

Identifying Innovative Engineering Strategies for Co-Producing Hydrogen (H₂) with High Temperature Stationary Fuel Cell Systems (FCS) using Economic and Environmental Models

Whitney Colella,¹ Aerel Rankin¹

Sandia National Laboratories¹

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Background: Poly-generation

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.

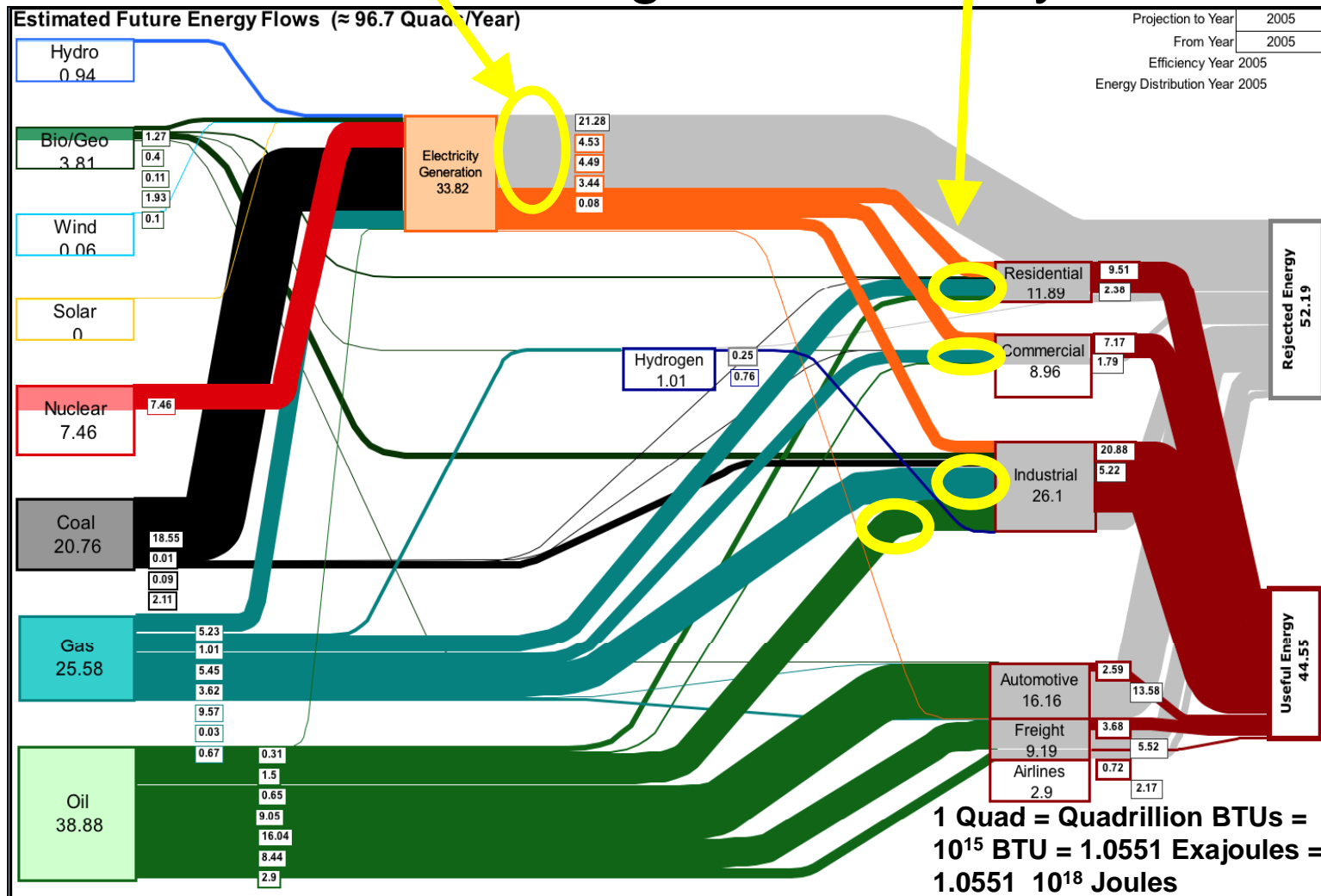


Figure by Gene Berry, Lawrence Livermore National Laboratory

Stationary fuel cell systems (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 CO₂ as conventional systems, if they are designed to **recover heat** and with **high end-use capacity utilization**. They make no CO₂ if fueled by renewable H₂.

CHP fuel cell systems (FCS) can be designed to also produce hydrogen as fuel for vehicles or industry. Their waste heat can be recovered for cooling power.



Natural gas, propane, or biogas fuel such as anaerobic digester gas (ADG) or landfill gas

Electricity

Heat

Hydrogen

Cooling Power

Background: Hydrogen Co-Production

Hydrogen Co-Production Integrated with Stationary Fuel Cell Systems (H₂-FCS) can provide H₂ with lower costs, fuel use, & emissions than other H₂ supply chains.

H₂-FCS Concept:

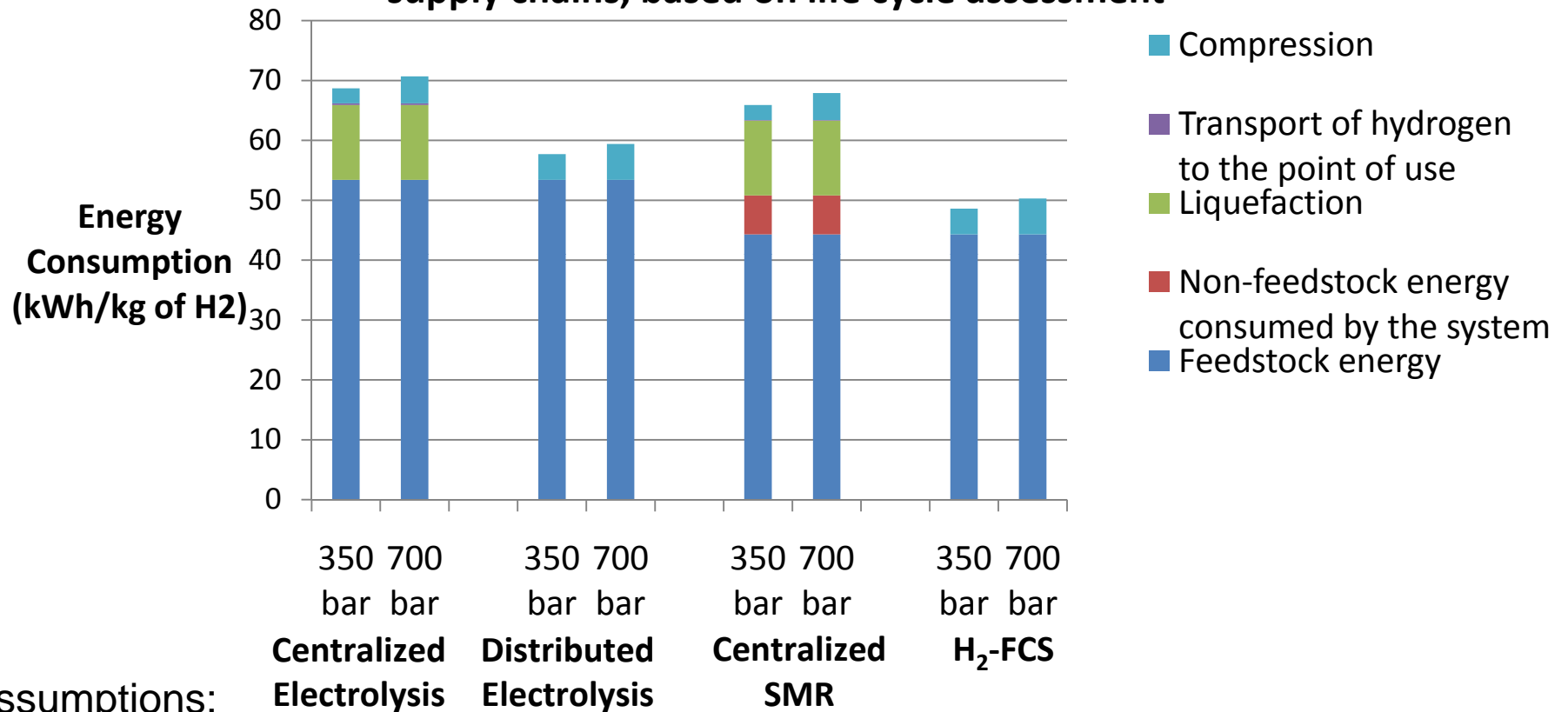
- A conventional distributed fuel cell system can provide clean electricity and recoverable heat to nearby buildings. This system can be re-designed to also provide excess hydrogen (H₂) for supplying H₂ vehicles or industry (merchant H₂).
- H₂-FCS can provide H₂ with lower costs, fuel use, & emissions.

Advantages of this Approach:

- H₂-FCS can supply H₂ locally, without the added H₂ transport infrastructure and related capital costs, energy use, and emissions seen with centralized production.
- H₂-FCS can supply H₂ in response to H₂ demand, and as a H₂ vehicle fleet grows. When H₂ demand is low, H₂-FCS can sell more electricity and heat instead, and thereby retain high system capacity utilization and lower costs.
- H₂-FCS can address the “chicken-or-egg” problem associated with a lack of H₂ refueling stations for initial H₂ fleets.
- H₂-FCS can improve fuel security by relying on local, widely-available feedstock.
- H₂-FCS can make H₂ with less additional fuel than distributed steam methane reforming (SMR) by reusing high temperature fuel cell waste heat to warm the endothermic steam reforming process to make excess H₂.
- Synergistic benefits include that a lower fuel utilization increases overall efficiency (i.e., higher Nernst Voltage, lower mass transport losses, lower cooling requirement and associated air blower parasitic load.)
- Less energy is needed to make and to transport H₂ to vehicles using H₂-FCS compared with centralized electrolysis, distributed electrolysis, or centralized SMR.

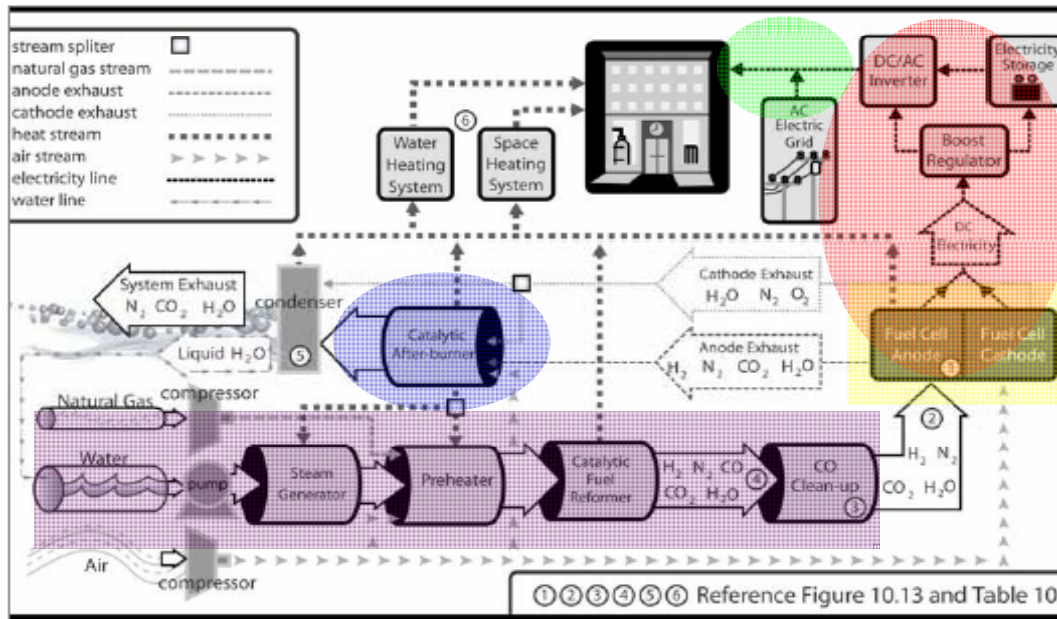
H₂-FCS consumes less energy to make and to transport H₂ compared with other H₂ supply chains.

Energy requirements for providing H₂ to refuel vehicles via various supply chains, based on life cycle assessment



Assumptions:

- Centralized electrolysis plant is located in Palm Springs, CA. 100% of electricity used is wind power. H₂ is transported by diesel-fueled truck to Los Angeles (LA).
- Distributed electrolyzer is located at fueling station & consumes 100% wind power.
- Steam methane reforming (SMR) plant is located in Long Beach, CA; H₂ is transported by a diesel-fueled truck to LA.

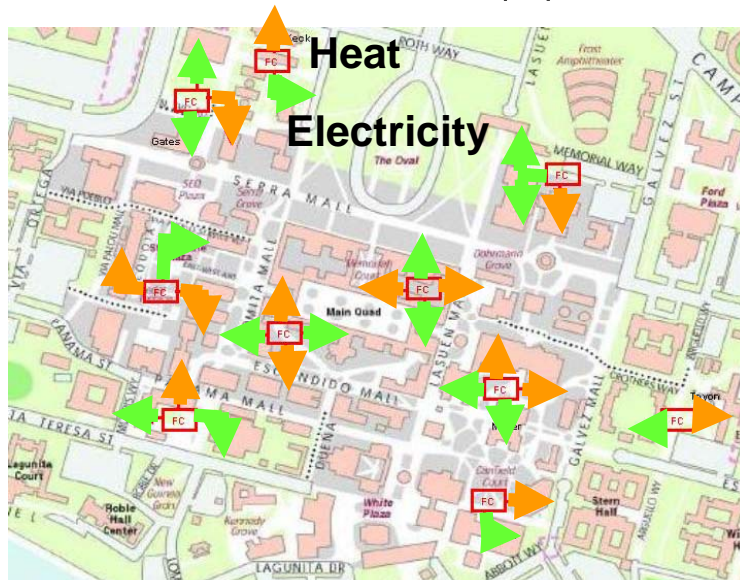


**Methodology:
Novel
operating
configurations**

Systems can be installed stand alone or networked

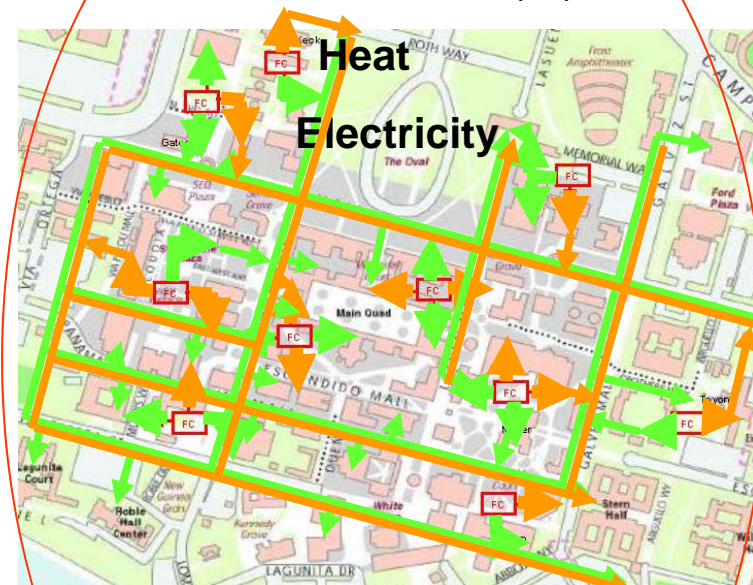


stand alone (S)



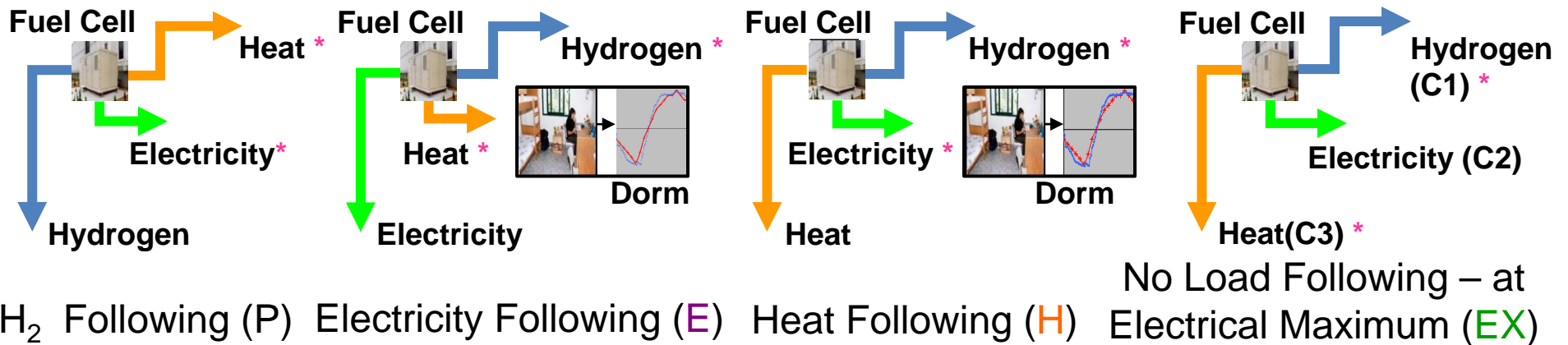
Fuel cells can NOT convey or sell excess heat or electricity into the distribution grid to reach other buildings. One system serves only one building. Buildings can import additional heat and electricity. FuelCell Energy currently installs its units this way.

networked (N)

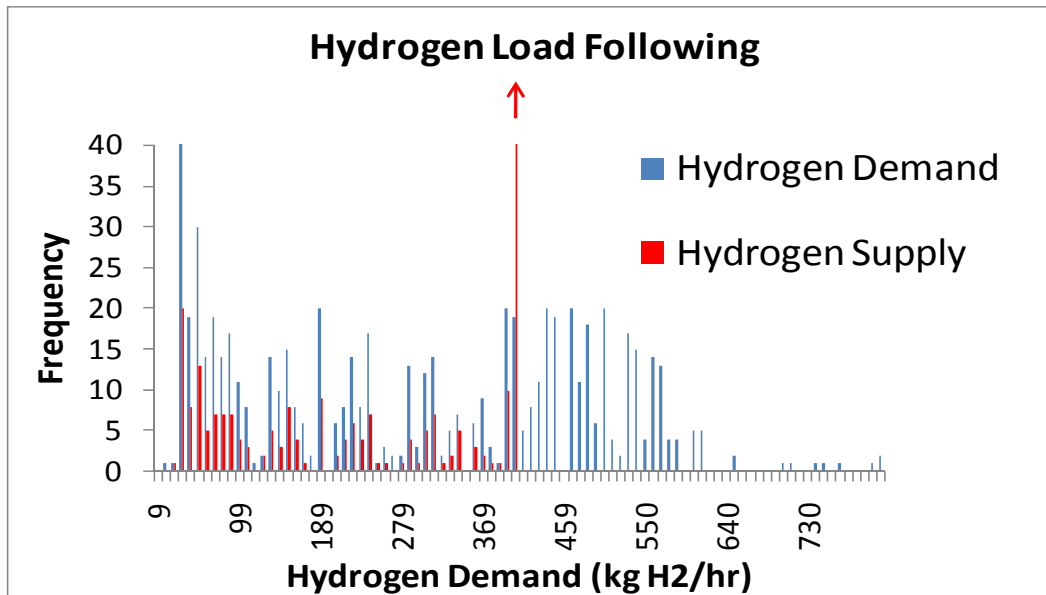


Networks have energy distribution channels. Fuel cells CAN convey excess heat or electricity into the distribution grid to reach other buildings, and sell back electricity to the grid. Transmission Loss: Electrical ~0%, Thermal ~8%.

Novel approaches also include H₂, electricity, or heat load following; in contrast to no load following



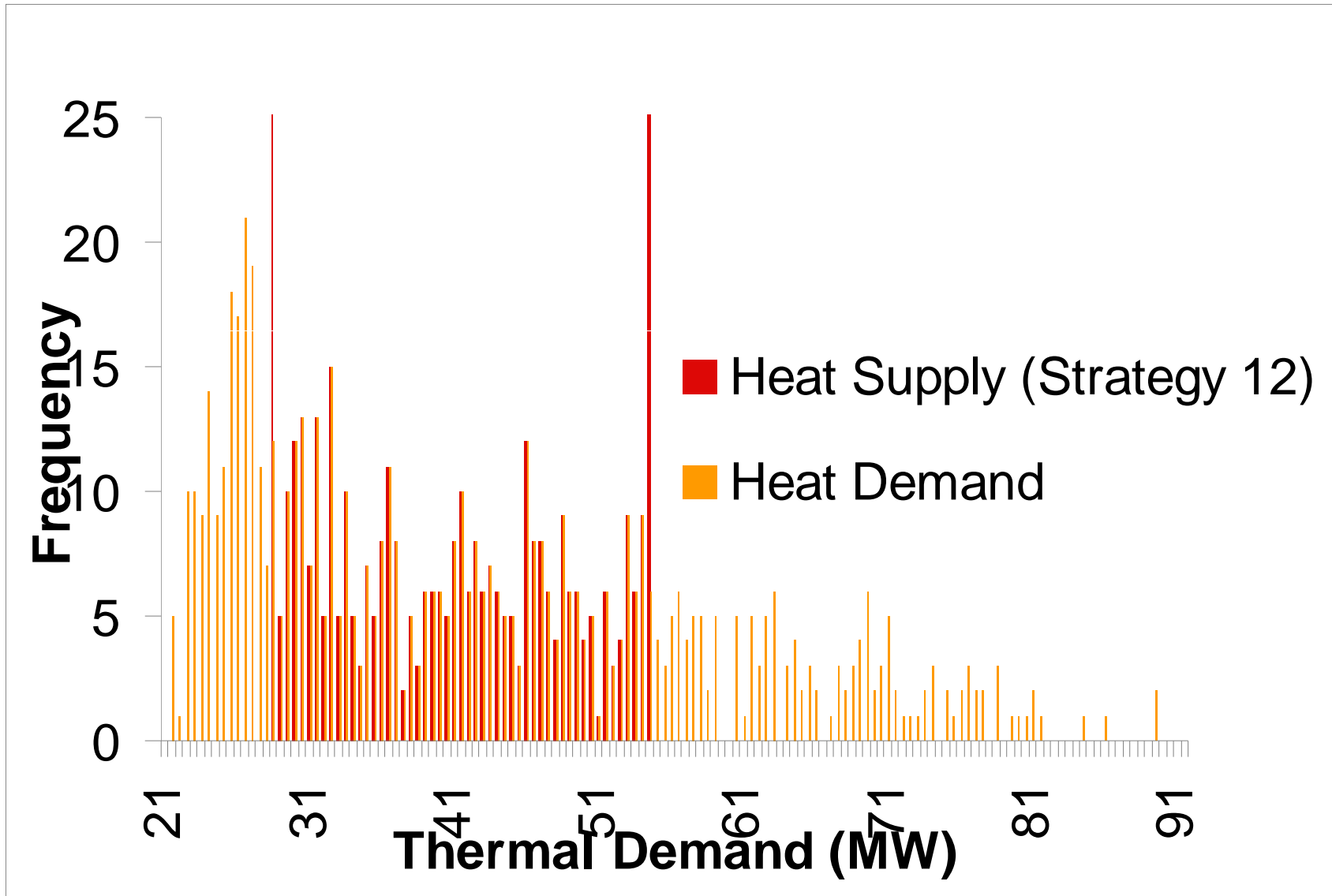
Note: * distinguishes byproducts



Histogram of H₂ demand and supply under load following conditions

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.

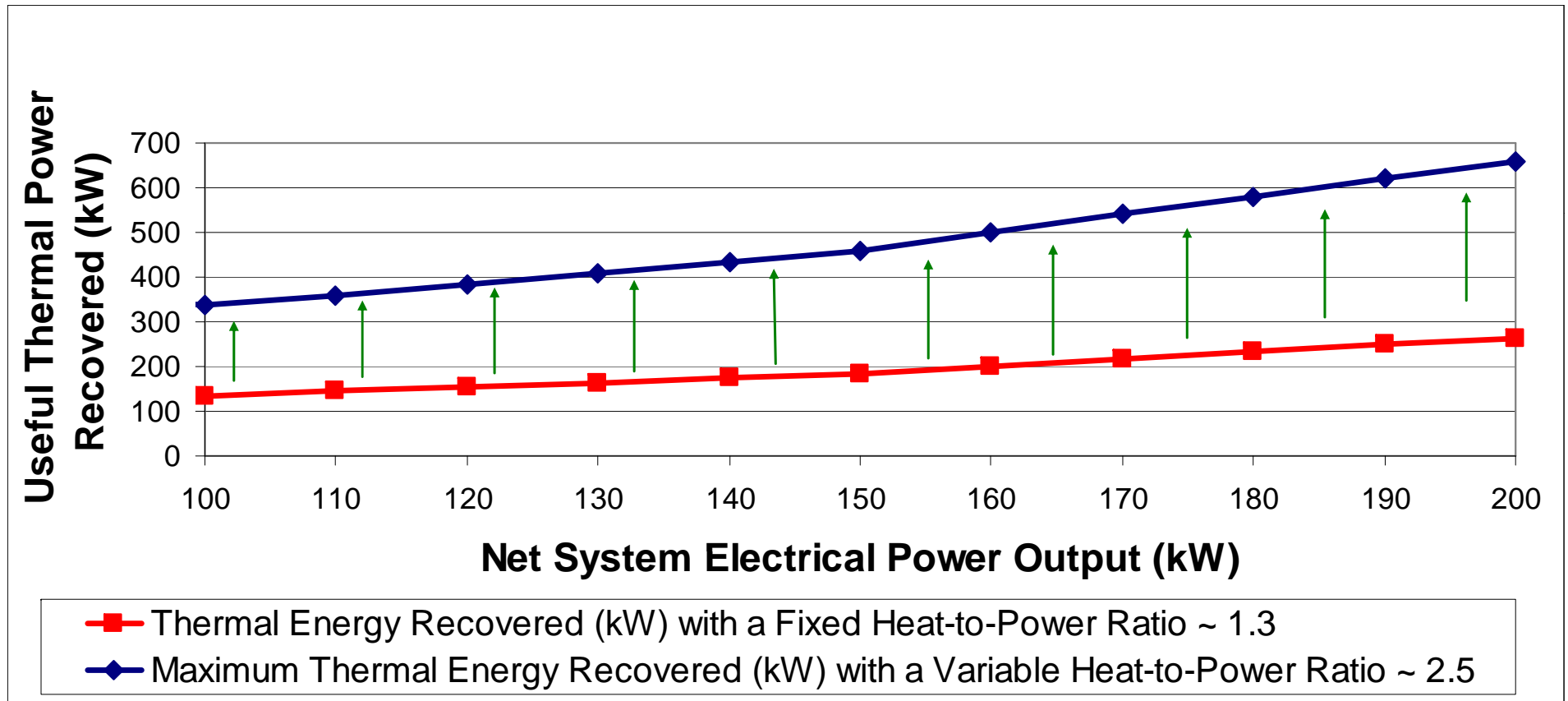
Load following is physically constrained by the system's energy output range and ramp rate.



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

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

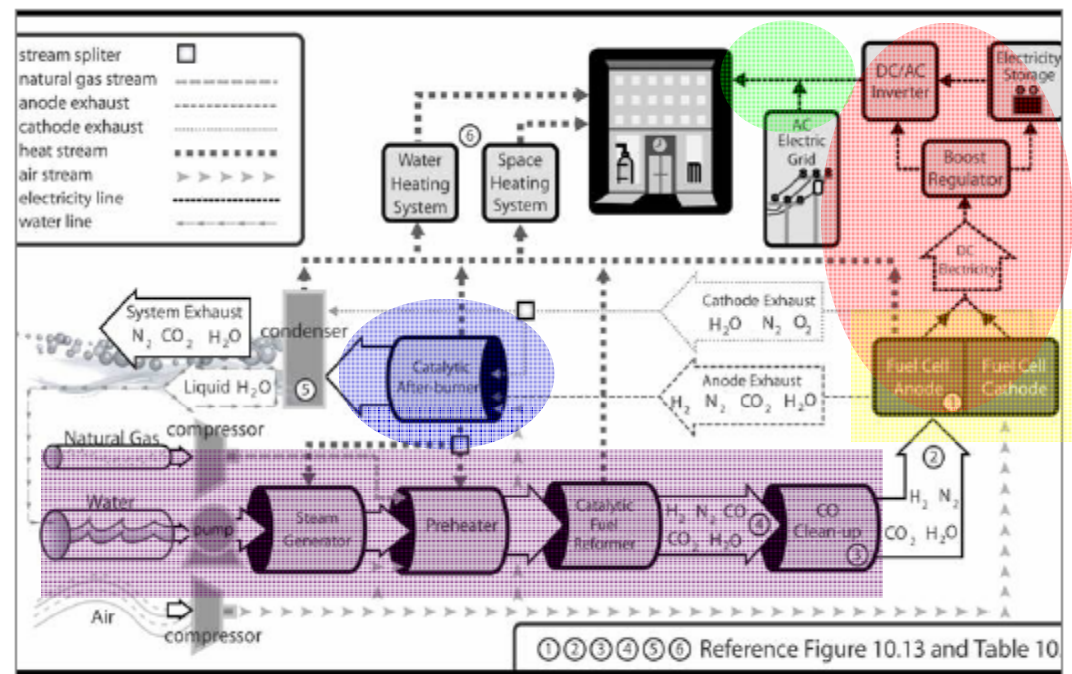
III Vary the system's electrical configuration

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

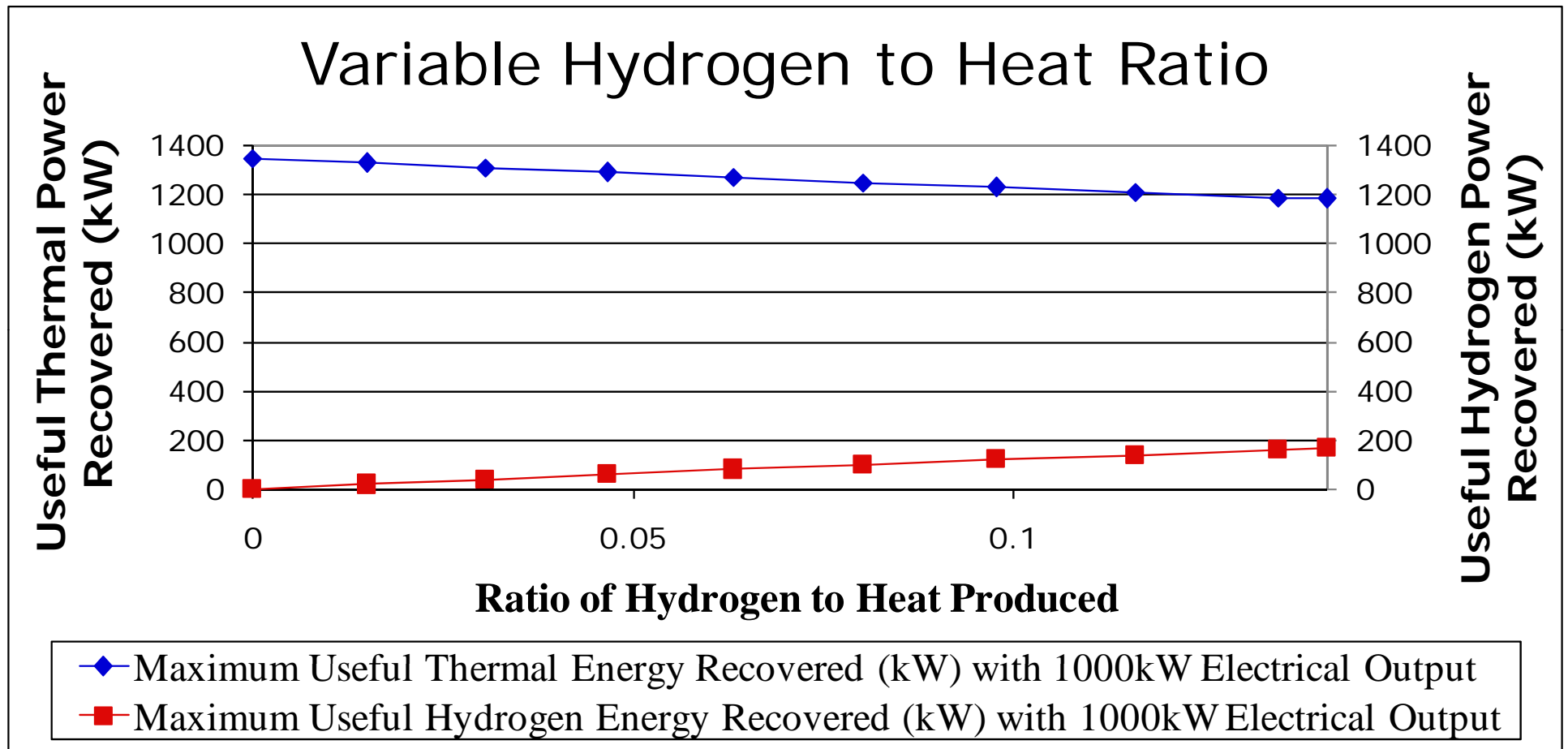
V Use resistance heater, which results in increased fuel cell stack run time, but potentially under less cyclical demands

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

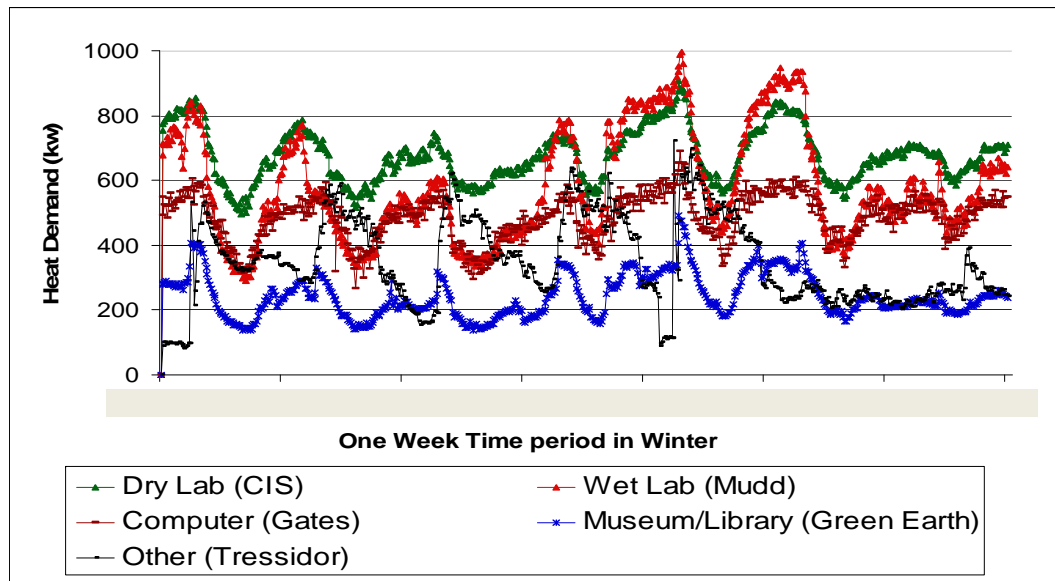
FuelCell Energy design – Option V: Resistance heater



Novel approaches include variable heat-to-H₂ ratio (Y).



A FCS with a variable heat-to-hydrogen ratio can convert thermal energy into H₂ energy over a certain range of ratios. This ratio reflects the conversion efficiency of using FCS waste heat to warm endothermic steam reforming reactions to make H₂. Each 1 kW of FCS waste heat can make up to 1 kW of H₂ energy (ideal heat transfer).

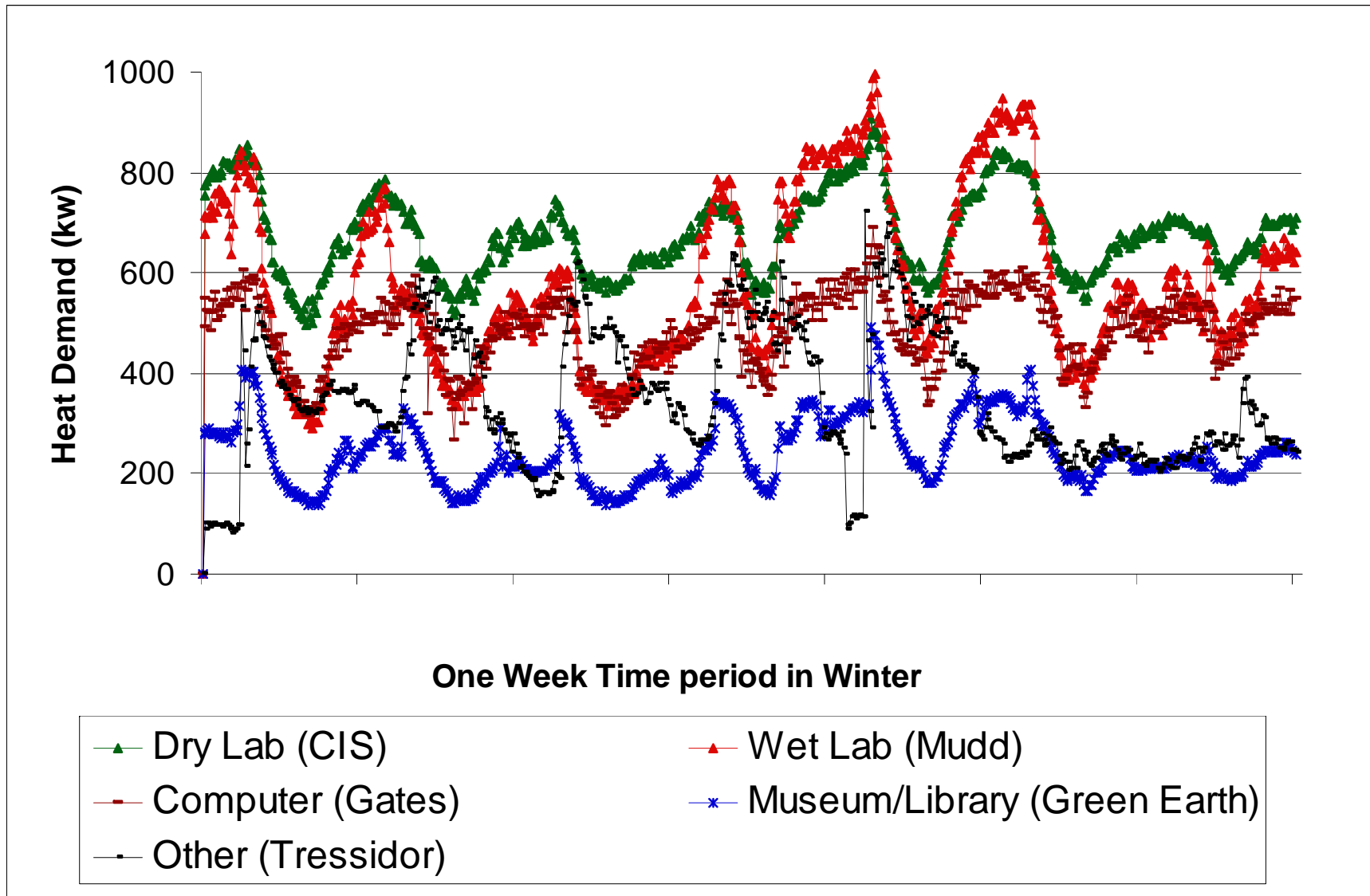


**Methodology:
Simulation design**

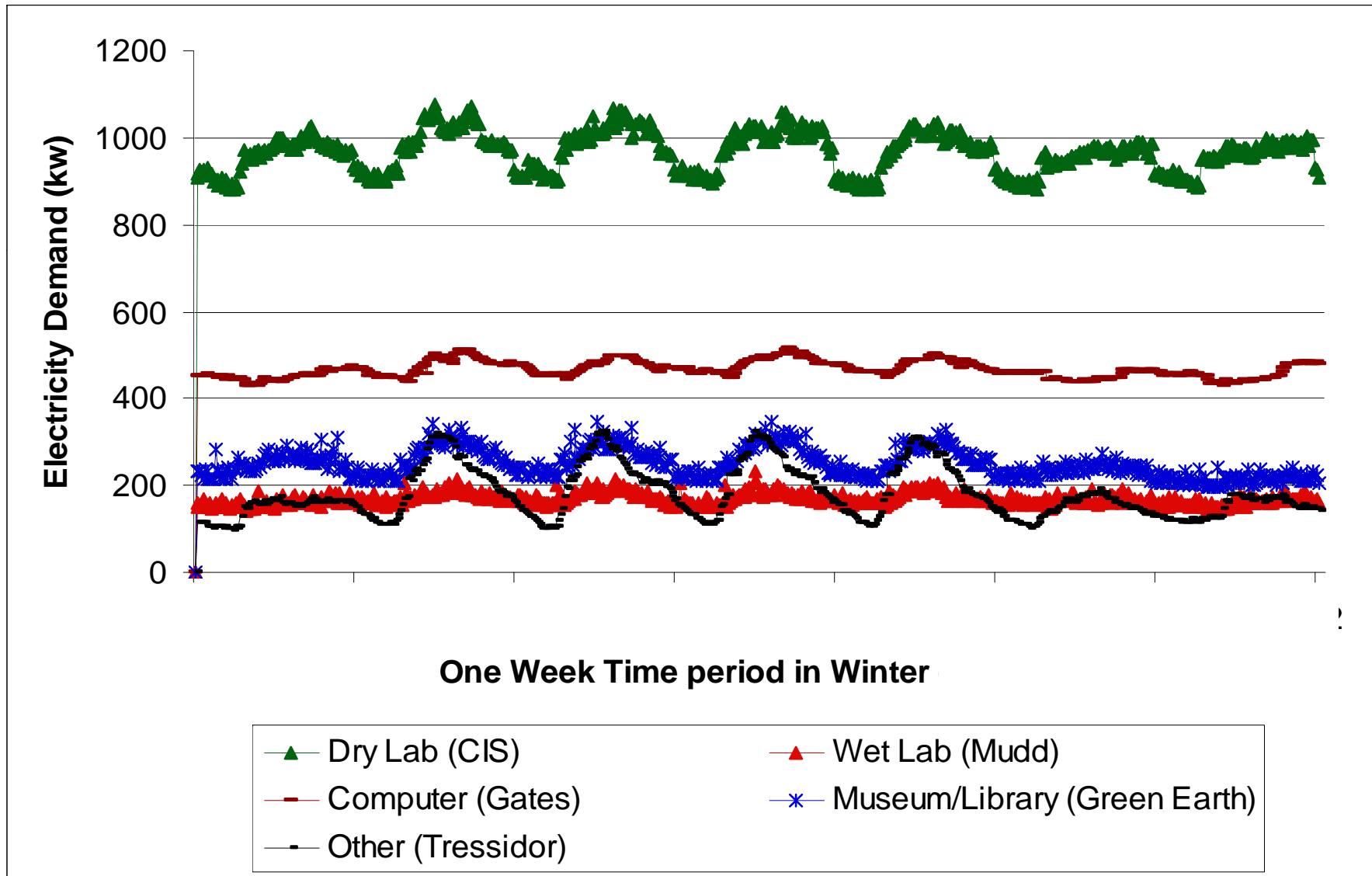
We model the economics and environmental impacts of H₂-FCS using novel operating strategies. The model

- Examines novel operating strategies not common in commercial industry
 - Novel approaches include thermal and electrical networking (N); variable heat-to-power ratio (V); variable heat-to-H₂ ratio (Y); and H₂, electricity, or heat load following (P, E, or H).
- Optimizes the percentage installation of H₂-FCS for
 - minimum CO₂ emissions, or
 - maximum combined energy cost savings both for building owners in using both electricity and heat and for H₂ consumers (H₂ vehicle owners, merchant H₂, etc.) in using H₂ compared with competing technologies.
- Optimizes FCS installation for
 - a particular location
 - climatic region
 - building load curves
 - FCS type, and
 - competitive environment.
- Shows trade-offs amongst competing goals:
 - cost savings to building owners and H₂ consumers, CO₂ reductions, FCS installed capacity and manufacturer sales.

Model tests H₂-FCS against demand data for electricity & steam measured in real-time from 20 buildings & for projected vehicular H₂ demand, each hour in a year.



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



Model investigates 13 novel operating strategies.

Strategy	Primary Control			Secondary Control	Tertiary Control	
	Electrically and Thermally Networked (N) or Stand Alone (S)?	Variable Heat-to-Power Ratio (V), Fixed Heat-to-Power Ratio (F)?	Variable Heat-to-Hydrogen Ratio (Y)	Electricity Power Load Following (E), Heat Load Following (H), Hydrogen Load Following (P), or No Electricity Load Following (EX)?	Electricity Power Load Following (E), Heat Load Following (H), Hydrogen Load Following (P), No Heat Load Following (HN, HX), or No Electricity Load Following (EN, EX)?	Electricity Power Load Following (E), Heat Load Following (H), Hydrogen Load Following (P), No Heat Load Following (HN, HX), or No Electricity Load Following (EN, EX)?
i	N	F	Y	E	HN	P
ii	N	V	Y	E	P	HX
iii	N	F	Y	EX	HN	P
iv	N	V	Y	EX	P	HX
v	N	V	Y	H	P	EN
vi	N	V	Y	H	P	E
vii	N	V	Y	E	H	P
viii	N	V	Y	H	P	EX
ix	N	V	Y	EX	H	P
x	N	V	Y	EX	P	H
xi	N	V	Y	P	H	EN
xii	N	V	Y	P	H	EX
xiii	N	V	Y	P	H	E

Strategies i to xiii are all electrically and thermally networked (N), with a variable heat-to-H₂ ratio. A number of novel operating strategies are investigated with primary, secondary and tertiary controls for H₂, electricity, and heat load following. Most FCS are now installed as [SFEXHN].

Model tests FCS against competing H₂ generators. FCS waste heat is reused for steam reforming to H₂.

- The model optimizes for the minimum total electricity, heating, and H₂ yearly costs by altering the installed fuel cell system capacity.
- The total yearly costs include, but are not limited to, the fuel cell system capital, maintenance, and fueling costs and the competing generators' electricity, heating, and H₂ costs.
- All demand not supplied by fuel cells is purchased from the competing generators.
- A fuel cell system load following controls will match the hourly demand if it is within the physical constraints of the system.
- Results are compared to a base case of no fuel cells installed. In the base case, all energy demands are supplied by competing electricity, heat, and H₂ generators.
- H₂ production is included in the fuel cell system operation in a manner similar to steam methane reforming (SMR). Waste heat from the high temperature fuel cell system supplies the energy needed for the endothermic steam reforming process for converting natural gas fuel to H₂.

Case study: We show example results based on realistic input assumptions.

- The competing H₂ generator is assumed to be a stand-alone steam methane reformer (SMR) with a fixed CO₂ to H₂ production ratio of 7.49 kg CO₂/kg H₂.
- The fuel cell systems can sell back electricity to the grid at the same price as the competing electricity generator charges (similar to net-metering but without a constraint on the total quantity of electricity sold back to the grid in one year).
- Each 1 kWt of fuel cell system waste heat can produce 1 kW of H₂ energy, up to a maximum. Heat is transferred with 100% efficiency between the fuel cell waste heat and endothermic steam reforming to produce additional H₂.
- The H₂ production rate is limited to 5% of the total fuel energy entering the system resulting in maximum H₂ production of about 17% of total recoverable heat produced.
- The total increase in fixed costs for the H₂ production, compression, and dispensing equipment and installation is estimated at 25% of the total capital and installation cost of the standard fuel cell system (not including warranty or shipping costs).
- H₂ is produced on demand just-in-time, with no H₂ storage.
- No tax on carbon dioxide (CO₂) emissions exists, but all California state and U.S. federal incentives are available.
- Case study results are shown for optimizing for both cost & CO₂ emission reductions. Sensitivity study results are shown for three different commercial H₂ prices.

Case study: We realistically describe the engineering performance characteristics of novel H₂-FCS.

Fuel Cell System Operating Data	Quantity	Units
Maximum Electrical Output	1000 kilowatts (kw)	
Minimum Electrical Output	880 kilowatts (kw)	
Maximum Heat-to-Electric Power Ratio	1.35	
Minimum Heat-to-Electric Power Ratio	0.7	
Baseline Heat-to-Electric Power Ratio for Fixed Heat-to-Power Ratio Operation	0.7	
Natural Gas Fuel Consumption (in Units of Energy) Per Unit of Electric Power Output	6,824 natural gas /kwh of recovered heat	British Thermal Units (BTU) of
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 natural gas /kwh of recovered heat	British Thermal Units (BTU) of
Baseline System Electrical Efficiency	50%	
Baseline System Heat Recovery Efficiency	30 to 35%	
Baseline Hydrogen Recovery Efficiency	5% to 0%	
Baseline System Heat Losses (Percent)	15%	
Baseline System Combined Electrical, Heat and Hydrogen Recovery Efficiency	85%	
Heat Recovery Efficiency of Burner-Heater for Marginal Heating (Variable Heat to Power Ratio Scenarios Only)	90%	
Fuel Cell System Lifetime	5 years	

1 MWe MCFC system performance is based on system currently in production at Fuel Cell Energy, Inc. Baseline heat recovery efficiency is 30% up to 35%. Baseline H₂ recovery efficiency is 5% down to 0%.

Case study: We realistically describe financial operating data for H₂-FCS and competing generators.

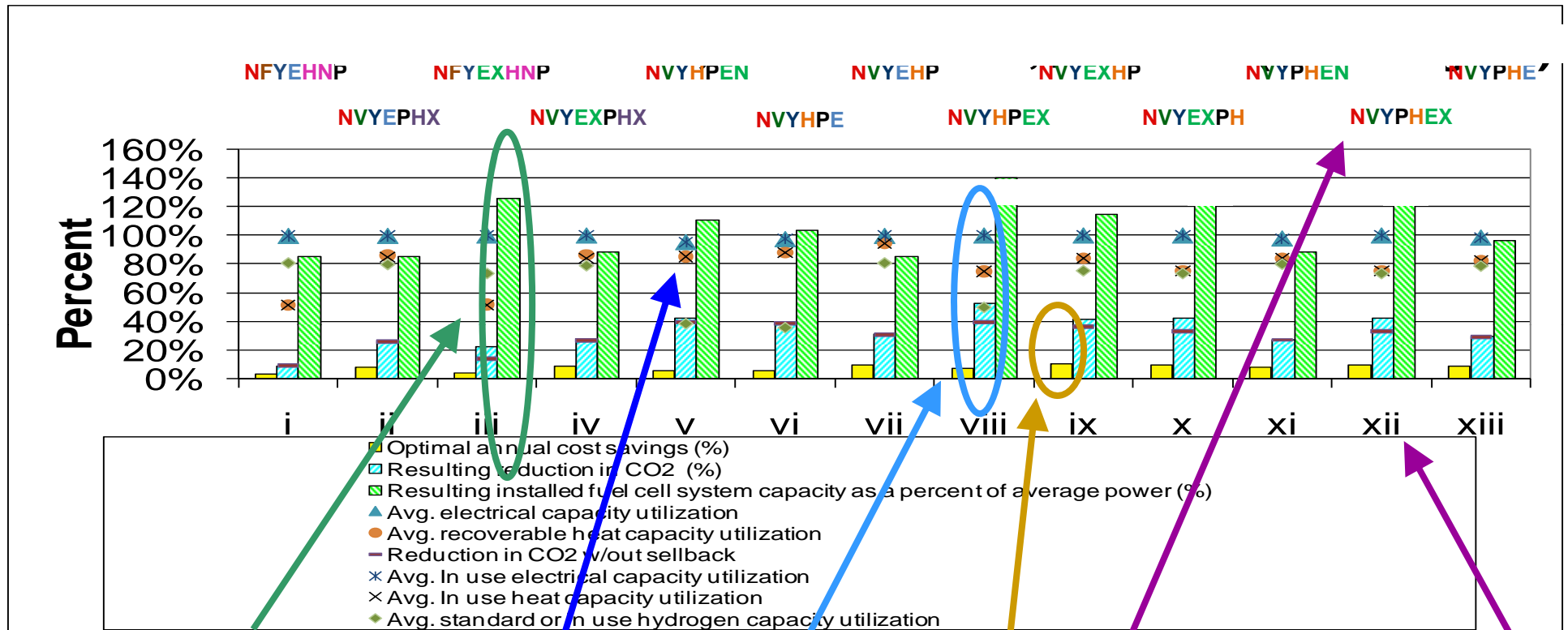
Fuel Cell System and H ₂ Co-Production Cost -- Fixed Cost per year	Amount Borrowed (or Credited) at	
	Time t = zero [P] (\$)	Annuity [A] (\$)
Capital Costs of 1000 kW Fuel Cell System and H ₂ Generator	\$ 4,000,000	\$ 986,446
Installation Costs Including H ₂ Generator	\$ 1,250,000	\$ 308,264
Commissioning 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 \$3,000/kWe or 30% of Capitol Costs	\$ 1,605,000	\$ 395,811
Fuel Cell System Fixed Costs -- Total Yearly Fixed Costs		
		707,031

Competing Generator: Natural Gas Combined Cycle Gas Turbine Plant	Quantity	Units
Price of steam for heating including carbon tax impact	0.056	\$/kWh steam
Price of electricity including carbon tax impact	0.085	\$/kWh electricity
Baseline System Heat Recovery Efficiency	0.22	
Baseline System Electrical Efficiency	0.40	
Baseline System Heat Losses	0.38	
Competing Generator: Distributed Steam Methane Reforming Hydrogen Generator		
H ₂ Price	2.00 or 4.00 or 23.64	\$/kg H ₂
CO ₂ Emission	7.49	kg CO ₂ /kg H ₂ produced

1 MWe MCFC system costs are based on Fuel Cell Energy's system. The MCFC is tested against a CHP combined cycle gas turbine (CCGT) and a SMR H₂ generator.

Results

Case study: We show benefits to electricity, heat & H₂ consumers; FCS manufactures; and the environment.



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

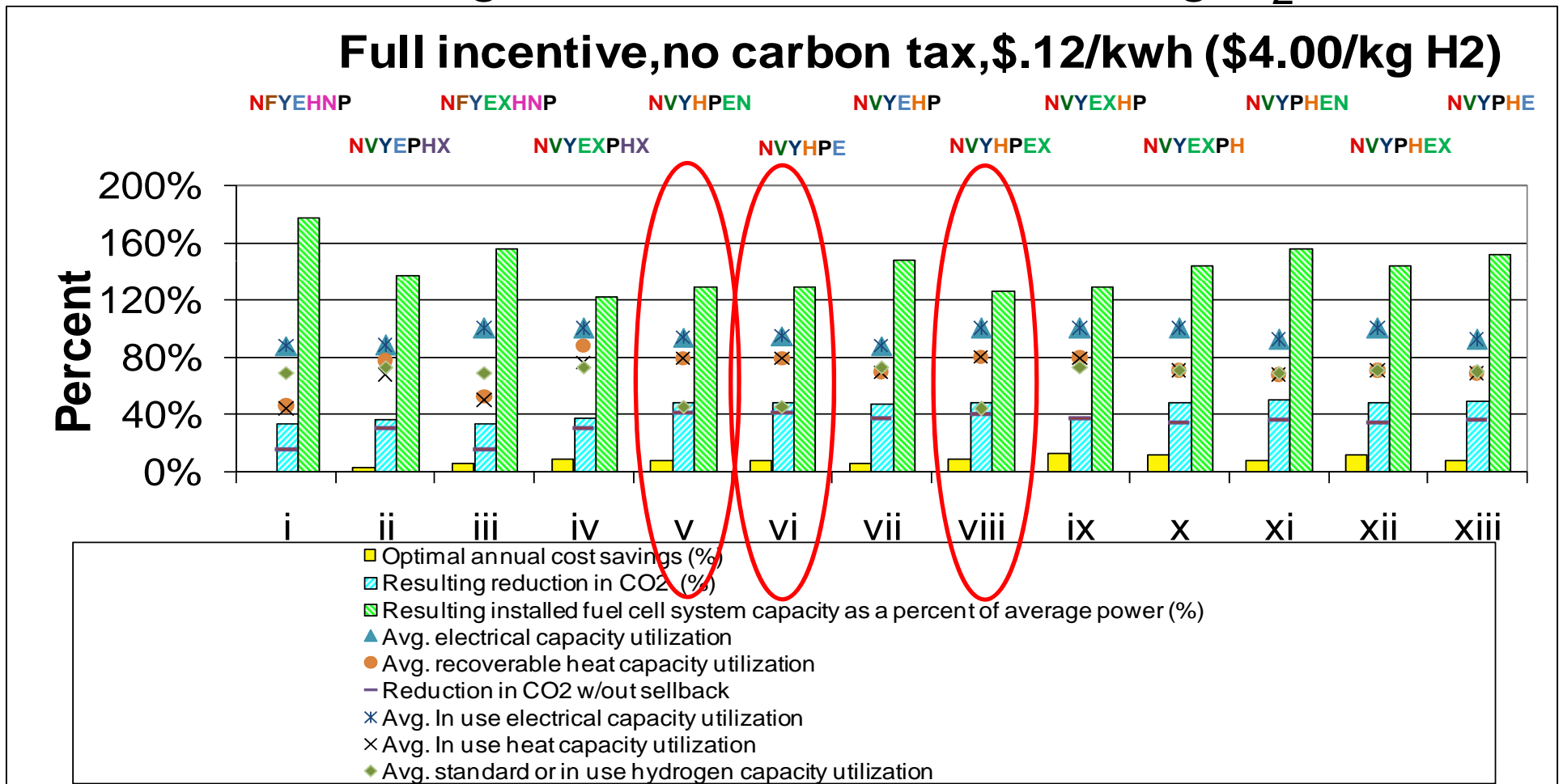
- ▲ Electrical capacity utilization
- Heat capacity utilization
- ✱ In use electrical capacity utilization
- ✕ In use heat capacity utilization
- ◆ Hydrogen capacity utilization

**Highest Blue = "blue
 skies", lowest CO₂**

Strategy name and number

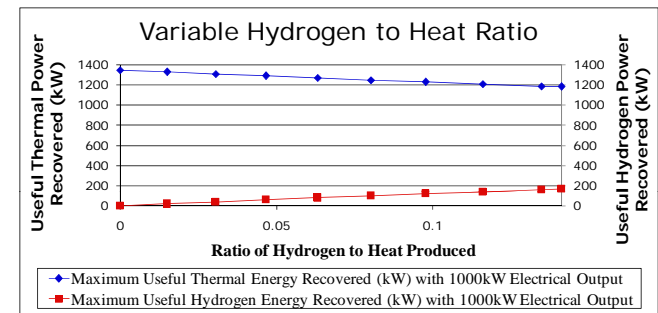
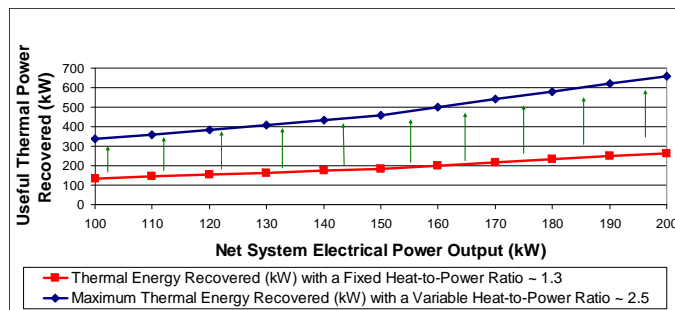
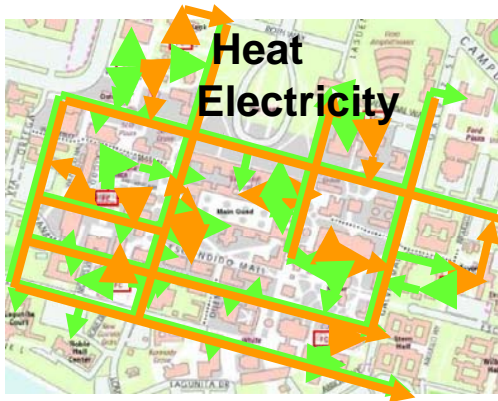
**Highest yellow = highest
 combined energy cost
 savings for building
 owners and H₂ consumers**

CO₂ emissions are lowest with our approach of networking, variable heat-to-power & H₂-to-heat ratios, first load following heat & then load following H₂.



Strategies with the lowest CO₂ emissions are v [NVYHPEN], vi [NVYHPE], and viii [NVYHPEX]. These strategies first follow heat demand [H] as the primary control, and then load follow H₂ demand [P] as the secondary control. Less fuel is wasted.

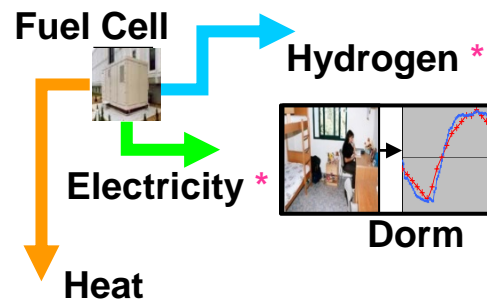
CO₂ emissions are lowest with our approach of electrical and thermal networking, variable heat-to-power ratio, variable H₂-to-heat ratio, first load following heat & then load following H₂. Less fuel is wasted.



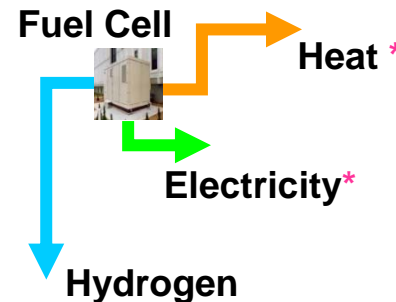
Networked (N)

Variable heat-to-power (V)

Variable H₂-to-heat ratios (Y)

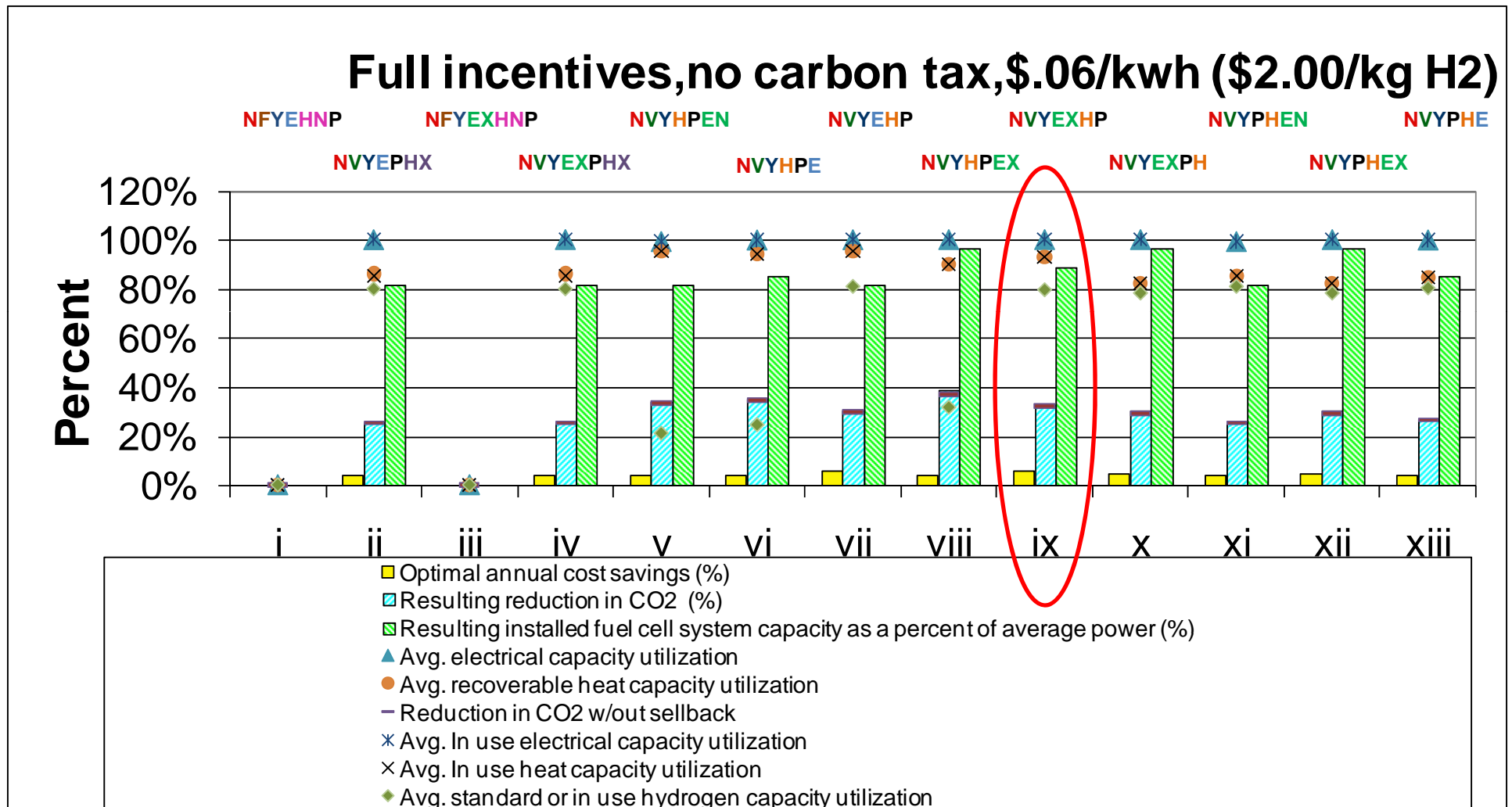


Heat Following (H)



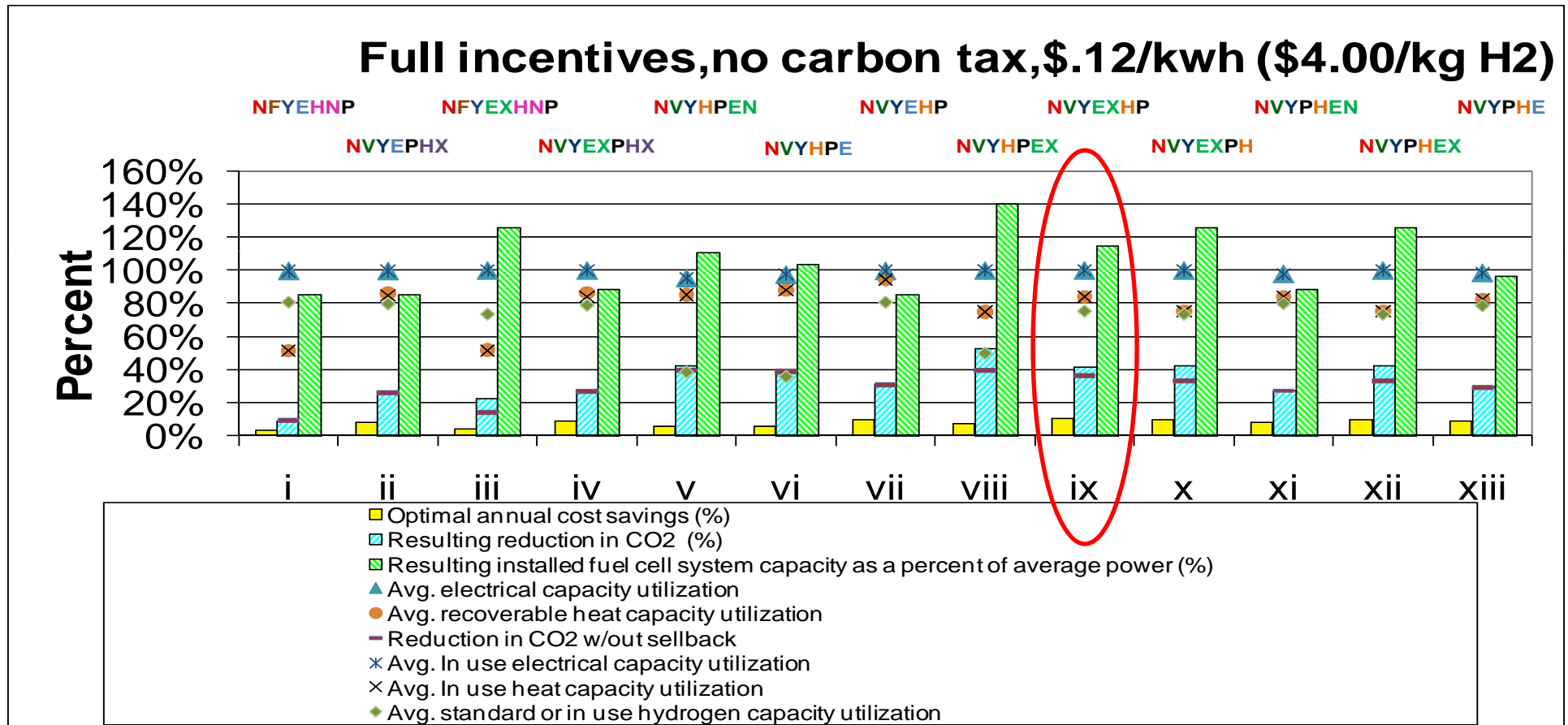
H₂ Following (P)

Energy costs are lowest with our approach of maximum FCS electrical output, with heat & then H₂ load following.



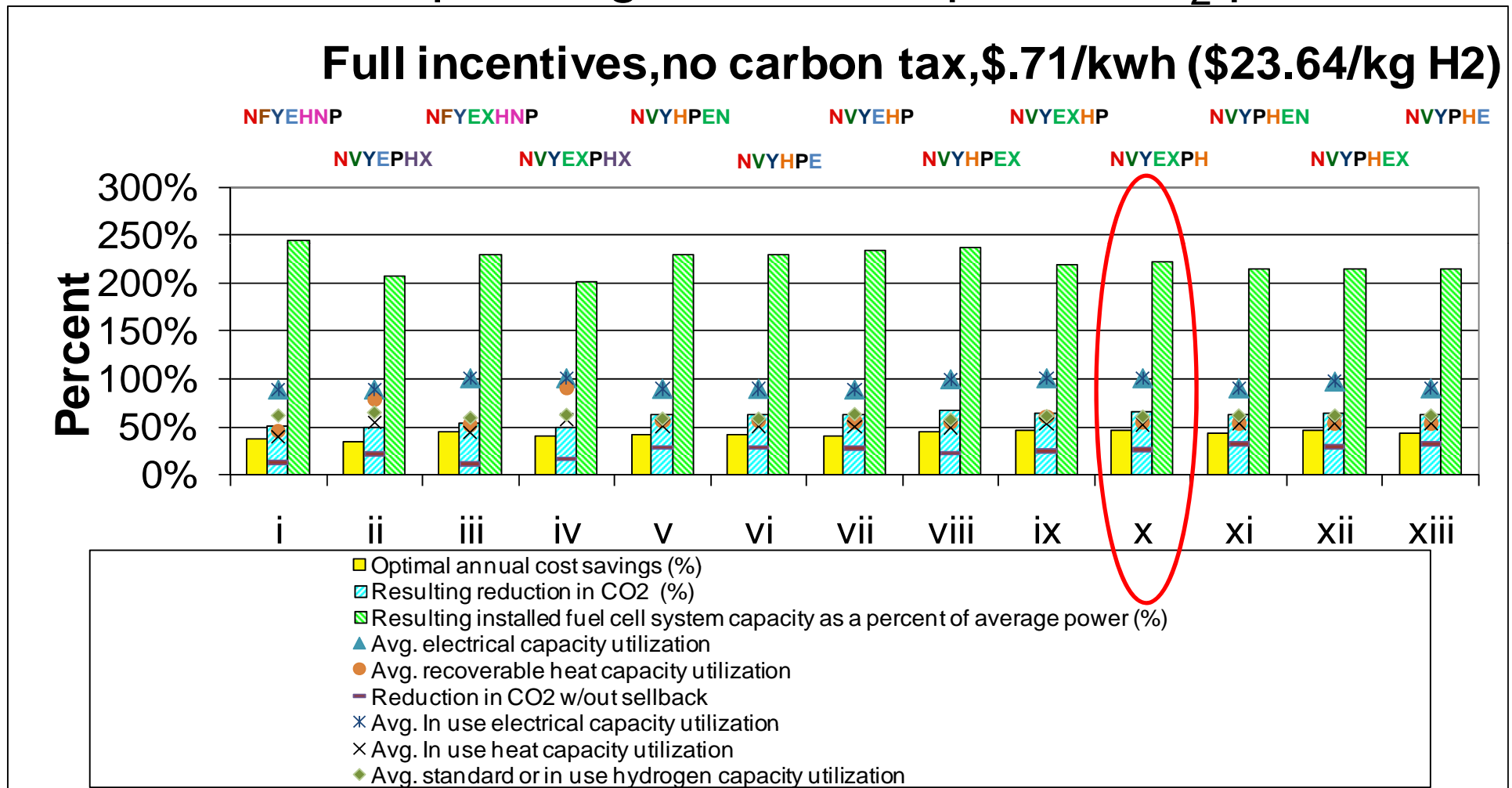
When the competing H₂ generator's price is \$2/kg H₂, the most economical strategy is ix [NVYEXHP]. The second best strategy is vii [NVYEHHP]. In this scenario, the electrical load following (E) is close to the maximum and therefore mimics EX.

Energy costs are lowest with our approach: H₂-FCS make the most electricity, sell any excess back to the grid, and locally make heat and H₂ with load following.



When the competing H₂ generator's price is \$2 or \$4/kg H₂, the most economical strategies are ix [NVYEXHP] (1st) & vii [NVYEHHP] (2nd). Grid-connected systems can sell excess electricity to the grid. By contrast, heat and H₂ demand are locally constrained; less fuel is wasted when they are made via load following, yielding higher cost savings.

Energy costs are lowest with our approach of maximum electricity, heat & H₂ load following, but in a different control order depending on the competitive H₂ price.



For a competing generator H₂ price of \$23.64/kg H₂, the most economical strategy changes to x [NVYEXPH]. The second best strategy is again xii [NVYPHEX].

Cost optimization favors maximum electrical output, and heat & H₂ load following.

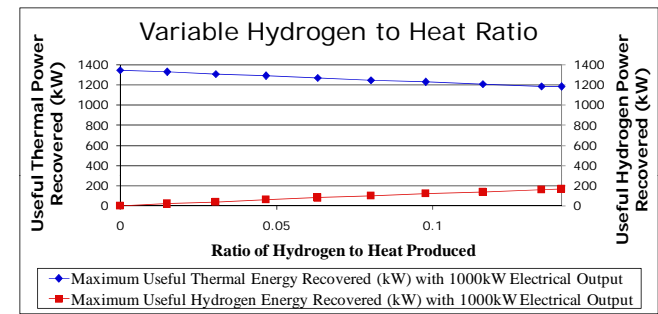
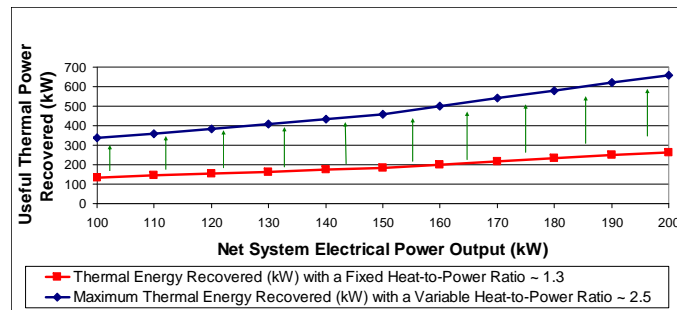
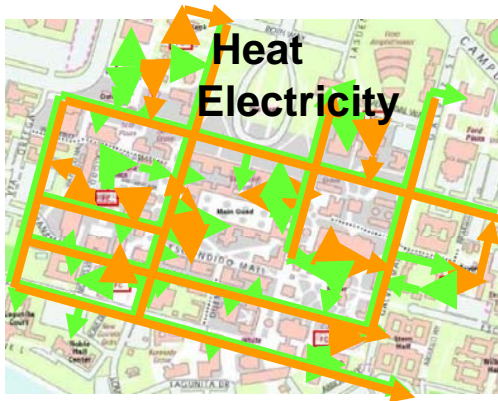
The most economical strategies investigated tended to combine a) electrical and thermal networking (N), b) a variable heat-to-electric power ratio (V), and c) a variable heat-to-H₂ ratio (Y) with these three characteristics 1) maximum electrical output (EX), 2) heat load following (H), and 3) H₂ load following (P).

- As long as systems are grid-connected with a competitive electricity sell-back price, they can sell excess electricity not used in the local area for revenue.
- By contrast, both heat and H₂ demand are locally constrained, without storage in these models. Less fuel is wasted when they are produced in load following mode, yielding higher energy cost savings.

As the competing generator H₂ price changes, the strategies with the highest cost savings change.

- As the competing generator H₂ price changes, the optimal order changes for primary, secondary, and tertiary control of 1) maximum electrical output, 2) heat load following, and 3) H₂ load following.
- For example, as the H₂ price increases from \$4/kg to \$23.64/kg, the most economical strategy changes from [NVYEXHP] with H₂ load following as the tertiary control to [NVYEXPH] with H₂ load following as the secondary control.
- In other words, as the competing generator H₂ price increases, it becomes more important to operate fuel cells with H₂ load following.

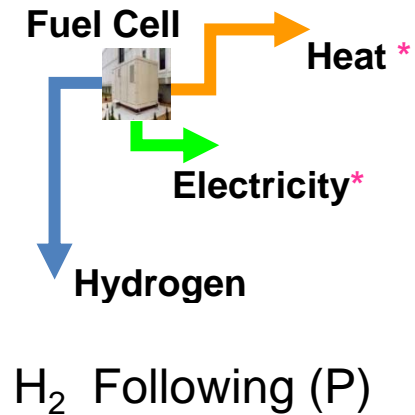
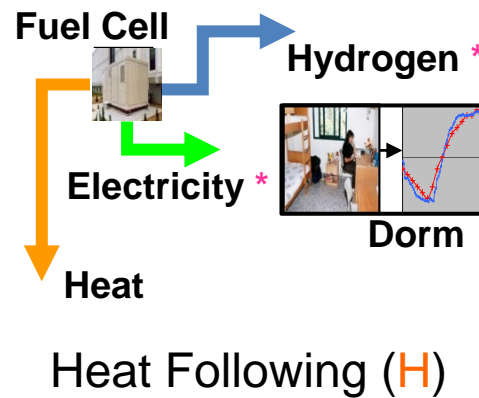
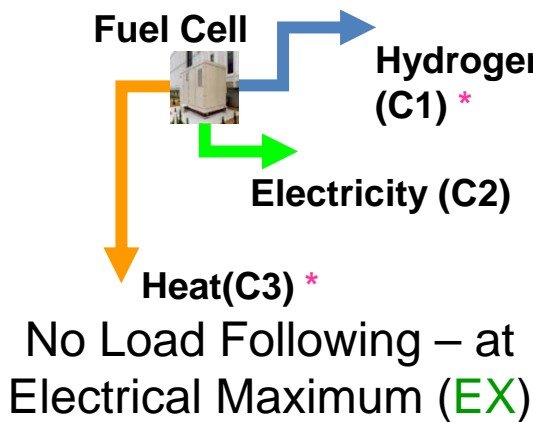
Costs are lowest with our approach of electrically and thermally networking, variable heat-to-power ratio, variable H₂-to-heat ratio, maximum electrical output, first load following heat & then load following H₂.



Networked (N)

Variable heat-to-power (V)

Variable H₂-to-heat ratios (Y)



Conclusions

Summary – Key take-away points

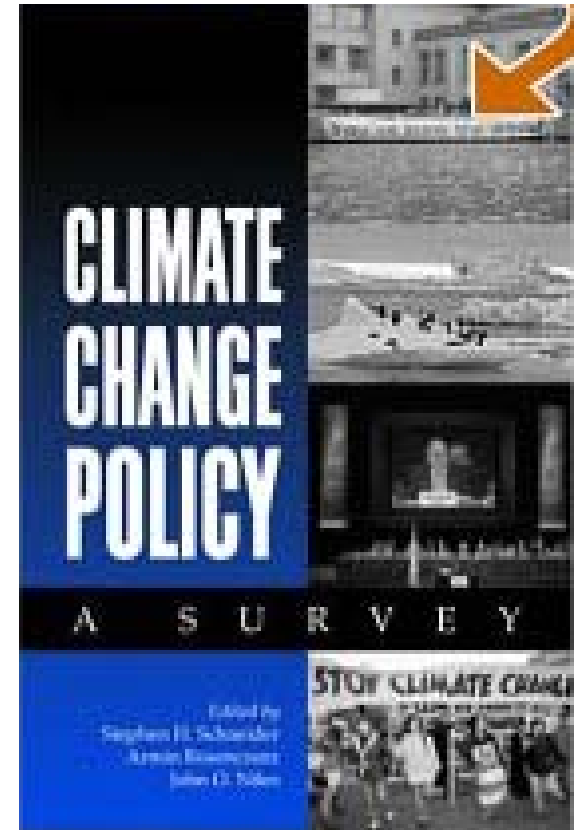
Our novel H₂-FCS designs have the lowest CO₂ emissions & costs of any H₂ production method to-date.

Global CO₂ emissions from H₂, electricity, and heat are lowest when H₂-FCS are electrically and thermally networked, use variable heat-to-power & H₂-to-heat ratios, and load follow heat and H₂ demands.

Global energy costs from H₂, electricity, and heat are lowest when H₂-FCS are networked, use variable heat-to-power & H₂-to-heat ratios, produce at their maximum electrical output continuously, and load follow heat and H₂ demands.

Publications

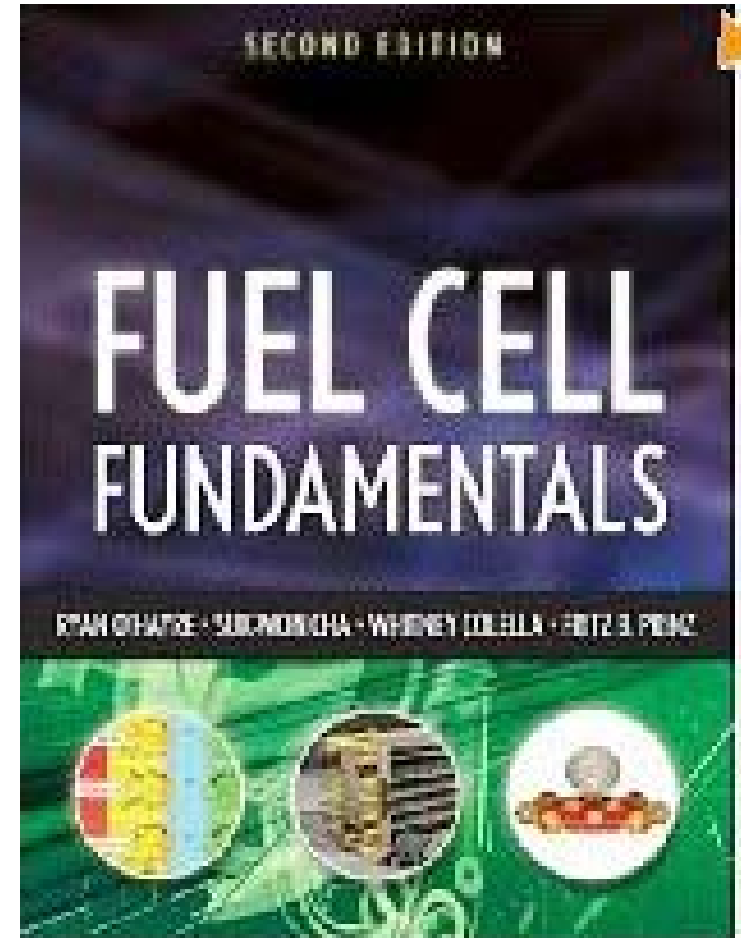
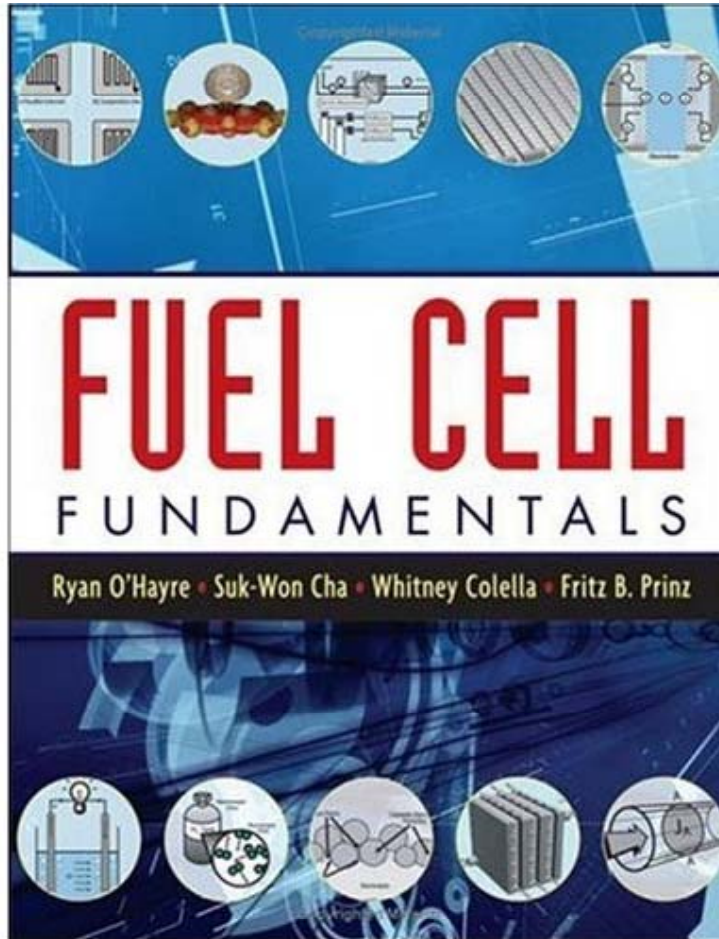
Climate Change Science and Policy educates policy makers and engineers on hydrogen and climate.



“**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

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. 1st & 2nd editions available.

Collaborators



Aerel Rankin and Pere Margalef are university students who contributed to this work.

Aerel Rankin is an M.S. candidate in Mechanical Engineering (ME) at the University of New Mexico. Aerel holds a B.S. in ME from the University of Washington. His educational focus is sustainable energy devices.



Pere Margalef is a Ph.D. candidate in ME at the University of California, Irvine (UCI) at the National Fuel Cell Research Center (NFCRC). Pere holds a M.S. degree in Environmental Engineering from UCI. His dissertation focuses on hydrogen cogeneration.



**Sarah Kelly is a UCI student who contributed to this work.
Prof. Jack Brouwer advises Sarah.**

Sarah Kelly is an M.S. in ME at UCI NFCRC. Sarah holds a B.S. in ME from Iowa State University. Her research centers on high temperature fuel cells.



Dr. Jack Brouwer is Adjunct Associate Professor in ME at UCI and the Associate Director of NFCFC. Dr. Brouwer holds a Ph.D. in ME from the Massachusetts Institute of Technology (MIT). He leads a team of researchers in experimental & theoretical investigation of fuel cells, electrolyzers, gas turbine engines, fuel processing, photovoltaics, wind turbines & other novel energy systems.



Matt Abbott and Melahn Parker are university students who contributed to this work.

Matthew Abbott is a junior Computer Science student at Texas A&M University. His academic focus is on Computational Science and Engineering



Melahn Parker studied for his engineering Ph.D. at Stanford University. His other degrees include a B.Sc. in Aeronautics (Stanford), a B.Sc. in Chemical Eng. (MIT) 2000, an M.Eng. in Aerospace Eng. (MIT) 2001, and a M.Sc. Chemical Eng. (Caltech) 2003.



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- Professor Daniel M. Kammen

