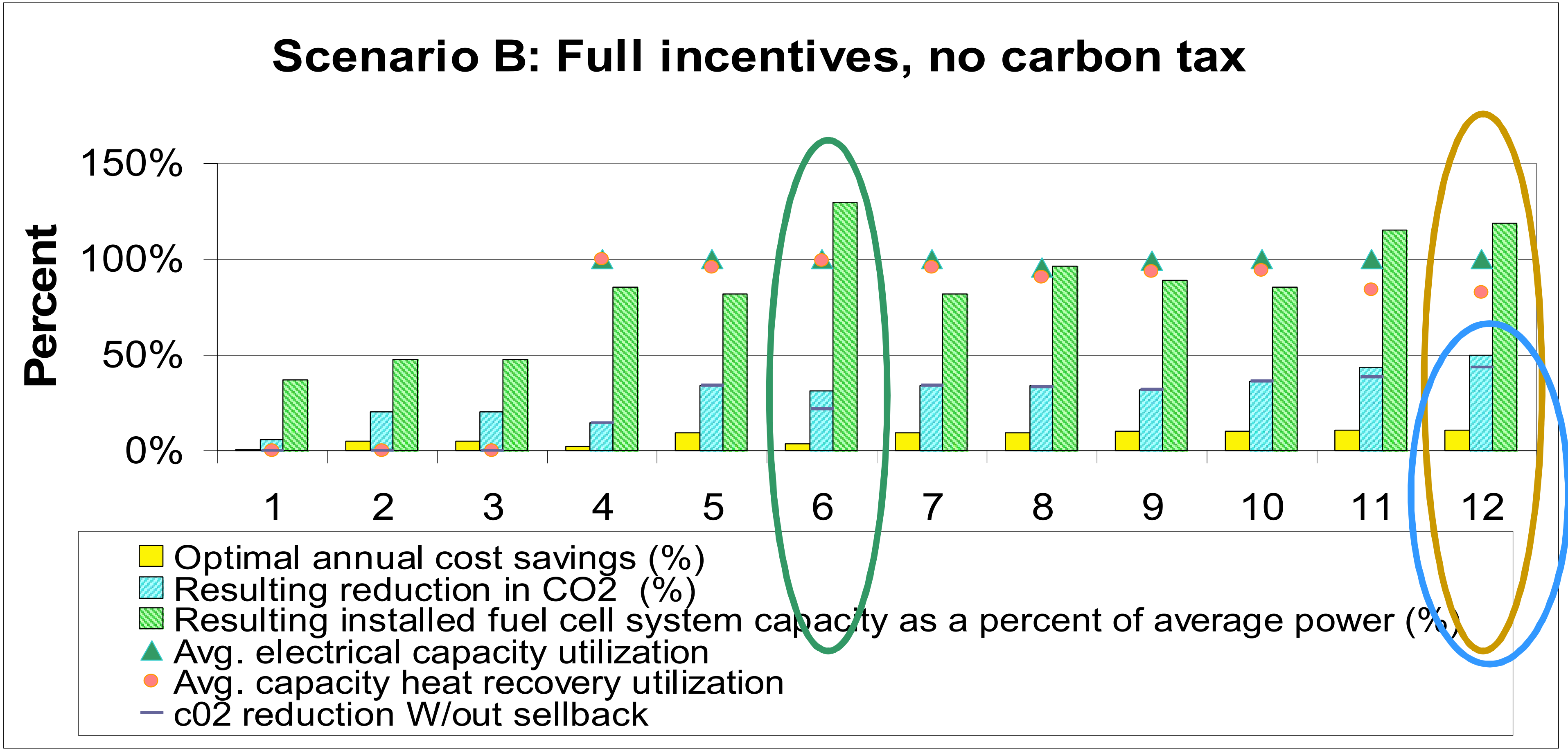
For optimal cost savings, building owners and fuel cell makers profit most from different strategies



Strategy 12 [NVEXH] = *novel* = most cost savings, least CO_2 for optimal savings

Strategy 6 [NFEXHN] = *plain vanilla* = most revenue/ sales

Results for Scenario B: full incentives, $0/MT$CO_2$