EXECUTIVE SUMMARY

Gas Engine-driven Heat Pump (GHP) Cold Climate Field Demonstration

ESTCP Project EW-201515

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ACRONYMS AND ABBREVIATIONS

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BAS	Building Automation System
CCHP	Cold Climate Heat Pump, a type of ASHP designed for cold climate use
COP	Coefficient of Performance
DOAS	Dedicated Outdoor Air System
DoD	United States Department of Defense
EER	Energy Efficiency Ratio
eGRID	Emissions & Generation Resource Integrated Database
ESTCP	Environmental Security Technology Certification Program
GHP	Gas engine-driven Heat Pump
HVAC	Heating, Ventilation and Air Conditioning
NIST	National Institute of Standards & Technology
NSGL	Naval Station Great Lakes
VAV	Variable Air Volume packaged HVAC unit; provides variable air flow, gas heating, and electric air conditioning with electric reheat
VRF	Variable Refrigerant Flow, aka VRV (variable refrigerant volume) (Daikin's proprietary VRF design)

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1.0 INTRODUCTION

Variable refrigerant flow (VRF) heat pump systems are increasingly used in small commercial buildings in the U.S. as a high efficiency heating and cooling option for multi-zone applications. However, the complexity of VRF configurations and the customized design for specific buildings make it difficult to monitor and predict energy savings relative to baseline heating, ventilation and air conditioning (HVAC systems). Due to limited field data available for VRF systems, especially in colder climates, energy savings are often based on energy modeling or data from controlled laboratory testing. This ESTCP demonstration provided a unique opportunity to directly compare measured performance data for two VRF heat pump technologies to the baseline variable air volume (VAV) system and determine the potential energy and economic benefits for United States Department of Defense (DoD) facilities.

This field study was a side-by-side demonstration of two VRF heat pump technologies that offer significant potential for energy and cost savings, and improved comfort with zoned temperature control. One VRF system was a natural gas engine-driven heat pump (GHP)—an emerging technology designed to reduce peak electric demand and generate savings in both annual energy costs and life-cycle costs compared to conventional equipment. The second VRF system was an electric cold climate heat pump (CCHP)—a relatively mature technology, designed for colder ambient conditions without supplemental heating.

2.0 OBJECTIVES

The objective of this demonstration was to quantify the energy savings and economic benefits of two VRF heat pump technologies for cold climate DoD applications based on measured performance data. The VRF performance was also compared to the measured baseline performance of the VAV system for the same building. This evaluation compared peak electric demand, site and primary energy use, and full-fuel-cycle GHG emissions for each type of equipment. The economic assessment determined annual energy and life-cycle costs based on measured energy use data, installed costs, and local utility rates. Qualitative benefits, such as reliability and comfort were also explored. The overarching goal was to identify the potential benefits of VRF systems for DoD facilities as well as other commercial markets.

3.0 TECHNOLOGY DESCRIPTION

The overall GHP design is similar to an electric heat pump but with an advanced natural gas engine in place of an electric motor (Figure 1). The NextAire™ GHP uses high-efficiency scroll compressors and a variable-speed engine with a demonstrated long life (30,000 hours). GHPs combine high efficiency heating (rated at 1.2-1.4 coefficient of performance [COP]) and cooling (0.95-1.2 COP). During cooling, GHPs consume natural gas in place of electricity, significantly reducing peak electric demand in comparison to electric chillers or electric heat pumps. During heating, GHPs are rated 50% more efficient than standard gas furnaces or boilers commonly used at DoD facilities. Heat recovered from the engine cooling jacket and exhaust can supplement the GHP output during heating mode to increase the overall system efficiency. Heat recovery also allows GHPs to deliver a higher supply temperature at cold ambient conditions. In contrast, electric heat pumps often require inefficient resistance heating to supplement their heating capacity at low outdoor temperatures.

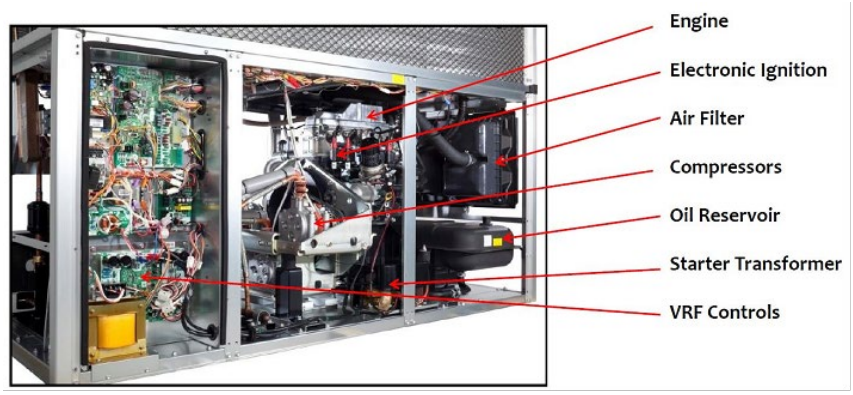

Figure 1. The GHP Utilizes Two Scroll Compressors and an Advanced Natural Gas Engine

Electric VRF heat pumps, such as the CCHP unit demonstrated in this project, are a mature technology with several U.S. manufacturers and a modest but growing market. 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. Electric VRF systems typically use variable-speed electric motors to drive variable-speed or multi-stage compressors and a single refrigerant circuit with individually controlled fan coils to provide zoned heating and cooling (Figure 2). Both the gas and electric heat pumps featured in this demonstration used the same type of indoor VRF fan coil units and controllers provided by the same manufacturer.

Studies report energy savings up to 30% compared to conventional HVAC systems [Thorton]; however, energy savings are typically based on manufacturer data and modeled simulations. Due to the custom nature of VRF installations, direct comparisons of energy use and economics can be difficult to quantify.

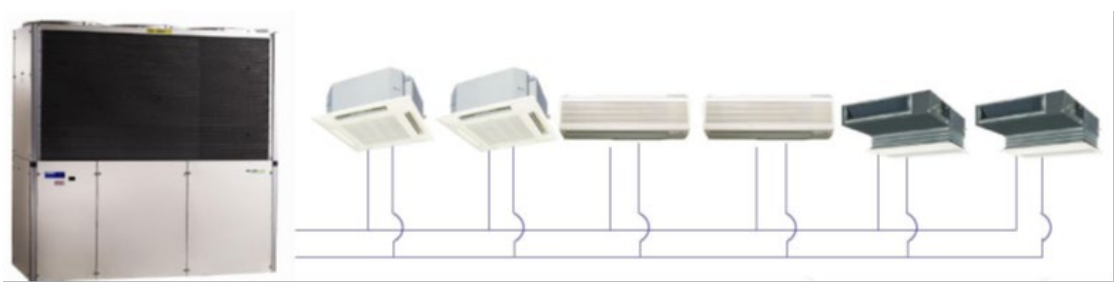

Figure 2. GHP System Utilize the Same Indoor VRF Air Handlers as the Electric VRF System

In addition, the performance of all air source heat pumps (both electric and gas engine-drive) varies significantly with ambient temperatures, so performance and energy savings for one climate will not be the same as a different climate. VRFs are primarily installed in moderate or hot climates that can benefit from their high cooling efficiency. In colder climates, VRFs are often installed in heated mechanical rooms or with backup electric resistance heaters, thus increasing installed costs and reducing energy savings [Swanson, Schuetter]. Recently some manufacturers have introduced cold climate versions of electric VRF systems without supplemental heating; but limited field data is available to validate their performance. This demonstration provided measured field data needed to validate modeled energy savings for VRF systems, especially in colder climates.

4.0 PERFORMANCE ASSESSMENT

The field site was a small multi-zone office building at Naval Station Great Lakes (NSGL) in North Chicago, Illinois. The building was divided into two thermal zones, one served by the GHP and the other served by the electric CCHP. Since VRF systems typically do not provide ventilation, these were paired with a single dedicated outdoor air system (DOAS) sized to meet ventilation requirements and deliver supply air at space neutral conditions. Prior to the VRF installation, GTI conducted 12 months of baseline monitoring of the existing VAV system to characterize its performance across the full range of operating conditions. VRF heat pump performance data was then collected during the following year.

Measured energy use data was weather-normalized. Energy use for each VRF heat pump system was also normalized to the total building load to allow for a direct comparison to the baseline VAV system. This controlled for changes in on-site routines or activities over the course of the baseline and VRF system monitoring. GHP performance metrics were directly compared to CCHP to evaluate the performance objectives. Energy consumption for both VRF systems was also compared to the baseline. Site and primary energy, full-fuel-cycle GHG emissions, annual energy costs and life-cycle costs were calculated based on normalized energy use.

4.1 BASELINE CHARACTERIZATION

During heating operation, the baseline VAV electric consumption was found to be higher than expected. Without a building automation system (BAS) for integrated controls, the central VAV gas heating and distributed VAV-boxes operated independently resulting in excessive electric resistance heating by the VAV boxes and a higher peak electric demand. Although the baseline system did not operate as designed, this may be typical VAV operation for smaller buildings or sites without a central BAS.

4.2 MEASURED PERFORMANCE OBJECTIVES

4.2.1 Peak Electric Demand Reduction

Both VRF systems significantly reduced peak electric demand by eliminating the electric resistance trim heating in the winter and the summer overcooling/electric reheat approach used in VAV systems (Table 1).

Table 1. Peak Electric Demand Reduction

	Savings over Baseline VAV	Savings over CCHP/DOAS
GHP/DOAS – Heating Season	90% (59 kW)	82% (30 kW)
GHP/DOAS – Cooling Season	79% (34 kW)	36% (5 kW)

For typical buildings, the highest electric demand occurs during the summer cooling operation due to conventional electric air conditioning; however, electric heating can create a secondary winter peak. This demonstration illustrates how the growing use of electric heat pumps can increase the winter peak electric demand, potentially exceeding the summer cooling peak, especially in cold climates.

4.2.2 Savings in Life-cycle Costs

The National Institute of Standards & Technology (NIST) Building Life-cycle Cost program was used to determine the economic benefits for each technology. The GHP/DOAS met the performance objective for savings in both annual energy costs and life-cycle costs compared to the CCHP/DOAS. Based on measured data, the GHP/DOAS reduced energy costs by 41% compared to the CCHP/DOAS and by 71% compared to the baseline. Despite lower than expected part-load performance, GHP/DOAS life-cycle costs were 4% lower than CCHP/DOAS and 29% lower than the VAV baseline.

4.2.3 Primary Energy Savings

Primary energy use (i.e., full-fuel-cycle) accounts for all upstream energy used to generate power or to supply fuel to the building meter. In other words, primary energy includes all energy for fuel extraction (natural gas, oil, coal, renewables), conversion (e.g., power generation), and distribution (pipelines, power transmission lines). Primary energy is a more comprehensive approach to evaluate energy use and is more relevant to energy security for DoD facilities than the energy metered at the site. A growing number of codes and standards are shifting to the use of full-fuel-cycle or primary energy use as the metric to quantify the environmental impact of appliances, rather than site energy. For this analysis, primary energy was calculated based on measured energy use and primary energy factors for electricity and natural gas. Both VRF systems had significantly lower natural gas and electricity use compared to the baseline VAV, reducing primary energy use by about 57%. This validates published VRF modeling studies reporting savings from 20% to 60% relative to VAV systems [EES Consulting]. Primary energy use for the GHP/DOAS did not meet the performance objective of 10% savings relative to the CCHP/DOAS due the GHP/DOAS lower than expected part-load performance.

4.2.4 Reduction in Full-Fuel-Cycle GHG Emissions

Full-fuel-cycle GHG emissions were calculated based on estimated annual energy use and regional carbon dioxide equivalent emission factors to estimate upstream emissions from power generation, transmission, or distribution of the energy to the building meter. Emission factors for electricity were based on published non-baseload power generation mixes for the Emissions & Generation Resource Integrated Database (eGRID) regions. Natural gas emission factors were also based on the published regional average [GTI]. Both VRF systems significantly reduced full-fuel-cycle GHG emissions by 55%-63% compared to the baseline VAV system. GHP/DOAS full-fuel-cycle GHG emissions were 13% lower than CCHP/DOAS but did not meet the performance objective of 20% due to lower than expected part-load performance. In addition, GHP engine exhaust emissions were not included due to lack of available data but would increase the total full-fuel-cycle GHG.

4.2.5 Comfort and Reliability

Comfort and reliability were qualitative performance objectives to assess the impact of VRF systems on the multi-zone conditioned space and its ability to meeting space conditioning loads over a wide range of real-life conditions. VRF heat pump configurations provide zoned space conditioning and are expected to improve comfort as well as energy efficiency. Measured data showed both VRF heat pumps successfully maintained zone temperatures within +/-2°F of the setpoint during typical operation. Feedback from the field site also confirmed claims of improved comfort.

With the baseline VAV system, the building tenants complained about low temperatures in the winter and used electric space heaters to address comfort issues. The field site chose to keep the demonstration VRF systems at the conclusion of the field study.

As an emerging technology, heat pumps must prove to be as reliable as conventional HVAC equipment to gain market acceptance. The GHP/DOAS did not meet this success criteria due to multiple installation/component issues and reduced performance which impacted the total delivered heating capacity. As shown in Figure 3, the CCHP also failed to meet the heating load at very cold ambient conditions, indicating a need for supplemental heat for this climate (American Society of Heating, Refrigerating and Air-Conditioning Engineers [ASHRAE] Zone 5).

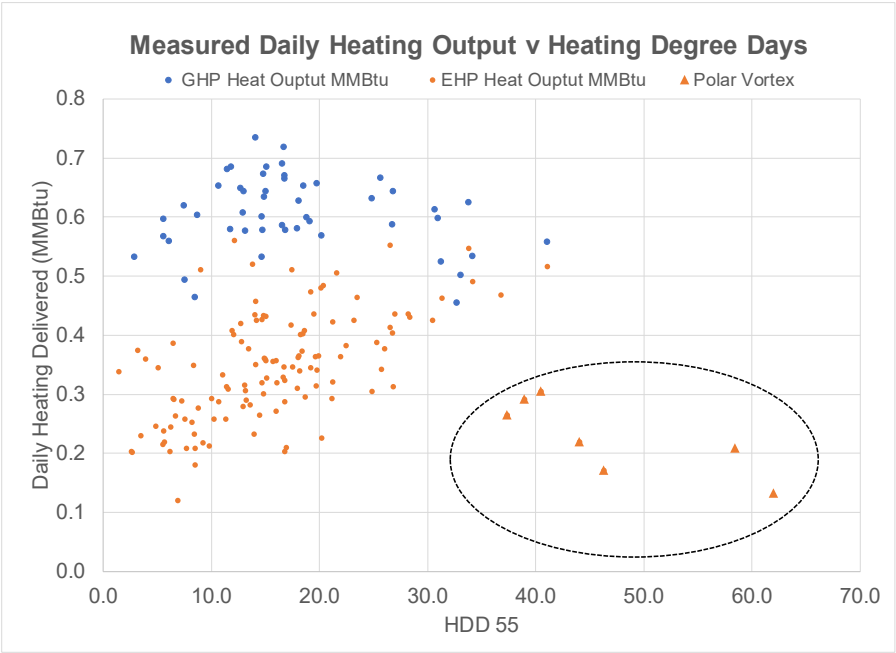

Figure 3. CCHP Was Not Able to Meet the Heating Load at Extreme Cold Temperatures

5.0 REGIONAL PERFORMANCE ASSESSMENT WITH ENERGY MODELING

To apply these demonstration results to the broader DoD community, GTI conducted hourly simulations using EnergyPlus models to predict the energy savings and economic benefits of the VRF systems for various climates. EnergyPlus models of DOE reference buildings (small office) were modified to match the layout and floorspace of the field site. EnergyPlus equipment models were adapted to measured field data from the demonstration and optimized to be more representative of typical HVAC operation. The VAV baseline was modeled with integrated controls (such as would be seen with a BAS), thus reducing the higher than expected electric resistance heat discovered during baseline monitoring. Hourly energy simulations were conducted for five different climates to predict regional energy and economic benefits for the baseline and VRF systems. The following sections address each performance objective based on modeled energy performance.

Modeled results for different regions show GHP/DOAS had the lowest peak electric demand for heating or cooling (Figure 4). The magnitude of demand reduction was higher for colder climates (Chicago, Helena) than warmer climates (Los Angeles). Both VRF systems reduced peak electric demand compared to the baseline due to elimination of electric resistance heating. For colder climates, CCHP/DOAS had a higher winter peak electric demand than summer. Note that winter peak demand for CCHP/DOAS would increase if electric resistance heat was used to provide the necessary supplemental heating at low ambient temperatures.

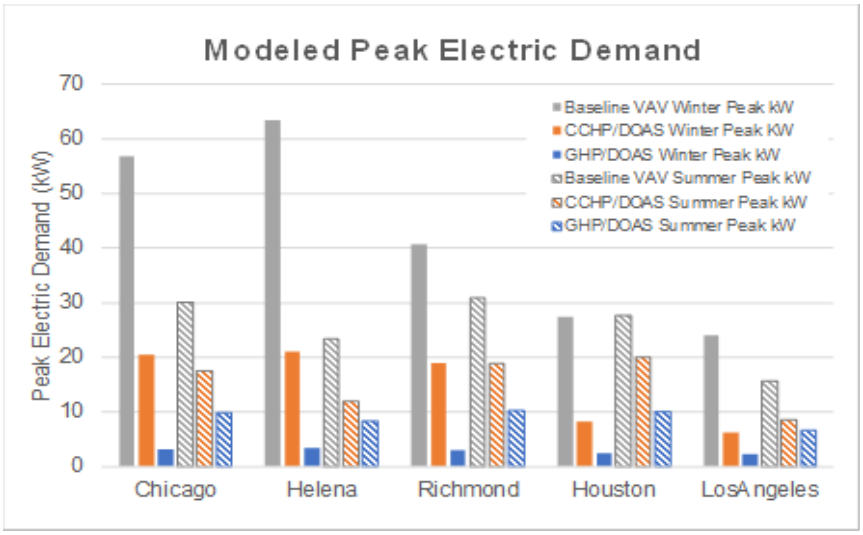

Figure 4. Regional Modeled Comparisons for Peak Electric Demand

Primary energy was calculated using modeled energy use and regional primary energy factors based on non-baseload electricity mix per eGrid 2016. Modeled results show significant savings in primary energy for both VRF systems compared to the baseline for all regions (Figure 5). Primary energy savings for the VRF/DOAS ranged from 47% to 62% compared to baseline. GHP/DOAS primary energy savings were slightly higher than the CCHP/DOAS in colder climates, and slightly lower in warmer regions.

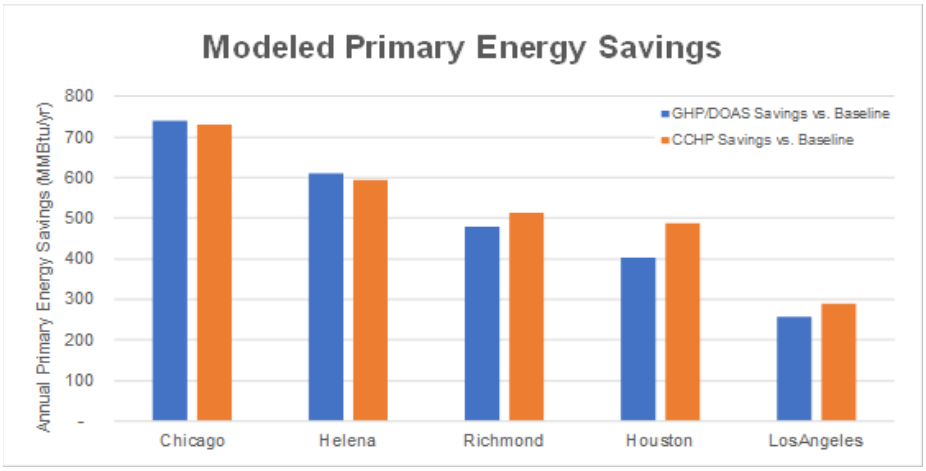

Figure 5. Regional Modeled Comparisons for Primary Energy Savings

Regional GHG emission factors were used to estimate full-fuel-cycle GHG emissions based on non-baseload electricity mix per eGrid 2016. Modeled results show significant savings in full-fuel-cycle GHG for both VRF systems compared to the baseline VAV for all regions (Figure 6). VRF/DOAS generated savings in GHG emissions from 51% to 62% compared to baseline. For the GHP/DOAS, GHG savings were slightly higher than the CCHP/DOAS in colder climates, and slightly lower in warmer regions.

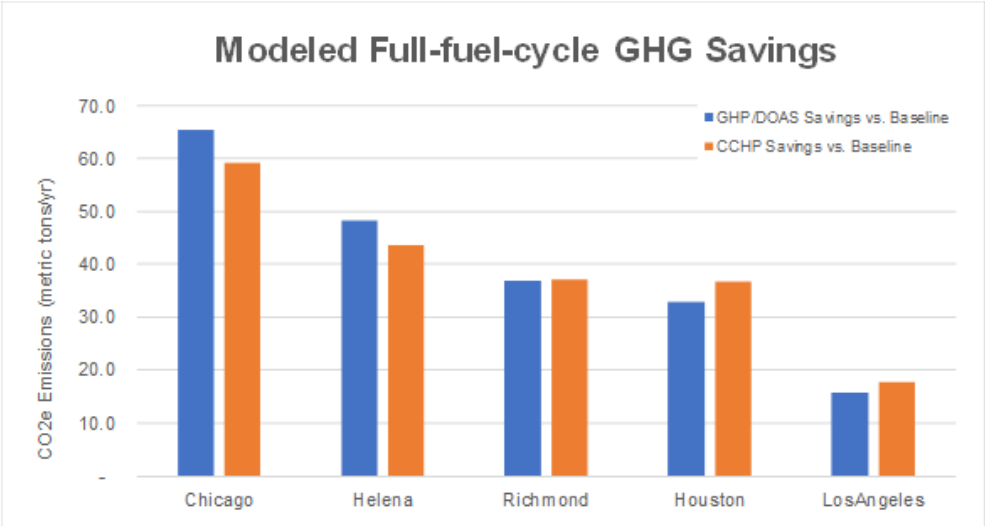

Figure 6. Regional Modeled Comparisons for Full-fuel-cycle GHG Emissions

6.0 COST ASSESSMENT

The NIST Building Life-cycle Cost program was used for the life-cycle cost assessment for each technology. The cost assessment included actual equipment costs and installation costs based on rule-of-thumb or RS Means 2016 estimates. Aside from the engine maintenance for the GHP, it was assumed that maintenance costs were similar for the baseline VAV and both VRF systems. To address customers' concern about unexpected service costs for the GHP engine maintenance, one manufacturer offers a service agreement included with the equipment purchase. This scheduled maintenance plan provides engine maintenance (oil change and belts) at intervals of 1,000, 2,000, and 3,000 runtime hours. This option was selected for the demonstration and also used for the cost assessment.

Annual energy costs were based on the incremental composite rates provided by the field site. Utility demand charges and energy rate structures can vary widely by state and can impact energy cost savings. As expected, modeled energy savings were lower than measured savings due to a more optimized VAV operation baseline with less resistance heat operation. The efficiency of the VRF heat pumps (CCHP: 12.3 energy efficiency ratio (EER)/2.3 COP; GHP: 1.3 COPg heating/cooling) exceeds the baseline VAV efficiency (9.5 EER/80%) but only covers a portion of the heating and cooling load, as the ventilation load is met by the standard efficiency DOAS (11.3 EER/80%).

Modeled results shown in Figure 7 indicate that VRF systems reduced annual costs in all regions. GHP/DOAS had the highest savings in annual energy costs for cold climates with lower savings for moderate and hot climates with high cooling loads (i.e., Houston and Los Angeles).

Annual energy costs for CCHP/DOAS would increase if electric resistance heat was used to provide the necessary supplemental heating at low ambient temperatures.

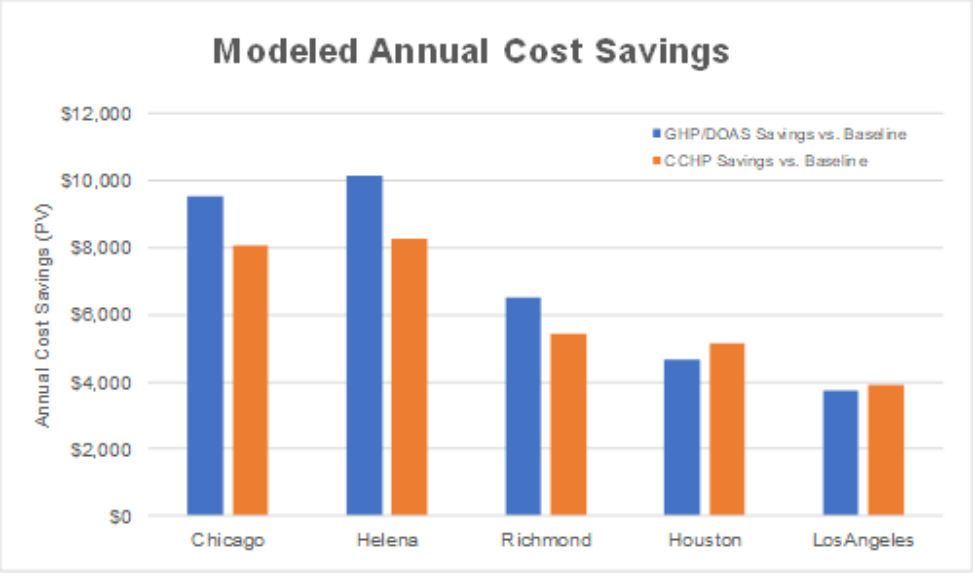

Figure 7. Regional Modeled Comparisons for Annual Cost Saving (PV)

Based on energy pricing for the field site, modeled results show both VRF systems reduced life cycle costs compared to the baseline VAV system in most climates. Savings in life-cycle costs were highest in cold climates (e.g. Chicago, Helena). The GHP/DOAS had savings in life-cycle costs for all locations except Los Angeles (Figure 8). Modeled results indicate the CCHP/DOAS has potential to reduce life-cycle costs in all locations. As previously discussed, life-cycle costs for CCHP/DOAS would significantly increase if supplemental heating was added for operating at low ambient temperatures.

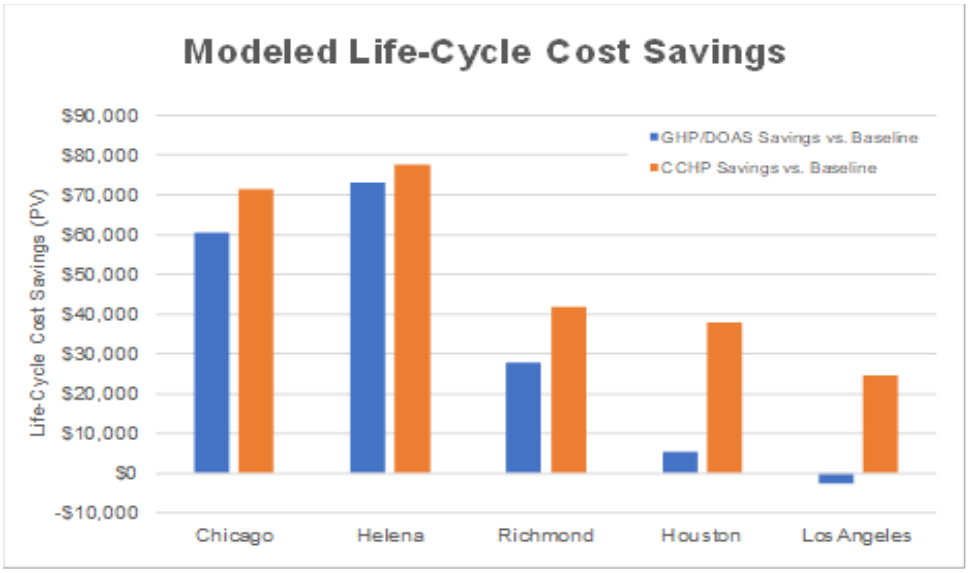

Figure 8. Regional Modeled Comparisons for Savings in Life-Cycle Costs

Modeled results in Table 2 compare GHP/DOAS economics to the baseline VAV. The GHP/ DOAS was cost-effective in cold climates (e.g. Chicago, Helena) with simple paybacks of five years. Although the GHP/DOAS reduced annual costs in all climates, additional development to optimize performance and reduce first costs is needed to achieve sufficient payback in warmer climates.

Table 2. Life-cycle Assessment of GHP/DOAS with Respect to Baseline VAV Based on Modeled Data

	Equipment Premium	First Cost Premium	Annual Savings (PV)	Life-Cycle Cost Savings (PV)		Simple Payback (years)	SIR
Chicago	$32,000	$47,000	$8,970	$60,640	18%	5	2.3
Helena	$32,000	$47,000	$10,015	$73,181	22%	5	2.6
Richmond	$32,000	$47,000	$6,229	$27,747	8%	8	1.6
Houston	$32,000	$47,000	$4,376	$5,513	2%	11	1.1
Los Angeles	$32,000	$47,000	$3,710	($2,485)	-1%	Not Achieved	1.0

7.0 IMPLEMENTATION ISSUES

Several regulations apply to the use of VRF systems for DoD facilities. Best Practices for Variable Refrigerant Flow (VRF) System is summarized in the Unified Facilities Criteria UFC 3-410-01 Heating, Ventilating, and Air Conditioning Systems. Requirements for VRF systems are addressed in detail in Appendix D of the full report.

This demonstration presented several important findings and valuable lessons learned. Baseline monitoring highlighted operational issues with the existing baseline VAV system. As confirmed by the manufacturer, a BAS is required to integrate controls for the central gas heating and distributed VAV-boxes. Without a BAS at the field site, the central VAV gas heating and the indoor VAV-boxes operated independently resulting in excess electric resistance heating especially during temperature recovery from night/weekend setback. As a result, the baseline operation had higher than expected peak electric demand and higher energy costs. Although the baseline system did not operate as designed, this may be a typical situation for smaller buildings or sites without a central BAS. Since VAV systems are widely used for multi-zone applications, such as office buildings, retro-commissioning and/or retrofitting integrated controls may improve efficiency and reduce energy costs for existing equipment.

Based on this demonstration, VRF systems improved comfort while providing significant energy savings, lower peak electric demand, and lower annual costs compared to conventional VAV systems. Both CCHP and GHP systems have the potential to reduce life-cycle costs depending on regional heating/cooling loads and energy pricing. The demonstration also identified operational issues and limitations for both VRF technologies in this application. The field site experienced a number of outages of both VRF equipment and conventional HVAC equipment (e.g. the DOAS igniter). Several outages were due to equipment installation issues, highlighting the importance of well-trained service providers, a common concern for emerging technologies.

For this demonstration in ASHRAE Climate Zone 5, the electric CCHP was unable to meet the heating load for several days. This specific VRF heat pump model was designed for cold climate applications without supplemental heating. For this demonstration, the CCHP was oversized based on the de-rated heating capacity at low temperatures to match the estimated peak heating load.

During the monitoring period, ambient temperatures dropped below winter design conditions on several occasions. During extreme cold, the CCHP continued to function but was unable to maintain zone temperatures and operated at very low efficiencies. As weather conditions become less predictable with more extreme temperatures, the CCHP will require a means of supplemental heating for reliable cold climate operation. The use of supplemental heat will impact both energy use and life-cycle costs.

As a key finding, this demonstration highlights how VRF heat pumps regularly operate at very low part-loads even when sized appropriately. This is amplified when paired with a DOAS which can reduce the facility heating or cooling loads. Currently, GHP manufacturer rating is based on full-load capacity and efficiency at select rating conditions; however, depending on the climate, the heat pump might never operate at those specific conditions. By design, VRF systems usually operate at lower part-loads by modulating to meet the multi-zone heating and cooling loads. Existing GHP performance ratings are not a good indicator of seasonal performance. Current efforts to update GHP standards, developed prior to the introduction of VRF products, will include performance metrics that reflect actual installed conditions, including part-load operation. This evolution of GHP performance standards will help support the development of more optimized designs.

Part-load operation adversely impacted the performance of both heat pumps; however, the specific GHP model used in the demonstration had much lower than expected performance at low part-load operation. This extent of decreased part-load performance is not inherent in this class of technology and could be due to product-specific controls or engine sizing. GHPs use variable-speed engines to enable them to closely follow the load and maintain efficiency. This is an important finding and warrants further investigation to optimize part-load performance.

In summary, both VRF heat pumps demonstrated improved comfort along with significant potential for energy savings and economic benefits compared to conventional HVAC. While this demonstration compared an emerging technology (GHP) with a more mature technology (CCHP) that has multiple manufacturers and decades of design optimization, both VRF heat pumps had operational limitations in this cold climate application. Results further suggest the need for additional research and development to optimize GHP performance and reduce installed costs in order to improve regional economics and support broader market adoption.

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