Fuel Cell Combined Heat and Power Commercial Demonstration

Whitney G. Colella *(Principal Investigator) PhD, MBA*
Heather Dillon, *PhD*
Siva Pilli, *PhD*
Viraj Srivastava, *PhD*

Pacific Northwest National Laboratory (PNNL)

United States (U.S.) Department of Energy (DOE)
Fuel Cell Technology (FCT) Program
Annual Merit Review

Washington, D.C.
May 14-18th, 2012
PNNL Project Manager: Dale King
Market Transformation & Technology Development Manager: Peter Devlin

U.S. Department of Energy
Energy Efficiency and Renewable Energy
Bringing you a prosperous future where energy is clean, abundant, reliable, and affordable

This presentation does not contain any proprietary, confidential, or otherwise restricted information

Pacific Northwest
NATIONAL LABORATORY
Proudly Operated by Battelle *Since 1965*

Project ID: MT006

Overview

Timeline

- Project start date: Q4, FY10
- Project end date: Q4, FY16
- Percent complete: *33%*

Budget

- Total Project Funding
  - DOE: $3,000k
  - Contractor: $670k
- FY 10 DOE Funding: $3,000k
- FY11 DOE Funding: $0k
- FY12 DOE Funding: $0k
  - FY12 Cost Share Provided by Contractors: $670k

Barriers

- Technical and Economic issues preventing full commercialization of fuel cell systems (FCSs)
- Lack of long term validated performance data for 5 kilowatt electric (kWe) to 100 kWe FCS
  - Energy performance
  - Durability
  - Reliability
  - Installation, operation, and maintenance costs

Partners

- Project Lead: PNNL
- Sub-contractors:
  - ClearEdge Power Inc. and four commercial / community partners

PNNL project supports Fuel Cell Technology (FCT) Program areas and barriers

Objective: ***To demonstrate combined heat and power (CHP) FCSs, objectively assess their performance, and analyze their market viability in commercial buildings.***

DOE Barriers	Project Outcomes
Lack of real world data/validation	Provides independent assessment of technical barriers with continuously-measured data from CHP FCSs.
Fuel cell cost and durability	Provides independent assessment of economic performance and system durability with continuously-measured data from CHP FCSs.
DOE Program Areas	
Technology Validation	Evaluates FCS durability, efficiency, production, and economics against stated manufacturer specifications.
Market Transformation	Provides analysis of engineering, economic, and environmental performance data from CHP FCSs in the field to reveal commercialization "bottlenecks" -- where industry needs to spend the greatest effort to achieve high market penetration.
Education	Provides technically accurate and objective information to key target audiences via conference presentations and publications.

PNNL has developed an approach to validate performance of CHP FCS over time

Establish Baseline Models → Deploy CHP FCS → Monitor Systems → Analyze Data → Collaborate

Establish baseline model to evaluate cost and technical performance of CHP FCSs.

Acquire CHP FCSs for demonstration

- Acquisitions through open competition
- Both United States (U.S.) and foreign companies solicited
- Manufacturers and end-users expected to team

Monitoring and analysis of data remotely.

- Engineering Performance including heat recovery and building site specifics
- Financial Performance including IRR, payback, cost
- Environmental Performance including GHG and end of life
- Performance and overall cost data analyzed and recommendations will be documented and provided to DOE.

Discuss results with trade groups, potential customers, and industry.

FCS company provides all FCSs. Commercial entities and communities host installation sites

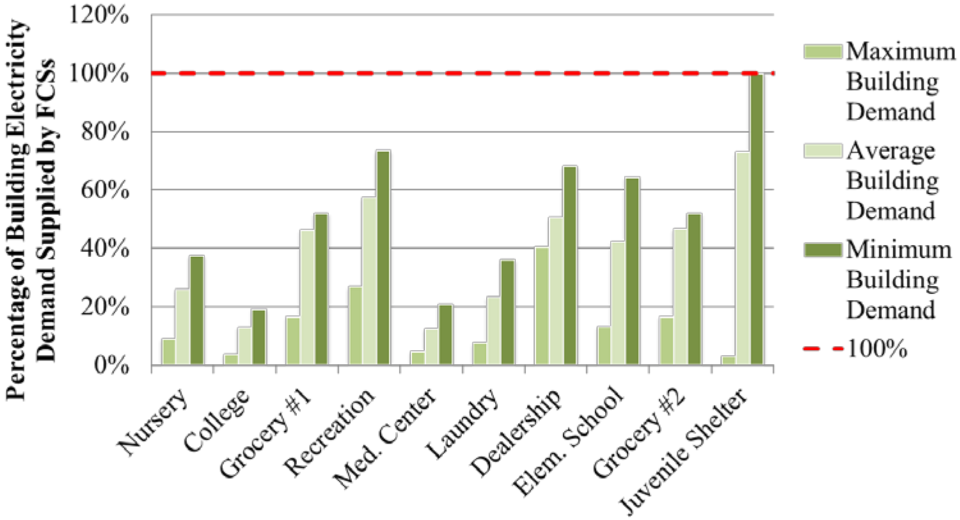
Partner	Sector	Number of FCSs	DOE Cost Share [$]	Cost Share [%]
FCS Manufacturer	Industry	15	$473k	38%
Plant Nursery	Commercial	3	$83k	36%
College	Local Gov.	2	$82k	44%
Grocery Store	Commercial	5	$158k	37%
Recreation	Commercial	5	$150k	37%

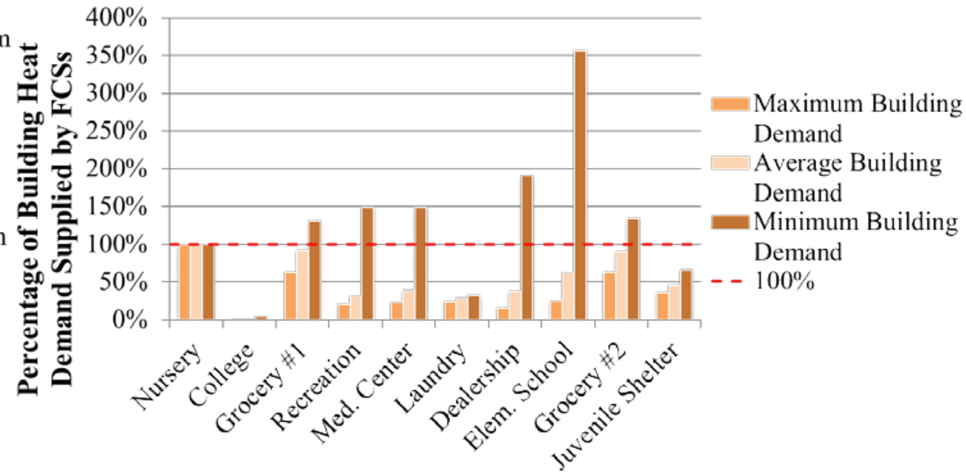
Collaborators include organizations operating retail, education, food provision, and recreation/community buildings.

PNNL has established baseline performance models

- PNNL finalized Technical Requirements and Evaluation Criteria documents
- PNNL refined existing baseline cost models
- PNNL developed a building simulation model with output of space heating demand and demand seen by FCS
  - DOE Commercial Reference Buildings: Large Office New Construction 90.1-2004
    - 46,320 m^2
    - Boiler and 2 chillers
  - DOE Commercial Reference Buildings: Small Office New Construction 90.1-2004
    - Office, 511 m^2
    - Gas furnace and unitary DX

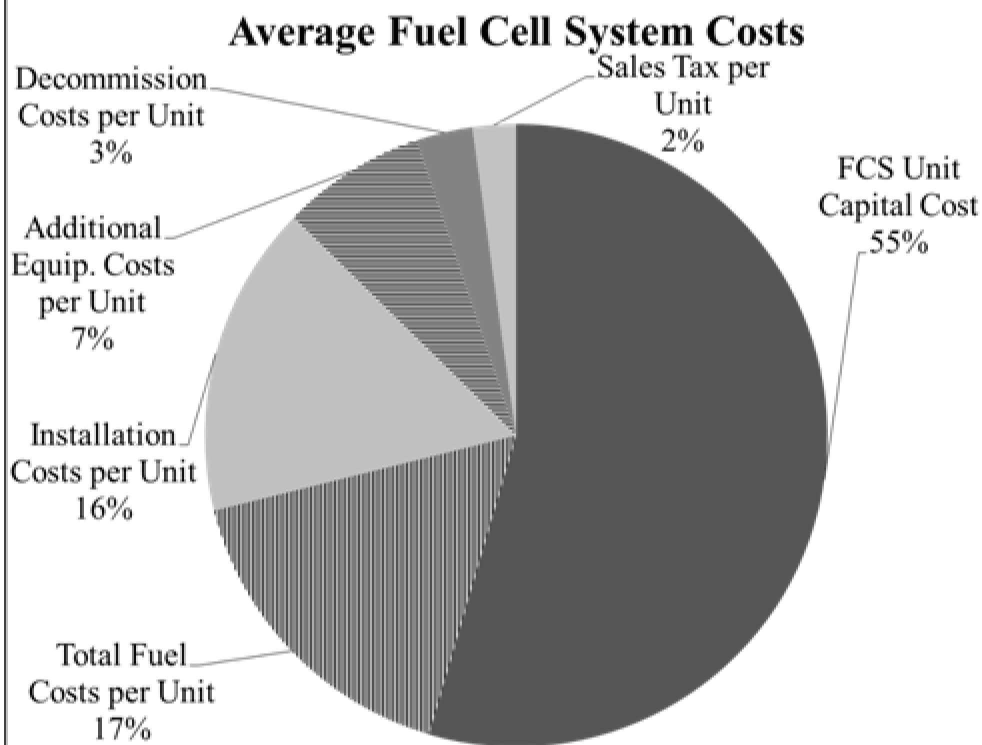
Installation sites have been down-selected such that electricity supplied and heat recovered by the FCSs is expected not to exceed electricity/heat building demands in most instances





- Excess electricity can be sold back to the utility for a credit because FCSs will be grid-connected with net metering.
- In a few cases, FCS heat supply is above building heat demand, but only at southern installation locations during the summer. When CHP FCSs are installed so that they have a high heat utilization, PNNL computer models indicate that they are more economical and more environmentally benign.

Total project costs (*C*) include capital costs, fuel, installation, added equipment, decommissioning, and sales tax over five years.



Average marginal cost of power/energy : Standard Approach

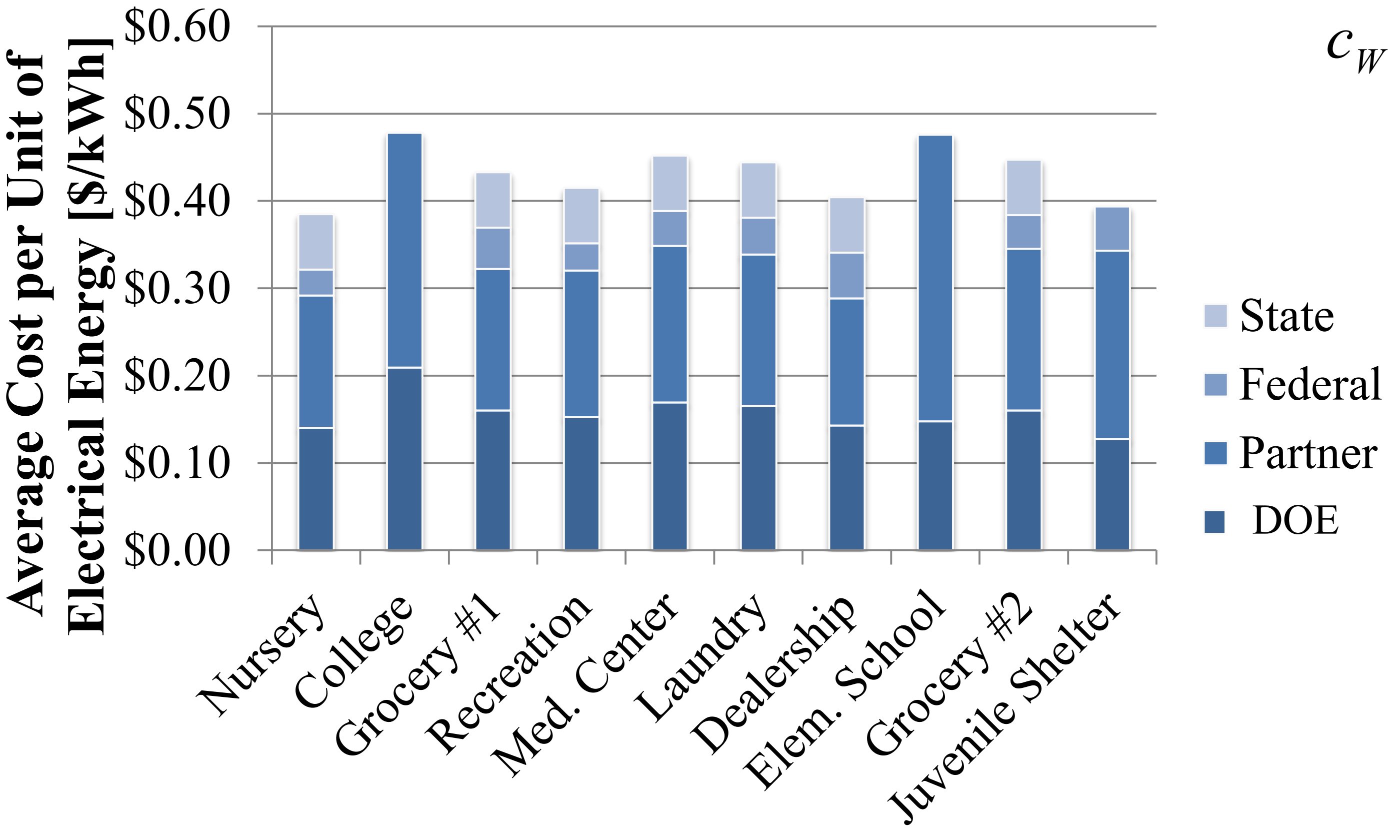
$$c_{W,P} = \frac{C}{\dot{W}_E}; \quad c_{Q,P} = \frac{C}{\dot{Q}}; \quad c_P = \frac{C}{\dot{W}_E + \dot{Q}}$$

$$c_{W,E} = \frac{C}{\dot{W}_E t_{op}}; \quad c_{Q,E} = \frac{C}{\dot{Q} t_{op}}; \quad c_E = \frac{C}{(\dot{W}_E + \dot{Q}) t_{op}}$$

Average marginal cost of power/energy : Management Accounting Approach

$$\frac{C\frac{\dot{Q}}{\dot{W}_E + \dot{Q}}}{\dot{Q} t_{op}} = \frac{C\frac{\dot{W}_E}{\dot{W}_E + \dot{Q}}}{\dot{W}_E t_{op}} = \frac{C}{(\dot{W}_E + \dot{Q}) t_{op}} = C_p$$

The average cost per kilowatt is high. This parameter does not consider the value of the heat output.

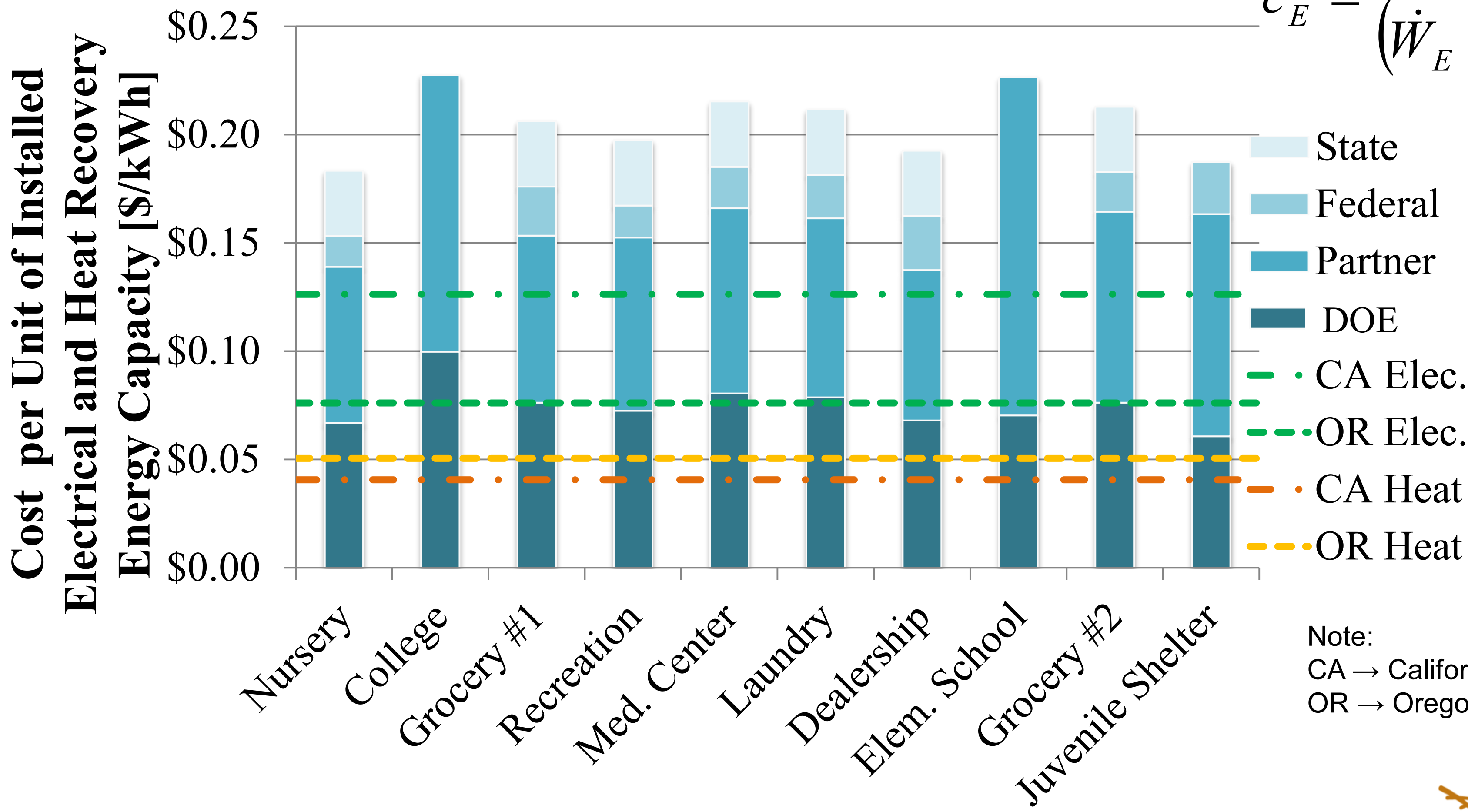


$$c_{W,E} = \frac{C}{\dot{W}_E t_{op}}$$

About 1/3rd of project costs are generally covered by DOE, our industrial partners, and combined state and federal tax incentives. When only electrical energy is considered, the cost per unit of energy is very high for the CHP FCSs.

The average per unit cost per unit of combined electrical and heat recovery energy is a valuable parameter for cost comparisons.

$$c_E = \frac{C}{\left(\dot{W}_E + \dot{Q}\right)t_{op}}$$

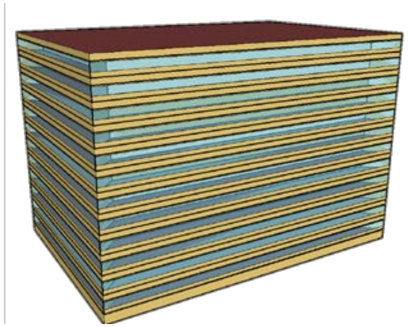


Note:
CA → California, USA
OR → Oregon, USA

Both state and federal incentives are needed to make FCSs approach being cost competitive with California electricity prices.

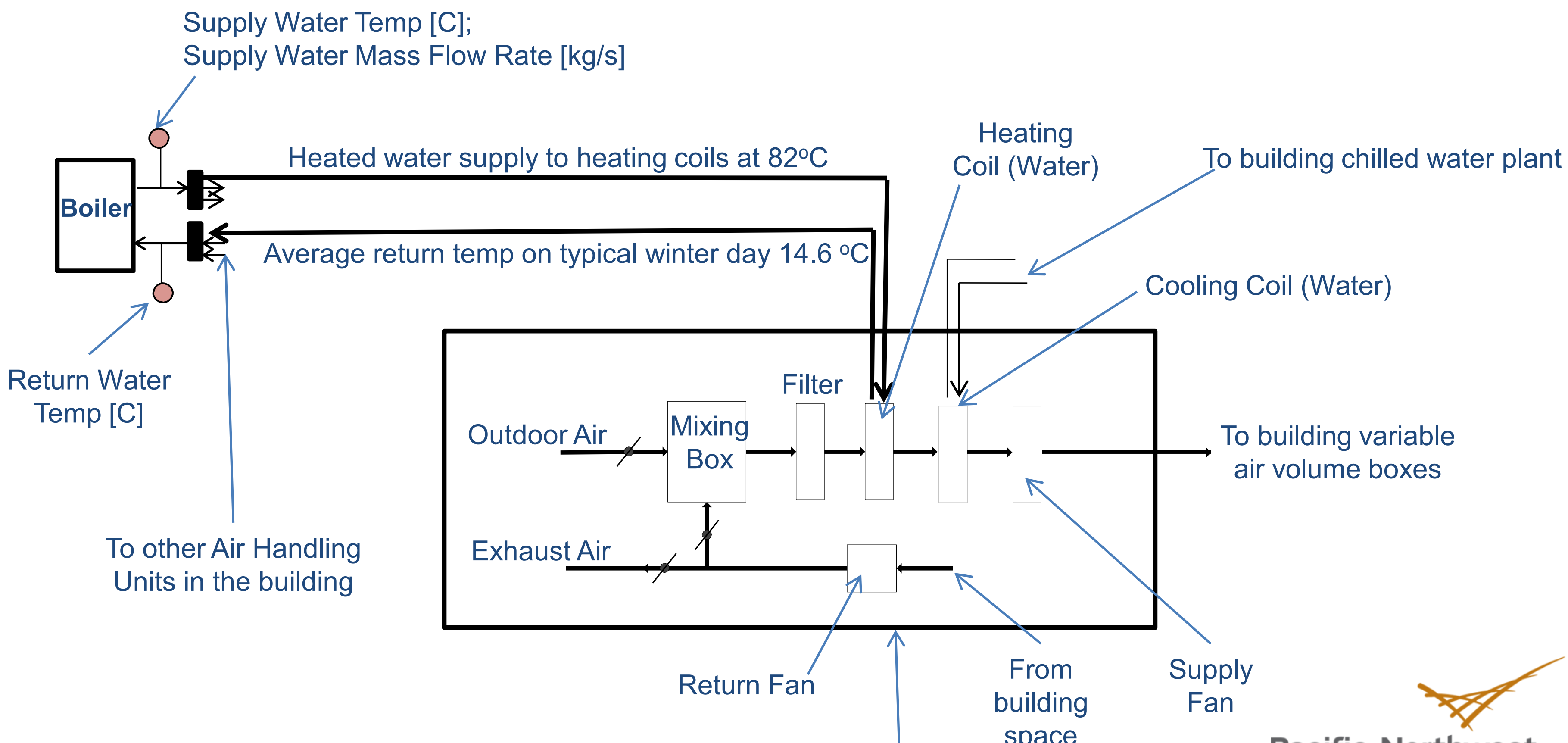
Large Office Model Simulated

Number of floors: 12 plus basement
Floor Area: 46,320 m^2 (498,633 ft^2)
Simulated in San Francisco climate zone



Exterior View

Heating System Components and Simulation Data Collected

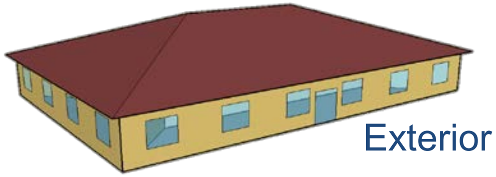


Building Air Handling Unit
(Arrows indicate air flow path)

FY 12 Technical Accomplishments and Progress

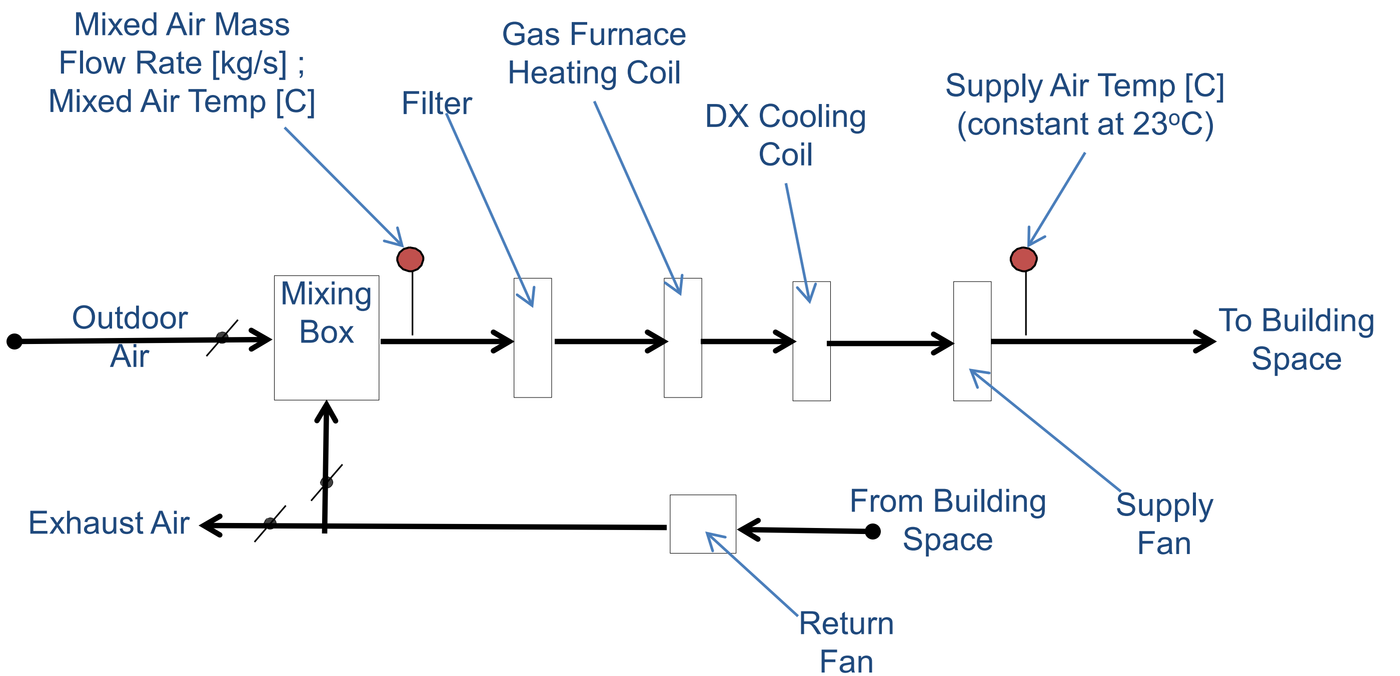
Small Office Model Simulated

Number of floors: 1
Floor Area: 511 m^2 (5,500 ft^2)
Simulated in San Francisco climate zone



Exterior View

Heating System Components and Simulation Data Collected



Packaged rooftop air conditioner

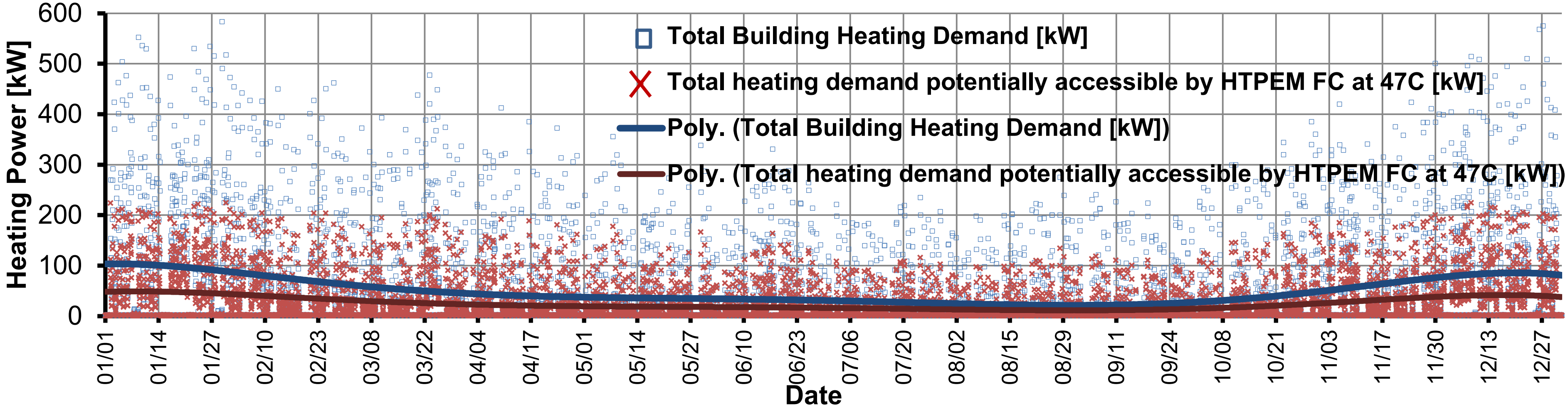
(Arrows indicate air flow path)

Pacific Northwest NATIONAL LABORATORY

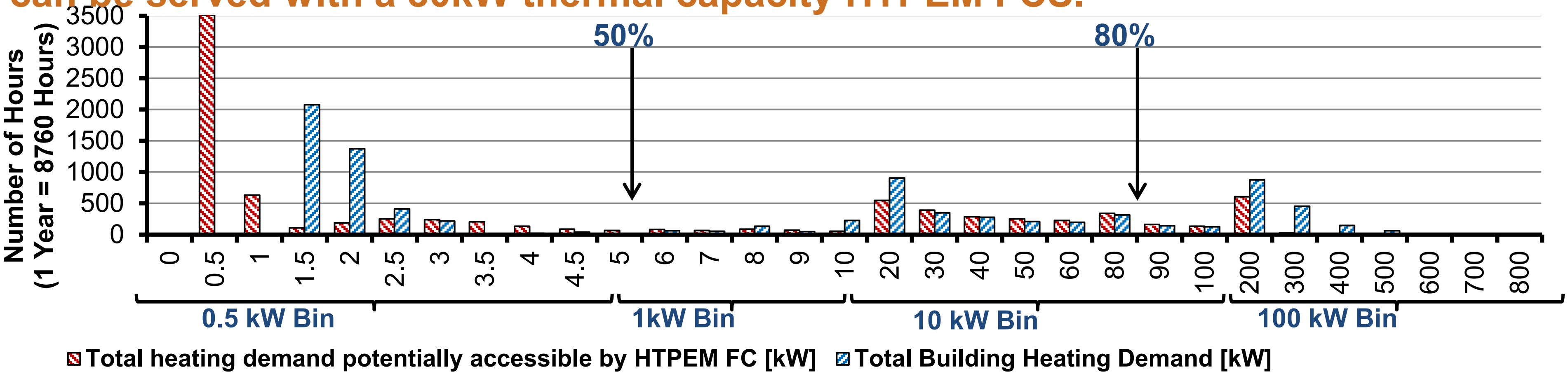
Proudly Operated by Battelle *Since 1965*

FY 12 Technical Accomplishments and Progress

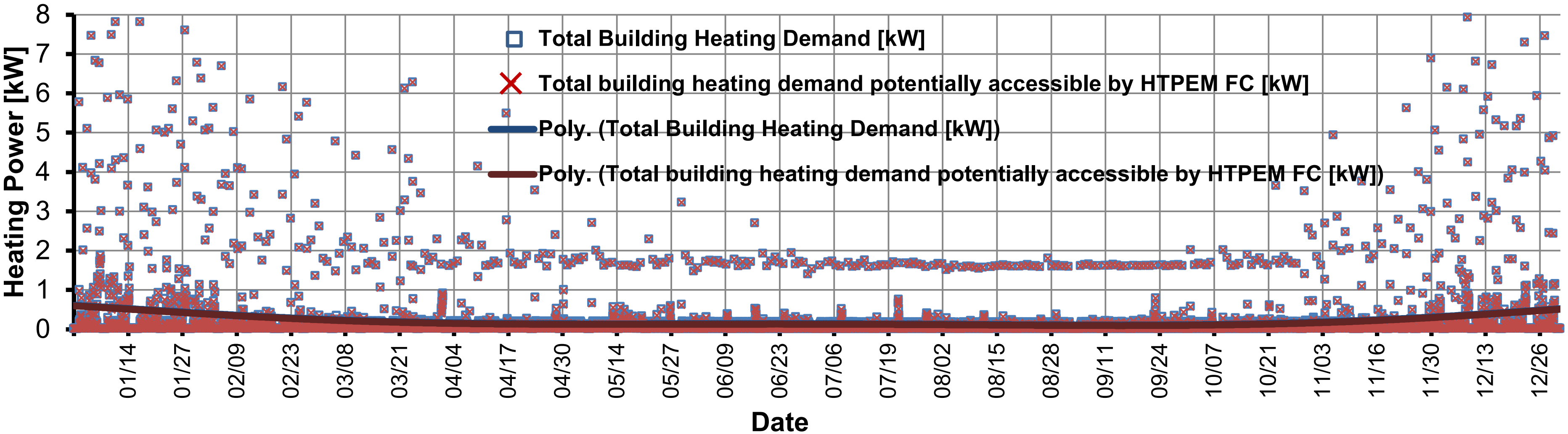
In a large office, a HTPEM FCS with an exhaust temp. of 47°C can potentially access, at a maximum, 50% of the total building heating demand. Space heating demand is at ~82°C (hydronic loop) and hot water heating demand is at ~ 60°C



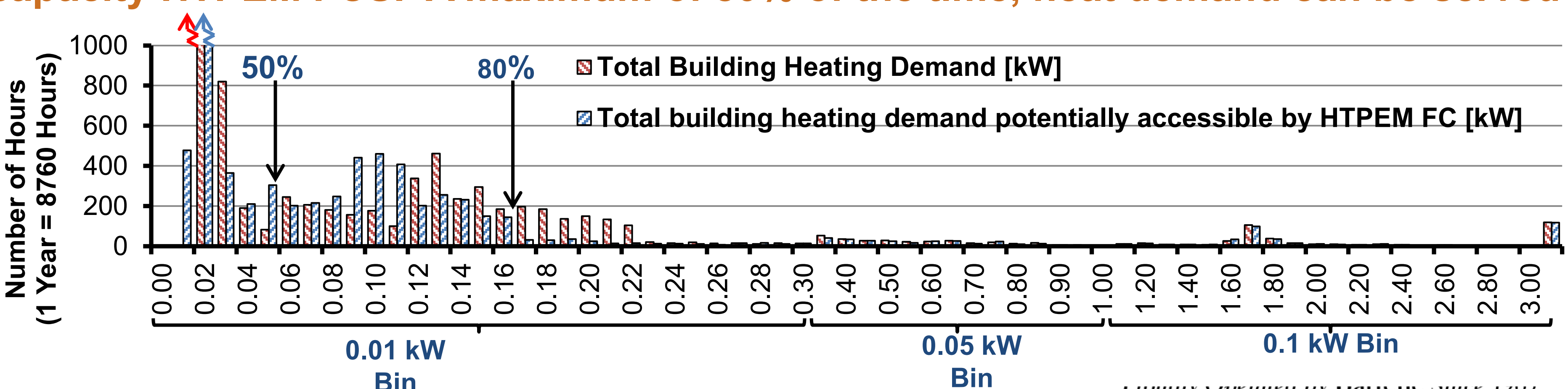
A maximum of 50% of the time, the heat demand can be served with a 5kW thermal capacity HTPEM FCS. A maximum of 80% of the time, the heat demand can be served with a 80kW thermal capacity HTPEM FCS.



In a small office, a HTPEM FCS with an exhaust temp. of 47°C can potentially access, at a maximum, 90% of the total building heating demand. Space heating demand at ~23°C (air loop) and hot water heating demand at ~ 60°C

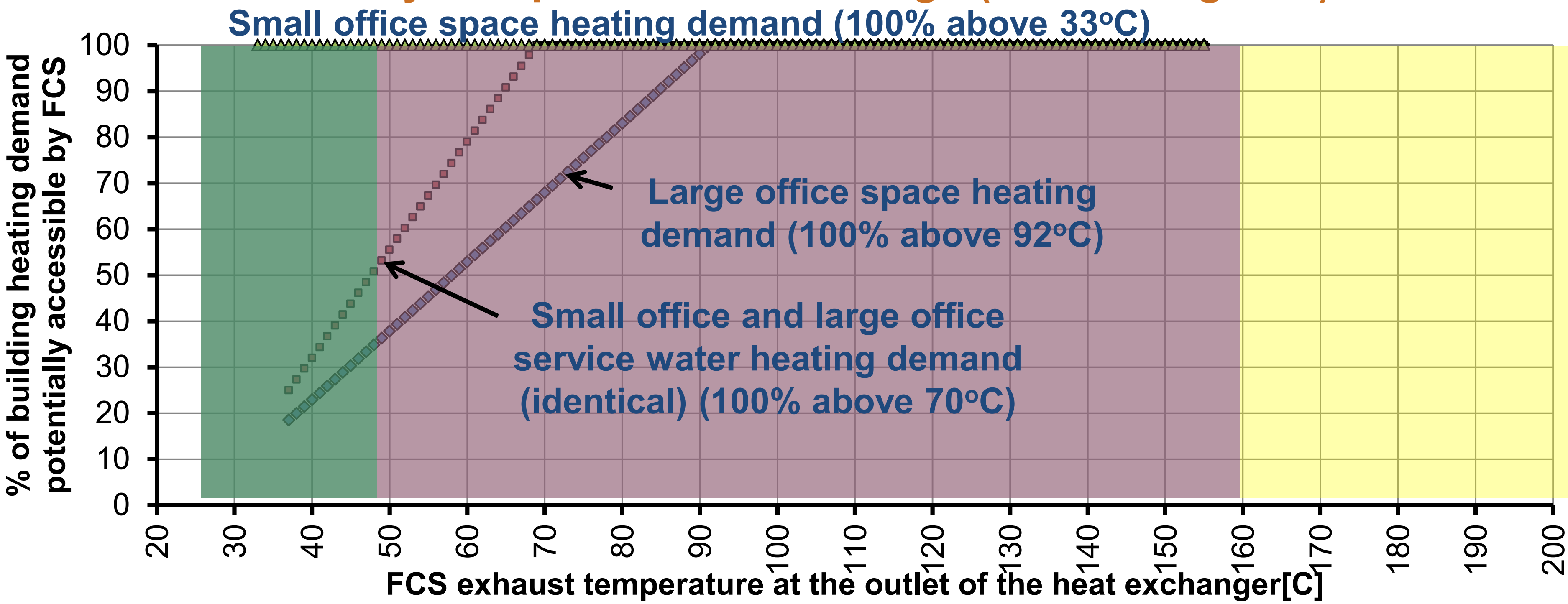


A maximum of 50% of the time, heat demand can be served with a 0.05 kW thermal capacity HTPEM FCS. A maximum of 80% of the time, heat demand can be served



FY 12 Technical Accomplishments and Progress

SOFC FCS has access to full range of small and large office hot water and space heating demands (shown in yellow). HTPEM FCS potentially has access to the majority of this range (shown in purple). ClearEdge HTPEM FCS has access only to a portion of this range (shown in green)



ClearEdge HTPEM FCS Exhaust Temperature 25°C to 47°C

HTPEM FCS Exhaust Temperature 25°C to 160°C

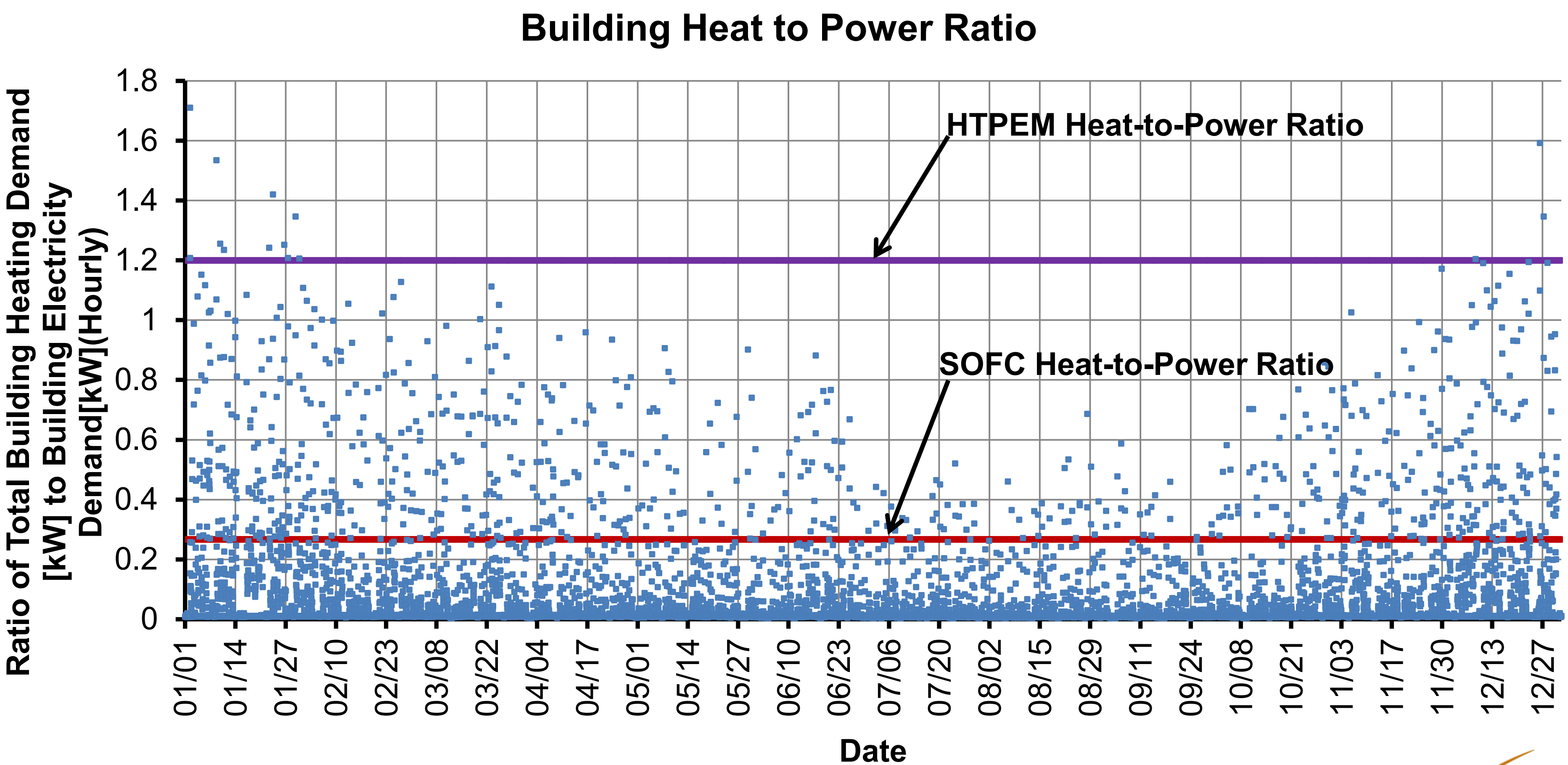
SOFC FCS Exhaust Temperature 25°C to 315°C

Pacific Northwest NATIONAL LABORATORY

Proudly Operated by Battelle *Since 1965*

FY 12 Technical Accomplishments and Progress

Heat-to-power ratio of SOFC is about ~0.26. Heat-to-power ratio of HTPEM is about ~ 1.2. The majority of building heat demand is more consistent with the SOFC heat-to-power ratio



Pacific Northwest NATIONAL LABORATORY

Proudly Operated by Battelle *Since 1965*

FY 12 Technical Accomplishments and Progress

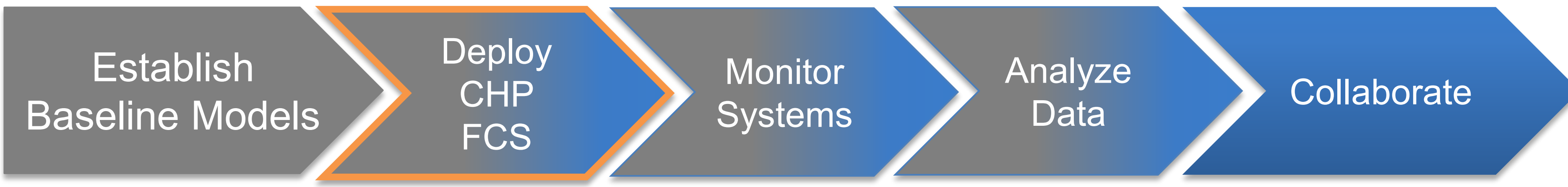
Summary of Simulation Results

	Large Office	Small Office
Space heating system		
Type	Hydronic	Air based
Supply temperature from space heating system	82°C (temp of hydronic fluid)	23.3°C (temp of supply air)
Average return temp on typical winter day	14.6 °C	21.8 °C
Annual use	386,320 kWh	1,390 kWh
% of total building heat demand	87%	72%
Peak space heating demand on typical winter weekday	398 kW	8.2 kW
Average space heating demand (when the system is operating) in typical winter weekday	155 kW	3 kW
% of hours annually where the space heating load is in part potentially accessible by HTPEM FC at 47°C	94% (8235 hours)	100% (8760 hours)
% of hours annually where the space heating load is in part potentially accessible by HTPEM FC at 47°C	48.3% (186,599 kWh)	100% (1,390 kWh)
Service water heating system		
Type	Hydronic	Hydronic
Supply temperature from service water heating system	60°C (temp of water)	60°C (temp of water)
Water Mains Temperature (return temperature into service water heating system)	14.3 °C to 18.5 °C	14.3 °C to 18.5 °C
Annual use[2]	47,073 kWh	551 kWh
% of total building heat demand	13%	28%
Peak service water heating demand on typical winter weekday	18.6 kW	2.4 kW
Average service water heating demand (when the system is operating) in typical winter weekday	9.6 kW	1.7 kW
% of hours annually where the service water heating load is in part potentially accessible by HTPEM FC at 47°C	100% (8760 hours)	100% (8760 hours)
% of hours annually where the service water heating load is in part potentially accessible by HTPEM FC at 47°C	72% (33,866 kWh)	72% (396 kWh)

Summary of Simulation Results

	Large Office	Small Office
FCS Thermal Capacity Required		
HTPEM FCS thermal capacity required to serve the building heating demand 50% of the time (4380 hours)	5 kW	0.05 kW
HTPEM FCS thermal capacity required to serve the building heating demand 80% of the time (4380 hours)	80 kW	0.16 kW
HTPEM FCS thermal capacity required to serve 50% (large office 216,696 kWh, small office 970 kWh) of the building heating demand quantity	185 kW	1.65 kW
HTPEM FCS thermal capacity required to serve 80% (large office 346,714 kWh, small office 1552 kWh) of the building heating demand quantity	300 kW	5 kW

PNNL is acquiring CHP FCSs for deployment and one contract has been issued



- Acquisitions through open competition resulted in one final contract in FY11
  - Solicitation was circulated to manufacturers, suppliers, researchers, and others around the U.S., Europe, and Asia. No restrictions on foreign manufacturer participation at full cost share
- First vendor came on-board in FY12 and 15 FCS are currently in operation
  - Four deployment sites
    - Two sites in Northern California
    - One site in Southern California
    - One site in Oregon
  - Total of 15 CHP FCSs deployed
  - Wide variety of industrial locations including organizations operating retail, education, food provision, and recreation/community buildings.
- Additional contract for new performance data is currently in process

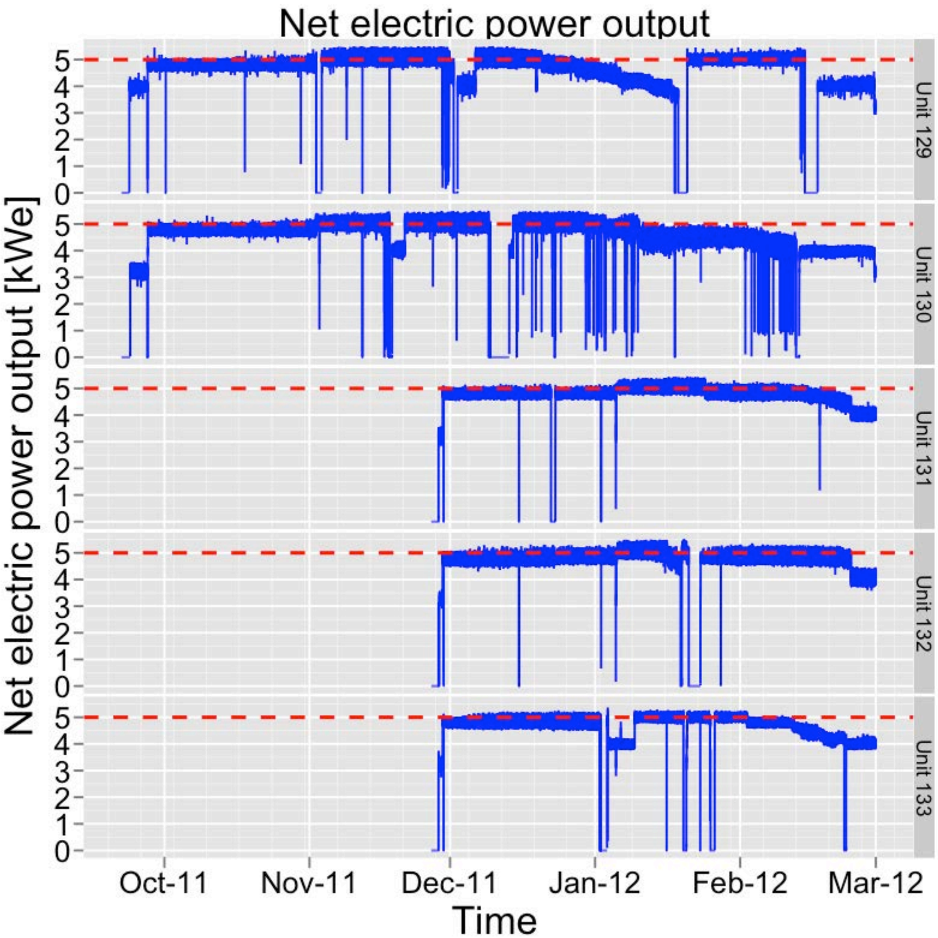
PNNL is remotely monitoring key parameters every second, for five years

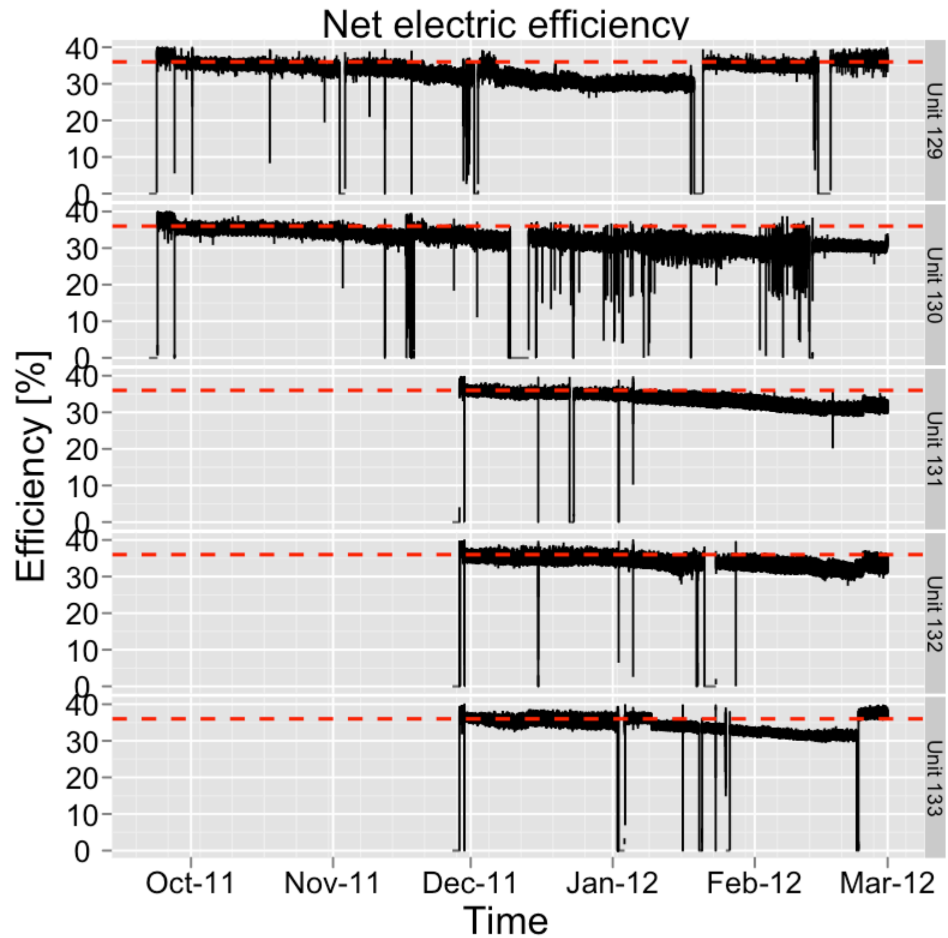
- PNNL is currently remotely monitoring several parameters at 1 second intervals for 15 operating units
  - Instantaneous and cumulative power output
  - FCS voltage at the inverter
  - Exported FCS current
  - Heating and Cooling temperatures of water
  - Heat exchanger cooling fan speeds
  - Fuel inlet flow rate and cumulative fuel use
  - Exhaust temperature
  - Heat generation rate & cumulative heat out
  - Cumulative system time on load
  - System availability

PNNL has developed an approach to validate performance of CHP FCS over time

- PNNL analyzing more than 33 million data points per day
- Measured data on FCSs indicate an average electrical output of ~4.8 kWe, slightly below the manufacturer-stated electrical output goal of 5 kWe.
- Measured data on FCSs indicate an average net system electrical efficiency of ~34% (HHV), slightly below the manufacturer-stated electrical efficiency goal of 36%.
- Availability (A_o) quantifies the system operating time when compared to the total time since commissioning. A_o was measured at ~97%.

CHP FCSs – Data Analysis: Net electric power and electric efficiency for first five units



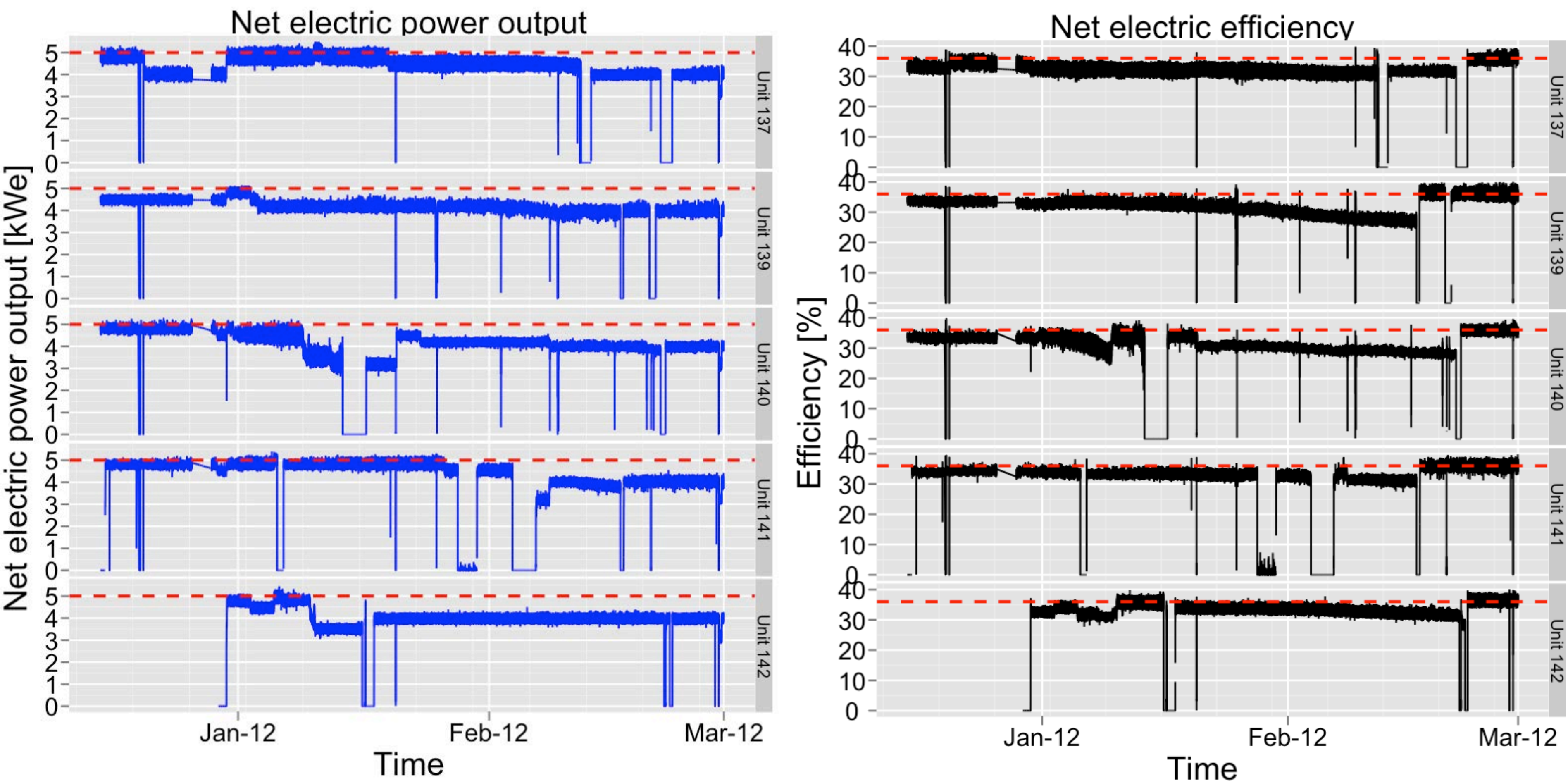


Data analysis is based on HHV.
Red dotted line is manufacturer-stated value.

Pacific Northwest
NATIONAL LABORATORY

Proudly Operated by Battelle *Since 1965*

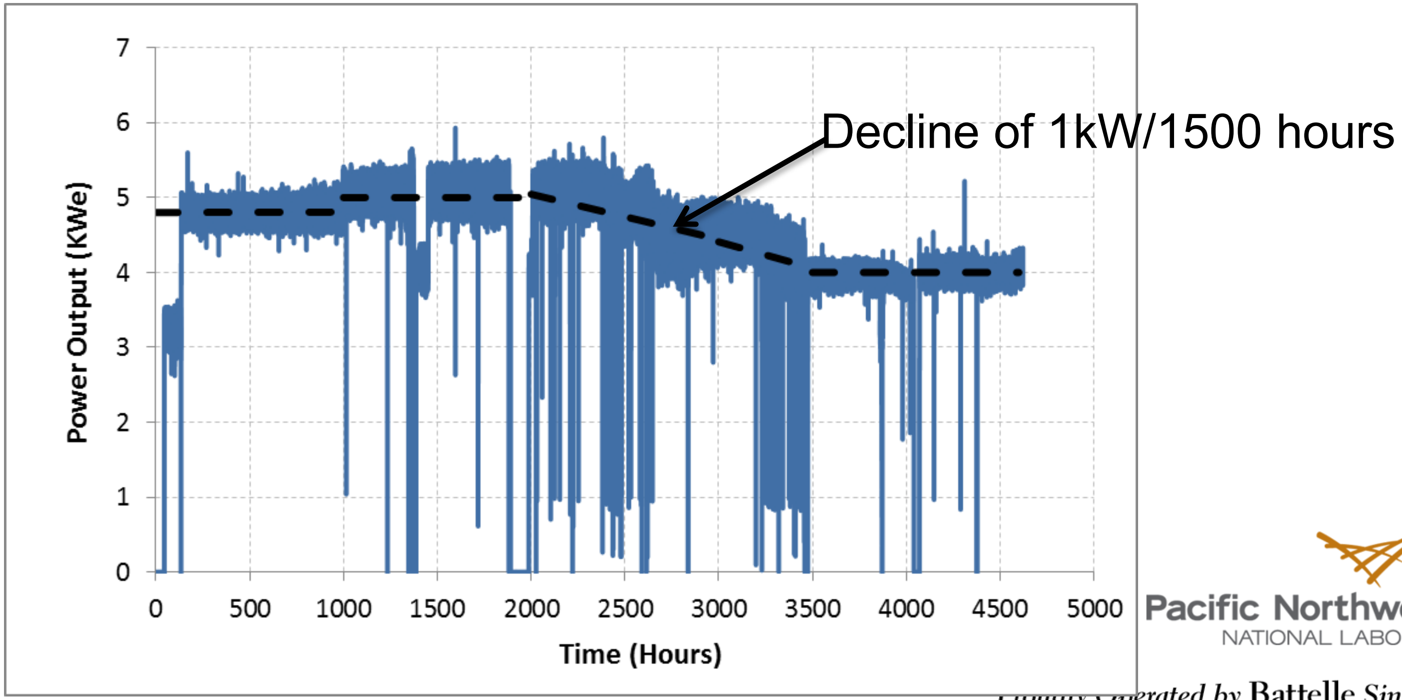
CHP FCSs – Data Analysis: Net electric power and electric efficiency for second five units



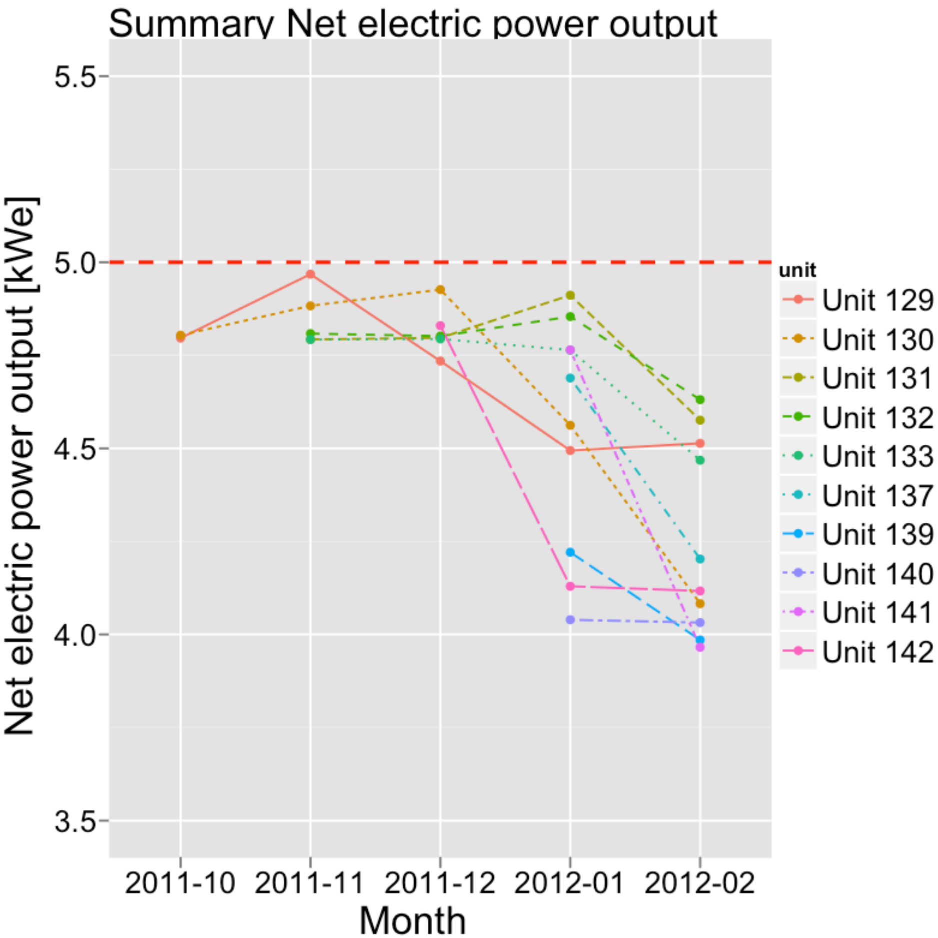
Data analysis is based on HHV. Red dotted line is manufacturer-stated value. Efficiency increase in late February reflects new, lower system setpoint adopted.

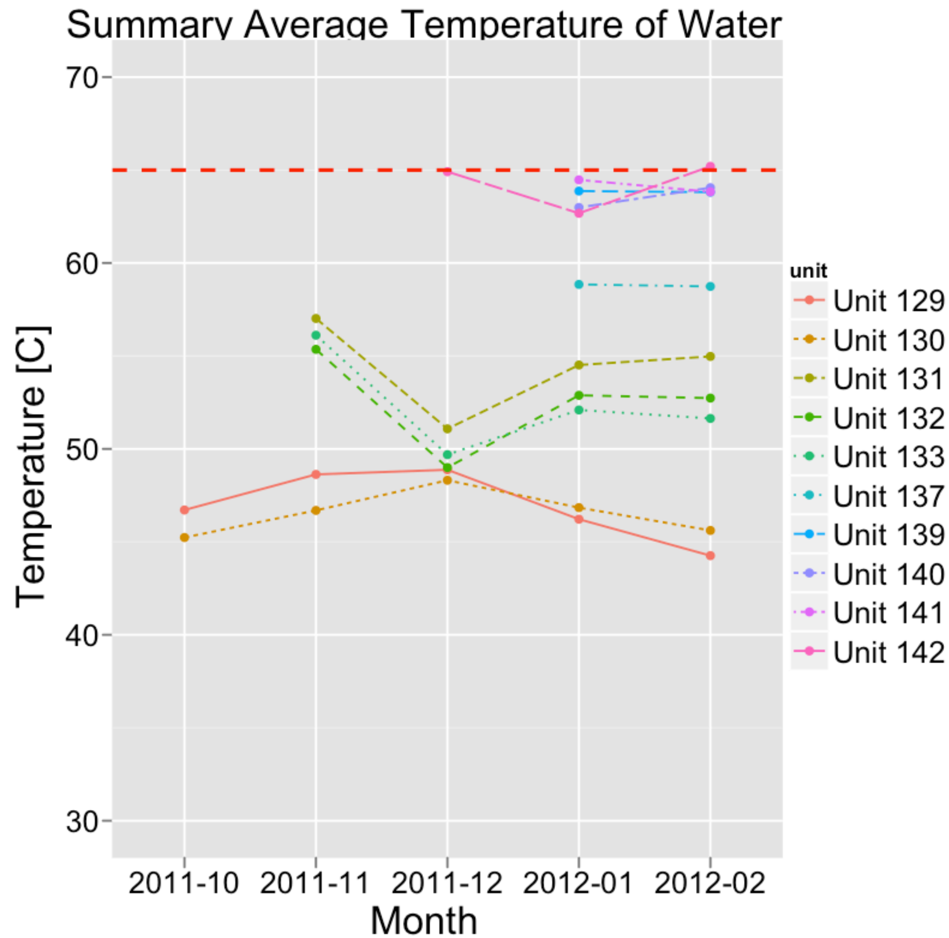
Decline in Electric Power Over Time - Unit 130

- A decline in electric power output of approximately 20% was observed over a 1,500 hour period between Dec 14 2011 (2000 hours) and Feb 14 2012 (3500 hours).
- Power output declined from approximately 5 kWe to 4 kWe over this time period. The decline was calculated by plotting a simple linear regression curve (dashed line) of the power output data.
- This decline represents a maximum degradation rate during the observation period. This decline could be partly a result of HTPEM membrane degradation and/or fuel cell stack degradation.



CHP FCSs – Data Analysis: Average monthly performance efficiency and power output

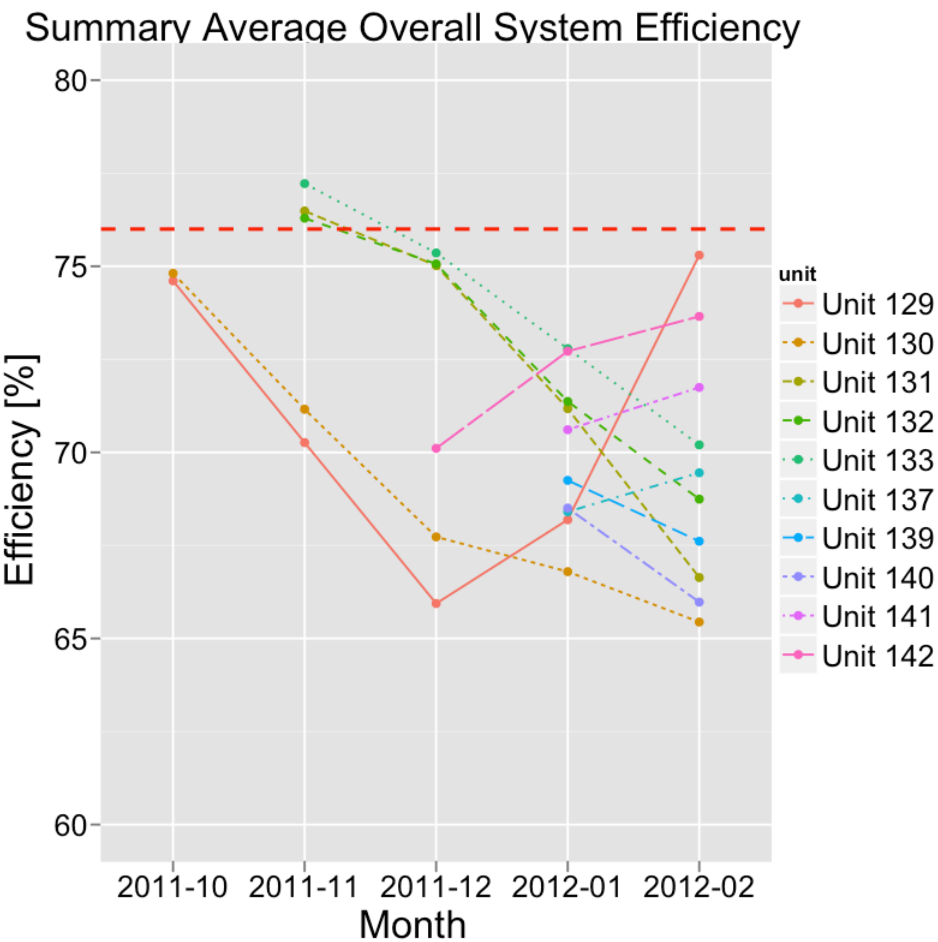


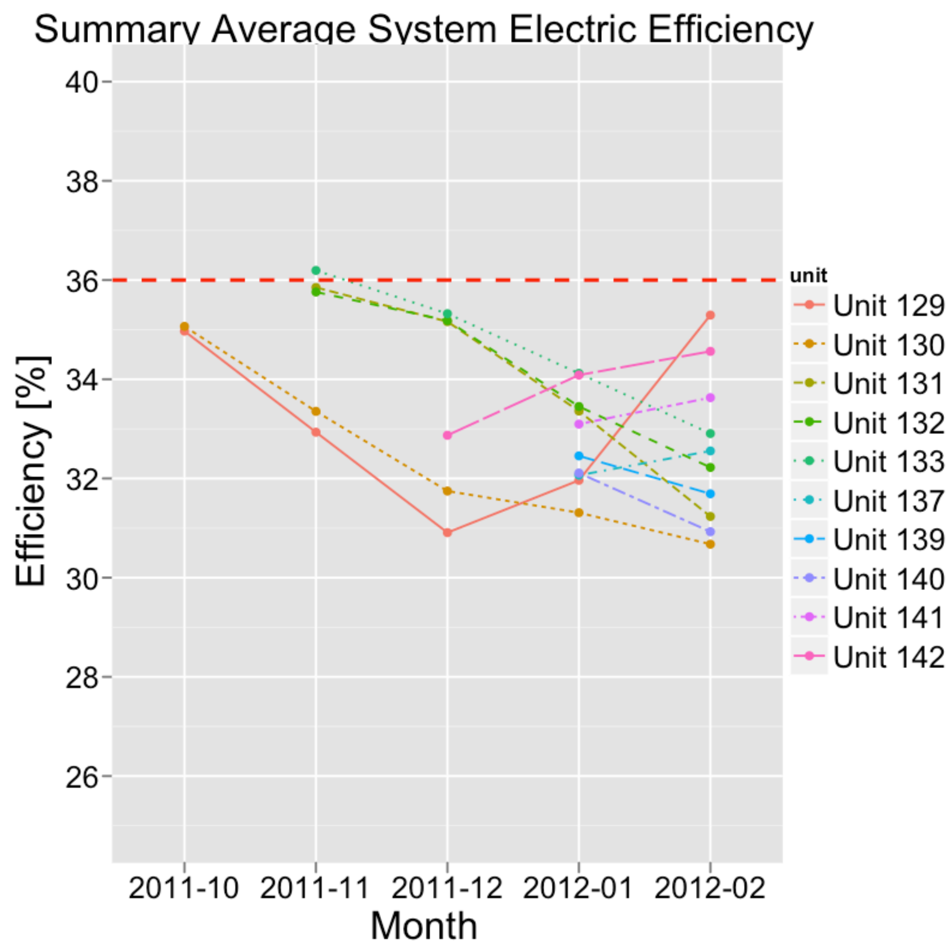


Data are based on a calculated value for the heat recovered, based on HHV.
Red dotted line is manufacturer-stated value. For average temperature of water, the measured value is lower due to the low hydronics inlet temperatures at the installation sites.

FY 12 Technical Accomplishments and Progress

CHP FCSs – Data Analysis: Average monthly performance efficiency and power output





Data are based on a calculated value for the heat recovered, based on HHV. Red dotted line is manufacturer-stated value.

Manufacturer-stated data are compared with measured data (10 CHP FCSs averaged)

	Manufacturer Stated Data	Average Performance of 10 FCS	Percent (%) Deviation
Average net electric power output [kWe]	5	4.46 Standard Deviation = 0.3	11
Average net heat recovery for external heating [kWth]*	5.5	5.06 Standard Deviation = 0.4	8
Max Temperature to site [°C]	65	55.4 Standard Deviation = 6	15
Average net system electrical efficiency (%)	36	33.1	8
Average net heat recovery efficiency* (%)	40	37.4	7
Overall net system efficiency (%)	76	70.4	7

* Net heat recovery data are calculated values, derived from real-time measured values.
Measured data is for 10/2011-2/2012, once the system reached steady state operation.
Standard deviation is for the 10 FCS.

Results

- System Availability (A) varies between 89% and 99%

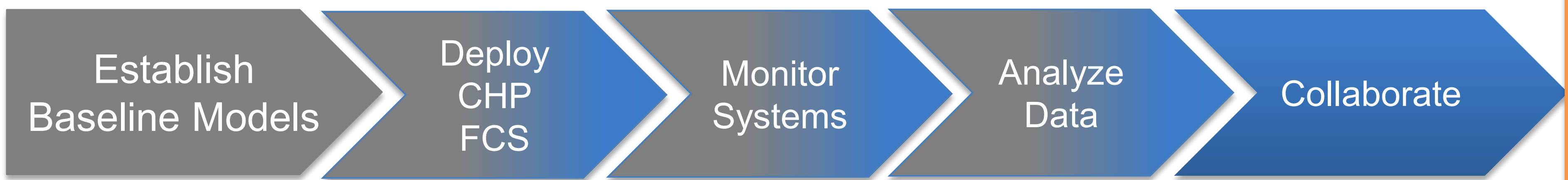
	Availability (A) Definition	Formula	Average Performance of 10 FCS
A_o	quantifies the system operating time when compared to the total time since commissioning.	$A_o = \frac{t_{operating}}{t_{total}}$	95.9

- Performance at Rated Values (PRV) varies between 19% and 0.3%

	Performance at Rated Values (PRV) Definition	Formula	Average Performance of 10 FCS
PRV_{eff}	quantifies the system time operating at or above the rated electric efficiency (η=36%).	$PRV_{eff} = \frac{t_{efficiency\_above\_rated}}{t_{total}}$	8.9
PRV_p	quantifies the system time operating at or above the rated electricity output (5 kWe).	$PRV_p = \frac{t_{elec\_above\_rated}}{t_{total}}$	7.4
PRV_t	quantifies the system time operating at or above both the rated electricity output (5 kWe) and rated efficiency (η=36%).	$PRV_t = \frac{t_{elec\_and\_eff\_above\_rated}}{t_{total}}$	0.5

Downtime is included in the reported (A) and (PRV) values.

PNNL is validating performance of CHP FCS over time



- Initial baseline cost and technical performance models complete

- FC Partner contract completed in FY11
- 15 FCS have been deployed

- Monitoring and analysis of data is underway. Several new performance definitions have been established and systems have been benchmarked

- Active dialog with partners and stakeholders has been established
- More than 13 external public presentation of initial results
- 3 peer reviewed articles have been submitted for publication

PNNL has developed an approach to validate performance of CHP FCS over time

- Collaboration efforts include manufacturers, building owners, future customers
- PNNL is trying to engage and inform stakeholders in different industry venues
  - PNNL presented initial data analysis results to more than 13 conferences and trade groups
  - PNNL has submitted 3 peer reviewed journal articles for publication on this topic in FY12
- Initial outreach has resulted in considerable interest in using PRV definitions to quantify performance of other FCS by the industry
- Collaboration efforts have resulted in changes by the manufacturer to improve system availability and performance by changing setpoint strategies
- Video presentations summarizing progress periodically posted on PNNL website: http://tinyurl.com/3n5ykxu
- Critical review & model feedback: Argonne National Lab
- Webinar: Argonne, Sandia, NREL, and Livermore

Remaining FY 12 Activities

- Continue data acquisition and analysis
  - Techniques will be developed to quantify and evaluate the types of down time experienced by FCS as more operating data is collected
- Continue collaboration with partners
  - Industry partners are considering strategic changes to setpoint due to PNNL analysis and collaboration
  - Continue dialog with industry to understand the best way to quantify system performance
  - Continue publications and presentation to make performance data available to future consumers

Milestones and Deliverables Status

- Baseline Model Input Completion (Q4, FY10)
  - Status: ***Complete***
- Completion of detailed CHP FCS Program Plan (Q4, FY10)
  - Status: ***Complete***
- Go/No-Go decision based upon detailed program plan cost estimate (Q1, FY11)
  - Status: ***Complete – Available funding commensurate with project cost estimates***
- Complete acquisition of CHP FCSs (Q3, FY11)
  - Status: ***Complete***
- Install and commission Combined Heat and Power Fuel Cell Systems (Q4, FY11)
  - Status: ***Complete, 15 units have been installed***
- Complete monitoring of systems (Q4, FY16)
  - Status: ***In progress***
- Issue final documentation of demonstration (Q4, FY16)

Project Summary

- **Relevance:** To demonstrate combined heat and power (CHP) FCSs, objectively assess their performance, and analyze their market viability in commercial buildings.
- **Approach:** PNNL is analyzing continuously-measured data from CHP FCSs installed in light commercial buildings to independently assess technical and economic barriers that are currently preventing full commercialization of CHP FCSs.
- **Technical Accomplishments and Progress:**
  - PNNL has developed baseline models for cost, building performance, FC performance.
  - PNNL has analyzed real-time data for systems currently in the project
- **Collaboration:** PNNL has started a conversation with the public, manufacturers, and project partners via papers and presentations.
- **Proposed Future Research**: Continue monitoring of FCS already in project and add additional systems from additional partners.

Technical Back-Up Slides

Key Model Features

DOE Commercial Reference Buildings: Small Office New Construction 90.1-2004

Available Fuel Types	gas, electricity
Principal Building Activity	Office
Total Floor Area (m^2)	511 (2003 CBECS)
Building Shape	Rectangle
Aspect Ratio	1.5
Number of Floors	1
Window Fraction (Window to Wall Ratio)	
South	0.244
East	0.198
North	0.198
West	0.198
Total	0.212
Shading Geometry	None
Azimuth	0.0
Thermal Zoning	core zone with four perimeter zones
Floor to Ceiling Height (m)	3.1
Roof type	Attic (2003 CBECS)
Exterior walls	
Construction Type	Mass wall (2003 CBECS)
Gross Dimensions - Total Area (m^2)	281.5
Net Dimensions - Total Area (m^2)	222.0
Wall to Skin Ratio	0.32
Roof	
Construction Type	Attic (2003 CBECS)
Gross Dimensions - Total Area (m^2)	598.8
Net Dimensions - Total Area (m^2)	598.8
Roof to Skin Ratio	0.68

Window Dimensions (m^2)	
South	16.7
East	11.2
North	16.7
West	11.2
Total Area (m^2)	55.8
Operable area (m^2)	0
Foundation	
Foundation Type	Mass Floor
Construction	4in slab w/carpet
Dimensions - Total Area (m^2)	511.0
Interior Partitions	
Construction	2x4 steel-frame with gypsum board
Dimensions - Total Area (m^2)	0
Internal Mass	
Construction	15 cm wood
Dimensions - Total Area (m^2)	1,022.5
Thermal diffusivity (m^2/s)	1.84E-07
Air Barrier System	
Infiltration (ACH)	0.45
HVAC	
System Type	PSZ-AC (2003 CBECS)
Heating Type	Gas furnace (2003 CBECS)
Cooling Type	Unitary DX (2003 CBECS)
Fan Control	Constant volume (2003 CBECS)

Key Model Features

DOE Commercial Reference Buildings: Large Office New Construction 90.1-2004

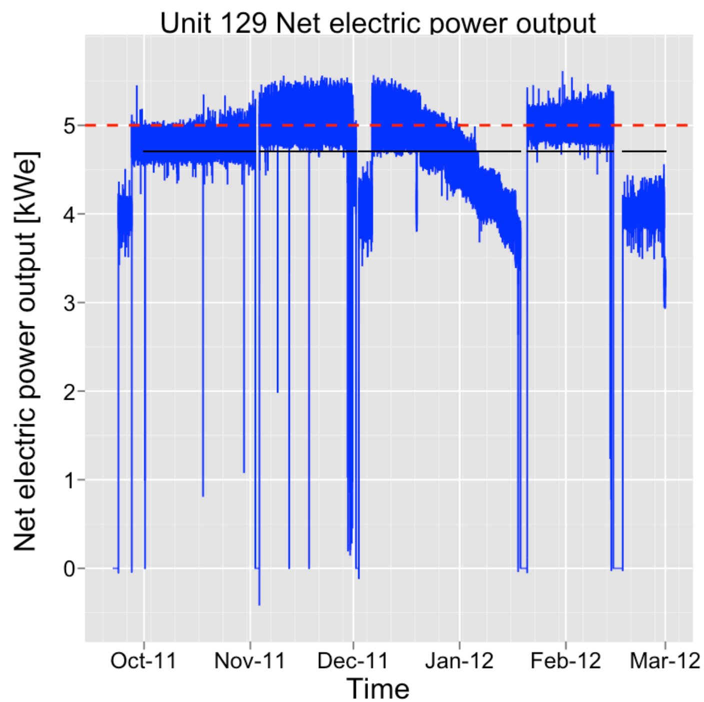
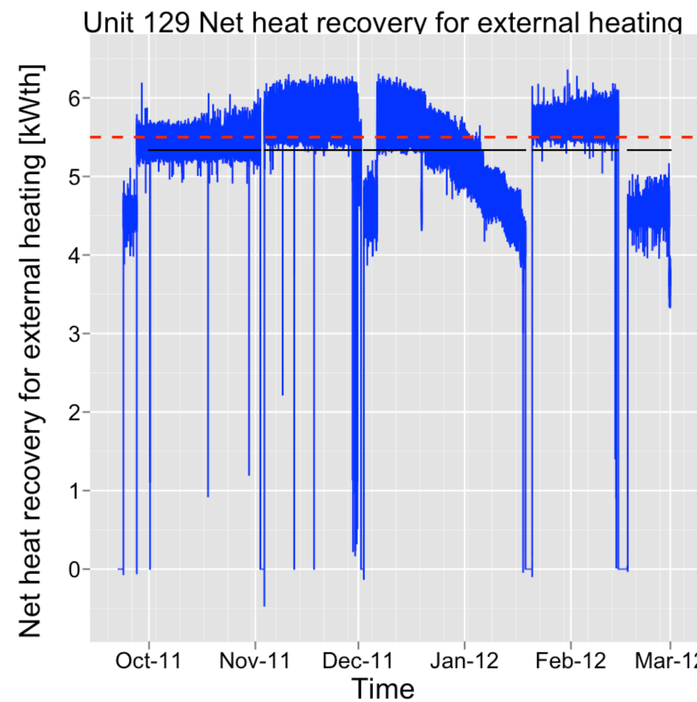
Available Fuel Types	gas, electricity
Principal Building Activity	Office
Total Floor Area (m^2)	46,320 (2003 CBECS)
Building Shape	Rectangle
Aspect Ratio	1.5
Number of Floors	12 plus basement
Window Fraction (Window to Wall Ratio)	
South	0.38
East	0.38
North	0.38
West	0.38
Total	0.38
Skylight/TDD Percentage	0.0
Shading Geometry	None
Azimuth	0.0
Thermal Zoning	core zone with four perimeter zones on each floor
Floor to Ceiling Height (m)	2.74
Floor to Floor Height (m)	3.96
Roof type	Built-up flat roof, insulation entirely above deck (2003 CBECS)
Exterior walls	
Construction Type	Mass wall (2003 CBECS)
Gross Dimensions - Total Area (m^2)	11,590
Net Dimensions - Total Area (m^2)	6,954
Wall to Skin Ratio	0.77
Roof	
Construction Type	IEAD
Gross Dimensions - Total Area (m^2)	3,563
Net Dimensions - Total Area (m^2)	3,563
Roof to Skin Ratio	0.24

Window Dimensions (m^2)	
South	1,391
East	927
North	1,391
West	927
Total Area (m^2)	4,636
Operable area (m^2)	0
Foundation	
Foundation Type	Basement
Construction	4 in slab w/carpet
Dimensions - Total Area (m^2)	3,563
Interior Partitions	
Construction	2x4 steel-frame with gypsum board
Dimensions - Total Area (m^2)	8,524
Internal Mass	
Construction	15 cm wood
Dimensions - Total Area (m^2)	92,641
Thermal diffusivity (m^2/s)	1.84E-07
Air Barrier System	
Infiltration (ACH)	0.10
HVAC	
System Type	MZ-VAV (2003 CBECS)
Heating Type	Gas boiler (2003 CBECS)
Cooling Type	2 water cooled chillers (2003 CBECS)
Fan Control	Variable (2003 CBECS)

Data Collected from Simulation Model

- Outdoor Dry Bulb [C]
- Space Heating System: Heating Demand [kW]
- Space Heating System: Inlet Node Flowrate [kg/s]
  - Varies based on Space Heating demand in the building
- Space Heating System: Inlet Node Temperature [C]
  - Varies based on heating load in the space
- Space Heating System: Outlet Node Temperature [C]
  - Constant at 82C
- Space Heating Load Seen by FC [kW]
  - Calculated by: If Inlet Node Temperature < 47C then
    - 47-Inlet Node Temperature x Mass Flow Rate x Specific Heat of Water
    - Else 0

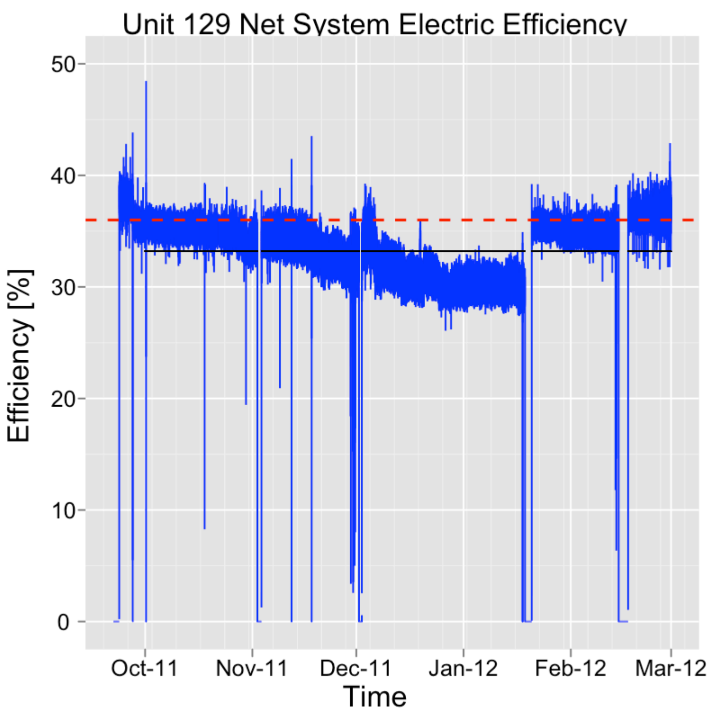
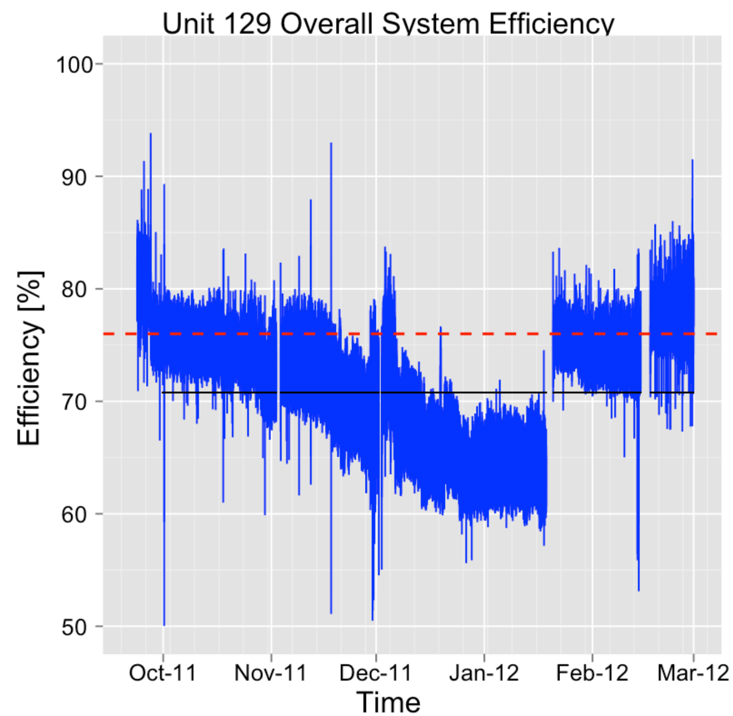
CHP FCSs – Representative Data Analysis

FCSs produce between 4.6 and 5 kWe of net electricity over time (measured values).	FCSs are estimated to recover 5.3 to 5.6 kWth of heat for the building at a maximum* over time.
	

Red dotted lines at 5 kWe and 5.5 kW_{th} represents manufacturer-stated values.

Solid black line represents average of measured values (downtime is not included)	Solid black line represents average of derived values. *Net heat recovery data are calculated values, derived from real-time measured values. Data represent maximum recoverable heat

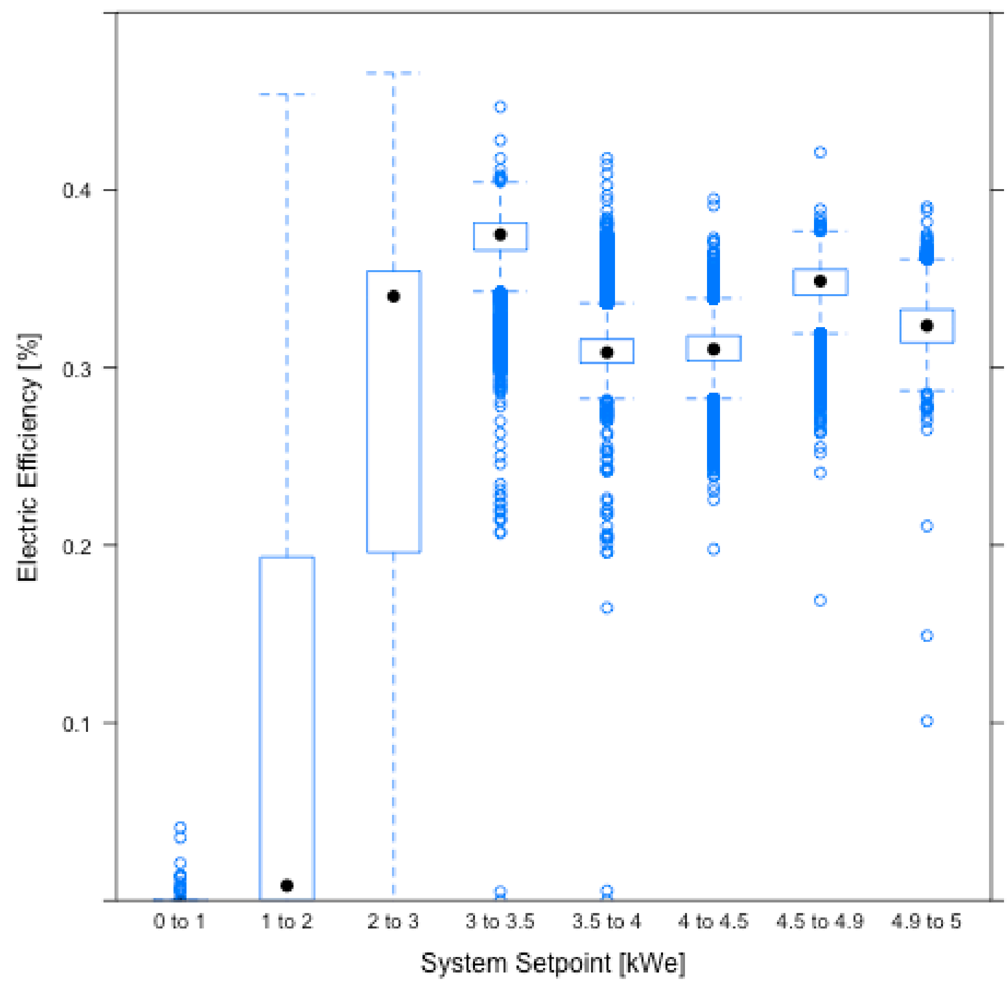
CHP FCSs – Representative Data Analysis

Net system electricity efficiency is between 33% and 36%.	Overall net system efficiency (net electrical + net heat recovery efficiency) is 72% to 78%.
	
Values are based on higher heating value (HHV).	Data is based on a calculated value for the heat recovered, based on HHV.

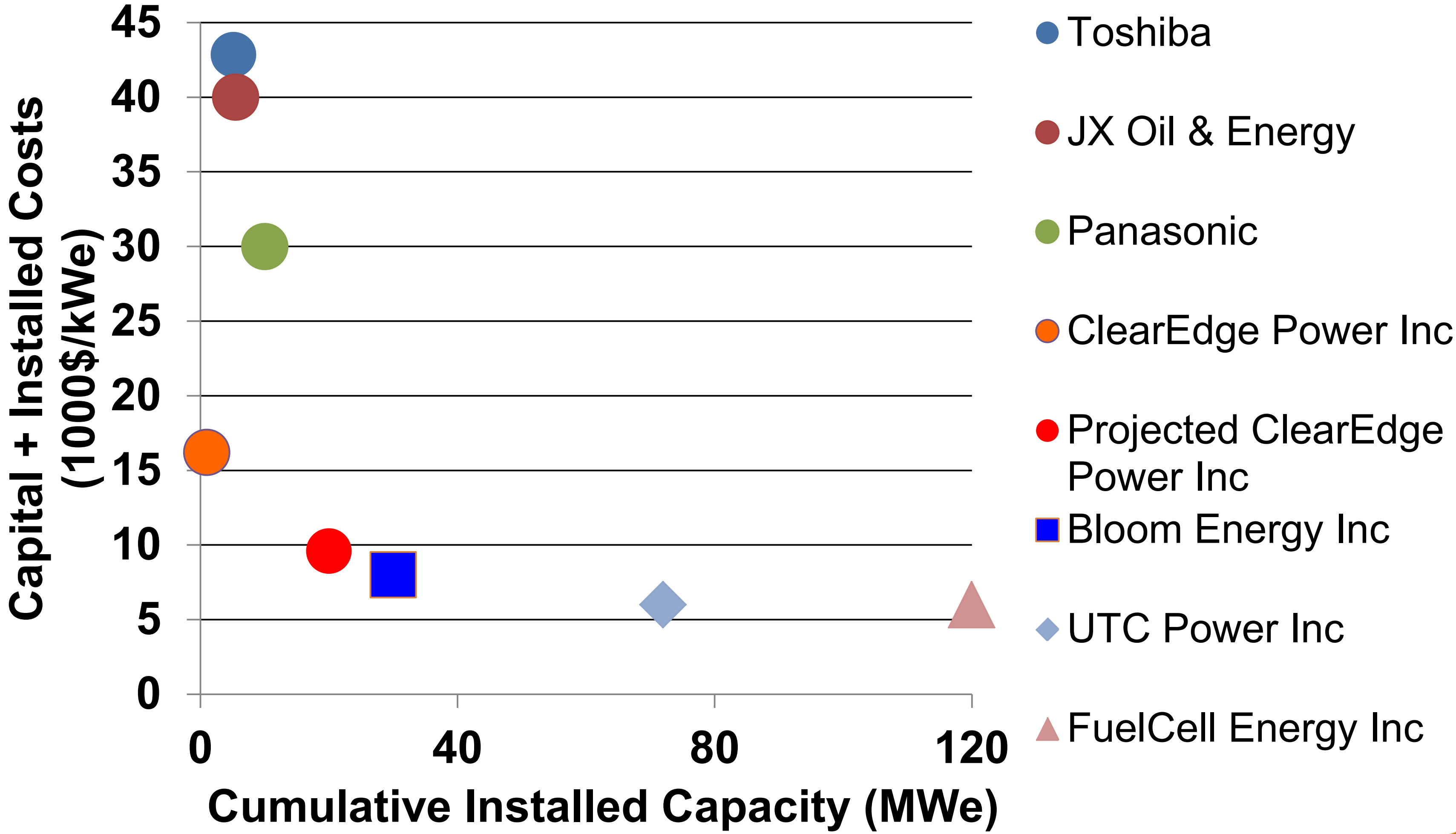
Red dotted lines at 36% and 76% represents manufacturer-stated value.
Solid black line represents average of measured values.

CHP FCSs – Data Analysis Insights

- The analysis team observed that the systems operate more efficiently at slightly lower setpoints. For one example unit shown the optimal setpoint for the unit based on historic operating performance is between 4.5 and 4.9 kWe.
- The manufacturer agreed and is now experimenting with a lower operation setpoint in all the units.
- This resulted in lower power output but higher efficiency for most units



Products with a higher installed capacity generally have lower capital and installed costs.



References: (1) International Energy Agency (IEA) 2010 Report, Stationary Fuel Cells Annex 25. (2) ASME Fuel Cell Conference 2011, Keynote Presentation by ToHo Gas Company. (3) Katrina Fritz-Intwala, UTC Power, IEA Advanced Fuel Cells Annex 25 Meeting No. 5, Orlando, FL, Oct. 31, 2011. (4) Christian Lorenz, E.ON Ruhrgas AG, Essen, Germany.

To report a *PRV_t* between 80% and 97%, the rated electrical output and the rated electrical efficiency would need to be lowered.

	Unit 130			Unit 129	
PRV_t	97%	96%	80%	97%	80%
Average net electric power output [kWe]	null	3.3 kWe	4.5 kWe	3.4 kWe	3.7 kWe
Average net system electrical efficiency	null	25%	30%	28%	30%

These numbers are optimized assuming power and efficiency are equally important.

Environmental performance and air pollution emissions

Environmental performance can be quantified by calculating the GHG mitigation cost.	Air pollution emissions can be quantified by calculating the human health cost that directly results from air pollution.

The $CO_{2equivalent}$ is the mass of carbon dioxide (CO_2) that would have an equivalent warming effect as a mixture of CO_2, methane (CH_4), and nitrous oxide (N_2O).

$$CO_{2equivalent} = m_{CO_2} + 23m_{CH_4} + 296m_{N_2O}$$

m_i is the mass of each species, and 23 and 296 are the global warming potentials (GWP), which are estimates of the relative global warming contribution of a unit of GHG emission compared to the emission of a unit mass of CO_2. The United Nations' Intergovernmental Panel on Climate Change conducts analyses for a range between $20/metric tonne and $100/metric tonne of $CO_{2equivalent}$.

Species	Human Health Cost [$/metric tonne]
Carbon Monoxide (CO)	114
Nitrogen Oxide (NO_x)	21,100
Particulate Matter-2.5 ($PM_{2.5}$)	203,000
Particulate Matter-2.5-to-10 ($PM_{2.5-10}$)	22,500
Sulfur Oxide (SO_x)	83,300
Volatile Organic Compound (VOC)	1,460