13th IEA Heat Pump Conference
April 26-29, 2021 Jeju, Korea

Next-Generation Residential Space Conditioning System in the United States

Ammi Amarnath[a,*], Sara Beaini[a], Aaron Tam[a], Jerine Ahmed[b]

[a] Electric Power Research Institute, 3420 Hillview Avenue, Palo Alto, CA, 94304, USA
[b] Southern California Edison, 1515 Walnut Grove Ave., Rosemead, CA, 91770, USA

Abstract

This paper reports on ongoing work integrating a variable-capacity heat pump with additional heating and cooling technologies to provide efficiency and other benefits for residential customers. The Next-Generation Residential Space Conditioning System (Next-Gen RSCS) was tested in three leading U.S. laboratories as well as field evaluated at three homes in California. The Next-Gen RSCS integrates advanced HVAC technologies, including a variable-capacity compressor and variable-speed indoor blower, auto demand response, fault detection and diagnostics, intelligent dual-fuel heating, integrated heat recovery ventilation, and zonal control. An alternative refrigerant, R-32, was evaluated in laboratory testing as a possible future enhancement. An assessment was also performed on duct losses for single- versus multi-zone duct configurations with variable-capacity equipment. The field evaluation saw positive customer feedback, with users appreciating how quiet the units were, how quickly they cooled or heated the space, and their ability to control the temperature in individual spaces. The paper also begins a discussion to extrapolate project results beyond California climates, conditions, and demographics.

Keywords: Variable-capacity heat pump; alternative refrigerant; auto demand response; zonal control; field demonstration; energy savings; non-energy savings

1. Introduction

Cooling and heating of buildings to achieve comfortable temperature and humidity levels accounts for a large portion of the residential energy use in the United States (48%) and California (31%). Improving cooling and heating system efficiency are clear targets for improving residential energy use. Many emerging space conditioning technologies offer improvements in efficiency, but they were not integrated into a single heating, ventilation, and air-conditioning (HVAC) system, nor were they optimized for local climates. This project evaluated individual heat pump technology improvements and integrated them into a variable-capacity heat pump system that could provide higher efficiency space conditioning for California climate zones.

Results of early project work were presented at the American Council for an Energy-Efficient Economy (ACEEE) Summer Study in 2018 [1] followed by a presentation of updated project results at the American Society for Heating Refrigeration and Air Conditioning Engineers (ASHRAE) Winter Meeting in January 2019 [2]. Both papers and presentations focused on laboratory results for the Next-Gen RSCS obtained at three leading U.S. laboratories (Electric Power Research Institute in Knoxville, TN, Pacific Gas & Electric Applied Technology Services in San Ramon, CA, and Western Cooling Energy Center in Davis, CA). A final report, issued in April 2019 [3], documented project findings and included early field test results obtained at three residential sites in California. This IEA paper uses information presented in the final report and additional field test data obtained since April 2019 to provide a discussion of heating and cooling field test results. Also

* Corresponding author. Tel.: +1-650-855-1007.
E-mail address: aamarnath@epri.com.

included in this paper is a discussion of Next-Gen RSCS advantages: how they can satisfy customer needs and provide utility benefits and how they might be extrapolated beyond California applications.

2. Next-Gen RSCS System Features

The portfolio of advanced features incorporated into the Next-Gen RSCS (See Figure 1) included a variable-capacity compressor and variable-speed fan using state-of-the-art inverter technology; integrated heat recovery ventilation to exchange heat between the incoming air and the exhaust air to and from the conditioned space; intelligent dual-fuel technology to select the most economical means of heating to decrease energy cost and empower consumers to choose between electricity and natural gas; zonal control using mechanical dampers controlled by thermostat setpoints to avoid conditioning unoccupied rooms; demand-response strategies that take advantage of variable capacity to save energy; advanced fault detection and diagnostics to facilitate proper installation, operation, and maintenance; and alternative refrigerants for improved efficiency and reductions in global warming. Figure 2 summarizes which features were evaluated in the laboratory (Phase 1 and Phase 2) and field evaluation (Phase 3) portions for the study.

Fig 1. Next-Generation Residential Space Conditioning Enhancing Features

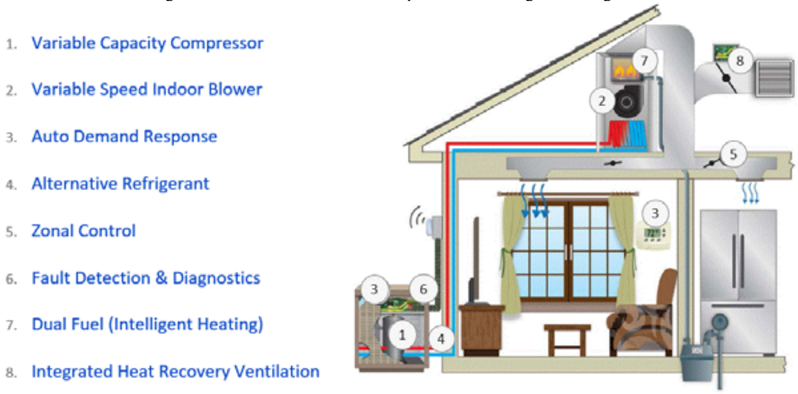


Fig 2. Technology Features Evaluated in Lab (Phase 1 and 2) and Field (Phase 3)

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

2.1 Benefits and Potential Barriers

An assessment of the benefits and potential barriers of the Next-Gen RSCS features was performed as part of the technology transfer planning effort and is summarized in Table 1.

Table 1 Benefits and Potential Barriers of Next-Gen RSCS Features

Feature	Benefits	Potential Barriers
Variable Capacity	Greater comfort, lower energy costs, improved noise, smoother operation, possible reliability improvements	Higher equipment cost and complexity, harmonics
Alternative Refrigerants	Lower Global Warming Potential (GWP), performance improvement, and lower energy cost	Requires regulatory approval
Dual Fuel	Lowest possible heating costs based on fuel selection	Higher equipment costs
Fault Detection and Diagnostics	Improved maintenance and reliability, lower energy costs	Higher cost of control systems
Integrated Ventilation/Heat Recovery Control	Lower energy costs	Higher equipment costs
Zonal Control	Lower energy costs, better controllability, greater comfort	Higher equipment costs require additional user training
Auto Demand Response	Lower demand charges, greater comfort	Higher equipment costs

2.2 Energy Cost Savings

The testing and analysis in this project and the literature review provided information on the potential operating savings resulting from deployment of the Next-Gen RSCS. In summary, the energy savings for each feature determined by this project, and in a cursory review of the literature review, are provided in the following paragraphs. (More details are provided in Section 6.3 of the Final Report [3] regarding the work reported in the literature on each system feature.)

- Variable capacity[1] – Current study - 22% to 32% energy savings; 35% [4] and 36% [5] energy savings in other studies.
- Alternative refrigerant – Current study - R-32 shows 1.2% to 3.0% improvement in cooling efficiency and improvement in heating capacity by 5% at 25°F and by 10% at 62°F; 1% [6] to 9% [7] energy savings in other studies.
- Dual fuel – Current study - for average electric and gas prices, the highest energy cost savings were 22% for California climate zone 3 (Oakland); no quantitative results were found in the recent literature.
- Fault detection & diagnostics – Current study - Inform maintenance alerts to avoid inefficient operation (no quantitative results obtained): High energy reductions were found to be possible in the literature depending on the nature and severity of the faults detected and resolved [8].
- Integrated heat recovery ventilation control – Current study - 1.3% to 3.8% energy savings in this study; 30% or more energy efficiency improvement in other studies [11, 12].[2]
- Zonal control – Current study - up to 50% savings at 40% capacity; 10% load reduction would result in 12.8% power reduction; 16% to 25% [13, 14] in other studies.
- Auto demand response – Current study - 50% power reduction resulted in only a 38.2% capacity reduction, and a 70% power reduction resulted in only a 61.8% capacity reduction; savings depend on specific utility and customer conditions.

[1] The efficiency savings obtained with variable speed are due to reduced temperature differences in the system at part-load conditions as the compressor speed is reduced as well as reduction/elimination of start and stop transients as the load is followed compared to on-off modulation with a single-speed system.

[2] Energy savings were greatest when the climate was extreme (very hot or very cold) and the residence was tight and well insulated.

Examining and accumulating the savings achieved by each feature indicates that energy savings of approximately 50% are achievable by integrating all the features studied.

2.3 Non-Energy Cost Savings

The technologies deployed in the Next-Gen RSCS will generally have higher first costs than the technologies they are replacing, but these costs will be offset by lower energy costs and lower maintenance costs as well as other benefits discussed below, including improved reliability and greater comfort.

2.4 Reliability

The use of fault detection and diagnostics (FDD) will increase reliability of the units by anticipating failures and alerting the occupant and contractor to permit timely maintenance and repair to reduce system downtime. Variable capacity should provide smoother operation, reducing equipment stops and starts, thus reducing stress on components, resulting in increased equipment life.

2.5 Safety

The anticipated higher reliability of the Next-Gen RSCS should provide greater occupant safety when comfort is a safety issue (as in extreme climate situations). Since R-32 is classified as A2L refrigerant (lower flammability and lower toxicity), regulation will need to provide the appropriate usage guidelines to address flammability issues in the equipment design, placement, and operation to ensure that safety is equivalent to or better than the equipment that it is replacing.

2.6 Consumer Appeal

In addition to the reduced operating cost, improved reliability, and safety issues aforementioned, the following Next-Gen RSCS advantages should appeal to consumers:

- The Next-Gen RSCS will provide greater comfort during normal operation due to use of variable capacity to permit load following, closer temperature control, and less on-off cycling.
- The timely use of FDD will increase reliability of the units, reducing downtime, repair bills, and intermittency of space-conditioning.
- The use of a furnace and a heat pump as heating options affords the user with the opportunity to take advantage of the lowest price source of heating. This should appeal to cost-conscious consumers.

2.7 Demand Benefits

According to California's Energy Efficiency Strategic Plan [15], HVAC is the single largest contributor to peak power demand in the state, comprising up to 30% of total demand in the hot summer months. The auto demand response and variable-capacity features of the Next-Gen RSCS can significantly reduce HVAC system peak demand.

Intelligent, variable-capacity space-conditioning equipment has been demonstrated to reduce power by 60% during peak events, while continuing to provide cooling to the conditioned space [16]. Variable-capacity systems have the unique attribute of going to a state of higher operating efficiency when the compressor speed is reduced. This Next-Gen RSCS project confirmed that power reductions would exceed capacity reductions when operating the unit below maximum speed. This provides demand savings and increased cooling capacity compared to equivalent single-speed units. According to the Strategic Plan, the California Energy Commission estimates that a peak demand reduction of 1,096 MW in the residential and small commercial sectors could be achieved through high-quality HVAC installations by 2020. (Next-Gen RSCS installations would certainly qualify as high-quality installations.) Assuming market penetration of 20% and the ability of the system to reduce peak demand by 60%, the cumulative peak demand reduction for California would be approximately 1.5 GW. Thus a 1–1.5 GW in demand reduction due to deployment of units similar to the Next-Gen RSCS appears to be an aggressive but potentially achievable goal. These savings, if achieved, will enable electric utilities to avoid building new power plants and consequently avoid adding substantial capital costs to their systems. Customers will benefit accordingly as reduced utility system costs should result in lower rates than would otherwise be mandated.

2.8 Energy and Environmental Benefits

As indicated in Section 2.2, energy cost savings of 50% appear to be technologically achievable when deploying the Next-Gen RSCS compared to commonly used residential HVAC systems. This could result in savings of 475 GWh/yr or $83 million annually in California, assuming market penetration of 20%, 4750 GWh/yr for single-family HVAC energy use in California in 2014 [17], and an average residential electric rate of $0.176/kWh. Assuming an equipment life of 15 years, the Next-Gen RSCS could save California ratepayers over $1 billion over the lifetime of the equipment. Based on the standard emission factor (0.331 kg/kWh saved) and energy savings of 475 GWh/yr or 475 million kWh/yr, the Next-Gen RSCS could provide a reduction of 157 million kg of CO_2 emission per year in California.

In addition to these CO_2 emissions savings, use of a refrigerant such as R-32 could also contribute to a reduction in global warming. Assuming typical leakage rates, an R-32 system (GWP of 675) will emit only 33% as much CO_2-equivalent direct emissions as the equivalent R-410A (GWP of about 2100) system over its lifetime. This value may be even lower in reality because systems using R-32 will have a lower refrigerant charge than R-410A systems. These global warming savings, while substantially less than the equivalent CO_2 emissions savings due to lower energy use, are still significant.

The environmental benefits achieved by deploying the Next-Gen RSCS compared to commonly used residential HVAC systems could be a major step in helping utilities achieve their environment mandates.

3. Field Evaluation

A field evaluation of the Next-Gen RSCS was performed in three occupied residential households, one in each of the California investor-owned utilities (IOU) service territories (Pacific Gas & Electric [PG&E], Southern California Edison [SCE], and San Diego Gas & Electric [SDG&E]). The field study included retrofitting each home with a new ducted split variable-capacity heat pump unit (VCHP) with refrigerant R-410A, provided by Daikin/Goodman. Table 2 lists the specifications of the three homes that participated in the field evaluation.

Table 2 Field Testing Host Sites Specifications

Host Site	**West Sacramento**	**Chino Hills**	**San Diego**
Utility	PG&E	SCE	SDG&E
CA Climate Zone	12	10	7
Area (ft^2)	2507	1850	1906
Home Vintage	2008	1993	1980
Existing Ducting, Heating System (pre-install)	Ducted AC with Gas Furnace	Ducted AC with Gas Furnace	Ducted AC with Gas Furnace
Location of Ducts	Attic	Attic	Attic
AC Size (tons) (pre-install)	3-ton Condenser 4-ton AHU	4	4
Floors	2	2	1
Number of Residents	4 + 1 pet	4 + 1 pet	1 + 3 pets

The objective of the field evaluation was to assess the functionality of the Next-Gen RSCS features in residential homes and evaluate the performance with respect to the customer experience. For the field evaluation, each home—depending on its configuration and climate—evaluated a subset of the key features discussed next. After installing the Next-Gen RSCS with new ducting insulation, each home was instrumented with power meters for the indoor and outdoor units, temperature and relative humidity sensors in each zone, and pressure differential sensors across each zone damper in the attic ducting. Data collection spanned over one year to capture both the heating and cooling season. Data analysis included comparing variable-capacity heat pump performance to a single-speed Seasonal Energy Efficiency Ratio (SEER) 14 HVAC unit, as well as comparing the field-testing data with the lab-testing data.

3.1. Variable-Capacity Compressor and Blower Field Performance

The cooling and heating seasonal analysis of the field data for the Next-Gen RSCS both show energy consumption within 20% of the lab data model, which was developed with steady-state testing. A 2-ton model of the system was tested in laboratories at outdoor temperatures at 10˚F increments from 65˚F to 105˚F for cooling, and at 62˚F, 47˚F, 35˚F, 25˚F, and 15˚F for heating. The indoor condition was kept constant at 75˚F dry bulb and 63˚F wet bulb for cooling and 70˚F and 57˚F, respectively, for heating, and each condition was tested at high (100%), intermediate (50%), and low (30%) compressor speed. While the lab- and field-tested systems are of different rated capacities and different setpoints may have been used, the efficiency of the system should be comparable. The cooling performance of the units shows a range of Energy Efficiency Ratio (EER) between 10 and 25, which agrees with the range of EER found in the laboratory testing performed earlier in the study. Figures 4, 5, and 6 show the West Sacramento site field data compared to the laboratory testing results as well as a SEER 14 baseline system. The results clearly illustrate the benefits of a variable-capacity system, with much higher efficiency as the system reduces its compressor speed to intermediate and low stage.

Fig 4. West Sacramento Site High-Stage Field Data

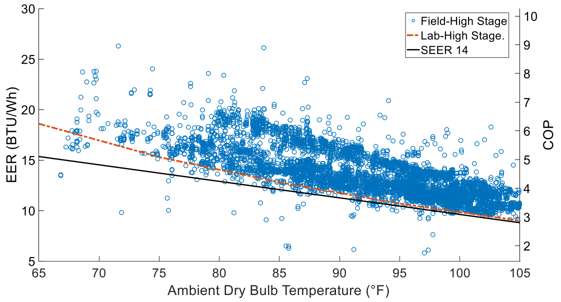


Fig 5. West Sacramento Site Intermediate-Stage Field Data

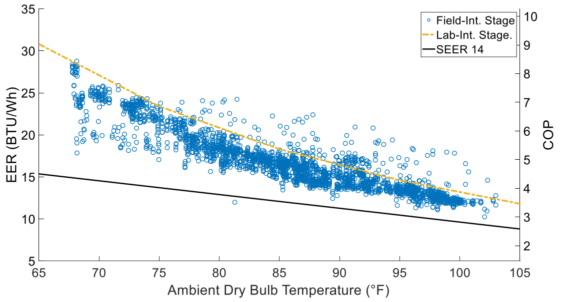
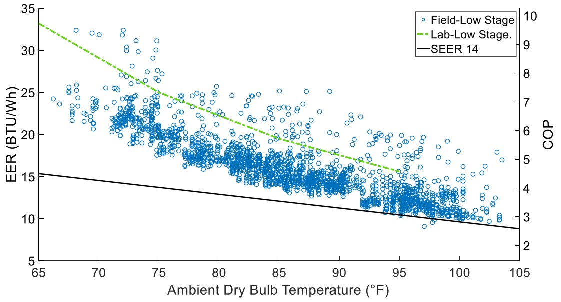


Fig 6. West Sacramento Site Low-Stage Field Data



3.2. Dual-Fuel (Intelligent Heating) Field Performance and Operation

Once the breakeven temperature[3] was set for each of the three host sites, the Next-Gen RSCS performed as expected in the heat pump mode and gas furnace mode throughout the duration of the heating season. The Next-Gen RSCS dual-fuel capability provides an important choice for the residential customer to adjust the unit settings based on economic factors (utility rates), efficiency factors (heat pump vs. gas furnace), or environmental factors (reduction of carbon footprint).

Having a controller that automatically receives pricing information and sets the breakeven temperature accordingly would minimize the need for customer interaction (unless they chose to do so.) Future work is needed to develop a versatile/intelligent heating controller that can receive a signal based on utility prices and customer choice/preference (price, efficiency, fuel mix distribution), which would optimize the Next-Gen RSCS's performance in the heating mode.

3.3. Auto Demand Response (ADR) Field Performance

The unit capacity reduction is less than the unit power reduction when operating below maximum speed and capacity; therefore, customer comfort is not as compromised while energy and demand savings can be realized during a utility-led demand response event.

Field ADR testing was conducted in both the heating and cooling mode. Heating mode demand response of 30% or 50% demand reduction both resulted in 4.9% variation between power and capacity change (the power reduction was 4.9% more than capacity reduction). During the cooling mode test, a 50% demand reduction resulted in 8.4% variation between power and capacity change.

3.4. Zonal Control Field Performance

The three host sites for the field evaluations were set up with variable-speed heat pumps and new insulated ducting that was zoned into either two, three, or four zones depending on the housing configuration and square footage. An important observation learned from the field evaluation is the significance of setting up the zoning controls through the zone weightings to minimize the possibility of overflow in small zones.

When installing variable-capacity equipment with ductwork located in unconditioned space, zoning controls provide added system efficiency where the system would operate in part-load capacity when not all the zones are called on for conditioning.

3.5. Customer Feedback Regarding Field Test Units

The following summarizes the homeowners' feedback on their experience with the Next-Gen RSCS:

- They appreciate how much quieter the Next-Gen RSCS operates compared to their previous single-speed AC unit.
- They like how quickly it cools or heats the space.[4]
- They like having an app-based controller for the thermostats to turn on and set the temperature of individual zones.
- They like the ability to control temperatures in individual spaces (that is, an advantage and nice attribute of zonal control is to control zones independently).
- While zonal control is a convenient feature for the occupants, it added complexity to the VCHP system when there were more than two zones. Airflow was too forceful in certain zones, making it noisy in some rooms. Once the weighting of the zones was adjusted, this mitigated the effect of the airflow imbalance.

The laboratory and field evaluation of the Next-Gen RSCS features in residential homes resulted in recommendations to extend the benefits of the Next-Gen RSCS concept, which are summarized in Section 4.

4. Configuring the Next-Gen RSCS into Different Models

Two of the recommendations made in the study final report [3] are worth exploring in this forum and in terms of extending the scope of the project beyond California. The first is to examine the suitability of each

[3] The *breakeven temperature* is defined as the temperature at which the cost of heating using the gas furnace and the electric heat pump is equal. Above the breakeven temperature, it is more economical to run the heat pump; below the breakeven temperature, it is more economical to run the furnace.

[4] This is in comparison to the older, poorly operating system that was replaced.

feature of the Next-Gen RSCS for the conditions being considered: climate, customer demographics,[5] electricity rates, configuration, and delivery system. The second is to integrate the most desirable features into a model of the Next-Gen RSCS most suitable for those conditions.

The premise of both recommendations is that each feature will differ in value depending on customer demographics, utility rates, and climate. What features are most likely to be of value, and what are the variables affecting this value? The reported study focused on forced air delivery systems for single-family residential systems in California climates.[6] How would the features perform if incorporated into other delivery systems and in other climates?

Variable-capacity inverter-driven technology is the key to many of the system advantages. Being able to vary the compressor and fan speed to follow the load provides smooth, efficient, unobtrusive operation. It is also the key to efficient **demand response**, providing more efficient operation while also reducing demand. Capacity modulation is also the key to efficient zonal control. Variable capacity is the cornerstone of the Next-Gen RSCS and is likely to be incorporated into all models of future units.

Variable capacity can be, and is, used with other delivery systems, including systems using refrigerant piping for distribution as well as hydronic systems. As such, it should be applicable to a wide range of HVAC configurations in the United States and abroad.

The advantages of variable capacity are most apparent at off-design conditions and may not be useful when many hours occur at high-temperature conditions. Nonetheless there should be sufficient hours in "shoulder" periods and the need for zoning and demand response to make this feature valuable.

Fault detection and diagnostics are a robust technology that, with proper sensors and controls, should be viable across the entire range of customer demographics, climates, and delivery systems. Early detection of inefficient operation and impending failures is needed for all HVAC systems. Potential savings are likely to be highest when the need for heating and cooling are highest, but FDD systems should be generally applicable across the United States and abroad.

Zonal control can be managed effectively with a variable-capacity system that can respond to changes in occupancy. Matching the Next-Gen RSCS to operate with a variety of delivery systems should make it applicable across the United States and abroad. Climate and demographic differences should not hamper its operation.

Integrated heat recovery ventilation preheats or precools the air entering the conditioned space, providing fresh air ventilation efficiently by exchanging heat between a fresh air and exhaust air stream. This system requires a heat exchanger and flow path that can be independent or integrated with the HVAC system and thus can be effectively added to any delivery system that requires a forced ventilation system. Energy savings should be highest at extreme temperatures (high outdoor temperatures for cooling and low outdoor temperature for heating), but the savings are modest compared to the savings achievable by other features.

R-32 as an **alternative refrigerant** to R-410A appears to have cooling mode performance advantages over R-410A that are highest at high outdoor temperature and thus would be most advantageous as a replacement in hotter climates. This could apply to other climates in the United States and abroad but not typically in heavily populated areas of Europe. R-32 has already been approved and has seen wide adoption in Japan and is seeing more penetration in China and European countries. The environmental advantages of R-32 compared to R-410A are clear, and performance appears comparable for milder cooling and heating conditions.

Dual fuel is the feature that is most sensitive to electricity and gas rates and climate. Dual fuel using a gas furnace or other gas heating device and an electric heat pump works best economically when there are many heating hours at moderately cold temperatures where the both the furnace and the heat pump can each operate for enough hours to offset their capital cost. If most of the heating is at low temperature and gas prices are economical, it would likely pay to just have a furnace for heating. Where most of the heating is at mild temperatures and the electricity prices are economical, just a heat pump with or without electric resistance backup might be most economical for heating.

Economical operation of the dual-fuel option depends on both the gas and electric rates and the climate. Since heat pump efficiency degrades as the outdoor temperature is reduced and gas furnace efficiency is relatively constant with outdoor temperature, there is a temperature at which the heat pump and furnace operating costs are the same—the breakeven temperature. If gas prices are very low or electric prices are very high, the breakeven temperature will be high and the furnace will carry the crux of the heating load. The

[5] Pertinent customer demographics include number, mobility, and age of occupants and how it affects factors such as occupancy and the usefulness of zoning and sensitivity to temperature settings.

[6] For the most part, the results in the study were obtained for relatively dry climates. For hot, humid climates, coils will need to be designed for greater latent load removal, and thus, likely need to be deeper. The RSCS's integration of the multiple features studied should remain applicable to such climates.

opposite is true when electric prices are low and gas prices are high. Gas and electric prices vary dramatically globally as does local climate, so the operation of the dual-fuel heat pump needs to be evaluated on a case-by-case basis with regard to these variables.

In configuring the Next-Gen RSCS for a particular customer segment or climate, the features discussed above should be considered and built upon to develop a model best suited for the demographics, configuration, and climate of interest.

A premium model might include all energy efficiency features of the Next-Gen RSCS. The base model could be a variable-capacity heat pump with demand response, fault detection and diagnostics, and zonal control—all of which are crucial features to benefit from the efficient operation of variable-capacity heat pump. The intermediate model could include intelligent heating as an additional feature to the base model.

5. Concluding Remarks

While the current project conducted the testing and evaluation of each of the features to quantify the potential for energy savings and performance benefits, a future project would be needed to develop a model that evaluates the cost effectiveness of each feature. The model would need to evaluate energy and demand cost savings for each feature for different climate zones for representative housing, demographics, and occupancy situations.

Acknowledgments

The authors would like to acknowledge the California Energy Commission for its support and funding of this project under award number CEC EPC-14-021. Also, they would like to acknowledge Daikin/Goodman who supplied the variable-capacity heat pump units and provided research guidance.

References

[1] Beaini S, Amarnath, A, Hunt W, Domitrovic R, Krishnamoorthy S, Harrington C, Modera M, Davis R, Hinokuma R, "Evaluation of the Next Generation Residential Space Conditioning System for California," 2018 ACEEE Summer Study on Energy Efficiency in Buildings.

[2] Beaini S, Amarnath A, Hunt W, Domitrovic R, Krishnamoorthy S, Harrington C, Modera M, Davis R, Hinokuma R, Blatt M, "Next Generation Residential Space Conditioning System for California," (AT-2019-C035). ASHRAE 2019 Winter Conference Proceedings, January 14, 2019.

[3] Amarnath A , Beaini S , Hunt W, Domitrovic R, Tam A, Vaddiraj A, Davis RA, D'Albora MD, Modera M, Harrington C, Krishnamoorthy S, Blatt M, Development and Testing of the Next Generation Residential Space Conditioning System for California. Final Project Report, CEC-EPC-14-021, April 2019.

[4] Yunhua L, "Variable Frequency Drive Applications in HVAC Applications", in New Applications of Electric Drives, book edited by Miroslav Chomat, ISBN 978-953-51-2233-3, December 9, 2015.

[5] Lawrence R, Blatt M, Adjustable Speed Drives in Residential Appliances, White Paper, EPRI for CEC/PIER 500-10-022, March 14, 2014.

[6] Li H, and By B, Soft-optimized System Test of Refrigerant R-32 in 3-ton Split System Heat Pump, Goodman Manufacturing for AHRI Low-GWP AREP, December 19, 2012.

[7] Xu X, Hwang Y, Rademacher R , Performance Measurement of R32 in Vapor Injection Heat Pump System, University of Maryland, International Refrigeration and Air Conditioning Conference at Purdue, July 16-19, 2012.

[8] Mowris R, Eshom R, Jones E, "Laboratory Measurements of Residential HVAC Installation and Maintenance Faults", Fault Detection Diagnosis and Repair of Residential HVAC Systems, September 10, 2013 – Davis, CA.

[9] Francisco PW, "Measuring residential duct efficiency with the short-term co-heat test methodology", University of Illinois, Energy and Buildings 38 (2006) 1076–1083.

[10] Modera, MP, Remote Duct Sealing in Residential and Commercial Buildings: "Saving Money, Saving Energy and Improving Performance, Lawrence Berkeley National Laboratory, April 21, 2006.

[11] Hekmat D, Feustel HE, Modera MP, "Ventilation Strategies and their Impacts on the Energy Consumption and Indoor Air Quality in Single-Family Residences", Energy and Buildings, Vol. 9, p. 239-251, 1986.

[12] Jokisalo J, Kurnitska J, Torkki A, "Performance of balanced ventilation with heat recovery in residential buildings in cold climate", International Journal of Ventilation, Vol. 2. 2003.

[13] Oppenheim, P., Energy Implications of Blower Overrun Strategies for a Zoned Residential Forced-Air System, University of Florida, ASHRAE Transactions, Vol. 97, Part 2, 1991.

[14] Electric Resistance Heating, DOE http://energy.gov/energysaver/electric-resistance-heating Accessed July 6, 2016.

[15] California's Long Term Energy Efficiency Strategic Plan – September 2008 - http://www.cpuc.ca.gov/WorkArea/DownloadAsset.aspx?id=5305 California Public Utilities Commission.

[16] Variable-Speed Heat Pumps for Energy Efficiency and Demand Response: Field Testing High-Efficiency Systems in a Simulated-Occupancy Home in Knoxville, Tennessee. EPRI, Palo Alto, CA 3002003925, 2014.

[17] Advancing Water and Energy Efficient Strategies and Technologies in California, Attachment 12, Energy Efficiency Data, GFO-15-317, November 2015.