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Cold Climate Field Demonstration of Variable Refrigerant Flow (VRF) Heat Pump and Variable-Air-Volume (VAV) System

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Abstract

Heat pump variable refrigerant flow (VRF) systems are increasingly used in U.S. small commercial buildings to provide cost-effective efficient heating and cooling for multi-zone applications. The complexity and customized design of VRF systems for specific buildings make it difficult to predict energy savings relative to other HVAC systems. Due to limited VRF field data, especially in colder climates, energy savings are often based on energy modeling or laboratory data obtained under controlled conditions. A field demonstration at Naval Station Great Lakes (NSGL) in Illinois offered a unique opportunity to directly compare measured performance data for a VRF system to the baseline variable-air-volume (VAV) system for the same building. The objective of this demonstration was to evaluate the performance of two VRF systems: an electric cold climate heat pump and a natural gas engine-driven heat pump in a side-by-side installation for a small office building compared to the existing VAV system. This paper will focus on the benefits and limitations of the electric CCHP VRF system compared to the baseline VAV system for cold climate applications. The VRF system paired with a dedicated outdoor air system (DOAS) significantly reduced the facility peak electric demand, greenhouse gas emissions, and energy costs compared to a conventional VAV system.

Keywords: Variable Refrigerant Flow (VRF); Variable-Air-Volume (VAV); Air Source Heat Pump; Cold Climate Heat Pump

1. Introduction

GTI Energy conducted a field demonstration of two side-by-side heat pump technologies with variable refrigerant flow (VRF) at a small office building at Naval Station Great Lakes (NSGL). This demonstration compared the installed performance of an electric cold climate heat pump (CCHP) VRF system and a natural gas engine-driven heat pump (GHP) VRF system relative to the baseline performance of an existing variable-air-volume (VAV) system for the same building. The objective was to quantify the energy use, economics, and qualitative benefits of each technology for cold climate DoD applications. Parameters evaluated included natural gas and electric consumption, peak electric demand, primary energy, full-fuel-cycle emissions, lifecycle costs, and simple payback. Additional details on this demonstration are available on the Environmental Security Technology Certification Program (ESTCP) website. [1] This paper will focus on the benefits and limitations of the electric CCHP VRF system compared to the baseline VAV system for cold climate applications.

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2. Cold Climate VRF Heat Pumps and DOAS

The selected demonstrated site was a multi-zone office building, a common application for VRF technologies. Heat pump VRF technologies are well suited for multi-zone building types including schools, retail, hospitals, and hotels. VRF systems are often paired with dedicated outside air systems (DOAS) that provide ventilation directly to the conditioned space. For this configuration, DOAS capacity and air flow are sized to meet the ventilation requirements for each zone and to deliver supply air at space neutral conditions. VRF fan coils are used in place of the VAV-boxes to meet the remaining internal and skin loads of the building providing heating and cooling to meet the thermostat setpoints for each individual zones.

Electric VRF heat pumps are a mature technology with several U.S. manufacturers offering products, but have yet to achieve the 30%-50% market share they currently have in Asia and Europe. VRF systems are increasingly used for multi-zone commercial buildings, driven by the potential for energy savings, economic benefits, and improved comfort with zoned temperature control. Studies report energy savings up to 30% compared to conventional HVAC systems [2]; however, energy savings are typically based on manufacturer data and modeled building energy use. Due to the custom nature of VRF installations, direct comparisons of energy use and economics can be difficult to quantify. In addition, the performance of all air source heat pumps varies significantly with ambient temperatures, so performance and energy savings for one climate will not be the same as a different climate.

VRFs are typically installed in warm climates that benefit from their high cooling efficiency. In colder climates, VRFs are often installed in heated mechanical rooms or with backup electric resistance heaters increasing installed costs and reducing energy savings. [4, 5]. Recently manufacturers have introduced cold climate versions of electric VRF systems without supplemental heating. Additional field studies are needed to validate modeled energy savings for VRF systems, especially in colder climates.

3. VRF and DOAS Field Demonstration

This demonstration provided detailed field data on the installed cold climate performance for both the baseline VAV system and an electric CCHP VRF system. A full calendar year of baseline data was used to characterize the performance of an existing VAV system across the full range of heating and cooling loads. The VRF systems were then installed at the field site and monitored from October 2017 to May 2019. These datasets provided a direct comparison between the VRF systems and the baseline equipment to quantify their relative energy savings and site-specific life cycle costs (LCC). Qualitative benefits, such as reliability and comfort, were also addressed.

3.1. Field Site

NSGL, located in northern Illinois in ASHRAE Climate Zone 5, was selected for this cold climate demonstration with cold and moderately long winters averaging 131 days/year below freezing and -5°F design temperature. Based on NOAA 30-year normals, this location averages 1078 cooling degree days per year (CDD55) and 4362 heating degree days per year (HDD60) [3]. Shown in Figure 1, the field site was a single-story multi-zone office building with an existing conventional VAV system. The north wing, circled in red, was selected for the demonstration due to symmetric zones and higher heating loads. The north wing was divided into two equivalent sections with similar zones and thermal loads. One section was served by the electric CCHP VRF while the other was served by an equivalent GHP VRF system.

The baseline HVAC system was a ground-mounted VAV system with 500 MBH modulating gas heating (80% Te) and 30-tons electric cooling (9.5 EER). The system included 19 VAV-boxes with electric resistance reheat to provide zone temperature control. Historic utility data for the total building indicated the system capacity was about twice the typical heating and cooling load.

Two 2-pipe heat pump VRF systems were specified as retrofit equipment for this application. A total of twenty cassette-style VRF fan coil units were installed above the ceiling panels throughout the building. The VRF systems were paired with a conventional DOAS to provide ventilation with gas-fired heating (80%Te) and electric DX cooling (11.3 EER) sized to match the baseline ventilation rate (800 cfm). For cold climates, gas heating is needed to meet the required temperature rise for conditioning 100%OA. The DOAS delivered conditioned air at 64°F (17.8°C) directly to each zone via ceiling diffusers. The DOAS was able to use the existing ductwork which significantly reduced installation costs for this site.

Fig. 1. (a) A multi-zone office building selected for the cold climate demonstration site. (b) The demonstration VRF/DOAS replaced a VAV system serving the north wing, circled in red.

To ensure proper sizing, the design engineering firm developed load calculations based on code-required minimums taking into account a range of DOAS setpoints based on a 60°F (15.6°C) supply temperature to address outdoor latent loads during the cooling season and a neutral 70°F (21.1°C) during the heating season. A 10% safety factor was added to both heating and cooling capacities. Due to its reduced capacity at lower ambient temperatures, the electric CCHP outdoor unit was oversized to meet the heating load at the coldest design conditions. A 12-ton CCHP outdoor unit was paired with approximately 8-ton VRF indoor fan coil capacity.

3.2. Measurement and Verification Approach

3.2.1. Baseline HVAC Monitoring

Gas and electric consumption of the existing VAV system was monitored for a full calendar year. Outdoor air, return air, and supply air temperatures were also measured. Room temperatures and relative humidity were monitored in each conditioned zone to quantify any significant changes in comfort.

3.2.2. Demonstration Monitoring

The CCHP VRF was instrumented with gas and electric meters to measure energy use. One compact watt meter monitored total electric consumption at the outdoor condensing unit; a second watt meter measured the total energy use for the indoor fan coils. DOAS air temperatures, gas and electric consumption were also monitored. The efficiency of the VRF system was calculated by the ratio of total energy (heating and cooling) delivered to total energy consumed for a given period. Due to the design of the cassette-style VRF fan coil units, it was challenging to accurately measure the supply and return air to calculate the total energy delivered by the individual fan coil units to the conditioned space. An alternative approach was used to monitor the total heating and cooling delivered by the VRF system by measuring changes in enthalpy at the refrigerant lines, as shown below in Figure 2.

A Coriolis flow meter was installed in the liquid refrigerant piping to measure the mass flow rate of the refrigerant delivered to/from the indoor fan coils. Thermocouples and pressure sensors were installed in the refrigerant lines adjacent to the outdoor unit. Enthalpy of the liquid and vapor refrigerant was calculated based on R410A properties using the National Institute of Standards and Technology Reference Fluid Thermodynamic and Transport Properties Database [6]. Heating or cooling delivered was calculated based on the enthalpy change between the vapor and liquid refrigerant lines. In previous studies, this method of measurement was successfully validated through comparison of measured field data to laboratory data at similar conditions. This approach improved accuracy and reduced M&V costs compared to air side measurements at each fan coil unit.

3.3. Data Analysis

Data was recorded at 5-minute intervals and downloaded remotely via a cellular modem to provide real time access to performance data. Measured performance data was collected for a calendar year for both the baseline and VRF performance and then normalized based on heating and cooling degree days and the total measured space conditioning load.

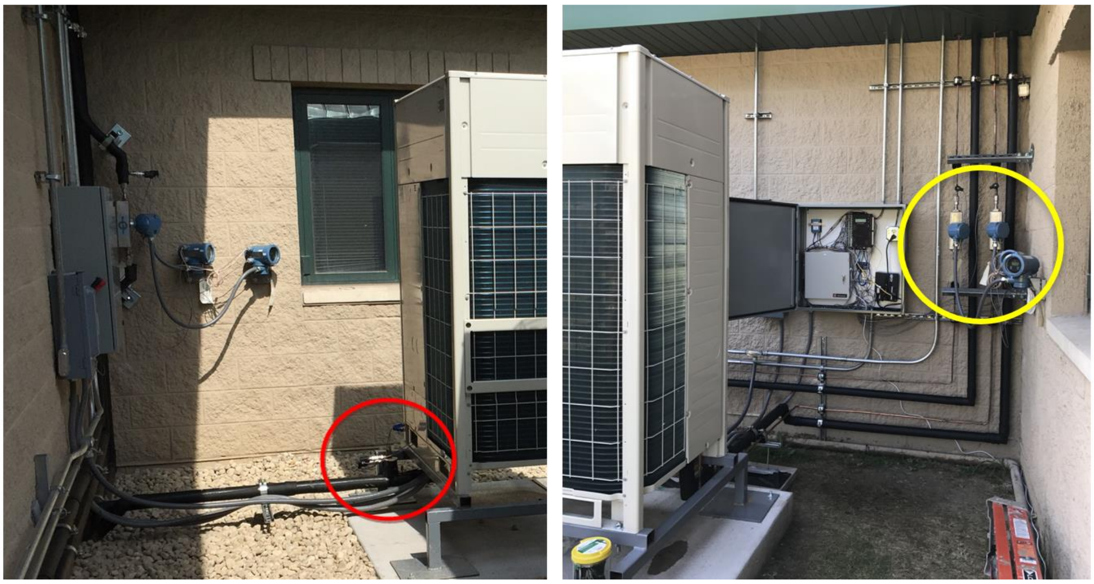

Fig. 2. (a) Pressure and temperature sensors in the refrigerant lines (circled in red) were used to calculate total heating/cooling delivered. (b) Coriolis meters (circled in yellow) measured the mass flow rate of the liquid refrigerant.

3.3.1. Baseline Performance

Measured energy use for the baseline VAV system was highly correlated to heating and cooling degree days. As shown by the graph on the left in Figure 3, cooling energy use was linear with respect to cooling degree days, base temperature 60°F (15.6°C). For heating, natural gas and electric consumption was also linear with respect to with heating degree days, base temperature 55°F (12.8°C).

During heating operation, energy use for the VAV-boxes was higher than expected. Electric resistance heating provided by the VAV-boxes is designed to provide only trim heating and to adjust temperatures between zones. Baseline data shown in Figure 4 shows the VAV-boxes at peak electric heating (orange) while the outdoor unit's modulating gas burner (blue) operated at low fire. Per the manufacturer, a building automation system (BAS) is required to integrate the controls for the gas burner and the VAV-boxes reheat elements. Without a BAS, the outdoor unit and VAV-boxes operate independently resulting in excess electric resistance heating and higher peak electric demand. This may be typical operation for smaller buildings or sites without a central BAS.

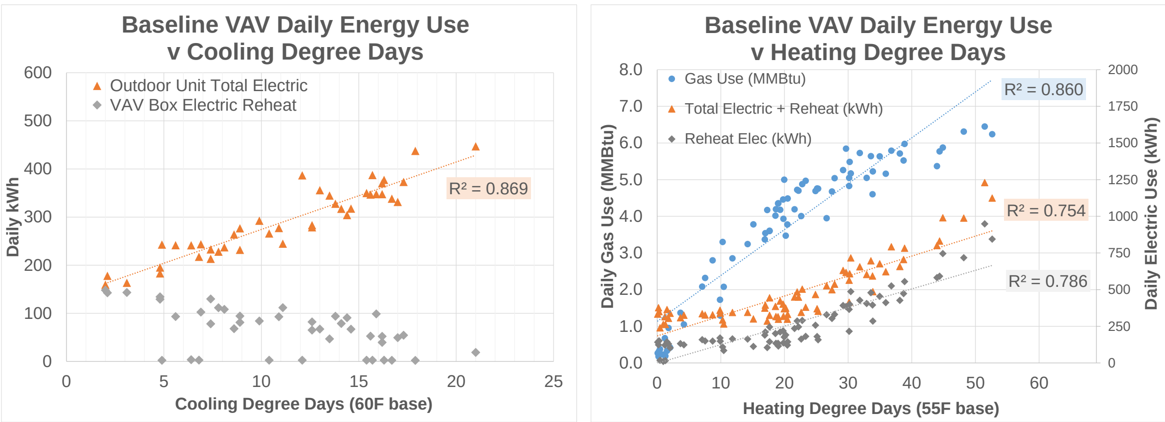

Fig. 3. Graphs show the baseline VAV measured energy use correlated with (a) cooling degree days and (b) heating degree days. VAV electric reheat consumption was higher than expected during heating (shown in gray)

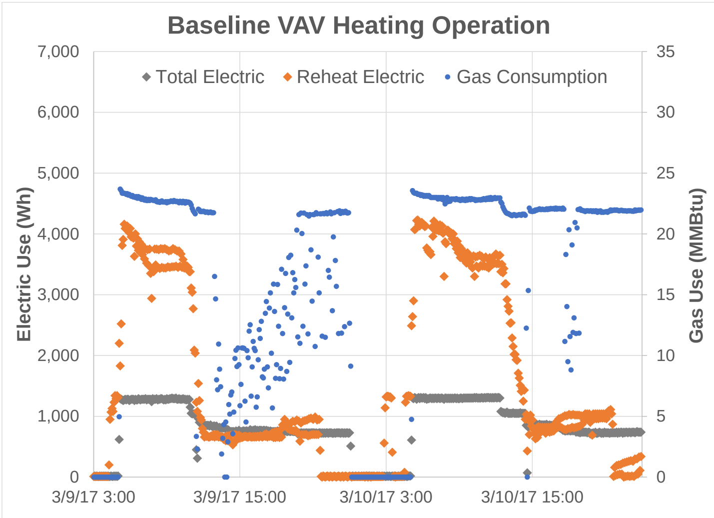

Fig. 4. Electric resistance heating provided by the VAV-boxes (shown in orange) operated at high levels when the modulating gas burner was at low-fire, resulting in higher than expected energy use during heating.

3.3.2. VRF Cooling Performance

In addition to offering higher cooling efficiency, VRF provides zoned cooling eliminating the over-cooling and reheat energy used by VAV systems. Figure 5 shows the measured energy use of the CCHP VRF and DOAS with respect to cooling degree days. Performance was based on a limited dataset due to unrelated component issues and operational outages. Daily average cooling efficiency ranged from 13 to 25 EER, exceeding the specified 12.3 EER rating for 95°F (35°C) due to milder ambient temperatures during this period. Cooling efficiencies decreased with lower part load. Part load for this assessment was calculated as the ratio of measured cooling delivered relative to the rated total capacity. Since the CCHP outdoor unit for this demonstration was oversized to meet peak heating capacity, the system operated at very low part loads (15% to 25%) during cooling. In addition, the DOAS operated with a 64°F set point year-round which reduced the building cooling load.

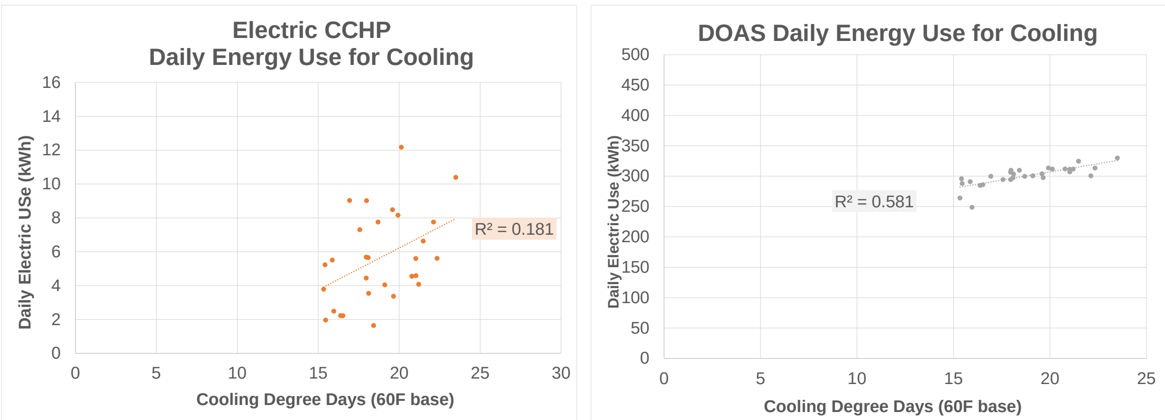

Fig. 5. (a) Left: CCHP VRF measured electricity consumption for cooling with respect to cooling degree days. (b) Right: DOAS measured electricity consumption with respect to cooling degree days

3.3.1. VRF Heating Performance

Figure 6 shows the measured energy use of the CCHP VRF and DOAS during heating correlated with respect to heating degree days. Daily average heating efficiency ranged from 0.5 to 4.0 COP, compared to manufacturer specifications of 4.1 COP at 47°F and 2.3 COP at 17°F.

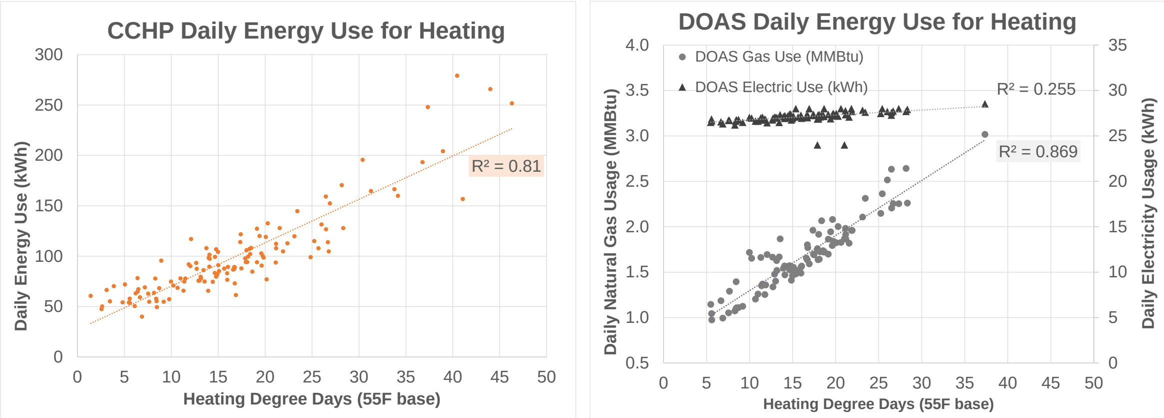

Fig. 6. (a) Left: CCHP VRF measured electricity consumption for heating correlated to heating degree days. (b) Right: DOAS measured electricity consumption correlated to heating degree days.

Ambient temperatures had a larger impact on heating COP than part load operation (Figure 7). For this assessment part load was calculated as the ratio of measured heating delivered relative to the rated total capacity. Heating capacity and efficiency of all air source heat pumps decrease with lower ambient temperatures. For this demonstration, the CCHP did not meet the heating load for seven days at daily average temperatures at or below 16°F, shown circled in the graphs in Figure 7. This indicates the need for supplemental heating for this climate zone. The manufacturer-rated minimum temperature for this CCHP model is -4°F. For this region, the ASHRAE 99% design temperature is -5°F; however, during the demonstration ambient temperatures reached historic lows dropping down to -23°F due to the Polar Vortex in January 2019.

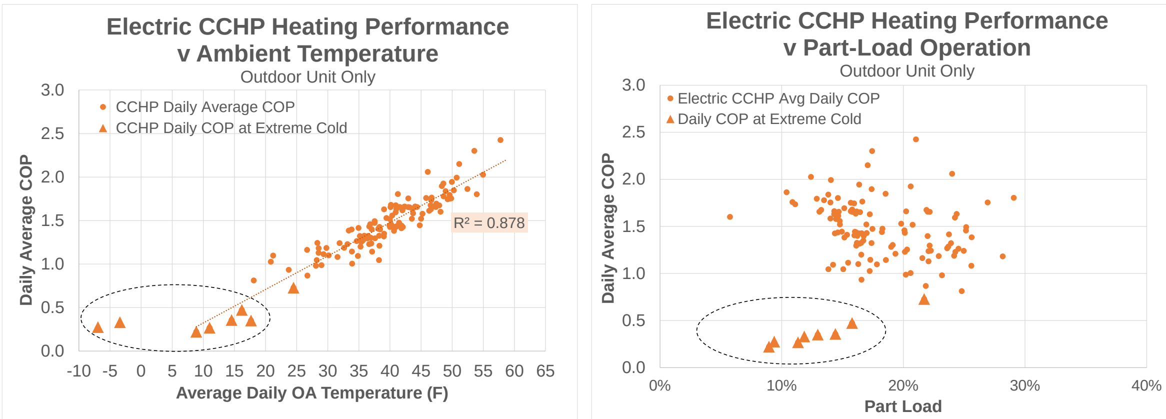

Fig. 7. Graphs show (a) the decreasing measured heating efficiency with respect to ambient temperatures and (b) the minor impact of part load on heating efficiency. During extreme cold temperatures (circled), efficiency dropped below 1.0 COP and the CCHP VRF was unable to meet the building heating load.

3.4. Energy Savings

To estimate annual energy and cost savings, measured energy use data was normalized to published Typical Meteorological Year version 3 (TMY3) cooling and heating degree days based on the National Centers for Environmental Information National Oceanic and Atmospheric Administration Annual Climate 30-year Normals (1981 to 2010) for Waukegan National Airport [3]. Energy use for the CCHP VRF system was normalized with respect to the total building load. Energy savings for the VRF/DOAS were calculated with respect to the baseline VAV system. Primary energy and full-fuel-cycle GHG emissions were calculated based on estimated annual energy use. Primary energy and full-fuel-cycle emissions takes into account all upstream energy used to generate power or to supply fuel to the building meter. Primary energy is a more comprehensive approach to evaluate energy use and may be more relevant to energy security for DoD facilities than the energy metered at the site. A growing number of codes and standards are adopting full-fuel-cycle metrics to quantify the environmental impact of different energy sources and appliances.

A summary of the results is presented in Table 1. The VRF/DOAS system had lower natural gas and electricity use compared to the baseline VAV, reducing primary energy use by 68% and full-fuel-cycle CO2e emissions by 70%. Modeled annual savings for VRF relative to VAV systems range from 20% to 60% for various climates [7]. These results are at the high end of the range due to higher than expected baseline energy use for the VAV system. The VRF/DOAS reduced summer peak electric demand from 43.2 kW to 14.5 kW. The VRF system provides very high efficiency cooling and eliminates the need for electric reheat used in the VAV-boxes. For heating, the baseline VAV peak electric demand (65.4 kW) is higher than expected due to the lack of integrated controls, as previously discussed; however, VRF/DOAS heating operation resulted in a high winter peak electric demand (36.8 kW), exceeding the facility summer peak demand. The peak electric demand in buildings is typically driven by electric cooling, but the use of electric heating creates a secondary winter peak. With the growing use of electric heat pumps, the winter heating peak demand is likely to exceed the summer cooling peak especially in cold climates.

Table 1. Normalized Annual Energy Use

	Baseline VAV with Electric Reheat	Electric CCHP VRF	DOAS	Total VRF/DOAS System	Annual Savings	
Gas Use (therm)	5,474		2,651	2,651	2,823 therms	52%
(kWh)	160,414		77,686	77,686	87,728 kWh	
Electric Use (kWh)	125,713	41,349	9,326	50,675	75,038 kWh	60%
Heating Peak Electric Demand (kW)	65.4	35.5	1.3	36.8	28.6 kW	44%
Cooling Peak Electric Demand (kW)	43.2	8.6	5.9	14.5	28.7kW	66%
Annual Primary Energy (MMBtu)	1,995			853	1,142 MMBtu	57%
(kWh)	584,674			249,877	334,798 kWh	
Full-Fuel-Cycle CO2e Emissions (metric tons)	158.2			66.7	91.5 MT	58%

Assumptions: Natural gas: Primary energy factor: 1.09; Full-fuel-cycle CO2e emissions: 147 lb./MMBtu
Electricity primary energy factor (2016eGrid Non-baseload RFCW): 3.26; Full-fuel-cycle CO2e emissions: 2,133 lb./MWh

3.5. Economic Assessment

Table 2 presents a comparison of annual O&M costs for the baseline VAV system and the CCHP VRF/DOAS. Total energy costs were reduced by 51%. Energy costs per square foot of the facility dropped from the baseline $2.21/sqft ($23.79/sqm) to $1.08/sqft ($11.63/sqm) for the VRF/DOAS. These energy and cost savings may be higher than typical cold climate applications due to higher than expected electric resistance heating for the baseline VAV system. Energy prices were based on incremental composite rates provided by the field site ($0.0559/kWh; $10.3037/kW; $0.49/therm). Utility demand charges and rate structures can vary widely from state to state. Demand charges for the field site were calculated from the highest hourly peak kW during the past 12 months, whether summer or winter. For this demonstration, the highest peak electric demand occurred during the heating season for both the baseline VAV system (65.4 kW) and demonstration VRF/DOAS (36.8 kW).

Table 2. Estimated Annual O&M Costs with Winter Peak Electric Demand

	Baseline VAV with Electric Reheat	VRF/DOAS System	Annual Savings	
Annual Energy Costs ($/yr.)	$9,714	$4,134		
Heating Peak Electric Demand Charge	$8,086	$4,547		
Total Energy Cost	$17,800	$8,680	$9,120	51%
$/Floor Area	$2.21/sqft ($23.79/sqm)	$1.08/sqft ($11.63/sqm)	$1.13/sqft ($12.16/sqm)	
Annual Maintenance Costs	$1,200	$1,200		
Total O&M Costs	$19,000	$9,880	$9,120	48%

Assumptions: $0.0559/kWh; $10.3037/kW; $0.49/therm

Maintenance tasks for CCHP VRF systems differ from more central systems such as VAV. Some sources predict VRF/DOAS have higher maintenance costs than conventional equipment [2], while other publications expect similar or lower maintenance costs [8]. Increasing the number of fan coil units can significantly increase maintenance costs; however, the design for this field site included twenty VRF fan coil units which was similar to the baseline nineteen VAV-boxes. Maintenance for the baseline VAV included annual economizer and terminal unit maintenance, while VRF maintenance included biannual condensate system cleaning and filter changes for the fan coil units [2]. Based on conversations with the manufacturer and facility staff, it was assumed no other repairs or refrigerant replacement are needed over the 15-year equipment lifetime. For the economic assessment, maintenance costs were assumed to be similar for both systems.

Table 3 presents the incremental costs, LCC and simple paybacks for the CCHP VRF compared to the baseline VAV system. VAV installed costs were based on published estimates of $20/sqft ($215/sqm) [13]; a similar range of installed costs were found using R.S. Means. CCHP VRF equipment costs ($2.6K per ton) were based on invoices from the demonstration. VRF installation costs were based on mature market estimate ($6K/ton) plus a $20K engineering design. DOAS installed cost ($1.3K/ton) were based on 2016 R.S. Means. VRF/DOAS installed cost of $22.7/sqft ($454/sqm) and incremental cost of $2.73/sqft ($29.38/sqm) aligns with previous studies [2,7]. Note this includes the additional costs for oversizing the CCHP VRF system for a cold climate which is offset by recent reductions in VRF equipment prices. Based on this assessment, replacing a conventional VAV system with a VRF/DOAS in a cold climate has potential to reduce LCC by about $84,660 (25%) with a simple payback of 3 years. This does not include any equipment or energy use for supplemental heating.

Table 3. Life Cycle Costs

	Baseline VAV with Electric Reheat	VRF/DOAS System	
Equipment Cost	$40,000	$49,600	
Installed Cost (retrofit)	$161,000	$183,000	
$/Floor Area	$20.0/sqft ($215.3/sqm)	$22.7/sq. ft ($454.0/sqm)	
Incremental First Costs		$22,000	$2.73/sq. ft ($29.38/sqm)
LCC Savings		$84,660	25%
Simple Payback		3 years	

<u>Assumptions</u>: 15 years equipment life assuming no component or refrigerant replacement; 3.0% discount rate

4. Conclusion

This field study offered a unique assessment of the cold climate performance of an electric cold climate heat pump VRF/DOAS system for a multi-zone office building. Detailed measured field data allowed a direct comparison of the VRF/DOAS system with the baseline conventional VAV system to quantify their relative energy savings and economic benefits. These results can also be used to validate energy savings and cost savings predicted by energy modeling and simulation tools. Based on this demonstration, VRF/DOAS systems can reduce O&M costs and primary energy use (up to 50%) in cold climates. Several factors contribute to the VRF/DOAS energy savings. VRF with ductless fan coils eliminates duct losses associated with forced air HVAC systems. In addition to higher cooling efficiency, VRF can provide zoned cooling eliminating the need for over-cooling and reheat energy use. During heating operation, VRF trim heating is more efficient than electric resistance heating used in VAV-boxes. Likewise, the use of DOAS has multiple energy-saving benefits including more effective humidity control, less over-ventilation, and lower fan energy [9]. These savings may be higher than some sites due to the higher than expected energy use for the baseline VAV system when operated without a building management system.

This demonstration also identified some limitations for electric CCHP VRF systems. Despite the cold climate design and oversizing to meet the heating load, the electric CCHP required supplemental heating to maintain heating capacity for ASHRAE Climate Zone 5. Although the VRF/DOAS system reduced the summer peak electric demand at the field site, VRF/DOAS operation significantly increased the winter peak electric demand, much higher than the summer peak. For typical buildings, the peak electric demand occurs during the summer cooling operation due to electric air conditioning, but the use of electric heating can create a secondary winter peak demand. With growing use of electric heat pumps, the winter peak demand is likely to exceed the summer cooling peak especially in cold climates.

Future research will focus on more efficient and cost-effective approaches to use supplemental gas-fired heating to enable electric CCHP VRF systems to operate in cold climates and to minimize the impact and energy costs of increasing winter peak electric demand.

Acknowledgements

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