Hydrogen Energy Stations for Electricity and Hydrogen Co-Production

ARB Chair's Seminar Series

February 28, 2007

Tim Lipman, PhD

telipman@berkeley.edu

Inst. of Transportation Studies

University of California, Berkeley

Talk Overview

- Current UC Berkeley Research Projects
- Hydrogen Energy Station Overview
- Recent Analysis Results
- Previous Analysis Results
- High Temp. FC Based Stations
- Conclusions

ITS-Davis BEV Cost Study for ARB (1998-2000)

Type of battery -->	**Pb/acid**		**NiMH Gen2**		**Li-ion**		**NiMH Gen4**	
Driving range (miles) -->	65	110	90	165	140	260	100	190
Retail cost, Taurus ($)								
Base case	**24,553**	**29,422**	**28,034**	**35,759**	**27,678**	**32,448**	**25,487**	**29,692**
Retail cost, Escort ($)								
Base case	**19,784**	**23,384**	**22,725**	**28,822**	**22,280**	**25,948**	**20,623**	**23,904**
Break-even, Taurus ($/gal)								
Base case	**2.64**	**4.14**	**4.19**	**6.66**	**2.77**	**4.33**	**1.83**	**2.91**
Break-even, Escort ($/gal)								
Base case	**3.27**	**4.84**	**5.04**	**7.73**	**3.38**	**5.06**	**2.40**	**3.59**

Note: Costs in Year 2000 $s

New UCB Transportation Sustainability Research Center

- Based at Inst. of Transportation Studies With:
  - Univ. of California Transportation Center
  - Energy and Resources Group
  - Univ. of California Energy Institute
  - Center for Global Metropolitan Studies
  - Berkeley Institute for the Environment
- Alex Farrell Named Initial Director and Tim Lipman as Research Director
- Various Research Projects Underway Including BIE Working Group for Alternative Transp. Fuels

UC Berkeley FCV Research Program

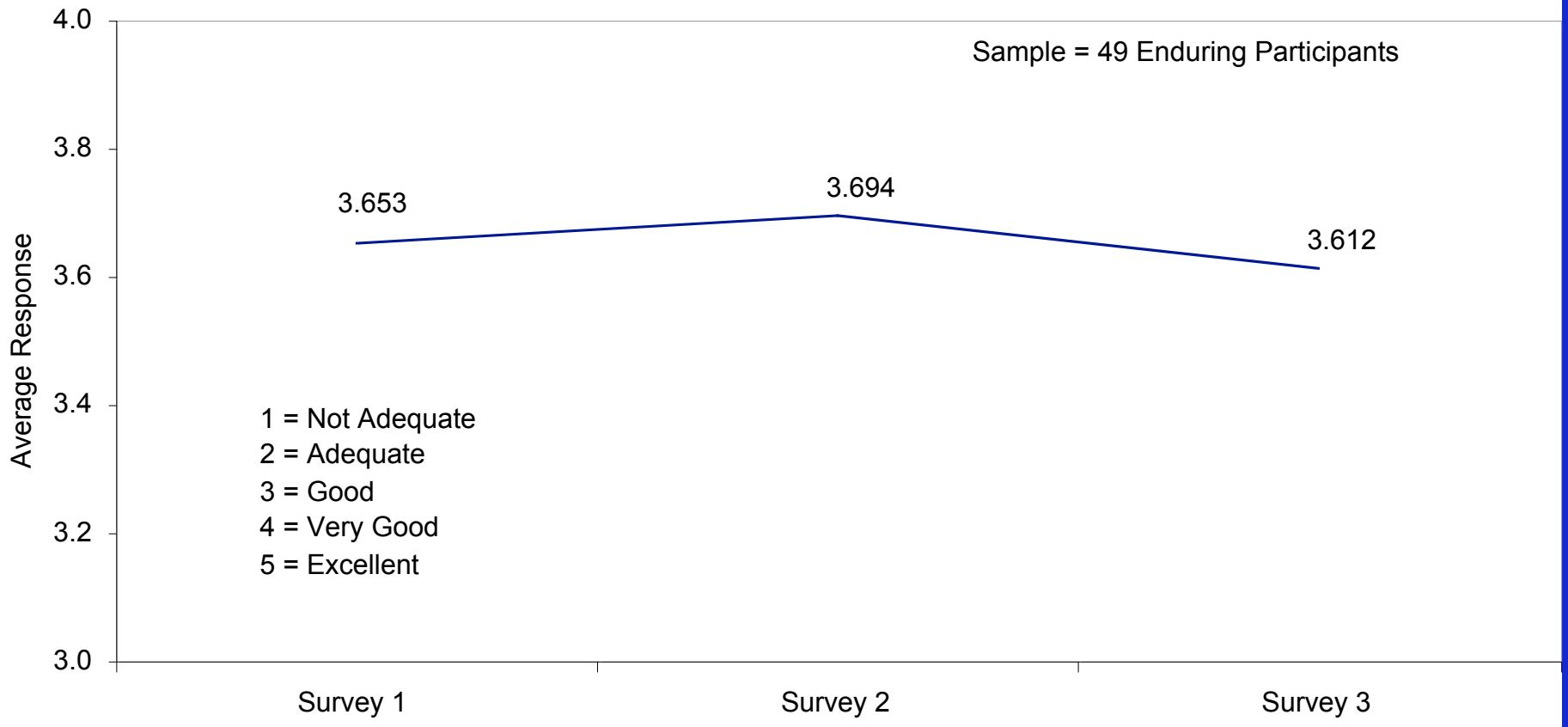
UC Berkeley FCV Research Program

- Multiple Users at the California PATH Facility at the Richmond Field Station Will Drive Approx. 10,000 Miles per Year for Two Years
- UCB Researchers Worked with DCX to Conduct Market Research Associated with F-Cell Fleet Placements -- Report Now Available
- Obtained Caltrans Funding to Conduct "Drive and Refuel" Clinics and Focus Groups to Explore Early Niche Markets
- Hydrogen Infrastructure Studies In Collaboration with UC Davis

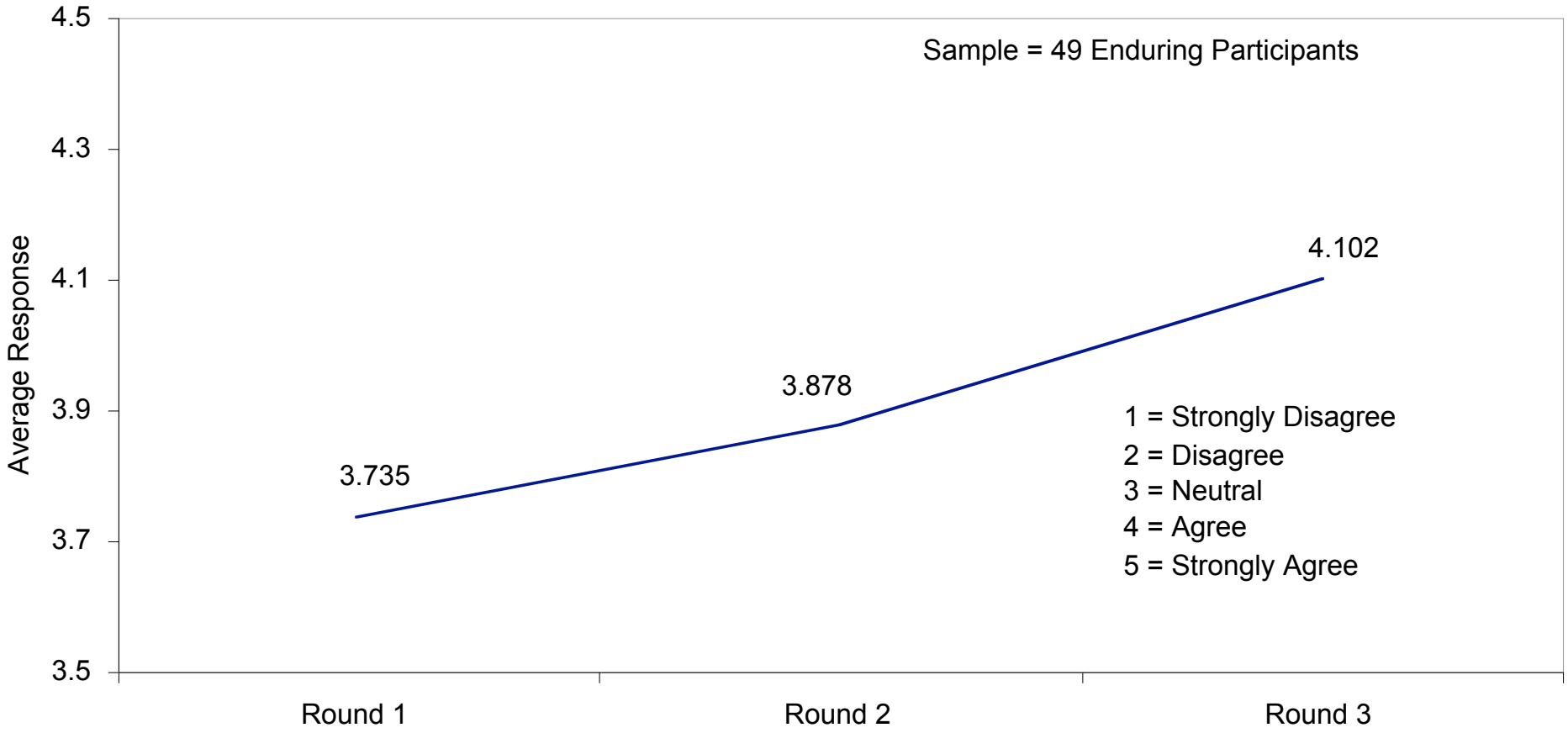
F-Cell "Consumer Response" Study

- A Three Round Longitudinal Survey Over Eight Months, in Attempt to Get Past the "Novelty Effect"
- 65 Drivers Completed the First Round Survey and 49 Drivers Completed All Three Rounds
- Generally High Acceptance Except with Regard to Driving Range
- Sample Was "Self-Selected" to a Significant Extent, so Not a Statistically Significant Cross-Section

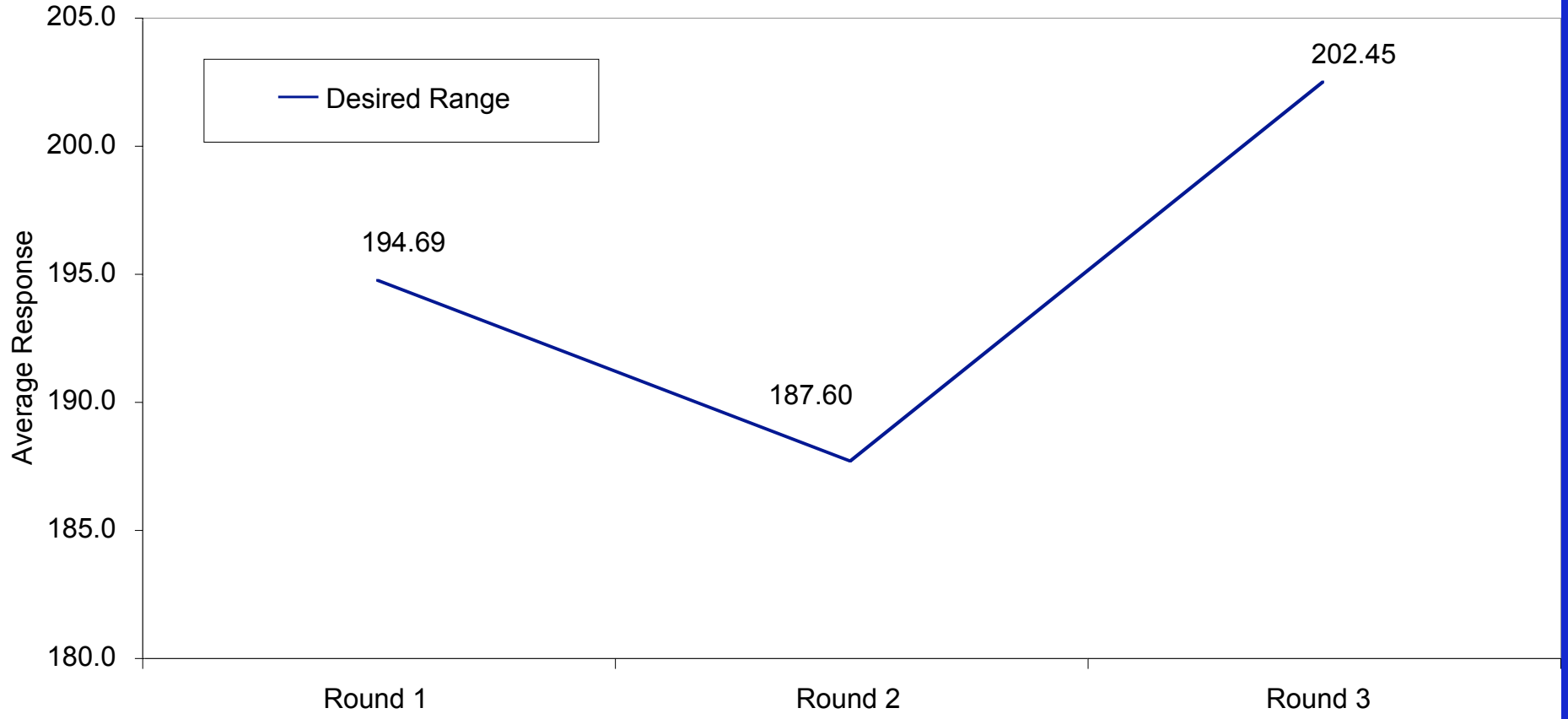
What is Your Overall Impression of the F-Cell?



I Feel Equally Safe in a Hydrogen Vehicle Compared with Gasoline



What Do You Think is an Acceptable Range for the F-Cell?



EasyConnect Project at Pleasant Hill

- Site of Future "Transit Village" -- $500 Million Development by Millennium Partners
- EasyConnect is a Caltrans Funded Project to Address Transit System "Last Mile" Problem
- Users Can Select Various Low-Speed Vehicles From an Electronic Locker System to Travel From/To BART Station and Their Work Location
- Coming Soon: "CleanCharge" Project Component
  - Addition of 2 NEVs and Demonstration Charging Station
  - 5 kW Stationary PEM Fuel Cell to Provide Charging in Parking Lot
  - Project in Collaboration with CA Stationary Fuel Cell Collaborative, CIWMB, Altergy Systems, and Contra Costa County (and BART and Caltrans)

EasyConnect Project at Pleasant Hill

EasyConnect Project at Pleasant Hill: New "CleanCharge" Component

Pacific Region CHP Application Center

- The PRAC is a U.S. DOE and CEC Sponsored Project to Promote Further Development of Combined Heat and Power (CHP) for Energy Efficiency in the Pacific Region (CA, NV, HI)
- Partnership Between UCB, UCI, and SDSU
- Education and Outreach and Direct Project Assistance Efforts
- Upcoming BioEnergy Conference in Napa from April 18-20, 2007: www.cabioenergy.com
- http://www.chpcenterpr.org

Caltrans Energy Analysis Support

- Task Order Based Contract to Provide Analysis Assistance to Caltrans for Clean Energy Technology Analysis Efforts
- First TO is Examining Potential for Ammonia-Based Hydrogen Storage and Delivery Systems to Support Low-Carbon Fuel Cell Demo/Pilot Projects
- Other TOs Will Examine Emissions from Backup Generators and Potential CHP Opportunities
- Steve Prey is Primary Caltrans Contract/Sponsor

NSF MUSES GHG/Auto Project

- Multi-Campus Effort to Examine Potential Impacts of Automobile Sector GHG Policies on Producers and Auto Industry Materials Flows
- Led by Univ. of Michigan and Rochester Inst. of Technology with UCB/UCD and Northeastern Univ.
- UCB/UCD are Leading Vehicle Technology Cost and Performance Analysis and Collaborating with RIT on Policy Aspects
- Univ. of Michigan is Leading the Materials Flows/LCA and Consumer Response/Behavior Efforts
- http://sitemaker.umich.edu/autopolicydesign/home

Hydrogen Infrastructure Analysis

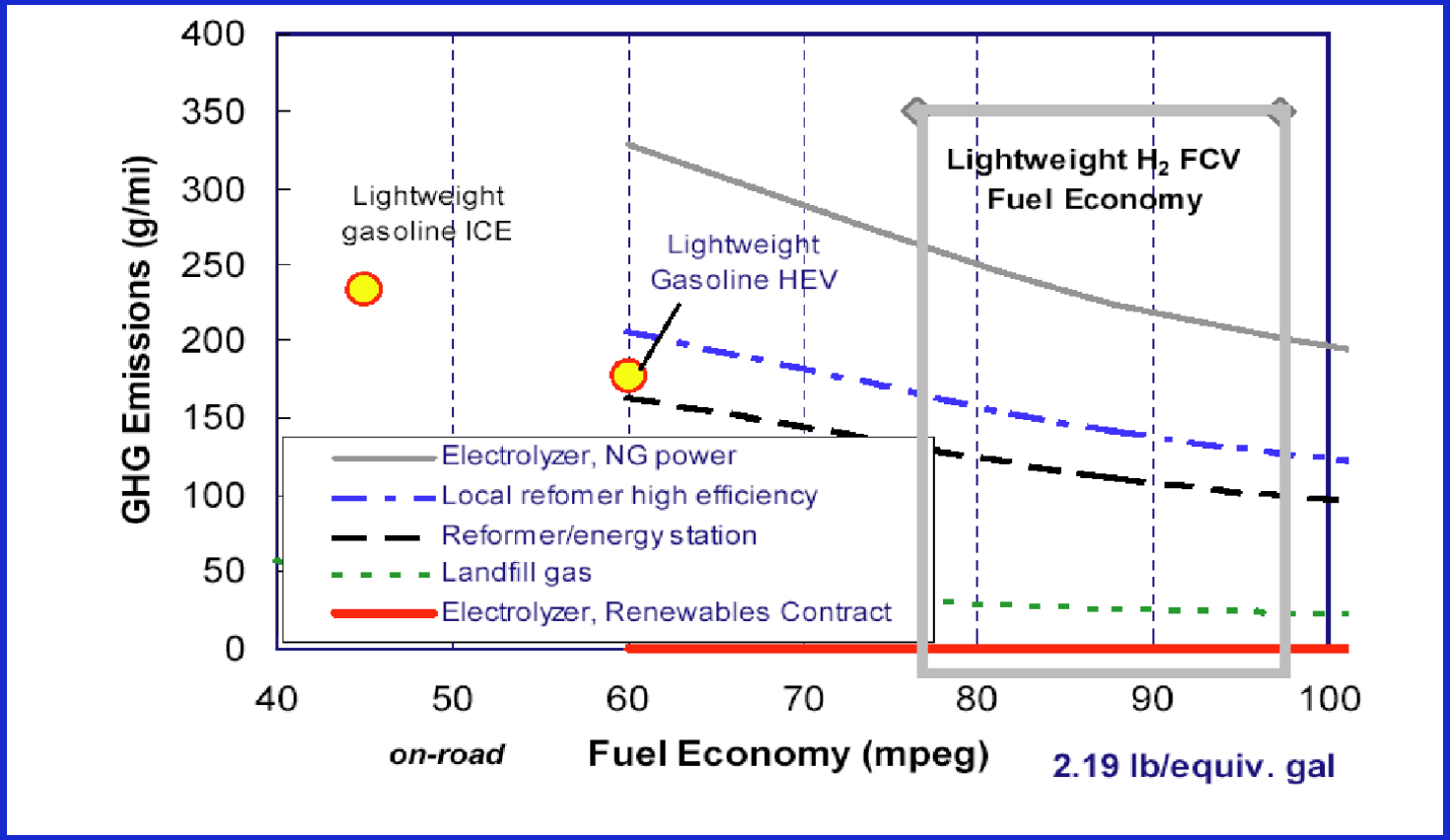
- Fundamental "Chicken or the Egg" Question
  - Private consumers will not buy vehicles without significant refueling infrastructure
  - Energy companies reluctant to invest in infrastructure without a clear business case
  - Economics of hydrogen production/distribution for low levels of vehicle demand are challenging

?!

Hydrogen Energy Station Overview

- Basic Idea is Co-Production of Electricity and Hydrogen to Capture Potential Synergies (e.g. natural gas reformer scaling effects)
- Stations Can Be Either Reformer Based or Electrolyzer Based (or even H2 combustion gen-set)
- Many Different Possible Settings (not just service stations)
- Can Be Mainly for Electricity or Hydrogen Production, or Adaptable/Variable Over Time
- Techno-Economic Analysis Requires Many Assumptions and Considerable Input Data

Hydrogen Production: Need a Transition



Source: BKI, 2001

Hydrogen Energy Stations

Called out in the Governor's California Hydrogen Highway Network Executive Order:

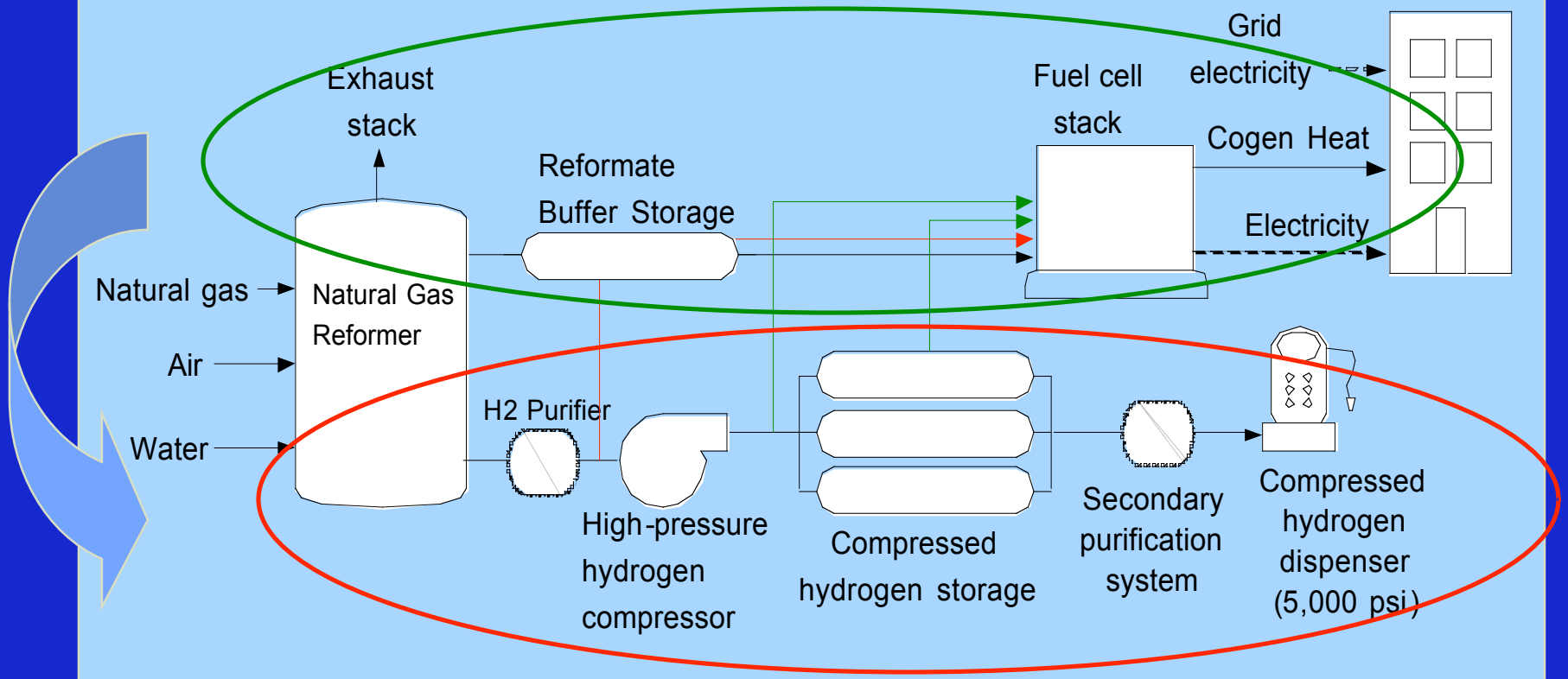
"Whereas, the *economic feasibility* of a hydrogen infrastructure *is enhanced by* building *hydrogen energy stations* that power vehicles as well as supply electricity for California's power needs"

Why Might This Be Interesting?

- Key Problem of Low Throughput at Initial Hydrogen Stations
  - Poor performance of capital investment
  - Risk of stranded assets if vehicle markets develop slowly
  - Mobile refuelers one solution but can't work everywhere
- Possibility of Cross-subsidization of Hydrogen Production with Electricity Cost Savings
  - Reduce effective cost of hydrogen production in high electricity cost areas
  - Fleet refueling facilities with nearby electrical loads
- Dual Use of Reformer -- Economies of Size?

Hydrogen Energy Station: One Design Based on PEM Fuel Cell

Distributed Power Generation Can Be Good Biz Model



Distributed Hydrogen Production for <30-50 Veh/Day is Probably Bad Biz Model

Hydrogen Energy Station in Las Vegas, Nevada

ChevronTexaco Energy Station Concept

New Chevron / AC Transit Station

Energy Station Economic Analysis

- Previous Work (2001-2002)
  - Initial analysis effort at UC Berkeley by Lipman et al. funded by the UC Energy Institute, the Energy Foundation, DaimlerChrysler, and BP
  - MATLAB based model "CETEEM" -- consists of several hundred Simulink blocks along with Excel spreadsheets + macros for input/output
  - First analysis compared service station and office building energy station settings and various configurations, with southern California utility rates and building loads
  - Report (EDT-03) available through UCEI at:

    http://www.ucei.berkeley.edu/Working_Papers/WPS.html#EP

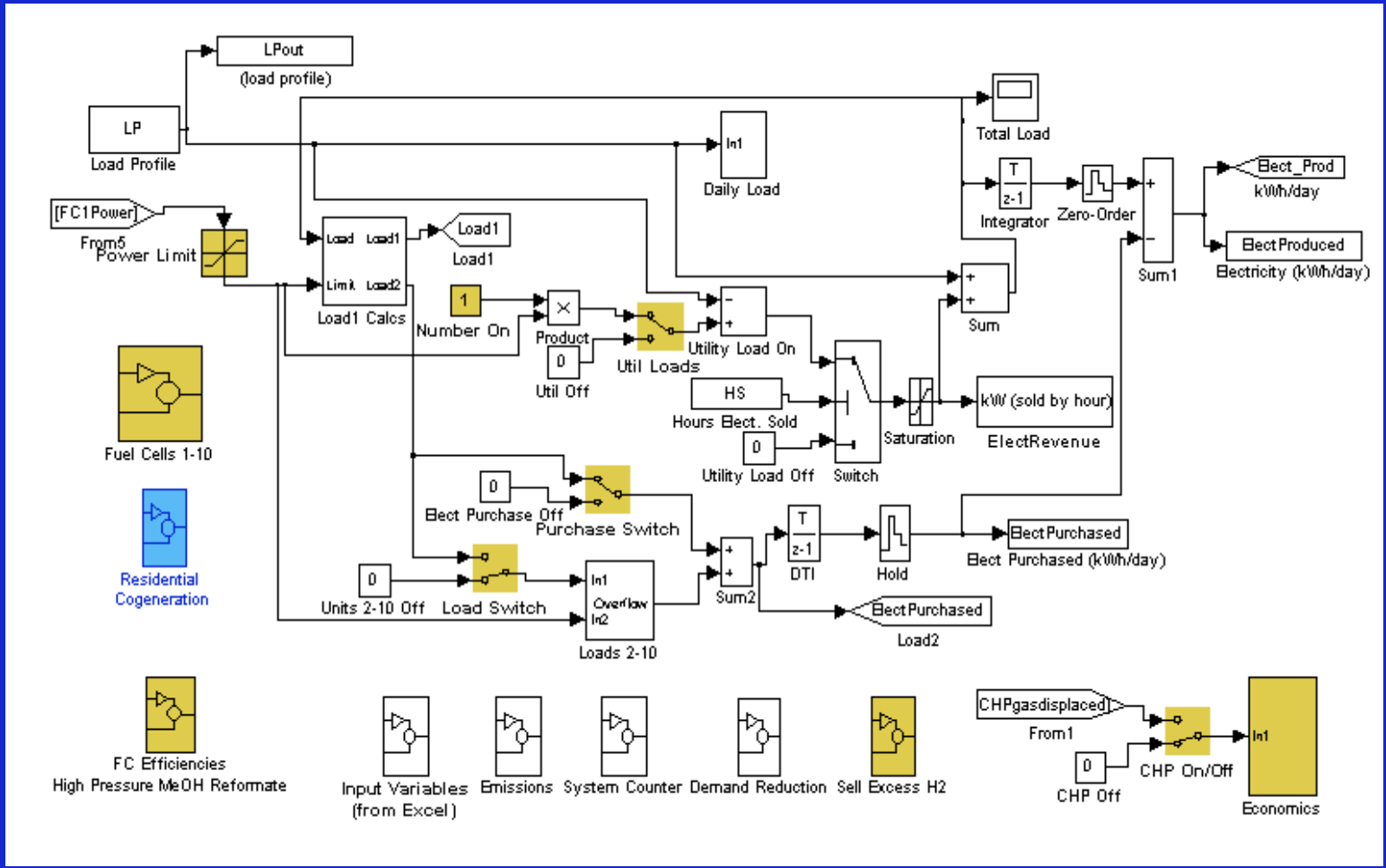
- Current Work (2005-2006+)
  - Funded by UC Davis Hydrogen Pathways Program
  - Revisiting Analysis with New and Improved Input Data and Assumptions

Key Analysis Variables

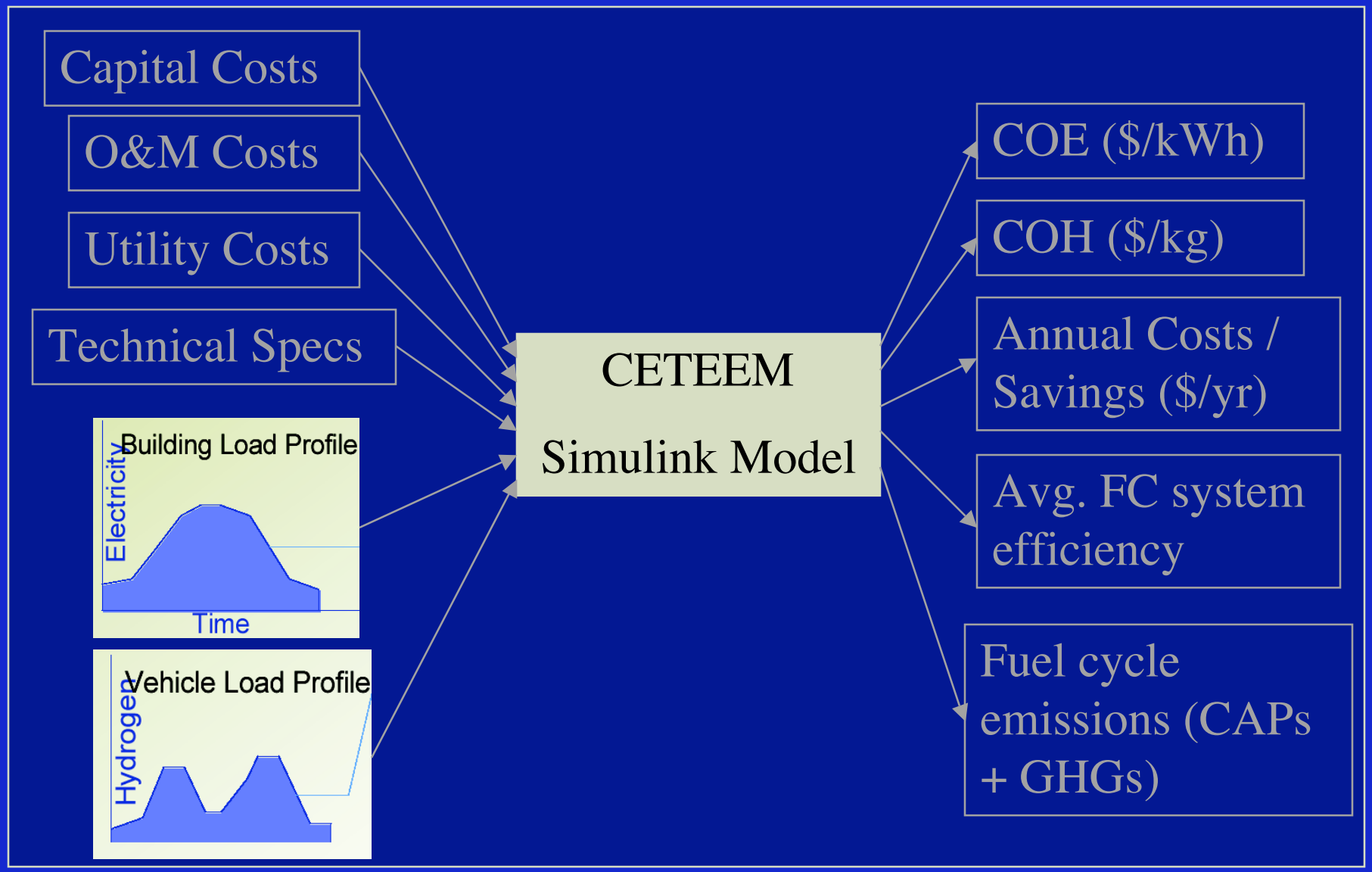
- Technical
  - Fuel cell size
  - Reformer capacity
  - Compressor size
  - Storage system size
  - Fuel cell system performance
  - Reformer/PSA performance
  - Compressor power use
  - CHP system performance
  - Emission factors
- Economic
  - Fuel cell capital costs
  - Fuel cell O&M costs
  - Reformer/PSA capital costs
  - Reformer/PSA O&M costs
  - Fuel costs
  - Electricity costs (energy and demand)
  - H2 storage system costs
  - H2 dispensing system costs
  - CHP equipment costs
  - Building electrical load profiles (“before” and “after”)
  - Building thermal load profiles
  - Electricity prices (with sell-back scenario)
  - Installation, interconnection, and permitting costs

CETEEM Top Level (Simulink)

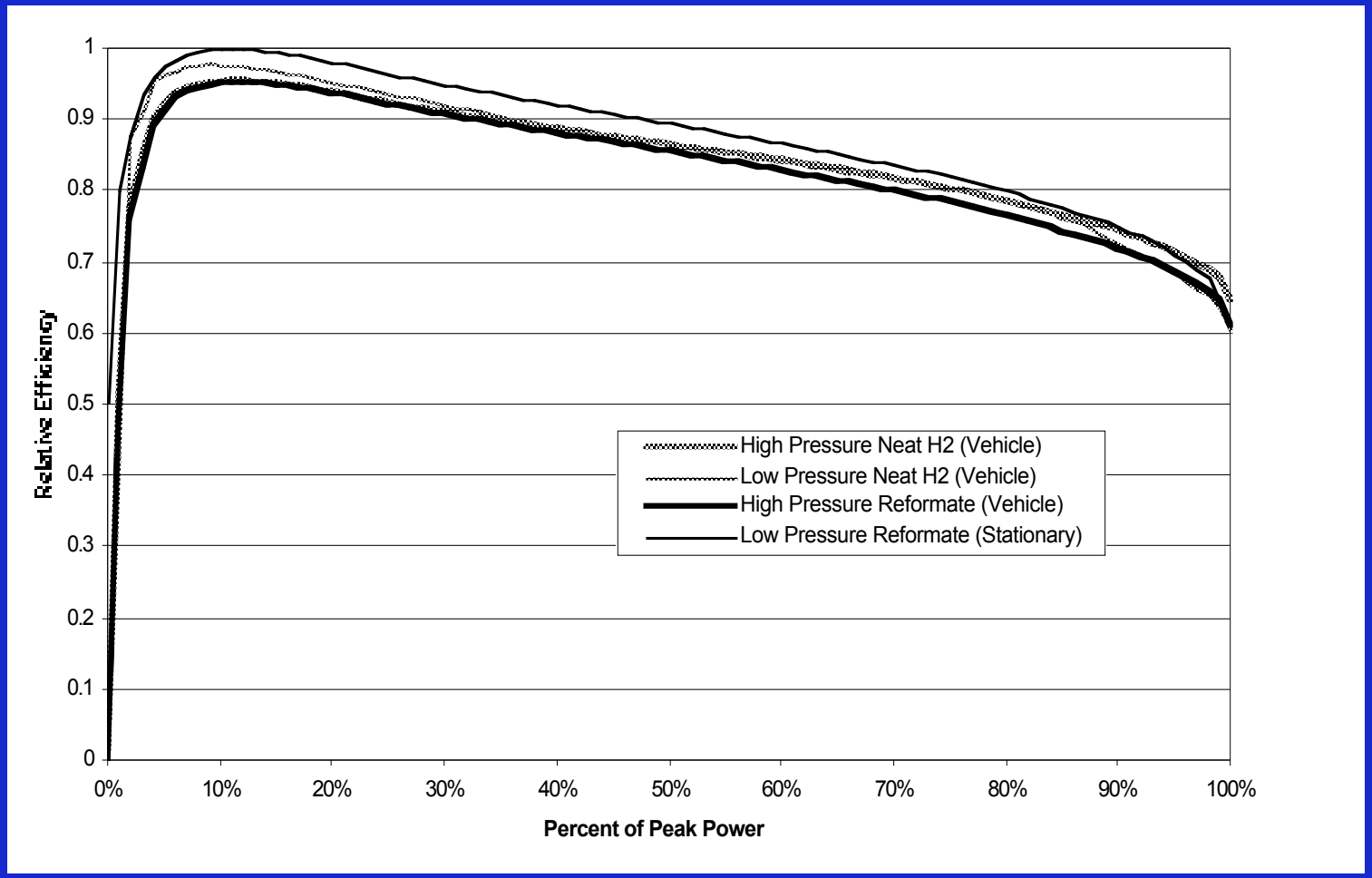
Clean Energy Technology Economics and Emissions Model



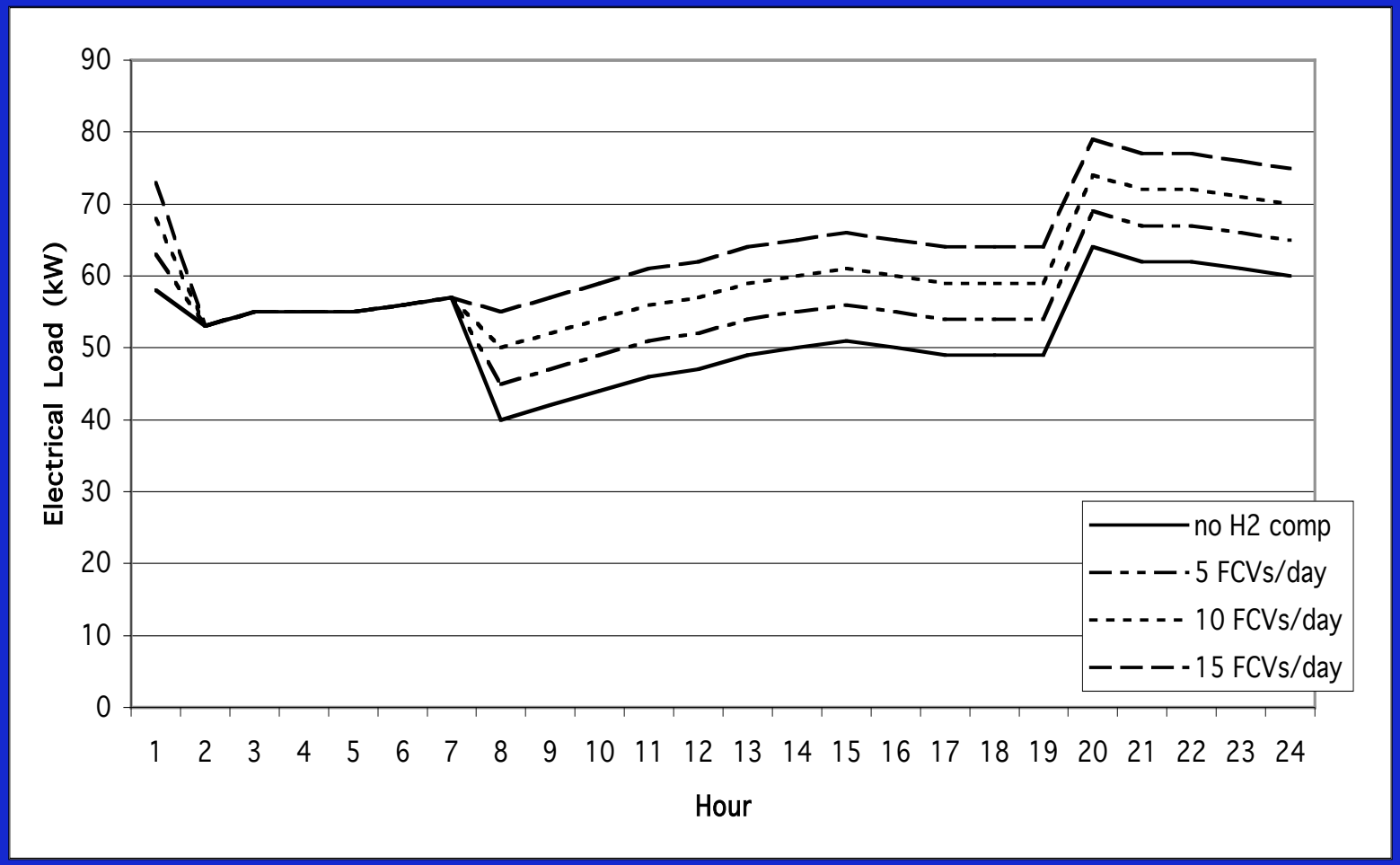
CETEEM Inputs and Outputs



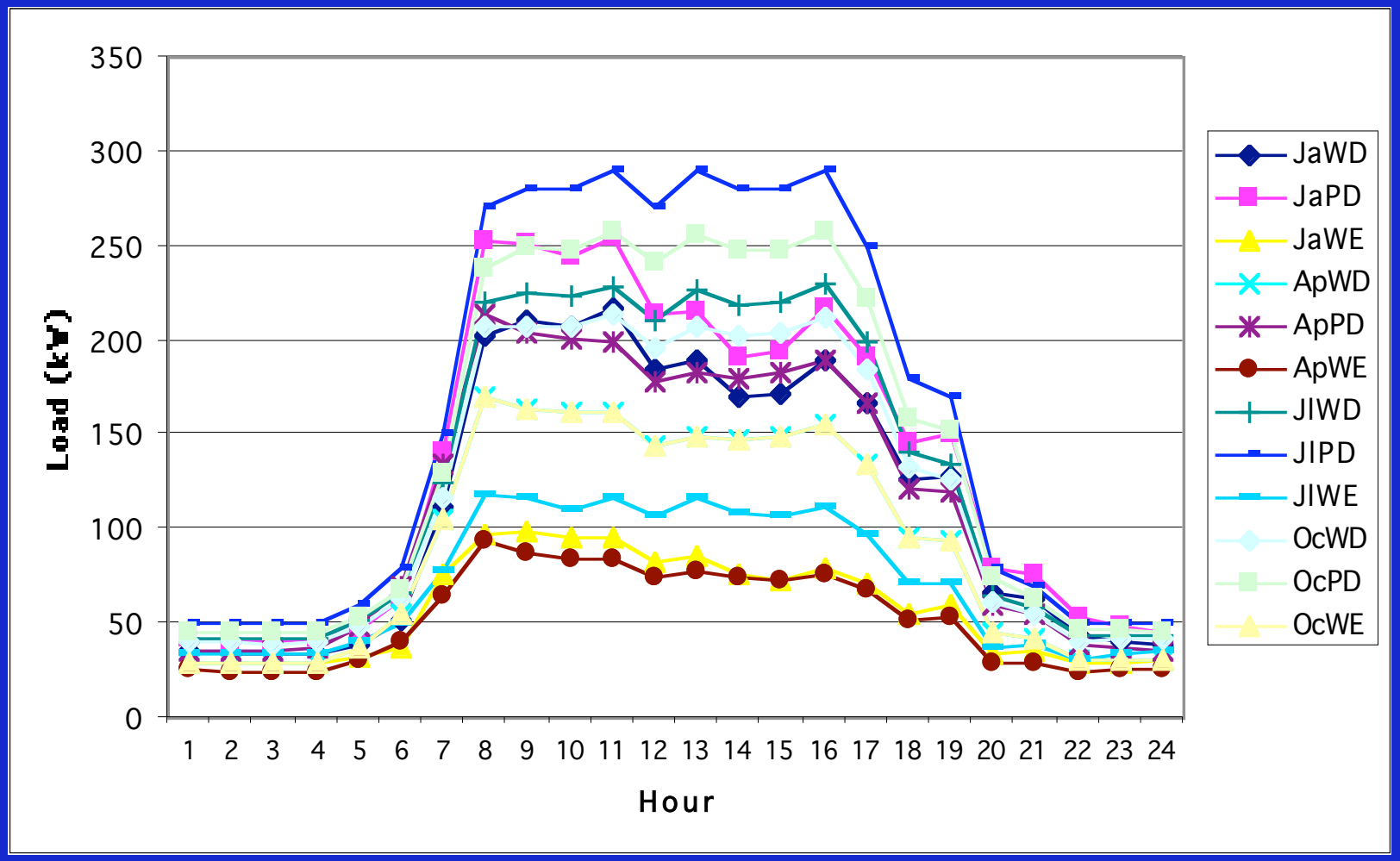
Fuel Cell System Characterization



Service Station Electrical Load with H2 Compressor Electricity Use



Medium-Sized CA Office Building Loads



New Analysis Cases

- Recently Completed Several New Service Station Design Cases Including Export of Grid Power
- Various Fuel Cell Sizes and Other Variables
- Improvements Since First Round of Analysis in 2002-2003:
  - Better analysis of reformer and hydrogen storage sizing
  - Near term cost estimates based on CHREC
  - Better data on PEM system performance from UTC

New Analysis Cases

- Base Case Assumptions:
  - Service station location with consistent/predictable H2 demand
  - NG reformer based design (NG@$7/GJ)
  - Electricity costs (PG&E commercial rate schedule):
    - $0.10/kWh + $4.9/kW-mo (winter)
    - $0.13/kWh + $10.3/kW-mo (summer
  - Nearby thermal load (hot water) to meet PUC 218.5 for SGIP incentive of $2.50 per Watt
  - 10 or 50 vehicles per day refueled and H2 sold at $20/GJ (~$3/kg)
  - PEM FC capital costs of $4,000/kW ($1,500/kW after SGIP)
  - PEM durability of 15,000 hours between stack replacements
  - Reformer and storage costs from CHREC analysis

New Analysis Case #1

- 40 kW PEM Fuel Cell with 10 Veh./Day Refueled
- All FC Power Used Onsite
- 24/7 FC Operation So Stacks Only Last Two Years
- 34 kg of H2 Storage
- Results:
  - Station Cost: $477,000
  - Electricity Produced: 350,400 kWh/yr
  - Avg. FC Efficiency: 33% (incl. reformer efficiency)
  - Annual Cost: $78,400/yr (incl. elect. cost savings and H2 revenue)
  - Cost of H2 Production (approx.): $3.32/kg

New Analysis Case #2

- 80 kW PEM Fuel Cell with 10 Veh./Day Refueled
- All FC Power Used Onsite
- 24/7 FC Operation So Stacks Only Last Two Years
- 38 kg of H2 Storage
- Results:
  - Station Cost: $579,300
  - Electricity Produced: 588,380 kWh/yr
  - Avg. FC Efficiency: 35% (incl. reformer efficiency)
  - Annual Cost: $64,900/yr (incl. elect. cost savings and H2 revenue)
  - Cost of H2 Production (approx.): $3.22/kg

New Analysis Case #3

- 80 kW PEM Fuel Cell with 10 Veh./Day Refueled
- All FC Power Used Onsite w/ Power Limit of 40 kW
- 24/7 FC Operation So Stacks Only Last Two Years
- 34 kg of H2 Storage
- Results:
  - Station Cost: $537,000
  - Electricity Produced: 350,400 kWh/yr
  - Avg. FC Efficiency: 37% (incl. reformer efficiency)
  - Annual Cost: $75,600/yr (incl. elect. cost savings and H2 revenue)
  - Cost of H2 Production (approx.): $3.33/kg

New Analysis Case #4

- 200 kW PEM Fuel Cell with 10 Veh./Day Refueled
- FC Power Used Onsite Plus Grid Export of Excess Power (price of $0.08/kWh)
- 24/7 FC Operation So Stacks Only Last Two Years
- 52 kg of H2 Storage
- Results:
  - Station Cost: $996,600
  - Electricity Produced: 1,752,000 kWh/yr
  - Avg. FC Efficiency: 33% (incl. reformer efficiency)
  - Annual Cost: $211,420/yr (incl. elect. cost savings and H2 revenue)
  - Cost of H2 Production (approx.): $3.18/kg

New Analysis Case #5

- 200 kW PEM Fuel Cell with 10 Veh./Day Refueled
- FC Power Used Onsite Plus Grid Export of Excess Power (price of $0.08/kWh)
- Six Hour per Day "Peak Shaving" Operation so Stacks Last Seven Years Between Replacement
- 106 kg of H2 Storage
- Results:
  - Station Cost: $939,700
  - Electricity Produced: 438,000 kWh/yr
  - Avg. FC Efficiency: 33% (incl. reformer efficiency)
  - Annual Cost: $115,900/yr (incl. elect. cost savings and H2 revenue)
  - Cost of H2 Production (approx.): $4.80/kg

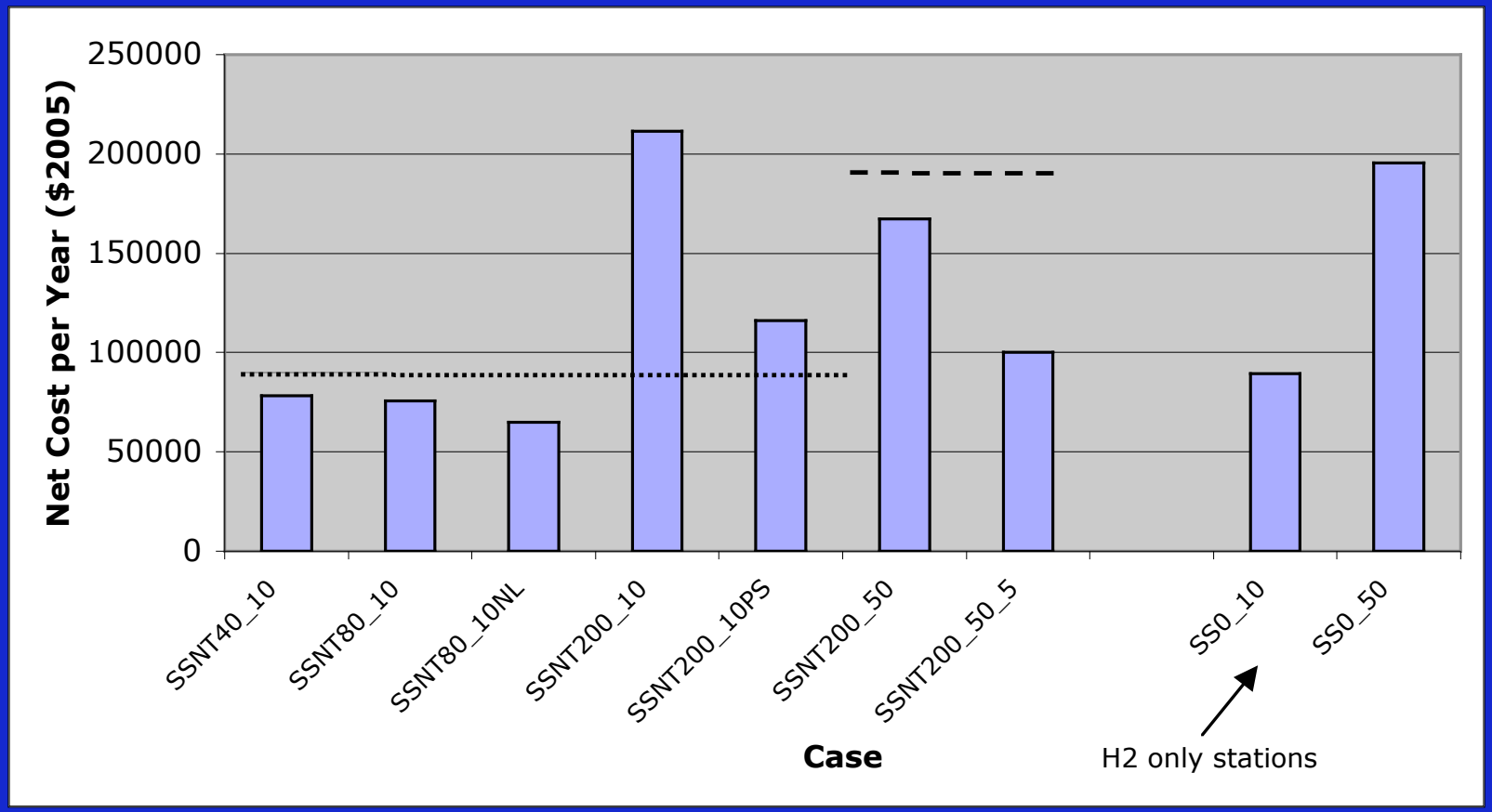
New Analysis Case #6

- 200 kW PEM Fuel Cell with 50 Veh./Day Refueled (add 2nd Refueling Pump)
- FC Power Used Onsite Plus Grid Export of Excess Power (price of $0.08/kWh)
- 24/7 FC Operation So Stacks Only Last Two Years
- 170 kg of H2 Storage
- Results:
  - Station Cost: $1,429,000
  - Electricity Produced: 175,200 kWh/yr
  - Avg. FC Efficiency: 33% (incl. reformer efficiency)
  - Annual Cost: $167,177/yr (incl. elect. cost savings and H2 revenue)
  - Cost of H2 Production (approx.): $2.50/kg

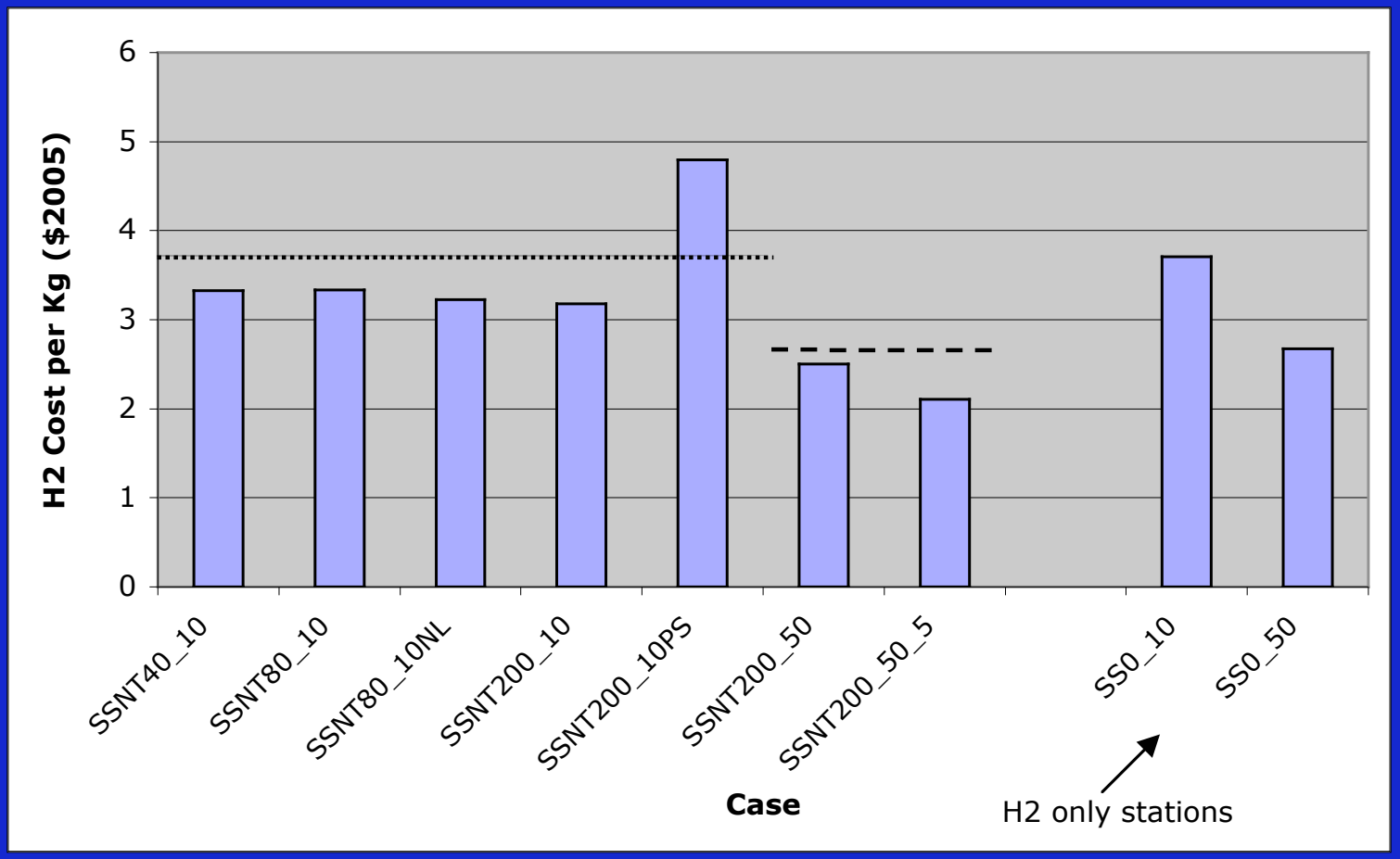
New Analysis Case #7

- 200 kW PEM Fuel Cell with 50 Veh./Day Refueled (add 2nd Refueling Pump)
- FC Power Used Onsite Plus Grid Export of Excess Power (price of $0.08/kWh)
- 24/7 FC Operation So Stacks Only Last Two Years
- Same as Case #6 Except with $5/GJ Natural Gas
- Results:
  - Station Cost: $1,429,000
  - Electricity Produced: 175,200 kWh/yr
  - Avg. FC Efficiency: 33% (incl. reformer efficiency)
  - Annual Cost: $100,310/yr (incl. elect. cost savings and H2 revenue)
  - Cost of H2 Production (approx.): $2.11/kg

Summary of Near Term Case Results



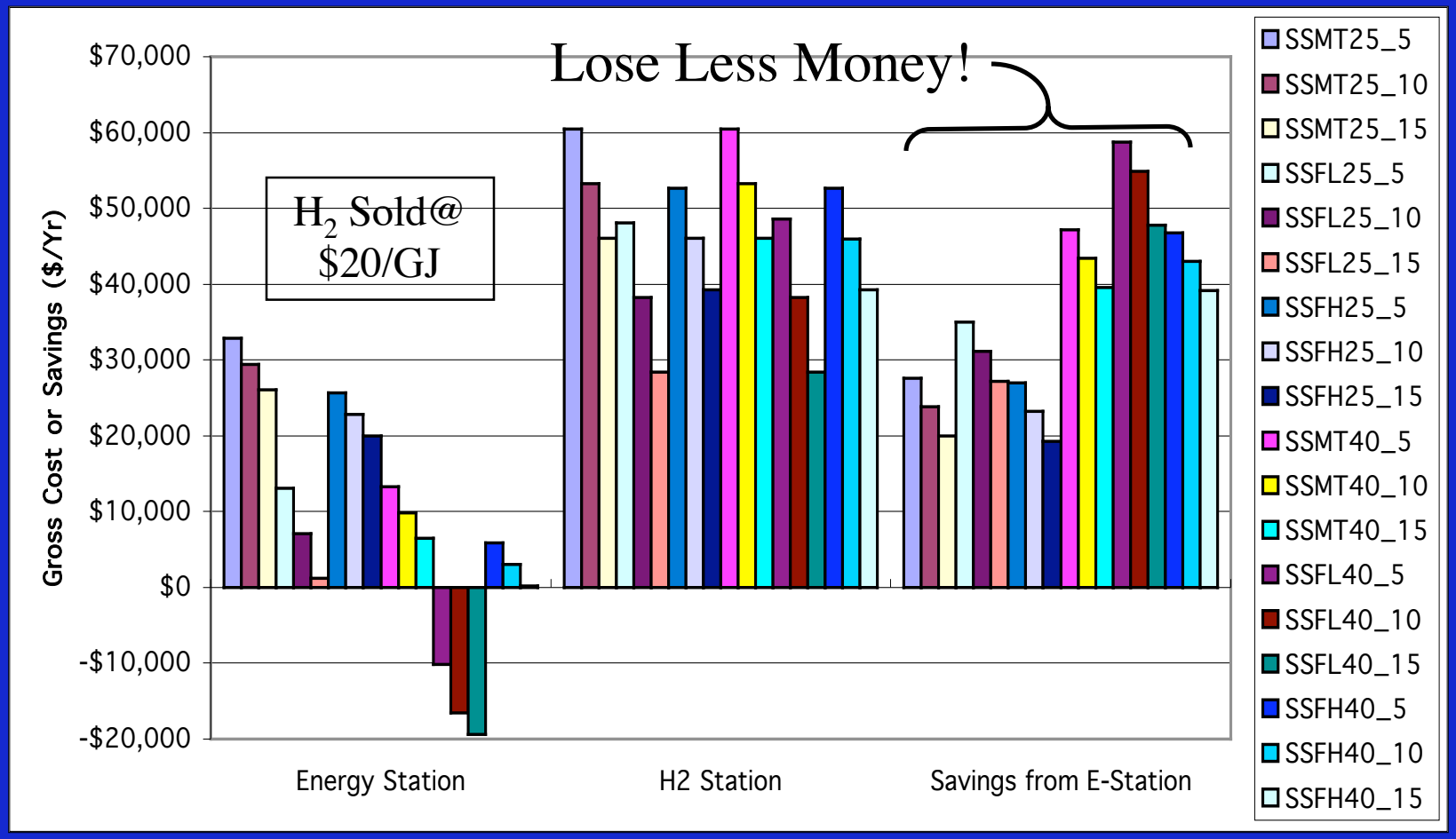
Summary of Near Term Case Results



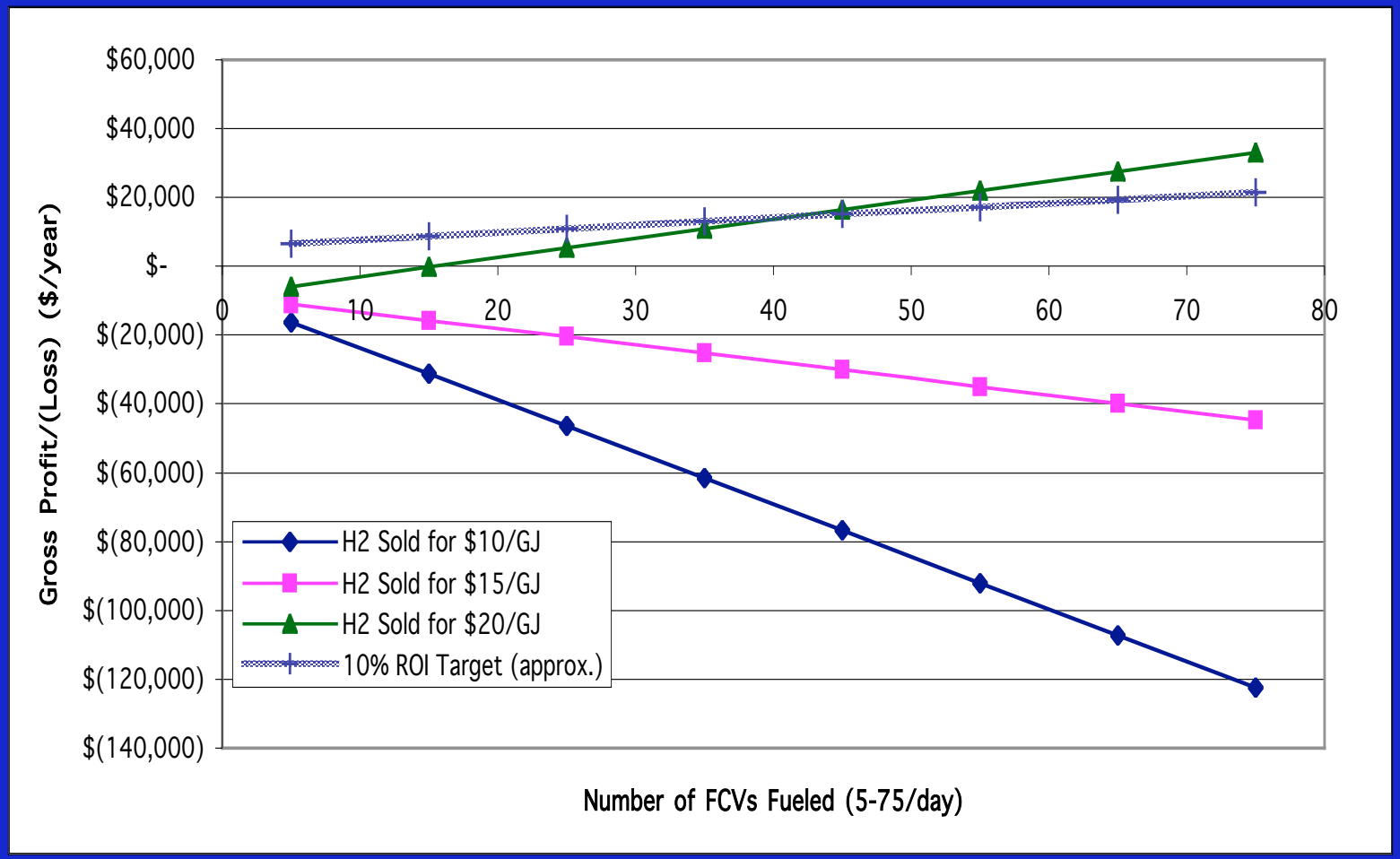
Older Analysis Cases (2001-2002)

- Capital Cost Forecast Estimates from the Technical Literature (medium term and future)
- Higher Production Volumes and Much Lower Capital Costs Than at Present
- No SGIP Incentive
- Waste Heat Recovery (hot water) at Office Buildings But Not at Service Stations
- Less Careful Sizing of Storage, Reformers, and Compressors

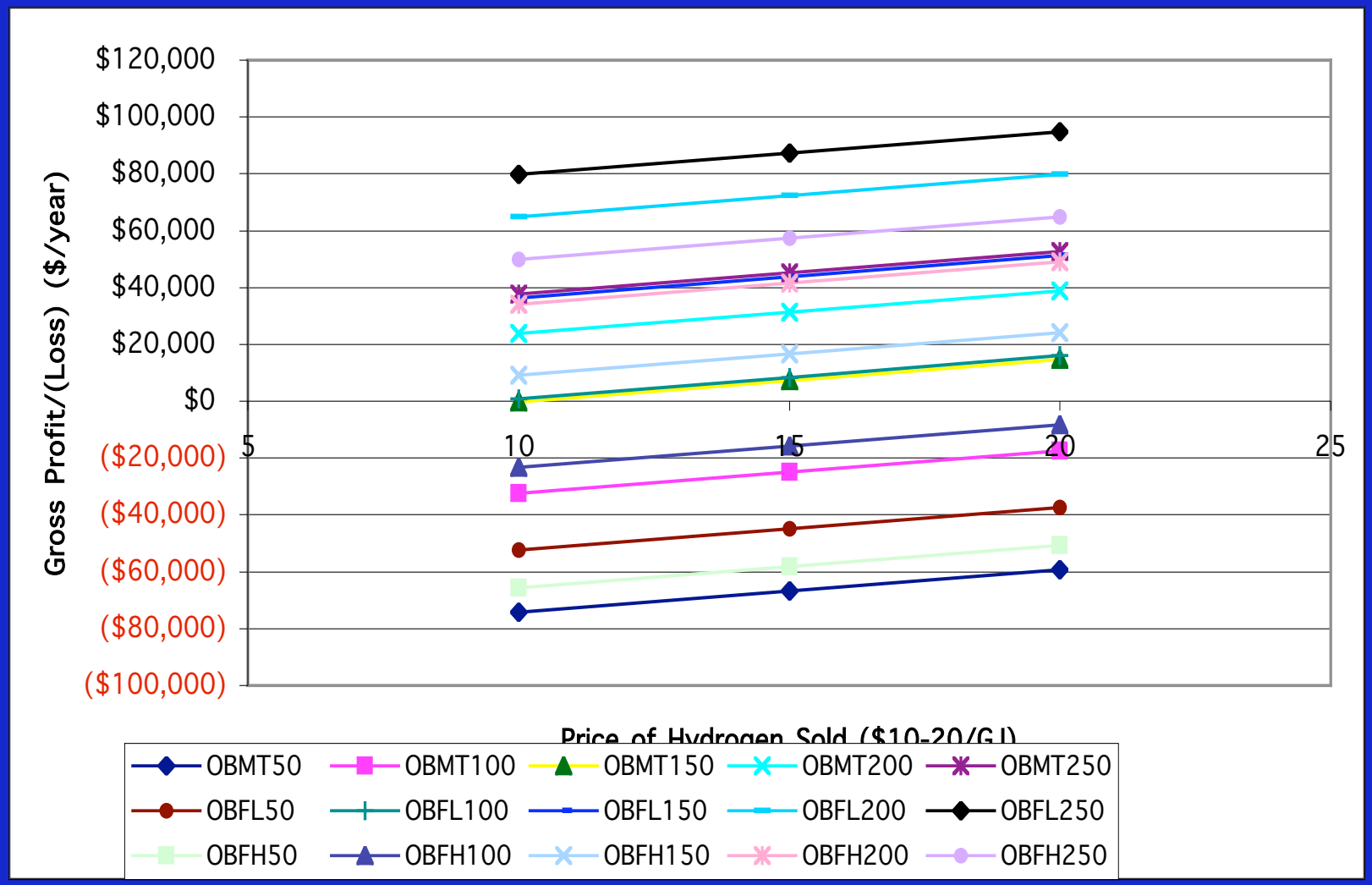
Energy Service Stations Can Lower Cost Barriers During Transition



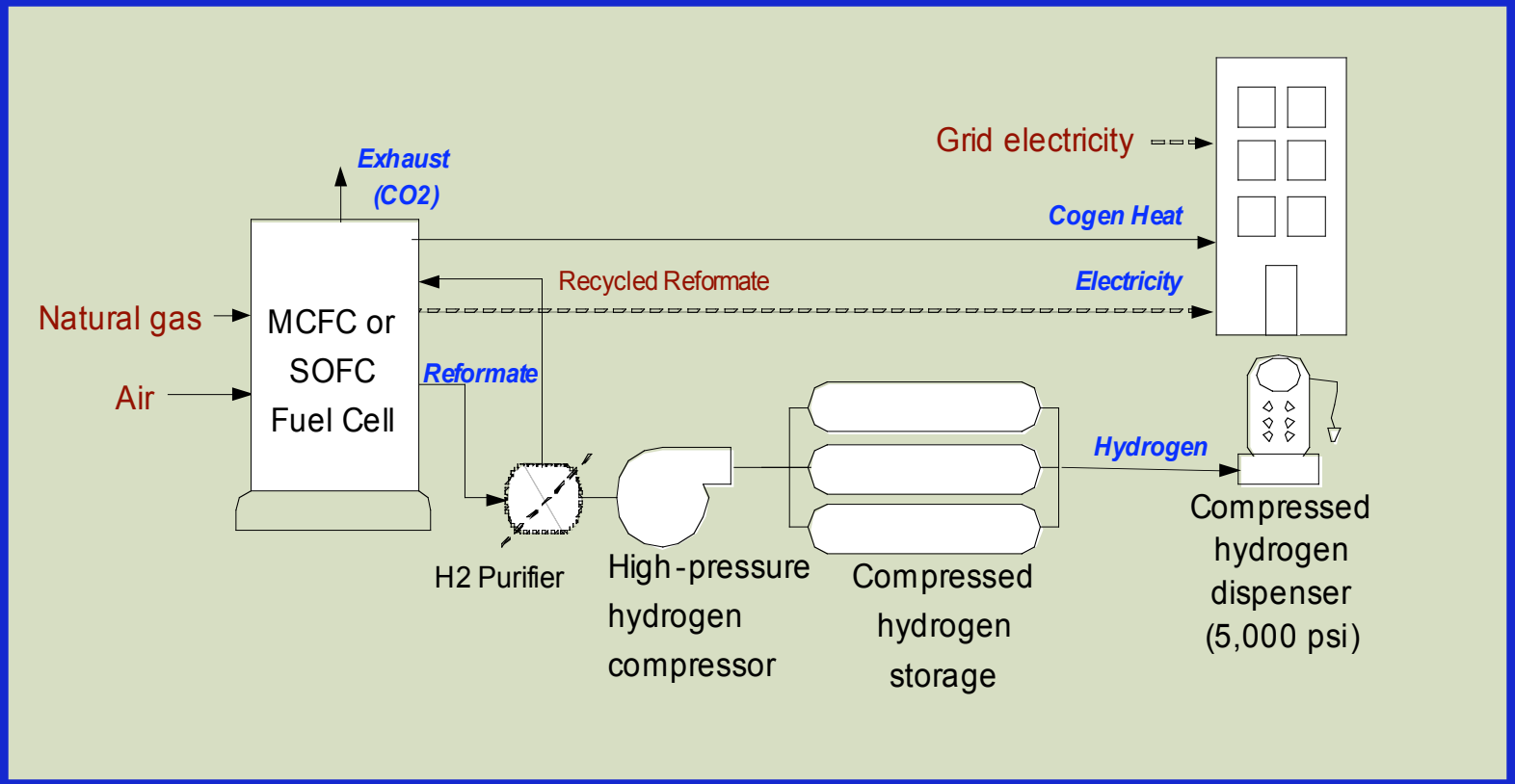
Older Results -- Energy Service Station w/40 kW Fuel Cell and "Future High" Costs



Older Results:
Office Building Energy Stations



High Temperature FC Designs



Santa Rita Jail Project

- 1 MW of molten carbonate fuel cells at Santa Rita jail in Dublin, CA
- Online in 2006
- $6.1 million project with approx. $2.4 million in incentives ($1.4 million SGIP and $1 million DoD)
- I calculate a simple payback period of 13-14 years
- Heat recovery should boost overall efficiency to 70+%

High Temperature FC Designs

- Air Products and Chemicals Inc. and FuelCell Energy Are Partnering with DOE on a MCFC Energy Station Demonstration Project
- Four-Phase Project, Currently in Phase 3: Design and Build
- Based on FCE 300 kW FC Unit, with PSA-Based Gas Clean-Up System for Purified H2
- System is Being Built and Tested in Connecticut for Demonstration in California in Late 2008 or early 2009
- Capability for Purified H2 Production of 4-7 kg/hr

Conclusions from Initial Work

- Economics of Supporting Small Numbers of FCVs at Service Stations Even With the Energy Station Concept Are Challenging
- However, the Losses Associated With Supporting Early FCVs With Hydrogen Fueling Can Potentially Be Reduced by Employing Energy Station Designs
- The Economics of Office Building-Based Energy Stations Appear Favorable Relative to Service Station Energy Stations (due to larger electrical loads and better CHP opportunities)
- Natural Gas Costs, Number of Vehicles Refueled, and Fuel Cell System Costs Are Key Sensitivities

Next Steps

- Near Term:
  - Additional Low-Temperature FC Based Designs
    - Re-run office building cases
    - PAFC designs (lower efficiency but greater durability)
    - Examine emissions results and make comparisons
    - Sensitivity analysis!
- Longer Term:
  - High Temp. MCFC (and maybe SOFC) Designs
  - More Careful Analysis of CHP
  - Additional Sites/Locations?

Thanks!