Packaged Roof Top Unit with Integrated Heat Pump and Indirect/Direct Evaporative Cooling

ET21PGE1902

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Issued: March 18, 2022

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Acknowledgements

Pacific Gas and Electric's Emerging Technology (ET) Team is responsible for this project. It was developed as part of Southern California Edison's Emerging Technologies Program under internal project number ET21PGE1902. Kelly Cunningham conducted this technology evaluation with overall guidance and management from Andrew Doeschot. Contact andrew.doeschot@pge.com for more information on this project.

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EXECUTIVE SUMMARY

A packaged heating, ventilation, and air conditioning (HVAC) system is an integrated piece of mechanical equipment that provides all three mechanical functions for a space. packaged roof top units (RTUs), which are the baseline technology assessed in this study, are the predominant method of building conditioning in California. It is estimated that 75% of commercial building floor area in California is conditioned with packaged systems [1]. The emerging technology assessed in this study is a packaged RTU that integrates a heat pump with an indirect-direct evaporative cooling (IDEC) system that is designed as a direct replacement for a traditional RTU. This project evaluates the packaged heat pump with IDEC in a field study and compares its performance to a baseline packaged RTU.

The IDEC system with a heat pump (Figure ES-1) combines the energy saving benefits of evaporative cooling with the capabilities of a heat pump. The IDEC system portion operates with 100% outdoor air filtered by MERV 13 filters on the inlet. The system operates using both indirect and direct cooling in series by passing the air through an indirect evaporative heat exchanger followed by direct evaporative media. The resulting supply air is below the wet bulb temperature of the ambient air, meaning that comfort can be maintained in buildings in dry climates like California using significantly less electricity than compressor-based air conditioners. The single-speed heat pump side of the system can provide either heating or cooling based on the position of the reversing valve. The supply air on the heat pump is recirculated from the room and filtered with a MERV 13 filter.

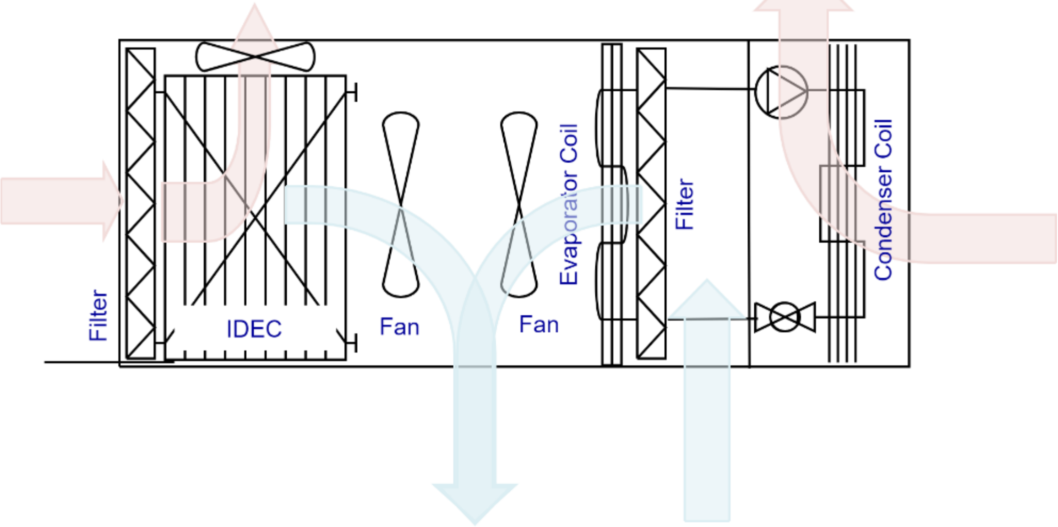

FIGURE ES- 1: EMERGING TECHNOLOGY COMBINING AN IDEC (LEFT) WITH A HEAT PUMP (RIGHT) INTO ONE PACKAGED RTU

A field evaluation was conducted in two similar classrooms in the same building at East Side Union High School District in San Jose, CA from June, 2021 through January, 2022. One classroom was conditioned with the baseline system and the other was conditioned with the newly installed packaged heat pump with IDEC. A simplified model based on outdoor weather correlations was built from the field data and energy impacts over an entire school year in four California cities were analyzed.

The packaged heat pump with IDEC technology demonstrated it was able to maintain thermal comfort, increase outside air for human health and performance, eliminate natural gas combustion for heating, and save electricity, even when including the electricity used for heating. The model showed that the expected energy impact in four California cities is a 4-33% reduction in electricity use and elimination of natural gas for heating (Figure ES-2).

Note that for a total energy calculation, assumptions on power generation and distribution must be made to estimate equivalence between kWh and therms, and the two cannot simply be added as they are shown in the stacked bar chart. The gas consumption in the figure is intended to serve as a visual reminder that gas consumption is eliminated with the packaged heat pump with IDEC technology.

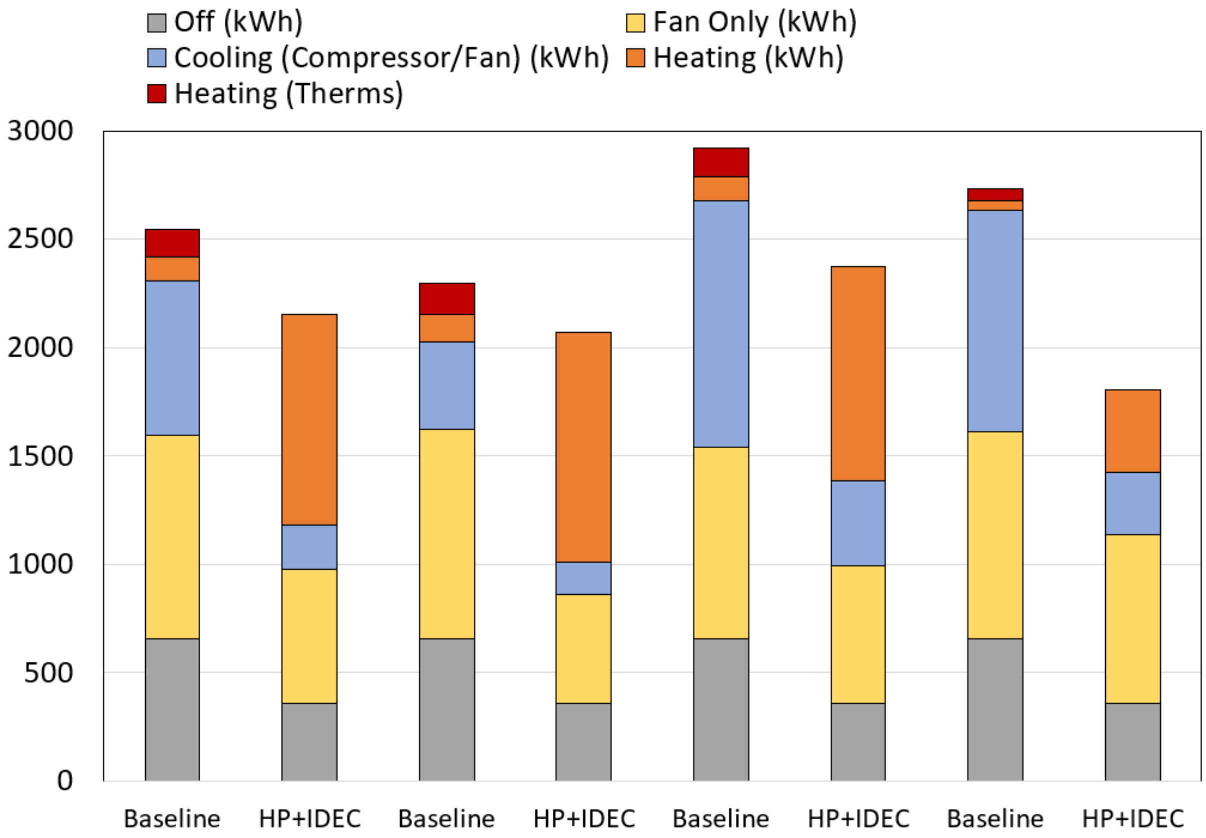

FIGURE ES- 2: BREAKDOWN OF ANNUAL ELECTRICITY AND NATURAL GAS FOR BASELINE AND PACKAGED HEAT PUMP WITH IDEC SYSTEMS FOR FOUR MODELED CITIES.

Electricity used was reduced through a combination of reduced standby power, improved ventilation system efficiency, and reduced use of compressor-based cooling in favor of more efficient evaporative cooling. Reduced standby power for the packaged heat pump with IDEC resulted in 45% energy savings in off mode. As building energy efficiency improves, standby power is an important load to consider that is often overlooked. The fan only mode energy use, which also included providing evaporative cooling when applicable, was reduced 18-48% in the packaged heat pump with IDEC over the baseline. Cooling mode with the compressor engaged had the most drastic savings, with 63-72% energy saving for the packaged heat pump with IDEC over the baseline.

The maximum 15-minute peak demand during the hottest hours of the summer was approximately the same for both the baseline and packaged heat pump with IDEC systems. The maximum 15-minute peak demand for the packaged heat pump with IDEC in heating mode increased to approximately 4-4.5kW compared to 0.7kW for the baseline, due to the use of the heat pump instead of gas heat.

The packaged heat pump with IDEC was estimated to consume 3,600-5,700 gallons of water annually to achieve this electricity savings, which equates to an average of 8.5 gallons consumed per kWh saved for cooling. For context, this is less water than the average person consumes annually for daily showers. The analysis also showed an expected increase in ventilation air of 25-59% above the baseline, which is an important finding expected to result in reduced probability of long-range airborne transmission of infectious disease and improved student performance.

The packaged heat pump with IDEC is manufactured in an RTU format that is a drop-in replacement for existing packaged RTUs. Installation was straightforward and required only the addition of a curb adapter, which is typical when switching between different RTU manufacturers. Remaining market barriers are potentially higher weight compared to lower-efficiency RTUs, a requirement for water service to the unit, and equipment first cost. Since this demonstration was the first packaged heat pump with IDEC RTU installed, production cost data is not yet available. As with all emerging technology, cost is expected to decrease with increased production.

The packaged heat pump with IDEC is a unique drop-in replacement for packaged RTUs that supports California’s goals for decarbonization and electricity savings. The assessment provides the required data needed to consider inclusion of the technology in an energy efficiency program. Since the technology is weather dependent, additional modeling is recommended to estimate savings impacts for additional building types and to determine if heat pump capacity is sufficient for California’s coldest climates. Additional demonstrations of the technology will increase awareness and confidence in the technology for end users.

ABBREVIATIONS AND ACRONYMS

CFM	Cubic Feet per Minute
kW	Killowatt
kWh	Killowatt-hour
IDEC	Indirect-Direct Evaporative Cooling
HVAC	Heating, Ventilation, and Air Conditioning
MERV	Minimum Efficiency Reporting Value
OA	Outdoor Air
RA	Return Air
RTU	Roof Top Unit
SA	Supply Air
SEER	Seasonal Energy Efficiency Ratio
VOC	Volatile Organic Compounds

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INTRODUCTION

A packaged heating, ventilation, and air conditioning (HVAC) system is an integrated piece of mechanical equipment that provides all three mechanical functions for a space. packaged roof top units (RTUs), which are the baseline technology assessed in this study, are the predominant method of building conditioning in California. It is estimated that 75% of commercial building floor area in California is conditioned with packaged systems [1]. An RTU generally consists of a mixing box for return air (RA) and outdoor air (OA), filter, evaporator coil (for cooling), supply fan, and gas furnace (Figure 1). A compressor-based refrigerant circuit is used to supply cooling to the evaporator coil. packaged RTUs that include a heat pump are also common, where the refrigerant circuit can switch directions using a reversing valve and provide heating with the indoor coil. Both gas furnace and electric resistance backup heat options are available. Efficiency improvements to RTUs have generally included small incremental improvements to the existing technology, such as variable speed fan motor controls, economizers to use outside air for cooling when possible, and increasing refrigerant circuit efficiency (which generally increases system size and weight).

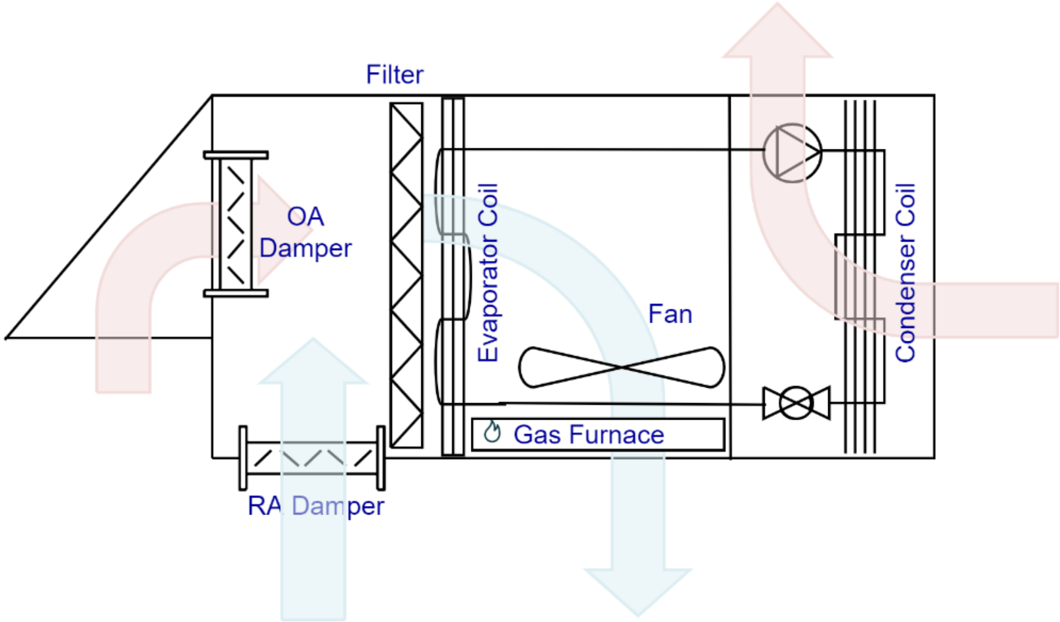


FIGURE 1. TYPICAL CONFIGURATION OF A ROOFTOP UNIT

The emerging technology assessed in this study is a packaged RTU that integrates a heat pump with an indirect-direct evaporative cooling (IDEC) system that is designed as a direct replacement for a traditional RTU. This project evaluates the packaged heat pump with IDEC in a field study and compares its performance to a baseline packaged RTU.

BACKGROUND

Indirect-direct evaporative cooling has been the subject of several emerging technology evaluations over the last 10 years [2] [3] [4]. Savings in electricity and peak demand have been compelling, however, the technology is still limited in its adoption relative to its potential. One significant market barrier is that indirect evaporative cooling technology in commercial buildings has historically been installed as a supplement to an existing building design with RTUs. Installing indirect evaporative cooling technology as a supplement, involves acquiring and maintaining two pieces of equipment (an RTU and an indirect-evaporative cooler) and making the necessary mechanical and control system modifications to interface the two pieces of equipment with the building. As a result, project costs and complexity increase and affect stakeholder motivation and ability to acquire the technology [5]. The packaged heat pump with IDEC is novel in that it is an all-electric, one-box, drop-in replacement for an RTU, which aims to support building decarbonization efforts and reduce the barriers to adopting evaporative cooling technology.

EMERGING TECHNOLOGY/PRODUCT

Combining the IDEC system with a heat pump (Figure 3) achieves the energy saving benefits of evaporative cooling with the capabilities of a heat pump. The IDEC system portion of the system with 100% outdoor air. The system operates using both indirect and direct cooling in series by passing the air through an indirect evaporative heat exchanger followed by direct evaporative media (Figure 2). The hot, dry outdoor air is first cooled indirectly with cool, moist air through a heat exchanger. Once precooled, ~45% of the cooled outdoor air is diverted to the wet channels of the heat exchanger to cool incoming outdoor air, while the other 55% is sent through the direct evaporative media where it is adiabatically cooled further before getting delivered to the space (Figure 2). A supply and exhaust fan control the ratio of the air streams and two pumps provide water for the indirect and direct evaporative processes. The resulting supply air is below the wet bulb temperature of the ambient air, meaning that comfort can be maintained in buildings in dry climates like California using significantly less electricity than compressor-based air conditioners [6]. However, indirect evaporative cooling does not provide any dehumidification capability and may not be sufficient to meet cooling requirements in California climates on days when humidity is elevated.

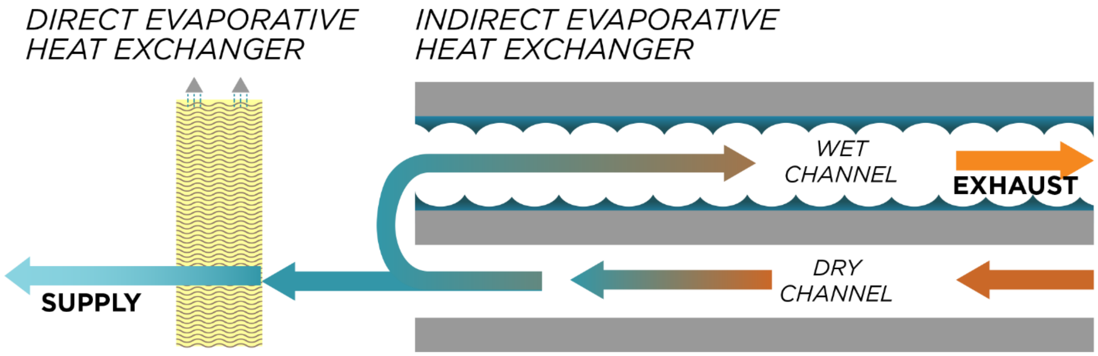


FIGURE 2. DIAGRAM OF THE INDIRECT-DIRECT COOLING PROCESS. OUTDOOR AIR ENTERS THE DRY CHANNEL, IS INDIRECTLY COOLED BY THE DIVERTED AIR BEING EXHAUSTED OUT THE WET CHANNEL AND IS THEN FINALLY DIRECTLY COOLED WITH WETTED EVAPORATIVE MEDIA, PRIOR TO BEING SENT INTO THE CONDITIONED SPACE.

The IDEC uses variable speed supply and exhaust fans to control the rate of outdoor air into the space. All air entering the IDEC is filtered with two-inch deep pleated filters with a minimum efficiency reporting value (MERV) of 13. The IDEC can run with the water off to supply outdoor air without cooling, either to provide a minimum outdoor air rate for ventilation and/or to provide cooling when the outside air temperatures are low (economizer). The single-speed heat pump side of the system can provide either heating or cooling based on the position of the reversing valve. The supply air on the heat pump is recirculated from the room and filtered with a MERV 13 filter. Additional backup heating via electric resistance heat strip or natural gas are available, however the model tested in this study did not include any backup heat. For the heat pump side, air is returned from the space, heated or cooled, and then mixed with the supply air from the IDEC. The basic operating modes for the system are:

1. Ventilation Mode
    a. Ventilation – minimum outside air rate supplied
2. Cooling Modes
    a. Economizer – increased outside air above minimum ventilation rate
    b. Indirect cooling – outside air is indirectly evaporatively cooled
    c. Indirect-direct cooling – outside air is indirectly and directly evaporatively cooled
    d. Heat pump (cooling) – recirculated air with compressor-based cooling
    e. Hybrid mode – mode 2c + 2d
3. Heating modes
    a. Heat pump (heating) – recirculated air with compressor-based heating
    b. Heat pump (heating) + ventilation – mode 1a + 3a

The on-board control system receives room temperature and thermostat settings via Modbus or Bacnet communication protocols and then selects the most efficient operating mode based on inside and outside air conditions.

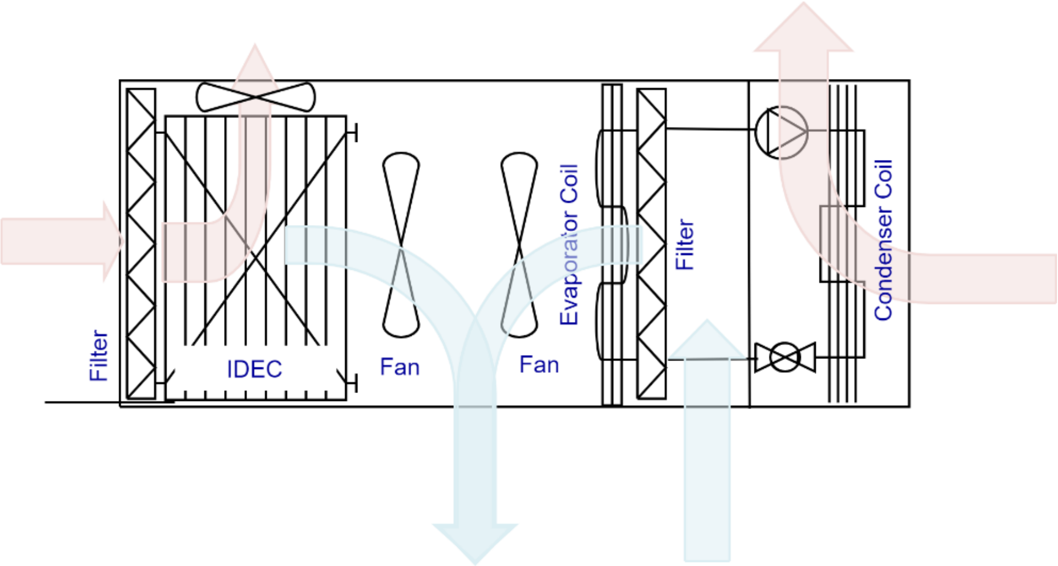


FIGURE 3. IDEC (LEFT) WITH A HEAT PUMP (RIGHT) INTO ONE PACKAGED RTU

In addition to the expected energy savings from the packaged heat pump with IDEC, increased amounts of outdoor air reduce concentrations of indoor pollutants, such as respiratory aerosols that increase risk of infectious disease spread and volatile organic compounds (VOCs) that off-gas from building materials and furniture. For example, in schools, higher ventilation rates have been demonstrated to improve student performance [7], reduce absence rates [8], and reduce transmission of influenza [9]. One concern with increased outdoor air rates, is introduction of intermittent wildfire smoke into buildings. The packaged heat pump with IDEC accepted standard 16”x25”x2” filters, which allows for use of filters with a minimum efficiency reporting value (MERV) up to 13. This test was conducted with MERV 13 filters which remove 50-90% of particles (depending on particle diameter) at each pass through the filter. Filters are installed on both the IDEC outdoor air intake and on the air recirculated through the heat pump to reduce the impact of indoor and outdoor pollutants. Additional items to consider are the water supply required for the packaged heat pump with IDEC, as well as the weight of the system compared to a typical RTU. The manufacturer reports that they are working to reduce the weight of the system, with the end goal of manufacturing a system with a weight comparable to a new, standard RTU.

ASSESSMENT OBJECTIVES

The emerging technology is designed to replace small-packaged RTUs. The target markets are building types that have high outside air requirements and generally use packaged RTUs, with classrooms identified as being the most promising market for the emerging technology. An emerging technology field evaluation was designed to test the packaged heat pump with IDEC in comparison to a baseline RTU in two side-by-side classrooms at a high school in San Jose, CA. The assessment objectives were to evaluate the packaged heat pump with IDEC performance compared to the baseline RTU in terms of:

- Maintaining indoor conditions (thermal comfort)
- Energy use (kWh/day) for cooling, heating, and ventilation
- Water use (gallons/day)
- Outside air delivered (average CFM/day)

An additional objective was to determine correlations of energy use and water use to outdoor temperature and humidity conditions so that predictions can be made about the energy and water use of the technology in other California climate zones.

TECHNOLOGY/PRODUCT EVALUATION

The field evaluation was conducted at East Side Union High School District in San Jose, Santa Clara County, California. Santa Clara County has long, warm arid weather, while the winters tend to be short, cold and wet. The warm season lasts about 4.3 months from early June to mid-October. The cold season lasts about 2.6 months from late-November to mid-February.

Two classrooms in the same building of similar square footage, duct work design, and exterior and interior wall geometries were selected for the field evaluation. The baseline unit was a 5-ton, high efficiency Lennox LGA RTU manufactured in 2001 with a manufacturer reported seasonal energy efficiency ratio (SEER) of 12 Btuh/Watt [10]. For comparison, the current federal minimum efficiency SEER for a similar RTU today is 14 Btuh/Watt [11]. The baseline system included a Pelican Wireless control system with an economizer controller. The system was set to provide a minimum amount of outside air during occupied hours. When the thermostat called for cooling and the outdoor air was 2°F less than the return air, the supply air increased to 100% outside air to provide additional "free" cooling. The emerging technology evaluated was a packaged heat pump with integrated IDEC system (Figure 5), which was designed to provide cooling capacity comparable to a typical 5-ton RTU. Details of the packaged heat pump with IDEC design are included in the "Emerging Technology/Product" section.

LENNOX INDUSTRIES INC.
DALLAS, TEXAS
5601L07769
M/N: LGA060HS2G
S/N: 5601L 07769
C/N: 70R10

HEATING DATA
INPUT: 78000 BTUH MAX
MANIFOLD PRESSURE: 3.5 IN. W.C.
GAS SUPPLY LINE PRESS: 10.5 IN. W.C. MAX 5.5 IN. W.C. MIN.
MAXIMUM OUTLET AIR TEMPERATURE: 170 °F
TEMPERATURE RISE: 25 – 55 °F
MAX. STATIC PRESSURE: 1.8 IN. W.C. FOR ALTITUDES TO: 4500 FT.
MANUFACTURER RECOMMENDED ORIFICE SIZE: 40 DMS
SEE INSTALLATION INSTRUCTIONS FOR INSTALLATIONS ABOVE 2000 FT.

CHAUFFAGE
PUISSANCE CALORIFIQUE BRUTE MAX: 78000 BTUH
PRESS A LA TUBULURE D'ALIMENTATION: 3.5 PO. C.E.
PRESSION ENTREE: 5.5 MIN 10.5 MAX PO. C.E.
TEMP. MAXIMALE D'AIR DE SORTIE: 170 °F

FIGURE 4. BASELINE LENNOX 5-TON RTU

FIGURE 5. PACKAGED HEAT PUMP WITH IDEC RTU

TECHNICAL APPROACH/TEST METHODOLOGY

SITE SELECTION

The field evaluation site selected two 1,060 ft^2 classrooms in building “A” at Evergreen Valley High School. Each classroom was served by a single-zone packaged RTU. The classrooms were both used for science classes and had similar square footage, duct work design, and exterior and interior wall geometries (Figure 6 and Figure 7). While the classrooms used to have exhaust systems for science experiments, the exhaust systems were no longer in use. The classroom on the north end of the building was used as the baseline classroom (Figure 8, green box) and the classroom on the south end of the building (Figure 8, orange box) was retrofitted with the packaged heat pump with IDEC. This configuration was selected due to the ease of access for a crane from the south side of the building. Note that both classrooms had an exterior south wall exposure, due to the separation of both ends of the building by a courtyard.

FIGURE 6. CLASSROOM SERVED BY BASELINE RTU (LEFT) AND CLASSROOM SERVED BY PACKAGED HEAT PUMP WITH IDEC (RIGHT)

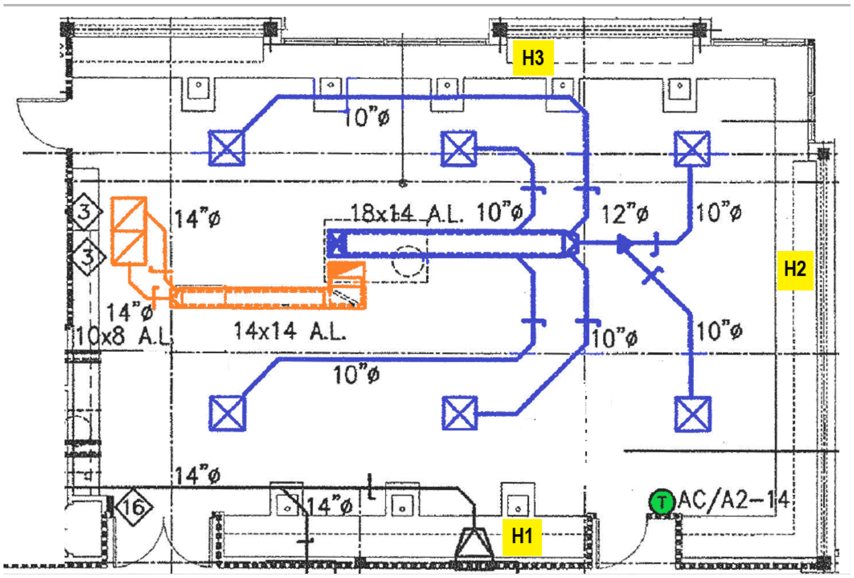


FIGURE 7. CLASSROOM FLOOR PLAN AND DUCTWORK LAYOUT SHOWING RETURN DUCTWORK (ORANGE), SUPPLY DUCTWORK (BLUE), AND THERMOSTAT LOCATION (GREEN). WHEN NO STUDENTS WERE PRESENT, INTERNAL LOADS WERE PROVIDED BY HEATERS (H1 AND H2) AND HUMIDIFIER (H3).

FIGURE 8. BUILDING A. SECOND STORY FLOOR PLAN (LEFT) AND SATELLITE VIEW (RIGHT)

INSTALLATION

The original structural plans for the building included a 900 lb weight for the Lennox units. The packaged heat pump with IDEC unit required installation of a 160 lb curb adapter in addition to the 1,080 lb operating weight of the unit, for a total of 1,240 lb. Curb adapters are commonly required when switching RTU brands to align the supply and return of the RTU with the existing ductwork. A structural review certified that the roof design was sufficient for the increase in weight.

An electrician was contracted to install a transformer to supply 208V to the packaged heat pump with IDEC from the existing 480V supply. Future product versions of the packaged heat pump with IDEC are expected to be available at typical standard operating voltages (e.g. 208V, 480V), with the need for the transformer limited to this emerging technology demonstration.

A mechanical contractor was contracted to disconnect the utilities (power, controls, natural gas, condensate) from the existing RTU; rig, remove, and recycle the existing RTU; design and fabricate a curb adapter to mate the packaged heat pump with IDEC to the existing supply and return air ducts; and rig, lift, and install the new curb adapter and packaged heat pump with IDEC. The contractor connected the power, installed a new water line to serve the evaporative section (from existing water service on the roof), and installed a new drain line (for condensate and evaporative section water) to the existing roof drain. The mechanical contractor ran low-voltage control wires for the compatible thermostat to the classroom. The new thermostat was installed in the location of the prior thermostat. Installation of the packaged heat pump with IDEC was completed in April 2021.

Researchers inspected the duct systems above the drop ceiling. Both appeared to be in good condition and were properly insulated and sealed. The duct systems were not modified in the installation.

TEST METHOD

Each classroom thermostat and RTU control system was set to heat the room to 68°F, cool the room to 72°F, and provide at least the minimum outdoor air ventilation rate between 7am – 5pm daily. Outdoor air rates could exceed the minimum depending on the status of the economizer for the baseline unit and the system mode for the packaged heat pump with IDEC. The teacher was not given control over the room temperature to improve the comparison between the two classrooms, however the researchers contacted the teachers to ensure they were satisfied with the room temperatures.

Researchers installed heating and humidification loads in each classroom (Figure 7) to simulate occupancy during unoccupied periods (summer and winter break). Commercially available heaters and a humidifier were selected to match design loads for the room as closely as possible (Table 1). The loads were distributed around the room and plugged into outlets served by different circuits. The humidifier was located next to a sink and connected to the water source. Fans in the heaters and humidifier mixed the room.

The heaters and humidifiers were wired to a control system and configured to operate on the following daily schedule: On: 8:30am, Off: 11:45 am, On: 12:30 pm, Off: 3:00pm. Data was collected using the simulated loads from June 25 through August 5, 2021, as well as during winter break from December 18, 2021, through January 2, 2022. When the students were present the heating and humidification loads were not used. Data collection ended on January 22, 2022.

TABLE 1. DESIGN LOADS AND ESTIMATED LOADS DELIVERED WITH SELECTED EQUIPMENT

	SENSIBLE LOAD (W)	LATENT LOAD (W)	TOTAL LOAD (W)	SOURCE
30 People	1,600	1,100		ASHRAE Handbook
Lighting/Plug Loads	1,600	-		1.5 W/ft^2
Total Design	**3,200**	**1,100**	**4,300**	
Humidifier	200	1,200		
Heaters (total for 2)	2,800			
Total Delivered	**3,000**	**1,200**	**4,200**	

FIGURE 9. HEATER (LEFT) AND STEAM HUMIDIFIER (RIGHT) USED TO SIMULATE LOADS IN CLASSROOMS DURING SCHOOL CLOSURE.

INSTRUMENTATION

BASELINE RTU

The baseline system was instrumented as illustrated in Figure 11 and described in Table 2. Temperature and humidity sensors were located at the RTU return, RTU supply, and in the room to monitor indoor conditions. In addition, power monitoring was connected to the heater and humidifier loads that were used while the school was closed. The most challenging measurements were the outdoor air, return air, and supply air flow. The single speed fan on the baseline RTU simplified the flow measurement. A high accuracy Ebtron flow transmitter was used to continuously measure the air flow on the supply duct, however it was not possible to install this sensor on the return duct due to space limitations. One-time outdoor air measurements using a flow capture hood (Alnor model #EBT731) were used to estimate the outdoor air fraction as a function of damper position. Damper position was set to a minimum position during occupied hours that correlated to an outdoor air fraction of about 37% (~600 CFM of outdoor air). Damper position was logged continuously.

FIGURE 10: EBTRON AIRFLOW TRANSMITTER

PACKAGED HEAT PUMP WITH IDEC

The packaged heat pump with IDEC system was instrumented as illustrated in Figure 12 and described in Table 3. Additional monitoring, in comparison to the baseline, included measurement of water flow to the evaporative cooler supply, as well as speed of the two supply air fans. Similar to the baseline classroom, temperature and humidity sensors were located at the RTU return, RTU supply, and in the room to monitor indoor conditions. In addition, power monitoring was connected to the heater and humidifier loads that were used while the school was closed. Two high-accuracy Ebtron flow transmitters were used to continuously measure both the air flow on the return and supply duct, and the relationship between outside air flow and the IDEC supply fan was determined. The IDEC supply fan was set to a minimum speed of 2.7 V (~530 CFM of outside air). IDEC fan speed was logged continuously.

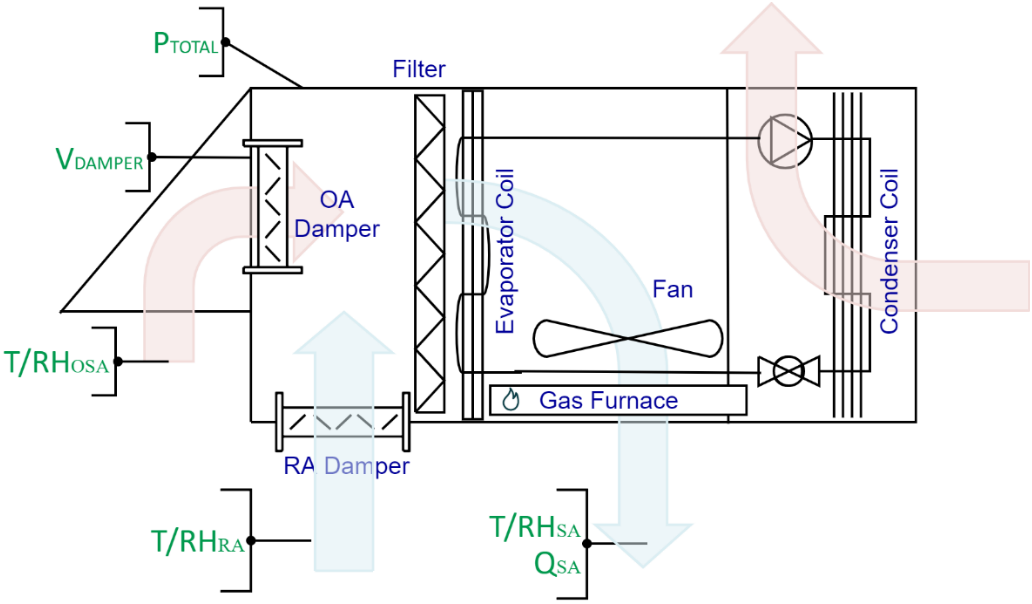


FIGURE 11. BASELINE RTU SCHEMATIC AND INSTRUMENTATION DIAGRAM (ROOM SENSOR NOT SHOWN)

TABLE 2. BASELINE RTU INSTRUMENTATION TABLE

ID	DESCRIPTION	SENSOR MODEL	SENSOR ACCURACY
PTOTAL	RTU total power	DENT Powerscout 3	±0.2%
VDAMPER	Control voltage – Damper	-	-
TOSA RHOSA	Temperature – Outside Air Relative Humidity – Outside Air	Vaisala HMP 110	±0.36 °F ±1.5%
TRA RHRA	Temperature – Return Air Relative Humidity – Return Air	Vaisala HMP 110	±0.36 °F ±1.5%
TROOM RHROOM	Temperature – Outside Air Relative Humidity – Outside Air	Vaisala HMP 110	±0.36 °F ±1.5%
TSA RHSA QSA	Temperature – Supply Air Relative Humidity – Supply Air Supply Air Flow Rate	EbtronGTC116e-PC/H Transmitter	±0.15 °F ±2% ±2%
PLOAD, 1 PLOAD, 2 PLOAD, 3	Room heater 1 power Room heater 2 power Room humidifier power	DENT Powerscout 3	±0.2%

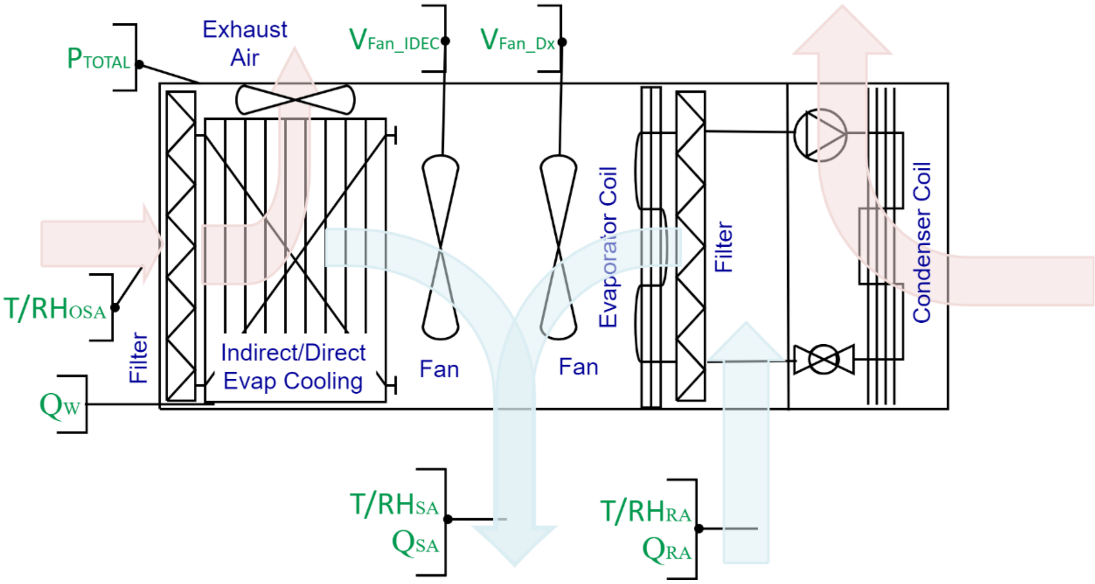


FIGURE 12. PACKAGED SYSTEM PLUS IDEC INSTRUMENTATION DIAGRAM (ROOM SENSOR NOT SHOWN)

TABLE 3. PACKAGED SYSTEM PLUS IDEC INSTRUMENTATION TABLE

ID	DESCRIPTION	SENSOR MODEL	SENSOR ACCURACY (VALUE OR PERCENT OF READING)
P_{TOTAL}	RTU total power	DENT Powerscout 3	±0.2%
V_{Fan_IDEC}	Control voltage – Fan for Indirect/Direct Evap Cooling	-	-
V_{Fan_DX}	Control voltage – Fan for Direct Expansion Cooling	-	-
T_{OSA} RH_{OSA}	Temperature – Outside Air Relative Humidity – Outside Air	Vaisala HMP 110	±0.36 °F ±1.5%
T_{RA} RH_{RA} Q_{RA}	Temperature – Return Air Relative Humidity – Return Air Return Air Flow Rate	EbtronGTC116e-PC/H Transmitter	±0.15 °F ±2% ±2%
T_{ROOM} RH_{ROOM}	Temperature – Outside Air Relative Humidity – Outside Air	Vaisala HMP 110	±0.36 °F ±1.5%
T_{SA} RH_{SA} Q_{SA}	Temperature – Supply Air Relative Humidity – Supply Air Supply Air Flow Rate	EbtronGTC116e-PC/H Transmitter	±0.15 °F ±2% ±2%
Q_W	Water Flow Rate	Omega FTB-4605	±2%

DATA SAMPLING AND LOGGING

Analog data streams, which include all sensors except for the Dent power meters and the Ebtron flow meters, were sampled six times per minute with a Datataker DT85M series 3, averaged over a one-minute period, and then logged once per minute to an internal memory card. The power meters and the Ebtron flow meters transmitted digital data over Modbus, which was logged once per minute to the internal memory card. In addition to instantaneous power, the average power over the one-minute interval reported by the Dent power meter was recorded. The data file for the day was automatically uploaded over a cell network every night at midnight.

CALCULATION METHODS

The following measurements were calculated as the **average for each hour** and analyzed 24 hours per day:

- Average outside air temperature (OAT) (°F)
- Average outdoor air dewpoint (OADP) (°F), where the dewpoint at each minute is calculated from the measured temperature and relative humidity and the dew point is calculated using a psychrometric function [12] at an atmospheric pressure of 1 atm.

The following measurements were calculated as the **average for each hour** and analyzed only during occupied hours (8:00 am – 4:00 pm):

- Average indoor air temperature (IAT) (°F) in each room
- Average indoor air dewpoint (IADP) (°F) in each room, where the dewpoint at each minute is calculated from the measured temperature and relative humidity and the

dew point is calculated using a psychrometric function [12] at an atmospheric pressure of 1 atm.

- Average outside air (OA) flow rate (CFM) for the baseline system, which was determined from the outside air damper position (10% minimum or 100% for economizer mode). A one-time measurement with a flow hood was used to estimate the outdoor air flow rate for each mode:
    - Minimum OA: 633 CFM
    - 100% OA Economizer: 1238 CFM
- Average outside air (OA) flow rate (CFM), for the packaged heat pump with IDEC, where the outside air flow rate each minute was determined based a one-time set of flow hood measurements. This relationship was determined during a commissioning visit where the control voltage (CV_{Fan_IDEC}) of the IDEC fan was set and then flow hood measurements were taken to determine flow rate ($V_{OA,\ CW}$).

  $V_{OA,\ CW}$ = 279.28 x CV_{Fan_IDEC} – 240.53 CFM

  for $V_{Fan\_IDEC} \geq 0.861$, else $V_{OA,\ CW} = 0$

- Therms for heating in the baseline system, where therms were calculated as the number of heating minutes in the hour multiplied by the furnace rated input of 0.013 therms/minute.

The following measurements were calculated as maximum 15-minute moving-average:

- Peak demand (kW) for each system

The following measurements were analyzed **by mode**:

- Power (kW) each minute, as a function of outdoor air temperature and/or dewpoint (if applicable). If the power was not a function of either, the average for the study period was calculated for that mode.

Additional calculations were made from the data with one-minute resolution to evaluate the equipment capacity and efficiency. Three different capacity metrics were calculated, which required calculating mass flow rates of the supply air (SA), return air (RA) and outdoor air assuming a minimum ventilation rate (OA,min):

$\dot{m}_{SA} = V_{SA} \times \rho_{air}$, where V_{SA} is the total supply air and ρ_{air} is the density of air
$\dot{m}_{OSA,min} = V_{min} \times \rho_{air}$, where V_{min} is the minimum ventilation required (450 CFM)
$\dot{m}_{RA} = \dot{m}_{SA} - \dot{m}_{OSA,min}$

The Sensible Room Capacity ($\dot{Q}_{sen,room}$) is the capacity delivered with respect to the room temperature (not accounting for any heating or cooling of the outdoor air). It is calculated from:

$$\dot{Q}_{sen,room} = C_{p,air} \times \dot{m}_{SA} \times (T_{RA} - T_{SA})$$

where $C_{p,air}$ is the specific heat of air T_{RA} and T_{SA} are return and supply air temperatures to the RTU.

The Total Room Capacity is calculated from the enthalpy (h) change in the return and supply air, which includes both change in temperature and dehumidification.

$$\dot{Q}_{tot,room} = \dot{m}_{SA} \times (h_{RA} - h_{SA})$$

The Sensible Equipment Capacity calculates the capacity delivered by the equipment, including conditioning the minimum required outside air (450 CFM):

$$\dot{Q}_{sen,equip} = C_{p,air} \times \left(\left(\dot{m}_{OSA,min} \times T_{OSA} + \dot{m}_{RA} \times T_{RA} \right) - \dot{m}_{SA} \times T_{SA} \right)$$

A related Coefficient of Performance (COP) metric was also calculated to show the efficiency at which capacity was provided:

$$COP = \dot{Q}/P_{Total}$$

Where the capacity and power have like units resulting in a dimensionless performance metric. The capacity equations are derived so that cooling results in a positive capacity. For heating capacity calculations, the absolute value of the result was taken. To similarly address the gas heating of the baseline unit, a COP metric was used to relate the heating capacity to the therms consumed in a dimensionless performance metric:

$$COP_{gas} = \dot{Q}/Therms_{Total}$$

MODE DETERMINATION AND FREQUENCY

The baseline system mode was determined for each minute of operation. The modes were determined using the following logic:

- Ventilation (Vent) only – system power shows fan on and damper is at minimum position
- Economizer (Econ) – system power shows fan on and damper is at maximum position
- Heat – system power shows fan on and algorithm tracking supply and mixed air return temperature detects heating
- Compressor Cooling (DX Cool) – system power shows compressor on
- Off – system power shows standby power only

The packaged heat pump with IDEC system mode was binned by mode for each minute of operation. The modes were determined using the following logic:

- Ventilation (Vent) only – system power shows fan on and ventilation supply fan speed is at minimum with no cooling of outdoor air observed
- Economizer (Econ) – system power shows fan on and ventilation supply fan speed is above minimum with no cooling of outdoor air observed
- Evaporative Cooler (EC) – system power shows fan on and ventilation supply fan speed is above minimum with cooling of outdoor air observed
- Heat Pump (DXH) – system power shows compressor on and algorithm tracking supply and mixed air return temperature detects heating
- Compressor Cooling (DXC) – system power shows compressor on and algorithm tracking supply and mixed air return temperature detects cooling. The compressor cooling mode can also include evaporative cooler operation.
- Off – system power shows standby power only.

- The number of minutes each mode was observed during the study period was summed and binned by outdoor air temperature.

RESULTS – TYPICAL EQUIPMENT OPERATION

To demonstrate the differences in operation from the baseline and packaged heat pump with IDEC system we illustrate three example days from different seasons: summer, fall, and winter.

For summer operation, the team picked a hot day from the study to demonstrate runtime where primarily cooling is expected (Aug 28, 2021) (Figure 13, top). The baseline unit starts using compressor (DX) cooling to maintain the desired setpoint as soon as the outdoor temp rises above a range where the economizer can be effective. For morning operation, the packaged heat pump with IDEC starts with evaporative cooling and does not engage the compressor until ~1.5 hours later than baseline. During the remainder of the day, the packaged heat pump with IDEC cycles between evaporative cooling and occasional compressor use, while the baseline cycles between compressor cooling and minimum ventilation modes. Overall compressor use for the baseline is significantly greater.

To represent shoulder/fall operation the team picked a day with a cold morning and mild to slightly warm afternoon (Oct 15, 2021). Both units begin the day with heating in which the hybrid uses the heat pump and the baseline uses a gas furnace to reach the morning setpoint. After this point in the day, both systems are in minimum ventilation mode, with the packaged heat pump with IDEC using reduced fan power compared to the baseline. As the day warms, the need for cooling arises. The baseline engages the compressor and cycles between the compressor cooling and minimum ventilation modes for the remainder of the day. The packaged heat pump with IDEC instead uses evaporative cooling for all cooling needs and does not turn on the compressor that day.

Winter operation was observed on a particularly cold day from the study where ventilation should be limited to minimum on both units and heating is the only other expected mode of operation (Dec 26, 2021). The day starts off similar to the shoulder season with recovery heating in both rooms, with a longer duration for both. This is the most similar operation from both units as they both, as expected, cycle between heating and ventilation modes over the day. The two main power/energy use differences here are fan power during ventilation mode, and the gas versus electric heating of the two units.

Across all of these days from different seasons there is a small but noticeable difference in standby power when no conditioning is being called for. While it may seem small as compared to the power use while on, it does add up as the unit is in this mode over half of the time.

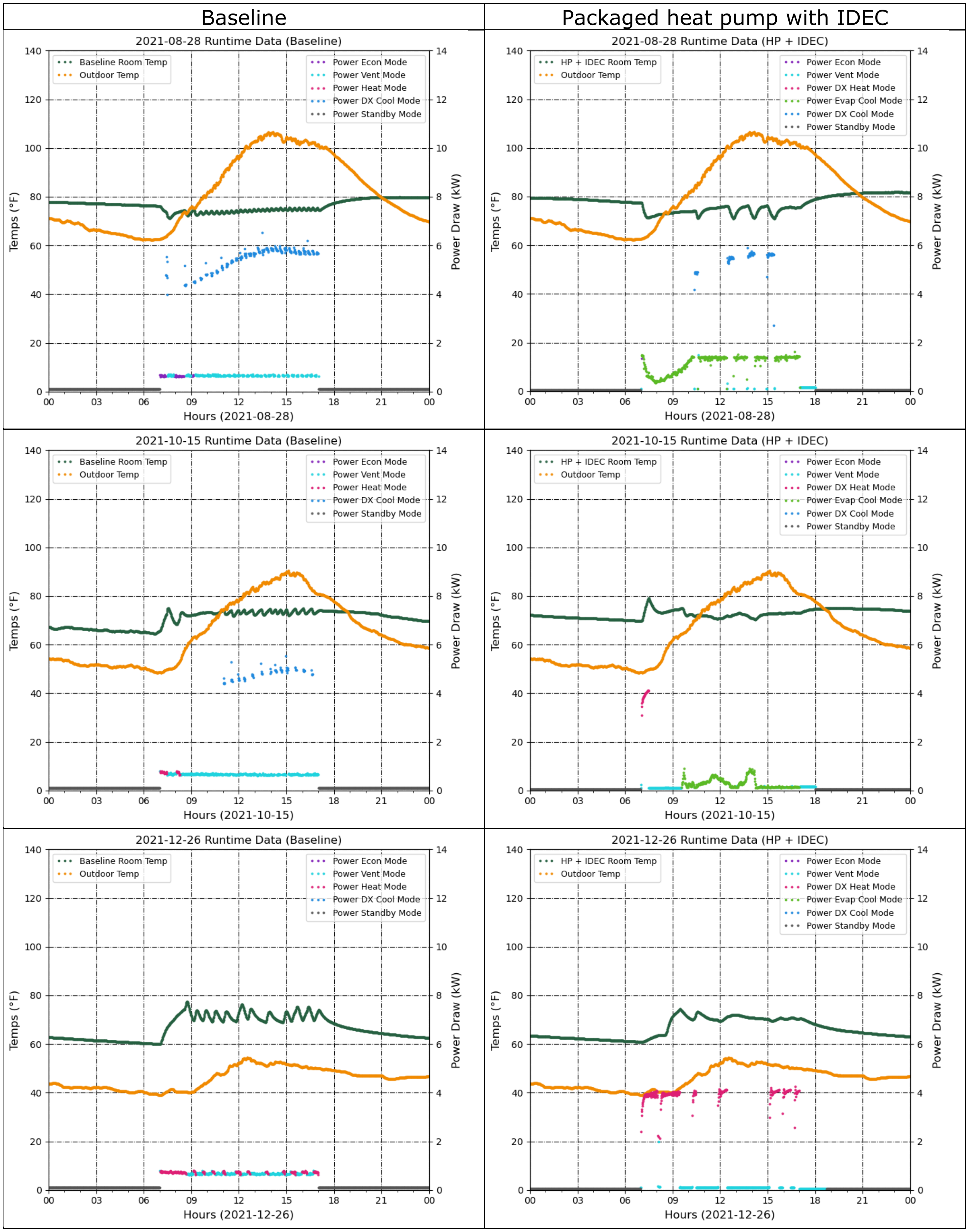


Figure 13: Baseline system (left) and packaged heat pump with IDEC system (right) for three example days

RESULTS – WEATHER CORRELATIONS AND MODEL DEVELOPMENT

Because HVAC energy efficiency measures are weather dependent, many operational parameters must be correlated to weather to provide accurate estimates of system performance under different weather conditions. Results are presented for full days of data collection, including days with both simulated (heater/humidifiers) and typical operation internal loads. Days where sensors, data acquisition equipment, or simulated load operation failed are excluded. In addition, weekend and holidays during the normal school operation (when simulated loads were not available) were excluded, based on the assumption that school districts with building management systems turn their HVAC systems off on weekends and holidays (unless overridden by an occupant). The remaining data consisted of 74 days (1777 hours) between June 25, 2021 – January 22, 2022.

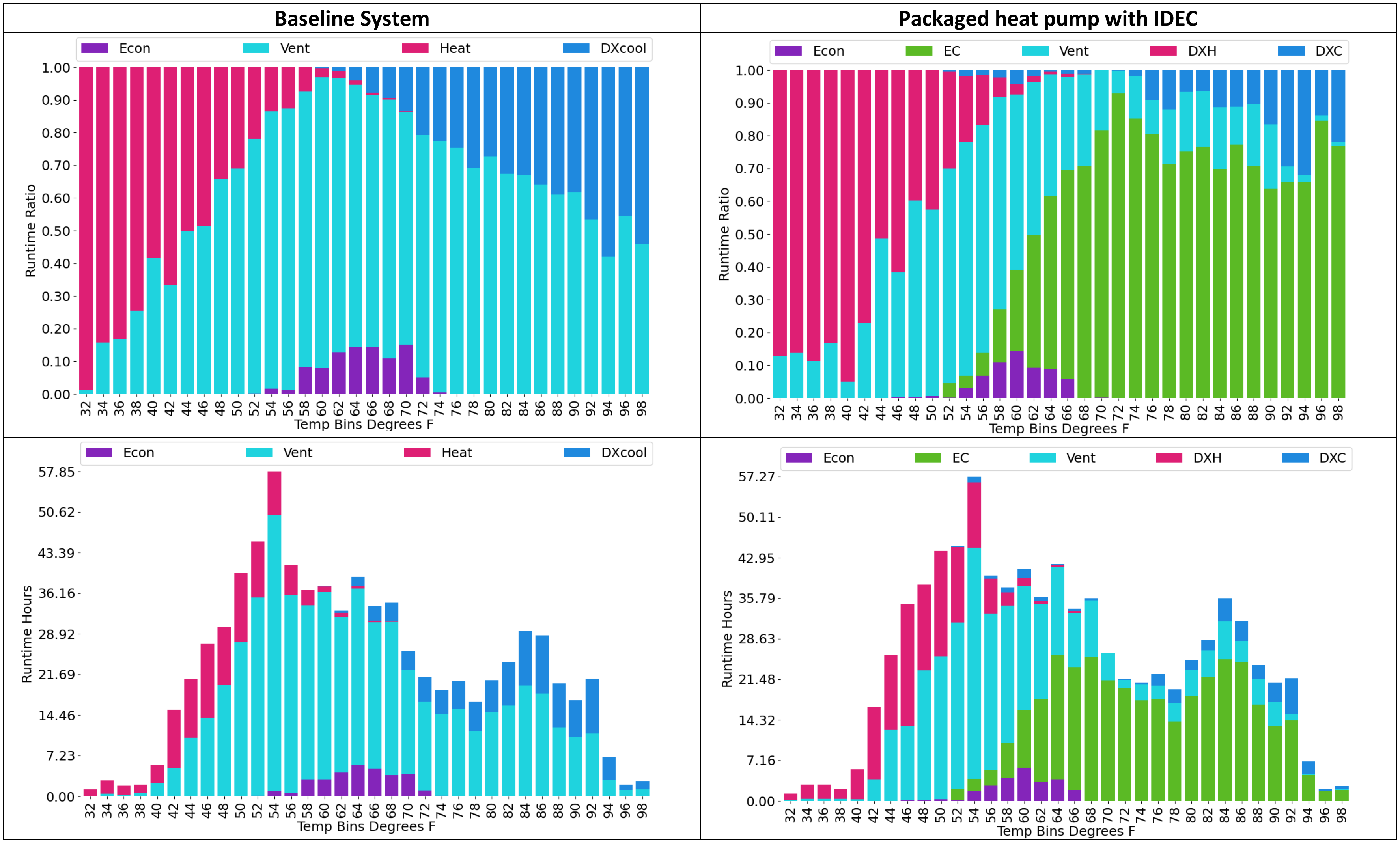
MODE DETERMINATION

The number of hours spent in each mode during the study period for each system was determined (Figure 14). The data was binned into 2-degree temperature bins, where the label of the bin represents the floor of the bin (e.g., bin 40 contains data for 40.00-41.99°F). Performance data was obtained for the 32-100°F outdoor air temperature range, although most data was between 42-94°F (Figure 14, bottom).

The binned mode data for the baseline (Figure 14, left) reflect typical operation of an HVAC system. Heating and minimum ventilation are the only modes below 52°F, with heating frequency increasing as temperature decreases. Above 54°F, the system begins to call for economizer cooling, which increases until the high limit of ~75°F. The HVAC system compressor cooling begins to engage about 62°F, which then increases as outdoor air temperature increases.

The binned data for the packaged heat pump with IDEC (Figure 14, right) reflect some similar patterns in comparison to the baseline system. The heating frequency is very similar, with the difference being that the heating is provided by heat pump instead of gas furnace. The economizer use is also very similar to the baseline system, although it turns off at a lower temperature in favor of evaporative cooling. The biggest difference is that the evaporative cooling mode drastically reduces the run time of compressor-based cooling, which is observed across the entire temperature range. Because the evaporative cooling mode operates with 100% outdoor air, it also delivers more ventilation to the space as an added benefit while reducing the compressor runtime.

Comparing the model predictions to the actual data showed that prediction for percent of time spent in heating mode was significantly underestimated for the first hour of the day due to recovery from the nighttime setback. The data were analyzed separately for just the first hour and a correction factor was determined. The heating runtime for the baseline system was multiplied by 1.85 and the heating runtime for the packaged heat pump with IDEC system was multiplied by 3.00 for the first hour of operation only. The correction factor represents the energy used to recover the room from the nighttime setback.


Baseline System

Packaged heat pump with IDEC

FIGURE 14. HVAC SYSTEM MODE FREQUENCY BINNED BY OUTDOOR AIR TEMPERATURE FOR BASELINE SYSTEM (LEFT) AND THE PACKAGED HEAT PUMP WITH IDEC (RIGHT). DATA IS PRESENTED FOR THE PERCENT DISTRIBUTION BY MODE (TOP) AND THE NUMBER OF HOURS OBSERVED IN EACH MODE (BOTTOM) BY TEMPERATURE BIN.

INDOOR CONDITIONS

The average hourly indoor conditions between 8:00 am-4:00 pm for both classrooms were generally within the indoor comfort zone defined by ASHRAE 55-2020 [13] for lower clothing levels (Figure 15). A few hours were colder in the winter mornings in both classrooms, which were still within the comfort zone if additional clothing is worn (e.g., jacket). The packaged heat pump with IDEC room had some hours warmer than the comfort zone, which was a result of overheating the room on the first hour of winter mornings. The manufacturer updated the control system to correct this during the study period.

The average daily indoor air temperatures (IAT) were similar (baseline average = 72.1°F and packaged heat pump with IDEC average = 72.3°F). The humidity ratio was slightly higher in the classroom with the packaged heat pump with IDEC (average = 0.0090) compared to the baseline classroom (average 0.0080) due to use of some direct evaporative cooling. The equates to an increase from 48 to 54% relative humidity at 72°F indoor temperature. Indoor humidity in both rooms were within the comfort zone.

The research team maintained direct communication with the teachers occupying the study classrooms. The teachers were satisfied with the thermal comfort of their classrooms.

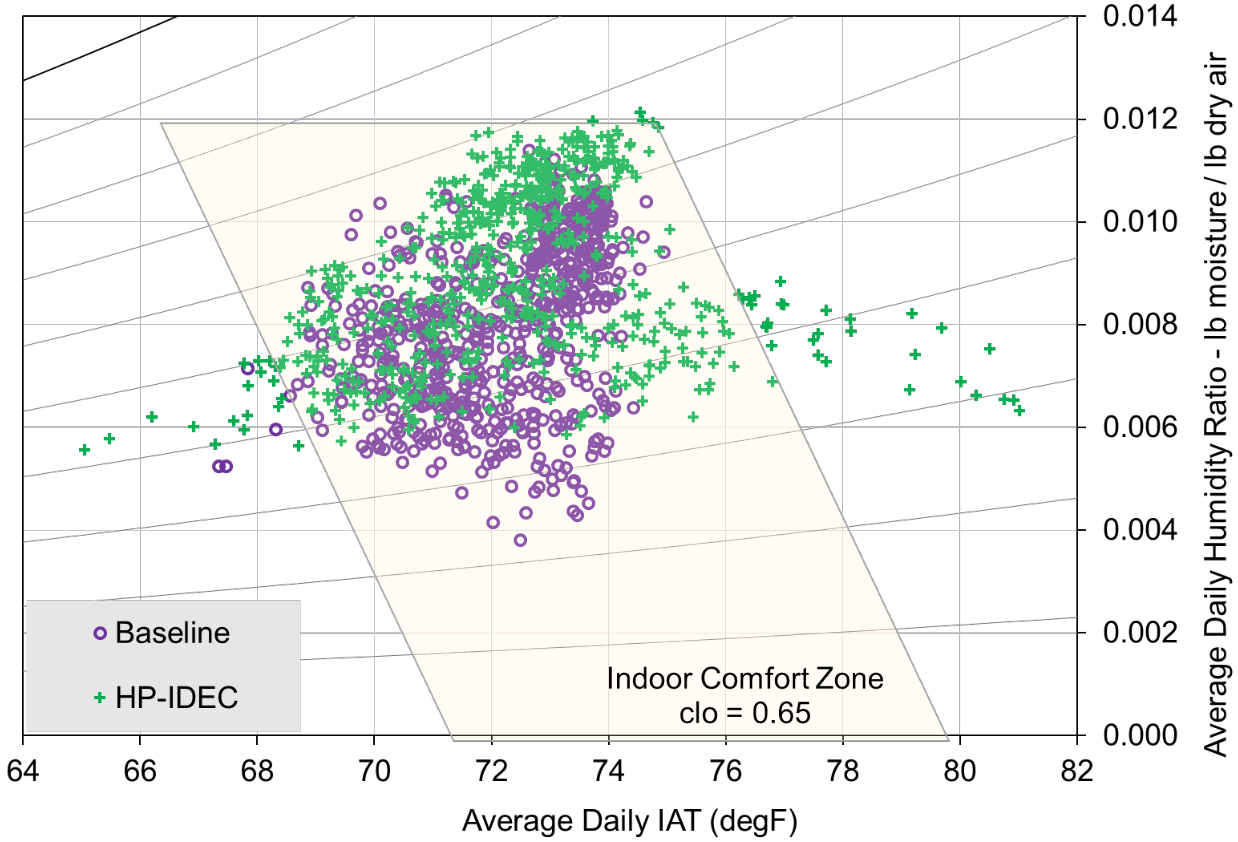


FIGURE 15. AVERAGE HOURLY INDOOR CONDITIONS BETWEEN 8:00AM - 4:00PM COMPARED FOR THE CLASSROOMS WITH THE BASELINE AND PACKAGED HEAT PUMP WITH IDEC SYSTEMS.

ENERGY USE

Energy use was determined for each mode for each system. When the energy use rate for the mode was a function of outdoor air temperature and/or outdoor air dewpoint, a least squares linear regression method was used to determine the best fit. The results are presented as energy use rates, where the total of energy used is the rate multiplied by the time in that mode.

The results are summarized in Table 4 for the baseline system. As expected, off, ventilation, economizer, and heating modes all had a constant power draw that was not a function of outdoor conditions. Additionally, the furnace input gas consumption was also a fixed rate. As expected, the cooling compressor power increased as the outdoor temperature increased. The correlation between outdoor air temperature and power for cooling is shown in Figure 16.

TABLE 4. ENERGY USE RATES FOR THE BASELINE SYSTEM AS A FUNCTION OF MODE

MODE	RANGE FOR CORRELATION	RESULT	UNITS
Off	-	0.093	kW
Vent	-	0.660	kW
Econ	-	0.632	kW
DXCool	Tdb = 60 - 100°F	0.0352*Tdb + 1.934 (R^2=0.68)	kW
Heat	-	0.729	kW
Heat	-	0.013	therms/min

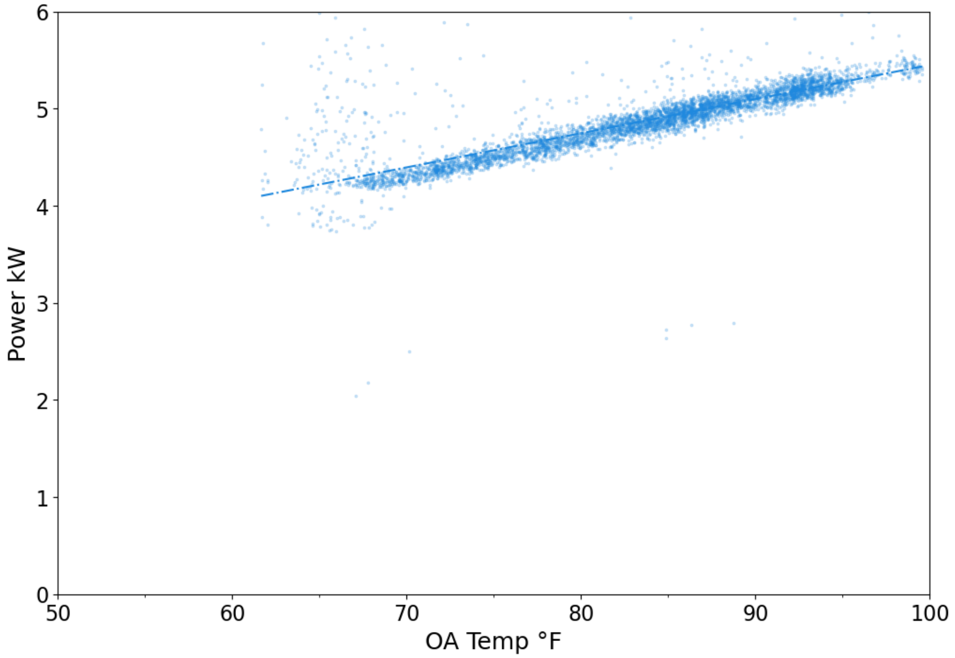


FIGURE 16. CORRELATION BETWEEN OUTDOOR AIR TEMPERATURE AND BASELINE SYSTEM COOLING POWER CONSUMPTION

The energy use rate results are summarized in Table 5 for the packaged heat pump with IDEC system. As expected, off, ventilation, and economizer all had a constant power draw that was not a function of outdoor conditions. Notably, the packaged heat pump with IDEC consumed only 55% of the baseline system power in off/standby, even though the packaged heat pump with IDEC contains a more sophisticated sensing and control system.

Additionally, the ventilation system power consumption was only 18% of the baseline system due to the high efficiency, variable speed fans used in the packaged heat pump with IDEC. This is important because a large number of hours of system operation are spent in ventilation mode.

As expected, the evaporative cooler power consumption increased as outdoor air temperature and dewpoint increased because of variations in fan speed and water pump operation (Figure 17, left). The system power increased as the outdoor temperature increased and decreased as outdoor dewpoint increased (Figure 17, right). This is because the DXCool mode includes hours where the evaporative cooler operated in addition to the compressor when dewpoint was low (which increases power due to pump and fans). The best fit is shown in Figure 17. Unexpectedly, the compressor heating power was not correlated to outdoor air temperature over the outdoor temperature range observed (32-60°F). Therefore, the average power was calculated for the heating mode (4.049 kW).

TABLE 5. ENERGY USE FOR THE PACKAGED HEAT PUMP WITH IDEC SYSTEM AS A FUNCTION OF MODE

MODE	RANGE FOR CORRELATION	RESULT	UNITS
Off	-	0.051	kW
Vent	-	0.118	kW
Econ	-	0.752	kW
EC	Tdb = 52 - 100°F Tdp = 22 – 60°F	0.0261*Tdb + 0.0241*Tdp - 2.4315 (R^2=0.41)	kW
DXCool	Tdb = 52 - 100°F Tdp = 40 – 60°F	0.0352*Tdb - 0.0459*Tdp + 4.1037 (R^2=0.71)	kW
DXHeat	Tdb = 32 - 60°F	4.049	kW

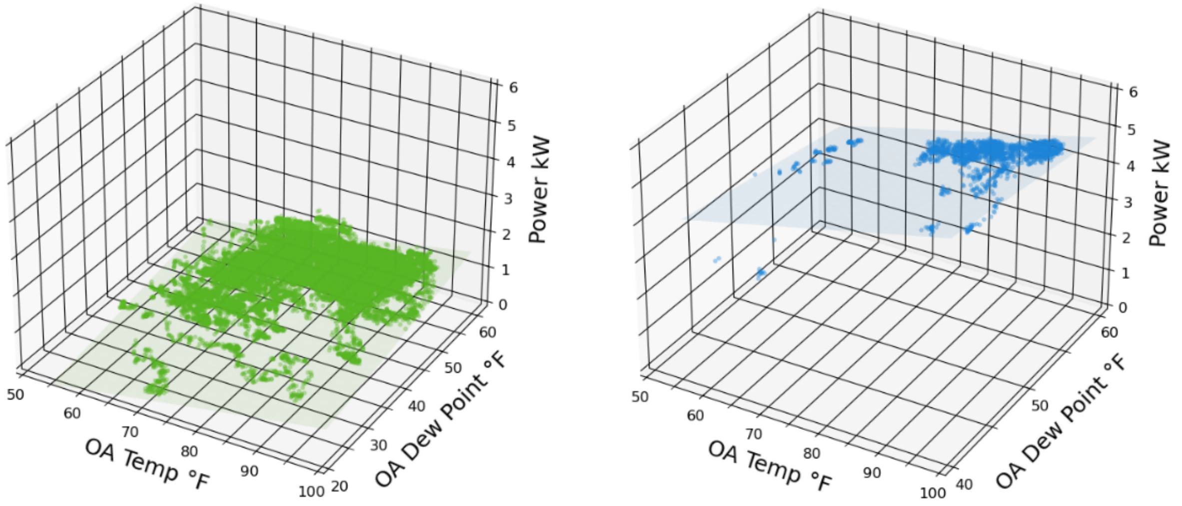


FIGURE 17. CORRELATION BETWEEN OUTDOOR AIR TEMPERATURE/DEWPOINT AND PACKAGED HEAT PUMP WITH IDEC SYSTEM COOLING POWER FOR EVAPORATIVE COOLING MODE (LEFT) AND DX COOL MODE (RIGHT)

WATER USE

The packaged heat pump with IDEC daily water use was highly variable because a water-level sensor replaces water as it is consumed, and the system drains and replaces the water periodically. The total water used per hour was correlated to outdoor air temperature only during hours that the evaporative cooler or DX cooling was running. The best fit equation is shown in Table 6 and the data used to derive the correlation is shown in Figure 18.

TABLE 6. WATER USE FOR THE PACKAGED HEAT PUMP WITH IDEC SYSTEM

MODE	RANGE FOR CORRELATION	RESULT	UNITS
Econ and DXC	Tdb = 52 - 100°F	0.149*Tdb – 7.070 (R^2 = 0.41)	Gal/hr
All others	-	0	Ga/hr

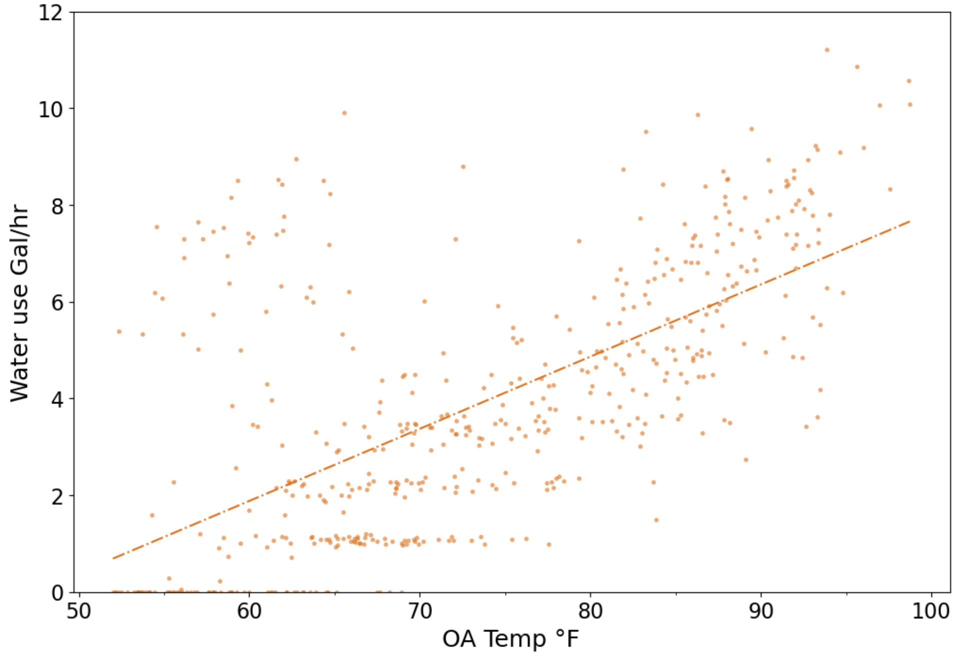


FIGURE 18. CORRELATION BETWEEN OUTDOOR AIR TEMPERATURE AND PACKAGED HEAT PUMP WITH IDEC WATER USE RATE

OUTSIDE AIR DELIVERED

The baseline outside air delivered was determined as one value for each mode (Table 7). The outside air delivered for the packaged heat pump with IDEC was correlated to outdoor air temperature and dewpoint during the hours that the evaporative cooler or DX cooling was running. The best fit equation is shown in Table 8 and the data used to derive the correlation is shown in Figure 18.

TABLE 7. OUTDOOR AIR FOR BASELINE SYSTEM

MODE	RANGE	RESULT	UNITS
Econ		1238	CFM
All others		633	CFM

TABLE 8. OUTDOOR AIR FOR PACKAGED HEAT PUMP WITH IDEC

MODE	RANGE	RESULT	UNITS
Econ and DXC	Tdb = 52 - 100°F Tdp = 22 – 60°F	Greater of: 513.5 or 29.99*Tdb + 24.94*Tdp – 2197 (R^2 = 0.41)	CFM
All others		513.5	CFM

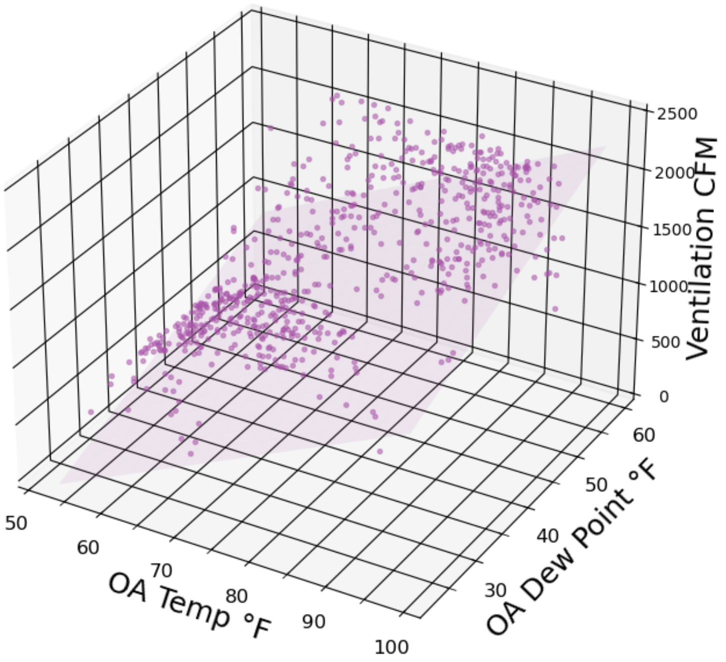


FIGURE 19. CORRELATION BETWEEN OUTDOOR AIR TEMPERATURE/DEWPOINT AND PACKAGED HEAT PUMP WITH IDEC VENTILATION RATE.

PEAK DEMAND

The maximum 15-minute peak demand during the hottest hours of the summer was approximately the same for both the baseline and packaged heat pump with IDEC systems. The maximum 15-minute peak demand for the packaged heat pump with IDEC in heating mode increased to approximately 4-4.5kW compared to 0.7kW for the baseline, due to the use of the heat pump instead of gas heat.

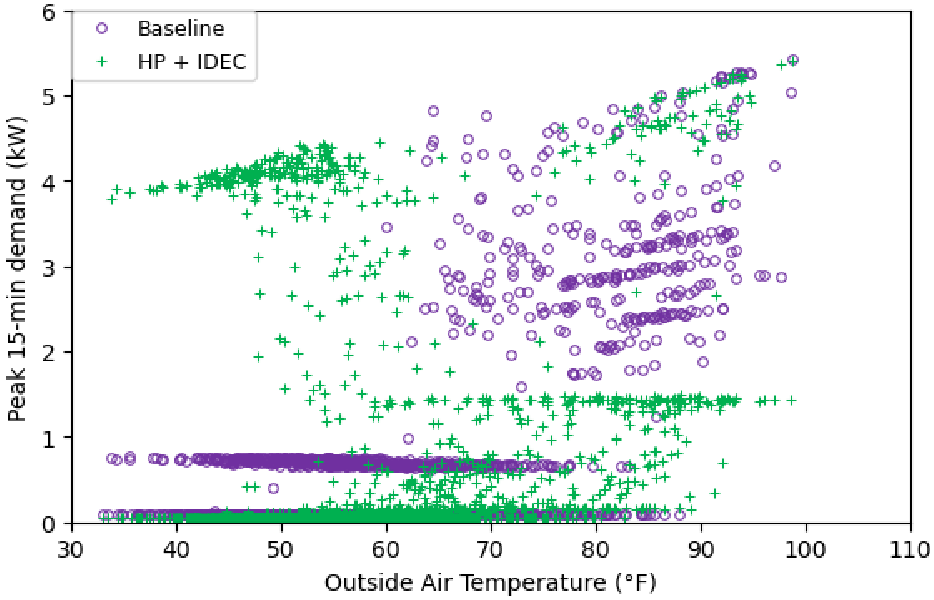


FIGURE 20. MAXIMUM 15-MINUTE PEAK DEMAND AS A FUNCTION OF OUTDOOR AIR TEMPERATURE

RESULTS – MODEL VALIDATION

The model described in "Results – Weather Correlations and model development" was applied to the actual weather observed at the demonstration location. At each hour for each system, the fraction of time spent in each mode was determined based on Figure 14 and system energy consumption, water use, and outdoor air provided was determined by the model described in Table 4 to Table 8. The total energy consumption, water use, and outdoor air predicted by the model was then compared to the actual consumption over the study period (Table 9).

Overall, the models matched the predictions well, with differences being less than 10 kWh or less than 5%. Differences result from the binning method used for outdoor air temperature by mode, as well as the simplified correlations that base resource consumption on the most significant dependent variables. Although the simplified model used has only moderate correlation to outdoor air conditions (r-squared values 0.4-0.7), the model worked well to predict the actual resources consumed when variations attributed to other variables (e.g. occupancy patterns) are averaged-out over time.

TABLE 9. TOTAL ENERGY CONSUMPTION, WATER USE, AND OUTDOOR AIR PREDICTED BY THE MODEL COMPARED TO ACTUAL CONSUMPTION OVER THE STUDY PERIOD

	BASELINE (MEASURED)	BASELINE (MODELED)	DIFFERENCE (%)	PACKAGED HEAT PUMP WITH IDEC (MEASURED)	PACKAGED HEAT PUMP WITH IDEC (MODELED)	DIFFERENCE (%)
Off (kWh)	97.1	100.0	3%	49.7	55.0	11%
Vent (kWh)	349.0	333.2	-5%	34.7	30.5	-12%
Econ (kWh)	19.6	16.7	-15%	17.8	14.5	-19%
EC (kWh)				260.2	235.5	-9%
DXCool (kWh)	459.3	445.8	-3%	167.5	149.1	-11%
Heat (kWh)	63.5	58.3	-8%	501.6	502.0	0%
Gas Heat (Therms)	67.9	69.4	2%			
Total kWh	**988.5**	**953.9**	-4%	**1031.4**	**986.6**	-4%
Total Therms	**67.9**	**69.4**	2%			
Total Water (gal)				1936.7	2057.8	
Average Ventilation Rate (CFM)	776.2	734.7	-5%	1166.1	1106.9	-5%

RESULTS – ANNUAL IMPACTS

Annual energy impact results were calculated for the San Jose climate, as well as three other major cities in California that have climates generally within the range covered by the model: San Francisco, Fresno, and Los Angeles (Figure 21, Table 10, and Table 11). Note that these annual impacts are only valid for a use case representative of the data used to develop the model: a classroom application with similar construction to the one in the field study. A more detailed building and internal load model (e.g., EnergyPlus) is needed to simulate the annual impacts for other building and use case types.

The energy analysis was divided into the following modes:

- Off – Standby power (kWh) for controls and crankcase heater
- Fan Only – Baseline fan (kWh) for recirculation/ventilation and packaged heat pump with IDEC fan (kWh) for ventilation and evaporative cooling
- Compressor Cooling – Baseline compressor and fan (kWh), and packaged heat pump with IDEC compressor and fans (kWh)
- Heating – Baseline fan (kWh) for recirculation/ventilation and gas (therms) and packaged heat pump with IDEC compressor and fans (kWh)

Note that for a total energy calculation, assumptions on power generation and distribution must be made to estimate equivalence between kWh and therms, and the two cannot simply be added as they are shown in the stacked bar chart in Figure 21. The gas consumption in Figure 21 is intended to serve as a visual reminder that gas consumption is eliminated with the packaged heat pump with IDEC technology.

Reduced standby power for the packaged heat pump with IDEC resulted in 45% energy savings in off mode. As building energy efficiency improves, standby power is an important load to consider that is often overlooked. The fan only mode energy use, which also included providing evaporative cooling with the packaged heat pump with IDEC, was reduced 18-48% (Figure 21) in the packaged heat pump with IDEC over the baseline. Cooling mode with the compressor engaged had the most drastic savings, with 63-72% energy saving for the packaged heat pump with IDEC over the baseline. The electricity savings in off, fan-only, and compressor cooling modes resulted in a total electricity savings (4-33%) for the packaged heat pump with IDEC over the baseline, even when compressor use for heating was included. In addition, the packaged heat pump with IDEC eliminated natural gas consumption.

The packaged heat pump with IDEC was estimated to consume 3,600-5,700 gallons of water annually to achieve this electricity savings, which equates to an average of 8.5 gallons consumed per kWh saved for cooling. For context, this is less water than the average person consumes annually for daily showers. The analysis also showed an expected increase in ventilation air of 25-59% above the baseline, which is an important finding expected to result in reduced probability of long-range airborne transmission of infectious disease and improved student performance.

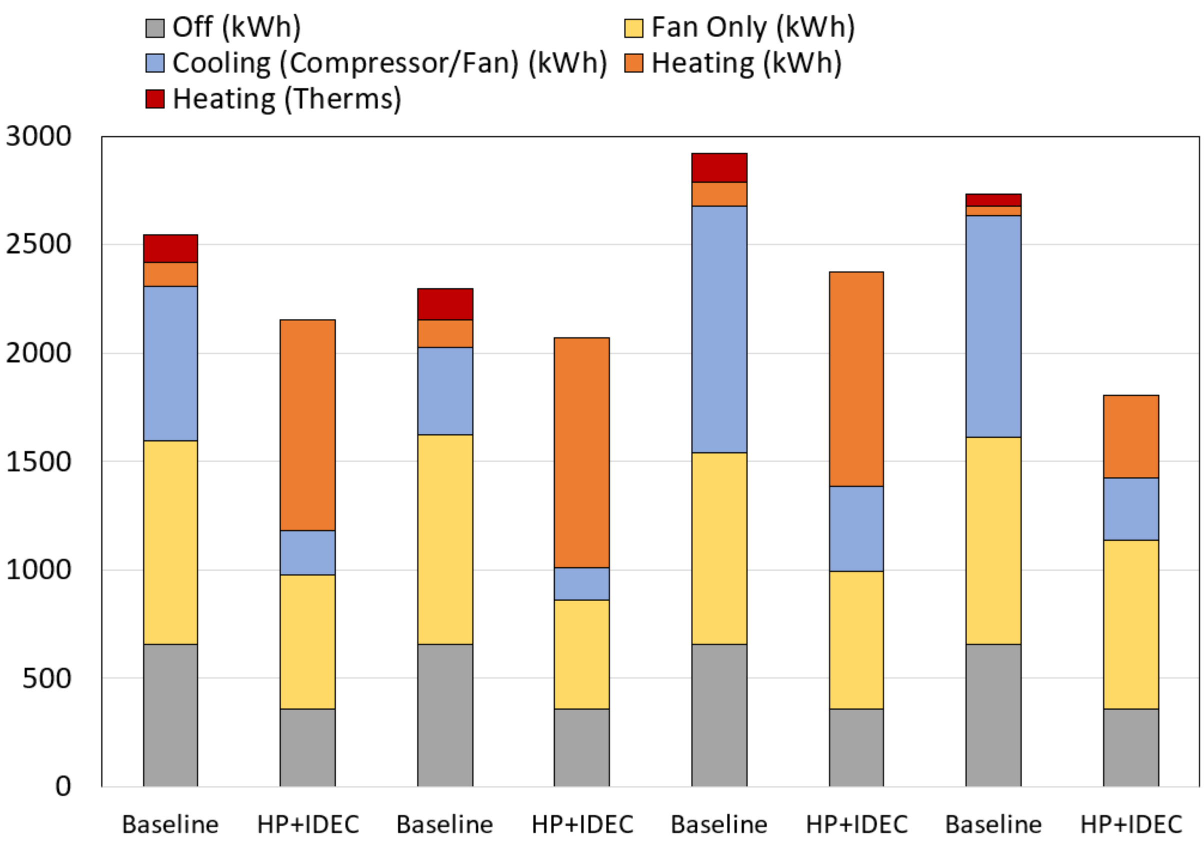


Figure 21. Breakdown of annual electricity and natural gas for baseline and packaged heat pump with IDEC systems for four modeled cities.

Table 10. Annual energy, water, and outdoor air impacts for San Jose and San Francisco

	SAN JOSE			SAN FRANCISCO		
Mode	Baseline	Packaged HP with IDEC	% Baseline	Baseline	Packaged HP with IDEC	% Baseline
Off (kWh)	**655**	**361**	**-45%**	**655**	**361**	**-45%**
Fan Only (kWh)	**939**	**617**	**-34%**	**968**	**501**	**-48%**
Vent (kWh)	876	84		901	97	
Cool - Econ (kWh)	63	56		67	66	
Cool - EC (kWh)		478			338	
Cooling (Compressor/Fan) (kWh)	**714**	**204**	**-71%**	**406**	**149**	**-63%**
Heating (kWh)	**109**	**973**		**123**	**1062**	
Total (kWh)	**2416**	**2155**	**-11%**	**2151**	**2072**	**-4%**
Heating (Therms)	**131**			**144**		

Total Water (gal)		**4471**			**3693**	
Average Vent Rate (CFM)	**749**	**1038**	**+39%**	**752**	**938**	**+25%**

TABLE 11. ANNUAL ENERGY, WATER, AND OUTDOOR AIR IMPACTS FOR FRESNO AND LOS ANGELES

	FRESNO			LOS ANGELES		
Mode	Baseline	packaged heat pump with IDEC	% Baseline	Baseline	packaged heat pump with IDEC	% Baseline
Off (kWh)	**655**	**361**	**-45%**	**655**	**361**	**-45%**
Fan Only (kWh)	**883**	**635**	**-28%**	**954**	**779**	**-18%**
Vent (kWh)	831	72		879	68	
Cool - Econ (kWh)	52	43		75	55	
Cool - EC (kWh)		520			656	
Cooling (Compressor/Fan) (kWh)	**1137**	**391**	**-66%**	**1027**	**285**	**-72%**
Heating (kWh)	**111**	**987**		**43**	**381**	
Total (kWh)	**2787**	**2375**	**-15%**	**2678**	**1806**	**-33%**
Heating (Therms)	**134**			**53**		
Total Water (gal)		**5326**			**5722**	
Average Vent Rate (CFM)	**742**	**1046**	**+41%**	758	1206	**+59%**

RESULTS – MINUTE DATA

Supply air temperature, power, sensible room capacity, total room capacity, sensible equipment capacity, and all coefficient of performance (COP) metrics for minute-resolution data as a function of outdoor air temperature are included in the Appendix. This data can be helpful in developing equipment models to support more in-depth modeling of additional building types and applications. Additional data is available from the research team by request. A summary of metrics at typical rating conditions (47°F for heating and 95°F for cooling is included in Table 12).

Supply air temperatures for the packaged heat pump with IDEC were approximately 10°F cooler than the baseline gas furnace, which is expected for heat pump technology (Appendix, top row). Supply air temperatures for the compressor-based cooling systems were similar, and evaporative cooling supply air temperatures were approximately 10°F warmer than the compressor-based cooling at the hottest outside air temperatures.

Heating capacity of the baseline system was higher than the packaged heat pump with IDEC (Table 12) which is expected for comparing a gas furnace to a heat pump. The capacity of the heat pump was adequate for maintain thermal comfort (Figure 15). The efficiency of the packaged heat pump with IDEC heat pump was 3.78 at 47°F when accounting for the conditioning of minimum ventilation air. The compressor-based cooling efficiencies between the two systems were comparable, with the evaporative cooling (EC) mode efficiency outperforming compressor-based cooling, as expected. Note the performance shown in the table below is only a snapshot of performance at specific outside air conditions. For performance trends versus outside air temperature, please see the Appendix.

TABLE 12: CAPACITY AND COP AT TYPICAL RATING CONDITIONS FOR THE BASELINE AND PACKAGED HEAT PUMP WITH IDEC SYSTEMS

	BASELINE CAPACITY (TONS)	BASELINE COP	PACKAGED HEAT PUMP WITH IDEC CAPACITY (TONS)	PACKAGED HEAT PUMP WITH IDEC COP
Heating (47°F)				
Sensible Room Capacity/COP	4.48	0.69	3.01	2.64
Sensible Equipment Capacity/COP	5.91	0.91	4.32	3.78
Cooling (95°F)				
Sensible Room Capacity/COP	2.67	1.79	2.69 (DX) 1.13 (EC)	1.94 (DX) 2.90 (EC)
Total Room Capacity/COP	3.70	2.47	2.90 (DX) 1.03 (EC)	2.09 (DX) 2.71 (EC)
Sensible Equipment Capacity/COP	3.59	2.40	3.70 (DX) 1.99 (EC)	2.66 (DX) 5.13 (EC)

DISCUSSION

The packaged heat pump with IDEC technology demonstrated was able to maintain thermal comfort, increase outside air for human health and performance, eliminate natural gas combustion for heating, and save electricity, even when including the electricity used for heating. A simplified model based on field test data showed that the expected energy impact in four California cities is a 4-33% reduction in electricity and elimination of natural gas for heating.

Electricity used was reduced through a combination of reduced standby power, improved ventilation system efficiency, and reduced use of compressor-based cooling in favor of more efficient evaporative cooling. Reduced standby power for the packaged heat pump with IDEC resulted in 45% energy savings in off mode. As building energy efficiency improves, standby power is an important load to consider that is often overlooked. The fan only mode energy use, which also included providing evaporative cooling with the packaged heat pump with IDEC, was reduced 18-48% in the packaged heat pump with IDEC over the baseline. Cooling mode with the compressor engaged had the most drastic savings, with 63-72% energy saving for the packaged heat pump with IDEC over the baseline.

The maximum 15-minute peak demand during the hottest hours of the summer was approximately the same for both the baseline and packaged heat pump with IDEC systems. The maximum 15-minute peak demand for the packaged heat pump with IDEC in heating mode increased to approximately 4-4.5kW compared to 0.7kW for the baseline, due to the use of the heat pump instead of gas heat.

The packaged heat pump with IDEC was estimated to consume 3,600-5,700 gallons of water annually to achieve this electricity savings, which equates to an average of 8.5 gallons consumed per kWh saved for cooling. For context, this is less water than the average person consumes annually for daily showers. The analysis also showed an expected increase in ventilation air of 25-59% above the baseline, which is an important finding expected to result in reduced probability of long-range airborne transmission of infectious disease and improved student performance.

The packaged heat pump with IDEC was manufactured in an RTU format that is drop-in replacement for existing packaged RTUs. Installation was straightforward and required only the addition of a curb adapter, which is typical when switching between different RTU manufacturers. Remaining market barriers are potentially higher weight compared to lower-efficiency RTUs, a requirement for water service to the unit, and equipment first cost. Since this demonstration was the first packaged heat pump with IDEC RTU installed, production system cost data is not yet available. As with all emerging technology, cost is expected to decrease with increased production.

CONCLUSIONS AND RECOMMENDATIONS

The packaged heat pump with IDEC technology demonstrated was able to maintain thermal comfort, increase outside air for human health and performance, eliminate natural gas combustion for heating, and save electricity, even when including the electricity used for heating. A simplified model based on field test data showed that the expected energy savings in four California cities is a 4-33% reduction in electricity and elimination of natural gas for heating. Peak demand for cooling was similar between the baseline and packaged heat pump with IDEC systems and peak demand for heating was increased due to the use of a heat pump instead of gas for heating. The packaged heat pump with IDEC was estimated to consume 3,600-5,700 gallons of water annually to achieve this electricity savings, which equates to an average of 8.5 gallons consumed per kWh saved for cooling. The analysis also showed an expected increase in ventilation air of 25-59% above the baseline, which is an important finding expected to result in reduced probability of long-range airborne transmission of infectious disease and improved student performance [7] [8].

The packaged heat pump with IDEC is a unique drop-in replacement for packaged RTUs that supports California's goals for decarbonization and electricity savings. Manufacturer performance claims were validated by the assessment. The assessment provides the required data needed to consider inclusion of the technology in an energy efficiency program. Since the technology is weather dependent, additional modeling is recommended to estimate savings impacts for additional building types and to determine if heat pump capacity is sufficient for California's coldest climates. Additional demonstrations of the technology will increase awareness and confidence in the technology for end users.

REFERENCES

[1] Itron Inc., "California Commercial End-Use Survey," California Energy Commission, Sacramento, 2006.

[2] Pacific Gas and Electric, "Climate Appropriate Cooling for a Grocery Store," Emerging technologies coordinating council, 2015.

[3] Southern California Edison, "Western Cooling Challenge Field Test - Advanced Indirect Evaporative Technologies," Emerging Technologies Coordinating Council, 2015.

[4] Southern California Edison, "Western Cooling Challenge Field Test - Restaurant Application (Evaporative pre cooling of supply and condenser air)," Emerging Technologies Coordinating Council, 2016.

[5] Southern California Edison, "Market Barriers to HVAC Retrofit Technologies," Emerging Technologies Coordinating Council, 2015.

[6] San Diego Gas and Electric, "Performance Evaluation of a Residential Indirect-Direct Evaporative Cooler," 2020.

[7] W. Fisk, "The ventilation problem in schools: literature review," *Indoor Air,* vol. 27, 2017.

[8] M. J. Mendell, E. A. Eliseeva, M. M. Davies, M. Spears, A. Lobscheid, W. J. Fisk and M. G. Apte, "Association of classroom ventilation with reduced illness absence: a prospective study in California elementary schools," *Indoor Air,* vol. 23, pp. 515-528, 2013.

[9] B. Stephens, "HVAC filtration and the Wells-Riley approach to assessing risks of infectious airborne diseases," The National Air Filtration Association Foundation, Virgina Beach, 2013.

[10] Lennox, "Packaged L Series Engineering Data," 01 05 1999. [Online].

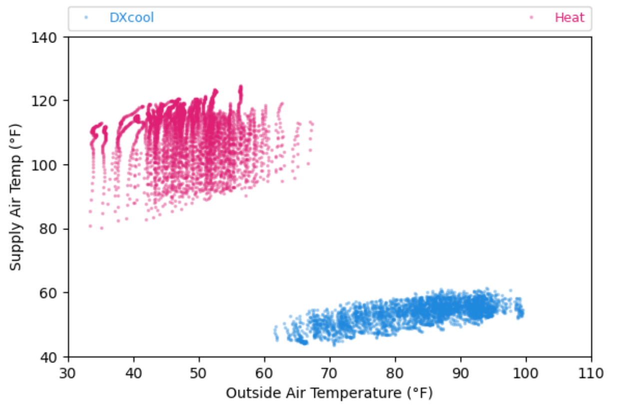
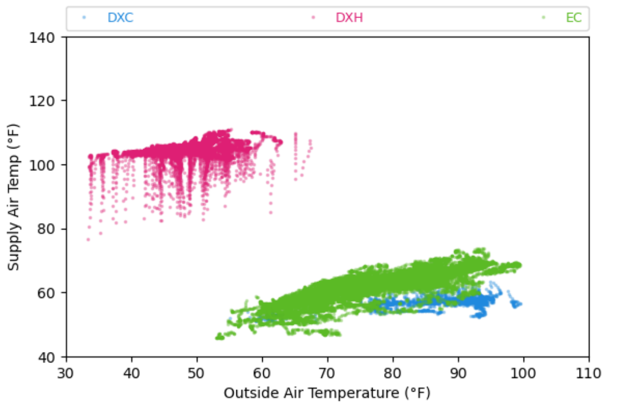
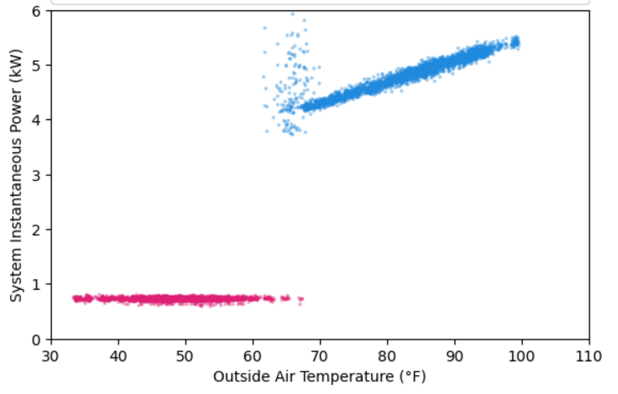
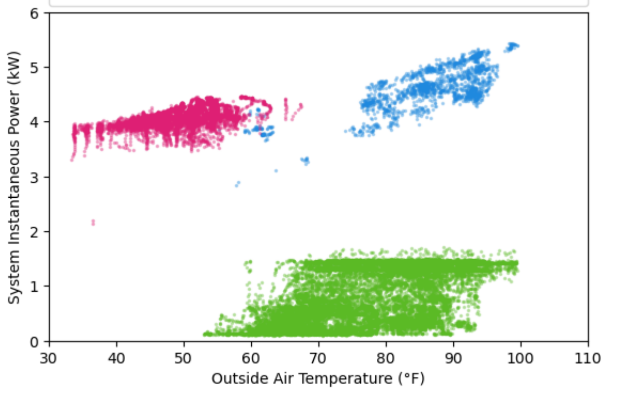
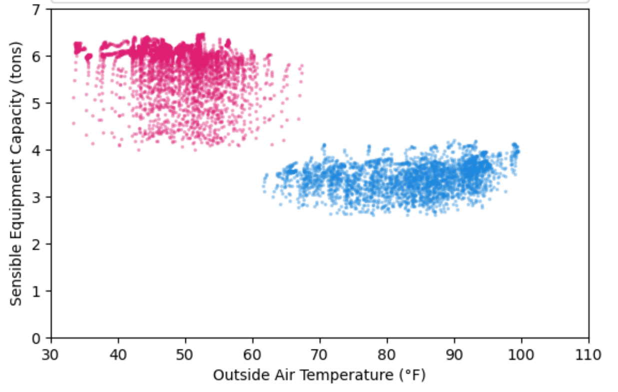
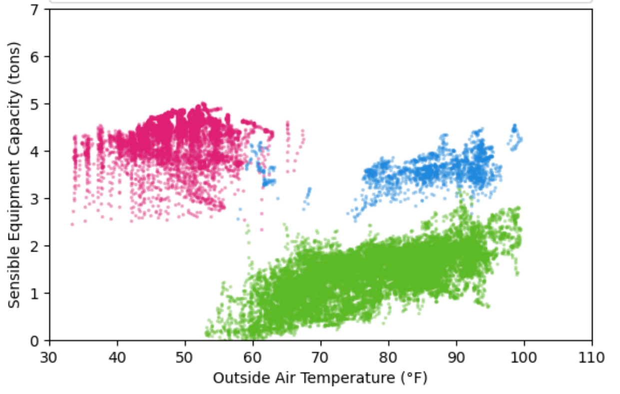
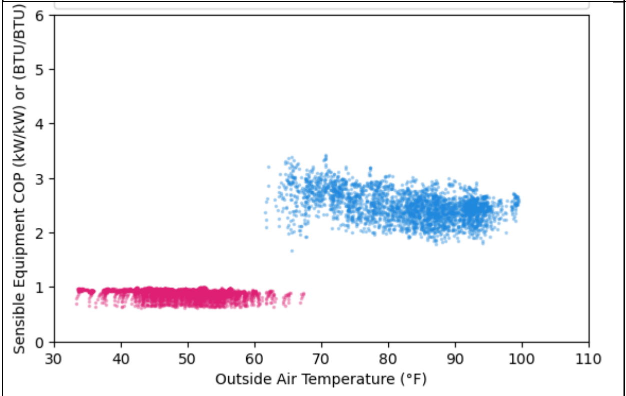
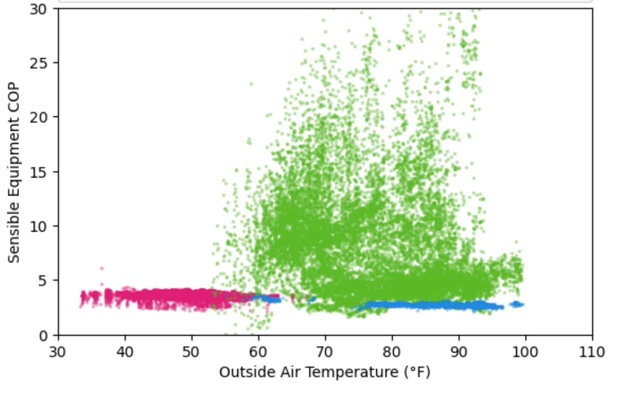
[11] Energy Efficiency and Renewable Energy Office, "Energy Conservation Program: Energy Conservation Standards for Residential Central Air Conditioners and Heat Pumps; Confirmation of effective date and compliance date for direct final rule," 26 05 2017. [Online]. Available: https://www.regulations.gov/document/EERE-2014-BT-STD-0048-0200. [Accessed 4 10 2021].

[12] Western Cooling Efficiency Center, "Psych: An Open Source Psychrometric Plug-in," [Online]. Available: https://wcec.ucdavis.edu/resources/software-resource-applications/. [Accessed 18 10 2021].

[13] ANSI/ASHRAE, "ANSI/ASHRAE Standard 55-2020 Thermal Enviornmetal Conditions for Human Occupancy," ASHRAE, Peachtree Corners, 2021.

[14] M. Modea, "Does Evaporative Cooling Make Sense in Arid Climates?," 2016.

APPENDIX – MINUTE RESOLUTION DATA

Baseline	Packaged heat pump with IDEC
	
	
	
	

Baseline	Packaged heat pump with IDEC