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Filer:	Cyrus Ghandi
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Development and Testing of the Next-Generation Residential Space Conditioner for California

CALIFORNIA ENERGY COMMISSION

CEC EPC-14-021 EPIC Project Results and Technology Recommendations

California Energy Commission
Electric Power Research Institute (EPRI)
Western Cooling Efficiency Center at University of California Davis

March 27, 2019

Project Funders and Partners with EPRI (Project Prime)

- Funders:
- Teaming Partners:
- Technology Provider:

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CALIFORNIA ENERGY COMMISSION

Commission Agreement Manager:
Jackson Thach

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Ammi Amarnath, Project Manager

Sara Beaini, PhD; Walt Hunt; Aaron Tam

Ron Domitrovic, PhD; Alekhya Vaddiraj

- Teaming Partners:

PG&E Pacific Gas and Electric Company®

Applied Technology Services, San Ramon, CA

Manny D'Albora, P.E. and Robert Davis, P.E.

UC DAVIS UNIVERSITY OF CALIFORNIA

WCEC WESTERN COOLING EFFICIENCY CENTER

Prof. Mark Modera, PhD, PE, Director

Curtis Harrington

Sreenidhi Krishnamoorthy, PhD

Robert Mcmurry

Theresa Pistochini

- Technology Provider:

DAIKIN Goodman Air Conditioning & Heating

Ryohei Hinokuma

Strategic Alliances Manager

Webinar Agenda: Project Results and Technology Recommendations

TOPIC	PRESENTER
Welcome & Background	*Jackson Thach, CEC and Ammi Amarnath, EPRI*
Project Overview: Scope, Features Tested, Summary Results	*Ammi Amarnath, EPRI*
Project Methodology	*Sara Beaini, EPRI*
Next-Generation Residential Space Conditioning System Evaluation Results	*Sara Beaini, Aaron Tam, EPRI* *Curtis Harrington, WCEC*
Recommendations and Lessons Learned	*Sara Beaini, EPRI* *Curtis Harrington, WCEC*
Technology Transfer	*Sara Beaini, EPRI*
Questions & Discussion	*All*

Project Overview: Scope, Features Tested, Summary Results

Ammi Amarnath

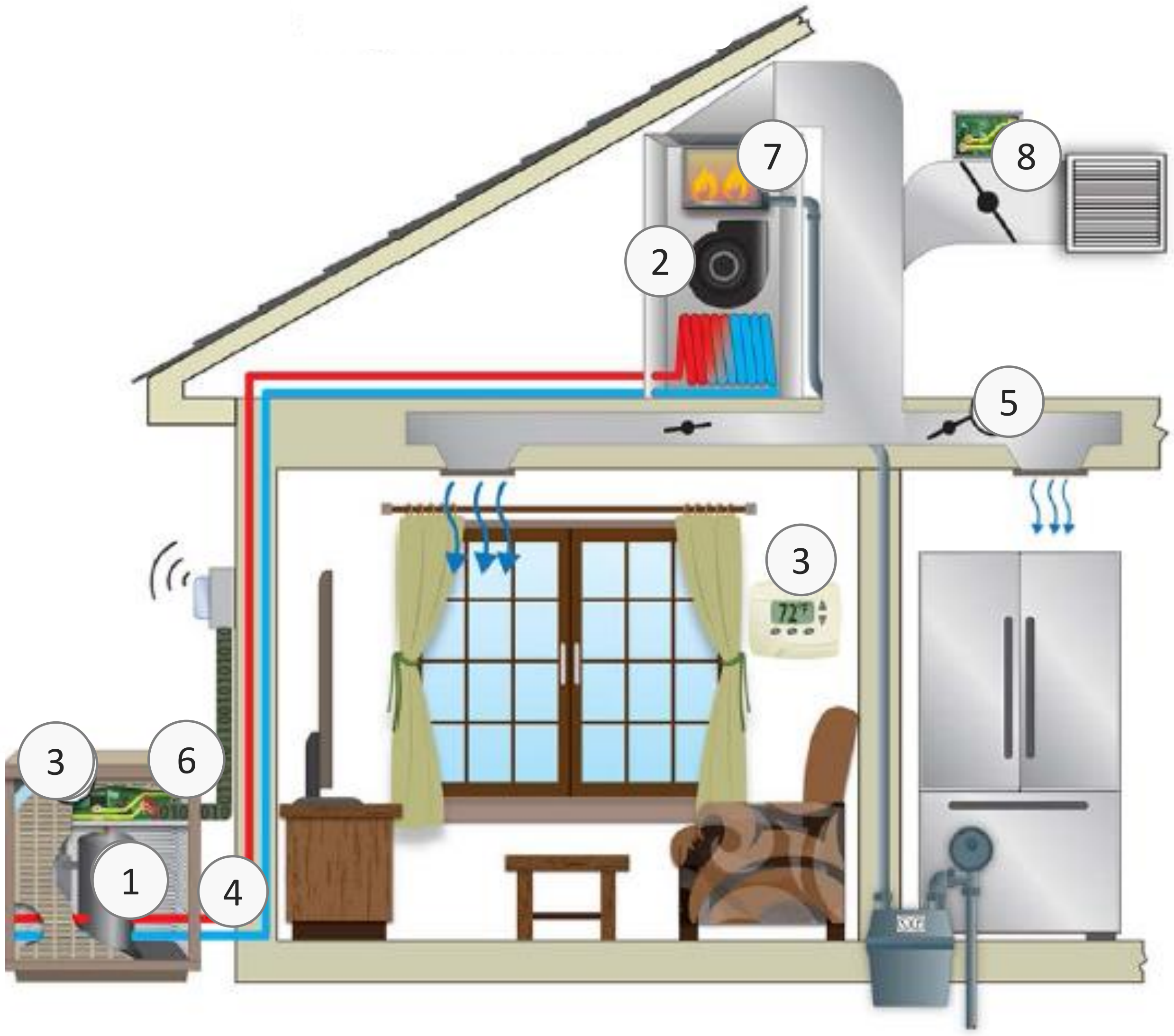
Project Objectives: Next Generation Residential Space Conditioning System (Next-Gen RSCS) for California

- Develop *Variable Capacity Smart HVAC System*, *integrating* best energy-efficient technologies for California consumers - *Next-Gen RSCS*
- Test in independent labs to evaluate more energy-saving technologies
- Assess various configurations of Next-Gen system, optimized for CA consumer
- Field test system in 3 real-world operating environments to compare with traditional HVAC performance
- Technology transfer for stakeholders and public

Next-Generation Space Conditioner Enhancing Technology Features

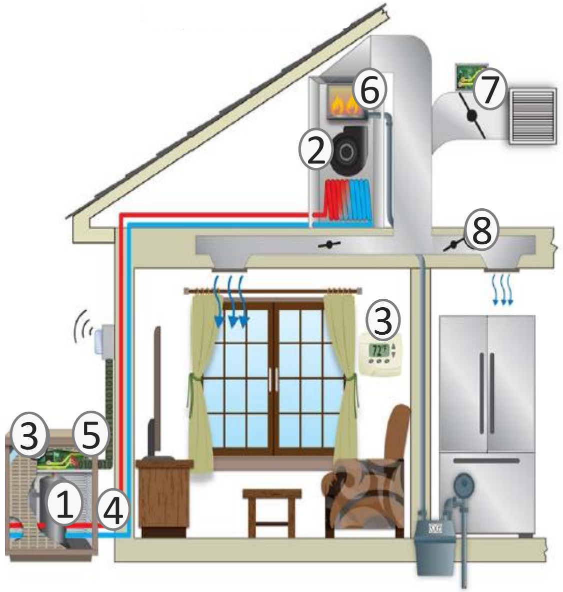
multiple energy efficiency features integrated into single system

1. Variable Capacity Compressor
2. Variable Speed Indoor Blower
3. Auto Demand Response
4. Alternative Refrigerant
5. Zonal Control
6. Fault Detection & Diagnostics
7. Dual Fuel (Intelligent Heating)
8. Integrated Ventilation Control



Next-Gen RSCS Summary Results

- Variable Capacity Compressor and Variable Speed Indoor Blower
  - Next-Gen RSCS provides 22-32% cooling energy savings and over 90% of annual heating load without backup for CA.
- Auto Demand Response (DR)
  - Variable capacity heat pump maintains customer comfort during DR event.
- Alternative Refrigerant
  - R-32 improves cooling efficiency by 2-3% and peak demand reduction by 7-8% compared to R-410A across CA climate zones
- Zonal Control
  - Zoning should be required for variable capacity heat pumps *with ducts in unconditioned space.*
- Fault Detection and Diagnostics (FDD)
  - FDD improves performance with up to 55% efficiency savings
- Integrated Ventilation
  - Additional 1-4% cooling energy savings and 1% for heating using VCHP with heat recovery ventilator (HRV)
- Dual Fuel (Intelligent Heating)
  - Dual fuel functionality adds system versatility for future intelligent heating capability



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Project Methodology

Sara Beaini

Technology Attributes Lab Tested in Phase 1 and Phase 2

	Technology Attributes	EPRI	PG&E	WCEC
Phase 1	Variable-Capacity Compressor	✓	✓	✓
	Variable-Speed Indoor Blower	✓	✓	✓
	Integrated Ventilation	✓		
	Demand Response	✓	✓	
	Dual Fuel (intelligent heating)		✓	
	Duct-loss assessment for single-zone			✓
Phase 2	Alternative Refrigerants	✓ (R-32)	✓ (R-32)	
	Zonal Control	✓ (R-32)		
	Fault Detection & Diagnostics		✓ (R-410A)	
	Duct-loss assessment for multi-zone			✓ (R-410A)

Technology Specifications

- Outdoor Unit: 2-ton rated cooling capacity heat pump with inverter drive compressor
  SEER 19-21 / HSPF 9.6-10.0
- Furnace: 80,000 Btu/hr modulating burner, ½-hp variable speed blower, Rated AFUE 97
- Indoor Coil
- Smart Thermostat

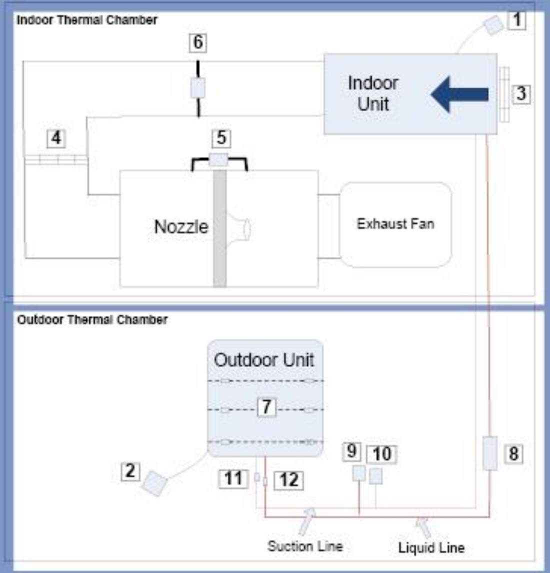
Daikin/Goodman residential heat pump units undergo testing at EPRI Thermal Laboratory, PG&E Applied Technology Services, and UC Davis Western Cooling Efficiency Center

Indoor Unit Setup at PG&E

EPRI Thermal Lab Environment Chambers

Outdoor Unit

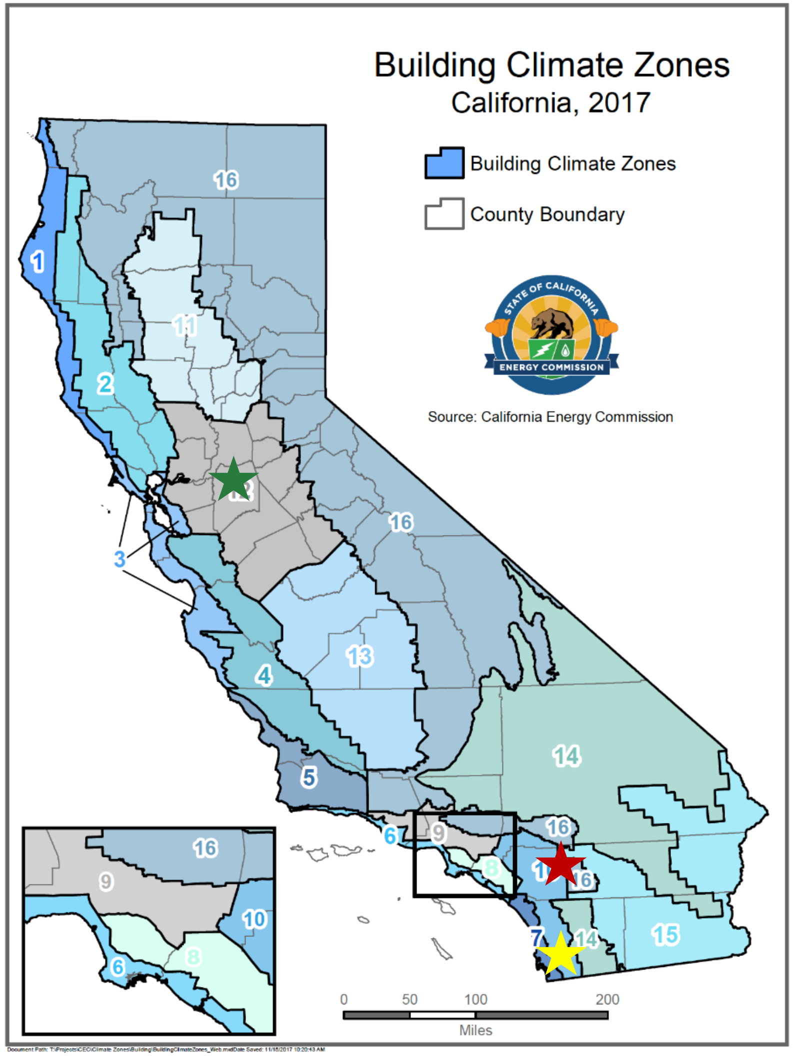
Ductwork Setup in WCEC Testing Chamber



Schematic of Test Setup

Laboratory Evaluation: Phase 1 and Phase 2

Phase 3 Field Evaluation



Attribute/IOU	PG&E	SCE	SDG&E
City	West Sacramento	Chino Hills	San Diego
Climate Zone	12	10	7
Area (Ft^2)	2507	1850	1906
Home Vintage	2008	1993	1980
Existing HVAC	Ducted AC with Gas Furnace	Ducted AC with Gas Furnace	Ducted AC with Gas Furnace
Location of Ducts	Attic	Attic	Attic
Existing AC Size (Tons)	3-ton Condenser 4-ton AHU	4	4
Floors	2	2	1
Number of Bedrooms	3	4	3
Number of Residents	4 + 1 pet	4 + 1 pet	1+3 pets
Installed Next-Gen RSCS	*4- ton ducted split w/ gas furnace*	*4- ton ducted split w/ gas furnace*	*4- ton ducted split w/ gas furnace*
New ducting	*R-6*	*R-8*	*R-8*

Technology Features Evaluated by Project Phase

Technology	Phase 1 Lab Test	Phase 2 Lab Test	Phase 3 Field Test
Variable-Capacity Compressor	✓		✓
Variable-Speed Blower	✓		✓
Integrated Ventilation	✓		
Demand Response	✓		✓
Dual Fuel (intelligent heating)	✓		✓
Duct-loss assessment for single-zone	✓		
Alternative Refrigerants		✓	
Fault Detection & Diagnostics		✓	
Zonal Control		✓	✓
Duct-loss assessment for multi-zone		✓	✓

Field Installation: Host Sites

PG&E site

SCE site

SDG&E site

Field Installation: System M&V

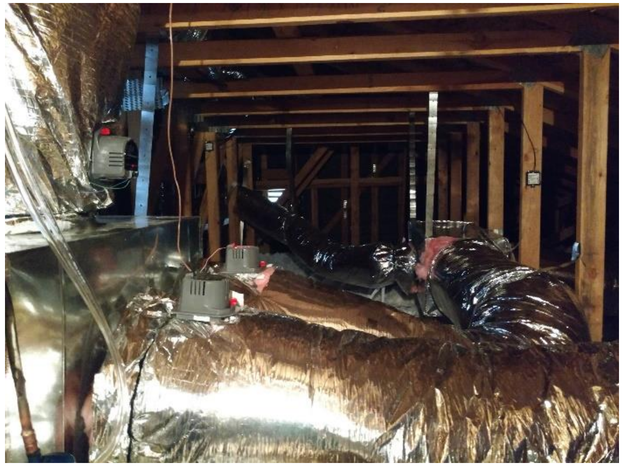
Outdoor Unit

Indoor Air Handling Unit

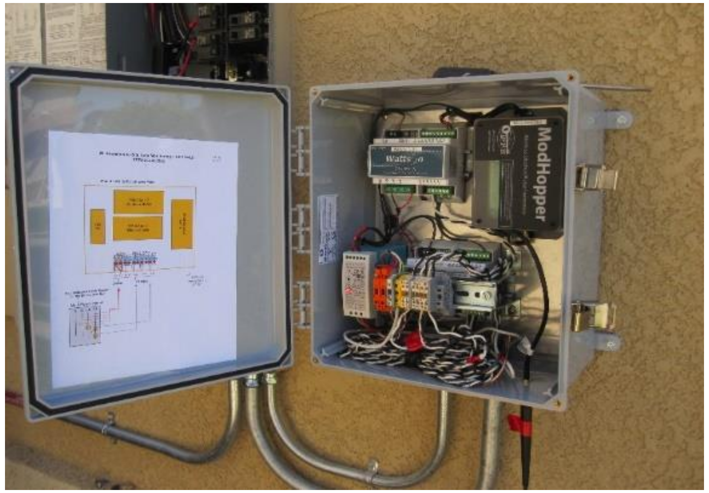
EWC Controller

Thermostat and sensors

Attic Ducting



EPRI M&V Box



Next-Gen RSCS Evaluation Results

Sara Beaini, Aaron Tam, Curtis Harrington

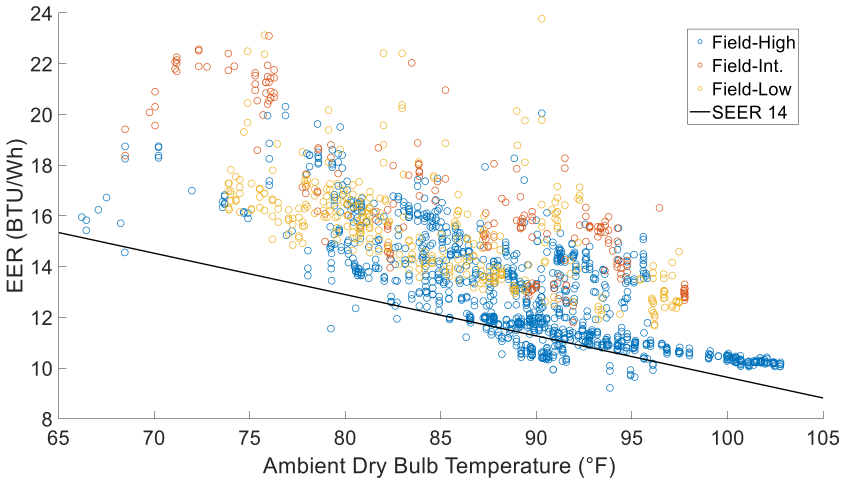
Next-Gen RSCS: Homeowner's Feedback

- Homeowners appreciate how much quieter the Next-Gen RSCS operates compared to previous singe speed AC unit
- Homeowners like how quickly it cools or heats the space
- Homeowners like having app-based controller with Thermostat to turn on specific zones
- Zonal control added complexity to the system use
  - Airflow was too forceful in certain zones, thus noisy in certain rooms
  - Adjusting weighting of the zones with Zonal Control board mitigated this effect

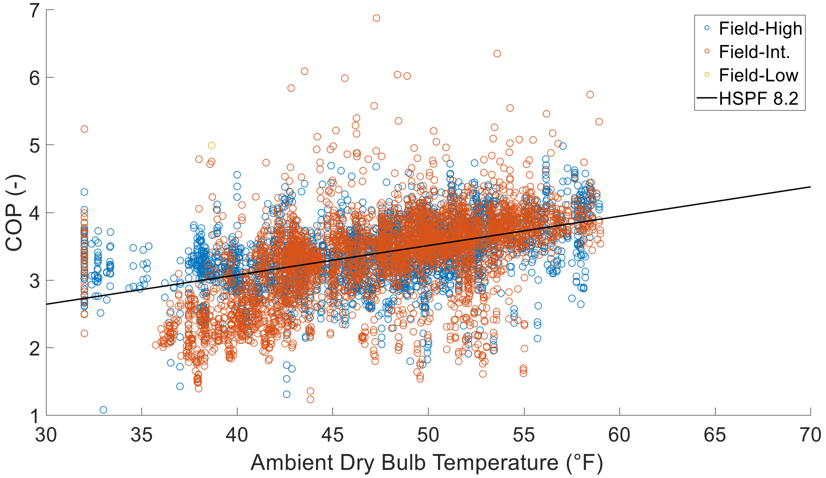
Next-Gen RSCS Evaluation Results

- Variable Capacity Compressor and Variable Speed Indoor Blower

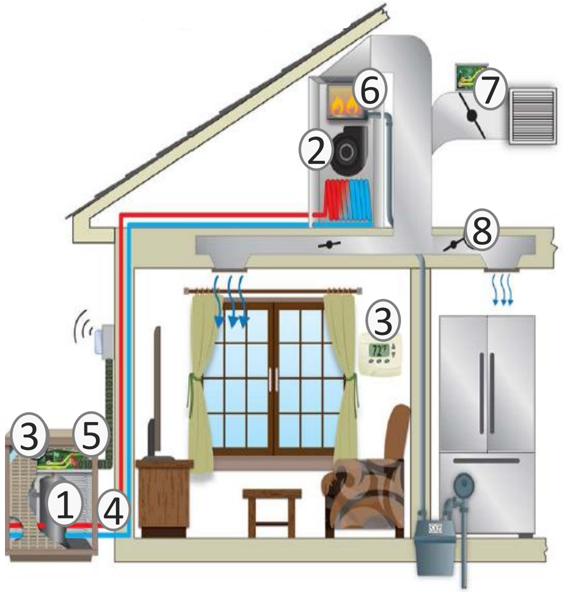
Variable capacity heat pump (SEER 21/HSPF 9.2) field data shows efficiency improvements over baseline (single speed SEER 14/HSPF 8.2)



Unit cooling efficiency results @ PG&E site



Unit heating efficiency results @ PG&E site



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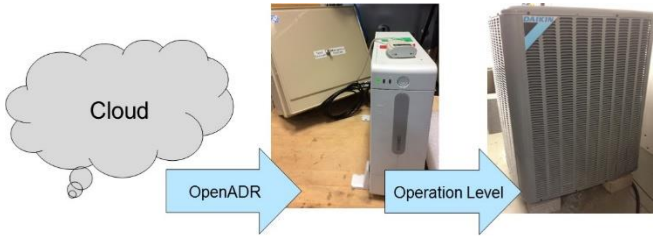
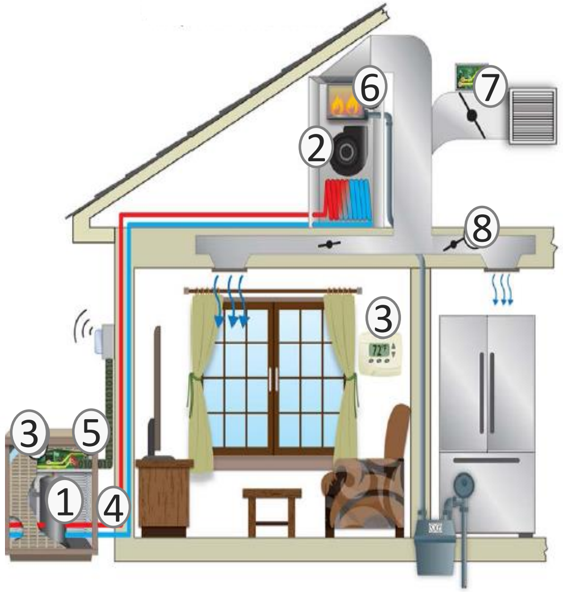
Next-Gen RSCS provides 22-32% cooling energy savings and over 90% of annual heating load without backup for CA.

Next-Gen RSCS Evaluation Results

- ## Auto Demand Response (DR)
  - Variable Capacity Heat Pump can serve as a valuable and flexible DR resource
  - Demonstrated ADR using OpenADR 2.0b
  - Capacity reduction is less than the power reduction (non-linear)



	Unit Power (W)	Percent Power Reduction	Approximate Cooling Capacity (Btu/h)	Percent Capacity Reduction
Baseline Case	1,866	-	17,000	-
Event 1: 50% Power	928	50.3%	10,500	38.2%
Event 2: 30% Power	558	70.1%	6,500	61.8%



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Variable capacity heat pump maintains customer comfort during demand response event.

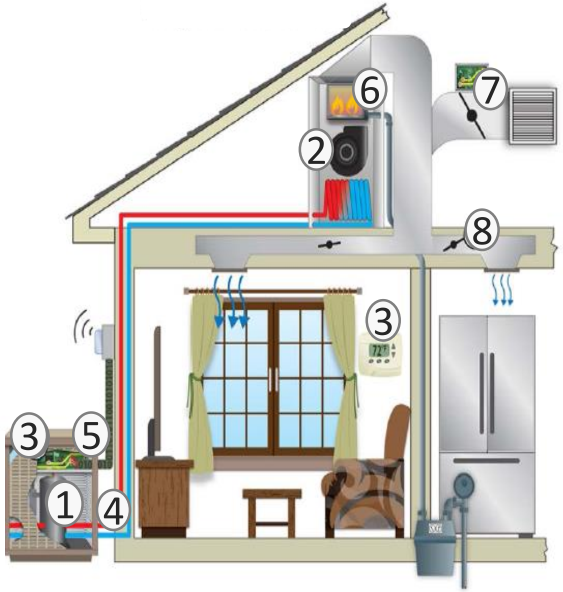
Next-Gen RSCS Evaluation Results

- Alternative Refrigerant

R-32 (GWP 675)

Effective drop-in refrigerant in a Variable Capacity Heat Pump (VCHP) compared to R-410A (GWP 2100)

- R-32 reduced system charge by 29% compared to R-410A.
- R-32 improved cooling performance by1.2 to 3.0% compared to R-410A.
- R-32 in HVAC equipment provided peak power reduction of 6.7%, 7.0% and 8.2% at 95°F, 105°F and 115°F compared to R-410A.
- R-32 increased heating capacity by 5% at 25°F and by 10% at 62°F, but COP was reduced by 2 to 4% compared to R-410A.



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Lower GWP refrigerant improves Energy Efficiency.
Lower GWP refrigerant reduces refrigerant charge.

Comparison of R-32 and R-410A in Variable Capacity Heat Pump

Equipment Cooling Efficiency Improvement for California Residences

California Climate Zone	Representative City	VCHP R-410A	VCHP R-32
1	Arcata	-	-
2	Napa	32.3%	+1.8%
3	Oakland	25.5%	+2.4%
4	San Jose	29.6%	+2.5%
6	Los Angeles	30.2%	+2.2%
7	San Diego	28.3%	+2.2%
8	Long Beach	29.9%	+3.0%
10	Riverside	30.3%	+2.2%
12	Stockton	28.6%	+2.5%
13	Fresno	28.2%	+2.6%
15	Blythe	22.4%	+2.7%

22 – 32% cooling efficiency improvement with **R-410A VCHP**

Additional 2 – 3% with **R-32 VCHP**

Equipment Cooling Peak Demand Reduction for Residences

Outdoor Temperature (F)	VCHP R-410A	VCHP R-32
95	3.7%	10.4%
105	3.3%	10.3%
115	2.6%	10.8%

3 – 4% peak demand reduction with **R-410A VCHP**

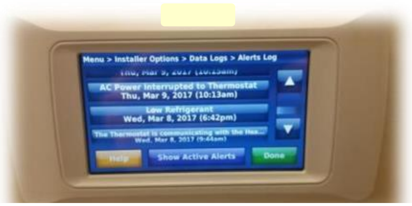
Additional 7 – 8% with **R-32 VCHP**

R-32 improves cooling efficiency by 2-3% and peak demand reduction by 7-8% compared to R-410A across CA climate zones.

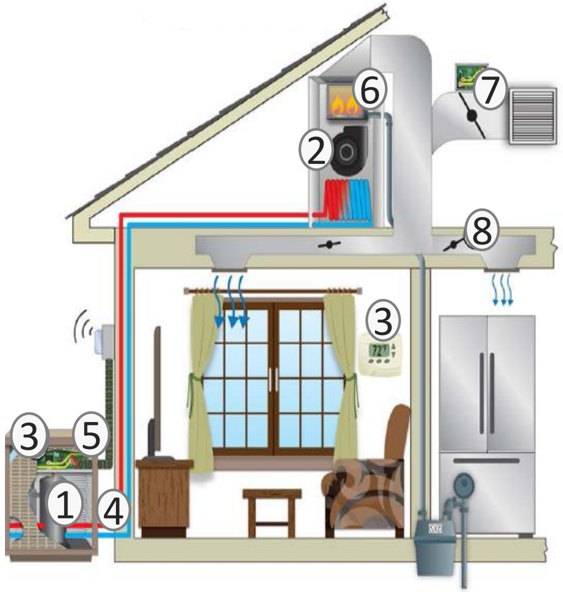
Next-Gen RSCS Evaluation Results

- ## Fault Detection and Diagnostics
  - *Ability to detect system degradation in performance and trigger diagnostics for service to remedy issues*
  - Detectable faults were identified in both heat pump and furnace
  - FDD system can provide up to 55% efficiency savings (literature)
  - *Feature refinement needed to provide notification in advance of fault occurrence*

Technician View



Homeowner View



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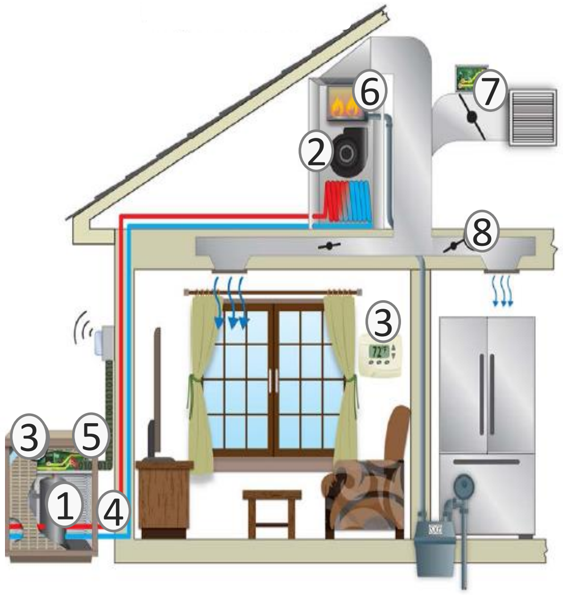
Fault detection and diagnostics improves performance with up to 55% efficiency savings

Next-Gen RSCS Evaluation Results

- ## Integrated Ventilation
  - *Using heat recovery ventilator (HRV) to provide fresh air ventilation efficiently by exchanging heat between a fresh air and exhaust air stream*

CA Climate Zone	City	Annual Energy Savings for Cooling Season		Percentage of Modeled Annual Heating Load Satisfied by VCHP	
		VCAC	VCAC + HRV	VCHP	VCHP + HRV
1	Arcata	-	-		
2	Napa	32.3%	+2.3%	91.1%	+0.9%
4	San Jose	29.6%	+1.8%	94.2%	+0.7%
10	Riverside	30.3%	+3.5%	93.9%	+0.7%
12	Stockton	28.6%	+3.2%	88.6%	+1.3%
13	Fresno	28.2%	+3.7%	87.5%	+0.9%
15	Blythe	22.4%	+3.6%	87.5%	+1.0%
16	Bishop	28.2%	+3.8%	95.5%	+0.7%



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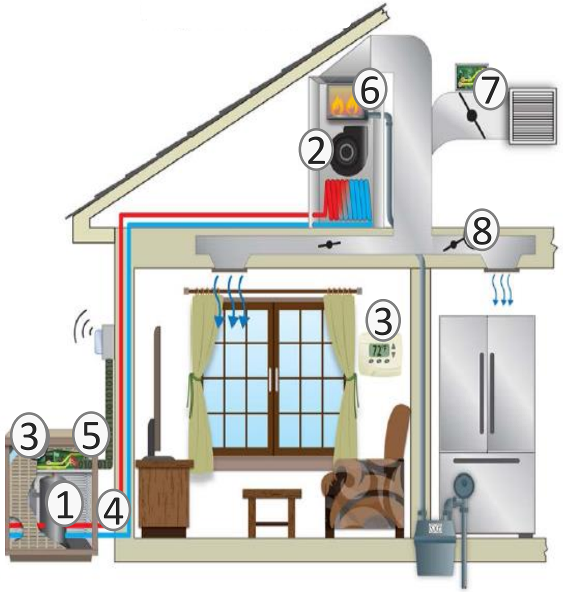
Additional 1-4% cooling energy savings and 1% for heating using VCHP with Integrated Ventilation for CA climate zones

Next-Gen RSCS Evaluation Results

- Dual Fuel Heating
- *means electric variable capacity heat pump with natural gas furnace for back up*

- Key Metrics to Assess:
  - **Breakeven temperature**: *Temperature below which it is cheaper to provide heat with natural gas*
  - **Balance point**: *Temperature below which heat pump can no longer provide all the heating requirements of the space*



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Dual fuel functionality adds versatility to Next-Gen RSCS to provide intelligent heating capability in the future

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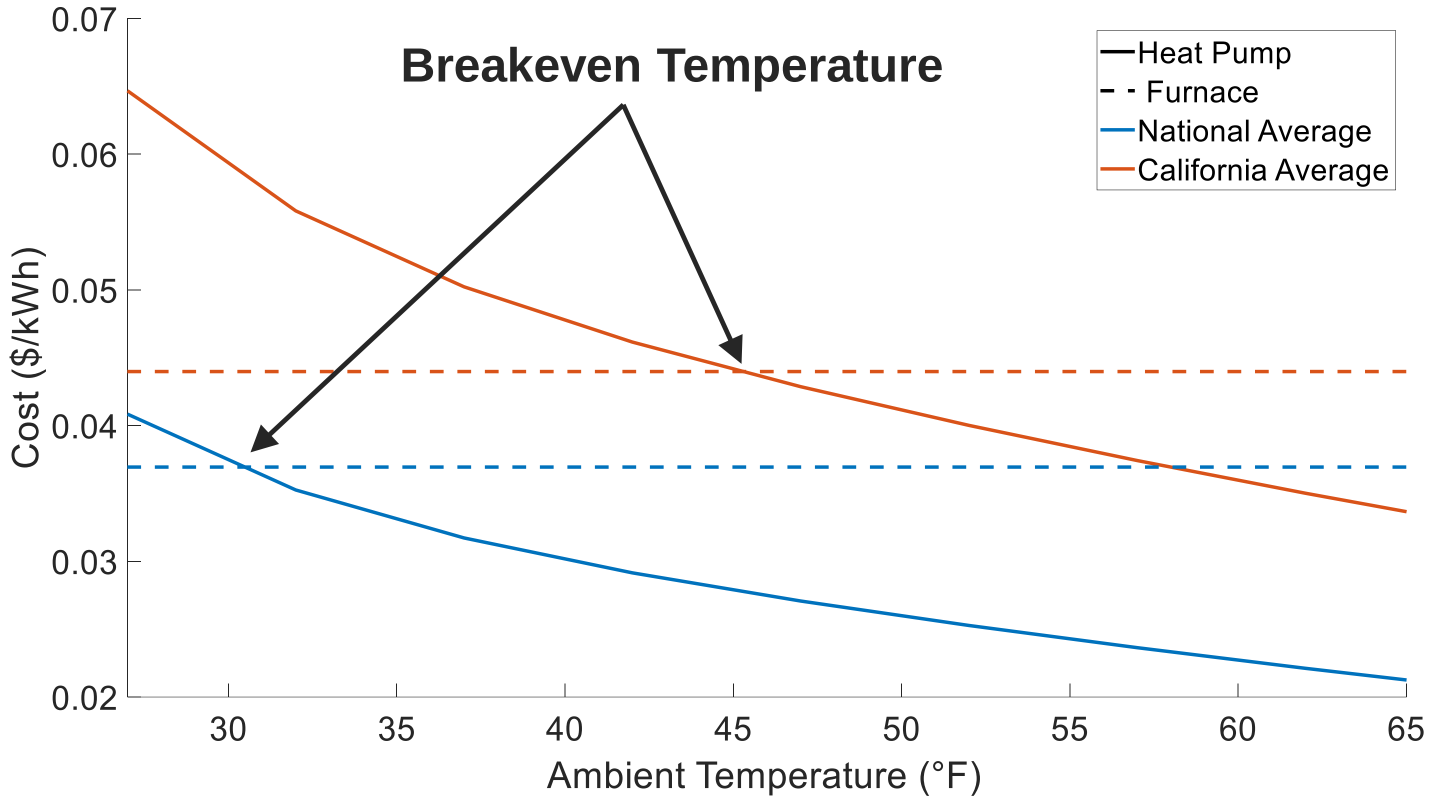
Next-Gen RSCS: Dual Fuel Heating Capability – cont.

Utility Rates Information

	Electricity [$/kWh]	Gas [$/thm]
California Average	0.19	1.25
National Average	0.12	1.05

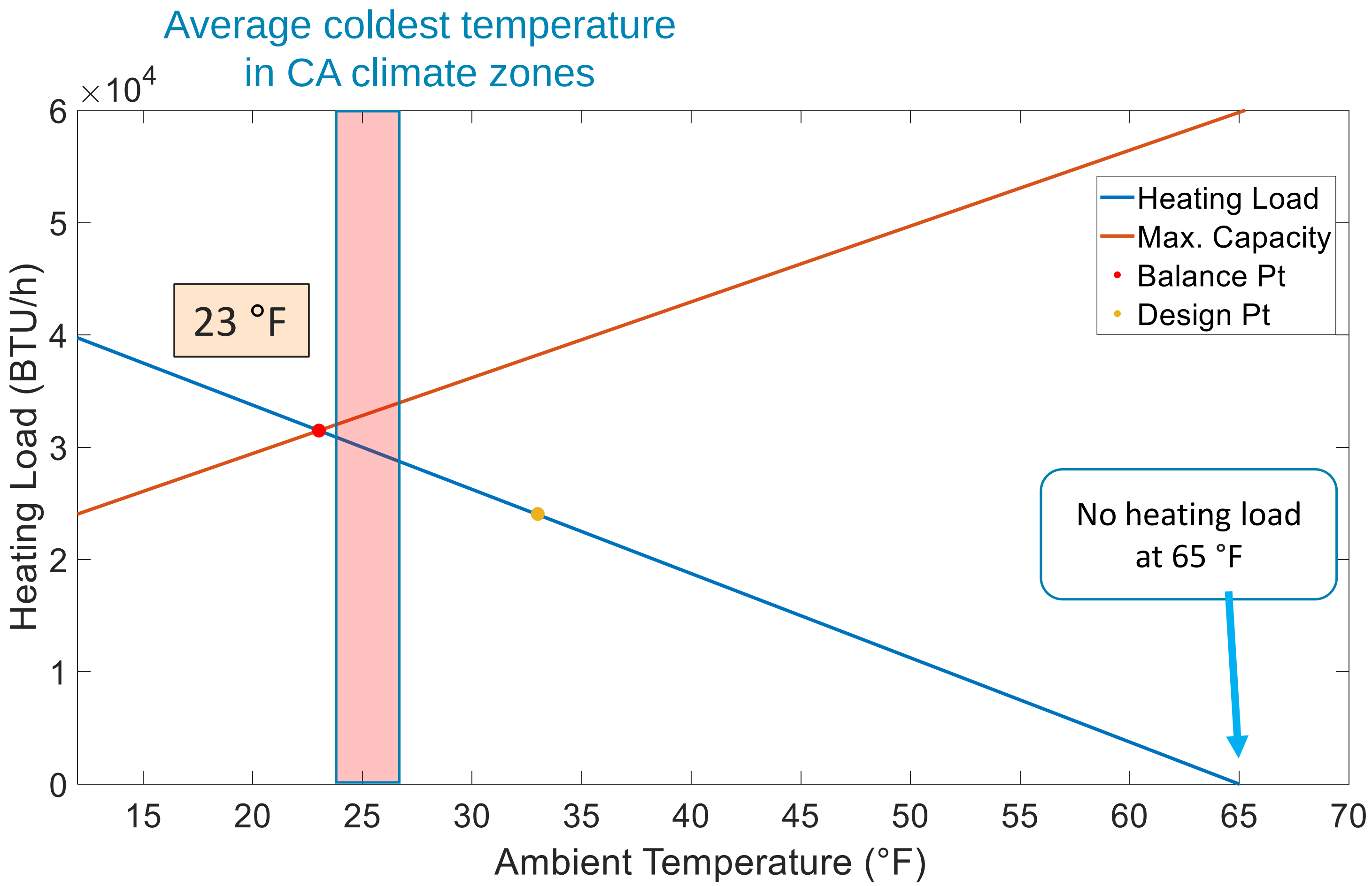


Utility rates are primary drivers for incentivizing heat pump usage

Next-Gen RSCS: Dual Fuel Heating Capability – cont.

Design Point for PG&E site

Outdoor Temperature	33°F
Indoor Temperature	70°F
Heating Load	24,000 Btu/h



Heat pumps are well suited for CA climate zones since they can meet almost all loads in the heating season *without backup*

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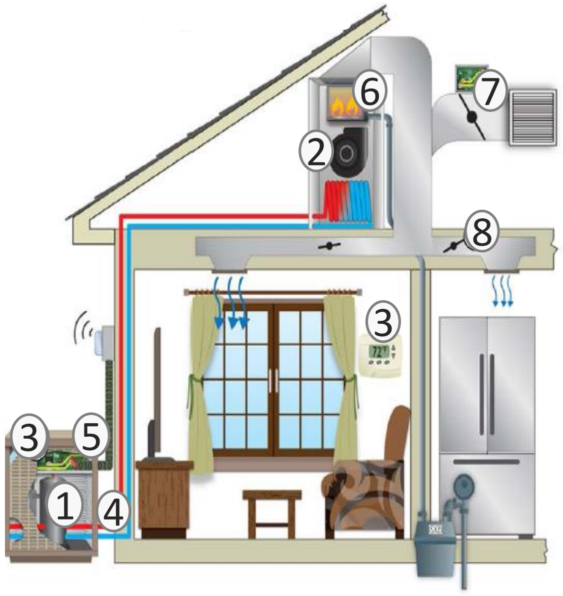
Next-Gen RSCS Evaluation Results

- Zonal Control

Separating conditioned space into smaller zones, separated by dampers with the ductwork and controlled with thermostat or unit controller

- Zoning should be required for variable capacity heat pumps (VCHP) with ducts in unconditioned space
- Require a *minimum of 2 zones* when installing VCHP **OR** place *ducts in **conditioned** space*
  - 2-zone equipment is well-established and poses few technical challenges
  - 2-zone systems would achieve much of the benefits
    - 39% better effectiveness at low speed vs. R-6 with no zoning
- Optimal zoning for the full range of operating speeds can be challenging
  - Coordination is needed between zone controller and fan speed



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Zoning should be required for variable capacity heat pumps *with ducts in unconditioned space.*

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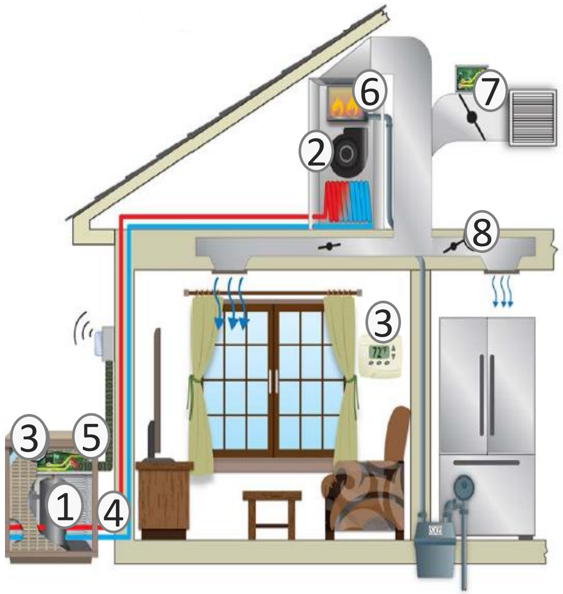
Next-Gen RSCS Evaluation Results

- Duct Delivery Effectiveness

How well ducts deliver the conditioned air to ducted space

- Duct loss assessment with variable capacity heat pump
  - Actual duct design for a 2-ton single-family system
  - Ducts located in unconditioned space (same temp as outdoor)
  - Standard new-construction duct insulation – R-6
  - No duct leakage



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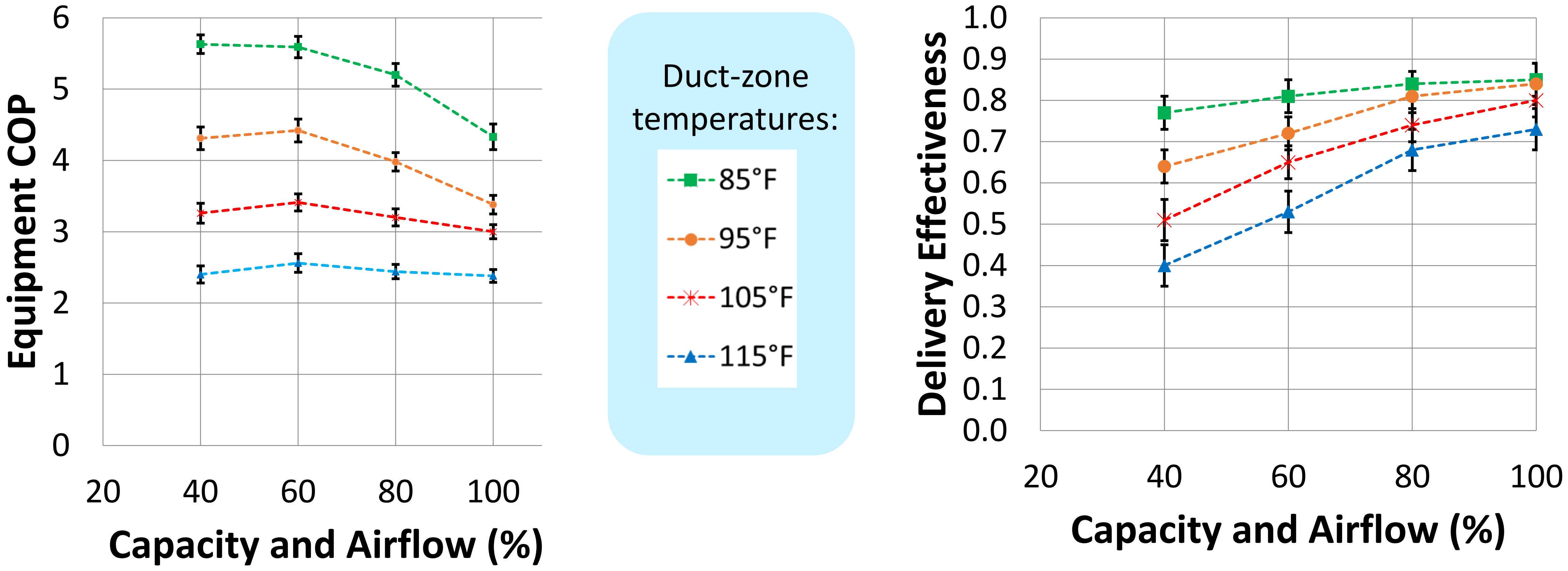
Maximum System COP depends on outdoor/attic temp

Equipment COP and Duct Efficiency vs. Compressor and Fan-Speed

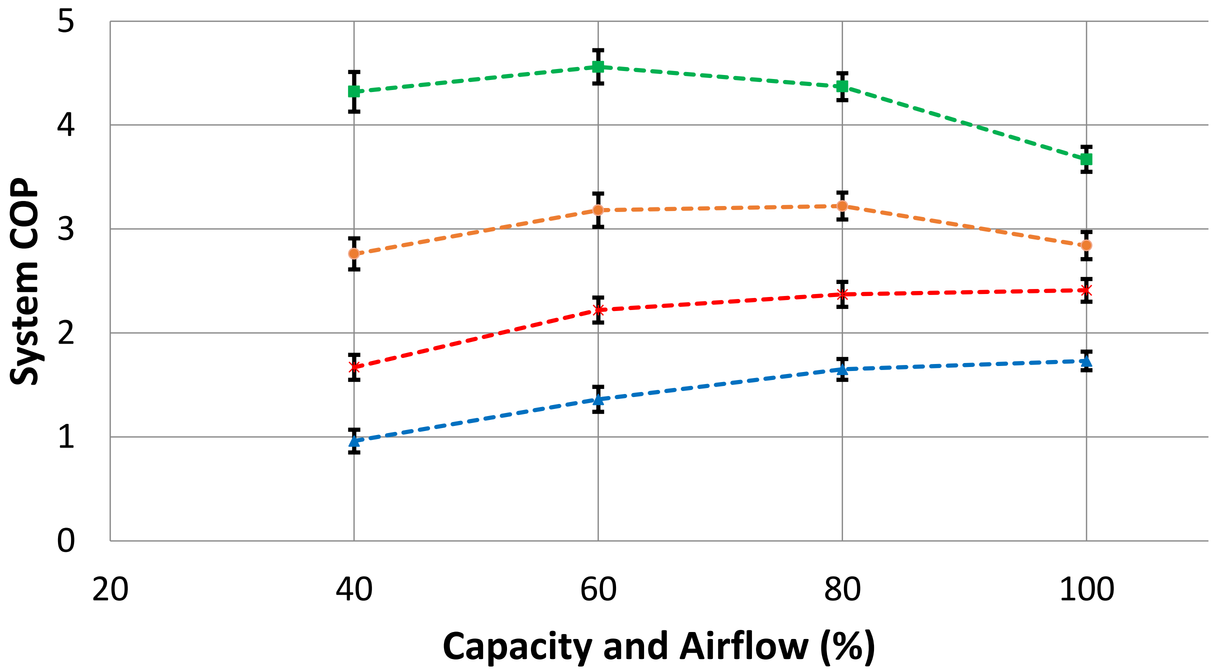


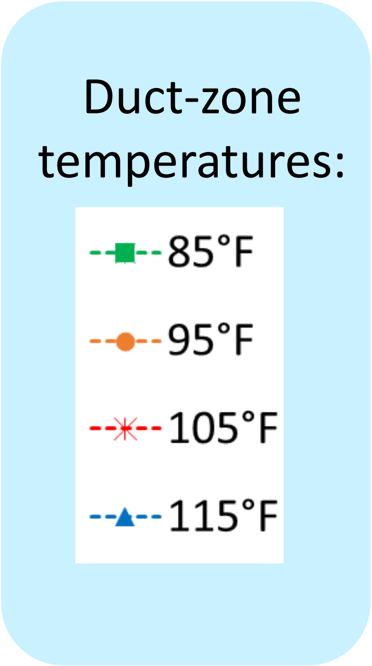
Equipment performance increases as speed is reduced

Delivery effectiveness decreases as speed is reduced

System COP

- System COP = Equipment COP x Delivery Effectiveness
  - *System COP describes overall efficiency including equipment and ducts*
- Maximum System COP depends on outdoor/attic temperature

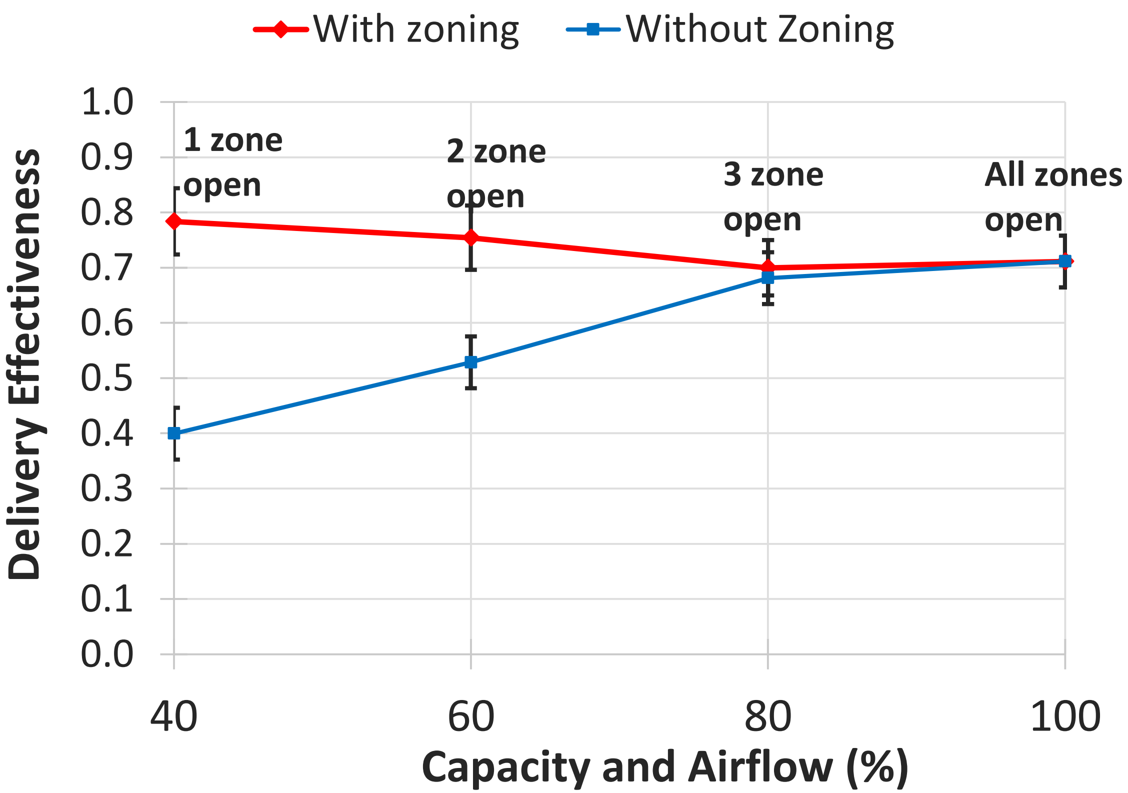


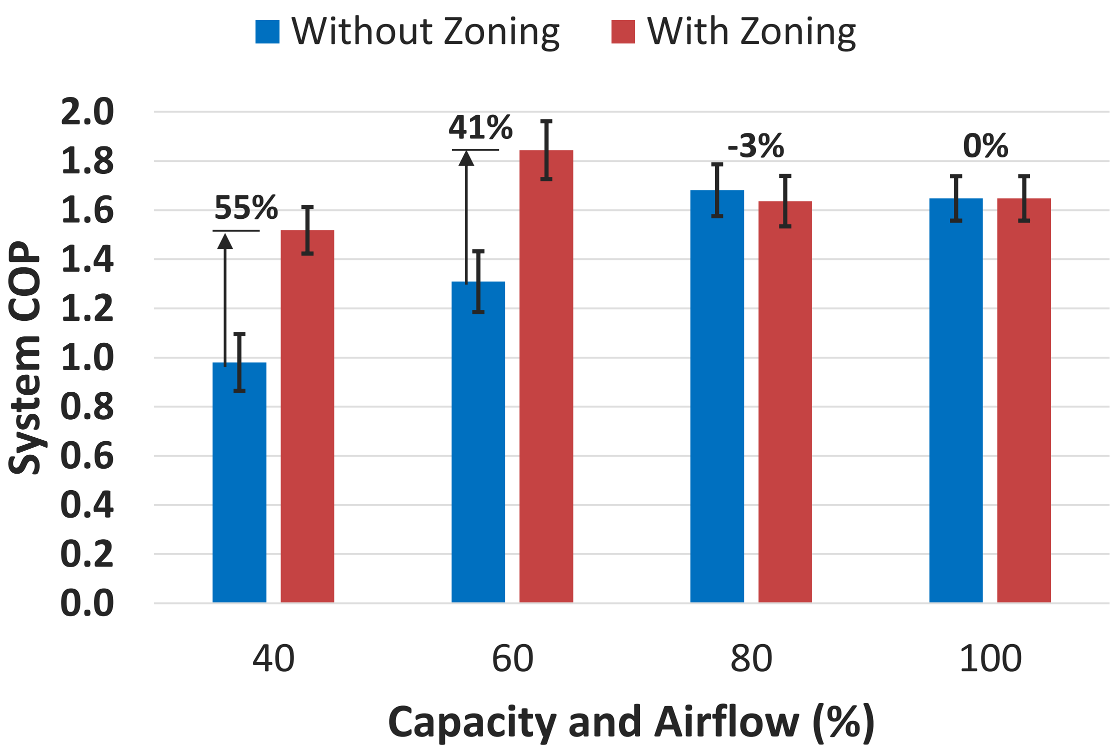


Optimal speed at high temperatures is 100%

Impact of Adding Zoning: (Attic: 115°F, Indoor: 75°F)

- 95% more cooling delivered when zoned at low speed
- 40-55% better system efficiency at low speed





Zoning can significantly reduce duct losses at low speed

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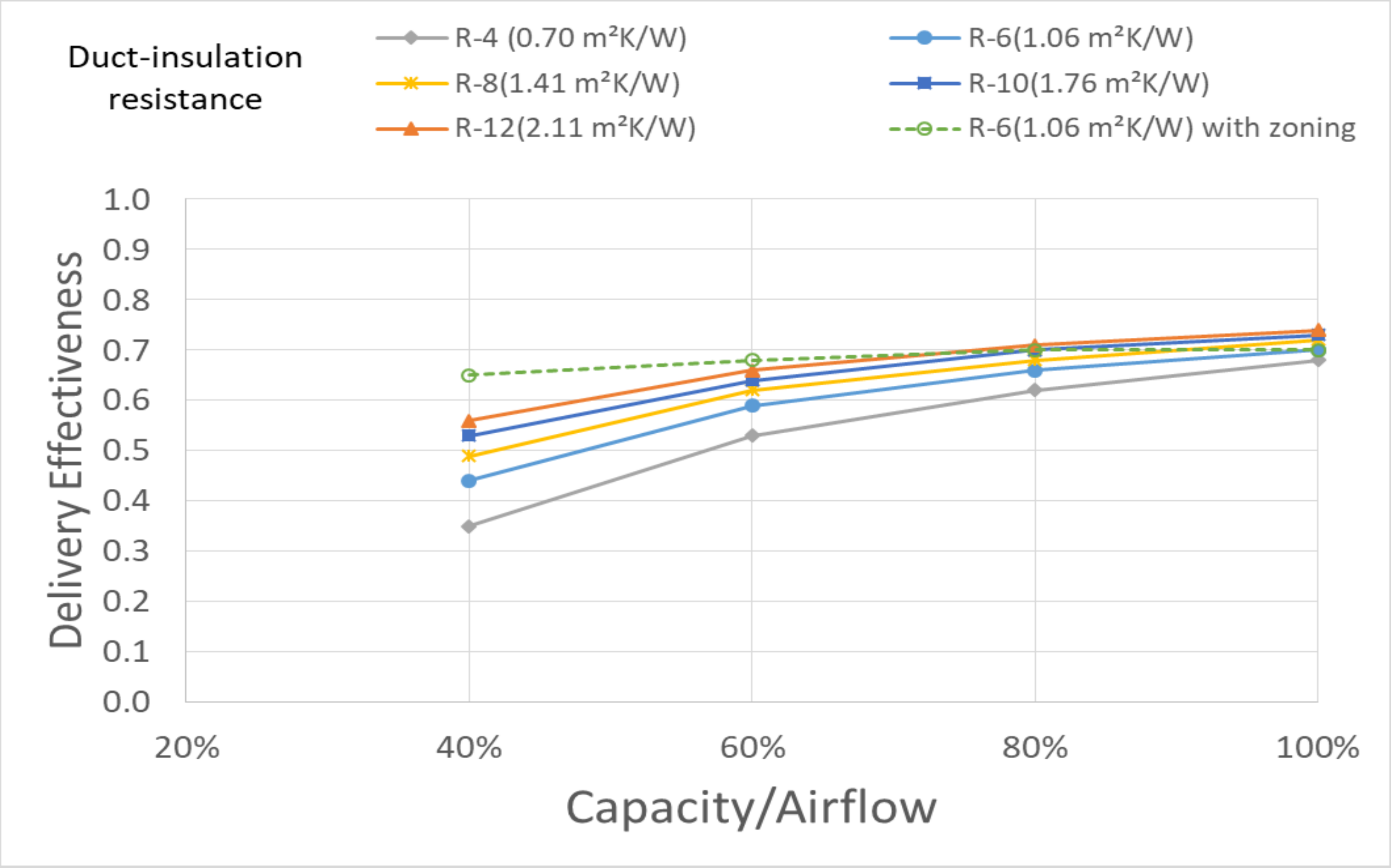
Zoning versus Adding Insulation: (Attic: 115°F, Indoor: 75°F)

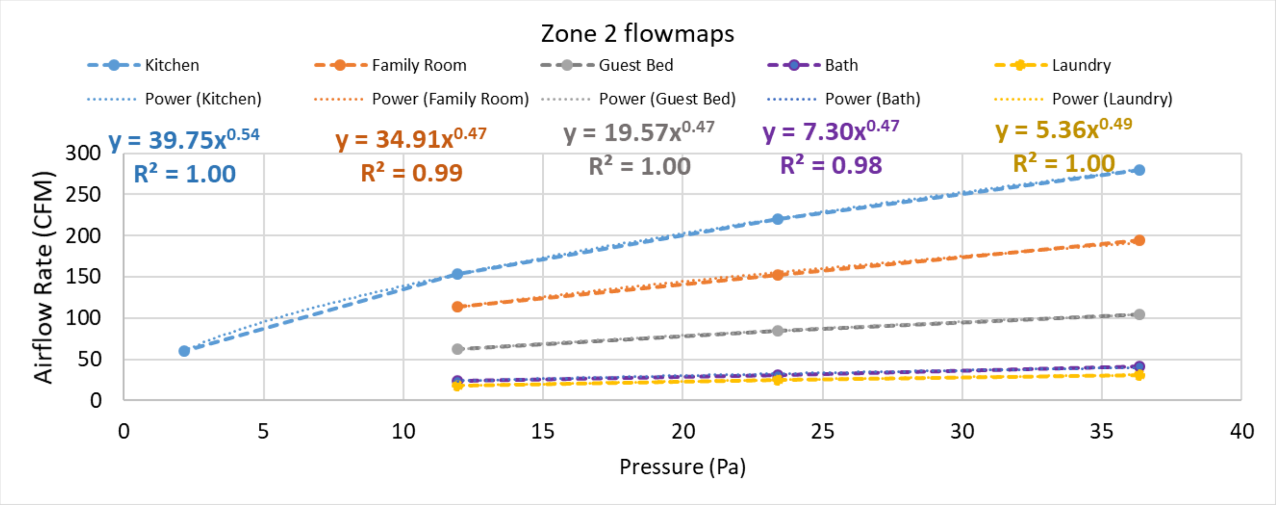
- R-6 with zoning had best performance
- All had similar effectiveness at high speed
- R-12 had 20% higher effectiveness than R-4 at low capacity



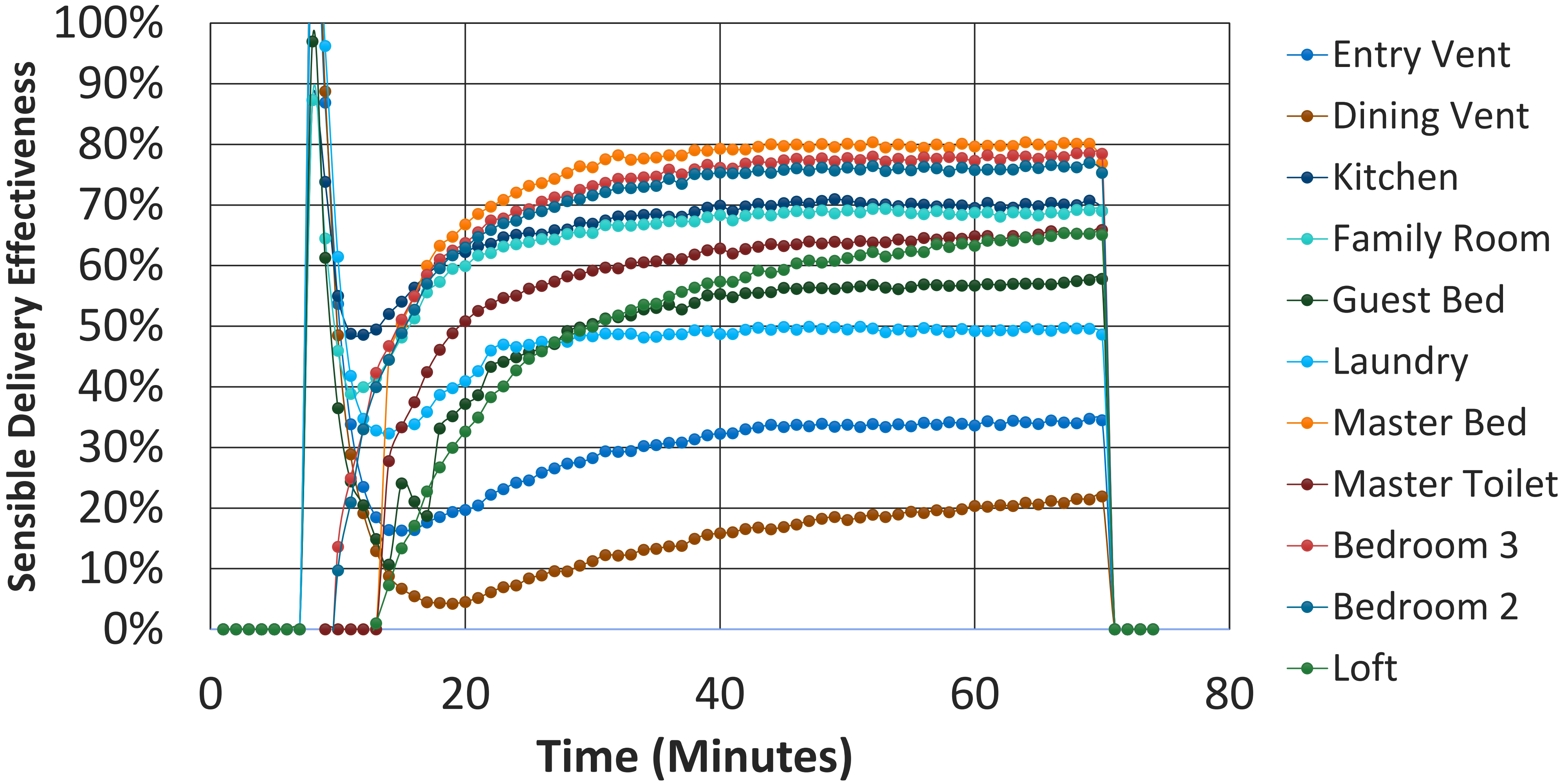
Field Evaluation of Duct Losses

- Delivery effectiveness for each grill monitored
  - Temperature at each grill
  - Temperature/Relative Humidity at equipment
  - Airflow mapped for each grill
  - Indoor and outdoor unit power

Allows us to develop flow map for ducting system



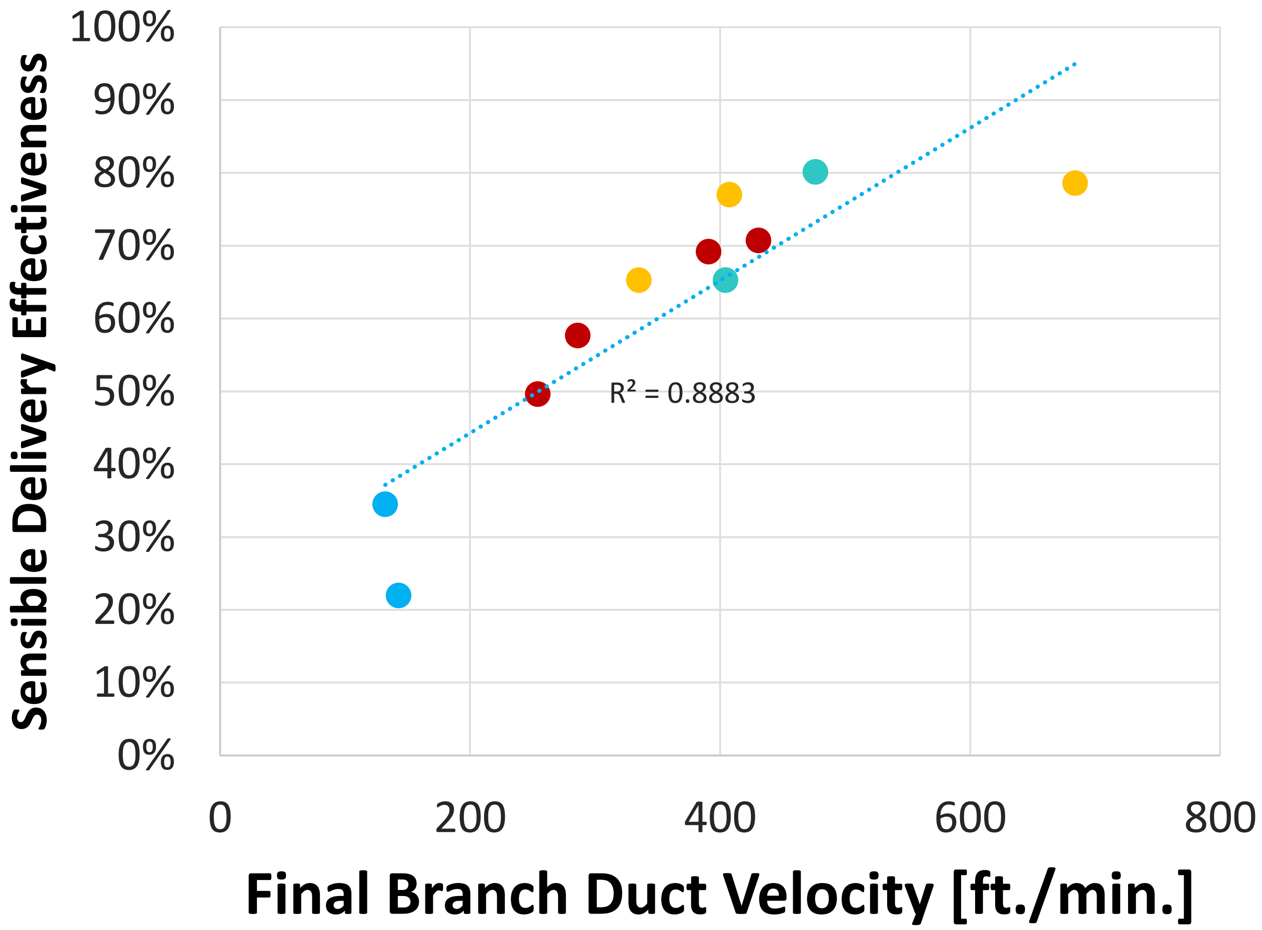
Delivery Effectiveness for Each Grill



Delivery effectiveness varies between grills and ranged from 20-80%.

Impact of Duct Velocity and Delivery Effectiveness

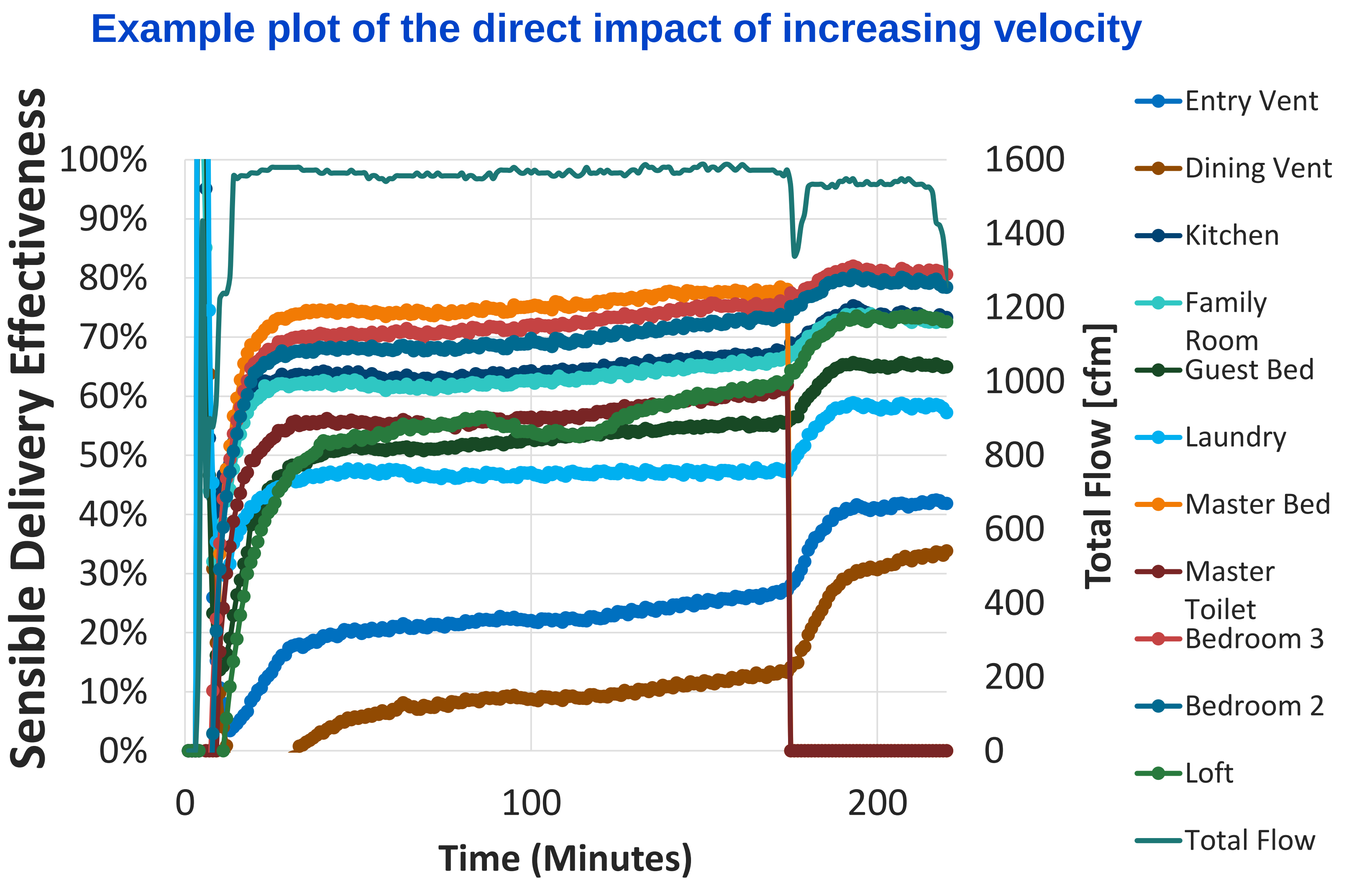
- Velocity is good indicator of effectiveness
- Lower velocity resulted in lower effectiveness
- Typical max velocity in res. = 600 ft/min



50% reduction in fan speed results in only 30% reduction in delivered capacity

Higher Velocity Resulted in Higher Delivery Effectiveness

- Zone 3 closed (Master Bed, Master Toilet) at ~175 minutes
- Airflow stayed relatively constant
- Remaining active grills had an increase in delivery eff.
  - 25% increase in velocity
  - 10% increase in delivery effectiveness



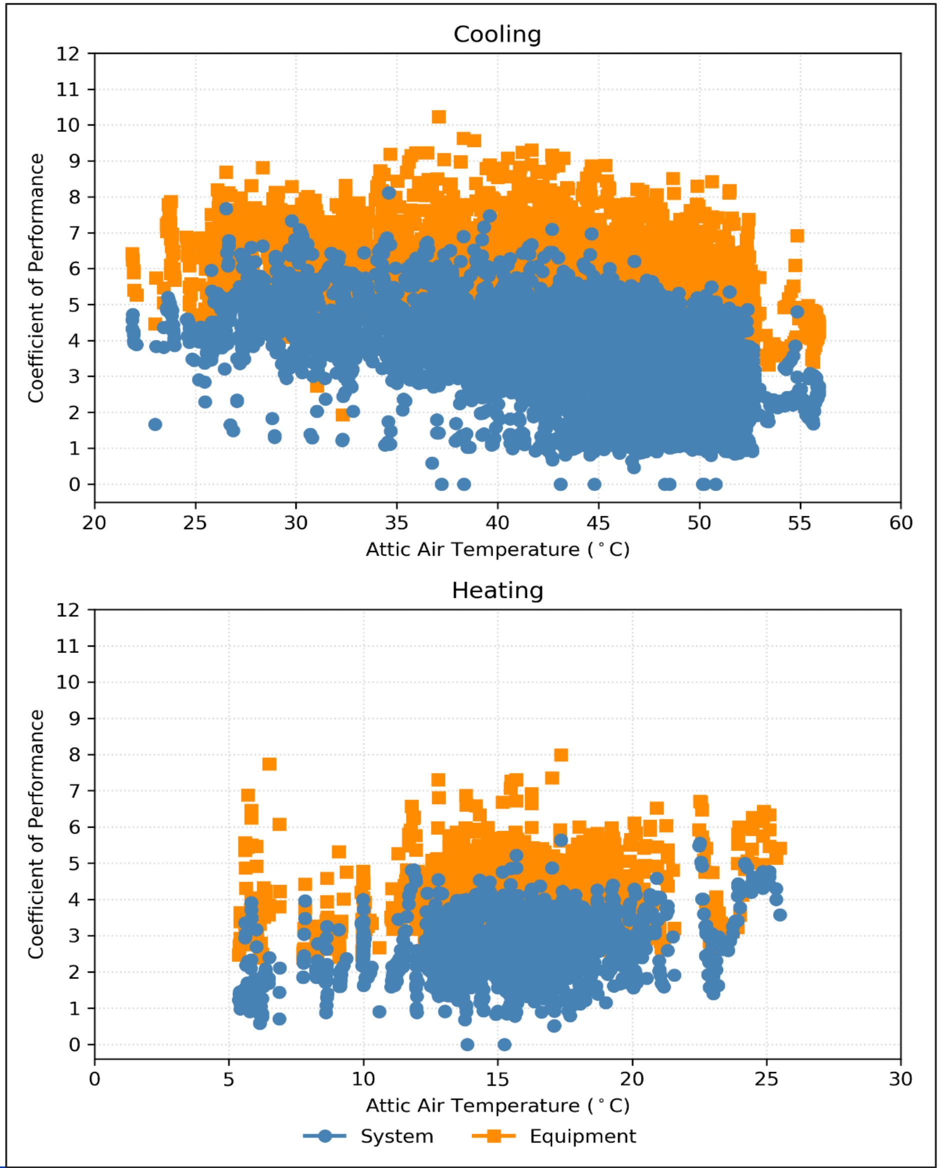
Equipment and System COP (SDG&E)

Cooling Data

- Average Equipment COP = 5.2
- Average System COP = 3.4
- Delivery Effectiveness = 65%

Heating Data

- Average Equipment COP = 3.8
- Average System COP = 2.6
- Delivery Effectiveness = 68%



Delivery effectiveness was good but not optimal

Recommendations and Lessons Learned

Sara Beaini, Curtis Harrington

ELECTRIC POWER RESEARCH INSTITUTE

Next-Gen RSCS: Takeaways

- **Variable-speed systems have tremendous possibilities**
  - Allow control of ratio of cooling and dehumidification
  - Ducts in unconditioned spaces can significantly impact variable-speed equipment performance
  - Duct location and insulation will impact choice of control algorithms

- **Best Solution: Variable-speed systems with zoning**
  - Combination of variable speed and zoning addresses equipment/duct interactions
  - Facilitates energy-efficient demand response programs
  - Increased duct insulation can also reduce equipment/duct interactions

Suggestion: Configure the Next-Gen RSCS into Different Models

Next-Gen RSCS Energy Efficiency Technology Feature	Efficiency/Cost Savings Potential compared to SEER 14 single speed without that feature	Base Model	Intermediate Model	Premium Model
Variable-Capacity Compressor & Blower	22% to 32% in this study	✓	✓	✓
Fault Detection & Diagnostics	Up to 55% from the literature	✓	✓	✓
Demand Response		✓	✓	✓
Zonal Control	Up to 50% savings at 40% system capacity	✓	✓	✓
Dual Fuel (intelligent heating)	Up to 22% for cases run		✓	✓
Integrated Ventilation	1-4% seasonal cooling energy savings			✓
Alternative Refrigerants	1.2% to 3% for cooling			✓

A request to the manufacturers to configure different models of Next-Gen RSCS for different market segments/climates/demographics

Opportunities for Future R&D

- Examine cost effectiveness of each feature in California
  - Develop model to evaluate energy and demand cost savings for each feature and corresponding incremental equipment cost for all California climate zones for representative housing, demographics and occupancy situations
- Zonal Control
  - Adding more zones (ex. 3-4) adds further complexities that need to be addressed in the design stage of the ducting work, with proper sizing with variable capacity heat pump
  - Zone controllers could incorporate feedback on airflow to avoid over-pressurizing smaller zones
- Codes and Standards (Title 24 and ASHRAE)
  - Examine ways to limit the heat transfer to ducts in unconditioned spaces such as attics (ex. adding insulation, zonal control and duct sizing)

Opportunities for Future R&D…continued

- Provide Heating Controller (Intelligent Heating)
  - Similar to demand response controller but receives signal based on efficiency preference, economics (utility prices), environmental factors (carbon footprint of fuel source)
- Dual fuel heat pump
  - Is a high efficiency furnace warranted for California climates (with limited heating hours and where some of those hours can be served by the electric heat pump)?
- Fault Detection and Diagnostics
  - Refine sensitivity of the controls to small changes in system performance → anticipate maintenance, halt system degradation as early as is possible
  - Thoroughly test in the laboratory by simulating incrementally small changes in selected parameters to examine the sensitivity of the controls to identifying gradual degradation in performance
- Alternative Refrigerants
  - Address technology and regulatory needs for the use of R-32 (GWP 675) (or equivalent) as a drop-in refrigerant for R-410a (GWP 2100) systems

Technology Transfer

Sara Beaini

Technology Transfer to Stakeholders

- *Leveraging Utility Energy Efficiency and Demand Response Programs for Commercialization and Market Transformation*
- Focused workshop with utilities and key stakeholders in early 2019
- EPRI Advisory Meetings with Utility Members
- EPRI Energy Efficiency and Demand Response Symposia
- EPRI Electrification Conference and Exposition 2018
- EPRI Next-Generation Heat Pump Deployment Initiative
- Supporting AHRI 1380 Standard for Automated Demand Response for VCHP
- Supporting future California Title 24 Building Standards
- Presentations at key industry meetings and conferences:
  - CEC EPIC Symposia
  - ACEEE 2018
  - ASHRAE 2019
  - etc…

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- Technical Advisory Committee

Questions & Discussion

Together…Shaping the Future of Electricity