

Heat Pump and Indirect Evaporative Cooling Packaged Unit (Hybrid RTU) – Lab Test

Final Report

ET22SWE0034



Source: Manufacturer

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September 18, 2025

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Executive Summary

Background

Rooftop packaged units (RTUs) provide heating, ventilation, and air conditioning (HVAC) for approximately 75 percent of commercial building floor area in California. RTUs use refrigerant vapor compression cycles to provide cooling and typically use integrated natural gas fired furnaces to provide heating.

Indirect evaporative cooling (IEC) and indirect-direct evaporative cooling (IDEC) can provide cooling at much higher efficiency in most California climates compared with typical vapor compression cooling systems. Most commercially available IEC and IDEC products are add-ons to conventional RTUs that need custom design for sizing and controls. The higher cost of custom design makes IEC and IDEC products cost-effective only for the larger systems seen in larger buildings.

An HVAC manufacturer has developed a rooftop packaged unit that includes a heat pump and Indirect-Direct Evaporative Cooling (Hybrid RTU) that has been commercially available since early 2024. This is a single piece of packaged equipment designed for new construction or retrofit, replacing typical RTUs in the most common size ranges for small and medium commercial buildings with simplified installation and no custom design work required for sizing or controls.

Objectives

The objective of this project was to complete laboratory testing of the Hybrid RTU equipment. The tests measured its capacity for cooling and heating, and energy consumption across a range of outdoor conditions that match California climate zones. The measured results were used to develop performance curves that will be used by future projects to estimate energy savings.

Methodology: Hybrid RTU Laboratory Testing

This project tested the Hybrid RTU in the UC Davis Western Cooling Efficiency Center environmental chambers. The equipment was tested across a range of outdoor conditions, including those that match the federal heat pump test standard, AHRI 210.240-2023 [1]. The Hybrid RTU can be rated in accordance with other Heat Pumps using these existing standards, but quantifying its true energy savings potential is not captured in these ratings because these ratings use high humidity operating conditions. For this reason, the equipment was tested using outdoor temperatures from this standard along with several additional conditions at lower humidity levels and at higher temperatures that better match California climate zones, and additional intermediate conditions needed to generate performance regression curves. The Hybrid RTU was tested across all relevant modes of operation for each of the outdoor conditions. The test data was used to produce performance curves for Energy Plus and CBECC-Com.

Findings

Cooling Results

When outdoor conditions are dry to moderately humid, the Hybrid RTU automatically starts to cool using very high efficiency low fan speed evaporative cooling, then increases fan speeds, and then if the evaporative section cannot meet the cooling load it uses the heat pump vapor compression cooling along with the evaporative cooling. In conditions with very high relative humidity, very rare in California, the Hybrid RTU will run in a Heat Pump only cooling mode with the setpoint minimum ventilation rate.

The test first looked at a typical AHRI cooling rating condition of outdoor temperature of 95 °F dry bulb and a cooling season humidity typical to most California climate zones of 50 °F dew point paired with the standard indoor condition of 80 °F dry bulb and 60.4 °F dew point. For these conditions, the Hybrid RTU, using both the IDEC high fan speed and HP high stage cooling supplied 3503 cubic feet per minute (“cfm”) with 56 percent outdoor air ventilation fraction, has a sensible cooling capacity of 5.1 tons for the room with coefficient of performance (COP) 3.4. When including credit for cooling outdoor air for ventilation, the Hybrid RTU has a system sensible cooling capacity of 7.7 tons with COP 5.2. This is high-efficiency performance and provides significantly more ventilation than typical conventional baseline RTUs.

For comparison, a leading very high efficiency variable speed heat pump RTU, has a rated EER of 13 and COP of 3.81 at 95 °F outdoor dry bulb temperature. It is difficult to make a direct comparison based only on rated efficiency because the test standards do not use outdoor air ventilation when testing typical vapor compression RTU heat pumps.

When the cooling load a space requires is less than the maximum cooling capacity of the HVAC equipment, the Hybrid RTU will run in evaporative cooling modes without the heat pump cooling. In the evaporative cooling modes in the same 95 °F dry bulb and 50 °F dew point outdoor and 80 °F dry bulb and 60.4 °F dew point indoor conditions, with low-speed fan setting, the IDEC delivered 510 cubic feet per minute (“cfm”) of ventilation with a room sensible cooling capacity of 0.9 tons and COP of 15.8 and system sensible cooling capacity of 1.6 tons and COP of 27.7. With the high-speed fan setting, IDEC delivered 1935 cfm of ventilation with a room sensible cooling capacity of 2.7 tons and COP of 11.1 and system sensible cooling capacity of 5.3 tons and COP of 21.9. These performance data are summarized below (see Table 1). These evaporative cooling modes provide significant cooling capacity at very high COP compared to baseline typical RTUs. The Hybrid RTU units are likely to run in evaporative cooling modes for a significant portion of the time.

Table 1: Cooling Performance at Outdoor Condition 95°F Dry Bulb 50°F Dew Point and indoor 80°F Dry Bulb 60.4°F Dew Point

Mode	Sensible Capacity - Room (Ton)	Sensible COP - Room	Sensible Capacity - System (Ton)	Sensible COP - System	Outdoor Air Fraction	Supply Air Flow Rate (CFM)
Hybrid Evaporative + Heat Pump	5.1	3.4	7.7	5.2	56%	3503
Evaporative (IDEC) - High Speed	2.7	11.1	5.3	21.9	100%	1935
Evaporative (IDEC) - Low Speed	0.9	15.8	1.6	27.7	100%	510

At an outdoor dry bulb temperature of 95°F dry bulb and a low cooling season humidity typical of California inland climate zones of 39°F dew point and 80°F dry bulb and 60.4°F dew point indoor conditions, the Hybrid RTU using both the IDEC high fan speed and HP high stage supplied sensible room cooling with a capacity of 6.1 tons and COP 4.1. With the same conditions and the evaporative section alone, the IDEC supplied sensible room cooling of 3.7 tons with COP 15.3 at high speed. With outdoor condition of 95°F dry bulb and 30°F dew point for evaporative section alone, the IDEC low speed provided sensible room cooling of 1.3 tons with COP 22.1. In these low humidity outdoor conditions that are common in inland California climate zones, the hybrid RTU evaporative cooling modes provide significant cooling capacity at extremely high COP compared with baseline typical RTUs while also providing 100 percent outdoor air.

For conditions representing peak cooling loads in inland California climate zones, that is, very hot 115°F dry bulb and fairly low humidity 46°F dew point, the high-speed IDEC evaporative cooling mode provided 2.0 tons of sensible room capacity with 8.3 COP or with credit for cooling outdoor air 8.5 tons of sensible system capacity with 35.3 COP. This evaporative cooling can provide much higher efficiency cooling during extremely hot weather events than what the baseline typical RTUs offer, which means significant potential for site and grid peak load reduction.

Cooling Water Use

The Hybrid RTU uses water for evaporative cooling with more water consumption at drier and hotter outdoor conditions, where the most energy is saved. Water usage comes from evaporation and from bleeding water to remove accumulating minerals. For the modes using evaporative cooling alone, the lab test upper bound estimate of water evaporation ranged from 2.1 to 2.5 gallons per ton-hour of system sensible cooling capacity.

The bleed water consumption depends on the hardness of the water supplied to the Hybrid RTU equipment. The Hybrid RTU uses an electrical conductivity sensor to bleed water when minerals concentration reaches a setpoint number of cycles of concentration. The manufacturer estimates that the bleed water fraction when soft water is supplied to the unit and a high concentration setpoint is used can be as low as 7% and for hard water with a low concentration setpoint can be as high as 63%. The previous field study found a bleed water fraction of approximately one third.

Heating Results

The ASHRAE and AHRI 210/240 standard heat pump heating rating tests demonstrated that when the Hybrid RTU was operated in high heat pump heating mode with no ventilation at outdoor conditions of 47°F dry bulb 39°F dew point and indoor 70°F dry bulb, it provided a room heating capacity of 3.0 tons with COP 3.2 in second stage. The second stage room heating capacity at outdoor conditions of 60°F dry bulb and 51.5°F dew point was 3.5 tons with COP 3.7. For outdoor 36°F dry bulb and 28°F dew point, the room heating capacity was 2.2 tons with COP 2.6.

Overall, the Hybrid RTU has significantly higher capacity for cooling than for heating and is a better fit for climate zones and building types that require more cooling and less heating. Depending on the system sizing, auxiliary electric resistance strip heat could be required during low outdoor temperatures, particularly if there are high ventilation requirements at the coldest times of day.

Outreach

The project team has contacted the California Energy Commission CBECC-Com developers to share the results that show the current assumptions about wet bulb effectiveness are conservative and are expected to slightly underestimate the energy savings. These slightly conservative assumptions are appropriate for use in code compliance.

The project team has reached out to CalTF and to San Diego Gas and Electric the California Statewide lead for HVAC efficiency programs to start the measure development process.

Recommendations and Next Steps

This project performed environmental chambers lab testing of the Hybrid RTU and developed performance curves for future use in EnergyPlus and CBECC-Com. This project directly prepares the way for future projects that will develop a new Hybrid RTU measure package. Future measure development projects will use the performance curves developed by this project in EnergyPlus to estimate energy savings. This project also developed comparison numbers for the evaporative cooling performance of this Hybrid RTU to validate the CBECC-Com assumptions for code compliance. With these validated numbers, the Title 24 building codes performance pathway can give efficiency credit for the Hybrid RTU technology supporting successful market adoption.

The project team's next steps include:

- Continue to engage with the California HVAC Program Administrator to determine what standards and requirements the equipment needs to meet to be included in the program as a new efficiency measure. Follow up with the Hybrid RTU manufacturer to support meeting those requirements.
- Continue to engage with the CalTF to present the to present the Hybrid RTU lab and field test

results to the CalTF Deemed Initiative Subcommittee to begin the measure development process

- Continue to recruit and prepare the team to do the next step measure development. WCEC will contribute to, or lead, the measure development efforts to ensure that the performance curves can represent equipment efficiency in the required modelling tools to predict energy savings.
- Continue to engage with EnergyPlus and CEC CBECC-Com software developers to promote the use of the performance curves for cost-benefit analysis and for code compliance.

Table of Contents

Executive Summary	ii
Background	ii
Objectives	ii
Methodology: Hybrid RTU Laboratory Testing	ii
Findings	iii
Outreach	v
Recommendations and Next Steps	v
Abbreviations and Acronyms	1
Introduction	3
Background	4
Hybrid Heat Pump RTU Technology	4
Simulation of Hybrid RTU Energy Performance	5
Previous Hybrid Evaporative Cooling and Natural Gas Heating RTU – Coolerado H80	5
Separate IEC Products	6
Barriers to Adoption of High Efficiency RTUs	7
Barriers to Adoption of RTU HPs	8
Previous Findings: Hybrid RTU Field Test [11]	8
Objectives	10
Methodology & Approach	11
Hybrid RTU Test Plan	12
Hybrid RTU Status	16
Laboratory Testing Methods	17
Lab Test Data Analysis	21
Results and Discussion	30
Performance Curves and Lookup Tables	44
Stakeholder Engagement	50
Equipment Manufacturer	50
CalNEXT Team	51
IOUs	51
CalITF	51
Stakeholder Feedback	51
Recommendations and Next Steps	52
References	54

APPENDIX A: Achieved Evaporative Section Test Conditions and Supply Air Conditions	56
Appendix B: Regressions	62
Regression for IDEC Supply Air Temperature dry bulb (SADB).....	62
Regression for IDEC Supply Air Temperature dewpoint (SADP)	66
Regression for IDEC Power	69
Regressions for IEC SADB.....	74
Regressions for IEC Power.....	78
Regressions for Heat Pump Heating High SADB	83
Regressions for Heat Pump Heating High Power	87
Regression for Heat Pump Heating Low SADB	93
Regressions for Heat Pump Heating Low Power	99
Appendix C: Calculation of Hybrid Performance from Separate Heat Pump and Evaporative Cooler Performance.....	105
Appendix D: Evaporative Water Consumption Calculations	109

List of Tables

Table 1: Cooling Performance at Outdoor Condition 95° F Dry Bulb 50° F Dew Point and indoor 80° F Dry Bulb 60.4° F Dew Point	iv
Table 2: Environmental Chamber Test Conditions for Evaporative Section.....	14
Table 3: Environmental Chamber Test Conditions for Heat Pump Section.....	15
Table 4: List of Modes and Number of Tests Conducted	20
Table 5: Hybrid RTU Instrumentation	23
Table 6: IEC AND IDEC Cooling.....	33
Table 7: DX Heat Pump Cooling	34
Table 8: IEC Hybrid Heat Pump High Cooling (Stage 2).....	35
Table 9: IDEC Hybrid Heat Pump High Cooling (Stage 2)	36
Table 10: IEC Hybrid Heat Pump Cooling Low (Stage 1)	38
Table 11: IDEC Hybrid Heat Pump Low Cooling (Stage 1).....	39
Table 12: Heat Pump Heating Results Table	43
Table 13: Standby and Ventilation Tests.....	44
Table 14: Example from the Hybrid Unitary HVAC Equipment Object performance map template, used by the National Renewable energy Lab hosted Technology Performance Exchange translation tool	49
Table 15: Example Multi-Variable Lookup Table generated by National Renewable energy Lab hosted Technology Performance Exchange translation tool [13]	50

List of Figures

Figure 1: Heat pump and indirect evaporative cooling packaged unit (Hybrid RTU).....	4
Figure 2: Sensible COP comparison – separate IEC performance with credit for ventilation cooling (A) vs performance only crediting room air cooling with a return air temperature of 80°F (B) in field test near Sacramento, California	6
Figure 3: Separate IEC connected to a conventional RTU.....	7
Figure 4: Predicted electric-only energy savings for the prototype Hybrid RTU field tested on San José roof top from binned regression model [11].....	9
Figure 5: Predicted total energy savings – including natural gas energy valued at one to one in kWh – for	

the prototype Hybrid RTU, field tested on San José roof top from binned regression model [11].	10
Figure 6: Psychrometric chart showing hourly outdoor air temperature and humidity conditions in all 16 California climate zones with the test standards laboratory test condition points.	13
Figure 7: Psychrometric chart showing the target test conditions marked with diamonds and hourly outdoor air temperature and humidity conditions in all California climate zones.	16
Figure 8: Custom curb support built for Hybrid RTU.	17
Figure 9: Hybrid RTU unit in WCEC environmental test chamber.	18
Figure 10: Control interface for Hybrid RTU.	18
Figure 11: Detail of added humidifier.	21
Figure 12: Hybrid RTU instrumentation diagram showing the variables measured.	26
Figure 13: Cooling test points overlayed on California climate zone data, with low humidity region marked by solid lines.	41
Figure 14: Process diagram of EnergyPlus integration of the Hybrid Unitary HVAC Equipment Object. [12]	48

Abbreviations and Acronyms

Acronym	Meaning
AC	Air Conditioner
AHR	Air Conditioning, Heating, and Refrigeration
AHRI	Air Conditioning, Heating, and Refrigeration Institute
AWHP	Air-To-Water Heat Pump
BPHE	Brazed Plate Heat Exchangers
CEC	California Energy Commission
COP	Coefficient of Performance
DAC	Disadvantaged Communities
EE	Energy Efficiency
ESP	External Static Pressure
ET	Emerging Technology
FHR	First Hour Rating
GHG	Greenhouse Gas
GWP	Global Warming Potential
HP	Heat Pump
HPWH	Heat Pump Water Heater
HTR	Hard-to-Reach
HVAC	Heating, Ventilation, and Air Conditioning
Hybrid RTU	Heat Pump and Indirect Evaporative Cooling Packaged Unit
IEC	Indirect Evaporative Cooler

Acronym	Meaning
IDEC	Indirect-Direct Evaporative Cooler
IOUs	Investor-Owned Utilities
kWh	Kilowatt-hour
MFHP	Residential Multi-Function Heat Pump
NEEA	Northwest Energy Efficiency Alliance
Q1	Quarter One
R&D	Research and Development
RAMP	Realizing Accelerated Manufacturing and Production for Clean Energy Technologies
RT	Refrigeration Ton
RTU	Roof Top Packaged Unit
SCE	Southern California Edison
SDG&E	San Diego Gas & Electric
U.S.	United States
WCEC	Western Cooling Efficiency Center

Introduction

The most common form of space conditioning equipment in commercial buildings is heating, ventilation, and air conditioning (HVAC) equipment packaged together in one integrated unit. Known as rooftop packaged units (RTUs), approximately 75 percent of commercial building floor area in California is conditioned with these packaged systems [2]. RTUs use refrigerant vapor compression cycles to provide cooling and, if they are heat pumps (HP), they can reverse the refrigerant flow direction to also provide heating.

Indirect evaporative cooling (IEC) and indirect-direct evaporative cooling (IDEC) can provide cooling at much higher efficiency in most California climates compared with the vapor compression cooling systems currently used in many commercial buildings [3, 4, 5, 6, 7]. In the past, these IEC and IDEC cooling systems have been add-ons to conventional RTUs. Large, custom-designed HVAC systems have typically required mechanical system designers to be familiar with the evaporative equipment to design and size them correctly. They also have required additional controls design and have been more cost-effective only for larger systems [5, 6, 7]. This study reports on a laboratory test of Hybrid RTU that includes a heat pump and indirect evaporative cooling packaged unit from a large HVAC manufacturer. This is a single piece of packaged equipment designed for new construction or retrofit, replacing typical RTUs in the most common size ranges for small and medium commercial buildings with simple installation and no custom design work required for sizing or controls.

This project laboratory tested a production-ready prototype version Hybrid RTU and produced performance curves that can be used in future projects to model and estimate energy savings across many different climates and building types. This technology is now commercially available from one large HVAC manufacturer.

Laboratory testing of the hybrid packaged unit will use the University of California, Davis (UCD) Western Cooling Efficiency Center (WCEC) environmental chambers and data acquisition infrastructure to measure Hybrid RTU equipment performance across a range of outdoor conditions that simulate California climate zones. The performance curves produced by the testing can be used in models such as EnergyPlus™ or CEC CBECC-Com to simulate energy consumption and allow estimates of energy savings compared with baselines in almost any climate zone and type of building. These models will focus future field demonstrations and future efficiency programs on the building types and climate zones that minimize cost, maximize energy savings, and target disadvantaged communities.

Project Activities:

- Equipment test plan

Environmental chambers preparation and equipment installation

- Equipment testing
- Data analysis, performance curve development, and report writing
- Stakeholder outreach

Background

Hybrid Heat Pump RTU Technology

The Hybrid RTU combines an IDEC system with a vapor compression heat pump, (see fig. 1). This combination produces the energy saving benefits of evaporative cooling with the capabilities of a heat pump. The IDEC system portion of the Hybrid RTU uses water and operates with 100 percent outdoor air filtered by MERV 13 filters on the inlet. The system operates by using both indirect and direct evaporative cooling in series. It does so by passing the outdoor air through an indirect evaporative heat exchanger followed by direct evaporative media. The resulting supply air can approach, or in some cases be below, the wet bulb temperature of the ambient air. The result is that comfort can be maintained in buildings in dry climates, which encompass most California climate zones, using significantly less electricity than compressor-only air conditioners. The two-speed heat pump side of the system can provide either heating or cooling based on the position of the refrigerant reversing valve. The return air entering the heat pump is recirculated from the room and filtered with a MERV 13 filter to provide healthy indoor air quality (IAQ).

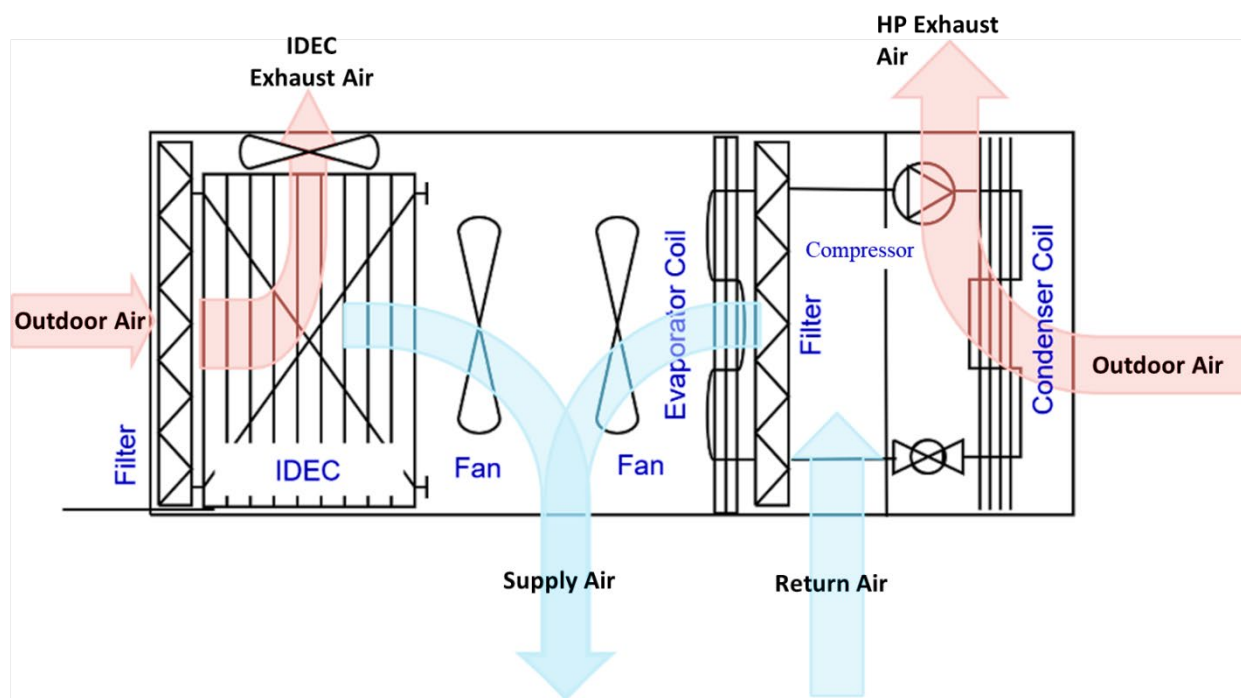


Figure 1: Heat pump and indirect evaporative cooling packaged unit (Hybrid RTU)

Source: UC Davis Western Cooling Efficiency Center

Many commercial buildings experience significant internal heat generation from occupants, plug loads, and solar heat gain from windows. As a result, they frequently need a larger cooling capacity than heating capacity. In conventional RTU HP applications for new construction or retrofits with single-speed equipment, in cooling dominated climates the HP system is often sized to meet the

larger cooling load, and as a result, it is oversized for the heating load. By using the Hybrid RTU instead, the very high efficiency IEC provides a significant portion of the cooling needed (see fig. 2). The heat pump part of the equipment can, therefore, be sized to meet the smaller heating load. This allows the Hybrid RTU equipment to be a similar size and weight as conventional RTUs, while still providing much greater cooling efficiency.

The heat pump is sized to meet the same heating requirements as the packaged unit's rated capacity. It includes the typical electric resistance strip heaters for defrosting and for supplemental heat if outdoor temperatures are extremely low. This Hybrid RTU and any evaporative cooling equipment also require a water line to the equipment location.

Because the IDEC equipment uses outdoor air to function and provides very high-efficiency cooling, it saves energy for the Hybrid RTU, while enabling it to provide a higher rate of ventilation. This means that, for the Hybrid RTU equipment, the largest energy savings are achieved by providing a higher rate of ventilation than conventional RTUs. This ventilation rate is also higher than the minimum required by the code.

For the Hybrid RTU, improved cooling efficiency from the IEC equipment and reduced required HP size produce the following benefits:

- Reduced cooling energy consumption at most times and similar cooling energy consumption in very humid outdoor conditions.
- Cooling energy consumption greatly reduced during hot weather with large reductions in peak loads.
- Smaller HP sizing, which:
 - Minimizes the equipment weight and size increases.
 - Reduces total refrigerant charge the potential for leakage.
 - Potentially reduces short cycling and increases efficiency compared to single speed RTU HP equipment; and,
 - Reduces the peak power draw of the Hybrid RTU equipment by reducing power draw of HP and reducing the size of electric resistance strip-heaters needed for defrost, with potential for retrofits to avoid the need for electrical service upgrades.

The Hybrid RTU has some of the requirements of evaporative cooling equipment including:

- Requires a water line to the equipment location.
- Requires seasonal maintenance (winterization and spring prep with air filter change).

Simulation of Hybrid RTU Energy Performance

EnergyPlus has separate IEC and RTU HP objects that can be used to simulate the performance of the Hybrid RTU. These EnergyPlus objects require performance curves for the Hybrid RTU equipment, to simulate the capacity and energy consumption for equipment sizing and operation. Future projects simulating Hybrid RTU performance will need to coordinate which piece of equipment will run in what mode at each time step, accounting for the interaction between the IEC and RTU HP supply pressure.

Previous Hybrid Evaporative Cooling and Natural Gas Heating RTU –

Coolerado H80

Previous emerging technology (ET) studies tested the Coolerado H80, which was a hybrid IEC and vapor compression RTU with natural gas-fired heating. Field tests in Davis and China Lake, California, which were completed by WCEC in 2013, showed 11 to 29 percent cooling energy savings, 25 to 37 percent peak cooling demand savings, and water consumption of approximately 50 gal/day per ton of cooling [8].

SCE also completed a field test (ET08SCE1160) showing cumulative energy savings of 39 percent and average demand reduction of 43 percent. These field tests identified issues, including low capacity and lower efficiency, when relative humidity was more than 50 percent. The conventional HVAC RTU weighs approximately 500 pounds, whereas the Coolerado H80 hybrid unit weighed 1,500 pounds (operational wet weight). This weight increase was identified as a barrier to adoption that may require a facility to perform major rooftop structural work. The high initial cost of \$15,595 (\$3,119 per ton) for the Coolerado H80 equipment was also identified as a barrier to market adoption. [9]

The H80 is no longer offered for sale.

Separate IEC Products

Previous work by the WCEC has tested separate IEC systems from multiple manufacturers as standalone cooling equipment or in combination with conventional RTUs [3, 4, 5, 6, 7, 6]. These tests have shown high efficiency at high outdoor temperatures, above 85°F, with a typical cooling sensible system coefficient of performance (COP) between 5 and 35 when cooling outdoor air and between 5 and 15 when measured on the basis of cooling the room with a return air temperature of 80°F, demonstrated in the results below (Figure 2B), compared with baseline vapor compression RTU systems with typical COP around 3.

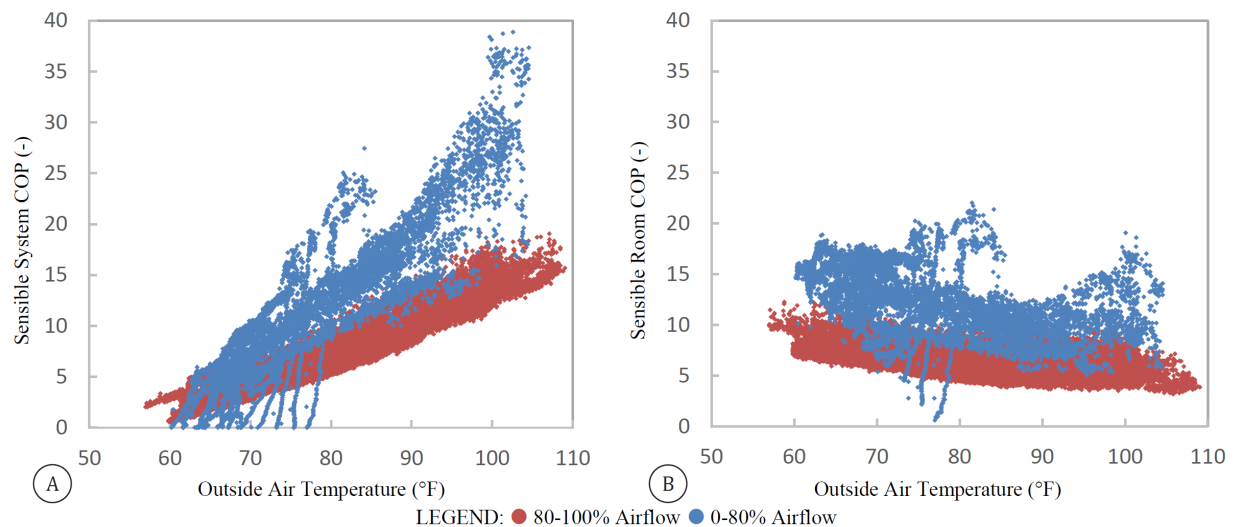


Figure 2: Sensible COP comparison – separate IEC performance with credit for ventilation cooling (A) vs performance only crediting room air cooling with a return air temperature of 80°F (B) in field test near Sacramento, California.

Source: UC Davis Western Cooling Efficiency Center

The above plots compare sensible system COP with credit for all ventilation cooling from an outside air temperature. The data are from all minutes of cooling operations over a one-month period. Chart B plots sensible room coefficient of performance with credit for only cooling the air below the room return air temperature over the same period.

Separate IEC and IDEC cooling systems have also been used as add-ons to conventional RTUs, (Figure 3), or add-ons to large custom designed HVAC systems. These separate IEC and IDEC systems face market adoption barriers because they require mechanical system designers to be familiar with the evaporative systems. This knowledge is required to correctly size the evaporative equipment, including its interactions with the conventional RTU equipment, and often requires additional controls designed to integrate it with the conventional equipment [5, 6, 7]. These extra costs for designing, building, and commissioning make separate add-on evaporative equipment only cost-effective mostly for larger systems [5, 6, 7].



Figure 3: Separate IEC connected to a conventional RTU.

Source: UC Davis Western Cooling Efficiency Center

Barriers to Adoption of High Efficiency RTUs

Based on previous WCEC work with K-12 schools, barriers to adoption of high efficiency RTU equipment include its larger size and weight. These dimensions can require structural engineering inspections and potentially expensive structural retrofits, in addition to higher equipment cost compared to minimum-efficiency RTU equipment [10].

This Hybrid RTU equipment is designed to have similar weight and size as typical high-efficiency vapor compression RTU equipment, reducing these barriers to adoption. The price of the Hybrid RTU equipment is expected to be higher than conventional minimum-efficiency and high-efficiency RTUs. Because this Hybrid RTU equipment design does not use any exotic materials or labor-intensive manufacturing processes, the price is expected to drop closer to conventional equipment as the scale of production increases. Rebate programs and incentives can also help to reduce the time needed to achieve higher-scale production and accelerate wide adoption of this energy saving technology.

Barriers to Adoption of RTU HPs

Typical RTUs use natural gas combustion furnaces for heating. Current options for replacing mixed fuel RTUs with all-electric HP RTUs significantly increase electric energy consumption. This often results in increased utility bills for commercial buildings due to the higher cost per unit of energy for electricity compared with natural gas. Electric demand charges further increase these operating costs. WCEC recently completed a field test of a prototype Hybrid RTU, which is very similar to the production-ready version of the equipment that will be laboratory tested in this project. These field test results show that the Hybrid RTU enables electrification of heating and cooling while keeping total electric energy consumption lower than the mixed fuel RTU baseline, while still eliminating natural gas consumption. By reducing the total electricity consumption, the Hybrid RTU offers an electrification option that is likely to reduce utility bills instead of increasing them. More detail is provided in the Previous Findings: Hybrid RTU Field Test [11] section.

A conventional HP RTU also uses electric resistance strip heaters for defrost and to provide supplemental heat. Electrical power consumption of the electric resistance strip heaters is typically at or near the COP of the HP RTU, multiplied by the HP RTU capacity for defrost mode operation. In defrost mode, the HP RTU compressor and the strip heaters operate at the same time. This often results in the unit consuming three to four times the power, compared with normal operation. Anecdotally we have heard from Villara, a large HVAC contractor, that retrofits from conventional mixed-fuel RTUs to HP RTUs often required electrical breaker and wire upgrades at each RTU rooftop curb. These retrofits were likely to require an upgrade of the whole building electrical service breaker panel, according to Villara, and sometimes required an upgrade of the electrical service wire and a potential upgrade to the drop transformer. These electrical upgrades can be costly, leading to delays in installation that may disrupt commercial operation of the building.

The Hybrid RTU reduces the required capacity of the HP equipment. This means that the sizing of the electric resistance strip heaters may be smaller than in a conventional HP RTU. This may reduce the need for additional electrical upgrades. More information is needed to understand the typical excess capacity in commercial building electrical breaker panels, service wires, and drop transformers to evaluate the likelihood of Hybrid RTU equipment fitting within the existing electrical infrastructure.

Previous Findings: Hybrid RTU Field Test [11]

WCEC field tested a prototype Hybrid RTU that is nearly identical to the production-ready version of the equipment that was laboratory tested in this project [11]. The field test monitored energy performance of both the prototype Hybrid RTU and an existing baseline conventional RTU that is serving two nearly identical classrooms at a high school campus in San José. The baseline unit was an existing high efficiency Lennox LGA060HS2G rated SEER 12, five-ton cooling capacity, R-22, with an economizer that had been installed in 2001. Both units used identical low pressure-drop MERV 13 filters, which were replaced at the same time.

The field test results show that the prototype Hybrid RTU enabled electrification of heating and cooling while keeping total electric energy consumption lower than the mixed-fuel RTU baseline, despite the Hybrid RTU completely eliminating natural gas consumption. This testing was conducted in a moderate climate (San José CA climate zone 4). For example, in the San José field test at outdoor conditions of 95°F dry bulb, the Hybrid RTU unit ran in ventilation mode at very high COP 70 percent of the time, resulting in large energy savings.

Hybrid RTU performance is expected to be even better in climates with hotter and drier conditions compared with San José (CZ4). WCEC developed a binned regression model from the field test data to predict the energy savings in four different California climate zones. (See Figure 4 and Figure 5).

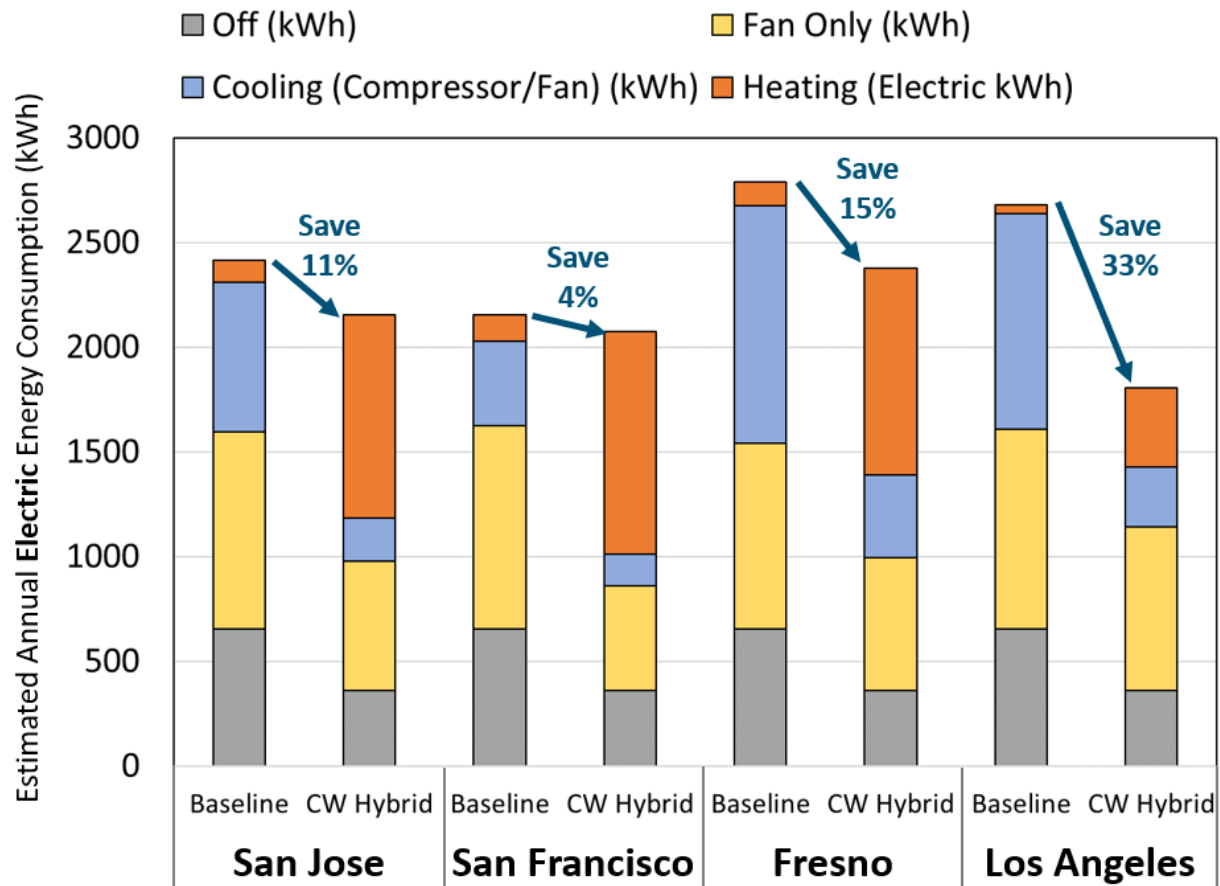


Figure 4: Predicted electric-only energy savings for the prototype Hybrid RTU field tested on San José roof top from binned regression model [11].

Source: UC Davis Western Cooling Efficiency Center

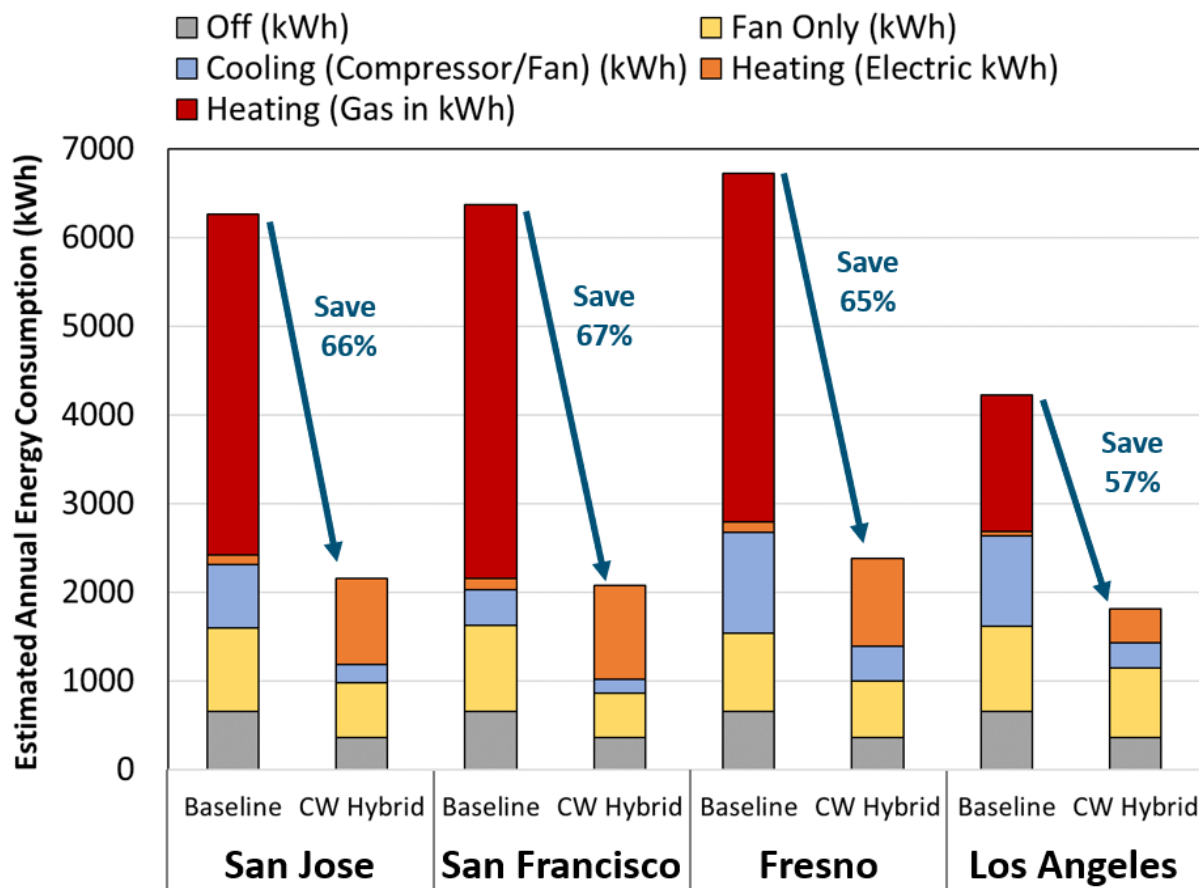


Figure 5: Predicted total energy savings – including natural gas energy valued at one to one in kWh – for the prototype Hybrid RTU, field tested on San José roof top from binned regression model [11].

Source: UC Davis Western Cooling Efficiency Center

By reducing the total electricity consumption and eliminating natural gas consumption completely, the Hybrid RTU is an electrification option that is likely to reduce utility bills.

Water consumption was measured in the San Jose field test resulting in an estimated average use of 8.5 gallons per kWh saved by the Hybrid RTU compared to the field test baseline existing 5 ton Lennox RTU rated as SEER 12 with economizer, installed in 2001 (Lennox LGA060HS2G, R-22). Historically, the cost of water is a small fraction of energy utility cost savings (typically less than 20 percent).

Objectives

Following the field test, which demonstrated large energy savings achieved by the Hybrid RTU, the next step is to complete a lab test and develop performance curves. The objectives of this lab test project are to:

- Collect stakeholder feedback related to market adoption barriers, performance testing, and energy modelling of the Hybrid RTU technology.
- Develop and refine an experimental plan for laboratory testing of the Hybrid RTU equipment.
- Analyze laboratory test data to develop multivariate regression curves and use them to generate performance curves for the Hybrid Unitary HVAC Equipment Object in EnergyPlus and for similar tables used by the Hybrid/Advanced IEC module in development for CBECC-Com; and,
- Engage with energy model software developers to support adoption and use of the performance curves.

The performance target for this project is the dissemination of a final report that will include the laboratory test results and the equipment performance curves. This final report will be disseminated to the target audience, which includes IOUs, the California Energy Commission CBECC-Com developer team (to request inclusion of performance curves in the code compliance energy simulation software), and other groups, such as UC Davis WCEC and other CalNEXT partners, that may implement the next ET projects for field demonstrations of the technology.

Methodology & Approach

The UC Davis team engaged with the equipment manufacturer to develop detailed test plans and ensure that the tests captured the expected equipment performance in real-world applications. The test plan was developed to provide the data needed by EnergyPlus and CEC CBEC-Com to accurately simulate Hybrid RTU equipment performance for energy savings estimates. Careful planning was required to account for the different modes of operation and variable speeds at which the equipment could function. The WCEC is at the forefront of test method development for hybrid systems and, in collaboration with Lawrence Berkeley National Laboratory, led the development of the EnergyPlus Hybrid Unitary Equipment Object that enables EnergyPlus simulation of this type of equipment.

The need to evaluate the performance of heating in winter conditions required the WCEC to modify environmental chamber hardware and controls. The team added a refrigeration unit to the outdoor chamber that can reduce the temperature to sub-freezing conditions. For low temperature tests, the outdoor chamber was refrigerated overnight to achieve steady testing conditions.

Voltage-controlled dampers were added to regulate exhaust pressures. The approach was to control these exhaust pressures to a zero-differential pressure to the chamber and/or use configurations that eliminate the sealed ducting connection for specific paths. A zero-differential pressure to the chamber indicates that no force is created in the duct that would help or hinder flow naturally being created at the exhaust of the unit.

The team placed the Hybrid RTU in the outdoor environmental chamber with the capability to match the temperature and humidity of a wide range of outdoor conditions. The complex nature of air paths through the Hybrid RTU unit, required addition of ducting to the outdoor chamber to allow for a third exhaust path from the unit. The Supply Air (SA) and Return Air (RA) from the unit was ducted into the indoor conditioning loop to control conditions and monitor performance characteristics. For evaporative cooling operation, the supply airflow rate was measured using a tracer gas system. For

heat pump operation the return air flow rate was measured using the nozzle box. These flow rates, along with temperature and humidity measurements, were used to calculate capacity and other performance metrics to develop the equipment performance curves.

Hybrid RTU Test Plan

The Hybrid RTU evaporative cooling section takes in outdoor air and can operate across a continuously variable air flow rate to deliver a continuously variable rate of cooling. The Hybrid RTU HP section takes in return air from the space and can operate at two different compressor and supply fan speeds to deliver two different rates of cooling and heating.

To develop accurate Hybrid RTU energy performance curves applicable to a range of climates, it is necessary to perform environmental chamber steady state operation tests across a broad range of conditions. This includes extremes in outdoor air temperature (OAT) and humidity, indoor air temperature and humidity, across the possible equipment speeds. These factors determine the rate of cooling or heating delivered by the system.

Because there is not a dedicated standard for evaluating this type of hybrid equipment, the team used AHRI 340/360 2022 standard for Performance Rating of Commercial and Industrial Unitary Air-conditioning and Heat Pump Equipment. This test standard defines the temperature, humidity, and operating conditions for tests to calculate the IEER and HSPF for the equipment. To supplement this testing standard, the team used concepts and methodologies from ANSI/ASHRAE 143-2015 Method of Test for Rating Indirect Evaporative Coolers, which WCEC helped to develop.

The diagram below (see fig. 6) shows small dots for each of the 8760 hourly outdoor air conditions for each of the 16 California climate zones from typical meteorological year data. There are circles showing the ASHRAE standards rating conditions. These test standards alone, however, do not accurately reflect the full range of California climate conditions and focus disproportionately on higher humidity conditions. This means that a standard IEER rating of the Hybrid RTU unit would significantly underestimate energy savings compared with a conventional RTU because it does not include the much less humid conditions common in California climate zones. These are the conditions under which the Hybrid RTU achieves the largest energy savings.

The test standard for HP heating and determination of the HSPF rating is sufficient for the Hybrid RTU equipment because the outdoor conditions effectively cover California climate zones. In heating mode, the evaporative part of the hybrid unit also runs dry without any water, so it does not change the temperature of ventilation air.

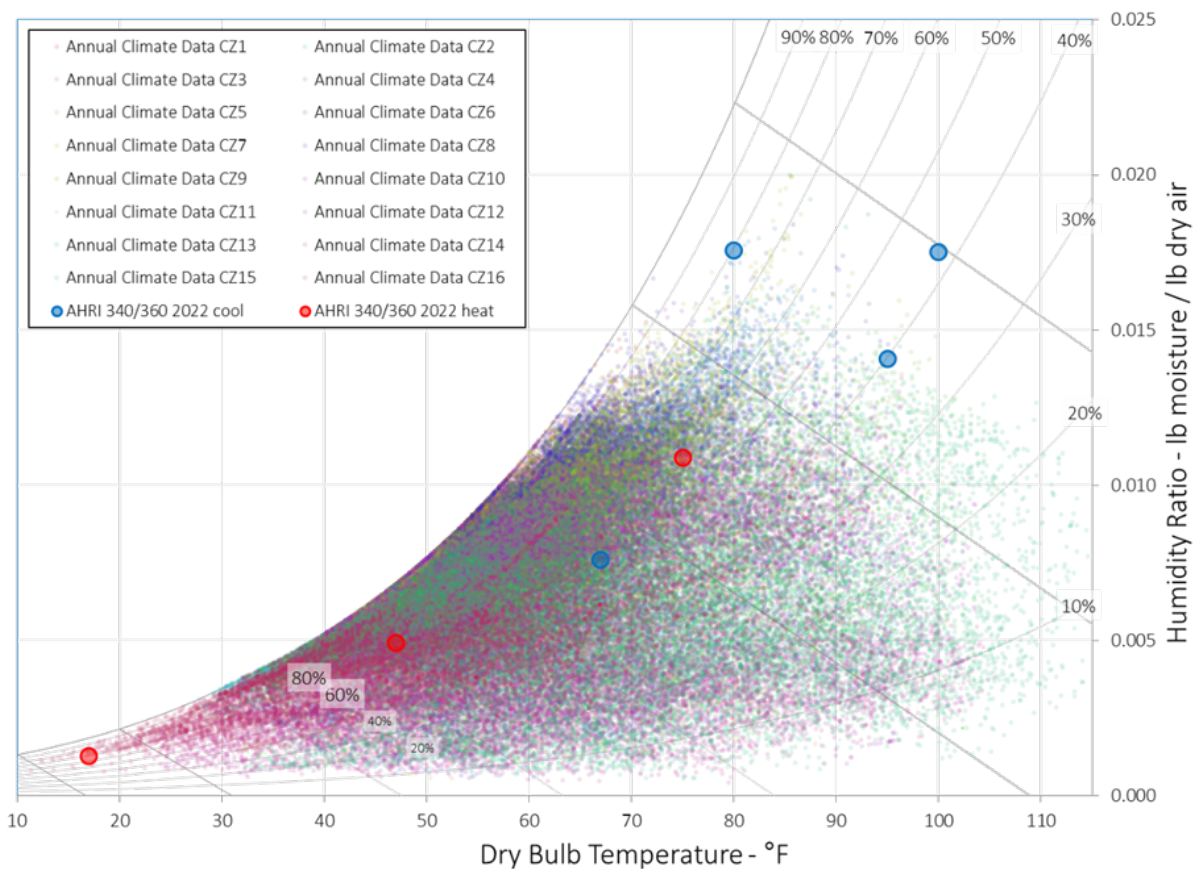


Figure 6: Psychrometric chart showing hourly outdoor air temperature and humidity conditions in all 16 California climate zones with the test standards laboratory test condition points.

Source: UC Davis Western Cooling Efficiency Center

WCEC selected specific environmental chamber test conditions for the evaporative section (see table 2 below), including less humid cooling conditions that are more representative of California climates (see fig. 7). Additional conditions were selected to align with measurements from the Western Cooling Challenge for comparison to other evaporative cooling equipment. Test conditions were also added to measure Hybrid RTU equipment energy performance in conditions to test dry evaporative section ventilation-only mode, and standby mode. Each test condition point takes considerable time and effort to achieve stable conditions and to test across relevant equipment modes of operation, so the total number of condition points had to be kept to the minimum sufficient number.

Table 2: Environmental Chamber Test Conditions for Evaporative Section

Conditions			
Test #	Outdoor Air Dry Bulb Temp °F	Outdoor Air Dew Point Temp °F	Source Notes
1	75	70	WCEC extreme humid condition
2	95	70	WCEC moderate humid condition
3	115	70	WCEC extreme temperature humid condition
4	75	50	WCEC mild mid humidity condition
5	95	50	WCEC moderate mid humidity condition
6	115	50	WCEC extreme mid humidity condition
7	75	30	WCEC mild dry condition
8	95	30	WCEC moderate dry condition
9	115	30	WCEC extreme dry condition

WCEC selected specific environmental chamber test conditions for the heat pump section (see table 3 below), with three different pairs of return air temperature and humidity levels, and including outdoor high humidity near freezing temperatures to test heating with defrost.

Table 3: Environmental Chamber Test Conditions for Heat Pump Section

Conditions					
Test #	Outdoor Air Dry Bulb Temp °F	Outdoor Air Dew Point Temp °F	Indoor Air Dry Bulb Temp °F	Indoor Air Dew Point Temp °F	Source Notes
1	75	70	80, 78, 75	60, 58, 56	WCEC extreme humid condition
2	95	70	80, 78, 75	60, 58, 56	WCEC moderate humid condition
3	115	70	80, 78, 75	60, 58, 56	WCEC extreme temperature humid condition
4	75	50	80, 78, 75	60, 58, 56	WCEC mild mid humidity condition
5	95	50	80, 78, 75	60, 58, 56	WCEC moderate mid humidity condition
6	115	50	80, 78, 75	60, 58, 56	WCEC extreme mid humidity condition
7	75	30	80, 78, 75	60, 58, 56	WCEC mild dry condition
8	95	30	80, 78, 75	60, 58, 56	WCEC moderate dry condition
9	115	30	80, 78, 75	60, 58, 56	WCEC extreme dry condition
10	60	51.5	65, 70, 75	<60	WCEC modeling heat
11	47	38.7	65, 70, 75	<60	AHRI 340/360 heat

Conditions

12

36

33

65, 70, 75 <60

Heat extreme humidity for defrost

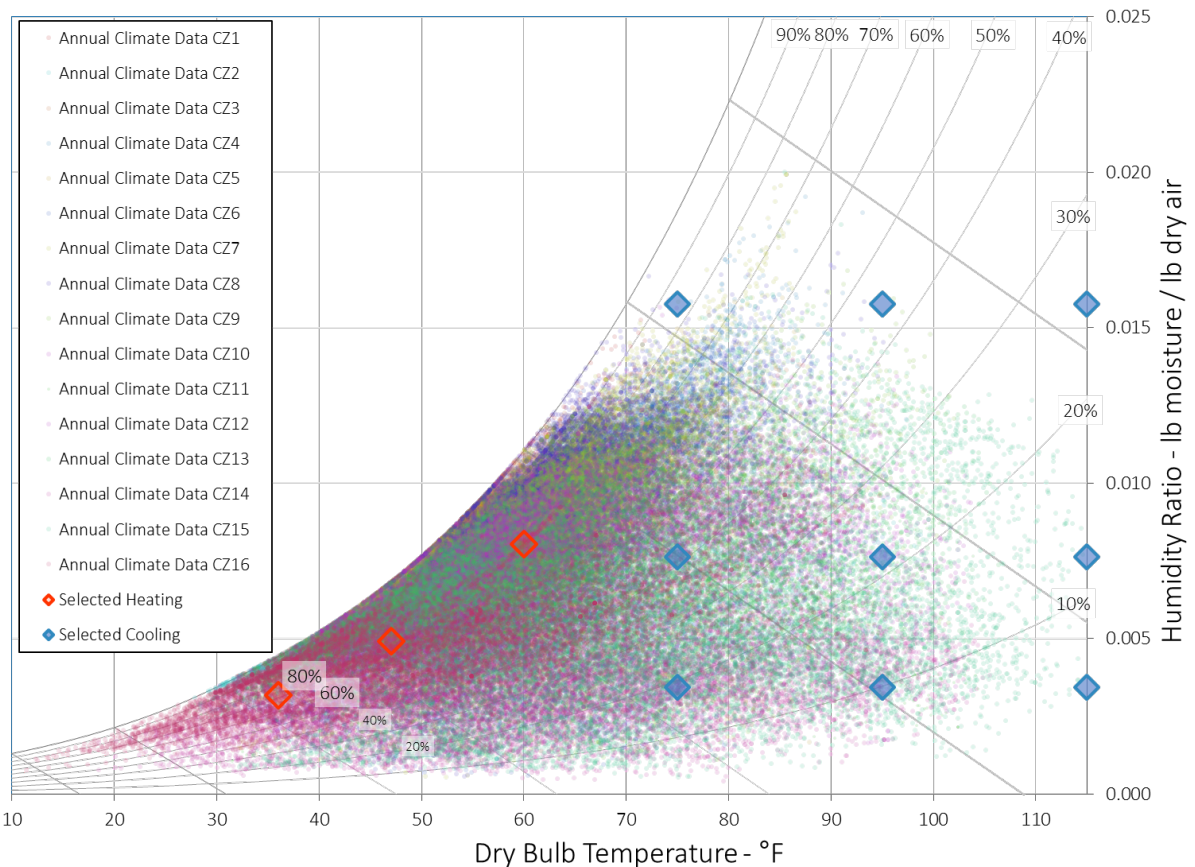


Figure 7: Psychrometric chart showing the target test conditions marked with diamonds and hourly outdoor air temperature and humidity conditions in all California climate zones.

Source: UC Davis Western Cooling Efficiency Center

Hybrid RTU Status

The unit tested in the lab was a production-ready prototype with all the hardware and controls that are included in the production equipment. For the final production version of the Hybrid RTU equipment, the manufacturer made only minor and cosmetic changes, like substitution of types of fasteners, and none of these would materially change the equipment's energy performance. The team maintained continuous communication with the manufacturer's engineers, sharing information about the Hybrid RTU operating modes and controls. Discussions informed the selection of outdoor

air flow rates for the IDEC section and the split between supply and exhaust at different outdoor conditions to be relevant to the operation of the equipment when it is installed in real buildings.

The production-ready Hybrid RTU prototype was updated for the United States to use 460V 60Hz electricity. The manufacturer completed tests of this prototype for electrical safety, Meridien lab tests (function, standard performance, extreme stress), and rain checks (for water tightness and ingress).

Laboratory Testing Methods

Setup

To replicate the support structure of an installation curb, the team built a custom rolling support from extruded aluminum and casters (Figure 8). Custom ducting was made to adapt the exhaust pathways and act as curb connection for the supply and return of the Hybrid RTU unit.

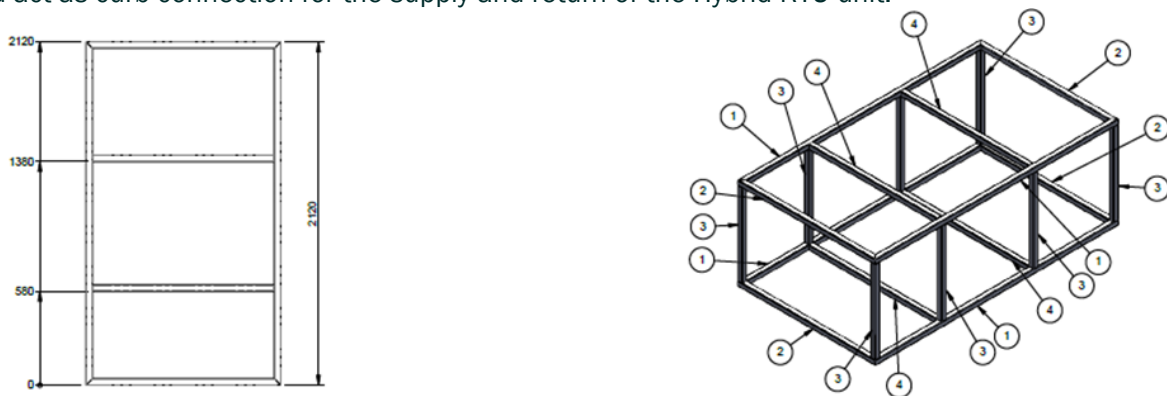


Figure 8: Custom curb support built for Hybrid RTU.

The ducting was made with one inch of interior insulation and was fully sealed along interior joints. The unit was placed on top of the custom curb frame and ducting, with weather sealing to minimize any air leaks at this junction. The unit was orientated in the test chamber, such that all the ducting could be routed to the appropriate locations. The team then connected the exhaust path ducting, attachments, and control dampers. Concurrent installation of sensors occurred during this phase, detailed in a later section. To finish installation the team routed the supply and return path ducting, connecting the Hybrid RTU to the indoor conditioning chamber. Below is a photo of the Hybrid RTU in its tested orientation and state (Figure 9).

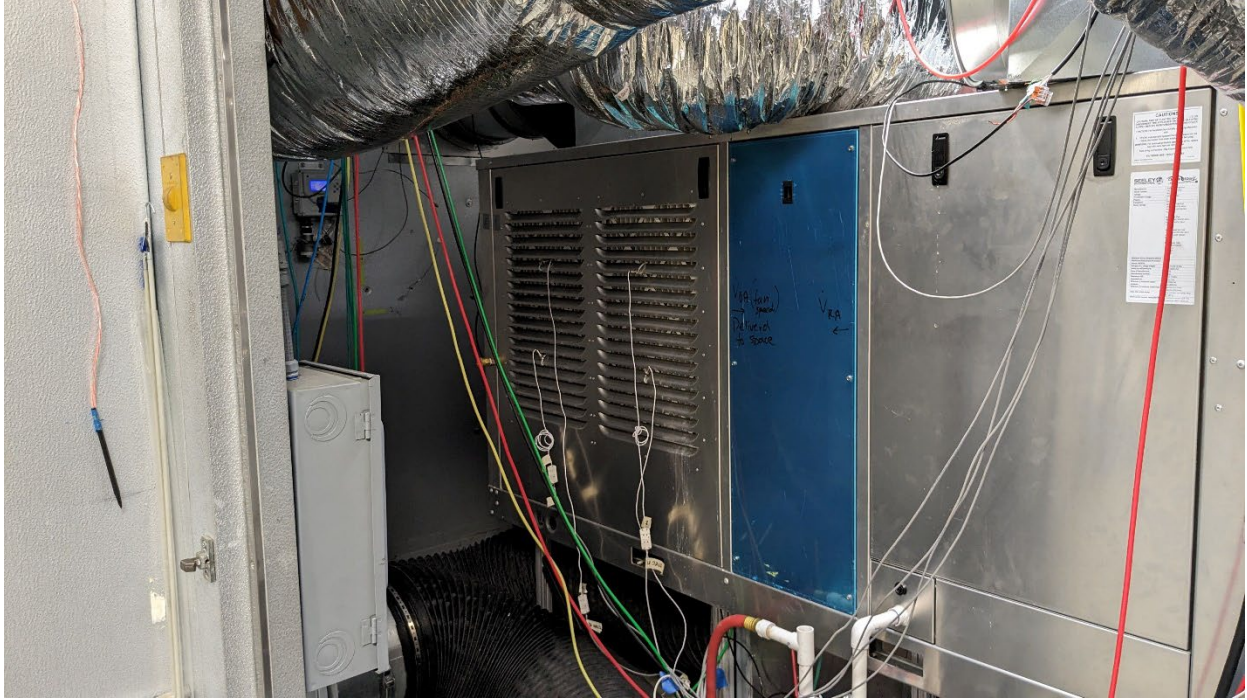


Figure 9: Hybrid RTU unit in WCEC environmental test chamber.

Source: UC Davis Western Cooling Efficiency Center

The Hybrid RTU was then connected to power, water inlet and drain connections, in preparation for an initial shakedown. The team then ran the unit in various operation modes to identify any potential issues before testing. Run modes were controlled by settings on the internal controller of the unit (Figure 10).



Figure 10. Control interface for Hybrid RTU.

Source: UC Davis Western Cooling Efficiency Center

To begin testing, the team checked the sensors outputs and ducted the Hybrid RTU to run investigatory flow tests. These tests were used to inform mode settings, adjust back pressure, and adjust flow rates for the condition testing as well as to measure supply fan power from each section in independent and hybrid operation. This was important to help understand the restriction and effect of the attached ducting and to help map the various flow paths under different conditions. The Hybrid RTU was run in a planned operation condition relevant to retrofits replacing a nominal 5-ton capacity RTU with the 2000 cfm typical air flow rate and the chamber fan and dampers were adjusted to achieve the target External Static Pressure (ESP) of 124.4 Pa defined by the test standards. At higher and lower air flow rates the target ESP was adjusted using the fan affinity law square exponential dependence. The team then ran each section of the Hybrid RTU separately and increased back pressure to match the ESP from the full flow. A tracer gas measurement of the SA flow for each section was done to disaggregate how much of the SA flow was provided by the evaporative section and heat pump section supply fans in separate and hybrid mode operating states. During this process, the fan power consumption was mapped across the range of equipment speeds for both separate and hybrid operation. This process determined the chamber and equipment settings and the flow fractions for all hybrid and ventilation modes. The team then ran tests for each mode of the Hybrid RTU at each of the environmental conditions relevant for that mode.

Testing

For each test, the team ran the Hybrid RTU until they observed steady state (SS) operation for 30-minutes for the evaporative section and 15 minutes for the heat pump section. Actuated dampers and the indoor chamber conditioning loop fan were controlled to adjust flow resistance caused to achieve the target external static pressure of 124.4 Pa defined by the test standards at 2000 cfm supply air flow rate for nominal 5-ton cooling capacity equipment. The temperature of the chambers were controlled by water-to-air heat exchanger coils modulated by Proportional-Integral-Derivative (PID)-controlled valves. Humidity was controlled by PID-controlled dampers that send part of the air flow through a dryer and the other part through a humidifier while maintaining a constant pressure drop.

The team used the outdoor chamber conditioning loop fan and actuated dampers to achieve close to zero pressure at the Hybrid RTU exhausts. The HP section tests were run with the outdoor coil exhaust ducting close to but not connected to the HP exhaust. For the evaporative section tests the outdoor chamber conditioning loop fan and exhaust control dampers were adjusted in tandem to get as close as possible to zero pressure at each exhaust. The zero static pressure measured at each exhaust is how the equipment would operate when it is installed on a rooftop. Direct measurement of the evaporative section supply air flow rate using tracer gas was used because the typical nozzle box flow measurements were subject to errors caused by air leaks out of the outdoor chamber due to the typically less than 25 Pa outdoor chamber pressure required to maintain zero pressure at the multiple exhausts.

Cooling

For cooling mode testing, the team ran tests at the environmental conditions selected in the test plan for all appropriate modes. This combined distinct modes (see table 4) and the test plan grid of nine outdoor conditions [three humidity ratios/dew points and three dry bulb temperatures]. Modes were only run in appropriate operational conditions, for example in the rare high outdoor humidity condition no water is supplied to the direct evaporative media so the evaporative section operates as an IEC.

Table 4: List of Modes and Number of Tests Conducted

Modes			
Indirect Evaporative Cooling (IEC) – High Humidity	IEC high speed (3tests)	IEC medium speed (3 tests)	IEC low speed (3 tests)
Indirect/Direct Evaporative Cooling (IDEC) – Medium and Low Humidity	IDEC high speed (6 tests)	IDEC medium speed (6 tests)	IDEC low speed (6 tests)
Heat Pump Cooling	HP high (9 Tests)	HP low (9 tests)	
Heat Pump Heating	HP high (9 tests)	HP low (9 tests)	

Heating

For heating mode testing, the team added a commercial freezer unit to the outdoor environmental chamber to cool the chamber to temperatures below freezing. Before this addition, the chamber was limited by the freezing point of the chiller loop glycol mixture. The team developed test procedures and performed conditioned tests at the three test conditions described in the test plan section.

Ventilation and Stand-by

Power usage was measured for the dry evaporative section ventilation-only mode at a steady state condition for approximately ten minutes, across a range of air flow rates. Finally, to complete all operational modes, the standby mode power usage was measured at above and below freezing outdoor chamber temperatures.

Defrost

For the outdoor near freezing test condition at 35 °F dry bulb and 28 °F wet bulb temperature a steam humidifier (see fig. 11) was used to add additional humidity beyond what the outdoor chamber loop humidifier could provide. In the initial tests extreme frost build up was observed and the unit did not initiate a defrost cycle. The manufacturer identified and fixed a bug in the defrost control programming. Subsequent testing showed the predictable periodic cycles of defrost with little visible frost accumulation. The team confirmed this to be consistent with expected defrost behavior,

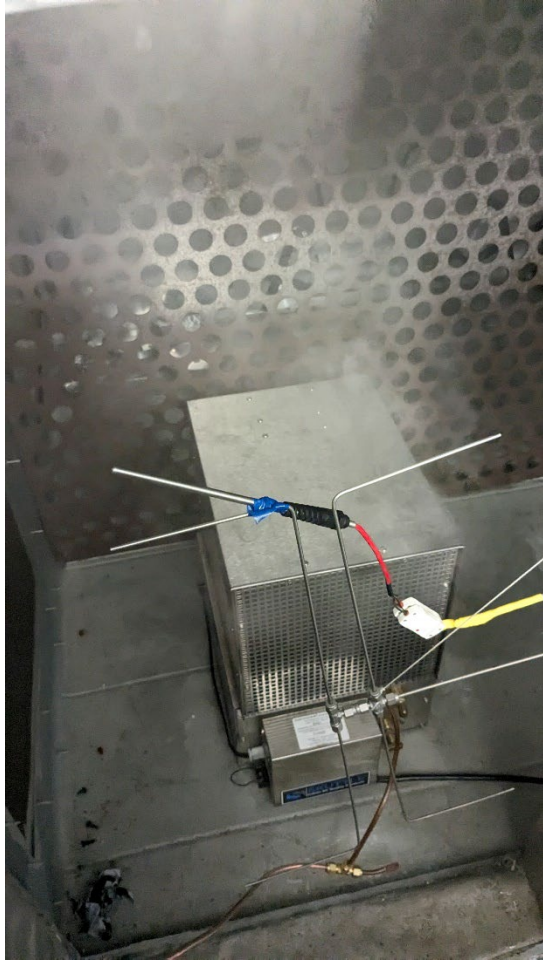


Figure 11: Detail of added humidifier.

Source: UC Davis Western Cooling Efficiency Center

Ventilation and Standby testing

The ventilation and standby power did not vary significantly with environmental conditions. The test team chose to run the hybrid RTU for 10-minute steady state tests to get the average power use and flow rate for vent only modes and while the unit is standby. Standby is a minimum power setting when the heating, ventilation, or cooling modes are not running but the control electronics are.

Lab Test Data Analysis

Data collection

The chamber and equipment were operated at the test settings for multiple hours to reach steady state operation. Test data collection was initiated and continued until the evaporative section reached 30-minutes or heat pump 15 minutes within the steady state criteria. During the test data collection, 30-second-averaged data were saved for the Hybrid RTU, and one-minute-averaged data were saved for the environmental chamber. The data were collected using National instruments

Compaq DAQ system and LabVIEW software. These data sets were aligned and averaged over the 30-minute steady state duration for summary calculations of all the tests. These average values were used to calculate desired capacity and operational metrics.

Temperatures and Humidity

The outdoor air temperature was controlled and monitored using a grid of 12 RTDs on the evaporative inlet and 5 RTDs on the heat pump outdoor coil inlet. The outdoor air dew point was controlled using a sampling grid at the outdoor chamber inlet for evaporative cooling tests and with a sampling grid at the heat pump outdoor coil inlet pulled by a vacuum pump through an OptiSonde chilled mirror hygrometer.

The supply and return air temperature and dew point were controlled and monitored using a Vaisala temperature and relative humidity probe and an OptiSonde RTD chilled mirror hygrometer placed in the return air ducting back to the Hybrid RTU. Multiple additional Vaisala temperature and relative humidity probes were placed in the evaporative supply air upstream of the evaporative section supply fan, in the heat pump supply air upstream of the heat pump section supply fan, and in both the return and supply ducts at the curb assembly of the Hybrid RTU. These temperature, dew point, and relative humidity measurements were then used in a psychrometric calculator to get any other psychrometric properties of desired air flows, like wet bulb temperature, humidity ratio, relative humidity, and air densities.

Air Flow Rates

Volumetric flow rates were measured and estimated in two ways, by using two nozzle boxes on each of the total flows into each chamber and with tracer gas injection measurements. The supply air flow for the evaporative section was measured directly using the tracer gas injection method. The return air flow for the heat pump section was measured using the indoor chamber nozzlebox and also checked directly using the tracer gas injection method to verify that return and supply air flow rates matched. Mass flows rates were calculated from the volumetric flows and densities calculated from the psychrometric properties of the given air flow.

Power

The total Hybrid RTU power consumption was measured on the power connection to the unit using a Dent PowerScout, which reads the values of all three phase currents and voltages. The power to each of the supply fans was measured using two more Dent PowerScouts.

Water Use

Problems with the water flow sensor and the intermittent flow of water bleed prevented reliable measurement of water consumption. This required that water use be determined from psychrometric calculations based on measurements of the evaporative section's inlet, exhaust, and supply air flow temperatures and humidity. These calculations were made using a combination of RTD, Vaisala T/RH, and chilled mirror measurements, along with air flow rate measurements using carbon dioxide tracer gas. The team estimates that the bleed water usage will typically be around a third of the evaporated water usage, as seen in the San José field test of a nearly identical Hybrid RTU unit and discussions with the manufacturer. Water bleed is actively controlled by an electrical conductivity sensor so the bleed water percentage will depend on the water hardness and conductivity setpoint with manufacturer estimates of 7% to 63%.

Pressures

External static pressure was measured at the curb interface of the Hybrid RTU, at both the SA and RA

plenums. This was accomplished using two of the channels on a DG8 differential pressure meter. Further static pressure measurements were recorded between the filter and evaporative heat exchanger, downstream of the heat pump indoor coil, and at the exit of all three exhaust paths. These measurements, along with measurements of chamber pressures, assisted the team to adjust chamber operation. All pressures were measured with an Energy Conservatory differential pressure gauge, and an atmospheric absolute pressure gauge in the outdoor environmental chamber.

The sensors used are detailed in table 5, and sensor placement in fig. 12.

Table 5: Hybrid RTU Instrumentation

Variable Label	Variable Description	Sensor Model	Sensor Accuracy (value or percent of reading)
PTOTAL	RTU total power	DENT PowerScout 3037	±0.7%
TOSA DPOSA	Temperature – Outside Chamber Air Dew Point – Outside Chamber Air	GE OptiSonde	±0.36 °F
TSA DPSA	Temperature – Supply Air Dew Point – Supply Air	GE OptiSonde	±0.27 °F dry bulb ± 0.36 °F dew point
TRA DPRA	Temperature – Return Air Dew Point – Return Air	GE OptiSonde	±0.27 °F dry bulb ± 0.36 °F dew point
TEA DPEA	Temperature – Evaporative Exhaust Air Dew Point – Evaporative Exhaust Air	GE OptiSonde	±0.27 °F dry bulb ± 0.36 °F dew point

Variable Label	Variable Description	Sensor Model	Sensor Accuracy (value or percent of reading)
THP,OA Coil	Grid of 4 inlet Temperature RTDs for Outdoor HP coil	Omega 100Ω class A platinum RTD-805	$\pm(0.15+0.002T)^{\circ}\text{C}$ $\pm(0.27+0.0036T)^{\circ}\text{F}$
TEC inlet	Grid of 12 inlet Temperature RTDs for Evaporative Cooler	Omega 100Ω class A platinum RTD-805	$\pm(0.15+0.002T)^{\circ}\text{C}$ $\pm(0.27+0.0036T)^{\circ}\text{F}$
T/RHEC,SA	Temperature and Relative Humidity for the Evaporative Chilled Supply Air	Vaisala HMP110	$\pm 1.5\sim 3.0\% \text{RH}$ (0–90 %RH) $\pm 2.5\sim 4.0\% \text{RH}$ (90–100 %RH) $\pm 0.36\sim \pm 0.72^{\circ}\text{F}^{*}$
T/RHHP,SA	Temperature and Relative Humidity for the Heat Pump Supply Air	Vaisala HMP110	$\pm 1.5\sim 3.0\% \text{RH}$ (0–90 %RH) $\pm 2.5\sim 4.0\% \text{RH}$ (90–100 %RH) $\pm 0.36\sim \pm 0.72^{\circ}\text{F}^{*}$
T/RHSA	Temperature and Relative Humidity for the Mixed Supply Air	Vaisala HMP110	$\pm 1.5\sim 3.0\% \text{RH}$ (0–90 %RH) $\pm 2.5\sim 4.0\% \text{RH}$ (90–100 %RH) $\pm 0.36\sim \pm 0.72^{\circ}\text{F}^{*}$
T/RHRA	Temperature and Relative Humidity for the Return Air	Vaisala HMP110	$\pm 1.5\sim 3.0\% \text{RH}$ (0–90 %RH) $\pm 2.5\sim 4.0\% \text{RH}$ (90–100 %RH) $\pm 0.36\sim \pm 0.72^{\circ}\text{F}^{*}$

Variable Label	Variable Description	Sensor Model	Sensor Accuracy (value or percent of reading)
QW	Water Flow Rate	Omega FTB-4605	±2%
QAir,SA	Hybrid RTU Supply Air Flow	WCEC developed Tracer Gas System	±1.6% of reading
QAir,SA,IDEC	IDEC Supply Air Flow	Nozzlebox Differential Pressure using Energy Conservatory APT	±1% of reading
QAir, RA	HP Return Air Flow	Nozzlebox Differential Pressure using Energy Conservatory APT	±1% of reading
Interior Air Flows	Flow rates across various interior equipment components	Differential Pressure using Energy Conservatory APT	±1% of reading
ESP	External Static Pressure	Differential Pressure using Energy Conservatory APT	±1% of reading

* Uncertainty for Vaisala sensors increases to upper bound if conditions are below 32 °F, above 104 °F, or above 90% RH

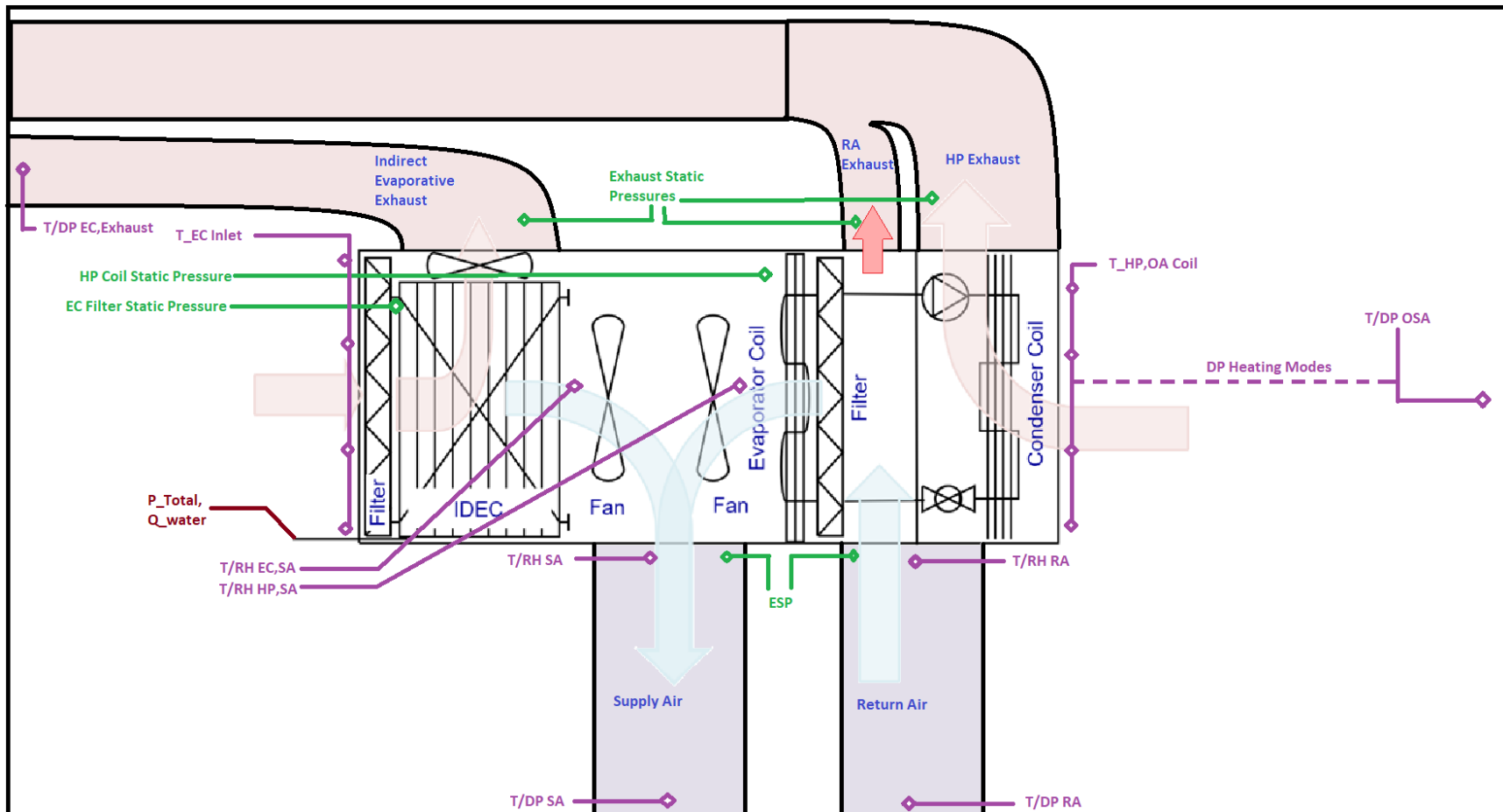


Figure 12: Hybrid RTU instrumentation diagram showing the variables measured.
Source: UC Davis Western Cooling Efficiency Center

Experimental Uncertainty

All sensors have unavoidable uncertainty in their readings, and the accuracy of each sensor is listed in Table 5. When these measurements are used to calculate other values, the uncertainties propagate through the equations to give a final uncertainty range for the result. The uncertainty range for the final metrics results are shown in the results section.

Calculating Airflow Measurements

Evaporative section supply airflow rates were measured for every mode and test condition of the Hybrid RTU using a tracer gas airflow measurement (ASTM E2029-11 Standard Test Method for Volumetric and Mass Flow Rate Measurement in a Duct Using Tracer Gas Dilution ASTM 2019). This method injects a measured mass flow rate of CO₂ into an air stream and then measures the CO₂ concentration downstream. From these two measures we can calculate the volume of the airflow (see Equation 1).

Equation 1:

$$\dot{V}_{Airflow} = \frac{\dot{V}_{CO_2} * 10^6}{C_{CO_2 \text{ downstream}} - C_{CO_2 \text{ background}}}$$

Where

$\dot{V}_{Airflow}$ is volumetric flow rate of air (cfm)

$\dot{V}_{CO_2}$ is volumetric flow rate of carbon dioxide (cfm)

$C_{CO_2 \text{ downstream}}$ is the concentration of carbon dioxide at the downstream of the sampling location (ppm)

$C_{CO_2 \text{ background}}$ is the concentration of carbon dioxide in the background air flow upstream of the injection location (ppm)

For the HP section, the return air flow rate was measured using nozzle box equipment in the indoor chamber conditioning loop.

Cooling Capacity

Cooling capacity is a measure of desired cooling work being performed on a process air stream. This capacity measure can be looked at in several ways depending on the use case. It can be evaluated from a perspective of the room by comparing the air entering the room to the air leaving the room, known as “room capacity.” Alternatively, cooling capacity can be evaluated from the perspective of the equipment by comparing the air entering the equipment to the supply air exiting the equipment, known as “system capacity”. For the evaporative section the system capacity includes the cooling to bring the outdoor air to the room temperature conditions. The heat pump section takes in air from the room so the room and system metrics are the same.

In periods requiring a higher ventilation rate during dry conditions, a hybrid system like the one evaluated in this study can greatly outperform conventional systems. For this reason, the team calculated the capacities and corresponding performance metrics in both ways. Doing so clearly demonstrates the Hybrid RTU's ability to efficiently cool the incoming ventilation air. Calculating these capacities is accomplished by multiplying the mass flow rates of corresponding air streams by their change in enthalpy compared to the room or compared to the outdoors for system capacity (see Equation 2). This is the net cooling produced by the equipment, including what is lost due to fan heat, as evaluated from the room or system, respectively.

Equation 2:

$$\dot{H}_{room} = \dot{m}_{SA} \cdot (h_{RA} - h_{SA})$$

$$\dot{H}_{system} = \dot{m}_{SA} \cdot ((F_{OSA} \cdot h_{OSA} + (1 - F_{OSA}) \cdot h_{RA}) - h_{SA})$$

$\dot{H}_{room}$ rate that enthalpy is added or removed from the room (kW)

$\dot{H}_{system}$ rate that enthalpy is added or removed to the air flowing through the equipment (kW)

h_{RA} specific enthalpy of return air (kJ/kg)

h_{SA} specific enthalpy of supply air (kJ/kg)

h_{OSA} specific enthalpy of outside air (kJ/kg)

$\dot{m}_{SA}$ mass flow rate of supply air (kg/s)

F_{OSA} outside air fraction in supply air (unitless)

$$\dot{m}_{SA} = \rho \dot{V}_{Airflow}$$

For hybrid cooling the individual supply air temperatures measured in separate operation were adjusted for the increased fan power and fan heat gain of hybrid operation and the mixed hybrid supply air flow rate and conditions were calculated, see Appendix C.

Calculating Coefficient of Performance

Coefficient of performance is a metric used to compare the amount of desired cooling energy to the amount of electrical energy used in the cooling process. To calculate this, cooling and electrical energy are converted into the same units and the ratio of cooling over electrical power is taken. Coefficient of Performance as calculated as follows (see equation 3):

Equation 3: COP including sensible and latent cooling

$$COP = \frac{\text{Cooling Energy Delivered}}{\text{Electrical Energy Consumed}} = \frac{\dot{H}}{\dot{E}_{system}}$$

$\dot{H}$ rate that enthalpy is added or removed, either room or system (kW)

$\dot{E}_{system}$ electrical power consumption (kW)

Calculating Wet Bulb Effectiveness

Wet bulb effectiveness (WBE) quantifies the extent to which an evaporative system can cool air to the wet bulb temperature of the incoming condition. This WBE metric (see Equation 4) is commonly used, as the wet bulb temperature represents the theoretical minimum temperature achievable through direct evaporative processes. The wet bulb effectiveness also generally remains consistent during variations in environmental conditions and system operation. WBE is the most common metric to describe performance of evaporative systems and is used as an input for some models of evaporative cooling systems in building energy simulation tools.

Equation 4:

$$WBE = \frac{T_{DB,in} - T_{DB,out}}{T_{DB,in} - T_{WB,in}}$$

$T_{DB,in}$ Dry bulb temperature of outside air entering evaporative section (°F)

$T_{DB,out}$ Wet bulb temperature of supply air leaving evaporative section (°F)

$T_{DB,in}$ Dry bulb temperature of outside air entering evaporative section (°F) $T_{WB,in}$ Wet bulb temperature of outside air entering evaporative section (°F)

Although WBE is typically used as a metric of direct evaporative performance, it can be applied for an indirect evaporative process. Indirect evaporative heat exchangers use a secondary air stream with an inlet wet bulb temperature lower than that of the primary stream, meaning it is possible to achieve over 100 percent effectiveness. Typical for advanced design indirect evaporative processes, the dew point temperature is the theoretical minimum temperature that can be reached. In most conditions this increases effective cooling at the cost of some additional water and fan power to draw additional air through the primary and secondary air streams.

Results and Discussion

Cooling Modes

The test results show that, at the typical AHRI rated cooling outdoor dry bulb temperature of 95 °F, and a cooling season humidity typical to most California climate zones of 50 °F dew point paired with the standard indoor condition of 80 °F dry bulb and 60.4 °F dew point, the Hybrid RTU using both the IDEC high speed and HP stage two supplied 3503 cfm with 56 percent outdoor air ventilation fraction, deliver a sensible cooling capacity of 5.1 tons for the room with coefficient of performance 3.4. When including credit for cooling outdoor air for ventilation, the Hybrid RTU has a system sensible capacity of 7.7 tons with coefficient of performance 5.2. This is high efficiency performance with significantly more ventilation being provided than typical conventional baseline RTUs.

For comparison, a leading very high efficiency variable speed heat pump RTU, has a rated EER of 13 and COP of 3.81 at 95 °F outdoor dry bulb temperature. It is difficult to make a direct comparison based only on rated efficiency because the test standards do not use outdoor air ventilation when testing typical vapor compression RTU heat pumps.

Many hours of the year, the cooling load required by a space is less than the maximum cooling load the HVAC equipment can deliver. During these times of less-than-maximum cooling load, the Hybrid RTU will run in evaporative cooling modes without the heat pump cooling. The evaporative cooling modes have variable speed fans that can ramp up and down to maintain the space temperature in a comfortable range. In evaporative cooling modes in the same 95 °F dry bulb and 50 °F dew point outdoor conditions paired with the standard indoor condition of 80 °F dry bulb and 60.4 °F dew point, the evaporative section would operate alone with low-speed fan setting, and the IDEC delivers 510 cfm, 100% outdoor air ventilation, with a room sensible cooling capacity of 0.9 tons and COP of 15.8, and system cooling capacity of 1.6 tons and COP of 27.7. With the high-speed fan setting, the IDEC alone delivered 1935 cfm, 100% outdoor air ventilation, with a room sensible cooling capacity of 2.7 tons and COP of 11.1 and system sensible cooling capacity of 5.3 tons and COP of 21.9. These evaporative cooling modes provide significant cooling capacity at very high COP compared to baseline typical RTUs. The Hybrid RTU units are likely to run in evaporative cooling modes for a significant portion of the time. For example, in the San José field test, at outdoor conditions of 95 °F dry bulb, the Hybrid RTU unit ran in evaporative section alone mode 70 percent of the time, accumulating large energy savings. The lab test results room sensible as well as system sensible cooling capacity and COP metrics in evaporative and hybrid modes are detailed below along with the estimate of the sensor accuracy bias uncertainties propagated through the calculations to these metrics (see tables 6 through 11).

At an outdoor dry bulb temperature of 95 °F dry bulb and a low cooling season humidity for California climate zones of 39 °F dew point and 80 °F dry bulb and 60.4 °F dew point indoor conditions, the Hybrid RTU supplied 3656 cfm with 58 percent outdoor air ventilation fraction using both the IDEC and HP high speed cooling, delivering a room sensible cooling capacity of 6.1 tons with coefficient of performance 4.1. When including cooling of outdoor air for ventilation, it has a system sensible capacity of 7.7 tons with coefficient of performance 5.2. This is high-efficiency performance with significantly more ventilation being provided than typical conventional baseline RTUs. When the required cooling load of a space is less than the maximum that the equipment can deliver, at these conditions, the high speed IDEC mode delivered 2088 cfm of ventilation with a room sensible cooling

capacity of 3.7 tons and COP of 15.3 and system sensible cooling capacity of 6.6 tons and COP of 27.1. With outdoor conditions of 95°F dry bulb and 30°F dew point and indoor conditions of 80°F dry bulb and 60.4°F dew point, low-speed IDEC delivered 451 cfm of ventilation, a room sensible cooling capacity of 1.3 tons and COP of 22.1, and system sensible cooling capacity of 1.9 tons and COP of 32.9. In these low-humidity outdoor conditions common in inland California climate zones, the Hybrid RTU evaporative cooling modes provide significant cooling capacity at extremely high COP compared with baseline typical RTUs.

In very hot 115°F dry bulb and moderately low humidity 46°F dew point condition, for peak cooling in inland California climate zones, and indoor conditions of 80°F dry bulb and 60.4°F dew point, the high-speed IDEC evaporative cooling mode provided 2.0 tons of room sensible capacity with 8.3 COP and 8.5 tons of system sensible capacity, 35.3 COP. This evaporative cooling can provide much higher efficiency cooling during peak cooling load weather events with significant potential for site and grid peak load reduction.

One metric of efficiency for evaporative cooling equipment is wetbulb effectiveness. If the evaporative cooling equipment cools the supply air to a dry bulb temperature equal to the outdoor wetbulb temperature that is defined as 100% wetbulb effectiveness, with lower supply air temperatures over 100%. This Hybrid RTU equipment when operating in evaporative only IEC mode with high outdoor humidity 70°F dew point achieved wetbulb effectiveness between 76% and 108%. The evaporative only IDEC mode with outdoor humidity between 30°F and 50°F dew point achieved wetbulb effectiveness between 105% and 135%.

The water circulation pump that supplies water to the indirect and direct evaporative media consumed electrical power in pulses with a relatively steady average of 10W.

It should be noted that in evaporative-only modes, the supply air temperature is not affected by the return air condition, as it is provided by cooling the outdoor air. For this reason, the room capacities and COPs are all calculated using the AHRI test standard return air condition of 80°F dry bulb and 60°F dew point. This can slightly inflate room total capacities so we have reported room sensible capacities and COPs to avoid this issue. As with all HVAC systems room capacity and COP will be lower when room temperatures are lower than the ASHRAE standard condition. When energy simulation software uses the performance curves developed in this project, it will use the simulated room temperature and humidity levels for each timestep to correctly calculate capacity and COP. For evaporative cooling the sensible system capacity and COP are calculated by adding the room sensible capacity and the sensible cooling that the evaporative section does to bring the outdoor air to the room condition. In the cases where the outdoor dry bulb is 75°F so it is lower than the indoor dry bulb, this results in a smaller system capacity and COP than the room capacity and COP.

For high humidity conditions (over 80°F dry bulb and relative humidity over 50 percent dew point over 60°F), somewhat rare in California, the performance of the evaporative modes is reduced and the Hybrid RTU will use more HP cooling. These high humidity conditions only account for 5.5% of all California cooling hours over 80°F dry bulb averaged across all climate zones. Operating in the HP hybrid modes at 95°F dry bulb and (almost never recorded in California) very high humidity of 70°F dew point, the Hybrid RTU would operate using the HP cooling and low speed evaporative section IEC mode to supply sufficient ventilation without consuming more energy than necessary. In hybrid HP stage two and IEC low speed with indoor 80°F dry bulb and 60°F dew point, it delivers room sensible

cooling capacity of 2.7 ton 2.2 COP and system sensible 4.8 ton 3.9 COP. At the highest dry bulb temperature and very high humidity condition, the Hybrid RTU will struggle, just as conventional HVAC units will. In these extreme conditions, the hybrid RTU was shown to have supply air temperature of 69°F, at flow rate 2228 CFM.

In high humidity conditions, the hybrid RTU would operate in hybrid mode with heat pump cooling and supply outdoor air for ventilation requirements. The laboratory testing included evaporative cooling operation without the heat pump cooling, even with very high humidity levels, so that the regressions can accurately show performance between medium and very high humidity conditions. At very high humidity levels, above what is typically seen in California climate zones, the evaporative cooling modes without heat pump cooling will supply air with enthalpy above the indoor air conditions, providing a negative room capacity, heating the room. Under these very high humidity conditions, the evaporative cooling modes still accomplish some cooling of the outdoor air with positive system capacity but are not able to cool it below the indoor air condition. When energy simulation software uses the performance curves developed in this project these effects are included.

In the high humidity outdoor conditions, very rare for California climates, the IEC cannot do as much evaporative cooling, so the air flow temperature changes are small. With these small temperature changes the small bias uncertainty from the high accuracy temperature sensors results in a larger relative uncertainty for the IEC results. At the highest outdoor temperature and humidity conditions the IEC supply air can still be above the room temperature so that the room sensible capacity and COP can be very small or negative, also leading to a larger relative uncertainty in the results. The system sensible capacity and COP show that even in these high temperature and high humidity conditions the IEC mode can still provide significant cooling of outdoor air.

For the cases where the outdoor dry bulb is 75°F and the indoor dry bulb is 80°F, the system sensible capacity and COP will be lower than the room capacity and COP because some of the cooling is provided freely from the outdoor air entering the equipment already at a lower temperature.

Table 6: IEC AND IDEC Cooling

COOLING													
	Airflow (CFM)		Outdoor Air Temperature (F)		Indoor Air Temperature (F)		Supply Air Temperature (F)		Sensible Room Capacity			Sensible System Capacity	
Mode	Total	Outdoor	Drybulb	Dewpoint	Drybulb	Dewpoint	Drybulb	Dewpoint	(Btu/hr)	Total Power (kW)	Sensible Room COP	(Btu/hr)	Sensible System COP
IEC													
IEC High	2296 ±2%	2296 ±2%	75 ±0.7%	70 ±0.5%	80	60	72 ±0.5%	69 ±0.5%	18957 ±7%	0.85 ±0.5%	6.5 ±7%	7164 ±22%	2.5 ±22%
	2099 ±2%	2099 ±2%	95 ±0.6%	70 ±0.5%	80	60	78 ±0.5%	69 ±0.5%	3718 ±30%	0.85 ±0.5%	1.3 ±30%	37376 ±5%	12.9 ±5%
	1867 ±2%	1867 ±2%	116 ±0.6%	70 ±0.5%	80	60	87 ±0.4%	71 ±0.5%	-12869 ±8%	0.85 ±0.5%	-4.4 ±8%	57011 ±3%	19.6 ±3%
IEC Medium	1242 ±2%	1242 ±2%	76 ±0.7%	70 ±0.5%	80	60	72 ±0.5%	70 ±0.5%	10580 ±7%	0.41 ±0.5%	7.6 ±7%	4967 ±18%	3.6 ±18%
	1257 ±2%	1257 ±2%	95 ±0.6%	70 ±0.5%	80	60	77 ±0.5%	70 ±0.5%	4644 ±15%	0.41 ±0.5%	3.3 ±15%	25139 ±4%	18.1 ±4%
	1240 ±2%	1240 ±2%	115 ±0.6%	70 ±0.5%	80	60	84 ±0.4%	70 ±0.5%	-5382 ±12%	0.41 ±0.5%	-3.9 ±12%	40350 ±3%	29 ±3%
IEC Low	658 ±2%	658 ±2%	75 ±0.7%	70 ±0.5%	80	60	72 ±0.5%	69 ±0.5%	5915 ±6%	0.2 ±0.5%	8.5 ±6%	2600 ±18%	3.8 ±18%
	698 ±2%	698 ±2%	95 ±0.6%	71 ±0.5%	80	60	76 ±0.5%	70 ±0.5%	3145 ±12%	0.2 ±0.5%	4.5 ±12%	14523 ±4%	21 ±4%
	646 ±2%	646 ±2%	115 ±0.6%	70 ±0.5%	80	60	81 ±0.5%	71 ±0.5%	-451 ±81%	0.2 ±0.5%	-0.7 ±81%	23388 ±3%	33.8 ±3%
IDEC													
IDEC High	1976 ±2%	1976 ±2%	77 ±0.7%	49 ±0.7%	80	60	59 ±0.6%	54 ±0.7%	44977 ±3%	0.85 ±0.5%	15.5 ±3%	37395 ±4%	12.9 ±4%
	1935 ±2%	1935 ±2%	95 ±0.6%	49 ±0.7%	80	60	65 ±0.6%	56 ±0.6%	32203 ±4%	0.85 ±0.5%	11.1 ±4%	63611 ±3%	21.9 ±3%
	2017 ±2%	2017 ±2%	114 ±0.6%	58 ±0.6%	80	60	71 ±0.5%	60 ±0.6%	20495 ±6%	0.85 ±0.5%	7.1 ±6%	95488 ±2%	32.9 ±2%
	1991 ±2%	1991 ±2%	75 ±0.7%	31 ±1.1%	80	60	52 ±0.7%	43 ±0.8%	63436 ±2%	0.85 ±0.5%	21.8 ±3%	51855 ±3%	17.9 ±3%
	2088 ±2%	2088 ±2%	95 ±0.6%	39 ±0.9%	80	60	61 ±0.6%	51 ±0.7%	44454 ±3%	0.85 ±0.5%	15.3 ±3%	78652 ±3%	27.1 ±3%
	2086 ±2%	2086 ±2%	115 ±0.6%	46 ±0.8%	80	60	69 ±0.5%	57 ±0.6%	23972 ±5%	0.85 ±0.5%	8.3 ±5%	102565 ±2%	35.3 ±2%
IDEC Medium	1301 ±2%	1301 ±2%	76 ±0.7%	50 ±0.7%	80	60	57 ±0.6%	54 ±0.7%	32713 ±3%	0.41 ±0.5%	23.5 ±3%	26649 ±4%	19.1 ±4%
	1243 ±2%	1243 ±2%	97 ±0.6%	50 ±0.7%	80	60	61 ±0.6%	56 ±0.6%	25390 ±3%	0.41 ±0.5%	18.2 ±3%	48014 ±3%	34.5 ±3%
	1262 ±2%	1262 ±2%	115 ±0.6%	50 ±0.7%	80	60	67 ±0.5%	59 ±0.6%	18152 ±4%	0.41 ±0.5%	13 ±4%	65910 ±2%	47.3 ±2%
	1282 ±2%	1282 ±2%	75 ±0.7%	32 ±1.1%	80	60	49 ±0.7%	42 ±0.8%	45537 ±2%	0.41 ±0.5%	32.7 ±2%	37491 ±3%	26.9 ±3%
	1364 ±2%	1364 ±2%	95 ±0.6%	31 ±1.2%	80	60	54 ±0.7%	45 ±0.8%	39870 ±3%	0.41 ±0.5%	28.6 ±3%	62082 ±2%	44.6 ±2%
	1250 ±2%	1250 ±2%	115 ±0.6%	36 ±1%	80	60	61 ±0.6%	51 ±0.7%	26527 ±3%	0.41 ±0.5%	19.1 ±3%	73862 ±2%	53.1 ±2%
IDEC Low	519 ±2%	519 ±2%	76 ±0.7%	50 ±0.7%	80	60	57 ±0.6%	53 ±0.7%	13579 ±3%	0.2 ±0.5%	19.6 ±3%	10983 ±4%	15.9 ±4%
	510 ±2%	510 ±2%	95 ±0.6%	52 ±0.7%	80	60	61 ±0.6%	56 ±0.6%	10962 ±3%	0.2 ±0.5%	15.8 ±3%	19207 ±3%	27.7 ±3%
	637 ±2%	637 ±2%	115 ±0.6%	50 ±0.7%	80	60	64 ±0.6%	56 ±0.6%	11430 ±4%	0.2 ±0.5%	16.5 ±4%	35804 ±2%	51.7 ±2%
	470 ±2%	470 ±2%	76 ±0.7%	30 ±1.2%	80	60	45 ±0.8%	40 ±0.9%	18725 ±2%	0.2 ±0.5%	27 ±2%	16205 ±3%	23.4 ±3%
	451 ±2%	451 ±2%	95 ±0.6%	30 ±1.2%	80	60	50 ±0.7%	42 ±0.8%	15312 ±2%	0.2 ±0.5%	22.1 ±2%	22798 ±2%	32.9 ±2%
	526 ±2%	526 ±2%	115 ±0.6%	32 ±1.1%	80	60	55 ±0.7%	46 ±0.8%	14965 ±3%	0.2 ±0.5%	21.6 ±3%	35096 ±2%	50.7 ±2%

Table 7: DX Heat Pump Cooling

COOLING													
Mode	Airflow (CFM)		Outdoor Air Temperature (F)		Indoor Air Temperature (F)		Supply Air Temperature (F)		Sensible Room Capacity (Btu/hr)	Total Power (kW)	Sensible Room COP	Sensible System Capacity (Btu/hr)	Sensible System COP
	Total	Outdoor	Drybulb	Dewpoint	Drybulb	Dewpoint	Drybulb	Dewpoint					
Heat Pump													
DX High	1575 ±1%	0	75 ±0.7%	51 ±0.7%	81 ±0.4%	60 ±0.6%	59 ±0.8%	55 ±0.6%	37894 ±3%	3.28 ±0.7%	3.4 ±3%		
	1568 ±1%	0	95 ±0.6%	55 ±0.6%	80 ±0.5%	62 ±0.6%	62 ±0.7%	57 ±0.6%	31247 ±3%	3.96 ±0.7%	2.3 ±3%		
	1582 ±1%	0	115 ±0.6%	53 ±0.7%	80 ±0.5%	62 ±0.6%	64 ±0.7%	59 ±0.6%	27577 ±4%	4.81 ±0.7%	1.7 ±4%		
	1566 ±1%	0	76 ±0.7%	44 ±0.8%	78 ±0.5%	58 ±0.6%	57 ±0.8%	53 ±0.7%	36586 ±3%	3.24 ±0.7%	3.3 ±3%		
	1571 ±1%	0	95 ±0.6%	48 ±0.8%	78 ±0.5%	58 ±0.6%	59 ±0.8%	54 ±0.7%	32704 ±3%	3.9 ±0.7%	2.5 ±3%		
	1598 ±1%	0	115 ±0.6%	59 ±0.6%	78 ±0.5%	58 ±0.6%	62 ±0.7%	56 ±0.6%	28853 ±4%	4.74 ±0.7%	1.8 ±4%		
	1585 ±1%	0	75 ±0.7%	44 ±0.8%	75 ±0.5%	56 ±0.6%	55 ±0.8%	51 ±0.7%	35204 ±3%	3.2 ±0.7%	3.2 ±3%		
	1592 ±1%	0	95 ±0.6%	57 ±0.6%	75 ±0.5%	56 ±0.6%	57 ±0.8%	53 ±0.7%	31337 ±3%	3.91 ±0.7%	2.4 ±3%		
	1565 ±1%	0	115 ±0.6%	60 ±0.6%	75 ±0.5%	56 ±0.6%	60 ±0.8%	54 ±0.7%	26534 ±4%	4.77 ±0.7%	1.6 ±4%		
DX Low	1246 ±1%	0	75 ±0.7%	58 ±0.6%	80 ±0.4%	63 ±0.6%	60 ±0.7%	56 ±0.6%	27407 ±3%	2.13 ±0.7%	3.8 ±3%		
	1256 ±1%	0	95 ±0.6%	60 ±0.6%	80 ±0.5%	62 ±0.6%	62 ±0.7%	57 ±0.6%	25161 ±3%	2.74 ±0.7%	2.7 ±3%		
	1265 ±1%	0	115 ±0.6%	52 ±0.7%	80 ±0.5%	62 ±0.6%	65 ±0.7%	59 ±0.6%	20145 ±4%	3.43 ±0.7%	1.7 ±4%		
	1247 ±1%	0	75 ±0.7%	45 ±0.8%	78 ±0.5%	58 ±0.6%	58 ±0.8%	53 ±0.7%	27995 ±3%	2.12 ±0.7%	3.9 ±3%		
	1249 ±1%	0	95 ±0.6%	49 ±0.7%	78 ±0.5%	58 ±0.6%	60 ±0.8%	55 ±0.7%	24843 ±3%	2.72 ±0.7%	2.7 ±3%		
	1260 ±1%	0	115 ±0.6%	60 ±0.6%	78 ±0.5%	58 ±0.6%	63 ±0.7%	56 ±0.6%	20949 ±4%	3.4 ±0.7%	1.8 ±4%		
	1279 ±1%	0	75 ±0.7%	42 ±0.9%	75 ±0.5%	56 ±0.6%	56 ±0.8%	51 ±0.7%	27188 ±3%	2.13 ±0.7%	3.7 ±3%		
	1241 ±1%	0	95 ±0.6%	47 ±0.8%	75 ±0.5%	56 ±0.6%	58 ±0.8%	52 ±0.7%	23346 ±3%	2.72 ±0.7%	2.5 ±4%		
	1268 ±1%	0	115 ±0.6%	52 ±0.7%	75 ±0.5%	56 ±0.6%	61 ±0.7%	54 ±0.7%	19909 ±4%	3.43 ±0.7%	1.7 ±4%		

Table 8: IEC Hybrid Heat Pump High Cooling (Stage 2)

COOLING													
Mode	Airflow (CFM)		Outdoor Air Temperature (F)		Indoor Air Temperature (F)		Supply Air Temperature (F)		Sensible Room Capacity (Btu/hr)	Total Power (kW)	Sensible Room COP	Sensible System Capacity (Btu/hr)	Sensible System COP
	Total	Outdoor	Drybulb	Dewpoint	Drybulb	Dewpoint	Drybulb	Dewpoint					
Hybrid Heat Pump High (Stage 2)													
IEC High	3871 ±1%	2296 ±2%	75 ±0.7%	70 ±0.5%	81 ±0.4%	60 ±0.6%	67 ±0.4%	65 ±0.4%	57272 ±3%	4.51 ±0.4%	3.7 ±3%	42705 ±4%	2.8 ±4%
	3667 ±1%	2099 ±2%	95 ±0.6%	70 ±0.5%	80 ±0.5%	62 ±0.6%	72 ±0.4%	65 ±0.4%	32354 ±5%	5.22 ±0.5%	1.8 ±5%	65964 ±3%	3.7 ±3%
	3449 ±1%	1867 ±2%	116 ±0.6%	70 ±0.5%	80 ±0.5%	62 ±0.6%	76 ±0.3%	66 ±0.4%	12658 ±13%	6.07 ±0.6%	0.6 ±13%	82159 ±2%	4 ±2%
	3862 ±1%	2296 ±2%	75 ±0.7%	70 ±0.5%	78 ±0.5%	58 ±0.6%	66 ±0.4%	64 ±0.5%	47760 ±4%	4.46 ±0.4%	3.1 ±4%	40642 ±5%	2.7 ±4%
	3670 ±1%	2099 ±2%	95 ±0.6%	70 ±0.5%	78 ±0.5%	58 ±0.6%	70 ±0.4%	64 ±0.4%	29723 ±6%	5.14 ±0.5%	1.7 ±6%	67436 ±3%	3.8 ±3%
	3465 ±1%	1867 ±2%	116 ±0.6%	70 ±0.5%	78 ±0.5%	58 ±0.6%	75 ±0.4%	65 ±0.4%	10076 ±18%	6.04 ±0.6%	0.5 ±18%	83351 ±2%	4 ±2%
	3881 ±1%	2296 ±2%	75 ±0.7%	70 ±0.5%	75 ±0.5%	56 ±0.6%	65 ±0.5%	63 ±0.5%	39510 ±5%	4.44 ±0.4%	2.6 ±5%	39936 ±5%	2.6 ±5%
	3691 ±1%	2099 ±2%	95 ±0.6%	70 ±0.5%	75 ±0.5%	56 ±0.6%	69 ±0.4%	63 ±0.5%	21983 ±9%	5.14 ±0.5%	1.3 ±9%	66388 ±3%	3.8 ±3%
IEC Medium	3432 ±1%	1867 ±2%	116 ±0.6%	70 ±0.5%	75 ±0.5%	56 ±0.6%	74 ±0.4%	64 ±0.5%	1449 ±178%	6.06 ±0.6%	0.1 ±178%	80515 ±2%	3.9 ±2%
	2817 ±1%	1242 ±2%	76 ±0.7%	70 ±0.5%	81 ±0.4%	60 ±0.6%	65 ±0.4%	63 ±0.4%	48058 ±3%	3.95 ±0.5%	3.6 ±3%	40935 ±3%	3 ±3%
	2825 ±1%	1257 ±2%	95 ±0.6%	70 ±0.5%	80 ±0.5%	62 ±0.6%	69 ±0.4%	64 ±0.4%	33821 ±4%	4.65 ±0.6%	2.1 ±4%	54256 ±2%	3.4 ±2%
	2822 ±1%	1240 ±2%	115 ±0.6%	70 ±0.5%	80 ±0.5%	62 ±0.6%	73 ±0.4%	64 ±0.4%	20799 ±6%	5.46 ±0.6%	1.1 ±6%	66264 ±2%	3.6 ±2%
	2808 ±1%	1242 ±2%	76 ±0.7%	70 ±0.5%	78 ±0.5%	58 ±0.6%	64 ±0.5%	62 ±0.5%	41969 ±3%	3.91 ±0.4%	3.1 ±3%	38874 ±3%	2.9 ±3%
	2828 ±1%	1257 ±2%	95 ±0.6%	70 ±0.5%	78 ±0.5%	58 ±0.6%	67 ±0.4%	62 ±0.5%	32865 ±4%	4.57 ±0.5%	2.1 ±4%	55764 ±2%	3.6 ±2%
	2838 ±1%	1240 ±2%	115 ±0.6%	70 ±0.5%	78 ±0.5%	58 ±0.6%	71 ±0.4%	63 ±0.4%	19527 ±7%	5.43 ±0.6%	1.1 ±7%	67512 ±2%	3.6 ±2%
	2827 ±1%	1242 ±2%	76 ±0.7%	70 ±0.5%	75 ±0.5%	56 ±0.6%	63 ±0.5%	61 ±0.5%	37184 ±4%	3.89 ±0.4%	2.8 ±4%	38168 ±4%	2.9 ±3%
IEC Low	2849 ±1%	1257 ±2%	95 ±0.6%	70 ±0.5%	75 ±0.5%	56 ±0.6%	66 ±0.5%	61 ±0.5%	27814 ±5%	4.57 ±0.5%	1.8 ±5%	54733 ±3%	3.5 ±2%
	2805 ±1%	1240 ±2%	115 ±0.6%	70 ±0.5%	75 ±0.5%	56 ±0.6%	71 ±0.5%	62 ±0.5%	12844 ±12%	5.46 ±0.6%	0.7 ±12%	64695 ±2%	3.5 ±2%
	2233 ±1%	658 ±2%	75 ±0.7%	70 ±0.5%	81 ±0.4%	60 ±0.6%	63 ±0.4%	60 ±0.5%	43054 ±3%	3.69 ±0.5%	3.4 ±3%	38940 ±3%	3.1 ±3%
	2266 ±1%	698 ±2%	95 ±0.6%	71 ±0.5%	80 ±0.5%	62 ±0.6%	66 ±0.4%	62 ±0.4%	32665 ±3%	4.4 ±0.6%	2.2 ±3%	43995 ±2%	2.9 ±2%
	2228 ±1%	646 ±2%	115 ±0.6%	70 ±0.5%	80 ±0.5%	62 ±0.6%	69 ±0.4%	63 ±0.4%	26077 ±4%	5.2 ±0.6%	1.5 ±4%	49749 ±2%	2.8 ±2%
	2224 ±1%	658 ±2%	75 ±0.7%	70 ±0.5%	78 ±0.5%	58 ±0.6%	62 ±0.5%	59 ±0.5%	38862 ±3%	3.64 ±0.5%	3.1 ±3%	36885 ±3%	3 ±3%
	2269 ±1%	698 ±2%	95 ±0.6%	71 ±0.5%	78 ±0.5%	58 ±0.6%	64 ±0.5%	60 ±0.5%	32836 ±4%	4.32 ±0.6%	2.2 ±4%	45536 ±2%	3.1 ±2%
	2244 ±1%	646 ±2%	115 ±0.6%	70 ±0.5%	78 ±0.5%	58 ±0.6%	67 ±0.5%	61 ±0.5%	26055 ±5%	5.17 ±0.6%	1.5 ±5%	51048 ±2%	2.9 ±2%
	2243 ±1%	658 ±2%	75 ±0.7%	70 ±0.5%	75 ±0.5%	56 ±0.6%	60 ±0.6%	58 ±0.6%	35999 ±4%	3.62 ±0.5%	2.9 ±4%	36187 ±3%	2.9 ±3%
	2290 ±1%	698 ±2%	95 ±0.6%	71 ±0.5%	75 ±0.5%	56 ±0.6%	63 ±0.6%	59 ±0.5%	29585 ±4%	4.32 ±0.6%	2 ±4%	44519 ±3%	3 ±3%
	2211 ±1%	646 ±2%	115 ±0.6%	70 ±0.5%	75 ±0.5%	56 ±0.6%	66 ±0.6%	60 ±0.5%	21231 ±6%	5.19 ±0.7%	1.2 ±6%	48250 ±2%	2.7 ±2%

Table 9: IDEC Hybrid Heat Pump High Cooling (Stage 2)

COOLING													
Mode	Airflow (CFM)		Outdoor Air Temperature (F)		Indoor Air Temperature (F)		Supply Air Temperature (F)		Sensible Room Capacity (Btu/hr)	Total Power (kW)	Sensible Room COP	Sensible System Capacity (Btu/hr)	Sensible System COP
	Total	Outdoor	Drybulb	Dewpoint	Drybulb	Dewpoint	Drybulb	Dewpoint					
Hybrid Heat Pump High (Stage 2)													
IDEC High	3551 ±1%	1976 ±2%	77 ±0.7%	49 ±0.7%	81 ±0.4%	60 ±0.6%	60 ±0.4%	55 ±0.5%	82761 ±2%	4.55 ±0.4%	5.3 ±2%	73010 ±2%	4.7 ±2%
	3503 ±1%	1935 ±2%	95 ±0.6%	49 ±0.7%	80 ±0.5%	62 ±0.6%	64 ±0.4%	57 ±0.4%	60864 ±3%	5.22 ±0.5%	3.4 ±3%	92942 ±2%	5.2 ±2%
	3599 ±1%	2017 ±2%	114 ±0.6%	58 ±0.6%	80 ±0.5%	62 ±0.6%	68 ±0.4%	59 ±0.4%	46280 ±4%	6.01 ±0.6%	2.3 ±4%	121559 ±2%	5.9 ±2%
	3566 ±1%	1991 ±2%	75 ±0.7%	31 ±1.1%	81 ±0.4%	60 ±0.6%	55 ±0.5%	49 ±0.6%	101485 ±2%	4.51 ±0.4%	6.6 ±2%	88133 ±2%	5.7 ±2%
	3656 ±1%	2088 ±2%	95 ±0.6%	39 ±0.9%	80 ±0.5%	62 ±0.6%	62 ±0.4%	54 ±0.5%	73083 ±3%	5.22 ±0.5%	4.1 ±3%	108426 ±2%	6.1 ±2%
	3668 ±1%	2086 ±2%	115 ±0.6%	46 ±0.8%	80 ±0.5%	62 ±0.6%	67 ±0.4%	58 ±0.4%	49629 ±4%	6.04 ±0.6%	2.4 ±4%	129203 ±2%	6.3 ±2%
	3542 ±1%	1976 ±2%	77 ±0.7%	49 ±0.7%	78 ±0.5%	58 ±0.6%	59 ±0.5%	54 ±0.5%	74009 ±3%	4.51 ±0.4%	4.8 ±3%	70890 ±3%	4.6 ±2%
	3506 ±1%	1935 ±2%	95 ±0.6%	49 ±0.7%	78 ±0.5%	58 ±0.6%	63 ±0.4%	55 ±0.5%	58339 ±3%	5.14 ±0.5%	3.3 ±3%	94332 ±2%	5.4 ±2%
	3615 ±1%	2017 ±2%	114 ±0.6%	58 ±0.6%	78 ±0.5%	58 ±0.6%	67 ±0.4%	58 ±0.5%	43134 ±4%	5.98 ±0.6%	2.1 ±4%	122656 ±2%	6 ±2%
	3557 ±1%	1991 ±2%	75 ±0.7%	31 ±1.1%	78 ±0.5%	58 ±0.6%	54 ±0.5%	48 ±0.6%	92529 ±2%	4.46 ±0.4%	6.1 ±2%	85997 ±2%	5.6 ±2%
	3659 ±1%	2088 ±2%	95 ±0.6%	39 ±0.9%	78 ±0.5%	58 ±0.6%	60 ±0.5%	52 ±0.5%	70152 ±3%	5.14 ±0.5%	4 ±3%	109764 ±2%	6.3 ±2%
	3684 ±1%	2086 ±2%	115 ±0.6%	46 ±0.8%	78 ±0.5%	58 ±0.6%	66 ±0.4%	57 ±0.5%	46293 ±4%	6.01 ±0.6%	2.3 ±4%	130266 ±2%	6.4 ±2%
	3561 ±1%	1976 ±2%	77 ±0.7%	49 ±0.7%	75 ±0.5%	56 ±0.6%	58 ±0.5%	53 ±0.5%	66530 ±3%	4.49 ±0.4%	4.3 ±3%	70130 ±3%	4.6 ±2%
	3527 ±1%	1935 ±2%	95 ±0.6%	49 ±0.7%	75 ±0.5%	56 ±0.6%	62 ±0.5%	55 ±0.5%	50869 ±4%	5.14 ±0.5%	2.9 ±4%	93249 ±2%	5.3 ±2%
	3582 ±1%	2017 ±2%	114 ±0.6%	58 ±0.6%	75 ±0.5%	56 ±0.6%	66 ±0.5%	57 ±0.5%	33756 ±5%	6 ±0.6%	1.6 ±5%	119779 ±2%	5.8 ±2%
	3576 ±1%	1991 ±2%	75 ±0.7%	31 ±1.1%	75 ±0.5%	56 ±0.6%	53 ±0.6%	47 ±0.6%	84851 ±2%	4.44 ±0.4%	5.6 ±2%	85227 ±2%	5.6 ±2%
	3680 ±1%	2088 ±2%	95 ±0.6%	39 ±0.9%	75 ±0.5%	56 ±0.6%	59 ±0.5%	51 ±0.6%	62083 ±3%	5.14 ±0.5%	3.5 ±3%	108659 ±2%	6.2 ±2%
	3651 ±1%	2086 ±2%	115 ±0.6%	46 ±0.8%	75 ±0.5%	56 ±0.6%	66 ±0.5%	56 ±0.5%	36661 ±5%	6.03 ±0.6%	1.8 ±5%	127380 ±2%	6.2 ±2%
IDEC Medium	2876 ±1%	1301 ±2%	76 ±0.7%	50 ±0.7%	81 ±0.4%	60 ±0.6%	59 ±0.4%	55 ±0.5%	70280 ±2%	3.96 ±0.5%	5.2 ±2%	62792 ±2%	4.6 ±2%
	2811 ±1%	1243 ±2%	97 ±0.6%	50 ±0.7%	80 ±0.5%	62 ±0.6%	62 ±0.4%	57 ±0.4%	54314 ±3%	4.71 ±0.6%	3.4 ±3%	77409 ±2%	4.8 ±2%
	2844 ±1%	1262 ±2%	115 ±0.6%	50 ±0.7%	80 ±0.5%	62 ±0.6%	65 ±0.4%	59 ±0.4%	44332 ±3%	5.46 ±0.6%	2.4 ±3%	92574 ±2%	5 ±2%
	2857 ±1%	1282 ±2%	75 ±0.7%	32 ±1.1%	81 ±0.4%	60 ±0.6%	54 ±0.5%	50 ±0.6%	83263 ±2%	3.93 ±0.5%	6.2 ±2%	74116 ±2%	5.5 ±2%
	2932 ±1%	1364 ±2%	95 ±0.6%	31 ±1.2%	80 ±0.5%	62 ±0.6%	58 ±0.4%	52 ±0.5%	69083 ±2%	4.64 ±0.6%	4.4 ±2%	92334 ±2%	5.8 ±2%
	2832 ±1%	1250 ±2%	115 ±0.6%	36 ±1%	80 ±0.5%	62 ±0.6%	63 ±0.4%	55 ±0.5%	52745 ±3%	5.45 ±0.6%	2.8 ±3%	101078 ±2%	5.4 ±2%
	2867 ±1%	1301 ±2%	76 ±0.7%	50 ±0.7%	78 ±0.5%	58 ±0.6%	58 ±0.5%	53 ±0.5%	63797 ±2%	3.92 ±0.4%	4.8 ±3%	60694 ±2%	4.5 ±2%
	2814 ±1%	1243 ±2%	97 ±0.6%	50 ±0.7%	78 ±0.5%	58 ±0.6%	61 ±0.5%	55 ±0.5%	53209 ±3%	4.63 ±0.5%	3.4 ±3%	78829 ±2%	5 ±2%
	2860 ±1%	1262 ±2%	115 ±0.6%	50 ±0.7%	78 ±0.5%	58 ±0.6%	64 ±0.5%	57 ±0.5%	42834 ±3%	5.43 ±0.6%	2.3 ±4%	93748 ±2%	5.1 ±2%
	2848 ±1%	1282 ±2%	75 ±0.7%	32 ±1.1%	78 ±0.5%	58 ±0.6%	54 ±0.5%	49 ±0.6%	76734 ±2%	3.88 ±0.4%	5.8 ±2%	72007 ±2%	5.4 ±2%
2935 ±1%	1364 ±2%	95 ±0.6%	31 ±1.2%	78 ±0.5%	58 ±0.6%	57 ±0.5%	50 ±0.6%	67641 ±2%	4.57 ±0.5%	4.3 ±2%	93724 ±2%	6 ±2%	

Table 9 (cont.): IDEC Hybrid Heat Pump High Cooling (Stage 2)

COOLING													
	Airflow (CFM)		Outdoor Air Temperature (F)		Indoor Air Temperature (F)		Supply Air Temperature (F)		Sensible Room Capacity (Btu/hr)	Total Power (kW)	Sensible Room COP	Sensible System Capacity (Btu/hr)	Sensible System COP
Mode	Total	Outdoor	Drybulb	Dewpoint	Drybulb	Dewpoint	Drybulb	Dewpoint					
Hybrid Heat Pump High (Stage 2)													
IDEC Medium	2848 ±1%	1250 ±2%	115 ±0.6%	36 ±1%	78 ±0.5%	58 ±0.6%	61 ±0.5%	54 ±0.5%	51203 ±3%	5.42 ±0.6%	2.8 ±3%	102225 ±2%	5.5 ±2%
	2886 ±1%	1301 ±2%	76 ±0.7%	50 ±0.7%	75 ±0.5%	56 ±0.6%	56 ±0.6%	52 ±0.6%	58616 ±3%	3.89 ±0.4%	4.4 ±3%	59957 ±2%	4.5 ±2%
	2835 ±1%	1243 ±2%	97 ±0.6%	50 ±0.7%	75 ±0.5%	56 ±0.6%	59 ±0.5%	54 ±0.5%	48008 ±3%	4.63 ±0.6%	3 ±3%	77754 ±2%	4.9 ±2%
	2827 ±1%	1262 ±2%	115 ±0.6%	50 ±0.7%	75 ±0.5%	56 ±0.6%	63 ±0.5%	56 ±0.5%	35891 ±4%	5.46 ±0.6%	1.9 ±4%	90903 ±2%	4.9 ±2%
	2867 ±1%	1282 ±2%	75 ±0.7%	32 ±1.1%	75 ±0.5%	56 ±0.6%	52 ±0.6%	47 ±0.7%	71513 ±2%	3.86 ±0.4%	5.4 ±2%	71262 ±2%	5.4 ±2%
	2956 ±1%	1364 ±2%	95 ±0.6%	31 ±1.2%	75 ±0.5%	56 ±0.6%	56 ±0.6%	49 ±0.6%	61941 ±3%	4.57 ±0.5%	4 ±3%	92644 ±2%	5.9 ±2%
	2815 ±1%	1250 ±2%	115 ±0.6%	36 ±1%	75 ±0.5%	56 ±0.6%	60 ±0.5%	53 ±0.6%	44226 ±3%	5.45 ±0.6%	2.4 ±3%	99371 ±2%	5.3 ±2%
IDEC Low	2094 ±1%	519 ±2%	76 ±0.7%	50 ±0.7%	81 ±0.4%	60 ±0.6%	59 ±0.5%	55 ±0.6%	50519 ±2%	3.7 ±0.5%	4 ±2%	47352 ±2%	3.8 ±2%
	2078 ±1%	510 ±2%	95 ±0.6%	52 ±0.7%	80 ±0.5%	62 ±0.6%	62 ±0.4%	57 ±0.5%	40561 ±3%	4.38 ±0.6%	2.7 ±3%	48968 ±2%	3.3 ±2%
	2219 ±1%	637 ±2%	115 ±0.6%	50 ±0.7%	80 ±0.5%	62 ±0.6%	64 ±0.4%	58 ±0.5%	37876 ±3%	5.22 ±0.6%	2.1 ±3%	62525 ±2%	3.5 ±2%
	2045 ±1%	470 ±2%	76 ±0.7%	30 ±1.2%	81 ±0.4%	60 ±0.6%	56 ±0.5%	52 ±0.6%	55598 ±2%	3.7 ±0.5%	4.4 ±2%	52712 ±2%	4.2 ±2%
	2019 ±1%	451 ±2%	95 ±0.6%	30 ±1.2%	80 ±0.5%	62 ±0.6%	59 ±0.4%	55 ±0.5%	44843 ±2%	4.4 ±0.6%	3 ±2%	52708 ±2%	3.5 ±2%
	2108 ±1%	526 ±2%	115 ±0.6%	32 ±1.1%	80 ±0.5%	62 ±0.6%	62 ±0.4%	56 ±0.5%	41474 ±3%	5.2 ±0.6%	2.3 ±3%	62118 ±2%	3.5 ±2%
	2085 ±1%	519 ±2%	76 ±0.7%	50 ±0.7%	78 ±0.5%	58 ±0.6%	57 ±0.6%	53 ±0.6%	46696 ±2%	3.65 ±0.5%	3.7 ±3%	45283 ±2%	3.6 ±2%
	2081 ±1%	510 ±2%	95 ±0.6%	52 ±0.7%	78 ±0.5%	58 ±0.6%	60 ±0.6%	55 ±0.6%	41050 ±3%	4.3 ±0.6%	2.8 ±3%	50497 ±2%	3.4 ±2%
	2235 ±1%	637 ±2%	115 ±0.6%	50 ±0.7%	78 ±0.5%	58 ±0.6%	62 ±0.5%	56 ±0.6%	37775 ±3%	5.19 ±0.6%	2.1 ±3%	63782 ±2%	3.6 ±2%
	2036 ±1%	470 ±2%	76 ±0.7%	30 ±1.2%	78 ±0.5%	58 ±0.6%	55 ±0.6%	51 ±0.7%	51887 ±2%	3.66 ±0.5%	4.2 ±2%	50633 ±2%	4.1 ±2%
	2022 ±1%	451 ±2%	95 ±0.6%	30 ±1.2%	78 ±0.5%	58 ±0.6%	57 ±0.6%	52 ±0.7%	45408 ±3%	4.32 ±0.6%	3.1 ±3%	54217 ±2%	3.7 ±2%
	2124 ±1%	526 ±2%	115 ±0.6%	32 ±1.1%	78 ±0.5%	58 ±0.6%	60 ±0.6%	53 ±0.6%	41585 ±3%	5.17 ±0.6%	2.4 ±3%	63376 ±2%	3.6 ±2%
	2104 ±1%	519 ±2%	76 ±0.7%	50 ±0.7%	75 ±0.5%	56 ±0.6%	56 ±0.7%	52 ±0.7%	44207 ±3%	3.63 ±0.5%	3.6 ±3%	44570 ±3%	3.6 ±3%
	2102 ±1%	510 ±2%	95 ±0.6%	52 ±0.7%	75 ±0.5%	56 ±0.6%	58 ±0.7%	53 ±0.6%	38333 ±3%	4.3 ±0.6%	2.6 ±3%	49477 ±2%	3.4 ±2%
	2202 ±1%	637 ±2%	115 ±0.6%	50 ±0.7%	75 ±0.5%	56 ±0.6%	61 ±0.6%	55 ±0.6%	32878 ±4%	5.21 ±0.7%	1.8 ±4%	60970 ±2%	3.4 ±2%
2055 ±1%	470 ±2%	76 ±0.7%	30 ±1.2%	75 ±0.5%	56 ±0.6%	53 ±0.8%	49 ±0.8%	49513 ±3%	3.63 ±0.5%	4 ±3%	49912 ±2%	4 ±2%	
2043 ±1%	451 ±2%	95 ±0.6%	30 ±1.2%	75 ±0.5%	56 ±0.6%	56 ±0.7%	50 ±0.8%	42839 ±3%	4.32 ±0.6%	2.9 ±3%	53188 ±2%	3.6 ±2%	
2091 ±1%	526 ±2%	115 ±0.6%	32 ±1.1%	75 ±0.5%	56 ±0.6%	59 ±0.7%	52 ±0.7%	37014 ±3%	5.2 ±0.7%	2.1 ±3%	60565 ±2%	3.4 ±2%	

Table 10: IEC Hybrid Heat Pump Cooling Low (Stage 1)

COOLING														
	Airflow (CFM)		Outdoor Air Temperature (F)		Indoor Air Temperature (F)		Supply Air Temperature (F)		Sensible Room Capacity (Btu/hr)	Total Power (kW)	Sensible Room COP	Sensible System Capacity (Btu/hr)	Sensible System COP	
Mode	Total	Outdoor	Drybulb	Dewpoint	Drybulb	Dewpoint	Drybulb	Dewpoint						
Hybrid Heat Pump Low (Stage 1)														
IEC High	3542 ±1.1%	2296 ±1.6%	75 ±0.7%	70 ±0.5%	80 ±0.4%	63 ±0.6%	68 ±0.4%	65 ±0.4%	44709 ±4%	3.24 ±2.2%	4 ±4%	32677 ±5%	3 ±5%	
	3355 ±1.1%	2099 ±1.6%	95 ±0.6%	70 ±0.5%	80 ±0.5%	62 ±0.6%	72 ±0.3%	65 ±0.4%	26830 ±6%	3.84 ±1.9%	2.1 ±6%	60259 ±3%	4.6 ±3%	
	3132 ±1%	1867 ±1.6%	116 ±0.6%	70 ±0.5%	80 ±0.5%	62 ±0.6%	78 ±0.3%	66 ±0.4%	5616 ±26%	4.56 ±1.6%	0.4 ±26%	75381 ±2%	4.8 ±3%	
	3543 ±1.1%	2296 ±1.6%	75 ±0.7%	70 ±0.5%	78 ±0.5%	58 ±0.6%	67 ±0.4%	65 ±0.5%	40196 ±4%	3.23 ±2.2%	3.7 ±5%	33161 ±5%	3 ±5%	
	3348 ±1.1%	2099 ±1.6%	95 ±0.6%	70 ±0.5%	78 ±0.5%	58 ±0.6%	72 ±0.4%	65 ±0.4%	22301 ±7%	3.83 ±1.9%	1.7 ±7%	60366 ±3%	4.6 ±3%	
	3127 ±1%	1867 ±1.6%	116 ±0.6%	70 ±0.5%	78 ±0.5%	58 ±0.6%	77 ±0.4%	66 ±0.4%	2170 ±88%	4.55 ±1.6%	0.1 ±88%	75661 ±2%	4.9 ±3%	
	3575 ±1.1%	2296 ±1.6%	75 ±0.7%	70 ±0.5%	75 ±0.5%	56 ±0.6%	67 ±0.4%	64 ±0.5%	31998 ±5%	3.22 ±2.2%	2.9 ±6%	32331 ±5%	2.9 ±5%	
	3340 ±1.1%	2099 ±1.6%	95 ±0.6%	70 ±0.5%	75 ±0.5%	56 ±0.6%	71 ±0.4%	64 ±0.5%	14206 ±12%	3.84 ±1.9%	1.1 ±12%	58770 ±3%	4.5 ±3%	
IEC Medium	3135 ±1%	1867 ±1.6%	116 ±0.6%	70 ±0.5%	75 ±0.5%	56 ±0.6%	76 ±0.4%	65 ±0.5%	-4165 ±34%	4.55 ±1.6%	-0.3 ±34%	74745 ±2%	4.8 ±3%	
	2488 ±0.9%	1242 ±1.6%	76 ±0.7%	70 ±0.5%	80 ±0.4%	63 ±0.6%	66 ±0.3%	64 ±0.4%	36605 ±3%	2.7 ±2.7%	4 ±4%	30854 ±3%	3.3 ±4%	
	2513 ±0.9%	1257 ±1.6%	95 ±0.6%	70 ±0.5%	80 ±0.5%	62 ±0.6%	69 ±0.3%	64 ±0.4%	28168 ±4%	3.29 ±2.2%	2.5 ±5%	48497 ±2%	4.3 ±3%	
	2505 ±0.9%	1240 ±1.6%	115 ±0.6%	70 ±0.5%	80 ±0.5%	62 ±0.6%	75 ±0.3%	65 ±0.4%	13790 ±8%	3.98 ±1.9%	1 ±8%	59433 ±2%	4.4 ±3%	
	2489 ±0.9%	1242 ±1.6%	76 ±0.7%	70 ±0.5%	78 ±0.5%	58 ±0.6%	65 ±0.4%	63 ±0.4%	34401 ±3%	2.69 ±2.7%	3.7 ±4%	31350 ±3%	3.4 ±4%	
	2506 ±0.9%	1257 ±1.6%	95 ±0.6%	70 ±0.5%	78 ±0.5%	58 ±0.6%	68 ±0.4%	63 ±0.4%	25527 ±5%	3.28 ±2.2%	2.3 ±5%	48639 ±2%	4.3 ±3%	
	2500 ±0.9%	1240 ±1.6%	115 ±0.6%	70 ±0.5%	78 ±0.5%	58 ±0.6%	73 ±0.4%	64 ±0.4%	11622 ±10%	3.97 ±1.9%	0.9 ±11%	59754 ±2%	4.4 ±3%	
	2521 ±0.9%	1242 ±1.6%	76 ±0.7%	70 ±0.5%	75 ±0.5%	56 ±0.6%	64 ±0.4%	62 ±0.5%	29591 ±4%	2.69 ±2.7%	3.2 ±5%	30525 ±4%	3.3 ±4%	
IEC Low	2498 ±0.9%	1257 ±1.6%	95 ±0.6%	70 ±0.5%	75 ±0.5%	56 ±0.6%	67 ±0.4%	62 ±0.5%	20045 ±6%	3.29 ±2.2%	1.8 ±7%	47061 ±3%	4.2 ±3%	
	2508 ±0.9%	1240 ±1.6%	115 ±0.6%	70 ±0.5%	75 ±0.5%	56 ±0.6%	72 ±0.4%	63 ±0.5%	7111 ±18%	3.97 ±1.9%	0.5 ±18%	58862 ±2%	4.3 ±3%	
	1904 ±0.9%	658 ±1.6%	75 ±0.7%	70 ±0.5%	80 ±0.4%	63 ±0.6%	64 ±0.3%	61 ±0.4%	32203 ±3%	2.37 ±3%	4 ±4%	28815 ±3%	3.6 ±4%	
	1954 ±0.9%	698 ±1.6%	95 ±0.6%	71 ±0.5%	80 ±0.5%	62 ±0.6%	67 ±0.3%	63 ±0.4%	26937 ±3%	2.97 ±2.5%	2.7 ±4%	38208 ±2%	3.8 ±3%	
	1911 ±0.9%	646 ±1.6%	115 ±0.6%	70 ±0.5%	80 ±0.5%	62 ±0.6%	70 ±0.3%	64 ±0.4%	19119 ±4%	3.65 ±2%	1.5 ±5%	42884 ±2%	3.4 ±3%	
	1905 ±0.9%	658 ±1.6%	75 ±0.7%	70 ±0.5%	78 ±0.5%	58 ±0.6%	63 ±0.4%	60 ±0.4%	31269 ±3%	2.36 ±3%	3.9 ±4%	29316 ±3%	3.6 ±4%	
	1947 ±0.9%	698 ±1.6%	95 ±0.6%	71 ±0.5%	78 ±0.5%	58 ±0.6%	66 ±0.4%	61 ±0.4%	25561 ±4%	2.96 ±2.5%	2.5 ±4%	38379 ±2%	3.8 ±3%	
	1906 ±0.9%	646 ±1.6%	115 ±0.6%	70 ±0.5%	78 ±0.5%	58 ±0.6%	69 ±0.4%	62 ±0.4%	18182 ±5%	3.65 ±2%	1.5 ±6%	43252 ±2%	3.5 ±3%	
	1937 ±0.9%	658 ±1.6%	75 ±0.7%	70 ±0.5%	75 ±0.5%	56 ±0.6%	61 ±0.5%	59 ±0.5%	28333 ±3%	2.36 ±3%	3.5 ±5%	28495 ±3%	3.5 ±4%	
	1939 ±0.9%	698 ±1.6%	95 ±0.6%	71 ±0.5%	75 ±0.5%	56 ±0.6%	64 ±0.5%	60 ±0.5%	21828 ±5%	2.97 ±2.5%	2.2 ±5%	36815 ±2%	3.6 ±3%	
	1914 ±0.9%	646 ±1.6%	115 ±0.6%	70 ±0.5%	75 ±0.5%	56 ±0.6%	67 ±0.5%	61 ±0.5%	15419 ±6%	3.64 ±2%	1.2 ±7%	42385 ±2%	3.4 ±3%	

Table 11: IDEC Hybrid Heat Pump Low Cooling (Stage 1)

COOLING														
Mode	Airflow (CFM)		Outdoor Air Temperature (F)		Indoor Air Temperature (F)		Supply Air Temperature (F)		Sensible Room Capacity (Btu/hr)	Total Power (kW)	Sensible Room COP	Sensible System Capacity (Btu/hr)	Sensible System COP	
	Total	Outdoor	Drybulb	Dewpoint	Drybulb	Dewpoint	Drybulb	Dewpoint						
Hybrid Heat Pump Low (Stage 1)														
IDEC High	3222 ±1.1%	1976 ±1.6%	77 ±0.7%	49 ±0.7%	80 ±0.4%	63 ±0.6%	60 ±0.4%	55 ±0.4%	70551 ±2%	3.28 ±2.2%	6.3 ±3%	63064 ±3%	5.6 ±3%	
	3191 ±1%	1935 ±1.6%	95 ±0.6%	49 ±0.7%	80 ±0.5%	62 ±0.6%	64 ±0.4%	56 ±0.4%	55328 ±3%	3.84 ±1.9%	4.2 ±4%	87234 ±2%	6.7 ±3%	
	3282 ±1.1%	2017 ±1.6%	114 ±0.6%	58 ±0.6%	80 ±0.5%	62 ±0.6%	69 ±0.4%	59 ±0.4%	39247 ±4%	4.51 ±1.7%	2.5 ±4%	114821 ±2%	7.5 ±2%	
	3237 ±1.1%	1991 ±1.6%	75 ±0.7%	31 ±1.1%	80 ±0.4%	63 ±0.6%	55 ±0.4%	48 ±0.5%	89224 ±2%	3.24 ±2.2%	8.1 ±3%	78191 ±2%	7.1 ±3%	
	3344 ±1.1%	2088 ±1.6%	95 ±0.6%	39 ±0.9%	80 ±0.5%	62 ±0.6%	61 ±0.4%	53 ±0.5%	67555 ±3%	3.84 ±1.9%	5.2 ±3%	102710 ±2%	7.8 ±3%	
	3351 ±1.1%	2086 ±1.6%	115 ±0.6%	46 ±0.8%	80 ±0.5%	62 ±0.6%	68 ±0.4%	58 ±0.4%	42574 ±4%	4.54 ±1.6%	2.8 ±4%	122455 ±2%	7.9 ±2%	
	3223 ±1.1%	1976 ±1.6%	77 ±0.7%	49 ±0.7%	78 ±0.5%	58 ±0.6%	59 ±0.4%	54 ±0.5%	66507 ±3%	3.27 ±2.2%	6 ±3%	63463 ±3%	5.7 ±3%	
	3184 ±1%	1935 ±1.6%	95 ±0.6%	49 ±0.7%	78 ±0.5%	58 ±0.6%	63 ±0.4%	56 ±0.5%	50937 ±3%	3.83 ±1.9%	3.9 ±4%	87268 ±2%	6.7 ±3%	
	3277 ±1.1%	2017 ±1.6%	114 ±0.6%	58 ±0.6%	78 ±0.5%	58 ±0.6%	68 ±0.4%	58 ±0.5%	35216 ±5%	4.51 ±1.7%	2.3 ±5%	114978 ±2%	7.5 ±2%	
	3238 ±1.1%	1991 ±1.6%	75 ±0.7%	31 ±1.1%	78 ±0.5%	58 ±0.6%	54 ±0.5%	47 ±0.5%	84984 ±2%	3.23 ±2.2%	7.7 ±3%	78528 ±2%	7.1 ±3%	
	3337 ±1.1%	2088 ±1.6%	95 ±0.6%	39 ±0.9%	78 ±0.5%	58 ±0.6%	61 ±0.4%	52 ±0.5%	62724 ±3%	3.83 ±1.9%	4.8 ±3%	102703 ±2%	7.8 ±3%	
	3346 ±1.1%	2086 ±1.6%	115 ±0.6%	46 ±0.8%	78 ±0.5%	58 ±0.6%	67 ±0.4%	57 ±0.5%	38371 ±4%	4.53 ±1.6%	2.5 ±5%	122595 ±2%	7.9 ±2%	
	3255 ±1%	1976 ±1.6%	77 ±0.7%	49 ±0.7%	75 ±0.5%	56 ±0.6%	58 ±0.5%	53 ±0.5%	59076 ±3%	3.27 ±2.2%	5.3 ±4%	62593 ±3%	5.6 ±3%	
	3176 ±1.1%	1935 ±1.6%	95 ±0.6%	49 ±0.7%	75 ±0.5%	56 ±0.6%	62 ±0.4%	55 ±0.5%	43104 ±4%	3.84 ±1.9%	3.3 ±4%	85637 ±2%	6.5 ±3%	
	3285 ±1.1%	2017 ±1.6%	114 ±0.6%	58 ±0.6%	75 ±0.5%	56 ±0.6%	67 ±0.4%	58 ±0.5%	28153 ±6%	4.51 ±1.7%	1.8 ±6%	114002 ±2%	7.4 ±2%	
	3270 ±1%	1991 ±1.6%	75 ±0.7%	31 ±1.1%	75 ±0.5%	56 ±0.6%	54 ±0.5%	46 ±0.6%	77345 ±2%	3.22 ±2.2%	7 ±3%	77636 ±2%	7.1 ±3%	
	3329 ±1.1%	2088 ±1.6%	95 ±0.6%	39 ±0.9%	75 ±0.5%	56 ±0.6%	60 ±0.5%	51 ±0.5%	54310 ±3%	3.84 ±1.9%	4.1 ±4%	101053 ±2%	7.7 ±3%	
	3354 ±1.1%	2086 ±1.6%	115 ±0.6%	46 ±0.8%	75 ±0.5%	56 ±0.6%	66 ±0.4%	56 ±0.5%	31070 ±5%	4.53 ±1.6%	2 ±6%	121608 ±2%	7.9 ±2%	
IDEC Medium	2547 ±1%	1301 ±1.6%	76 ±0.7%	50 ±0.7%	80 ±0.4%	63 ±0.6%	59 ±0.4%	55 ±0.4%	58752 ±2%	2.71 ±2.7%	6.4 ±3%	52758 ±2%	5.7 ±3%	
	2499 ±0.9%	1243 ±1.6%	97 ±0.6%	50 ±0.7%	80 ±0.5%	62 ±0.6%	62 ±0.4%	57 ±0.4%	48661 ±3%	3.34 ±2.2%	4.3 ±3%	71646 ±2%	6.3 ±3%	
	2527 ±0.9%	1262 ±1.6%	115 ±0.6%	50 ±0.7%	80 ±0.5%	62 ±0.6%	66 ±0.3%	59 ±0.4%	37329 ±3%	3.98 ±1.9%	2.7 ±4%	85760 ±2%	6.3 ±2%	
	2528 ±0.9%	1282 ±1.6%	75 ±0.7%	32 ±1.1%	80 ±0.4%	63 ±0.6%	54 ±0.4%	50 ±0.4%	71732 ±2%	2.68 ±2.7%	7.9 ±3%	64087 ±2%	7 ±3%	
	2620 ±1%	1364 ±1.6%	95 ±0.6%	31 ±1.2%	80 ±0.5%	62 ±0.6%	58 ±0.4%	51 ±0.4%	63441 ±2%	3.28 ±2.2%	5.7 ±3%	86569 ±2%	7.7 ±3%	
	2515 ±0.9%	1250 ±1.6%	115 ±0.6%	36 ±1%	80 ±0.5%	62 ±0.6%	63 ±0.4%	55 ±0.4%	45745 ±3%	3.97 ±1.9%	3.4 ±3%	94268 ±2%	7 ±2%	
	2548 ±1%	1301 ±1.6%	76 ±0.7%	50 ±0.7%	78 ±0.5%	58 ±0.6%	58 ±0.4%	54 ±0.5%	56239 ±2%	2.69 ±2.7%	6.1 ±4%	53185 ±2%	5.8 ±3%	
	2492 ±0.9%	1243 ±1.6%	97 ±0.6%	50 ±0.7%	78 ±0.5%	58 ±0.6%	61 ±0.4%	55 ±0.5%	45898 ±3%	3.33 ±2.2%	4 ±4%	71738 ±2%	6.3 ±3%	
	2522 ±0.9%	1262 ±1.6%	115 ±0.6%	50 ±0.7%	78 ±0.5%	58 ±0.6%	65 ±0.4%	58 ±0.5%	34937 ±4%	3.97 ±1.9%	2.6 ±4%	86006 ±2%	6.3 ±2%	
	2529 ±0.9%	1282 ±1.6%	75 ±0.7%	32 ±1.1%	78 ±0.5%	58 ±0.6%	53 ±0.5%	48 ±0.5%	69147 ±2%	2.66 ±2.7%	7.6 ±3%	64468 ±2%	7.1 ±3%	
	2613 ±1%	1364 ±1.6%	95 ±0.6%	31 ±1.2%	78 ±0.5%	58 ±0.6%	57 ±0.5%	50 ±0.5%	60278 ±2%	3.28 ±2.2%	5.4 ±3%	86606 ±2%	7.7 ±3%	

Table 11 (cont.): IDEC Hybrid Heat Pump Low Cooling (Stage 1)

COOLING													
Mode	Airflow (CFM)		Outdoor Air Temperature (F)		Indoor Air Temperature (F)		Supply Air Temperature (F)		Sensible Room Capacity (Btu/hr)	Total Power (kW)	Sensible Room COP	Sensible System Capacity (Btu/hr)	Sensible System COP
	Total	Outdoor	Drybulb	Dewpoint	Drybulb	Dewpoint	Drybulb	Dewpoint					
Hybrid Heat Pump Low (Stage 1)													
IDEC Medium	2510 ±0.9%	1250 ±1.6%	115 ±0.6%	36 ±1%	78 ±0.5%	58 ±0.6%	62 ±0.4%	54 ±0.5%	43310 ±3%	3.97 ±1.9%	3.2 ±4%	94489 ±2%	7 ±2%
	2580 ±0.9%	1301 ±1.6%	76 ±0.7%	50 ±0.7%	75 ±0.5%	56 ±0.6%	57 ±0.5%	53 ±0.5%	51044 ±3%	2.69 ±2.7%	5.6 ±4%	52331 ±2%	5.7 ±3%
	2484 ±0.9%	1243 ±1.6%	97 ±0.6%	50 ±0.7%	75 ±0.5%	56 ±0.6%	60 ±0.5%	54 ±0.5%	40289 ±3%	3.34 ±2.2%	3.5 ±4%	70136 ±2%	6.2 ±3%
	2530 ±0.9%	1262 ±1.6%	115 ±0.6%	50 ±0.7%	75 ±0.5%	56 ±0.6%	64 ±0.4%	57 ±0.5%	30170 ±4%	3.97 ±1.9%	2.2 ±5%	85076 ±2%	6.3 ±2%
	2561 ±0.9%	1282 ±1.6%	75 ±0.7%	32 ±1.1%	75 ±0.5%	56 ±0.6%	52 ±0.5%	47 ±0.6%	63904 ±2%	2.66 ±2.7%	7 ±4%	63597 ±2%	7 ±3%
	2605 ±1%	1364 ±1.6%	95 ±0.6%	31 ±1.2%	75 ±0.5%	56 ±0.6%	56 ±0.5%	49 ±0.6%	54163 ±3%	3.28 ±2.2%	4.8 ±3%	84978 ±2%	7.6 ±3%
	2518 ±0.9%	1250 ±1.6%	115 ±0.6%	36 ±1%	75 ±0.5%	56 ±0.6%	61 ±0.5%	53 ±0.6%	38506 ±3%	3.97 ±1.9%	2.8 ±4%	93545 ±2%	6.9 ±2%
IDEC Low	1765 ±0.8%	519 ±1.6%	76 ±0.7%	50 ±0.7%	80 ±0.4%	63 ±0.6%	59 ±0.3%	55 ±0.4%	39822 ±2%	2.38 ±3%	4.9 ±4%	37252 ±2%	4.6 ±3%
	1766 ±0.8%	510 ±1.6%	95 ±0.6%	52 ±0.7%	80 ±0.5%	62 ±0.6%	62 ±0.3%	57 ±0.4%	34820 ±2%	2.96 ±2.5%	3.5 ±4%	43182 ±2%	4.3 ±3%
	1902 ±0.9%	637 ±1.6%	115 ±0.6%	50 ±0.7%	80 ±0.5%	62 ±0.6%	65 ±0.3%	58 ±0.4%	30916 ±3%	3.67 ±2%	2.5 ±4%	55661 ±2%	4.4 ±2%
	1716 ±0.8%	470 ±1.6%	76 ±0.7%	30 ±1.2%	80 ±0.4%	63 ±0.6%	56 ±0.4%	52 ±0.4%	44956 ±2%	2.38 ±3%	5.5 ±4%	42626 ±2%	5.2 ±3%
	1707 ±0.8%	451 ±1.6%	95 ±0.6%	30 ±1.2%	80 ±0.5%	62 ±0.6%	59 ±0.4%	54 ±0.5%	39095 ±2%	2.97 ±2.5%	3.9 ±3%	46920 ±2%	4.6 ±3%
	1791 ±0.8%	526 ±1.6%	115 ±0.6%	32 ±1.1%	80 ±0.5%	62 ±0.6%	62 ±0.3%	56 ±0.4%	34532 ±2%	3.66 ±2%	2.8 ±3%	55257 ±2%	4.4 ±2%
	1766 ±0.8%	519 ±1.6%	76 ±0.7%	50 ±0.7%	78 ±0.5%	58 ±0.6%	58 ±0.4%	53 ±0.5%	39122 ±2%	2.37 ±3%	4.8 ±4%	37728 ±2%	4.7 ±4%
	1759 ±0.8%	510 ±1.6%	95 ±0.6%	52 ±0.7%	78 ±0.5%	58 ±0.6%	60 ±0.5%	55 ±0.5%	33799 ±3%	2.95 ±2.5%	3.4 ±4%	43337 ±2%	4.3 ±3%
	1897 ±0.9%	637 ±1.6%	115 ±0.6%	50 ±0.7%	78 ±0.5%	58 ±0.6%	63 ±0.4%	56 ±0.5%	29910 ±3%	3.66 ±2%	2.4 ±4%	55996 ±2%	4.5 ±3%
	1717 ±0.8%	470 ±1.6%	76 ±0.7%	30 ±1.2%	78 ±0.5%	58 ±0.6%	54 ±0.5%	50 ±0.6%	44321 ±2%	2.37 ±3%	5.5 ±4%	43086 ±2%	5.3 ±3%
	1700 ±0.8%	451 ±1.6%	95 ±0.6%	30 ±1.2%	78 ±0.5%	58 ±0.6%	57 ±0.5%	52 ±0.6%	38177 ±2%	2.97 ±2.5%	3.8 ±3%	47068 ±2%	4.7 ±3%
	1786 ±0.8%	526 ±1.6%	115 ±0.6%	32 ±1.1%	78 ±0.5%	58 ±0.6%	60 ±0.5%	54 ±0.6%	33732 ±3%	3.65 ±2%	2.7 ±3%	55590 ±2%	4.5 ±3%
	1798 ±0.8%	519 ±1.6%	76 ±0.7%	50 ±0.7%	75 ±0.5%	56 ±0.6%	56 ±0.5%	52 ±0.6%	36555 ±3%	2.37 ±3%	4.5 ±4%	36896 ±2%	4.6 ±4%
	1751 ±0.8%	510 ±1.6%	95 ±0.6%	52 ±0.7%	75 ±0.5%	56 ±0.6%	59 ±0.5%	54 ±0.6%	30580 ±3%	2.96 ±2.5%	3 ±4%	41766 ±2%	4.1 ±3%
	1905 ±0.9%	637 ±1.6%	115 ±0.6%	50 ±0.7%	75 ±0.5%	56 ±0.6%	62 ±0.5%	55 ±0.6%	27074 ±4%	3.66 ±2%	2.2 ±4%	55112 ±2%	4.4 ±3%
	1749 ±0.8%	470 ±1.6%	76 ±0.7%	30 ±1.2%	75 ±0.5%	56 ±0.6%	53 ±0.6%	49 ±0.7%	41867 ±2%	2.37 ±3%	5.2 ±4%	42246 ±2%	5.2 ±4%
	1692 ±0.8%	451 ±1.6%	95 ±0.6%	30 ±1.2%	75 ±0.5%	56 ±0.6%	56 ±0.6%	50 ±0.7%	35106 ±3%	2.97 ±2.5%	3.5 ±4%	45493 ±2%	4.5 ±3%
1794 ±0.8%	526 ±1.6%	115 ±0.6%	32 ±1.1%	75 ±0.5%	56 ±0.6%	59 ±0.5%	52 ±0.7%	31200 ±3%	3.65 ±2%	2.5 ±4%	54706 ±2%	4.4 ±3%	

The diagram below (Figure 13) shows the cooling test points overlayed on California climate zone data, with the low humidity region lower right quadrant marked by solid lines. The California climate zones have many more hours in conditions like the nine-test point grid's lower right quadrant. In this low humidity range, with mild cooling required range of conditions, the Hybrid RTU showed system sensible COPs ranging from 2.5 up to 51 for evaporative cooling IDEC mode (12.6 to 7.9 for hybrid modes). In this range of common outdoor conditions, the Hybrid RTU evaporative cooling modes are dramatically more efficient than typical RTUs. These lower right test points are the best proxy of how the unit is expected to perform in the California climate zones during most of the cooling season conditions, with outdoor air temperatures 70°F to 95°F or higher. Additionally, the conditions below a dew point of 57°F (0.010 humidity ratio) account for approximately 3/4 of all the total operation hours of the California cooling season averaged across all climate zones.

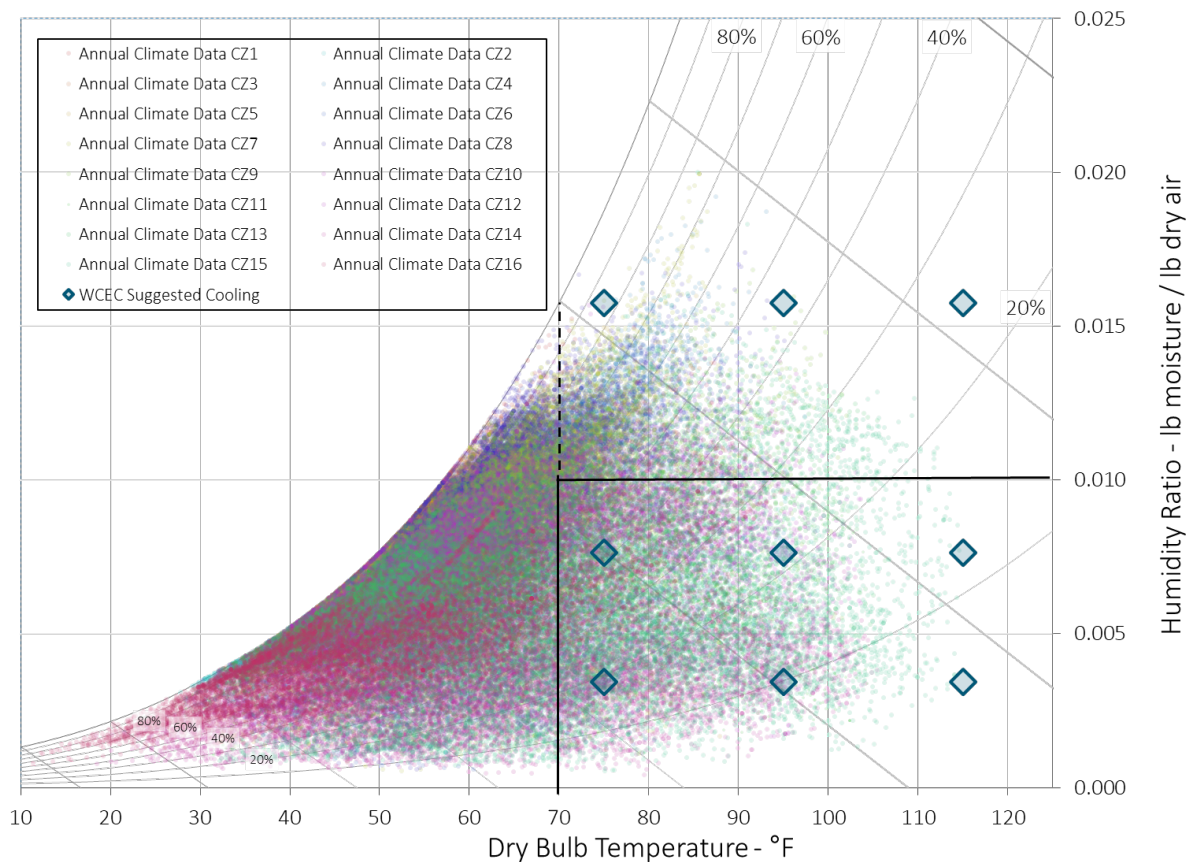


Figure 13: Cooling test points overlayed on California climate zone data, with low humidity region marked by solid lines.

Water Use

To reduce electric consumption, the Hybrid RTU uses water evaporation to indirectly and directly cool air. The Hybrid RTU uses water more quickly when outdoor conditions are drier and hotter. This water use is typically proportional to the difference between the outdoor dry bulb and wet bulb

temperatures at the inlet condition, known as “wet bulb depression” (WBD). In real-world installations, the water use is driven by both evaporation and by the need to bleed some water out of the system to remove dissolved solids minerals. Because of a failure in a water meter sensor during testing, and the intermittent operation of water refilling, the team was unable to reliably record bleed water consumption and the evaporative water consumption was not directly measured. The bleed water usage depends on the hardness of the water supplied to the unit which is the concentration of dissolved solids. The Hybrid RTU uses an electrical conductivity sensor to bleed water when minerals concentration reaches a setpoint number of cycles of concentration. The manufacturer estimates that the bleed water percentage when soft water is supplied to the unit and a high concentration setpoint is used can be as low as 7% and for hard water with a low concentration setpoint can be as high as 63%. In the San José field test of a nearly identical Hybrid RTU unit, the bleed water usage was approximately one-third of the evaporated water usage, well within the manufacturer expected range.

The evaporative water consumption was estimated from the measured sensible system cooling capacity by dividing by the enthalpy of vaporization of water at atmospheric pressure, see Appendix C for equations and details. Assuming that the secondary air remains at the supply air temperature and all cooling energy comes from the evaporation of water gives the upper bound of likely water consumption. This assumption gave results of water evaporation ranging from 2.1 to 2.5 gallons per ton hour of system sensible cooling capacity. In the hottest dry outdoor condition tested (115°F dry bulb and 46°F dew point), the high speed IDEC delivered 8.5 tons of sensible system capacity with 35.3 COP, 2.0 tons of sensible room capacity at 8.3 COP. The estimated evaporative water consumption is 2.2 gallons per ton-hr based on sensible system capacity or 9.44 gallons per ton-hr based on sensible room capacity, this equates to 19 gallons per hour. The team compared the Hybrid RTU lab test results with the San Jose field test baseline existing Lennox RTU rated 5 ton capacity, SEER 12 with economizer, installed in 2001 (Lennox LGA060HS2G, R-22), which has a COP of about 1.5 in these conditions. Comparing the sensible room COPs, the Hybrid RTU IDEC high speed reduces power consumption by 82% with upper bound of 4.9 gallons of water evaporated per kWh saved. Including bleed water usage of one third of evaporated water usage, the upper bound total water usage is expected to be approximately 6.5 gal/kWh saved for this hot and dry condition. This energy savings is sensitive to the comparison baseline COP, so this number cannot be generalized across different scenarios.

Heating mode

In heating mode, the unit performed as a conventional RTU heat pump during the heating season. Matching the ASHRAE and AHRI 210/240 standard heat pump heating rating tests, when the Hybrid RTU was operated in high heat pump-heating mode with no ventilation at outdoor conditions of 47°F dry bulb and 38.7°F dew point with indoor 70°F dry bulb, it provided room heating capacity of 3.0 ton with COP 3.2 in second stage and 2.2 ton with COP 3.1 in first stage. The stage two room heating capacity for outdoor conditions of 60°F dry bulb and 51.5°F dew point with indoor 70°F dry bulb was 3.5 tons with COP 3.7. For outdoor 36°F dry bulb and 28°F dew point with indoor 70°F dry bulb, stage two provided 2.2 tons with COP 2.6. For all the tested conditions, the unit was able to provide supply air temperatures ranging from 70 to 90°F. As with a conventional RTU heat pump during the heating season, adding cooler or cold ventilation air for the Hybrid RTU reduces the

heating capacity and reduces the room COP. To reduce energy consumption in heating operation for the Hybrid RTU or a conventional RTU, heating season ventilation rates should be set at the minimum that will accomplish the indoor air quality goals for the space. Full results and actual conditions of testing are detailed below (see table 12).

The Hybrid RTU uses reverse cycle defrost with on-demand defrost initiation control. The heating test with near freezing outdoor temperature and high humidity showed expected defrost initiation control, indicating that the manufacturer corrected an earlier bug in the control software. With the updated defrost control the on-demand strategy is expected to reduce energy consumption compared to the common timer only defrost initiation.

Overall, the Hybrid RTU has significantly higher capacity for cooling than for heating and is a better fit for climate zones and building types that require more cooling and less heating. Depending on the Hybrid RTU system sizing, auxiliary electric resistance strip heat could be required during low outdoor temperatures, particularly if there are high ventilation requirements. Similar to the situation for conventional RTU heat pumps, the Hybrid RTU will likely not be sized with sufficient heating capacity for aggressive thermostat setbacks.

Table 12: Heat Pump Heating Results Table

HEATING											
Mode	Airflow (CFM)		Outdoor Air Temperature (F)		Indoor Air Temperature (F)		Supply Air Temperature (F)		Room Capacity (Btu/hr)	Total Power (kW)	Room COP
	Total	Outdoor	Drybulb	Dewpoint	Drybulb	Dewpoint	Drybulb	Dewpoint			
Heat Pump											
Heat Pump High (Stage 2)	1488 ±1%	0	60 ±0.8%	52 ±0.7%	75 ±0.5%	52 ±0.7%	101 ±0.4%	51 ±0.7%	41942 ±2%	3.59 ±0.7%	3.4 ±3%
	1492 ±1%	0	47 ±0.9%	38 ±0.9%	75 ±0.5%	49 ±0.7%	97 ±0.5%	48 ±0.8%	35241 ±3%	3.41 ±0.7%	3 ±3%
	1476 ±1%	0	36 ±1.1%	27 ±1.3%	75 ±0.5%	42 ±0.9%	92 ±0.5%	41 ±0.9%	26459 ±4%	3.26 ±0.7%	2.4 ±4%
	1485 ±1%	0	60 ±0.8%	51 ±0.7%	70 ±0.5%	51 ±0.7%	96 ±0.5%	49 ±0.7%	42051 ±2%	3.37 ±0.7%	3.7 ±3%
	1497 ±1%	0	46 ±0.9%	38 ±0.9%	70 ±0.5%	59 ±0.6%	92 ±0.5%	56 ±0.6%	35363 ±3%	3.2 ±0.7%	3.2 ±3%
	1473 ±1%	0	36 ±1.1%	28 ±1.3%	70 ±0.5%	48 ±0.8%	86 ±0.5%	46 ±0.8%	26571 ±4%	3.02 ±0.7%	2.6 ±4%
	1486 ±1%	0	60 ±0.8%	52 ±0.7%	64 ±0.6%	50 ±0.7%	92 ±0.5%	49 ±0.7%	44534 ±2%	3.17 ±0.7%	4.1 ±2%
	1487 ±1%	0	47 ±0.9%	39 ±0.9%	65 ±0.5%	47 ±0.8%	88 ±0.5%	45 ±0.8%	36340 ±3%	3.05 ±0.7%	3.5 ±3%
	1475 ±1%	0	37 ±1.1%	29 ±1.3%	64 ±0.6%	46 ±0.8%	81 ±0.6%	44 ±0.8%	26250 ±4%	2.82 ±0.7%	2.7 ±4%
Heat Pump Low (Stage 1)	1080 ±1%	0	60 ±0.8%	52 ±0.7%	75 ±0.5%	55 ±0.7%	102 ±0.4%	54 ±0.7%	31558 ±2%	2.65 ±0.7%	3.5 ±2%
	1066 ±1%	0	47 ±0.9%	39 ±0.9%	75 ±0.5%	48 ±0.7%	97 ±0.5%	47 ±0.8%	25209 ±3%	2.6 ±0.7%	2.8 ±3%
	1061 ±1%	0	35 ±1.1%	28 ±1.3%	75 ±0.5%	40 ±0.9%	93 ±0.5%	39 ±0.9%	19803 ±4%	2.53 ±0.7%	2.3 ±4%
	1064 ±1%	0	60 ±0.8%	52 ±0.7%	70 ±0.5%	50 ±0.7%	98 ±0.5%	47 ±0.8%	31997 ±2%	2.49 ±0.7%	3.8 ±2%
	1073 ±1%	0	47 ±0.9%	38 ±0.9%	70 ±0.5%	45 ±0.8%	93 ±0.5%	42 ±0.9%	26024 ±3%	2.43 ±0.7%	3.1 ±3%
	1057 ±1%	0	36 ±1.1%	30 ±1.2%	71 ±0.5%	40 ±0.9%	89 ±0.5%	38 ±0.9%	20517 ±3%	2.38 ±0.7%	2.5 ±3%
	1065 ±1%	0	60 ±0.8%	51 ±0.7%	65 ±0.6%	50 ±0.7%	92 ±0.5%	49 ±0.7%	32623 ±2%	2.31 ±0.7%	4.1 ±2%
	1069 ±1%	0	47 ±0.9%	39 ±0.9%	65 ±0.6%	43 ±0.8%	88 ±0.5%	42 ±0.9%	26712 ±3%	2.27 ±0.7%	3.4 ±3%
		1061 ±1%	0	36 ±1.1%	29 ±1.2%	65 ±0.6%	39 ±0.9%	83 ±0.5%	38 ±1%	21351 ±3%	2.2 ±0.7%

Vent and Standby Power Use

Power consumption was measured for ventilation and standby with tests held for a 10-minute duration steady state operation (see table 13). Standby power may be lower in production units

because this production ready prototype included internal energy monitoring that will not be included in commercially sold equipment.

Table 13: Standby and Ventilation Tests

Test Name	Flow Rate	System Power
Stand by	0 CFM	0.107 kW
Vent	519 CFM	0.193 kW

Performance Curves and Lookup Tables

For modeling, the lab test performance data are fit using multivariate regressions. These regressions use independent variables of outdoor air temperature and humidity, return air temperature and humidity, and normalized mass flow rate and outdoor air fractions. The multivariate regressions will be used to generate performance curves for dependent variables of supply-air temperature, supply air humidity, and power use for either separate heat pump and IDEC equipment models or for the combined Hybrid Unitary HVAC Equipment Object model. These performance curves or lookup tables are required as inputs for Energy Plus and CBECC-Com.

For each appropriate dependent variable, regressions were created starting with a full set of independent variables and using stepwise selection to reduce to a minimum set of the independent variables, selecting equation forms to achieve the best fit according to regression quality statistics including R-squared, leave one out cross validation (LOOCV), F-statistic, and standard error. These measures were used to remove independent variables with low predictive value as determined by P-values above 0.05 and changes to the LOOCV. Engineering judgement was exercised to ensure the predicted value behavior is physically reasonable. Regressions quality statistics, perturbations plots, and residuals plots were inspected to verify regression accuracy and avoid runaway behavior outside the measured data ranges, see Appendix B.

Evaporative Cooling

Temperatures in degrees Fahrenheit, power in kW, and supply air flow rate in dry air basis kg/s

IDEC cooling using both indirect and direct evaporative cooling

$$IDEC\ SADB = 13.1258 + 0.2293 * OADB + 0.4470 * OADP + 6.5619 * SAflow$$

Standard error (RMSE) 0.87555 (°F)

$$IDEC\ SADP = 11.7768 + 0.1278 * OADB + 0.6013 * OADP + 2.6477 * SAflow$$

Standard error (RMSE) 0.54780 (°F)

$$IEC \text{ Total Power} = 0.14357 + 0.53363 * SAflow^2$$

Standard error (RMSE) 0.031914 (kW)

IEC cooling using only indirect evaporative cooling

$$IEC \text{ SADB} = 13.454 + 0.3725 * OADB + 0.3174 * OADP + 8.6093 * SAflow$$

Standard error (RMSE) 2.01139 (°F)

$$IEC \text{ SADP} = OADP$$

$$IEC \text{ Total Power} = 0.0962 + 0.2885 * SAflow^2$$

Standard error (RMSE) 0.053274 (kW)

IEC supply air dewpoint remains the same as the outdoor air taken in because there is no direct evaporation. IEC supply air dry bulb temperature has greater uncertainty due to the small temperature changes and larger relative contributions of the small bias uncertainty of the high accuracy temperature sensors.

Heat Pump Cooling

Stage 2 heat pump cooling.

HP Cooling High SADB

$$= -222.73 + 8.4584 * RADP - 0.063762 * RADP^2 + 0.097588 * OADB \\ + 0.00049038 * OADB^2 - 0.0014224 * RADP * OADB$$

Standard error (RMSE) 0.27809 (°F)

HP Cooling High SADP

$$= -122.65 + 4.8219 * RADP - 0.031606 * RADP^2 + 0.15477 * OADB \\ + 0.00031585 * OADB^2 - 0.0025284 * RADP * OADB$$

Standard error (RMSE) 0.25253 (°F)

HP Cooling High Power

$$= 11.754 - 0.37136 * RADP + 0.0036046 * RADP^2 + 0.019823 * OADB \\ + 0.00023387 * OADB^2 - 0.00044225 * RADP * OADB$$

Standard error (RMSE) 0.013562 (°F)

Stage 1 heat pump cooling.

HP Cooling Low SADB

$$= -154.143 + 6.6062 * RADP - 0.0513889 * RADP^2 - 0.141457 * OADB \\ + 0.00008876 * OADB^2 + 0.0016455 * RADP * OADB$$

Standard error (RMSE) 0.1836786 (°F)

HP Cooling Low SAMP

$$= -143.9676 + 6.1879 * RADP - 0.047974 * RADP^2 - 0.190814 * OADB \\ + 0.000655326 * OADB^2 + 0.0023699 * RADP * OADB$$

Standard error (RMSE) 0.21330 (°F)

HP Cooling Low Power

$$= 4.26063 - 0.12315 * RADP + 0.001035 * RADP^2 + 0.011167956 * OADB \\ + 0.000107232 * OADB^2 + 1.69862E - 05 * RADP * OADB$$

Standard error (RMSE) 0.0084926 (°F)

Heat Pump Heating

HP supply air dewpoint remains the same as the return air taken in because there is no condensation.

Stage 2 heat pump heating. Temperatures in degrees Fahrenheit

HP Heating High SADB

$$= -31.6301 + 1.5765 * OADP + 1.3958 * RADB - 0.0063 * OADP^2 - 0.0095 \\ * OADP * RADB$$

Standard error (RMSE) 0.15634 (°F)

HP Heating High SAMP = RADP

*HP Heating High Power = -0.2594 + 0.0399 * RADP + 0.0143 * OADB*

Standard error (RMSE) 0.01497 (kW)

Stage 1 heat pump heating. Temperatures in degrees Fahrenheit

HP Heating Low SADB

$$= 6.250199 + 0.631334 * OADP - 0.002553 * OADP^2 + 0.934472 * RADB$$

Standard error (RMSE) 0.18012 (°F)

HP Heating Low SADP = RADP

*HP Heating Low Power = -0.057845 + 0.005331 * OADP + 0.032411 * RADB*

Standard error (RMSE) 0.009475 (kW)

Hybrid Unitary HVAC Equipment Object

The EnergyPlus Hybrid Unitary HVAC Equipment Object, originally developed by WCEC in partnership with Lawrence Berkely National Laboratory, was created for modeling hybrid equipment like the Hybrid RTU tested in this project. The regressions above can be used to create energy performance lookup tables for each distinct mode of equipment operation. The model uses these tables to then pick optimal modes to meet needed building loads while minimizing electrical and other “fuel” use. The following diagram (see fig. 14) shows how the lookup tables are integrated into the EnergyPlus modeling process using the Hybrid Unitary HVAC Equipment Object. A similar approach is being developed for CBECC-COM, to validate the performance table values recommended for the Hybrid/Advanced IEC module, which is currently available as a research branch version.

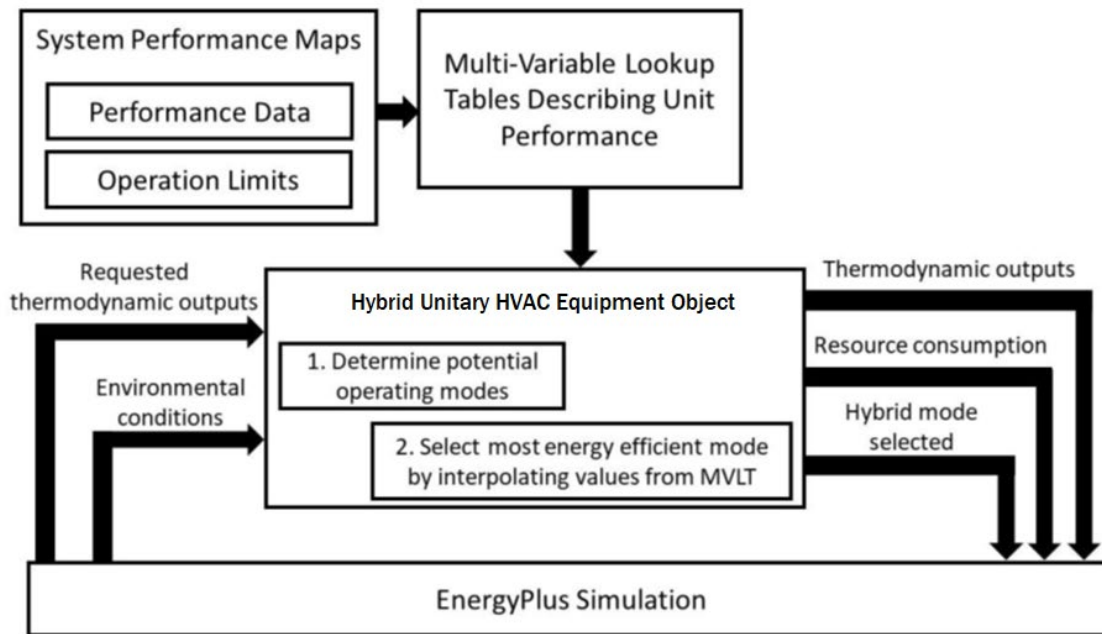


Figure 14: Process diagram of EnergyPlus integration of the Hybrid Unitary HVAC Equipment Object. [12]

Outdoor and indoor environmental conditions significantly impact the performance of each mode. These conditions, along with the mass flow rate of the process air and the proportion of outdoor air being delivered the space, are the most correlated to performance metrics. The output dependent variables are supply-air temperature, supply-air humidity ratio, external static pressure (ESP), power use, and water use.

For each mode of operation for the Hybrid RTU, the team creates a lookup table over the full operation range of independent variables for that mode. Independent variables (x_i) for the Hybrid Unitary HVAC Equipment Object model are [12]:

x_1 = outside air temperature ($^{\circ}\text{C}$) = T_{OSA}

x_2 = outside humidity ratio (g H₂O/g dry air) = ω_{OSA}

x_3 = return air temperature (dry bulb) ($^{\circ}\text{C}$) = T_{RA}

x_4 = return air humidity ratio (g H₂O/g dry air) = ω_{RA}

x_5 = normalized supply air mass flow rate (-) = $m_{SA}/m_{SA\ max}$

x_6 = outside air fraction (-) = $OSAF$

For each Hybrid RTU mode, the regressions were used to generate the data for the Hybrid Unitary HVAC Equipment Object performance map template, see Table 14, that is used by the National Renewable energy Lab hosted Technology Performance Exchange translation tool to generate the lookup table and EnergyPlus code (idf file) to compute the Hybrid RTUs performance at each time step in the simulation. The performance map template aggregates the input data in discrete data points for all combinations of independent variables over the expected operational range of each

mode, as the below example illustrates, see Table 15 [13]. The lookup tables generated by tables allow the Hybrid Unitary HVAC System Model to pick the appropriate mode for a given condition and generate the necessary dependent variables at each timestep of the model. Some dependent variables are also normalized to supply air mass flow rate. Normalizing variables to the supply air flow rate allows for performance data scaling across equipment sizes for different building simulations. Operation limits for each independent variable are imposed to provide a realistic range of operating conditions.

The Hybrid Unitary HVAC Equipment Object model's dependent variables (y_j) include [12]:

y_1 = supply air temperature ($^{\circ}\text{C}$) = T_{SA}

y_2 = supply air humidity ratio (g H₂O/g dry air) = ω_{SA}

y_3 = normalized total electric power (kJ/kg) = $W'_{elec}/\dot{m}_{SA\ max}$

y_7 = normalized water consumption (liters/kg) = $V'_{water}/\dot{m}_{SA\ max}$

y_8 = external static pressure (Pa) = ESP

For the Hybrid RTU, the variables y_4 , y_5 , or y_6 are not included, as these variables are used for tracking additional fuel usage metrics, and the Hybrid RTU uses only water and electricity in its operation. A similar set of lookup tables will be generated for use in the CBECC-COM Advanced IEC module.

Table 14: Example from the Hybrid Unitary HVAC Equipment Object performance map template, used by the National Renewable energy Lab hosted Technology Performance Exchange translation tool

Outside Air Temperature ($^{\circ}\text{C}$)	Outside Air Humidity Ratio (g/g)	Return Air Temperature ($^{\circ}\text{C}$)	Return Air Humidity Ratio (g/g)	Supply Air Mass Flow (kg/s)	Outside Air Fraction	External Static Pressure (Pa)	Supply Air Temperature ($^{\circ}\text{C}$)	Supply Air Humidity Ratio (g/g)	Total Electric Power (kW)	Supply Fan Electric Power (kW)	Water Consumption (liters/hr)
15	0.00294	-	-	0.2	1	5					
15	0.00294	-	-	0.675	1	60					
15	0.00294	-	-	1.15	1	175					
15	0.00442	-	-	0.2	1	5					
15	0.00442	-	-	0.675	1	60					

Table 15: Example Multi-Variable Lookup Table generated by National Renewable energy Lab hosted Technology Performance Exchange translation tool [13]

Lab based test conditions						Measured system performance (HMX only)		
Outside air temp. (C)	Outside air humidity ratio (-)	Return air dry bulb temp.(C)	Return air humidity ratio (-)	Supply air mass flow rate (kg/s)	Outside air fraction	$T_{db,SA}$ (°C)	ω_{SA} (%)	Elec. Power (W)
15	0.002	18	0.004	0.4	0.45	9.3	0.0021	141.15
15	0.002	18	0.004	0.4	0.54	9.0	0.0018	141.15
15	0.002	18	0.004	0.4	0.63	8.7	0.0015	141.15
15	0.002	18	0.004	0.4	0.73	8.4	0.0013	141.15
15	0.002	18	0.004	0.4	0.82	8.2	0.0010	141.15
15	0.002	18	0.004	0.4	0.91	7.9	0.0007	141.15
15	0.002	18	0.004	0.4	1.00	7.6	0.0004	141.15
15	0.002	18	0.004	0.52	0.45	9.4	0.0021	263.76
15	0.002	18	0.004	0.52	0.54	9.1	0.0018	263.76
15	0.002	18	0.004	0.52	0.63	8.9	0.0015	263.76
15	0.002	18	0.004	0.52	0.73	8.6	0.0013	263.76
15	0.002	18	0.004	0.52	0.82	8.3	0.0010	263.76
15	0.002	18	0.004	0.52	0.91	8.0	0.0007	263.76
15	0.002	18	0.004	0.52	1.00	7.8	0.0004	263.76

Stakeholder Engagement

The team engaged relevant stakeholders as part of the original project idea development, in the CalNEXT proposal scoring process, and through ongoing collaboration and input solicitation.

Equipment Manufacturer

The equipment manufacturer provided the equipment and worked collaboratively with WCEC to support development of the test plans and test methods. They have also advocated for the advanced capabilities in Energy Plus Hybrid Unitary Equipment Object to be adopted by CEC CBECC-Com, to enable accurate modeling of hybrid systems, including the Hybrid RTU and many other possible types of equipment. The CEC created and recently released a research-branch of CBECC-Com that includes the Hybrid Unitary HVAC System Model that can simulate the Hybrid RTU. This project generated performance curves for this equipment, which can validate the general medium-efficiency and high-efficiency equipment performance estimates previously provided to the CEC by the manufacturer. With this validation, the WCEC team will continue to encourage the CEC to include the simulation of Hybrid RTU equipment in future standard releases of CBECC-Com. This will also serve as an example for other manufacturers to follow in approving similar equipment in the future

Other HVAC manufacturers are also stakeholders of this project as a source of information about barriers to adoption. The WCEC team presented the prototype Hybrid RTU field test results in a

presentation and poster at a private WCEC-organized event for HVAC manufacturers and utility efficiency program providers, held in parallel with the 2024 ASHRAE winter conference and AHR Expo in Chicago. Attendees included HVAC manufacturers Daikin, Delta Controls, Geary Pacific Corp, Micrometl, Panasonic, Rheem, Seeley, and Trane, as well as energy efficiency program implementers Leidos and Amren, the National Energy Management Institute (NEMI), the Sheet Metal and Air Conditioning Contractors' National Association (SMACNA), and engineering consulting firms TRC and Emanant Systems.

CalNEXT Team

Key stakeholders for this project also include the target audiences of the teams that will use EnergyPlus, CBECC-Com and other energy modeling tools to estimate energy savings of the Hybrid RTU equipment and, in doing so, develop a new measure package for custom and deemed efficiency programs. These teams include UCD WCEC and, potentially, other CalNEXT partners such as Energy Solutions, TRC, and Alternative Energy Systems Consulting, Inc. (AESC). Energy Solutions, TRC, and AESC have provided feedback on this project, beginning in the idea stage and throughout development of the project plan. The UC Davis team has engaged with CalNEXT team members to prepare the team to do the next step measure development. WCEC will contribute to – or lead – the measure development efforts, to ensure that the performance curves accurately represent equipment efficiency in the required modelling tools to predict energy savings.

IOUs

Investor-owned utilities (IOUs) are additional key stakeholders for development and adoption of new Hybrid RTU efficiency measures for EE programs. In preparation for the next step measure development project, the team has reached out to and is setting up meetings with the California HVAC Program Administrator SDG&E to determine what standards and requirements the equipment needs to meet to be included in the program as a new efficiency measure. WCEC has engaged – and will continue to engage – with IOU representatives to share information about Hybrid RTU equipment and to learn how this new class of products can enable efficiency-program designs to overcome HP adoption barriers. The UCD team shared the production ready prototype Hybrid RTU field test results with utility stakeholders through a presentation at the Utility Energy Forum 2022. Multiple POU representatives expressed interest in the Hybrid RTU technology for their service areas. The UCD team has contacted SDG&E to map out next steps towards measure development.

CalTF

The California Technical Forum (CalTF) is a key stakeholder for the next steps measure development process. The team has reached out to and is scheduling a time to present the Hybrid RTU lab and field test results to the CalTF Deemed Initiative Subcommittee to begin this process.

The UCD team will continue to engage with the stakeholders identified above, including HVAC manufacturers, energy modelling tool developers, and IOU staff. The UCD team will continue to recruit and prepare the teams to perform next step measure development for the technology, including other CalNEXT team members, to maximize the impact of this project.

Stakeholder Feedback

As part of the CalNEXT proposal scoring process, the team received feedback from a CalNEXT partner saying the Hybrid RTU has “great potential in schools in DACs to improve indoor air quality.” This same partner suggested that any additional field studies “target a percentage of outreach to schools within DACs to field test” and that the UC Davis team reach out “to groups working within DACs to identify potential barriers to adoption”. This laboratory testing project included operations relevant to schools, which have higher ventilation rates than most commercial buildings and will, therefore, save more energy with this technology than building types with lower ventilation rates. For additional field testing, the project team will identify schools in DAC and HTR and will include outreach to better understand DAC-specific barriers to adoption.

One CalNEXT partner said, “this may be too much scope creep, but it would be interesting to explore the potential refrigerant emissions reduction of installing this technology vs. a VRF system, which would have a much higher refrigerant charge and many more field-installed connections that create opportunities for leaks.” The team agrees that this would be interesting, but that it is beyond the scope of this current project. Because the Hybrid RTU enables a smaller HP with a smaller refrigerant charge, and because the Hybrid RTU heat pump is factory sealed, the team expects it to reduce the maximum possible refrigerant leakage compared with a conventional RTU HP baseline and to have a much lower chance of refrigerant leakage, compared with VRF systems.

One CalNEXT partner recommended “adding an explanation for commercial building electrification of HVAC systems, highlighting current status and barriers to heat pump adoption.” See the background chapter section, “Barriers to Adoption of RTU HPs”, for more information.

A project manager at Southern California Edison (SCE) reviewed both the pre-draft and draft plan for this project, inquiring whether the “ET08SCE1160 - 5 ton Indirect Hybrid Unit Project is part of the background related to this technology”. The background chapter, “Previous Hybrid Evaporative Cooling and Natural Gas Heating RTU – Coolerado H80”, outlines the previous work with the Coolerado H80 multi-fuel Hybrid RTU. This and other previous work identified barriers to adoption of the Coolerado H80, including its high cost and much greater weight. This project tested a Hybrid RTU designed to reduce both the cost premium and the weight increase to overcome these barriers to adoption. The Hybrid RTU tested also utilizes heat pump heating to electrify the heating process.

The Vice President for Building Science and Engineering at a top manufacturer mentioned that the existing vapor compression system test standards do not use very hot dry conditions. He suggested that “we need performance curves for models to show the true advantage for evaporative equipment in California climates”. He also mentioned that “peak reduction has the potential to be very large with evaporative cooling technologies”. These statements match with previous WCEC expertise and measured results in this technology area.

Recommendations and Next Steps

This project performed environmental chambers lab testing of the Hybrid RTU and developed performance curves for future use in EnergyPlus and CBECC-Com. This project directly prepares the way for future projects that will develop a new Hybrid RTU measure package. Future measure development projects will use the performance curves, developed by this project, in EnergyPlus to estimate energy savings. This project also developed comparison numbers for the evaporative

cooling performance of this Hybrid RTU to validate the CBECC-Com assumptions for code compliance. With these validated numbers, the Title 24 building codes performance pathway can give efficiency credit for the Hybrid RTU technology supporting successful market adoption.

The project team's next steps include:

- Continue to engage with the California HVAC Program Administrator SDG&E to determine what standards and requirements the equipment needs to meet to be included in the program as a new efficiency measure. Follow up with the Hybrid RTU manufacturer to support meeting those requirements.
- Continue to engage with the CalTF to present the Hybrid RTU lab and field test results to the CalTF Deemed Initiative Subcommittee to begin the measure development process
- Continue to recruit and prepare the team to do the next step measure development. WCEC will contribute to, or lead, the measure development efforts to ensure that the performance curves can represent equipment efficiency in the required modelling tools to predict energy savings.
- Continue to engage with EnergyPlus and CEC CBECC-Com software developers to promote the use of the performance curves for cost-benefit analysis and for code compliance.

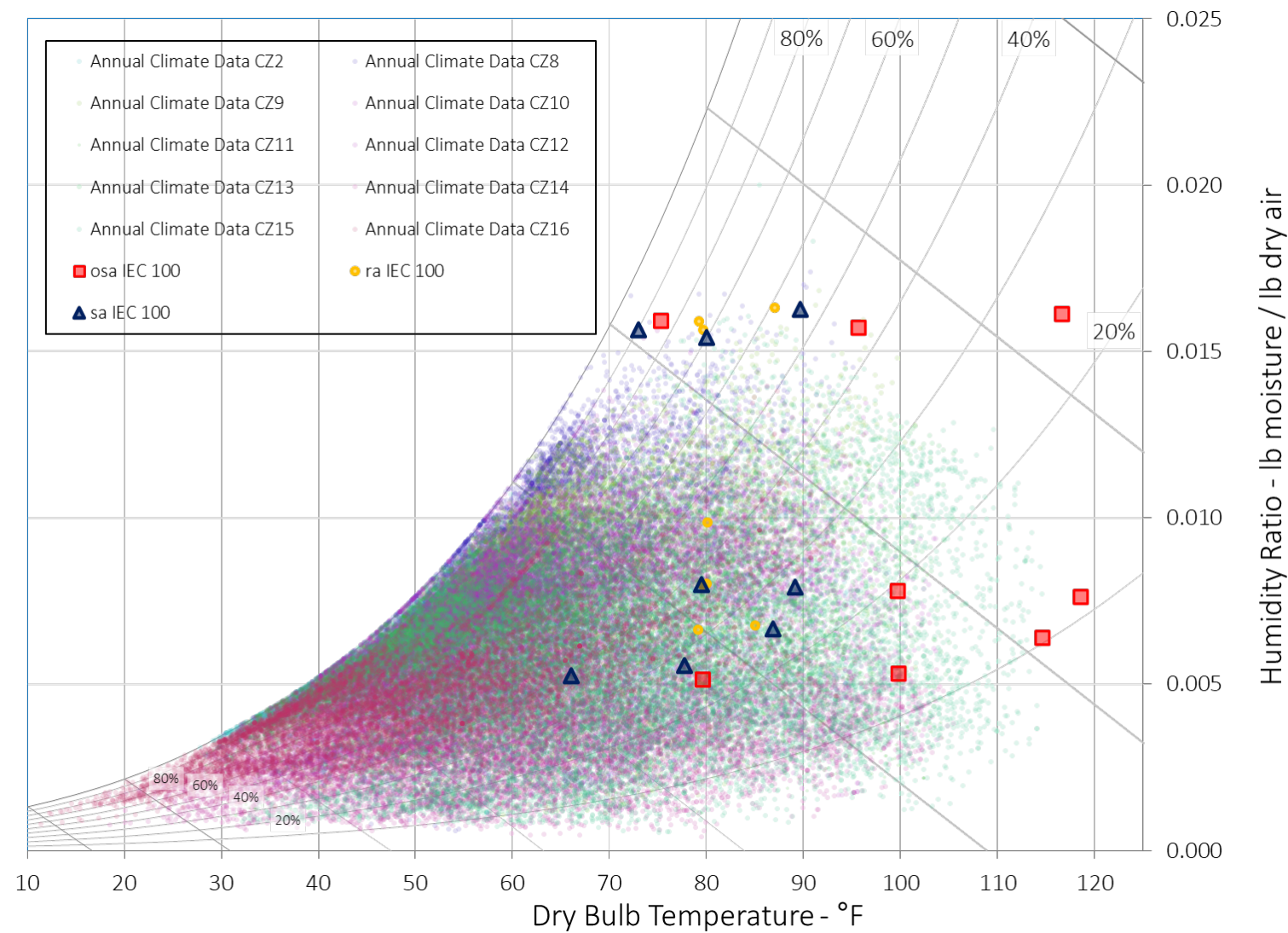
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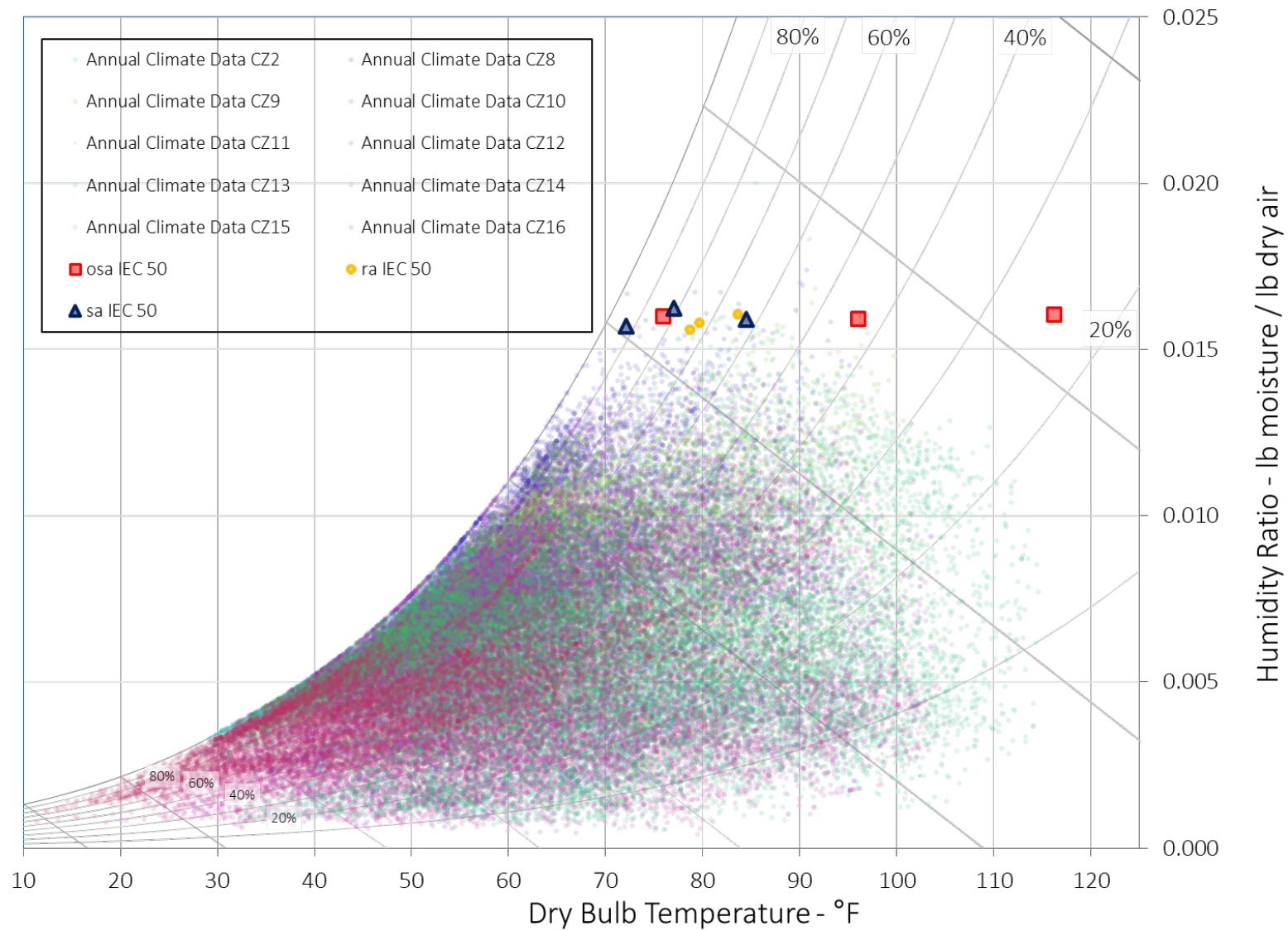
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APPENDIX A: Achieved Evaporative Section Test Conditions and Supply Air Conditions

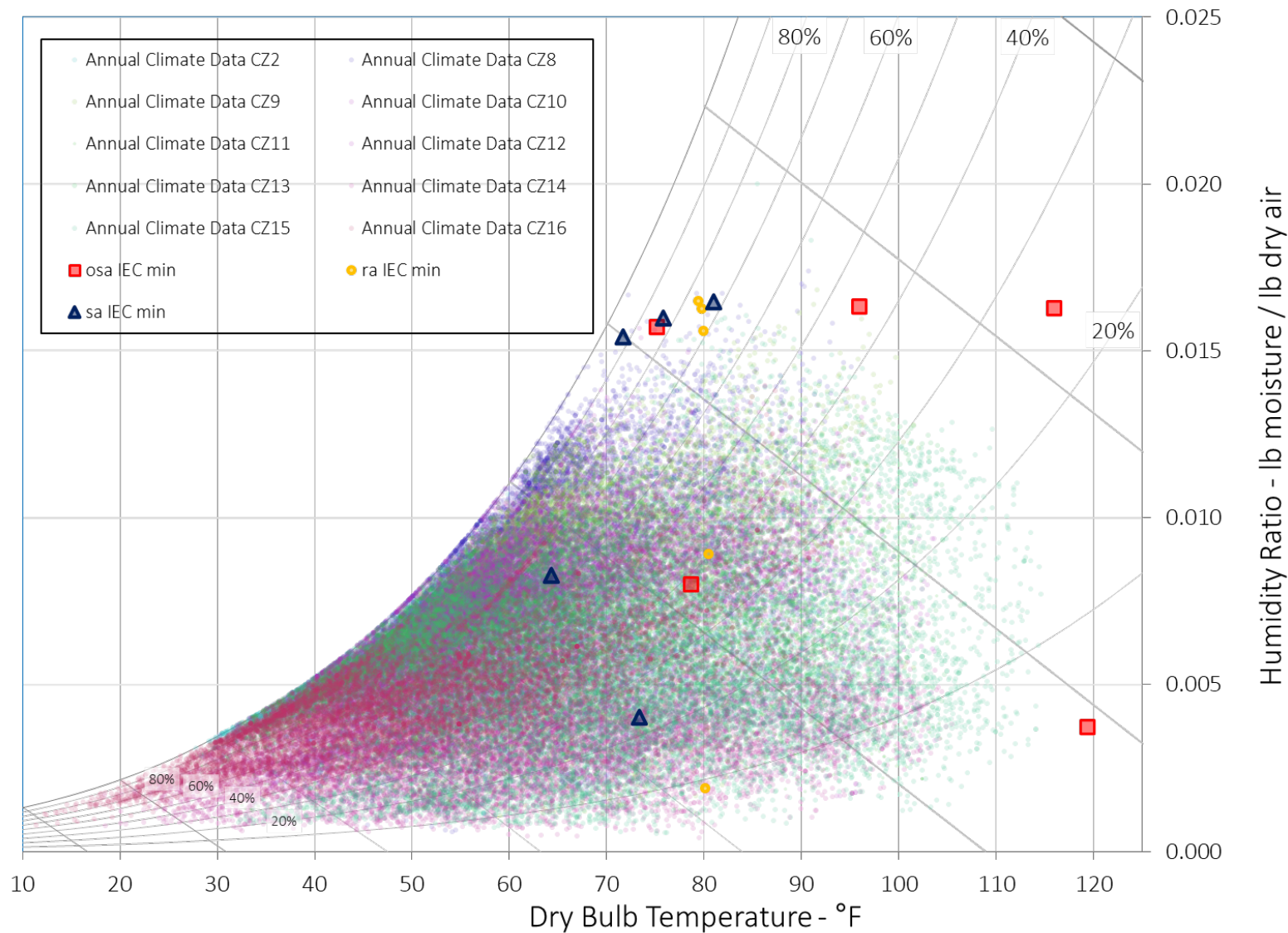


IEC High Speed Operation State Outdoor, Indoor, and Supply Air Conditions (overlay on dry CZ)

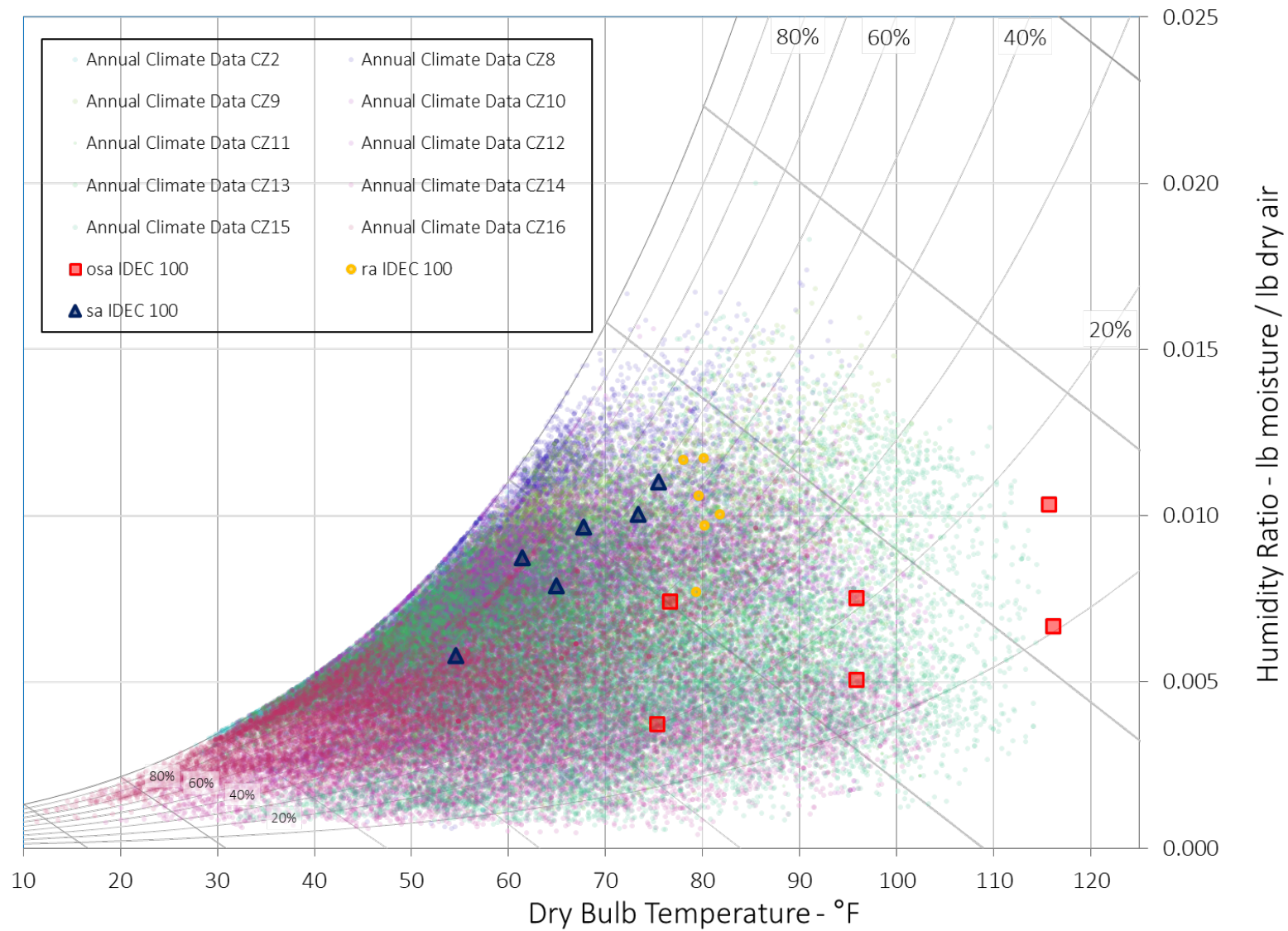




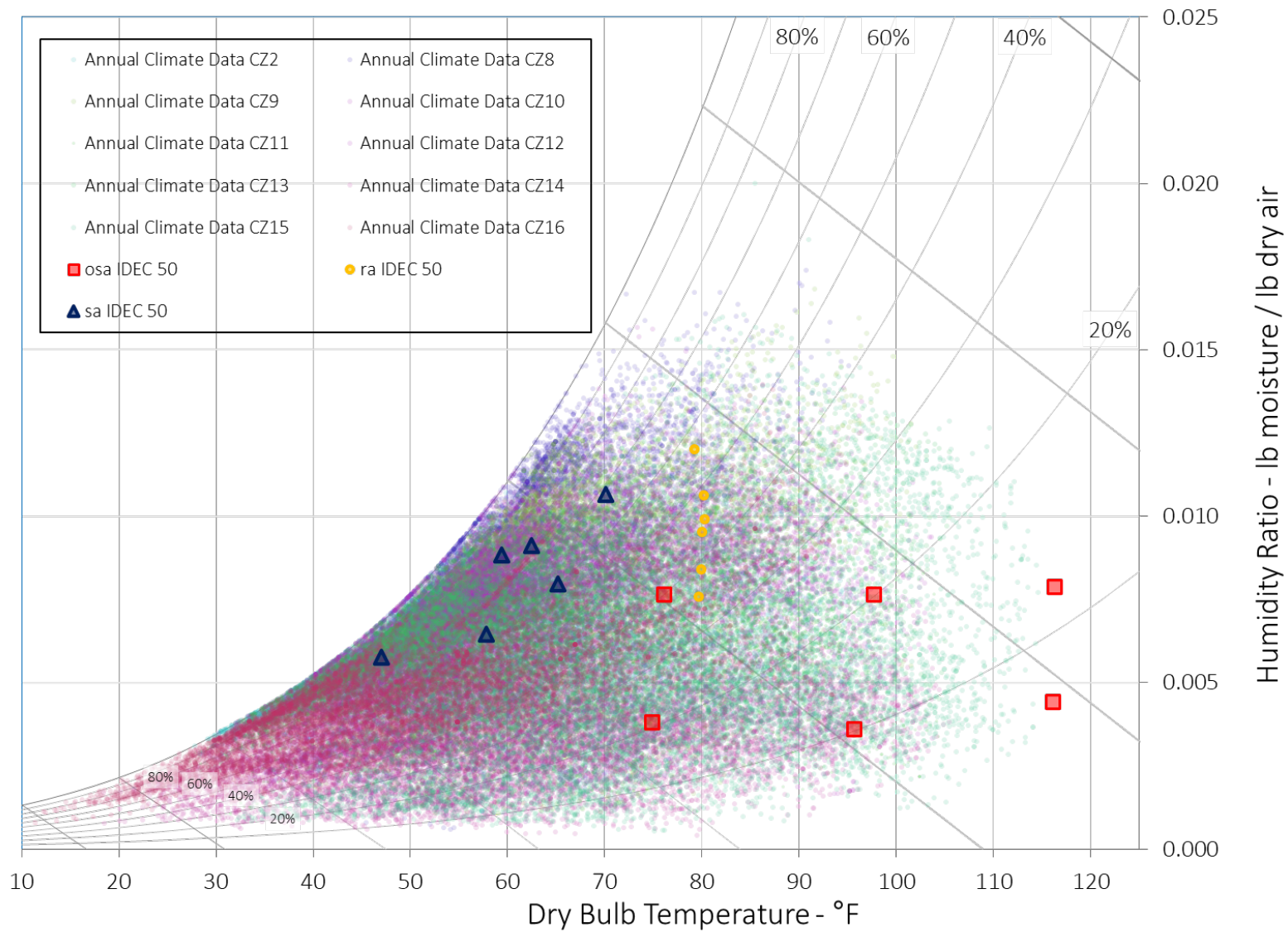
IEC Medium Speed Operation State Outdoor, Indoor, and Supply Air Conditions (overlay on dry CZ)



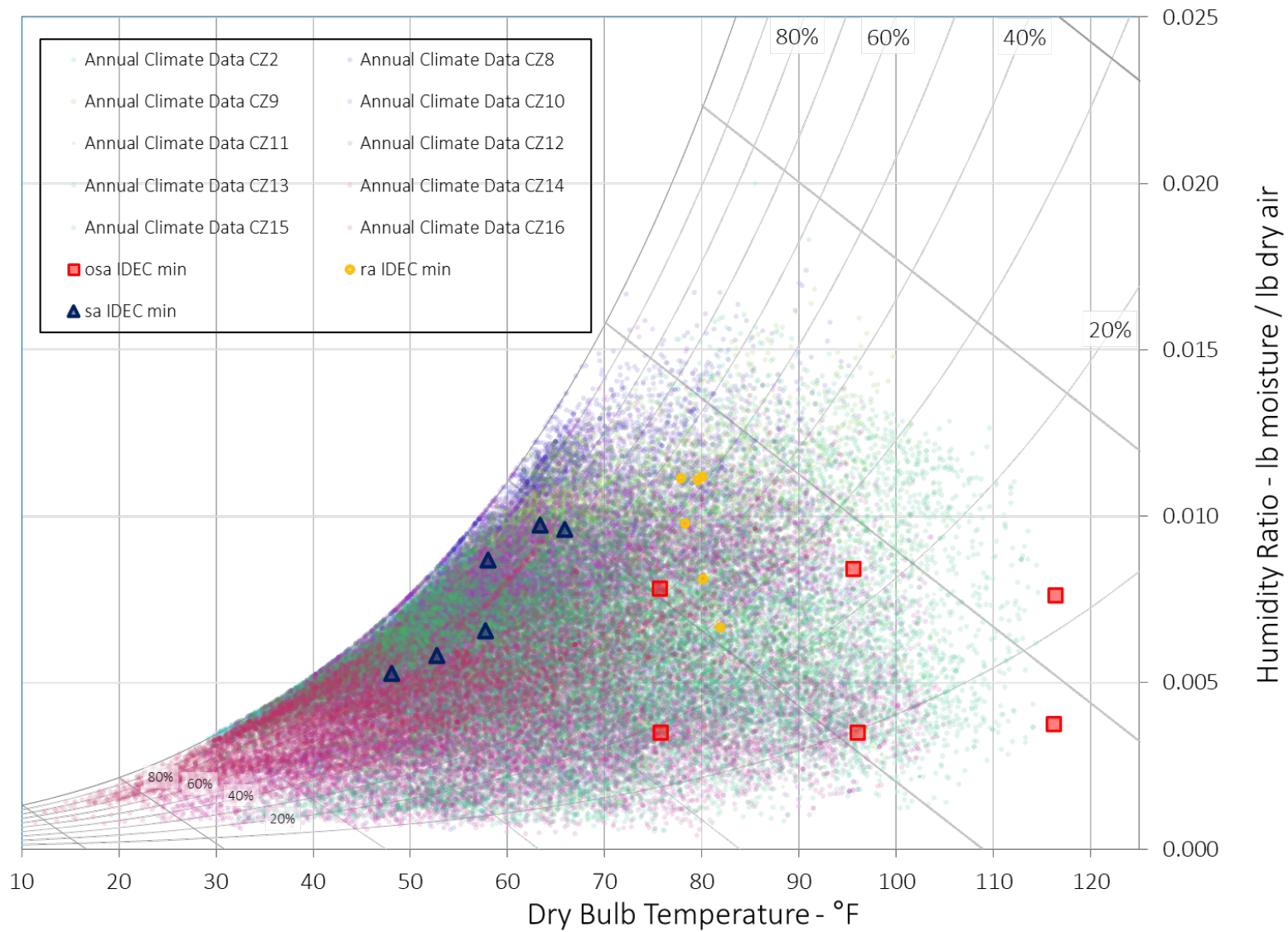
IEC Low Operation State Outdoor, Indoor, and Supply Air Conditions (overlay on dry CZ)



IDEC high speed Operation State Outdoor, Indoor, and Supply Air Conditions (overlay on dry CZ)



IDEC MEDIUM SPEED Operation State Outdoor, Indoor, and Supply Air Conditions (overlay on dry CZ)



IDEC Low Operation State Outdoor, Indoor, and Supply Air Conditions (overlay on dry CZ)

Appendix B: Regressions

Regression for IDEC Supply Air Temperature dry bulb (SADB)

Temperatures in degrees Fahrenheit and supply air flow rate in kg/s

$IDEC\ SADB = 13.1258 + 0.2293 * OADB + 0.4470 * OADP + 6.5619 * SAflow$
Standard error (RMSE) 0.87555 (°F)

OLS Regression Results

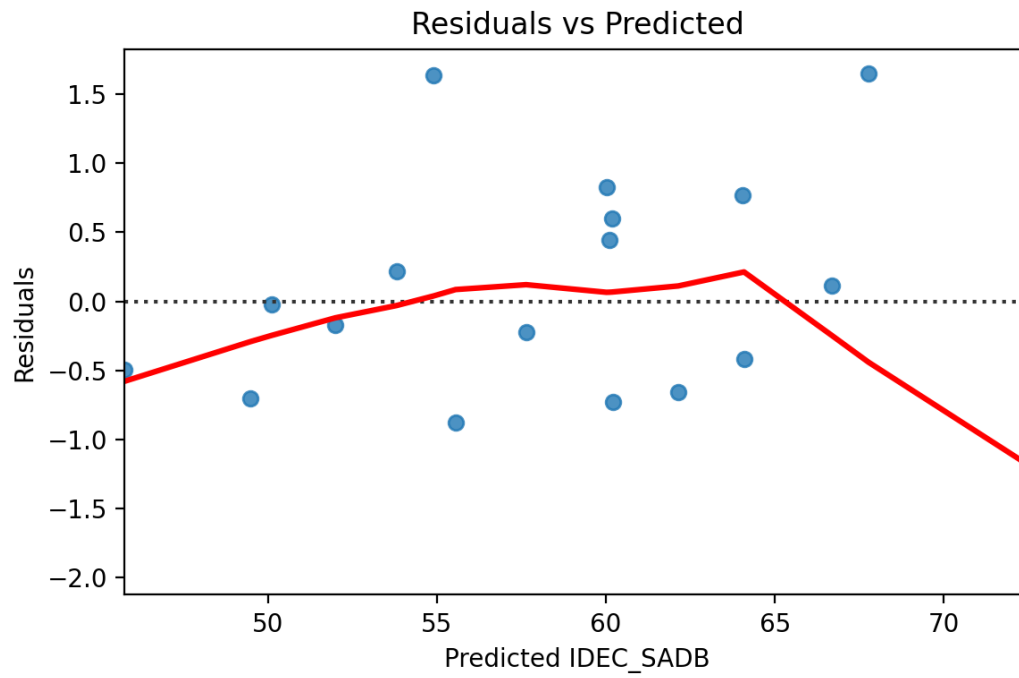
Dep. Variable:	IDEC_SADB	R-squared:	0.984
Model:	OLS	Adj. R-squared:	0.980
Method:	Least Squares	F-statistic:	282.9
Date:	Thu, 07 Aug 2025	Prob (F-statistic):	9.24e-13
Time:	18:52:07	Log-Likelihood:	-23.149
No. Observations:	18	AIC:	54.30
Df Residuals:	14	BIC:	57.86
Df Model:	3		
Covariance Type:	nonrobust		

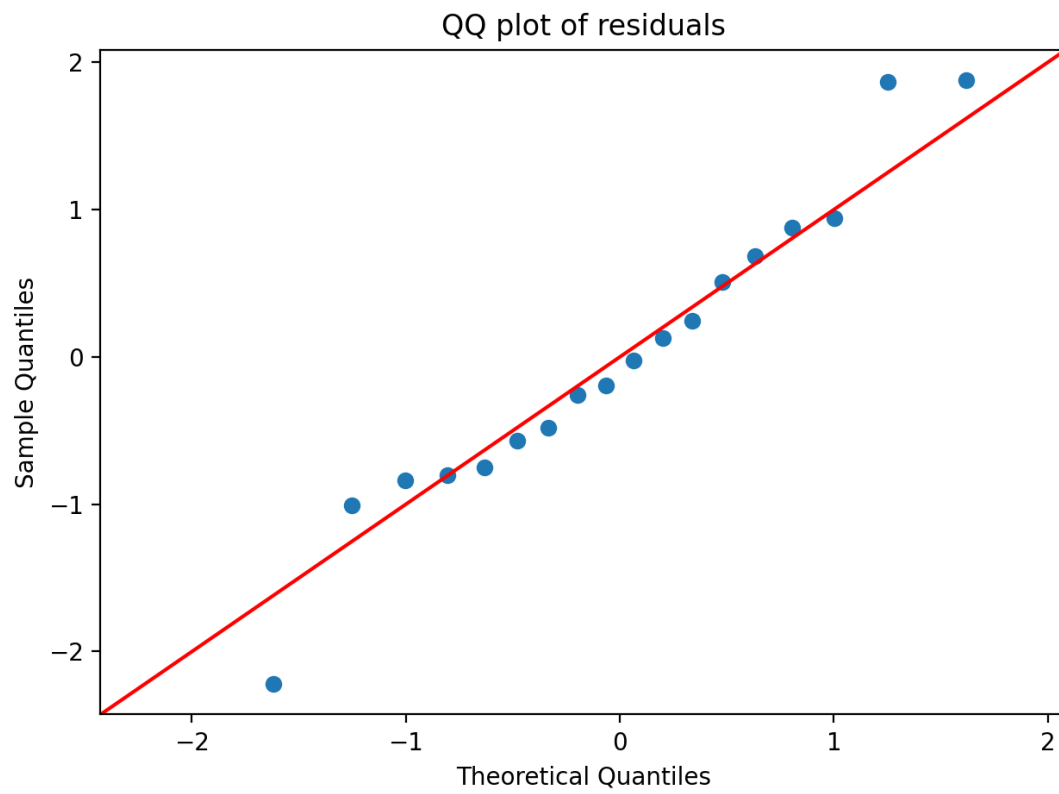
	coef	std err	t	P> t	[0.025	0.975]
const	13.1258	1.648	7.964	0.000	9.591	16.661
OA_DB	0.2293	0.015	15.328	0.000	0.197	0.261
OA_DP	0.4470	0.026	17.141	0.000	0.391	0.503
SA_mass_flow	6.5619	0.691	9.499	0.000	5.080	8.044

Omnibus:	0.363	Durbin-Watson:	1.770
Prob(Omnibus):	0.834	Jarque-Bera (JB):	0.018
Skew:	0.074	Prob(JB):	0.991
Kurtosis:	2.953	Cond. No.	747.

Notes:

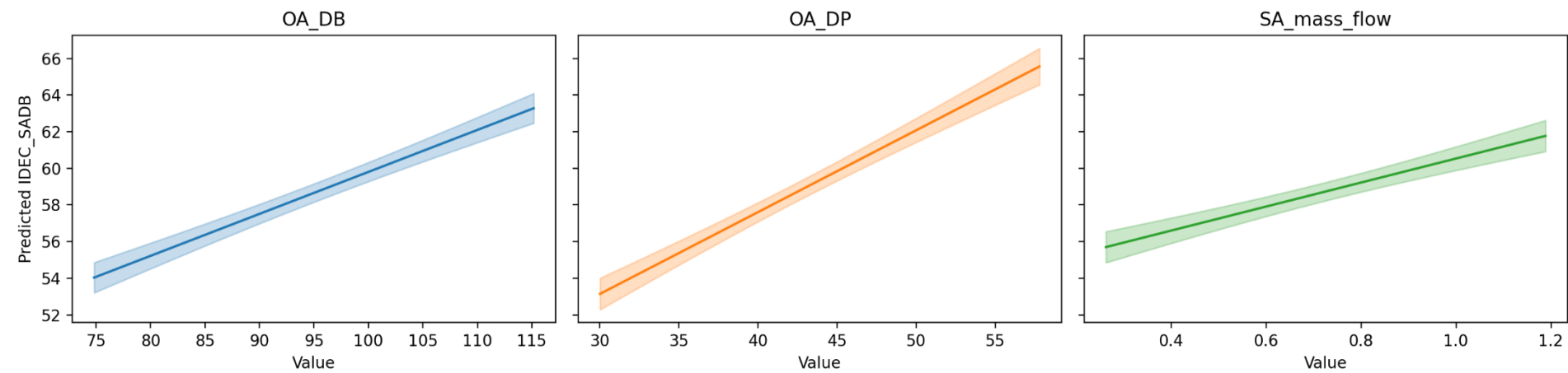
[1] Standard Errors assume that the covariance matrix of the errors is correctly





Perturbation plots with 95% model uncertainty bands

Separate Perturbation Plots with 95% Model Uncertainty



Regression for IDEC Supply Air Temperature dewpoint (SADP)

Temperatures in degrees Fahrenheit and supply air flow rate in kg/s

$$IDEC\ SADP = 11.7768 + 0.1278 * OADB + 0.6013 * OADP + 2.6477 * SAflow$$

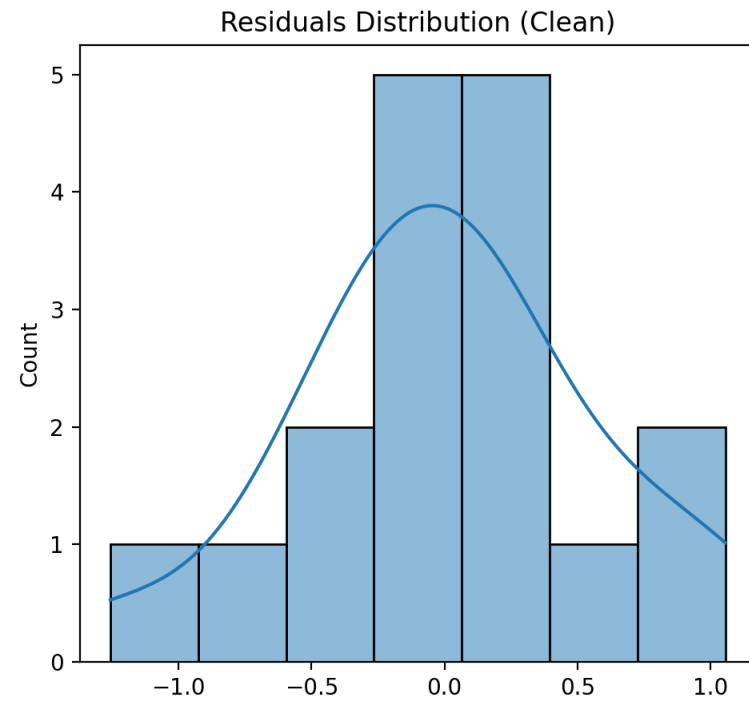
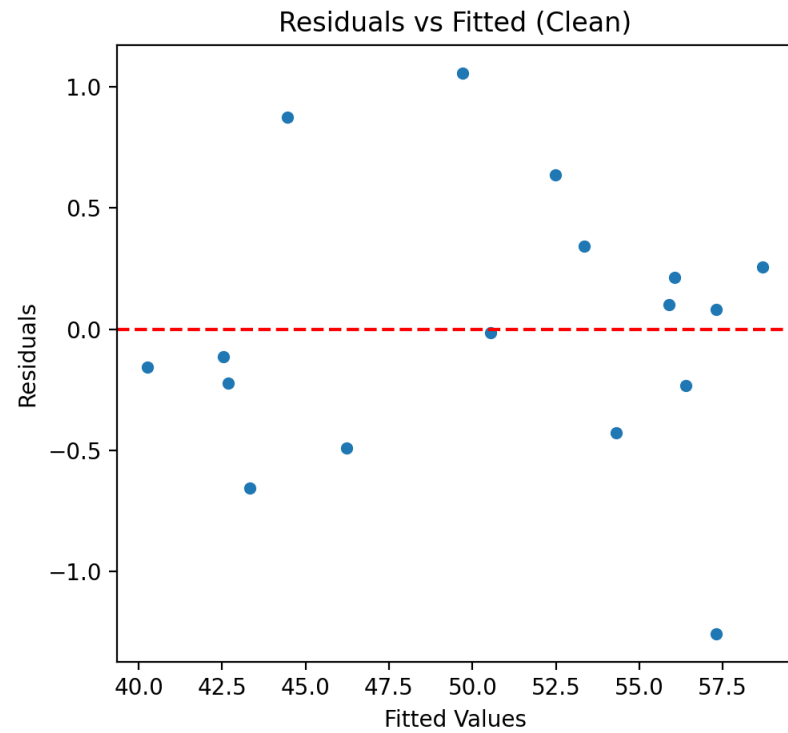
Standard error (RMSE) 0.54780 (°F)

Removed one outlier from data set

```
OLS Regression Results
=====
Dep. Variable:          IDEC_SADP    R-squared:                0.992
Model:                  OLS          Adj. R-squared:           0.990
Method:                 Least Squares  F-statistic:              523.3
Date:                  Thu, 07 Aug 2025  Prob (F-statistic):      8.42e-14
Time:                  19:19:09        Log-Likelihood:           -13.891
No. Observations:      17            AIC:                     35.78
Df Residuals:          13            BIC:                     39.11
Df Model:               3
Covariance Type:       nonrobust
=====
               coef    std err          t      P>|t|      [0.025    0.975]
-----
const         11.7768     1.154     10.209     0.000     9.285    14.269
OA_DB          0.1278     0.010     13.132     0.000     0.107     0.149
OA_DP          0.6013     0.017     34.622     0.000     0.564     0.639
SA_mass_flow   2.6477     0.449      5.896     0.000     1.678     3.618
=====
Omnibus:             0.684    Durbin-Watson:           1.125
Prob(Omnibus):       0.711    Jarque-Bera (JB):         0.047
Skew:                -0.113    Prob(JB):                 0.977
Kurtosis:             3.124    Cond. No.                  796.
=====
```

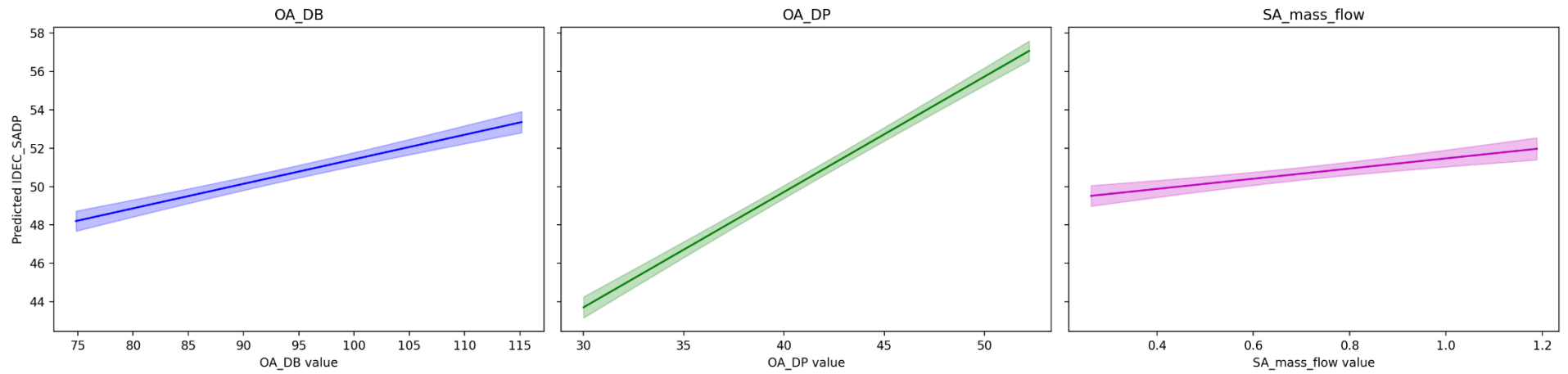
Notes:

[1] Standard Errors assume that the covariance matrix of the errors is correctly specified.



Perturbation plots with 95% model uncertainty bands

One-at-a-time Perturbation Curves (95% Bands)



Regression for IDEC Power

Power in kW and supply air flow rate in kg/s

$$IDEC\ Total\ Power = 0.14357 + 0.53363 * SAflow^2$$

Standard error (root mean squared) 0.031913 (kW)

```

=====
                        OLS Regression Results
=====
Dep. Variable:          Total Power (kW)    R-squared:                0.986
Model:                  OLS                Adj. R-squared:           0.985
Method:                 Least Squares      F-statistic:             1133.
Date:                  Sat, 14 Jun 2025    Prob (F-statistic):      2.80e-16
Time:                  16:01:58           Log-Likelihood:          36.464
No. Observations:      18                AIC:                    -68.93
Df Residuals:          16                BIC:                    -67.15
Df Model:               1
Covariance Type:       nonrobust
=====

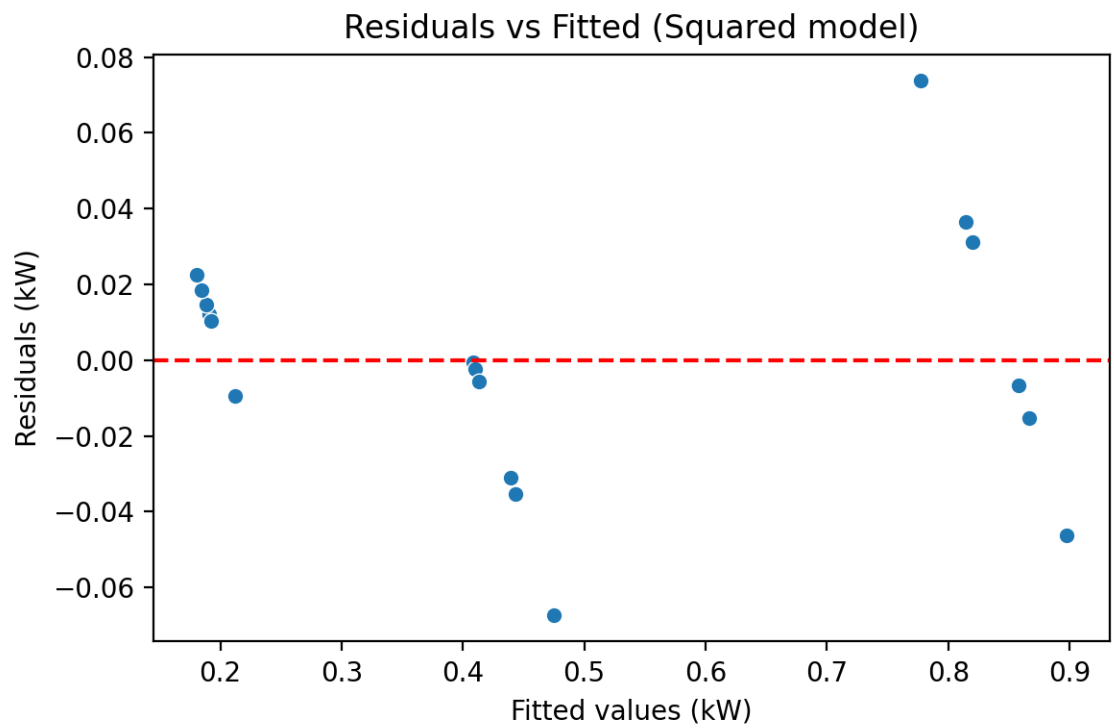
```

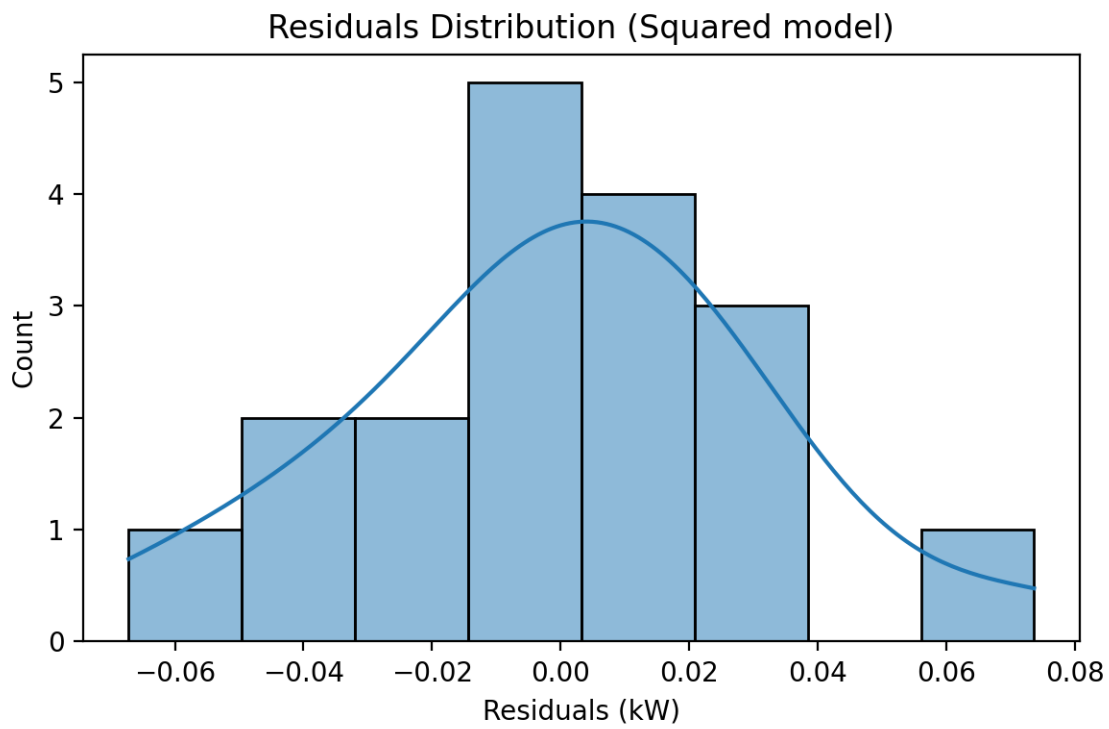
	coef	std err	t	P> t	[0.025	0.975]
const	0.1436	0.013	11.077	0.000	0.116	0.171
SA Flow^2	0.5336	0.016	33.658	0.000	0.500	0.567

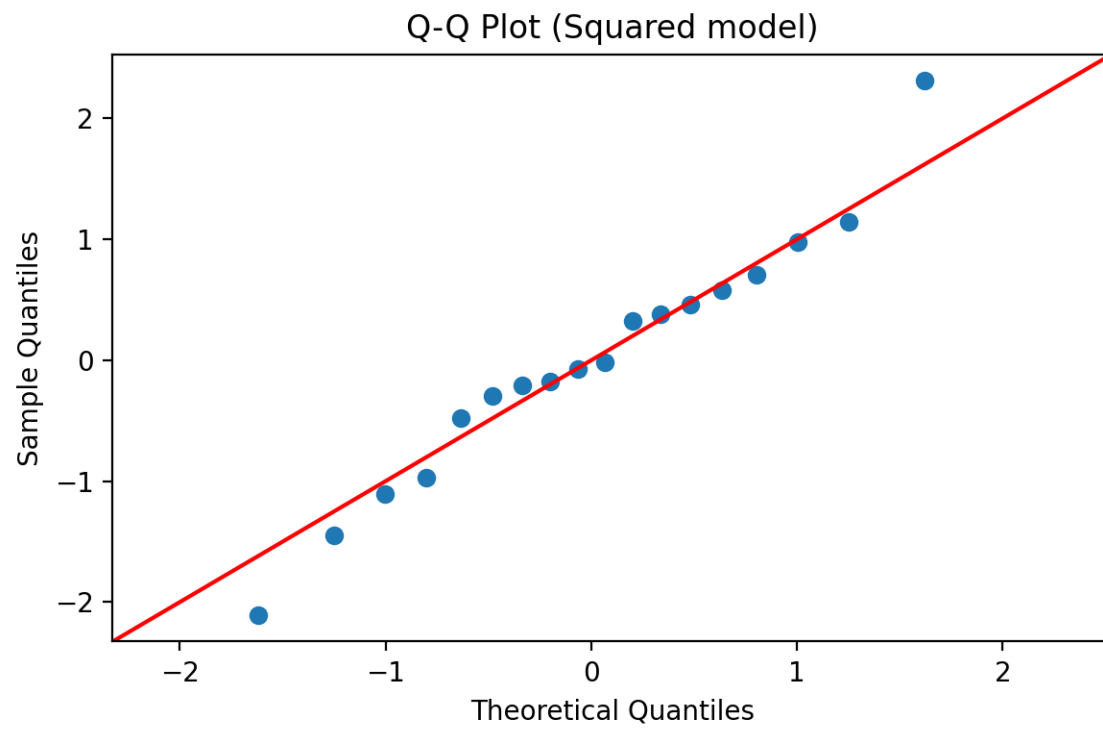
```

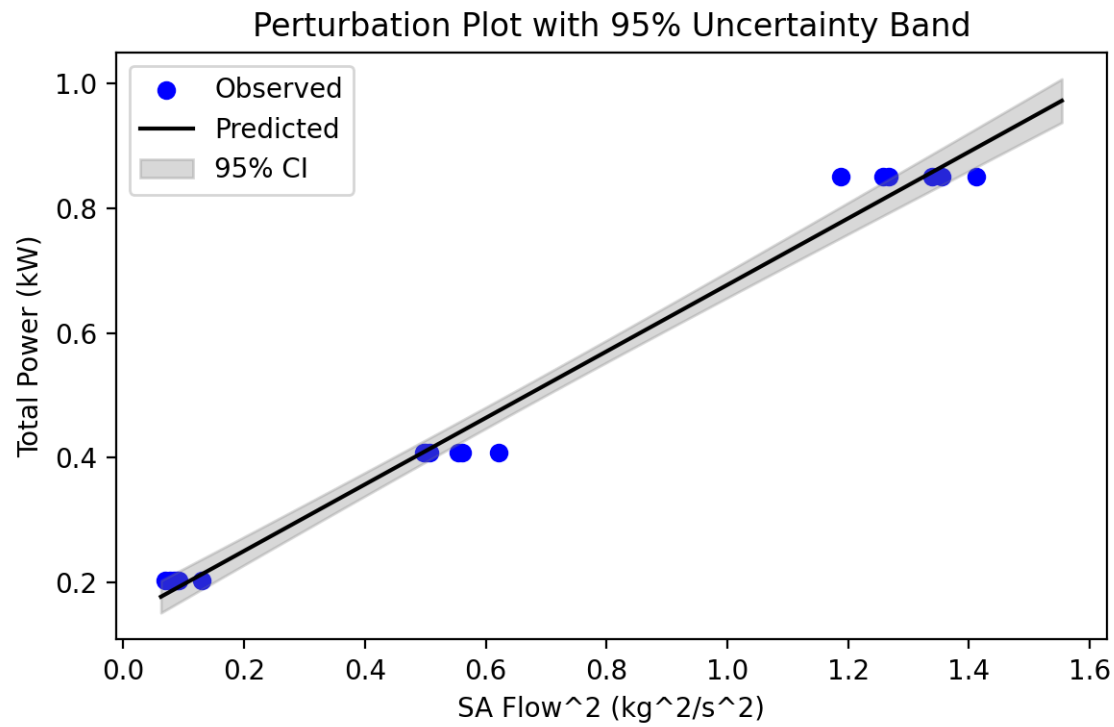
=====
Omnibus:                0.786    Durbin-Watson:           0.903
Prob(Omnibus):          0.675    Jarque-Bera (JB):        0.042
Skew:                   0.037    Prob(JB):                0.979
Kurtosis:               3.224    Cond. No.                2.98
=====
Notes:
[1] Standard Errors assume that the covariance matrix of the errors is correctly specified.

```









Regressions for IEC SADB

Temperatures in degrees Fahrenheit and supply air flow rate in kg/s

$$IEC\ SADB = 13.4544 + 0.3725 * OADB + 0.3174 * OADP + 8.6093 * SAflow$$

Standard error (RMSE) 2.01139 (°F)

Removed one outlier

OLS Regression Results

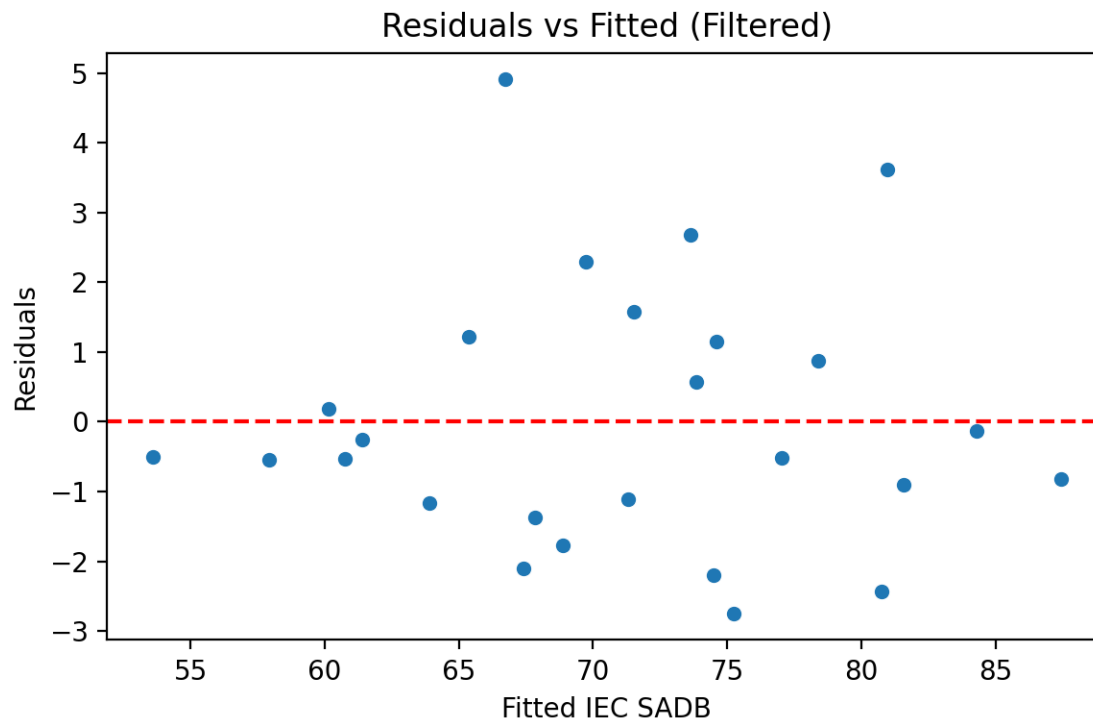
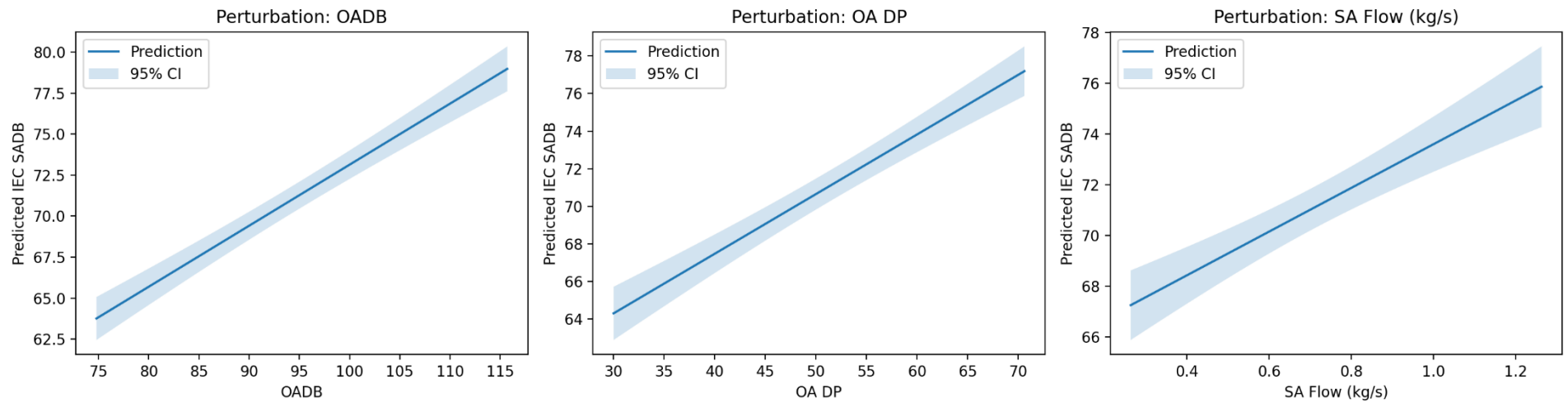
```
=====
Dep. Variable:          IEC SADB    R-squared:                 0.953
Model:                  OLS         Adj. R-squared:            0.947
Method:                 Least Squares   F-statistic:             150.1
Date:                  Sat, 14 Jun 2025   Prob (F-statistic):      8.50e-15
Time:                  22:36:22         Log-Likelihood:          -52.890
No. Observations:      26             AIC:                     113.8
Df Residuals:          22             BIC:                     118.8
Df Model:               3
Covariance Type:       nonrobust
=====
```

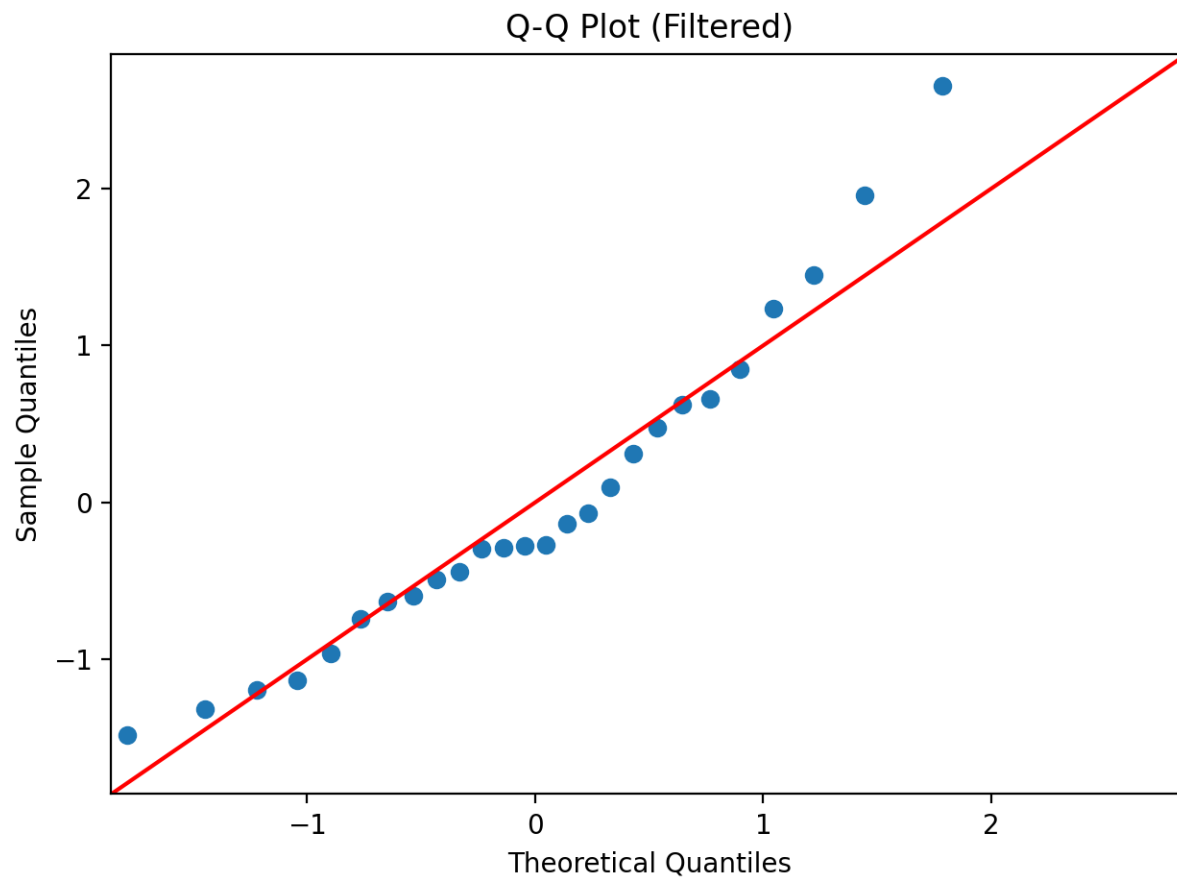
	coef	std err	t	P> t	[0.025	0.975]
const	13.4544	2.814	4.781	0.000	7.618	19.291
OADB	0.3725	0.025	14.950	0.000	0.321	0.424
OA DP	0.3174	0.026	12.256	0.000	0.264	0.371
SA Flow (kg/s)	8.6093	1.185	7.264	0.000	6.151	11.067

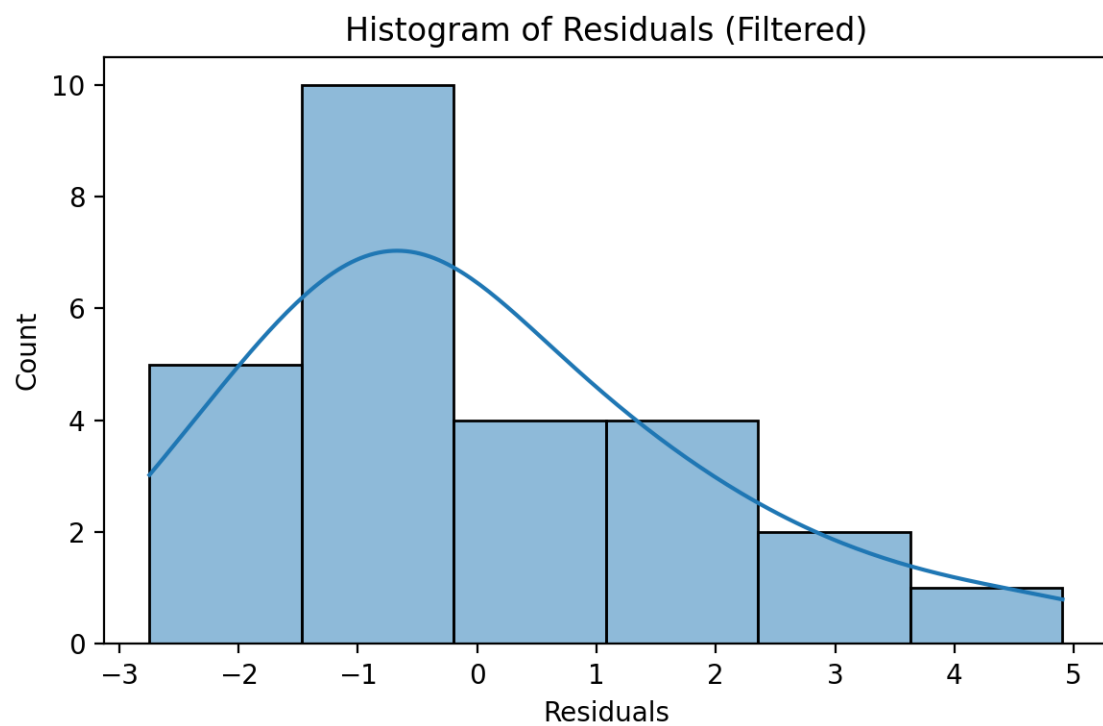
```
=====
Omnibus:                4.424    Durbin-Watson:           1.902
Prob(Omnibus):           0.109    Jarque-Bera (JB):        3.078
Skew:                    0.832    Prob(JB):                0.215
Kurtosis:                3.263    Cond. No.                 787.
=====
```

Notes:

[1] Standard Errors assume that the covariance matrix of the errors is correctly specified.







Regressions for IEC Power

Power in kW and supply air flow rate in kg/s

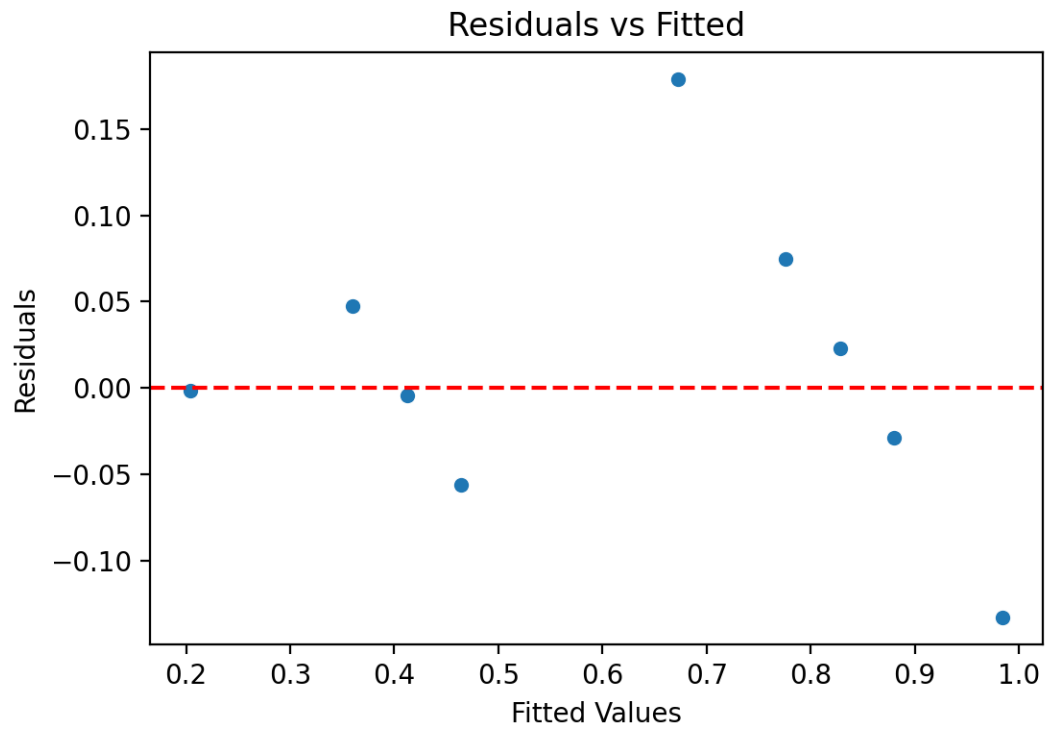
$$IEC \text{ Total Power} = 0.0962 + 0.2885 * SA_{flow}^2$$

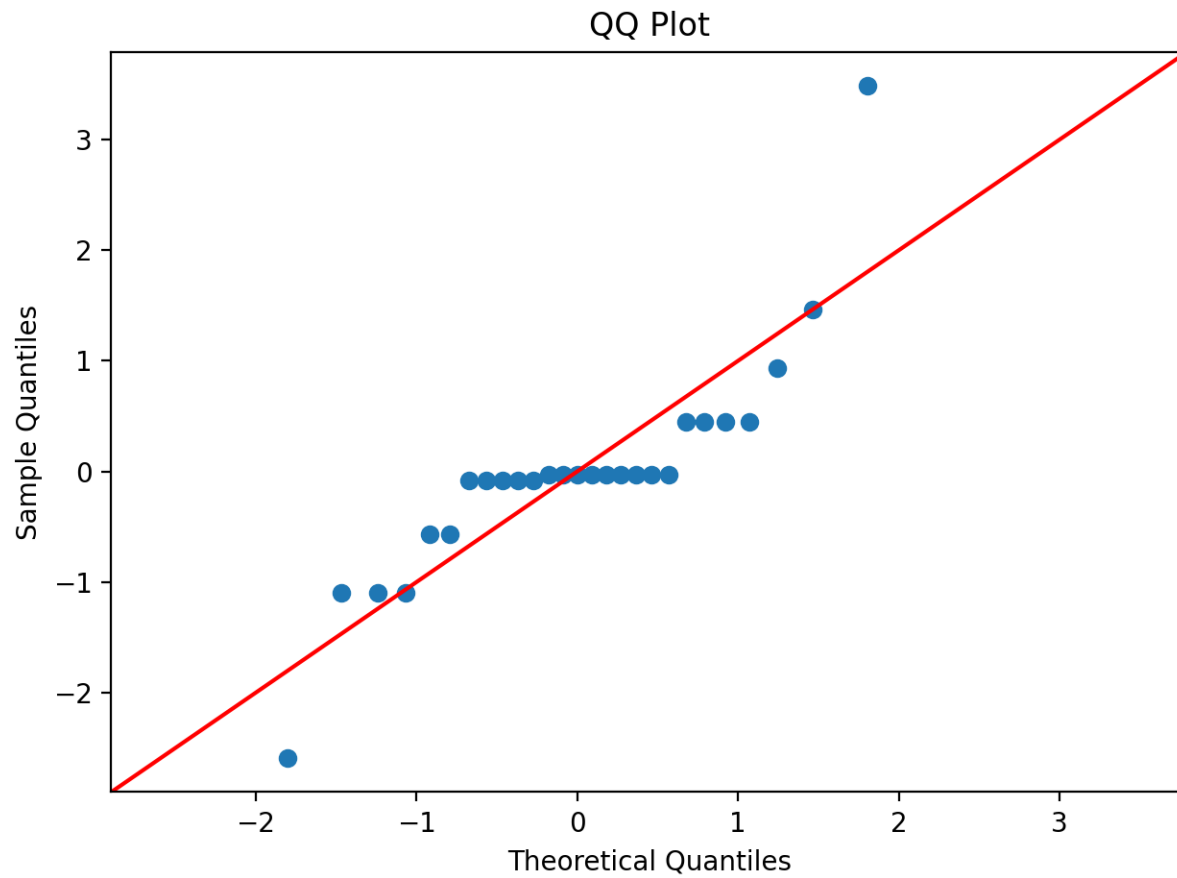
Standard error 0.053274 (kW)

```
=====
                        OLS Regression Results
=====
Dep. Variable:          IEC_Power      R-squared:                0.964
Model:                  OLS            Adj. R-squared:           0.963
Method:                 Least Squares   F-statistic:              670.7
Date:                  Sat, 14 Jun 2025 Prob (F-statistic):       1.41e-19
Time:                  23:08:28         Log-Likelihood:           41.900
No. Observations:      27              AIC:                     -79.80
Df Residuals:          25              BIC:                     -77.21
Df Model:               1
Covariance Type:       nonrobust
=====
                        coef      std err          t      P>|t|      [0.025      0.975]
-----
const                0.1524      0.017      9.233      0.000      0.118      0.186
SA_Flow2             0.5197      0.020     25.898      0.000      0.478      0.561
=====
Omnibus:              14.761    Durbin-Watson:           1.537
Prob(Omnibus):        0.001    Jarque-Bera (JB):        27.023
Skew:                 0.925    Prob(JB):                1.36e-06
Kurtosis:             7.538    Cond. No.:               2.94
=====
```

Notes:

[1] Standard Errors assume that the covariance matrix of the errors is correctly specified.





Power in kW and supply air flow rate in kg/s

$$IEC\ SA\ Fan\ Power = 0.1009 + 0.2810 * SAflow^2$$

OLS Regression Results

```

=====
Dep. Variable:      IEC SA Fan Power (kW)  R-squared:                0.964
Model:              OLS                    Adj. R-squared:           0.962
Method:             Least Squares          F-statistic:             663.0
Date:               Sat, 14 Jun 2025       Prob (F-statistic):       1.62e-19
Time:               23:21:15               Log-Likelihood:           58.348
No. Observations:   27                    AIC:                     -112.7
Df Residuals:       25                    BIC:                     -110.1
Df Model:           1
Covariance Type:    nonrobust
=====

```

	coef	std err	t	P> t	[0.025	0.975]
const	0.1009	0.009	11.244	0.000	0.082	0.119
SA flow ^2	0.2810	0.011	25.748	0.000	0.259	0.303

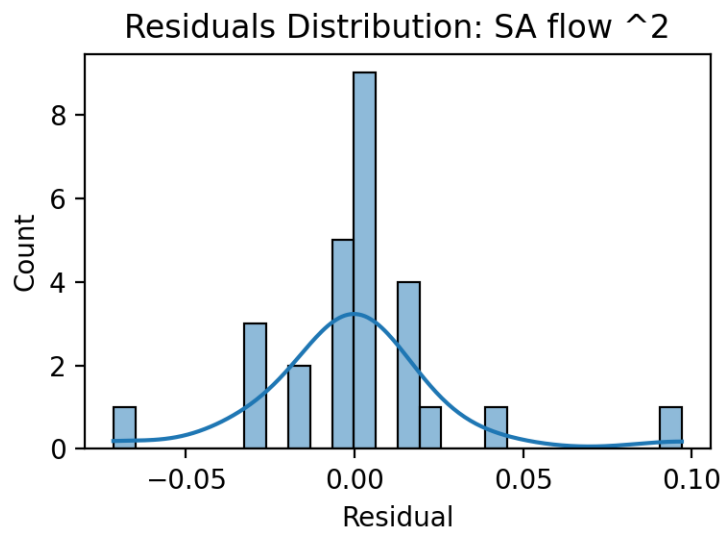
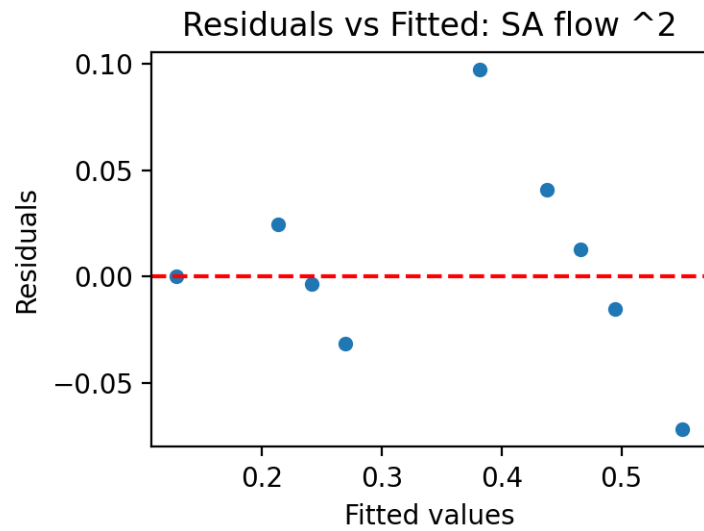
```

=====
Omnibus:            14.568  Durbin-Watson:           1.552
Prob(Omnibus):      0.001  Jarque-Bera (JB):       26.039
Skew:               0.923  Prob(JB):               2.22e-06
Kurtosis:           7.442  Cond. No.               2.94
=====

```

Notes:

[1] Standard Errors assume that the covariance matrix of the errors is correctly specified.



Regressions for Heat Pump Heating High SADB

Stage 2 heating. Temperatures in degrees Fahrenheit

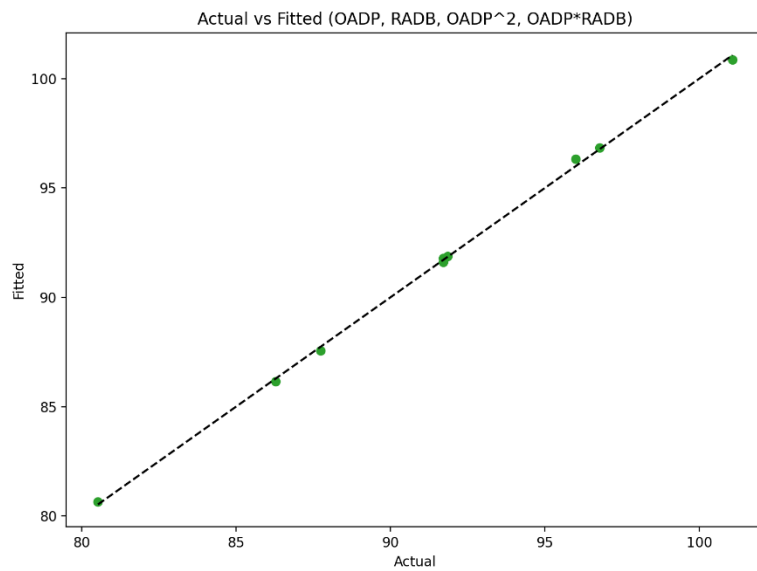
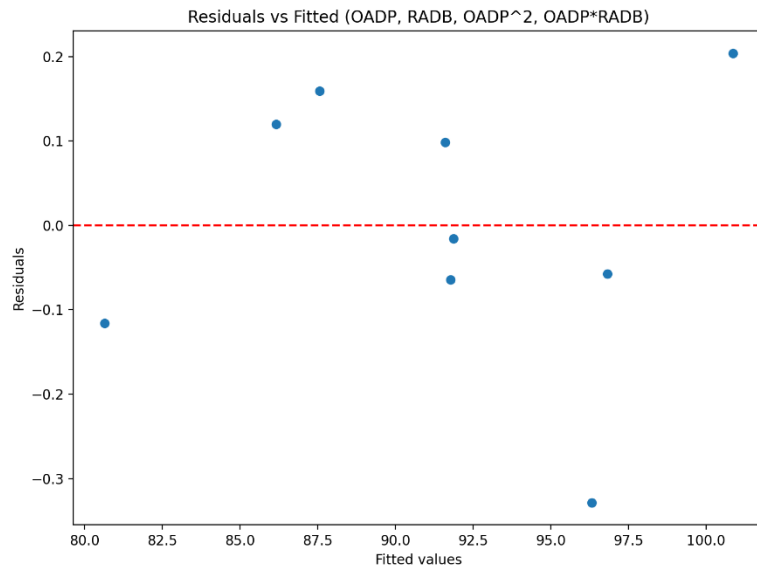
$$HP \text{ Heating High SADB} = -31.6301 + 1.5765 * OADP + 1.3958 * RADB - 0.0063 * OADP^2 - 0.0095 * OADP * RADB$$

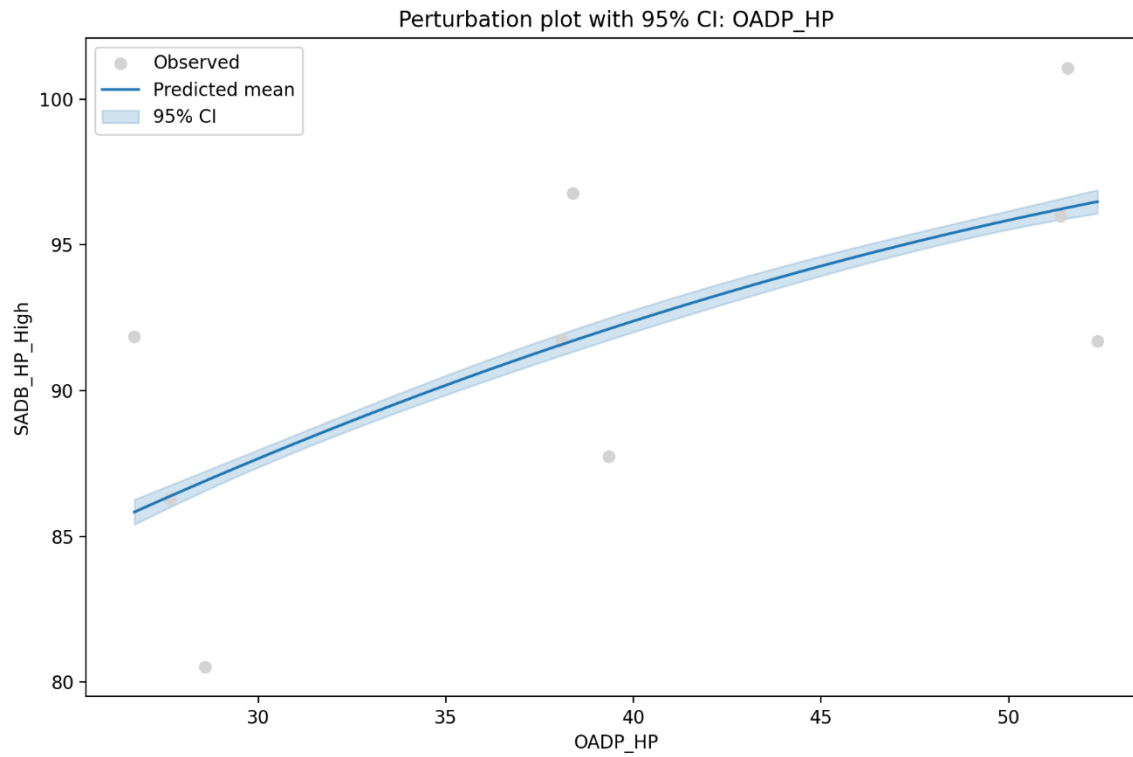
In-sample RMSE 0.15634258278726382

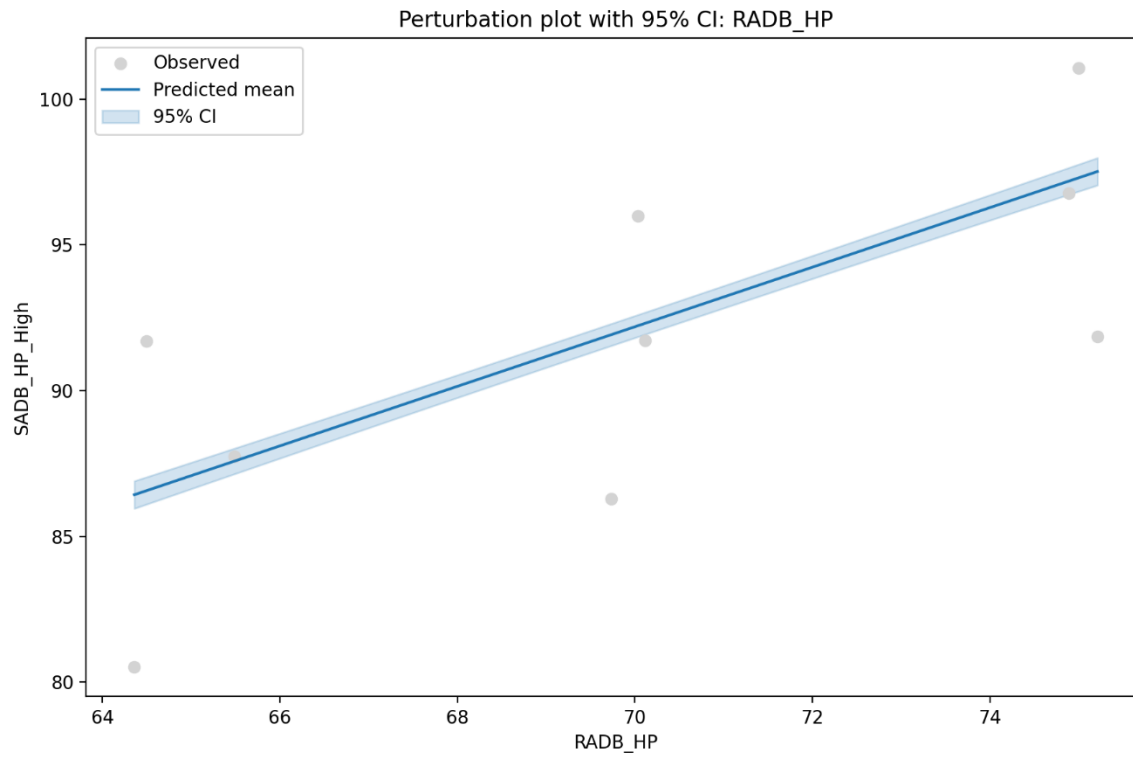
LOOCV RMSE 0.4209859783455509

OLS Regression Results						
=====						
Dep. Variable:	y	R-squared:	0.999			
Model:	OLS	Adj. R-squared:	0.999			
Method:	Least Squares	F-statistic:	1370.			
Date:	Thu, 07 Aug 2025	Prob (F-statistic):	1.60e-06			
Time:	22:38:35	Log-Likelihood:	3.9309			
No. Observations:	9	AIC:	2.138			
Df Residuals:	4	BIC:	3.124			
Df Model:	4					
Covariance Type:	nonrobust					
=====						
	coef	std err	t	P> t	[0.025	0.975]

const	-31.6301	5.741	-5.509	0.005	-47.571	-15.689
OADP_HP	1.5765	0.169	9.326	0.001	1.107	2.046
RADB_HP	1.3958	0.074	18.795	0.000	1.190	1.602
OADP_HP_sq	-0.0063	0.001	-5.482	0.005	-0.009	-0.003
OADP_HP_x_RADB_HP	-0.0095	0.002	-5.198	0.007	-0.015	-0.004
=====						
Omnibus:	1.573	Durbin-Watson:	1.598			
Prob(Omnibus):	0.455	Jarque-Bera (JB):	0.658			
Skew:	-0.645	Prob(JB):	0.720			
Kurtosis:	2.699	Cond. No.	2.47e+05			
=====						
Notes:						
[1] Standard Errors assume that the covariance matrix of the errors is correctly specified.						
[2] The condition number is large, 2.47e+05. This might indicate that there are strong multicollinearity or other numerical problems						







Regressions for Heat Pump Heating High Power

Stage 2 heating. Temperatures in degrees Fahrenheit

$$HP \text{ Heating High Power} = -0.2594 + 0.0399 * RADP + 0.0143 * OADB$$

Standard error (RMSE) 0.01496521 (kW) LOOCV RMSE: 0.02060859470784764 (kW)

```

=====
                        OLS Regression Results
=====
Dep. Variable:          y      R-squared:                0.995
Model:                  OLS    Adj. R-squared:           0.994
Method:                 Least Squares    F-statistic:        625.0
Date:                   Thu, 07 Aug 2025    Prob (F-statistic):  1.09e-07
Time:                   23:40:52    Log-Likelihood:      25.048
No. Observations:       9      AIC:                -44.10
Df Residuals:           6      BIC:                -43.50
Df Model:               2
Covariance Type:        nonrobust
=====

```

	coef	std err	t	P> t	[0.025	0.975]
const	-0.2594	0.107	-2.433	0.051	-0.520	0.002
OADB_HP	0.0143	0.001	22.701	0.000	0.013	0.016
RADB_HP	0.0399	0.001	27.386	0.000	0.036	0.043

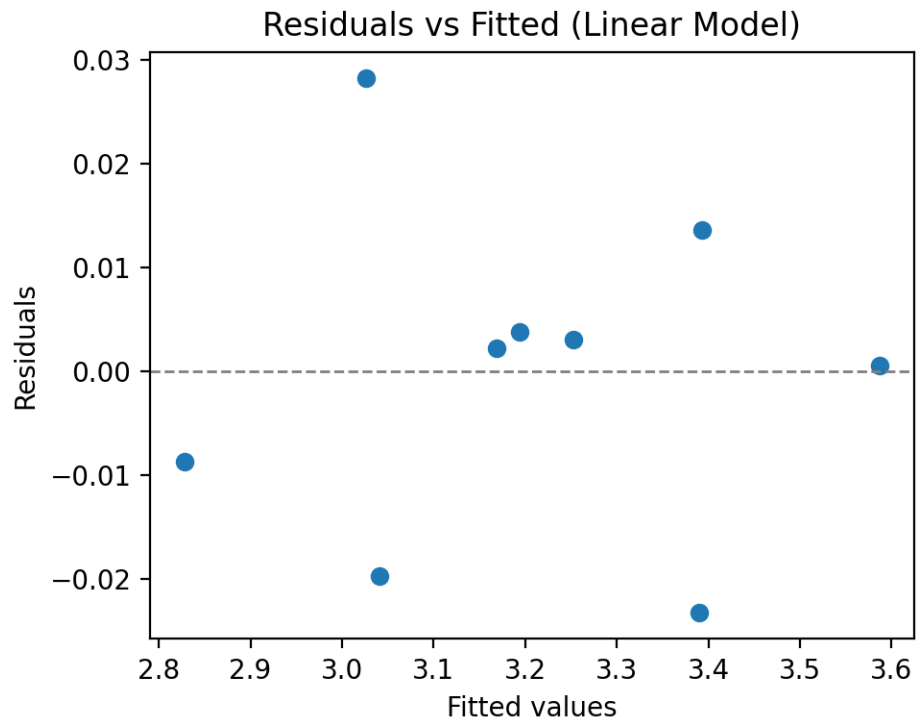
```

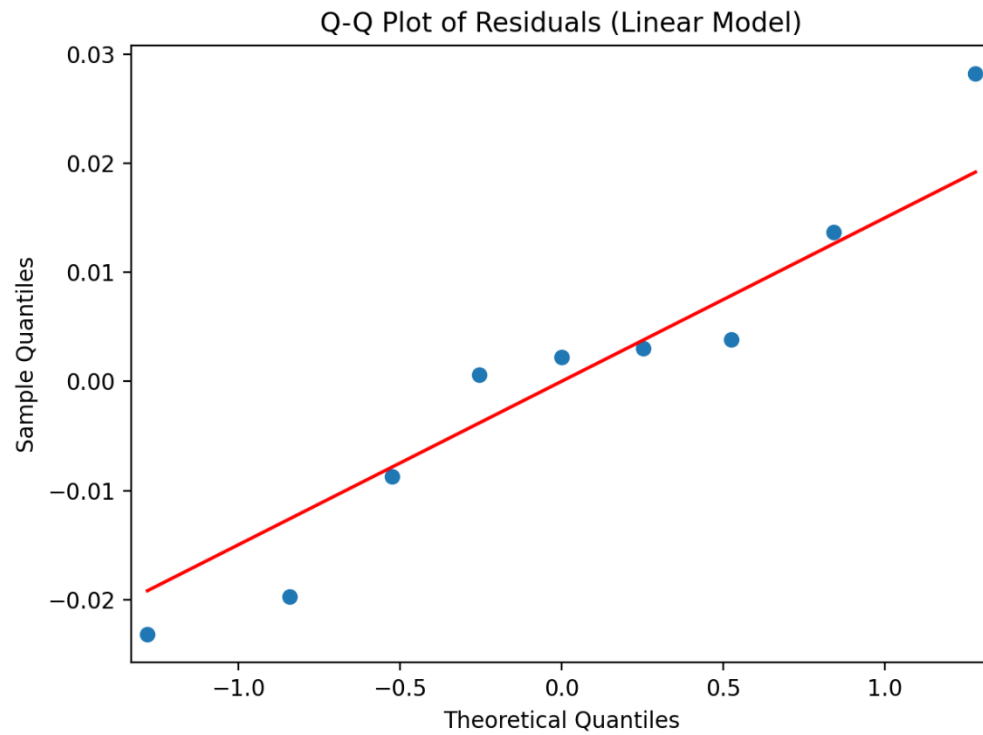
=====
Omnibus:                0.148    Durbin-Watson:          2.371
Prob(Omnibus):          0.929    Jarque-Bera (JB):         0.134
Skew:                   0.143    Prob(JB):                 0.935
Kurtosis:               2.474    Cond. No.                 1.48e+03
=====

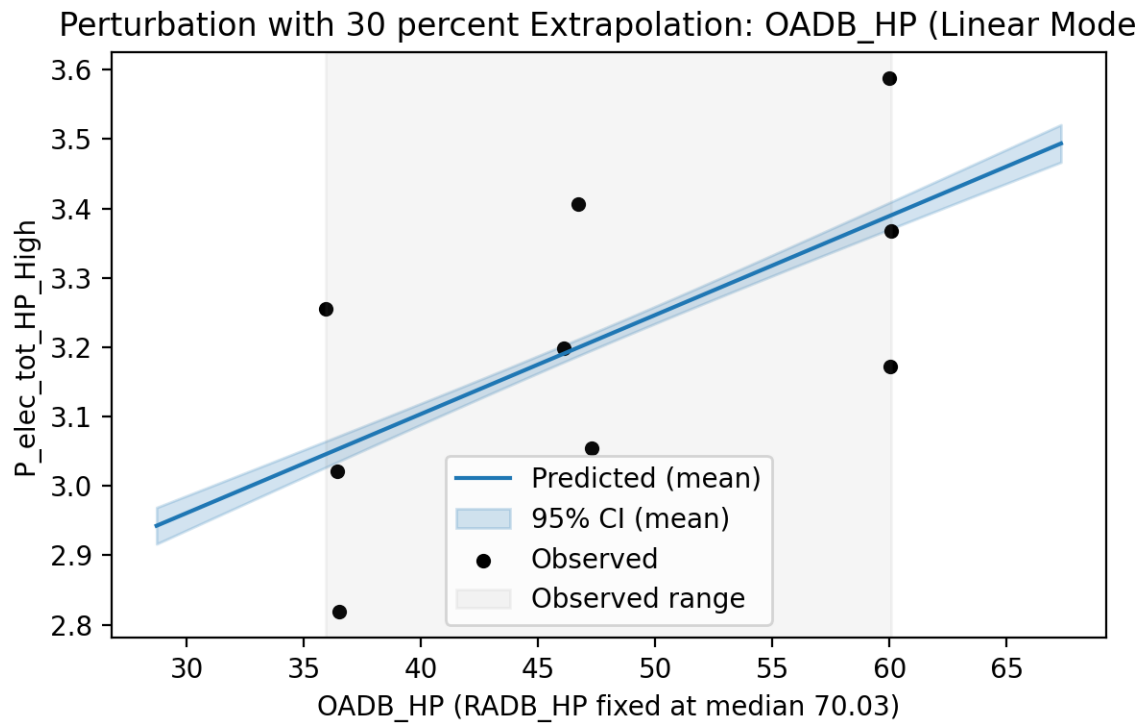
```

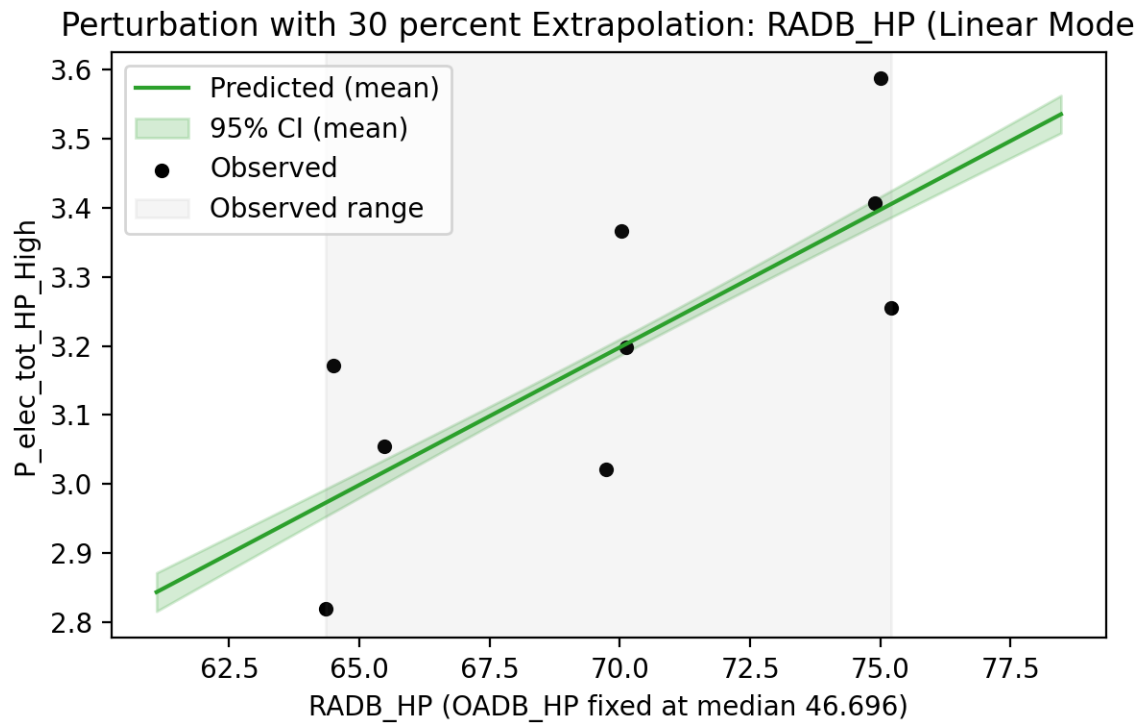
Notes:

- [1] Standard Errors assume that the covariance matrix of the errors is correctly specified.
- [2] The condition number is large, 1.48e+03. This might indicate that there are strong multicollinearity or other numerical problems.









Regression for Heat Pump Heating Low SADB

Stage 1 heating. Temperatures in degrees Fahrenheit

$$HP \text{ Heating Low SADB} = 6.250199 + 0.631334 * OADP - 0.002553 * OADP^2 + 0.934472 * RADB$$

In-sample RMSE 0.18012369108451332

LOOCV RMSE: 0.33484948380965024

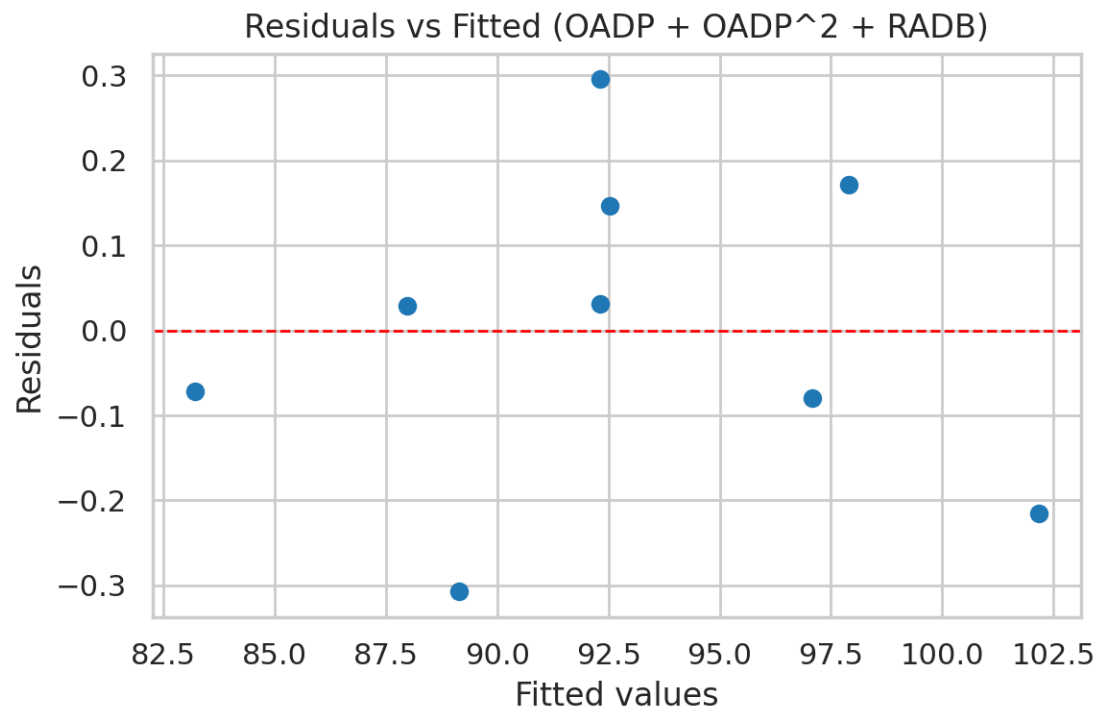
```

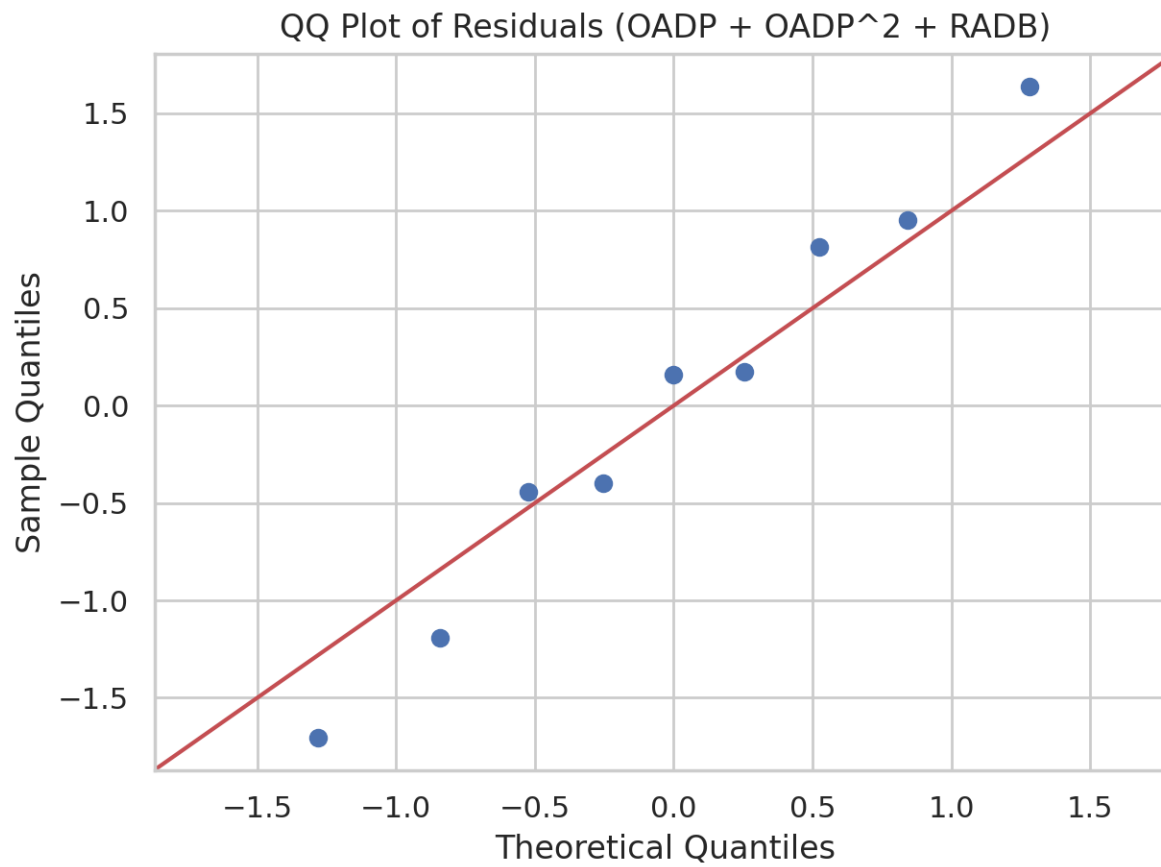
=====
                        OLS Regression Results
=====
Dep. Variable:          SADB_HP_Low    R-squared:                0.999
Model:                  OLS            Adj. R-squared:          0.998
Method:                 Least Squares   F-statistic:             1494.
Date:                   Fri, 08 Aug 2025 Prob (F-statistic):       8.44e-08
Time:                   00:10:27        Log-Likelihood:          2.6566
No. Observations:       9              AIC:                    2.687
Df Residuals:           5              BIC:                    3.476
Df Model:               3
Covariance Type:        nonrobust
=====
               coef    std err          t      P>|t|      [0.025    0.975]
-----
const          6.2502     2.657      2.352     0.065    -0.580    13.081
OADP_HP         0.6313     0.111     5.676     0.002     0.345     0.917
OADP_HP_sq     -0.0026     0.001    -1.872     0.120    -0.006     0.001
RADB_HP         0.9345     0.019    48.470     0.000     0.885     0.984
=====
Omnibus:            0.102    Durbin-Watson:           1.730
Prob(Omnibus):      0.950    Jarque-Bera (JB):         0.313
Skew:               -0.107    Prob(JB):                 0.855
Kurtosis:           2.112    Cond. No.                 6.07e+04
=====

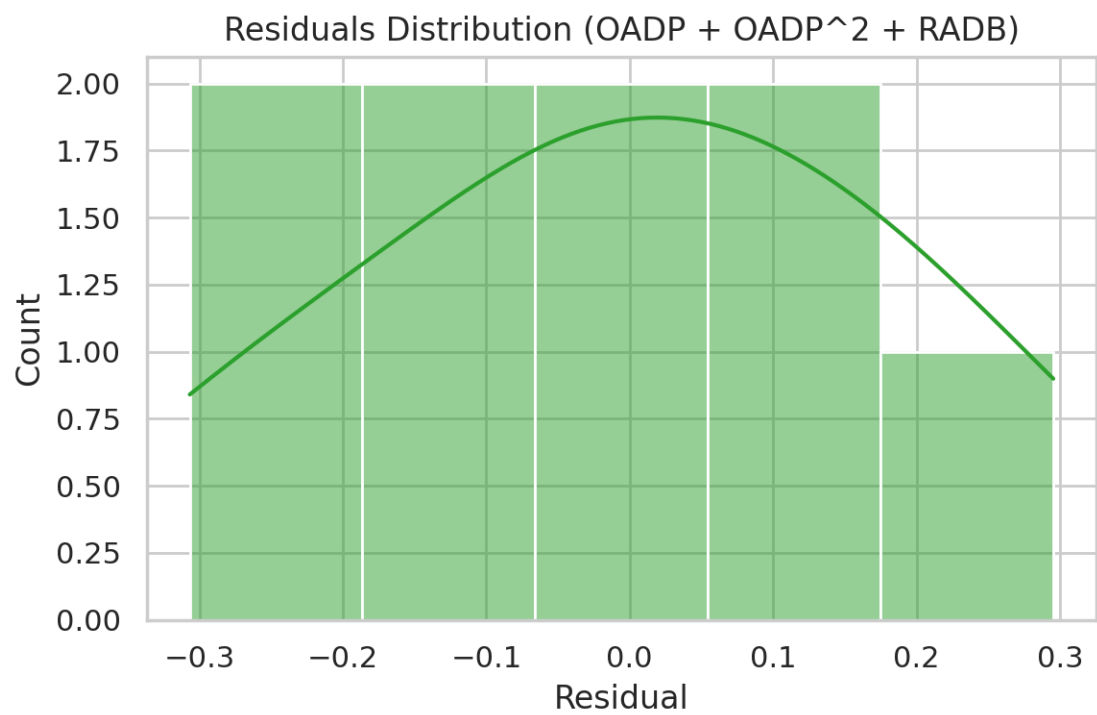
```

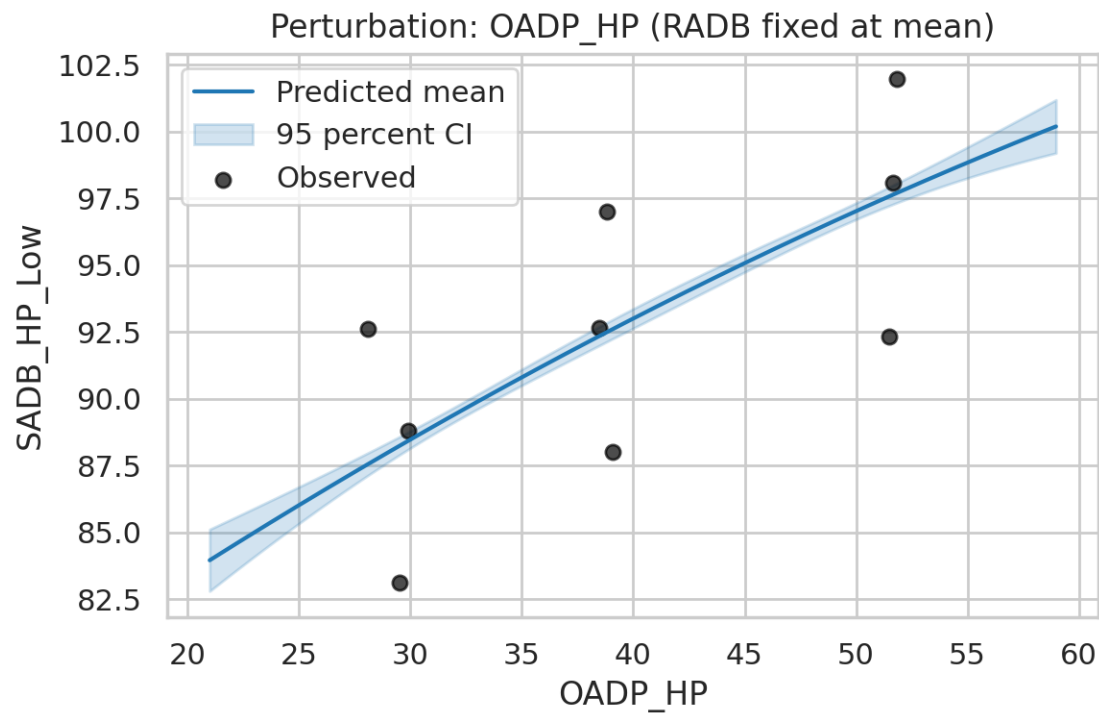
Notes:

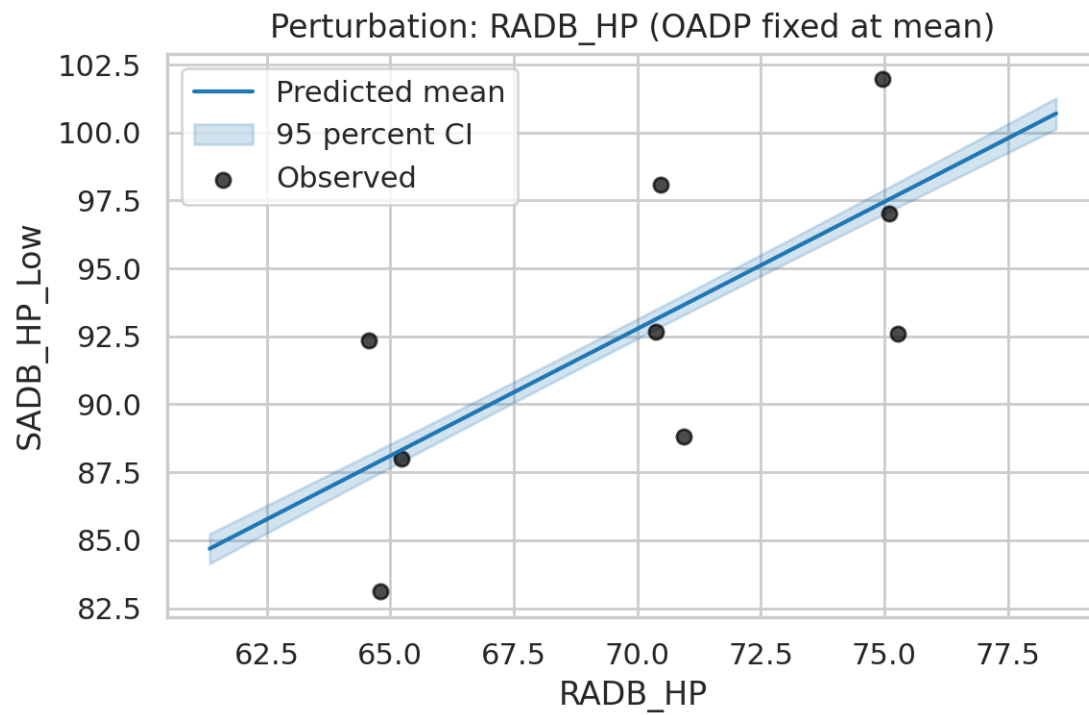
- [1] Standard Errors assume that the covariance matrix of the errors is correctly specified.
- [2] The condition number is large, 6.07e+04. This might indicate that there are strong multicollinearity or other numerical problems.











Regressions for Heat Pump Heating Low Power

Stage 1 heating. Temperatures in degrees Fahrenheit

$$HP \text{ Heating Low Power} = -0.057845 + 0.005331 * OADP + 0.032411 * RADB$$

In-sample RMSE: 0.009474998107105273

LOOCV RMSE: 0.013151433899946935 (kW)

OLS Regression Results

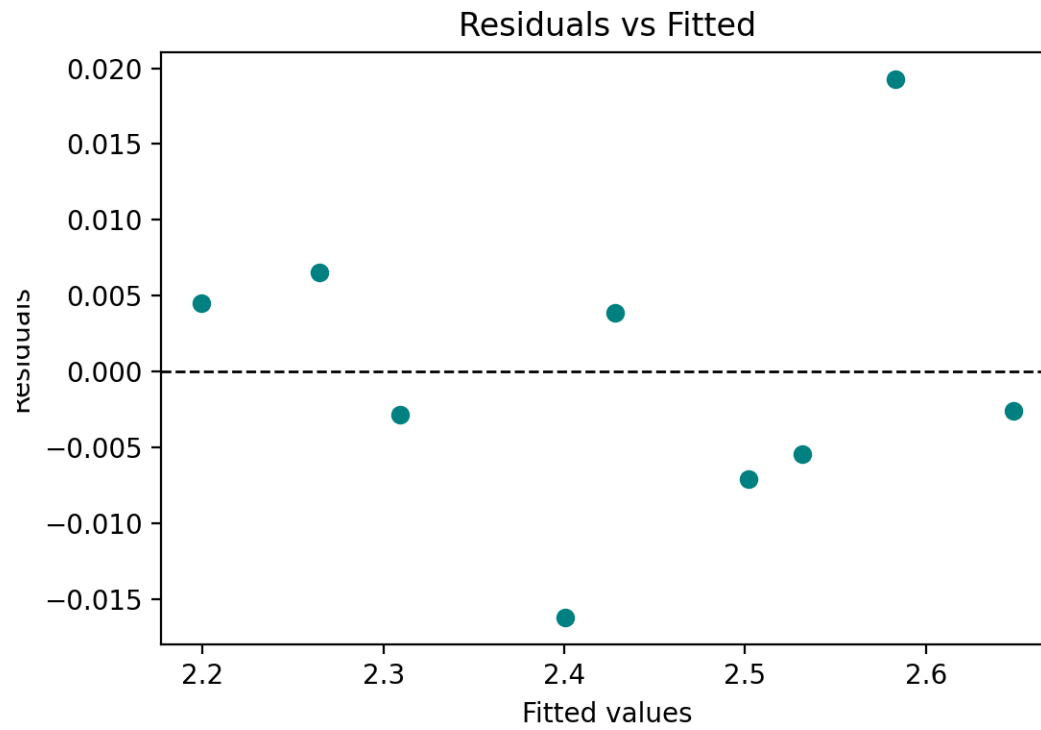
```
=====
Dep. Variable:    P_elec_tot_HP_Low    R-squared:                0.996
Model:            OLS                  Adj. R-squared:            0.994
Method:           Least Squares        F-statistic:              677.4
Date:            Fri, 08 Aug 2025      Prob (F-statistic):       8.57e-08
Time:            00:40:47              Log-Likelihood:           29.161
No. Observations: 9                   AIC:                      -52.32
Df Residuals:    6                   BIC:                      -51.73
Df Model:        2
Covariance Type: nonrobust
=====
```

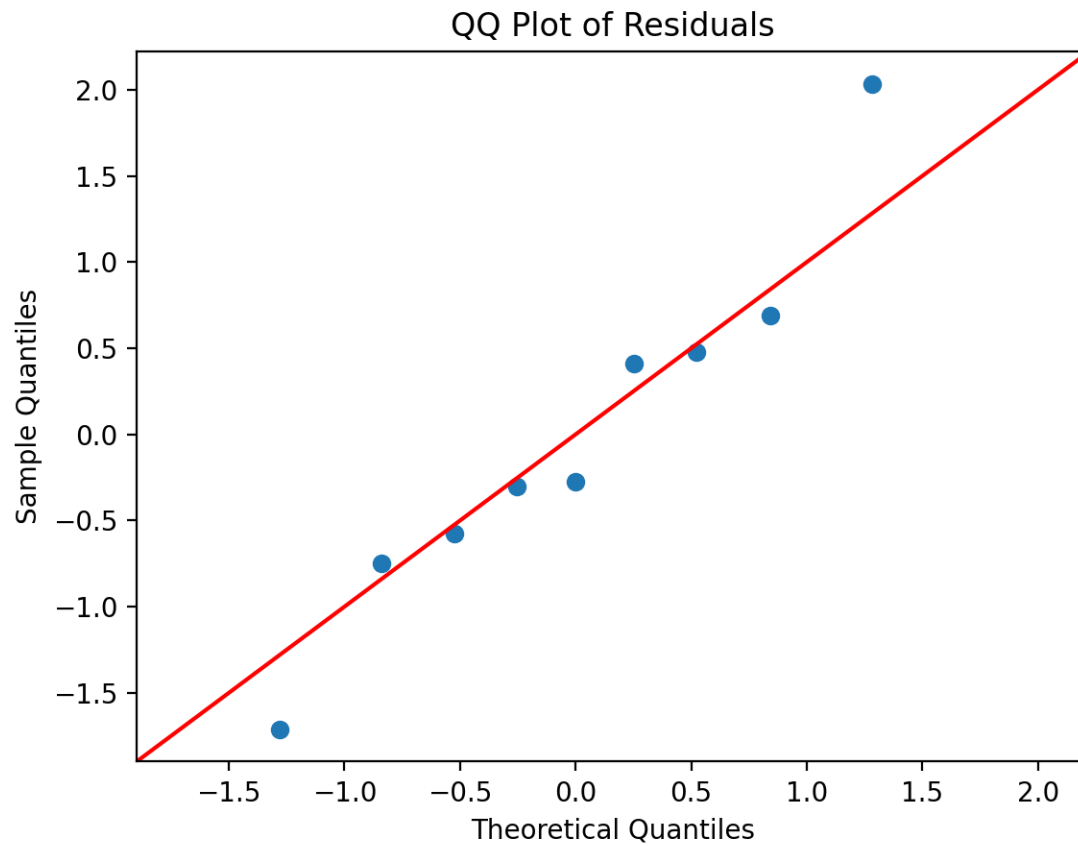
	coef	std err	t	P> t	[0.025	0.975]
const	-0.0578	0.068	-0.853	0.426	-0.224	0.108
OADP_HP	0.0053	0.000	12.704	0.000	0.004	0.006
RADB_HP	0.0324	0.001	35.135	0.000	0.030	0.035

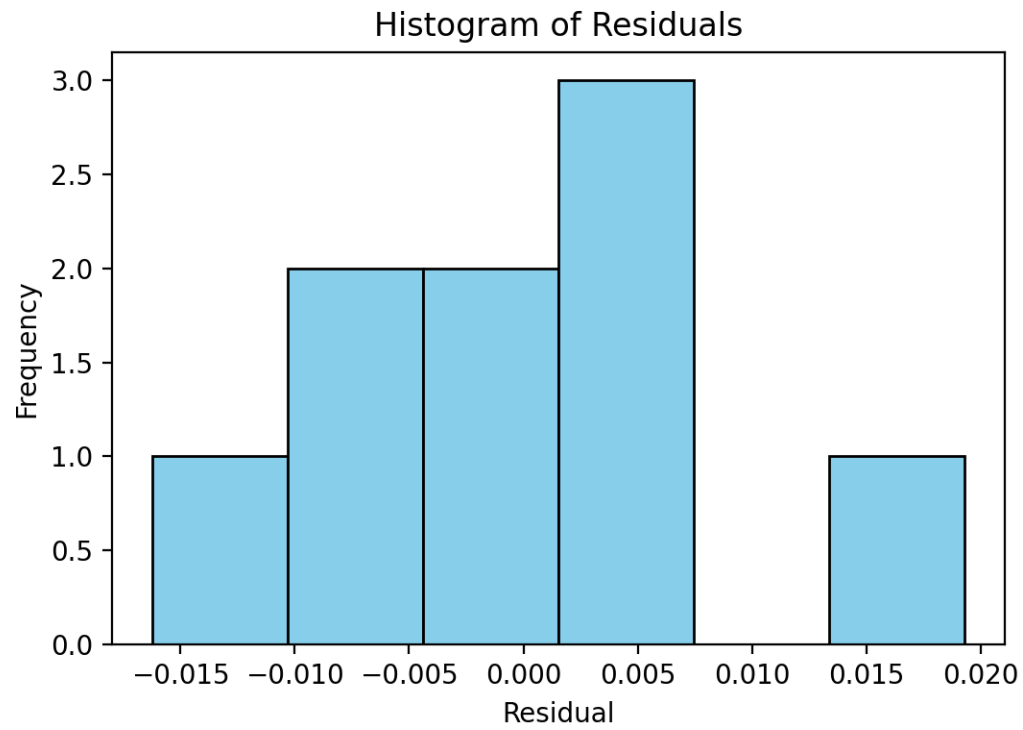
```
=====
Omnibus:            1.147    Durbin-Watson:           2.338
Prob(Omnibus):      0.564    Jarque-Bera (JB):         0.198
Skew:               0.362    Prob(JB):                 0.906
Kurtosis:           2.940    Cond. No.                 1.42e+03
=====
```

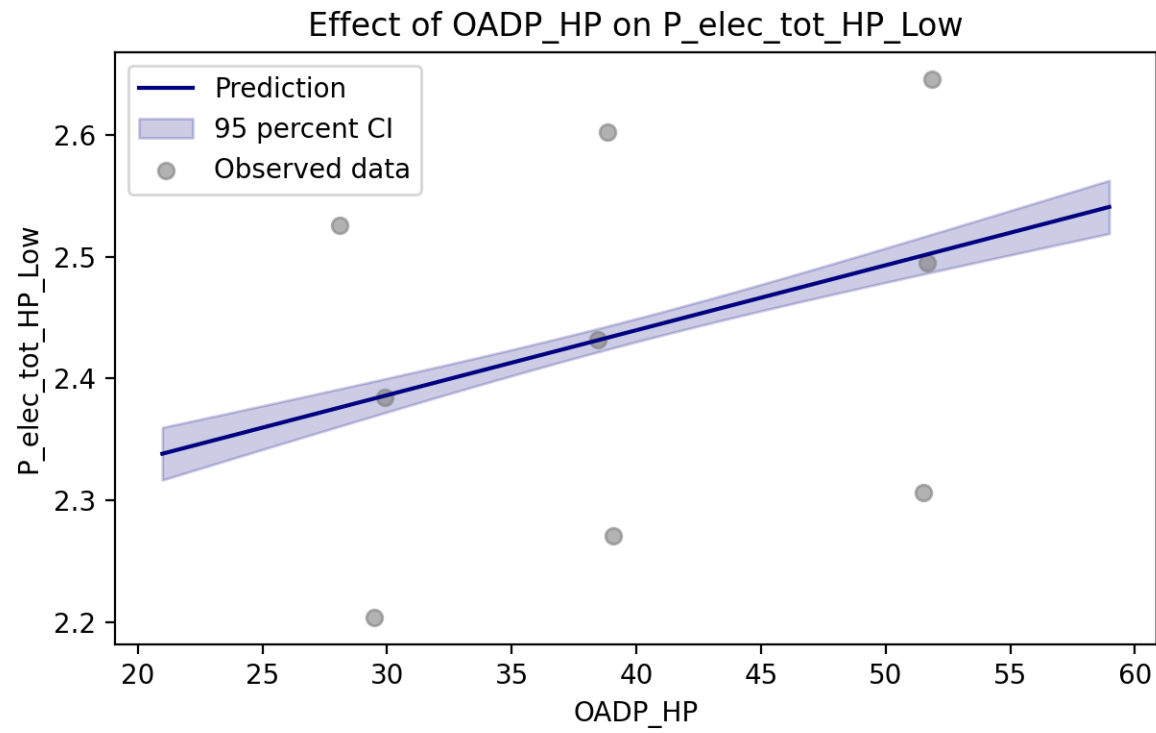
Notes:

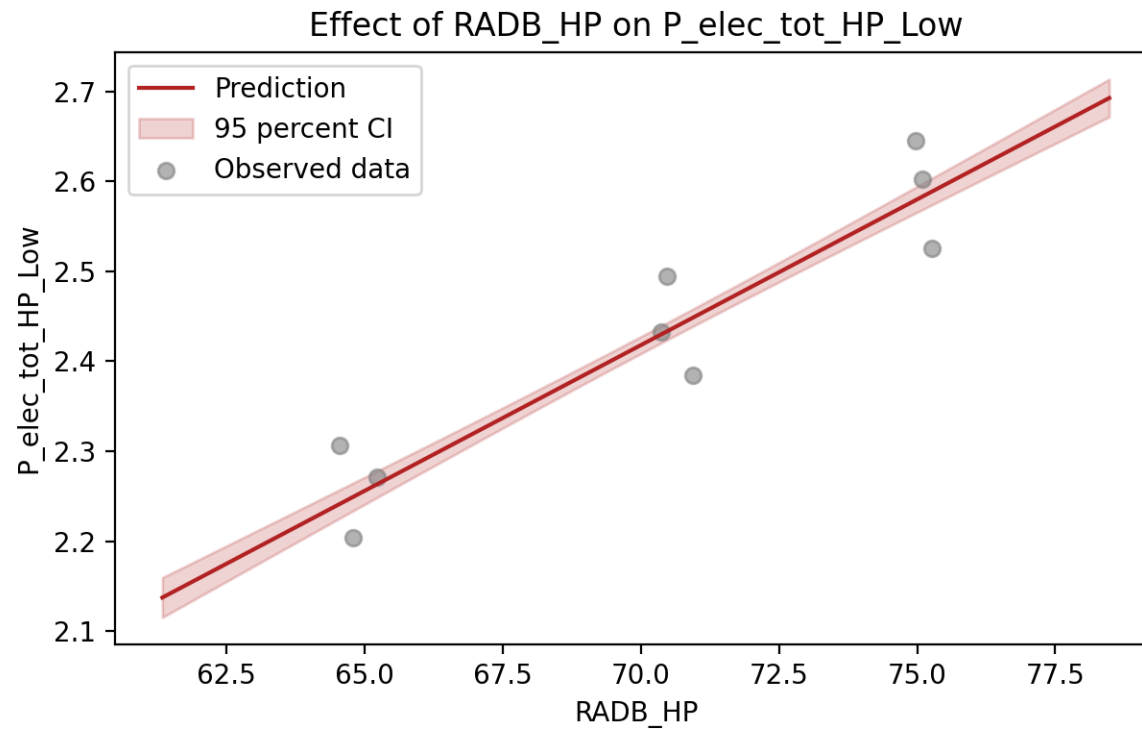
- [1] Standard Errors assume that the covariance matrix of the errors is correctly specified.
- [2] The condition number is large, 1.42e+03. This might indicate that there are strong multicollinearity or other numerical problems.











Appendix C: Calculation of Hybrid Performance from Separate Heat Pump and Evaporative Cooler Performance

The Heat Pump cooling mode regressions are used to estimate the supply air dry bulb and dewpoint temperatures and total power consumption if the heat pump were operating at the heat pump return air condition and the evaporative section outdoor condition tests for that combination. The power of the heat pump supply fan, and the evaporative supply and exhaust fans are adjusted to account for the higher power required to provide the same air flow rates in hybrid operation with higher external static pressure.

$$T_{SA,DX,hyb,reg} = -222.7 + 8.458 \cdot DP_{RA,DX} - 0.063761543 \cdot DP_{RA,DX}^2 + 0.097588285 \cdot T_{OA,IDEC} + 0.000490376 \cdot T_{OA,IDEC}^2 - 0.001422425 \cdot DP_{RA,DX} \cdot T_{OA,IDEC}$$

$$DP_{SA,DX,hyb,reg} = -122.653 + 4.821876 \cdot DP_{RA,DX} - 0.03161 \cdot DP_{RA,DX}^2 + 0.154768 \cdot T_{OA,IDEC} + 0.000316 \cdot T_{OA,IDEC}^2 - 0.00253 \cdot DP_{RA,DX} \cdot T_{OA,IDEC}$$

$$P_{elec,tot,DX,hyb,reg} = (11.75404 - 0.37136 \cdot DP_{RA,DX} + 0.003605 \cdot DP_{RA,DX}^2 + 0.019823 \cdot T_{OA,IDEC} + 0.000234 \cdot T_{OA,IDEC}^2 - 0.00044 \cdot DP_{RA,DX} \cdot T_{OA,IDEC}) \cdot 1000$$

$$P_{elec,tot,DX,hybrid} = P_{elec,tot,DX,hyb,reg} - P_{SA,fan,DX} + P_{SA,fan,DX,hybrid}$$

$$P_{elec,tot,IDEC,hybrid} = P_{elec,tot,IDEC} - P_{SA,fan,IDEC} + P_{SA,fan,IDEC,hybrid} - P_{exh,fan,IDEC} + P_{exh,fan,IDEC,hybrid}$$

$$P_{elec,tot,hybrid} = P_{elec,tot,DX,hybrid} + P_{elec,tot,IDEC,hybrid}$$

Hybrid air mixing at same flow rates as separate operation so do not need updated variable values

$$\dot{m}_{\text{hybrid,mix}} = \dot{m}_{\text{IDEC}} + \dot{m}_{\text{DX}}$$

Temperature change due to additional fan heat

$$T_{\text{SA,IDEC,hybrid}} = T_{\text{SA,IDEC}} + \frac{1}{cp_{\text{SA,IDEC,pre}}} \cdot \left[\frac{P_{\text{SA,fan,IDEC,hybrid}} \cdot \left| 0.056869019 \cdot \frac{\text{Btu/min}}{W} \right| - P_{\text{SA,fan,IDEC}} \cdot \left| 0.056869019 \cdot \frac{\text{Btu/min}}{W} \right|}{\dot{m}_{\text{IDEC}}} \right]$$

$$T_{\text{SA,DX,hybrid}} = T_{\text{SA,DX,hyb,reg}} + \frac{1}{cp_{\text{SA,DX}}} \cdot \left[\frac{P_{\text{SA,fan,DX,hybrid}} \cdot \left| 0.056869019 \cdot \frac{\text{Btu/min}}{W} \right| - P_{\text{SA,fan,DX}} \cdot \left| 0.056869019 \cdot \frac{\text{Btu/min}}{W} \right|}{\dot{m}_{\text{DX}}} \right]$$

Enthalpy of $h_{SA,IDEC,hybrid}$ and $h_{SA,DX}$ calculated from the adjusted dry bulb temperatures above and the IDEC RH or DX dewpoint temperatures respectively

$$h_{SA,DX,hybrid} = h \left(\text{AirH2O}, T = T_{SA,DX,hybrid}, D = DP_{SA,DX,hyb,reg}, P = P \right)$$

$$h_{SA,IDEC,hybrid} = h \left(\text{AirH2O}, T = T_{SA,IDEC,hybrid}, D = DP_{SA,IDEC}, P = P \right)$$

$$h_{SA,hybrid,mix} = \frac{\dot{m}_{IDEC} \cdot h_{SA,IDEC,hybrid} + \dot{m}_{DX} \cdot h_{SA,DX,hybrid}}{\dot{m}_{hybrid,mix}}$$

water balance

$$\omega_{SA,IDEC} = \omega \left(\text{AirH2O}, T = T_{SA,IDEC}, D = DP_{SA,IDEC}, P = P \right)$$

$$\omega_{SA,DX} = \omega \left(\text{AirH2O}, T = T_{SA,DX,hybrid}, D = DP_{SA,DX,hyb,reg}, P = P \right)$$

$$\omega_{SA,hybrid,mix} = \frac{\omega_{SA,IDEC} \cdot \dot{m}_{IDEC} + \omega_{SA,DX} \cdot \dot{m}_{DX}}{\dot{m}_{hybrid,mix}}$$

$$T_{SA,hybrid,mix} = T \left(\text{AirH2O}, h = h_{SA,hybrid,mix}, w = \omega_{SA,hybrid,mix}, P = P \right)$$

$$DP_{SA,hybrid,mix} = DP \left(\text{AirH2O}, h = h_{SA,hybrid,mix}, w = \omega_{SA,hybrid,mix}, P = P \right)$$

SA enthalpy at T_{SA} but DP_{RA} to only count sensible cooling

$$q_{room,sens,hybrid,mix} = \dot{m}_{hybrid,mix} \cdot (h_{RA,DX} - h \left(\text{AirH2O}, T = T_{SA,hybrid,mix}, D = DP_{RA,DX}, P = P \right))$$

$$\text{COP}_{\text{room,sens,hybrid,mix}} = \frac{q_{\text{room,sens,hybrid,mix}}}{P_{\text{elec,tot,hybrid}} \cdot \left| 0.056869019 \cdot \frac{\text{Btu/min}}{\text{W}} \right|}$$

$$q_{\text{system,sens,hybrid}} = \dot{m}_{\text{hybrid,mix}} \cdot (h_{\text{RA,DX}} - h(\text{AirH2O}, T = T_{\text{SA,hybrid,mix}}, D = DP_{\text{RA,DX}}, P = P)) + \dot{m}_{\text{IDEC}} \cdot cp_{\text{avg,system,IDEC2}} \cdot (T_{\text{OA,IDEC}} - T_{\text{RA,DX}})$$

$$cp_{\text{avg,system,IDEC2}} = \frac{cp_{\text{OA,IDEC}} + cp_{\text{RA,IDEC}}}{2}$$

Appendix D: Evaporative Water Consumption Calculations

The evaporative water consumption was estimated from the measured sensible system cooling capacity by dividing by the enthalpy of vaporization of water at atmospheric pressure. The sensible system cooling capacity was reduced to account for the reduction in evaporation due to the sensible heating of secondary air as it moves through the wet channels assuming that the manufacturer target primary to secondary air ratios were achieved, and that the secondary air reaches 0% or 80% of the difference between the IDEC supply air temperature that it started at to the outdoor dry bulb temperature (Secondary approach OAT = 0 or 0.8). The sensible system cooling capacity was also increased to account for the additional cooling required to cool the secondary air flow from the outdoor temperature to the exhaust temperature with the same assumptions. The secondary approach OAT = 0 gives the upper bound for water consumption and the 0.8 gives a lower bound.

$$cp_{\text{secondary, IDEC}} = Cp \left(\text{AirH}_2\text{O}, T = T_{\text{SA, IDEC}}, D = DP_{\text{OA, IDEC}}, P = P \right)$$

$$\text{secondary}_{\text{approach, OAT}} = 0.8$$

$$q_{\text{sens, secondary, IDEC}} = \dot{m}_{\text{IDEC}} \cdot \left(\text{IEC}_{\text{secondary, air, ratio}} - 1 \right) \cdot cp_{\text{SA, IDEC, pre}} \cdot \text{secondary}_{\text{approach, OAT}} \cdot \left(T_{\text{OA, IDEC}} - T_{\text{SA, IDEC}} \right)$$

$$q_{\text{secondary, unrecov, IDEC}} = \left(\dot{m}_{\text{IDEC}} \cdot \left(\text{IEC}_{\text{secondary, air, ratio}} - 1 \right) \cdot cp_{\text{SA, IDEC, pre}} \cdot \left(1 - \text{secondary}_{\text{approach, OAT}} \right) \right) \cdot \left(T_{\text{OA, IDEC}} - T_{\text{SA, IDEC}} \right)$$

$$m_{\text{water, IDEC, adjusted}} = \frac{q_{\text{system, sens, IDEC}} - q_{\text{sens, secondary, IDEC}} + q_{\text{secondary, unrecov, IDEC}}}{\text{Enthalpy}_{\text{vaporization}} \left(\text{Water}, P = P \right)}$$