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MECA Air Source Variable Refrigerant Flow Field Study

slipstream

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EXECUTIVE SUMMARY

BACKGROUND AND OBJECTIVE

Commercial building space conditioning is a significant building end use in cold climates like Michigan, where approximately 55% of *total* building energy use is the result of space conditioning and 40% results from space heating. There is a significant need for HVAC technologies in commercial buildings which are efficient and can reduce building energy consumption from space conditioning. Traditionally, Michigan has primarily relied on propane and natural gas for meeting space heating needs, which have efficiency limitations of 96-97%. Variable Refrigerant Flow (VRF) systems have the potential achieve seasonal heating efficiencies above 200% but have had historic challenges operating at the coldest hours of the year.

Slipstream has completed a field demonstration of VRF systems to demonstrate the energy savings potential from this technology. In addition, we also quantified the ability for these systems to maintain setpoints throughout the year, including the coldest and warmest hours. We used our findings to develop actions that utilities and program staff can take to overcome market adoption barriers.

APPROACH AND INITIAL MEASUREMENT

Our field demonstration began with locating two sites with VRF systems to monitor. We used our relationships with the largest VRF manufacturers (by sales) in Michigan to locate recent VRF installations that met our site criteria. As a result of this outreach effort, we located a hotel in Petoskey, MI and a hotel in Grand Rapids, MI. At each of these sites, we installed monitoring equipment to collect data on both energy usage, space temperatures and VRF supply temperatures. In addition to collecting data, we also interviewed key personnel at both sites to understand their experiences with the VRF system. One of the primary outcomes from interviewing was quantifying guest comfort (based on feedback/complaints operators receive from guests). In addition to guest comfort, we also asked questions related to system operation, maintenance, and overall satisfaction.

At each site, we monitored the VRF system for at least 12 months, to ensure that we captured seasonal performance. In addition to using this data to understand the energy usage of the VRF system, we also used our monitored energy data to calibrate energy models. These calibrated models were then developed with alternative HVAC systems to calculate energy savings.

In addition to energy monitoring, at one site we also captured additional temperature and air flow rate data to calculate the system’s coefficient of performance (COP). The COP calculation was completed for every timestep, allowing for a granular look into system performance.

ENERGY, ECONOMIC, AND EMISSIONS SAVINGS

We calculated the energy savings VRF systems over two typical hotel HVAC baselines. These common baselines were packaged terminal air conditioners (PTAC) with resistance heat and water source heat pumps (WSHP) with a gas fired boiler. Our analysis found that VRF systems were able to save 48% of HVAC energy over PTAC systems. Significant energy savings were driven by the increased heating efficiency of the VRF system. Over the WSHP system, the VRF system saved 52% of HVAC energy. Table 1 provides a summary of savings.

Table 1: Summary of savings for VRF systems over various baseline HVAC systems.

Baseline	Cooling	Heating	Heating	Fan	Heat Rejection / Pumping	Total	Total
	kWh/ft²	*kWh/ft²*	*therm/ft²*	*kWh/ft²*	*kWh/ft²*	*kWh/ft²*	*therm/ft²*
PTAC	0.23	4.38	0.00	0.30	0.00	4.92	0.00
WSHP	0.33	-2.68	0.33	-0.31	2.20	-0.46	0.33

Our analysis found favorable economics for VRF over both baseline systems. We used an assumed cost of 24 $/ft^2 for VRF, $6500/room for PTAC and 27 $/ft^2 for WSHP. We found that VRF saves 0.60 $/ft^2 over PTAC and 0.18 $/ft2 over WSHP. The payback for VRF over WSHP is immediate as the WSHP system has a higher capital cost. The payback over the PTAC system is 11 years, driven by the low capital cost of PTAC systems. PTAC systems may not be a typical alternative to VRF given that they are not considered a premium HVAC system from a guest experience or energy savings standpoint.

Lastly, we found that the VRF system was able to reduce emissions over both baseline alternatives. Over the electric PTAC system, VRF reduced CO2 generation by 2.67 kg/ft^2. Over the WSHP system, the CO2 reduction was 1.52 kg/ft^2. Emissions savings are reliant on the electric grid composition. With the current grid composition in Michigan, electricity consumed on-site results in three times more CO2 generation than burning natural gas. In the future, if additional clean energy generation sources are added to the grid, the CO2 impact of electricity consumption will be reduced. Alternatively, if on-site renewable energy sources are used, the CO2 generation is eliminated.

OWNER AND OCCUPANT SATISFACTION

At both demonstration sites, we thoroughly interviewed the site operators. Our primary objective was to understand if the system was meeting guest comfort and experience needs, as well as any other system challenges or successes (operational, maintenance, etc).

We found that both sites were satisfied with their VRF system. At one site, the owner stated he was very satisfied and occupant comfort was significantly improved, resulting in fewer guest complaints (as compared to their previous system). The other site stated that maintaining temperatures, even on the coldest days, has never been an issue for the VRF system.

One challenging point is acclimating guests to a system they are not used to (many guests are familiar with the traditional PTAC through-wall unit). The VRF system that was installed has a thermostat with more than “on/off” or “heat/cool” controls which has confused some guests. A potentially complicating factor is the VRF system’s quiet operation, which has caused guests to be uncertain if the VRF system is responding to their inputs.

CONCLUSIONS AND RECOMMENDATIONS

Based on the findings of this research, we compiled a list of recommendations for utility and programs staff to help foster the adoption of VRF in Michigan. This list is based on the key market barriers to adoption we identified. Our recommendations are based on developed strategies to overcome those key barriers. Below is a list of the key recommendations to increase the uptake of VRF in Michigan:

- Increase market awareness and confidence in VRF
- Overcome high first costs
- Overcome increased operational costs versus gas-fired systems
- Develop a formal program baseline
- Develop savings calculation
- Develop successful path for project delivery
- Increase contractor training and support
- Shorten operator learning curve

VRF has the potential to increase energy savings for efficiency programs as well as energy and cost savings for certain market segments. A defined program targeting these segments will grow the VRF market.

INTRODUCTION

Michigan is a cold climate state which contains three different ASHRAE climate zones; *cold humid – 5A*, *cold humid – 6A* and *very cold – 7*. These cold climate zones present a challenge from a commercial building space conditioning standpoint, as building HVAC energy use is typically 20-30% higher than more temperate climate zones, as shown in Figure 1.

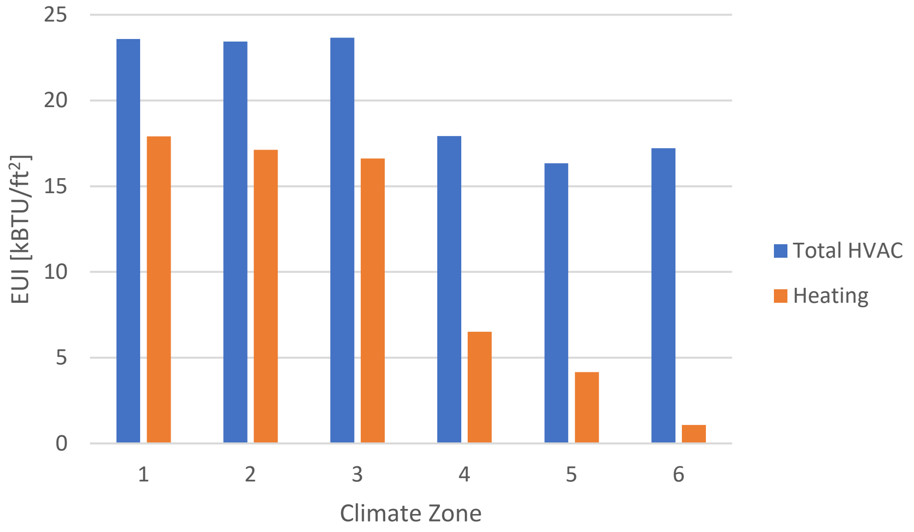


Figure 1: Energy use per square foot for a typical office building complying with IECC 2018, for various climate zones.

For Michigan buildings, 70-75% of the energy used for space conditioning is a result of heating. Overall, approximately 55% of *total* building energy use is the result of space conditioning and 40% from space heating. There is significant interest in HVAC technologies for commercial buildings which are efficient and can reduce building energy consumption from space conditioning.

Traditionally, Michigan has primarily relied on propane and natural gas for meeting space heating needs. This fuel mix has been successful in its inexpensive cost and use in inexpensive equipment such as furnaces and boilers. These design strategies have become the status quo in Michigan and many neighboring cold climate states.

As climate discussions have become more prominent, questions around the use of fossil fuels for heating have come to the forefront in cold climates. Historically, limited electric heating solutions have been available, as heat pumps previously have had cold climate performance challenges and electric resistance heating has extremely expensive operating costs.

In the past decade, significant technology advancements have been made for heat pumps which have made this technology viable in the Midwestern cold climate. This is a significant as heat pumps can produced heat with efficiencies two to three times greater than resistance heat. This efficiency results in significant energy savings and potentially energy cost savings. This research study reviews these newest heat pump advancements, specifically around variable refrigerant flow systems, which have had little independent review and field testing to provide stakeholders with the data and information required to make key decisions on whether heat pump technologies are ready for transforming the heating market in Michigan and the Midwest.

RESEARCH OBJECTIVE

This research study had the following We propose the following objectives:

- Evaluate the energy savings potential of ccVRF systems compared to traditional HVAC systems. Traditional system performance can be estimated through modeling. Confirm that ccVRF systems can meet the comfort demands (e.g. maintaining thermostat setpoints) of commercial buildings in Michigan.
- Develop the business case for ccVRF systems in MECA territory. Through interviews with owners, understand what issues are most important (energy costs, capital costs, system footprint/flexibility, comfort, etc). We'll also gather cost information to inform economic understanding.
- Connect local contractors and VRF manufacturers to increase the network of VRF capable installers in MECA territory; determine which key steps are needed for market transformation (e.g. training, marketing, etc.).
- Develop ccVRF case studies to disseminate the results to customers in MECA territory. These materials can outline the energy savings, comfort improvements and other facts which are important to owners (found through owner interviews).

PRODUCT REVIEW

A thorough review of VRF systems was conducted in Phase 1 of this project. This product review is attached in *Appendix A: Product Review*. In addition to the findings of Phase 1, we have included additional product and design information. This section will cover updated findings on product selection and sizing, design strategies, as well as supplemental heat.

MARKET SEGMENT

Although VRF systems have a wide variety of applications, they are not a universal solution. In this section, we develop the most common market segments for VRF systems. The VRF market can be split into two primary categories – Retrofit and New Construction.

Retrofit

Older or Historic Buildings. One of the best applications of VRF systems is in mid-sized older or historic buildings. These buildings often lack air conditioning systems, have low floor-to-floor heights, and typically have some form of hydronic heating system. VRF works well as a solution for these buildings because it can provide individual zone control while fitting into these historic buildings. The small refrigerant pipes can be run in ceilings and walls where ductwork and water piping may not fit. The indoor fan coil units (condensers) are typically smaller and lighter than other HVAC equipment, and can be placed on the roof, wall, or ground. Specifically for hotels (where PTAC units are common) VRF systems do not require puncturing the exterior. This has benefits of preserving the exterior finish while also preventing additional infiltration and higher in-room acoustic levels.

Buildings with Electric Heat. Existing buildings that use a significant amount of electric heat or an expensive alternative fuel like Propane, are applications where VRF systems result in significantly lower utility bills and attractive payback periods. For buildings which do not have gas service, VRF systems result in additional savings by eliminating cost of bringing in natural gas service.

New Construction

Hotels and Lodging. As will be discussed in the following sections of this report, VRF is a viable option for new hotels. VRF has quiet operation and a better aesthetic appearance than PTAC units. Meanwhile, it is less expensive to install compared to other higher end HVAC systems such as water-source VRF heat pumps or hydronic fan coil systems.

Multifamily. Multifamily buildings also have seen several VRF installations (in Chicago, IL). VRF systems are more efficient than wall, window, or split A/C systems. However, one barrier is how the tenant pays for utilities. Most frequently in multifamily buildings, a tenant pays for their electricity and gas usage. For buildings with VRF, individual tenant billing is difficult as multiple tenants are tied together on a single VRF system. As a result, the landlord will have to pay for heating and cooling for tenants with VRF systems and find ways to pass on the cost in the rent. Another drawback of VRF is that if a condenser unit goes down, all of the tenants tied to that system would lose heating and cooling. Installing back-up heating may be a consideration to reduce this impact. Given these challenges, VRF has been an effective system particularly in affordable housing where utility costs can be covered by the landlord. VRF also works well in nursing homes and dormitories, where tenants are not individually billed for utilities. Our interviewing of Michigan manufacturer representatives say nursing homes are one of their common applications for VRF.

Schools and Offices. Schools and offices have been another common application for VRF. VRF saves significant fan energy compared to all-air rooftop unit systems. VRF systems are paired with DOAS systems which can provide superior ventilation, particularly for schools where improved ventilation has shown to improve cognitive performance. One of the challenges for offices and schools is that VRF may not be as flexible for future renovations. Depending on the design, it can be difficult to add or upgrade an VRF indoor unit due to refrigerant line limitations. While this can also be true for ducted air systems, extending ductwork from an existing rooftop unit is typically a straightforward procedure.

Multi-Zone Mid-Sized Buildings. In new construction, VRF systems are an ideal fit for mid-sized buildings with many individual zones, such as hotels, multifamily, nursing homes, dormitories, schools, and offices.

Electrification and Sustainability Goals. For any new construction or retrofit building, if an owner is considering electrifying the building and not installing any natural gas, VRF should be considered for its high efficiency. In addition, many owners and organizations have developed sustainability goals, which VRF may be a viable solution for achieving those targets.

Applications not suitable for VRF

Large/Tall Buildings. Large and tall buildings are generally not the best application for VRF systems. The largest condenser unit is approximately 40 tons. As a modular system, VRF does not benefit from economies of scale for larger buildings like boilers, chillers, and rooftop units. There are also piping limitations as the compressors need to return all the refrigerant. The maximum *pipe length* between and indoor and outdoor unit is approximately 500 feet, typically resulting in approximately 250 feet between indoor and outdoor units. There are also height limitations – indoor units are limited to 130 feet below and 160 feet above the outdoor unit. Manufacturers have recommended air-source VRF for buildings up to 200,000 ft^2. Commonly, for buildings which exceed 200,000 ft^2, VRF becomes cost prohibitive when compared to other traditional boiler or chiller systems.

Small Buildings. Small buildings might be better served by one or more single-phase, residential style heat pumps. Buildings should consider VRF around 10,000 ft^2, although it may make sense for smaller buildings depending on the application.

Variable Loads/High Ventilation Rates. Buildings with highly variable loads or which require high ventilation rates are often not optimal for VRF systems. Hospitals, laboratories, meeting and conference centers, bars and restaurants, auditoriums, and cafeterias have high ventilation and exhaust requirements or variable occupancy. VRF systems can have a slower response time to respond to rapidly changing loads than traditional heating and cooling systems. To satisfy high ventilation rates, a large DOAS would be specified. For designs featuring large a DOAS, it is generally more economical to size the DOAS to also provide most of the heating and cooling.

System Switching. Buildings with existing HVAC systems with air conditioning and gas heat can be more difficult to retrofit with VRF. Common examples of this are Packaged Variable Air Volume systems. With these types of systems, a network of ductwork, reheat piping/electrical components, and other HVAC components exists. Typically, it is more economical to repair or replace these systems with a newer more efficient version than to retrofit to a VRF system. The low cost of natural gas means the heating savings is typically not substantial enough to justify the increased cost of a VRF retrofit.

PRODUCT BACKGROUND, SELECTION, AND SIZING

When air-source VRF first entered the North American market, these systems were only designed to operate to ambient outdoor temperatures as low as -5°F wet-bulb (which was typically sufficient for operation in Europe and Asia). In warmer parts of the United States, this wasn't a significant barrier, as ambient temperatures rarely reached sub-zero. Adopters of VRF were rewarded with energy savings from high cooling efficiencies and heat pump heating where resistance heat was typically relied on. However, the cold climate performance limited the viability of standalone VRF system in cold climates, including Michigan. In these climates, VRF was either not considered or was implemented using a supplemental heat approach (outlined later in the report). VRF manufacturers continued to push the cold climate performance bar and improved the technology to reach -13°F VRF. Still, VRF wasn't considered a standalone (i.e. no supplemental heat) option in locations, like Michigan, where the temperature could still drop to -20°F or -30°F during the winter.

To expand the market for VRF systems to colder climates, manufacturers in the last 5 years developed "Cold-climate" VRF (ccVRF) technology that can operate without supplemental heat in these regions. These systems use an outdoor unit featuring an inverter driven compressor with vapor injection to maintain capacity and efficient performance for space heating even at low outdoor temperatures. Because of this, it is designed to operate -22°F wet-bulb. Currently, minimal third-party testing and monitoring exists. However, as discussed below, preliminary test data and case studies published by the manufacturers indicate that ccVRF is feasible for cold climates.

ccVRF has advanced quickly in the last decade. Five years ago, VRF units were only rated to outdoor wet-bulb temperature of -10°F. Below this temperature the system would not operate. In the last two to three years, manufacturers now have units rated to perform as low as -22°F, with manufacturers stating they will operate below -30°F before shutting down. These are significant advancements, as designers now have multiple options for systems that can operate well below the heating design day conditions in climates such as northern Michigan.

Our initial market research finds that these -22°F rated cold climate units have a 10-20% cost premium compared to other VRF systems, depending on the manufacturer. The -13°F rated cold climate variants typically come at a lower cost premium than the -22°F rated systems.

While new cold climate and standard VRF systems now operate at colder ambient conditions, they still experience decreasing capacity. To meet the peak heating demand, systems are oversized, which could result in a performance penalty at part-load operating conditions and potentially lower energy savings. Figure plots the fractional capacity over a range of outdoor dry bulb temperatures. For most heating hours in southern Michigan, a -13°F rated VRF system will operate near rated capacity. This is advantageous as these systems are less expensive compared to the cold climate VRF systems.

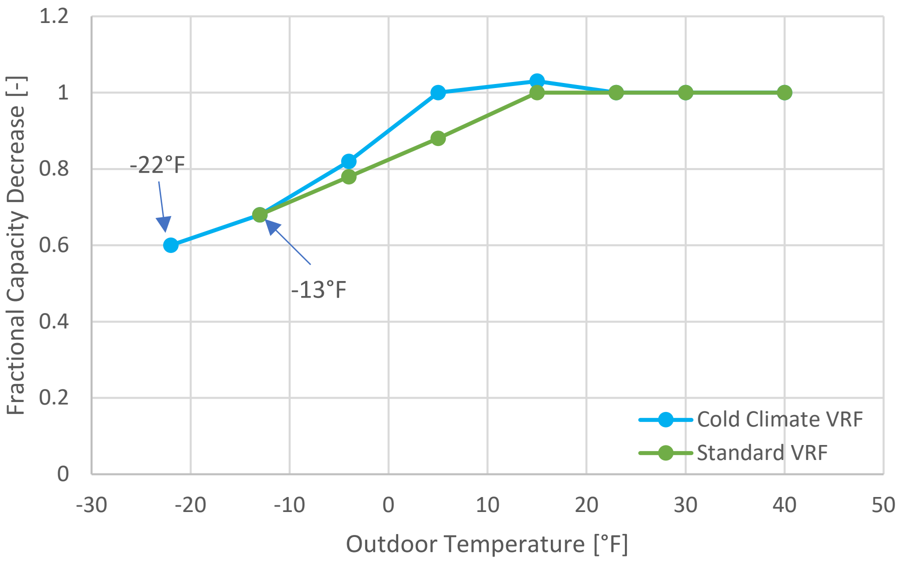


Figure 2: Plot of capacity versus outdoor dry bulb temperature. Capacity is fractional, with 1.0 equal to rated conditions.

DESIGN STRATEGIES

There are a number of design considerations and recommendations for VRF systems in cold climates which we summarized below (Swanson and Carlson 2015):

1. **Perform a load profile analysis** – Identify the indoor space requirements, occupancy schedules, and thermal loads and the outdoor climate design conditions. Consider locations for the outdoor condenser units and back-up or supplemental heat.
2. **Determine zoning and potential for simultaneous heating and cooling** – Determine how outdoor units will be connected to indoor zones. Account for limitations in refrigerant piping length and height. More zones on a single outdoor unit may be less expensive but more result in larger condensing units. More zone on a single condenser unit is more risk if the condenser unit fails. Also see if zoning allows for heat recovery between zones. This can provide significant energy savings but at the expense of increased equipment cost.
3. **Size the indoor and outdoor units –** Size equipment based on the peak cooling or heating load, whichever is larger. This should be done with the support of the basis of design manufacturer.
4. **Develop Fresh Air Ventilation Strategy** – Determine the method to provide fresh air to the spaces. VRF does not provide ventilation and should be provided by a separate dedicated outdoor air system or other means.
5. **Select Indoor Units** – Determine configuration of indoor unit based on space requirements, including if the unit is to mounted on the floor, wall, or ceiling.
6. **Layout Piping** – This step is often manufacturer specific. Unlike other applications, VRF refrigerant piping should be laid out straight with no refrigerant traps. Poor routing or piping rerouted in the field often leads to most VRF failures. It is highly recommended to consult the manufacturer when determining piping layout.

7. **Verify compliance with ASHRAE Standard 15 and 34** – Follow these standards to ensure safe refrigerant operation.
8. **Examine life-cycle costs**
9. **Integrate into control system** – VRF systems operate based on proprietary controls. If a building automation system is existing or planned to be installed, determine how to integrate BAS controls.
10. **Examine future building expansion and reconfiguration plans** – determine needs for the future and avenues for expansion. Note that VRF systems are difficult to add to without rerouting.

TYPICAL APPLICATIONS

Variable Refrigerant Flow systems are not a universal application for all building types or market segments. There are several building types or market segments that are ideal fits for VRF from an operation and economic perspective. This section outlines the most common and successful applications for VRF systems.

Older Existing Buildings. VRF systems are frequently recommended for older buildings looking to add air conditioning. These buildings often have challenges adding ductwork or hydronic piping to because of their low floor-to-floor heights or other physical layout constraints. These facilities also have the option of retaining the existing heating system to serve as supplemental or emergency heat in winter.

Hotel and Nursing Homes. VRF systems provide individual guest room control with less noise, no draft, and more energy efficiency than in-wall PTAC units. DOAS units are installed to serve the corridors and transfer air into guest rooms. VRF systems carry a significant cost premium over PTAC systems, however, VRF is a much higher quality HVAC system. Typically, owners selecting VRF are placing a premium on occupant experience.

Multifamily. Like hotels, VRF has significant benefits for multifamily buildings, especially related to occupant comfort. One significant barrier to VRF adoption in hotels is how tenants are billed for utility costs. Frequently, tenants have individual electric meters. VRF systems are not individual systems and it is difficult to charge tenants based on their HVAC usage.

Offices. Small to mid-size offices are a large building segment for VRF systems. This building segment has many different thermal zones including conference rooms, private offices and open office spaces. VRF provides flexibility to meet varying office designs and layouts.

Education. Similar to offices, VRF is often installed in schools. It can make a good replacement for wall unit ventilators in existing schools. Needs to be carefully coordinated with a DOAS unit to provide fresh ventilation to classrooms. Schools are often willing to implement technologies with longer paybacks.

SUPPLEMENTAL HEAT

For VRF systems unable to meet the heating design day conditions of a given location, there are several options for supplemental or auxiliary heat which make VRF viable.

DOAS System. The DOAS system can be sized to provide back-up or supplemental heating. By allowing the DOAS, ideally with an energy recovery ventilator (ERV), to provide non-neutral air to spaces can help supplement the heat to the VRF system. Design and control should be done carefully to balance the load between the electric but efficient VRF system and the gas DOAS unit, and to avoid a situation where the VRF system is trying to cool spaces from the DOAS system.

Secondary Heating System. If a secondary heating system is paired with the VRF system, backup electric or gas heat can be provided directly to spaces (likely in the form of baseboards). An additional benefit to this approach is that it provides a level of redundancy. A significant drawback is the additional cost of adding a secondary heating system in addition to the added level of controls.

Penthouse Approach. A common option for adapting VRF systems to cold climate operation is to install the outdoor condensers indoors, usually in a mechanical room or penthouse. These spaces are usually heated by gas heaters to 40 degrees or higher. Placing the outdoor condensing units in an enclosed space allows the VRF units to operate at a more efficient range at the expense of less efficient supplemental heat (typically natural gas). Mechanically operated dampers are installed to relieve heat during the cooling season, which can add significant cost. This method makes maintain and servicing the condenser units easier as they are located indoors. The penthouse approach is ideal for existing buildings with pre-existing space that can serve as a penthouse for the outdoor units. For new construction projects, the penthouse can be easily accounted for in the design, however these spaces take up valuable space and cost more to install. They also add an additional layer of controls.

REFRIGERANTS

Our preliminary research report on Variable Refrigerant Flow systems provided a comprehensive review of refrigerants and associated environmental impacts. This review is provided in *Appendix B: Refrigerant Review*.

RESEARCH METHOD

The research design for this project involved:

- Identifying two sites with VRF systems in Michigan

- Collecting energy use and temperature data from the two sites
- Interviewing key personnel at both field demonstration sites
- Using calibrated energy modeling to calculate energy savings for VRF systems
- Quantifying comfort from temperature data and personnel interviews

SITE OUTREACH AND SELECTION

Site Selection Criteria

A key task for this field demonstration was developing a large sample of sites in MECA territory with VRF systems or sites interested in retrofitting a VRF system. At the beginning of the project, our team developed a site selection criteria which was used for the decision making process on what sites were eligible or a "good fit" for participation in the study. This site selection criteria is provided in *Appendix C: Site Selection Criteria*. Our project team developed this criteria after extensive interviewing of manufacturers, engineers, contractors, building owners and program staff across the Midwest. There were 3 key priorities with the site section criteria:

Monitoring timeline. In order to quantify the winter performance of the VRF system, it was required that our team be able to monitor the VRF system during the coldest winter months. In addition, we also required capturing one shoulder season as well as the summer operation. This data set would allow for a complete analysis on the energy and comfort performance of VRF systems.

Design. The primary focus of this research was to evaluate air-source VRF systems without supplemental heat. A preferred criteria was that sites have a standalone air-source VRF system without any supplemental heat. Given the uncertainty on the number of those installations in Michigan, our project team did have optional criteria that would consider sites with supplemental heat if those supplemental systems could be easily isolated during the monitoring process.

Newest generation VRF technology. For this study to differentiate from previously published research, it was required that the project team evaluate the newest generation VRF systems. The site selection quantified this by seeking installs no older than 2017. Final verification of VRF system make and model were completed to verify the equipment.

Outreach Strategy

Our project team's primary strategy for outreach was to develop relationships with key stakeholders in Michigan. We prioritized connecting with the following groups: manufacturers, manufacturers sales representatives and contractors. Based on our experience, these stakeholders frequently have a broad view of the market including recent installs and potential ongoing projects. We contacted the three largest VRF manufacturers and sales representative. in terms of sales in Michigan: Daikin, Mitsubishi and LG. We were able to connect with a Fujitsu sales representative as well. We were able to interview these manufacturers to learn more about product offerings but also review our site selection criteria for this project. Our initial site outreach was limited to finding projects in MECA territory. A thorough review of projects from VRF stakeholders yielded no projects in MECA territory that fit the site selection criteria. As a result, we broadened the outreach scope to all of Michigan, while still meeting the specific requirements of the site selection criteria. The broadened scope resulted in a larger sample set of VRF projects. Table 2 below lists the VRF sites identified fitting the site selection criteria.

Table 2: Summary of sites identified during outreach.

Site Name	Location
Genesee Intermediate School District Admin Building	Zip Code 48507
DTMB New Veterans Home	Zip Code 48047
David Whitney Building (Hotel and Apartments)	Zip Code 48226
Elkton Pigeon Bayport Schools	Zip Code 48755
Stafford’s Perry Hotel	Petoskey
Drury Hotel	Grand Rapids
Mission Point Hotel and Resort	Mackinac Island
Harbor Farmz	Kalamazoo
Elementary School	Oswosso
Siena Heights University, St. Josheph Hall	Adrian
Hazel Findlay II	St. Johns
Courtyard by Marriott	Holland

Site Selection

Our team reviewed the site listed and selected two sites which fulfilled the site selection criteria for this study. Both sites were hotels, a common building type for VRF systems. One site was new construction while the other was a historic building with a VRF retrofit. One site was located in Grand Rapids, climate zone 5 while the other was located in Petoskey, climate zone 6. The historic site in Petoskey had a Mitsubishi CITY MULTI heat recovery VRF system while the new construction site in Grand Rapids has a Daikin Aurora VRV system. Additional details on both sites are found in the *Site Assessment* section below.

DATA COLLECTION

For the two sites that we selected, we collected field data to meet our study objectives, including setting up physical measurements and interviewing hotel staff to assess both owner/operator and occupant satisfaction.

Site Assessment

At each site we reviewed the facility, HVAC systems and personnel available for interviewing. Due to the COVID-19 pandemic, all preliminary work was done virtually. Sites were able to participate in multiple calls and provided needed information, including drawing sets and equipment information. Manufacturer’s sales representatives were also used as resources for understanding the systems when necessary. The following sections summarize both sites.

Stafford's Perry Hotel, Petoskey, MI

Figure 3: Image of the Stafford Perry Hotel in Petoskey, Michigan.

Stafford's Perry Hotel ("Perry") is a 60,000 square foot historic hotel in the downtown of Petoskey, MI. The hotel was originally built in 1899 and is listed on the National Register of Historic Sites. After several expansions and renovations, it now has 75 guestrooms and suites, a lower-level pub, 2nd floor lounge and banquet area, and offices and meeting spaces. At the time of construction, it was advertised as "fire-proof" due to it's brick exterior walls. Since then, there have been several renovations to improve the envelope, including additional insulation in the attic and walls and new windows.

The hotel does not have a single HVAC system type and is instead served by several different heating and cooling systems. Rooftop units (RTUs) were installed in the 1980's to serve some of the guest rooms. One RTU would serve 6 rooms with only a single thermostat, and as a result these systems led to frequent guest complaints. 18 rooms still are on RTUs. Another wing of the building has baseboard heating installed in the 1960's and has a separate Carrier chiller that provides chilled water from the roof.

The focus of this study is on the 35 rooms served by four Mitsubishi VRF systems. The first VRF system was installed in the spring of 2016 for 6 guest rooms. After that system proved successful, the three more VRF systems were installed in the winter of 2016-2017 (Figure shows VRF condenser units on roof). In total, 35 rooms on levels 3 and 4 are served by VRF units, all guest rooms except for a library, sitting room, and crib room. Figure shows example VRF supply grille, where ducted indoor fan coil unit is located above drop ceiling.

Figure 4: VRF units on the roof at Perry.

Figure 5: Supply air grille for indoor unit at Perry.

All four outdoor units are Mitsubishi Hyperheat models. VRF-1 and VRF-2 are 6-ton units and VRF-3 and VRF-4 are 8-ton units. These outdoor units are all located on the roof. All four are heat-recovery type units and each have their own branch controller box. Each guest room has its own concealed, ducted VRF indoor unit. Filters are installed in the return grilles. Each room has its own thermostat.

A makeup air unit was installed in the winter of 2016-2017 in conjunction with the VRF units. The unit provides gas-fired heating and is cooled by a separate air-cooled condensing unit. The unit also uses an energy recovery ventilator (ERV). The makeup air unit supplies fresh air to the level 3 and 4 corridors served by the VRF system. The gas heater is oversized to provide potential back-up heating to guest rooms in case the VRF system cannot keep up.

Our project team identified Reginal Smith, Stafford's Hospitality Vice President, as the key contact for this site. Mr. Smith was familiar with hotel operations, the decision to use VRF systems, and how guests have reacted to the new system.

Drury Inn & Suites, Grand Rapids, MI

Figure 6: Image of Drury Inn & Suites in Grand Rapids, Michigan.

Drury Inn & Suites ("Drury") is a 100,000 square foot, 7-story hotel in Grand Rapids, Michigan. The hotel was built in 2016. Drury Hotel operates more than 150 locations in 25 states. The chain has installed several VRF systems in the past 10 years with success. The Grand Rapids, MI location is the northern most location with a VRF system.

The Grand Rapids location has typical hotel layout and amenities. It has a 1st floor with a breakfast lobby, conference rooms, and an indoor/outdoor swimming pool. The remaining 6 floors are near identical guest room floors, with a perimeter guest room and core corridor layout. There are 180 rooms with approximately 30 rooms per floor.

The hotel is served by a Daikin VRV IV Heat Recovery VRF system. Each guest floor is served by one 24-ton VRF system. The first floor is served by two separate 24 ton VRF systems. Each condenser has heat recovery capability, and each indoor fan coil unit has its own branch selector box. The ducted concealed units are installed in each guest room and return air from the plenum. Indoor units on the 1st floor serve the lobby, kitchen/breakfast area, and meeting rooms. The swimming pool is served by a separate air handling unit.

Fresh air is provided by two makeup air units, one on each end of the building. These units contain energy recovery ventilators, hot water heating coils, and cooling coils served by a separate air-cooled condensing unit. Fresh air from these units are ducted directly into guest rooms.

We had two primary site contacts, Rob Warner, Vice President of Construction and Gregg Boyer, Director of Hotel Maintenance. Both contacts operate from the corporate level and were able to provide information not only on this specific site, but also overall company trends. We also had minimal contact with Kim Halbrehder, the hotel site manager.

Measurement

The following visits were conducted:

1. Preliminary site visit to assess proposed monitoring plan and identify alterations required to that plan
2. Installation site visit to install monitoring equipment
3. Follow up visits as needed to address any monitoring equipment malfunctions
4. Final visit to uninstall monitoring equipment (planned for spring of 2022)

After preliminary materials were gathered for each site, scheduled an electrician site visit to conduct the preliminary site visit. The purpose of the preliminary site was to assess the site conditions and identify any potential challenges with monitoring the circuits or placing of temperature loggers. *Appendix G: Preliminary Site Visit Plan* includes the preliminary site visit plan.

After the preliminary site visit was completed, we developed a unique monitoring plan for each site. At both sites, on-site data collection targeted energy usage of VRF systems, including sub metered usage of outdoor units, indoor units, and branch controllers. Additional data collection was centered around the make up air systems, including the DX component and fan. At both sites, the heating components of the make up air systems were gas fired and this end use was not captured for economic reasons. To implement data collection plan, each site was visited several times by a local electrician. The electricians used for each site were familiar with the buildings and had completed the electrical work of the VRF installations. For Perry, Bear River Electric was contracted and for Drury, Circuit Electric was contracted. Table 3 below summarizes the key measurement points and equipment used for both sites.

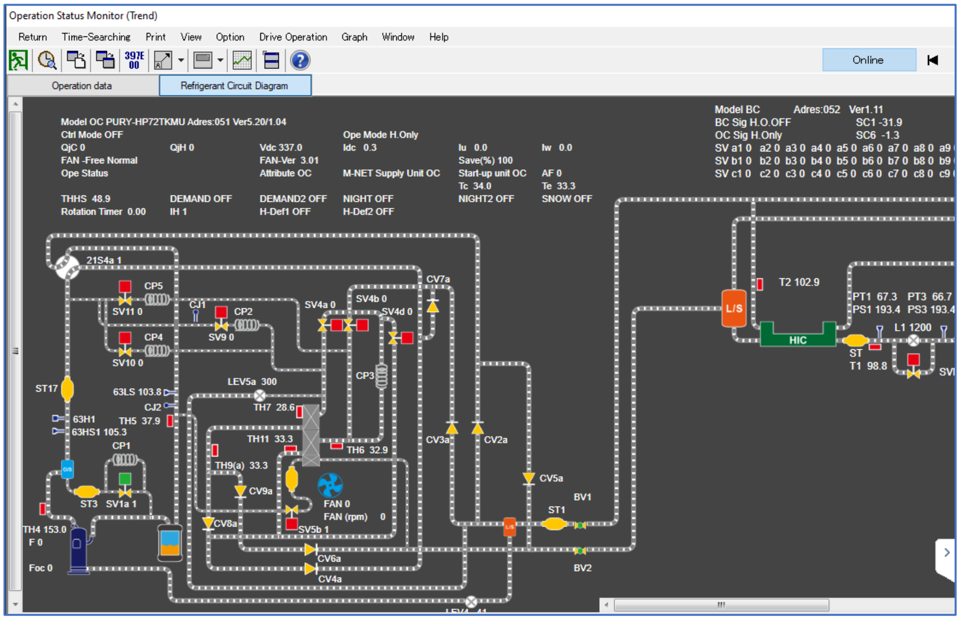
Table 3: Summary of measurement points, associated units, and equipment used to capture those points.

Point	Units	Equipment
VRF Outdoor Unit Power	W	eGauge EG4115
VRF Indoor Unit Power	W	

VRF Branch Selector Power	W	
MAU DX Condenser Power	W	
MAU Main Supply Fan Power	W	
Outdoor Dry Bulb Temperature	F	Onset Hobo MX1101 Logger
Outdoor RH	%	
Indoor VRF Supply Temperature	F	
Indoor VRF Supply RH	%	
Indoor Room Temperature	F	
Indoor Corridor Temperature	F	
Indoor VRF Air Flow	Cfm	Energy Conservatory TrueFlow, Alnor LoFlo 6200
Outdoor VRF Velocity	Ft/s	Velocicalc Air Velocity Meter

Onboard Monitoring Tool

In addition to our installed monitoring equipment, Mitsubishi granted our project team access to the Mitsubishi maintenance tool for the Perry site. This software suite has the capability of trending and recording data for the numerous onboard measurement points of the Mitsubishi VRF system. Some of the information provided by this tool includes individual thermostat setpoints, operating commands, defrost cycle operation, fan operation, refrigerant temperatures, and compressor power. While this research does not rely solely on that data set for energy saving calculations, it was a valuable source of information for further understanding the operation of the VRF system. One view of this tool is shown in Figure 7. Exported data showing guest room air temperature (measured at thermostat) and supply air temp are compared to the Hobo MX1101 logger measurements, as seen in Figure 8.



```
Model OC PURY-HP72TKMU Adres:051 Ver5.20/1.04
Ctrl Mode OFF                                   Ope Mode H.Only
QjC 0              QjH 0          Vdc 337.0      Idc  0.3               Iu  0.0            Iw  0.0
FAN -Free Normal                  FAN-Ver  3.01                         Save(%) 100
Ope Status                        Attribute OC   M-NET Supply Unit OC   Start-up unit OC   AF 0
                                                                        Tc  34.0           Te  33.3
THHS  48.9         DEMAND OFF     DEMAND2 OFF    NIGHT OFF              NIGHT2 OFF         SNOW OFF
Rotation Timer  0.00  IH 1        H-Def1 OFF     H-Def2 OFF
```

```
Model BC         Adres:052   Ver1.11
BC Sig H.O.OFF               SC1 -31.9
OC Sig H.Only                SC6  -1.3
SV a1 0   a2 0  a3 0  a4 0  a5 0  a6 0  a7 0  a8 0  a9
SV b1 0   b2 0  b3 0  b4 0  b5 0  b6 0  b7 0  b8 0  b9
SV c1 0   c2 0  c3 0  c4 0  c5 0  c6 0  c7 0  c8 0  c9
```

Figure 7: View of VRF system operation in the Mitsubishi Maintenance tool.

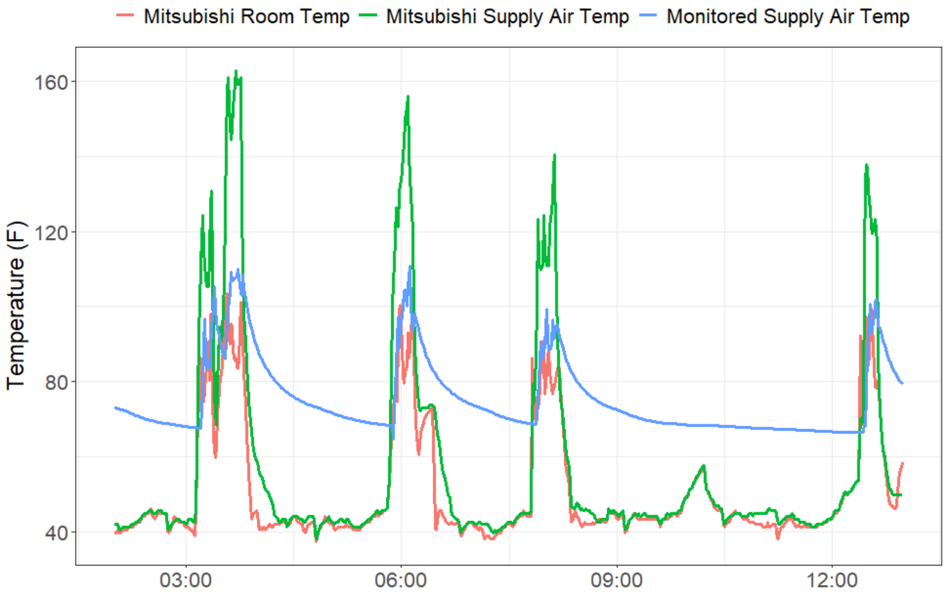


Figure 8: This plot compares the Mitsubishi onboard measurement of supply and room air temperature with our supply air temperature measurement for a single guest room on April 21^{st} 2021.

Coefficient of Performance

At Perry, we also made measurements to calculate the Coefficient of Performance (COP) of the VRF system. The definition of the COP for heat pumps is defined by the following equation, where Q_{indoor} is the energy delivered (in heating) or removed (in cooling) from spaces served by the VRF system. W_{system} is the electrical input for the entire system (fans, compressors, branch selectors, defrost, etc).

$$COP = \frac{Q_{indoor}}{W_{system}}$$

For typical equipment, such as furnaces or boilers, the COP (efficiency) would typically be between 0.8-0.96. For electric resistance heat, the COP is 1. However, for heat pumps, the COP is typically significantly higher than 1 (typically 2 – 4).

Monitoring the COP on VRF systems is difficult. Measuring the input power to the system (W_{system}) is straightforward (see Table 3). Measuring the energy delivered or removed (Q_{indoor}) is not straightforward. There are two possible strategies to accomplish this. The first is a refrigerant-side approach where refrigerant temperature and refrigerant flow rate are measured. One barrier to this approach is that measuring flow rate can be difficult, as the refrigerant is frequently in a mixed phase state. Furthermore, this method is intrusive, requiring cutting into the system to install measurement equipment. This would be a significant risk for an owner/operator as it would likely void manufacturer warranty.

The second strategy is an airside approach, where the temperature and flow rate of the air are measured. The primary drawback with this approach is that measuring the flow rate and temperature of air can be challenging, especially in circumstances where minimal or no ductwork is present (common with VRF system installations). However, this method is minimally intrusive, a major benefit when compared to the refrigerant side approach. Our research relied on airside measurements through two methods discussed below.

Indoor Airside Measurement. The primary strategy used for measuring the energy delivered (Q_{indoor}) was an indoor airside measurement. This involved measuring the energy delivered (or removed) by each indoor unit associated with a single outdoor unit (in this case, Stafford's Perry VRF-1). This method can be expensive, as it requires individual airflow measurements at all indoor units (and each fan speed) associated with the system that the COP is being measured on. In some cases, VRF systems can have 15-30 indoor units on a single outdoor unit. At Stafford's Perry hotel, VRF-1 had 8 indoor units, making this approach feasible.

Ideally, flow measurement and temperature logging equipment would be left in place for the duration of the study. However, it is not feasible to leave flow measurement equipment in place for the duration of this particular study. An alternative option we used for flow measurement was to make flow measurements at specific fan operating points to develop a correlation between measured fan power and flow rate. Pairing this air flow rate and fan power correlation with historic fan power measurements would provide historic air flow rate data.

Supply air was measured with temperature and relative humidity sensors mounted on the supply grill. Return air was measured with temperature and humidity sensors mounted in hidden locations (such as behind furniture).

Outdoor Airside Measurement. A secondary strategy used for measuring the energy delivered (Q_{indoor}) by the VRF system was an outdoor airside measurement. This strategy relies on the following thermodynamic relationship to determine Q_{indoor}, where $Q_{outdoor}$ is the energy rejected (or absorbed) by the outdoor unit and W_{system} is the energy input to the system.

$$Q_{indoor} = Q_{outdoor} + W_{system}$$

Based on this relationship, it is possible to determine Q_{indoor} by measuring $Q_{outdoor}$ and W_{system}. The measurement of $Q_{outdoor}$ requires measuring the inlet and outlet temperature at the outdoor unit, as well as the flow rate. The primary advantage of this strategy is that it minimizes the number of flow measurements required: one outdoor unit versus potentially many indoor units. Like the indoor air flow rate measurement, a correlation is developed between air flow rate and input power. There are several challenges to this strategy. The first is that unlike the indoor fans which can be manually set in specific operating modes, the outdoor fan is not controllable, making measurements at several different operating conditions difficult as the fan can rapidly change operating points (on the time scale of seconds). The second challenge is that it that in most scenarios, it is not possible to measure the components within the outdoor unit separately (compressor power, fan power). The circuitry design within the outdoor unit brings the input power to an inverter board, converting from AC power to DC power before the individual components. There is also additional risk (warranty) and complexity in opening a sealed unit and attempting measurements.

A final drawback to the outdoor airside measurement is that it is unable to capture the benefit of when the system is in heat recovery mode (providing both heating and cooling). In this scenario, the VRF system should have a very high COP, as it is providing both heating and cooling and as a result, operating the outdoor unit at a reduced power level. Unfortunately, at these operating conditions, measuring at the outdoor unit does not quantify Q_{indoor} fully. Table 4 provides an example of this scenario.

Table 4: This table summarizes three different operating scenarios - heating, cooling and mixed mode operation and the resulting COP with two different measurement/calculation methods.

	Heating Energy	Cooling Energy	Total Energy Delivered	Outdoor Energy	Input Energy	COP based on outdoor	COP based on indoor
Cool Only	0	600	600	600	200	3	3
Heat Only	600	0	600	600	200	3	3
Mixed	400	200	600	200	67	3	9

Stafford's Perry Hotel

Slipstream partnered with Bear River Electric to complete the monitoring equipment install on December 16th, 2020. E-Gauges with current transducers were installed in the electric power panels to measure the four outdoor condenser units (VRF-1, VRF-2, VRF-3, and VRF-4), all 32 indoor unit circuits, the four branch controllers, and the makeup air unit systems, including the ERV fan, makeup air unit fan, and makeup air condenser unit. Figure 9 shows an example eGauge and current transducers installation in an electric panel.

Figure 9: eGauge and current transducers installed in an electric panel.

In addition to power measurements of the VRF and MAU system, the electrician also installed temperature and humidity loggers in each guest room as well as the corridors on levels 3 and 4. In-room temperature loggers were attached to the back of furniture, as shown in Figure 10. Typical hallway temperature logger installation is shown in Figure 11. Room temperature and humidity measurements were recorded to analyze the thermal comfort related to maintaining setpoints. Hallway temperature measurement were taken to further understand the potential impact and interaction between the MAU system and VRF systems.

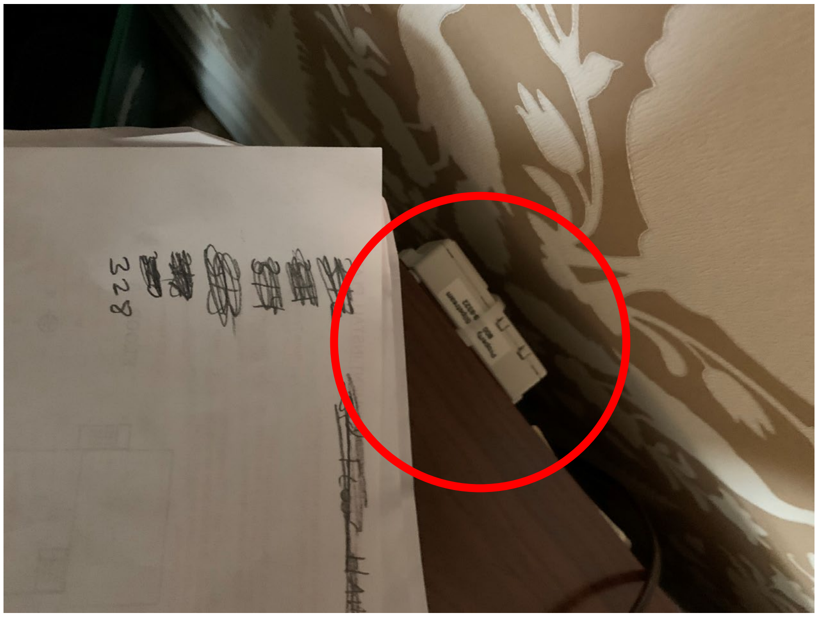


Figure 10: Hobo temperature logger affixed to back of desk.

Figure 11: Typical hallway temperature logger installation.

In addition to the base set of temperature measurements (each guest room and hallway temperature), we also installed additional temperature loggers required for approximating the heating and cooling COP. Slipstream installed supply air temperature and humidity loggers in the eight guest rooms served by VRF-1. These loggers were placed directly over the supply air grilles, as shown in Figure 12.

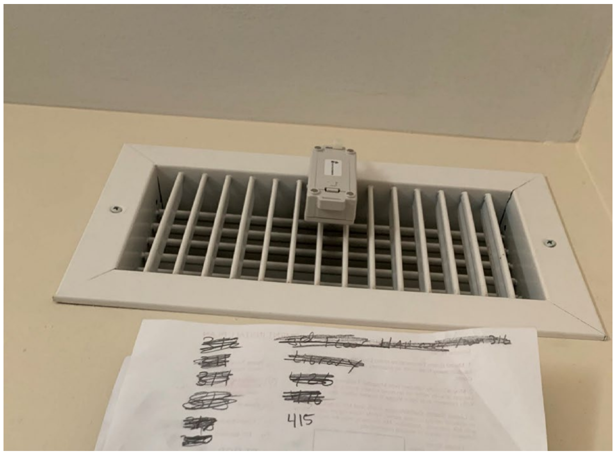


Figure 12: Temperature and humidity logger placed to capture the supply air temperature of the VRF indoor unit in a guest room.

Slipstream conducted an additional site visit in September 2021 to the Stafford’s Perry Hotel. At this site visit, our project team measure air flow at the 8 indoor units served by VRF-1[1]. As discussed previously, this additional dataset was required for the calculation of the COP of VRF-1. At each indoor unit, our project team used a TrueFlow airflow measurement device to measure the flow rate at all 3 available fan speeds (low, medium, high). The exact time of each flow measurement was recorded to allow the project team to align the flow measurement with the power measurement. Figure 13 shows the TrueFlow air flow measurement device and Figure 14 shows the air flow measurement. We also used a flow hood to spot check our air flow measurements and found general agreement between the flow hood and TrueFlow (within 10%).

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[1] Our project team was unable to access one of the 8 rooms, and therefore, only 7 measurements were made. The 8th room measurements were developed from the average of the measured rooms.

Figure 13: TrueFlow measurement device mounted in a box.

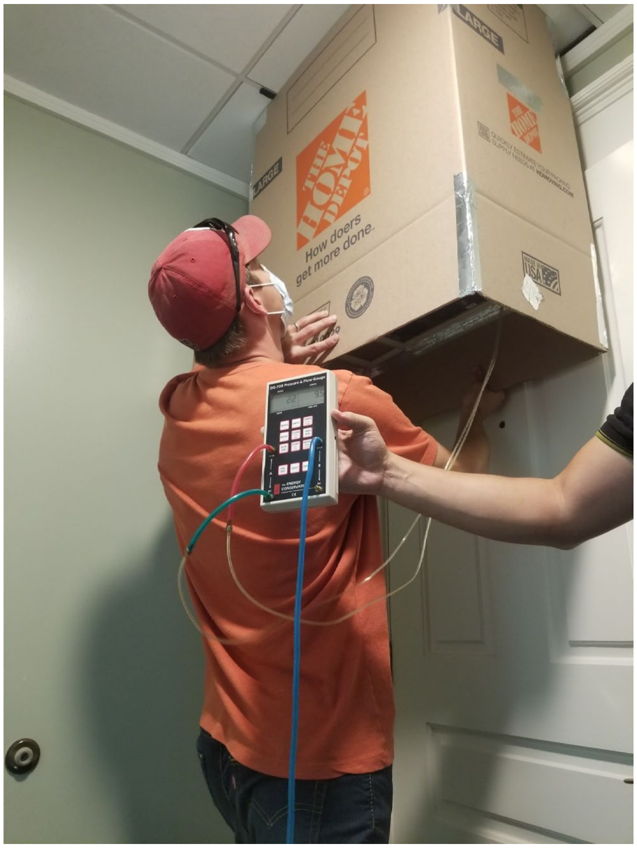

Figure 14: Making a flow measurement with the TrueFlow.

Our project team also attempted to make additional measurements on the outdoor unit to use as a spot check against our indoor airside measurement approach (Figure 15). As previously discussed, temperature and airflow measurements on the outdoor unit are an additional method to calculating the system coefficient of performance. We used eight hobo temperature loggers to measure the intake air temperature. A sample mounting is shown in Figure 16. Two temperature loggers were used to capture the outlet temperature from the top of the outdoor unit. We created a traverse and used a hot wire anemometer to make velocity measurements. Air velocity (ft/s) can be translated to air flow rate (cfm) by factoring in the cross-sectional area that the measurement is taken at. Both the temperature loggers and traverse locations are shown in Figure 17.

Figure 15: VRF-1 at Stafford's Perry hotel where outdoor airside measurements are being made.

Figure 16: Intake air temperatures on outdoor unit.

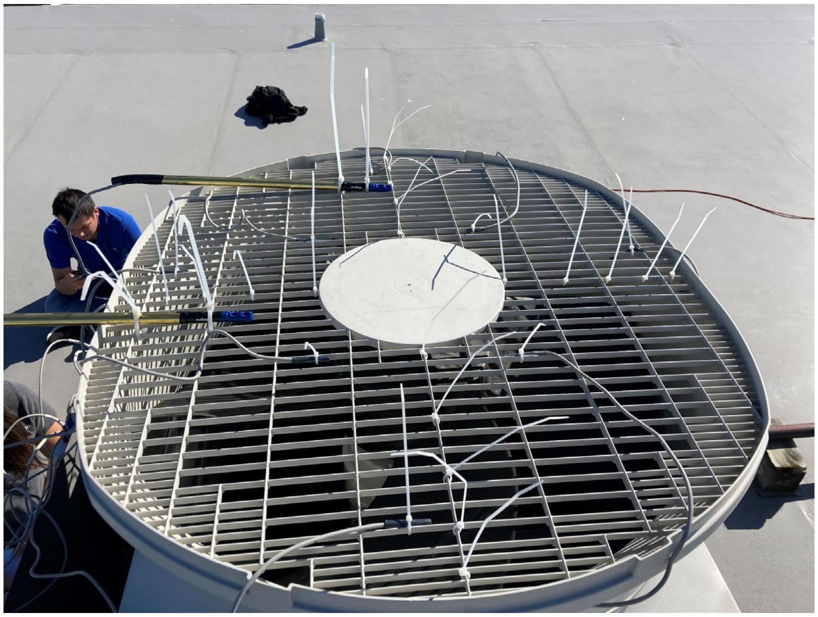

Figure 17: Outlet of outdoor unit. Two temperature probes are used to capture temperature. Zip ties mark traverse locations where velocity measures are to be made with hot wire anemometer.

After setting up the traverse locations and temperature logging equipment, our team had significant challenges recording velocity with the hot wire anemometer. As the outdoor fan cannot be controlled manually, our team attempted to force it into running at various speeds by controlling 6 of the associated indoor units. A team member set 6 of 8 rooms to a high heating setpoint to force the system to run at high speed. However, when trying to make the air velocity measurements, our team found it difficult to complete the velocity traverse in sufficient time before the fan speed would change. As a result, developing a full traverse at several different operating points was not possible. As this was a secondary method to capture the COP, to be used as a spot check, our team did not capture enough data to calculate the COP based on the outdoor unit.

The energy and temperature monitoring plan is included in *Appendix E: Site Monitoring Plan – Stafford Perry*. The air flow measurement monitoring plan is included in *Appendix F: Air Flow Measurement Plan – Stafford's Perry*.

Drury Inn & Suites

Slipstream partnered with Circuit Electric to install the monitoring equipment on February 11th, 2021. Based on the size of the hotel and available budget, Slipstream chose to focus monitoring on a sample of the building, floors 6 and 7 (64 total guest rooms). eGauges were installed on both dedicated outside air units (ERU-1 and -2, ERCU-1 and -2) which serve the entire hotel. eGauges were installed on the VRF systems which serve floors 6 and 7, 6A/6B and 7A/7B, as well as all associated indoor units. Lastly, based on the placement of our eGauges in electrical panel DH7, our team captured all 7 VRF condenser unit pairs. An eGauge installation is shown in Figure 18.

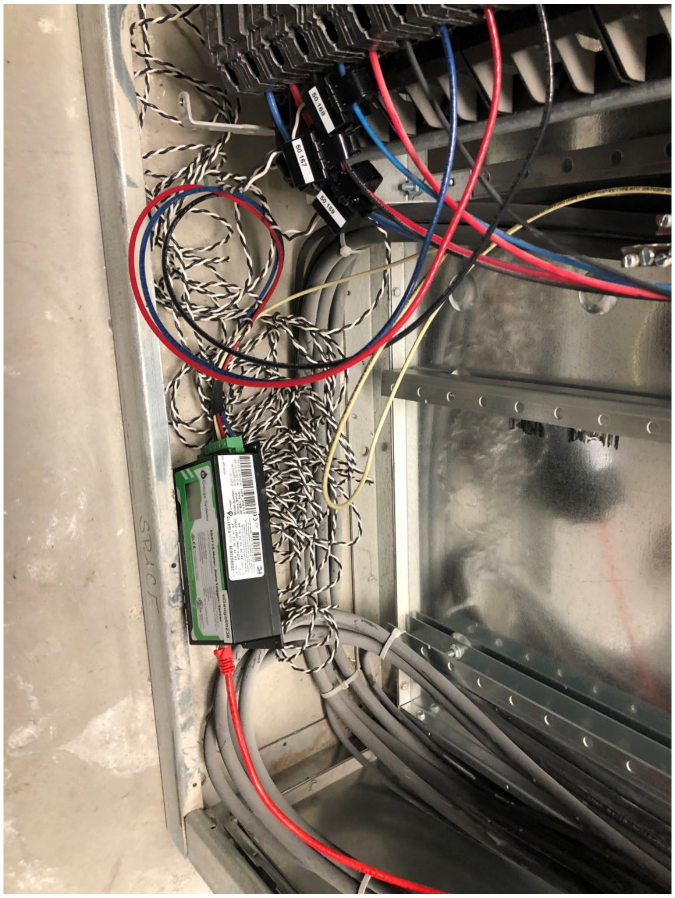

Figure 18: Sample eGauge and CT installation in electrical panel at Drury.

In addition to monitoring the power of the VRF systems and MAUs, Slipstream also installed temperature and humidity loggers in a sample of 16 rooms: eight on level 6 and eight on level 7. These loggers were installed behind furniture and were used to monitor the room air temperature, shown in Figure 19. Our team also installed temperature loggers to monitor both the supply air temperature from the VRF system, but also the supply air temperature from the make up air system. A sample of eight rooms (four on each floor) were selected for this supply air measurement. This sample was a subset of the 16 rooms that received room air temperature monitoring. Supply air temperature measurement were made with hobo loggers installed inside of supply air grilles, shown in Figure 20.

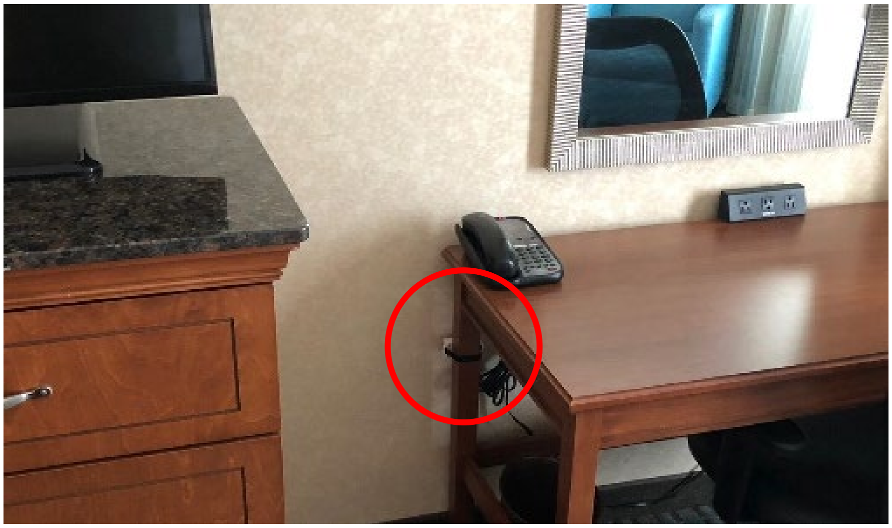

Figure 19: Sample Hobo temperature logger installation behind desk at Drury.

Figure 20: Sample Hobo temperature logger install in MAU supply duct at Drury.

The monitoring plan is included in *Appendix F: Site Monitoring Plan – Drury*.

Interviewing

At each site, we also conducted interviews with the building owner or operator. The interview was designed to help our project team understand the satisfaction with the VRF system in a variety of areas including, but not limited to, operating costs, maintenance, and overall experience. In addition, we also spent time discussing guest experience and comfort. Typically, it is also helpful to directly survey the occupants, but in this case, neither hotel wanted for the project team to directly survey the guests. As a result, our team relied on the building owners and operators to relay any typical challenges or complaints from guests, including the frequency. The interview guide is found in *Appendix G: Owner and Operator Interview Guide*.

Analysis and Calculation of Energy Usage, Savings and Coefficient of Performance

Measured data were first checked for gaps and extreme outliers (negative energy usage, for example). From there, basic statistics were examined for each system (VRF, MAU), including the average energy usage, energy usage versus outdoor temperature and peak usage. Where questionable, bad, or missing data was found, it was either resolved by more detailed investigation or removed from the set.

Energy. The first key metric we calculated from our data was the annual energy usage of the VRF systems. At both sites, we were able to capture one year of data, so an extrapolation was not required. At Perry, we were able to capture the total usage of all four VRF systems, including associated branch controllers and indoor units. At Drury, we captured only VRF system 6 and 7 (including all associated branch controllers and indoor units). As a result, for Drury, to estimate full system usage, we had to extrapolate the results from the 6th and 7th floors to the remainder of the building.

Energy savings. The next major metric to calculate was energy savings. As we did not have pre-VRF system data, we relied on calibrated energy modeling for both sites to calculate savings. Energy modeling was completed in eQuest 3.64, using manufacturer provided VRF performance curves. For Perry, the calibration captured only approximately 1/3 of the building (which contained the VRF systems). The model was calibrated to our sub-metered HVAC data (VRF and MAU). For Drury, the energy model was calibrated using both utility bill data and our sub-metered HVAC data. For inputs and parameters not defined by energy code (schedules, internal gains etc.), we used industry accepted modeling guidelines for reference, such as ASHRAE addendum AN (ASHRAE 2013) and the Department of Energy Commercial Building Prototype models (DOE 2020). Model calibration was done in compliance with ASHRAE Guideline 14 (ASHRAE Guideline 14 2014). Table 5 summarizes key parameters which were adjusted to calibrate the model.

Table 5: This table summarizes the modified parameters for calibration.

Parameter	Original Value	Calibrated Value
Roof Insulation	U-0.048	U-0.048
Mass Wall Insulation	U-0.09	U-0.141
Window U-value	U-0.57	U-0.57
Window SHGC	SHGC-0.39	SHGC-0.39
Infiltration ACH	1	3
Lighting Power Density	0.7 W/sqft	1.0 W/sqft
Equipment Power Density	0.25 W/sqft	0.75 W/sqft
Occupant Density	333 sqft/person	280 sqft/person
Occupancy Schedule	ASHRAE Addendum AN	Matched hotel occupancy pattern
Lighting/Misc Load Schedule	ASHRAE Addendum AN	Matched hotel occupancy pattern
VRF Fan Power	0.2 W/cfm	0.211 W/cfm
VRF Heat COP	3.49 COP	2.2 COP

VRF Cool EER	11.7 EER	10 EER
MAU Cool EER	11 EER	11 EER
MAU Heat Thermal Efficiency	80%	80%
MAU ERV Effectiveness	50%	50%
MAU Supply Fan Schedule	100% Constant volume	100% Constant volume

Once calibrated energy models were developed, we substituted the VRF HVAC system with a PTAC HVAC system, which is considered the baseline. In both models, baseline (PTAC) and proposed (VRF), the MAU system was unchanged. This results in energy savings calculated only from the PTAC replacement with VRF. The following equation summarizes the energy savings calculation:

$$Savings_{kWh} = E_{PTAC} - E_{VRF}$$

Coefficient of Performance. Lastly, we calculated the COP at Perry, VRF system "VRF-1":

$$COP_{VRF-1} = \frac{\sum_{1}^{8} Q_{indoor\ unit}}{W_{system}}$$

The total system power is

$$W_{system} = W_{outdoor\ unit} + W_{branch\ controller} + \sum_{1}^{8} W_{indoor\ unit}$$

Where $W_{outdoor\ unit}$ is the measured power of the outdoor unit, $W_{branch\ controller}$ is the measured power of the branch controller and $W_{indoor\ unit}$ is the measured power of an indoor unit. Each indoor unit was measured individually.

The energy delivered in each room by an indoor unit is defined by

$$Q_{indoor\ unit} = \dot{m}\left(h_{supply} - h_{return}\right)$$

The enthalpy of the supply and return air, h_{supply} and h_{return} respectively, are functions of temperature, pressure and relatively humidity. This calculation was done for each of the eight indoor units. Pressure was assumed to be constant.

The mass flow rate of the air, $\dot{m}$, was calculated using a correlation developed between air flow rate and measured power (at three points). A cubic root relationship was fit to the data, as defined by the following equation, and shown in Figure 21. This was conducted separately for each of the eight rooms[2].

$$\dot{m} = P^{1/3} + b$$

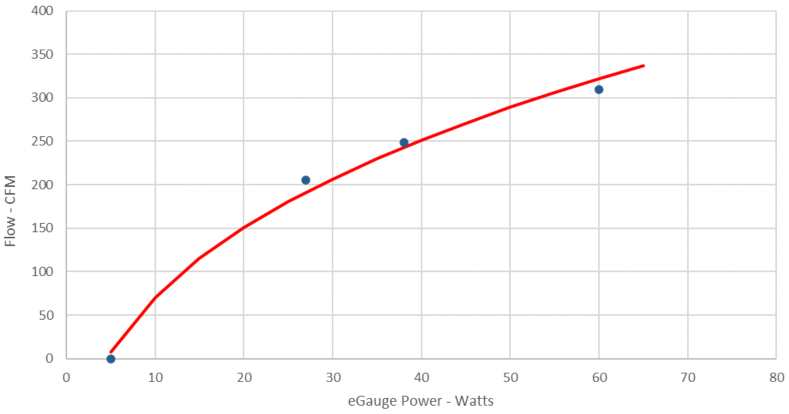

Figure 21: Curve fit of power and flow data.

Measurement Period

Our monitoring period varied between the two sites, based on when outreach was completed and when a site installation could be scheduled. Our target monitoring period for both sites was to capture as much of Winter 2020-2021 as possible. At Perry, installation occurred in mid-December 2020. At Drury, installation occurred in mid-February 2021. Given the late installation dates, we were able to negotiate extending the study period at both sites to include Winter 2021-2022. Figure 22 and Figure 23 show the outdoor temperatures seen at both sites during the monitoring period.

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[2] During our measurement visit, one of the eight rooms was occupied. As a result, we developed a flow vs power correlation based on the findings of the other 7 rooms.

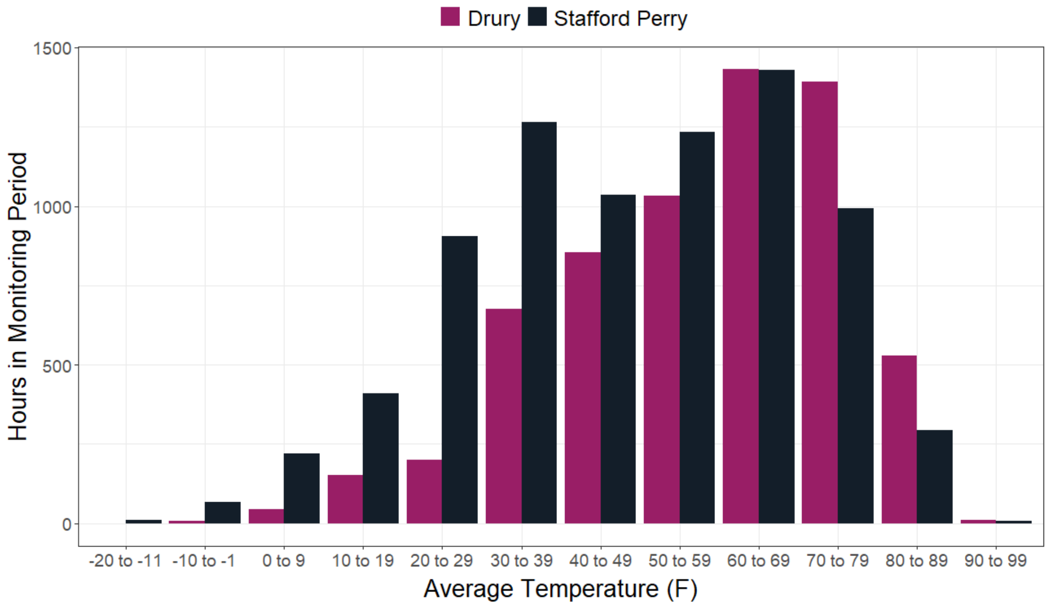

Figure 22: Binned average hourly outdoor air temperatures at each site during the course of the study.

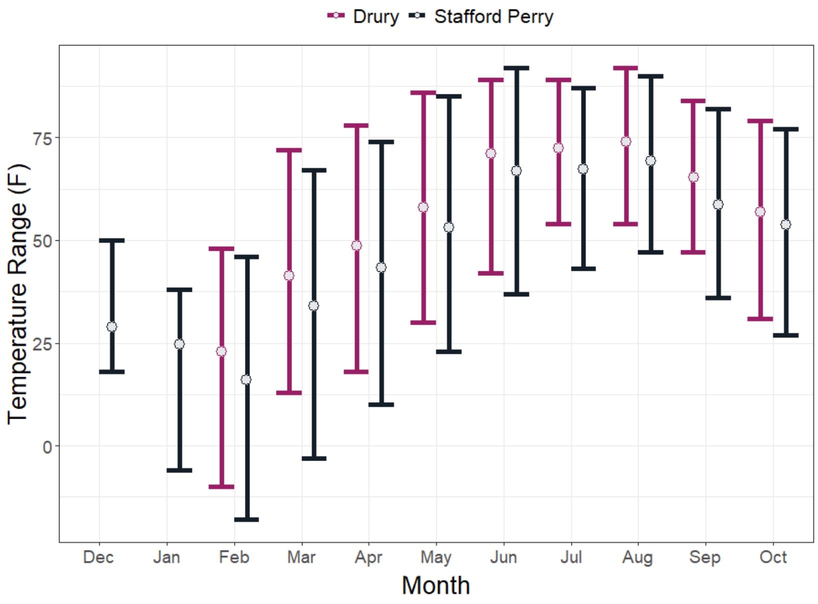

Figure 23: Monthly average temperatures (gray dots) and temperature extremes (bars) for each site.

RESULTS

The results of this study are discussed in the following sections, including (in order):

- general interview findings from our interviewing of stakeholders in Michigan
- energy, demand, and thermal performance
- economic results for both sites monitored
- owner and occupant comfort and satisfaction

INTERVIEWS

Owners

Slipstream staff interviewed nine building owners/operators for insights on their existing HVAC equipment and perceptions surrounding VRF systems. These building owners and operators did not currently own or operate buildings with VRF systems. Of the nine owners/operators, four were not familiar with VRF technology. All building owner/operators signaled the importance of system payback and most indicated that they wouldn't consider a project that had longer than a 3-5 year payback (e.g. one respondent received a bid for a VRF system with a 15-17 year payback and decided to not move forward). Most building owners/operators relied on a design engineering firm or HVAC contractor to determine their HVAC system selection and most were satisfied with the level of service they received. However, some shared how it can be difficult to get qualified contractors to make the trip to service their building in a rural location.

One respondent stated they would like to see it work in a cold climate and due to the strong winds (and extreme cold temperatures) would prefer to see a VRF installation at another building in their city before purchasing the system themselves. Our primary conclusion regarding operational concerns in cold climates was that VRF has had less traction in Western Michigan, meaning owners and operators have had less exposure to the successes of installed systems.

Maintenance was a big concern. A building owner/operator of a casino hotel that was familiar with VRF stated that his biggest concern was the “service-ability” of the system due to the extensive refrigerant piping that is required. He opted to install packaged terminal heat pumps (PTHPs) instead and was very satisfied with the quality of the space conditioning, the quick system payback and ease of servicing the units. Another respondent expressed concern moving from a central plant where there is one point of repair to VRF where there are many more points in the system that could require repair.

Slipstream spoke with one owner in northern Michigan considering VRF for their hotel building. They had expensive propane heating and an old building, making it an ideal application for a VRF system. They were mostly concerned with their existing air conditioning system and not being able to dehumidify the air enough. They have conducted multiple audits to improve their utility bills as well. Their largest barrier with the VRF system was its cost. They looked to MECA incentives to help improve the payback on the system but struggled with fuel switching restrictions on the incentives.

Manufacturers and Sales Representatives

Slipstream interviewed manufacturers and sales representatives from Daikin, Mitsubishi, LG, and Fujitsu about their products and the VRF work they have seen in the upper Midwest in recent years. One goal was to understand how well cold climate VRF systems work in this region. It was also important to understand any market barriers or market successes. Keeping mind throughout these discussions that there is inherent bias in such discussions with manufacturers selling a product.

All four representatives noted there is little to no independent field studies on the performance of the latest VRF technology. There was a clear need for independent data to show performance to help convince building owners and design and construction professionals the viability of the technology and how much it has advanced in the last 5 years. The representatives indicated a lack of consumer trust in the technology in cold climates, although that perception is improving as the VRF market expands.

All four representatives have noted an increase in VRF system use in the last few years, likely driven by the improved product performance, increased education and decreasing system costs. One Manufacturer claimed that the Wisconsin market for VRF increased 15% while another claimed a 50% increase in the last year. They also are projecting double digit increases over the next 5 to 10 years. These are significant market increases, however, the market still remains small compared to traditional gas-fired systems.

The manufacturers recommend installing VRF systems in a variety of commercial buildings, including hotels, mixed use developments, assisted living facilities, healthcare, schools, churches, and small offices. One manufacturer representative noted that a growing market for VRF in western Michigan is for indoor agriculture. One manufacturer felt that VRF is cost competitive with traditional HVAC systems at less than 200 tons of cooling, and that below 100 tons VRF is the best choice for energy efficiency. In addition to a reasonable option for new construction, VRF can also be easier to retrofit into old buildings as the indoor fan coil units take up less space than other systems and the refrigerant piping is small and easier to install in tight spaces than duct or hydronic pipe. Scenarios that are not favorable for VRF are large installations greater 200,000 ft^2 or buildings where individual zoning is not required.

The Fujitsu representative for Michigan said he believed that VRF costs 30% more than a traditional HVAC system. A Daikin representative noted that because VRF is a modular system, there are no cost benefits in scale as the building size increases. The cost per ton of a VRF system is largely fixed because of the limits on the size of each system due to refrigerant piping limitations. This makes it difficult for VRF to compete on large projects, where traditional boiler or chiller system costs per ton decrease as building size increases.

One of the previous challenges that all three VRF representatives highlighted was lack of education in the contractor and installer market. When a technology is not well understood, this leads to less recommendations for that system type by contractors or design firms. It also leads to increased costs as contractors estimate higher costs to address their uncertainties in installation and commissioning. All stated that over the last five years the pool of mechanical contractors installing VRF systems has grown considerably in large metro areas such as Detroit and Chicago, leading to more cost competitive pricing compared to other commercial HVAC systems. However, in western Michigan, there’s still a smaller pool of VRF installers. All manufacturer representatives agreed that increasing the awareness and comfort level with these systems at the contractor/installer/designer level will increase VRF adoption. Each manufacturer also provides service training for the Contractors and Owners to minimize this barrier.

Another decrease in cost is attributed to the use of new compression fittings for refrigerant piping such as Zoom Lock. Traditionally, copper refrigerant piping had to be brazed together, which is labor-intensive and requires skilled trade workers. Compression fittings are an alternative for many brazed joints which use a tool to compress a connector on the pipe. This results in faster and easier installation. Although faster, these fittings may lead to a greater chance for leaks if not installed correctly. One way to combat leaks in refrigerant lines is to leak test the system – which all three manufacturers offer and recommend. Leak testing is typically done by the installing contractor with input from the VRF manufacturer sales representative. Systems are leak tested at 400 psi for 600 hours.

The Daikin representatives noted the challenge of sizing VRF systems as compared to typical packaged rooftop units. There is much more additional cost to add capacity, requiring designers to be careful when selecting and sizing VRF systems. Oversized systems can lead to total system costs that are less competitive with traditional HVAC systems. So, proper system sizing is important. All three manufacturers interviewed currently help designers and contractors with system selection, sizing, and configuration on their projects.

All three also noted that ASHRAE 15 requirements for refrigerant volume can impact the refrigerant piping and VRF design. ASHRAE 15 limits for refrigerant usage are 26 pounds of system refrigerant per 1,000 cubic feet of room volume for any room that refrigerant passes through for standard buildings. This limits the size and length of piping available for a VRF system. For institutional facilities, such as healthcare, this limit decreases to 13 pounds per 1,000 cubic feet. VRF systems are successfully installed to meet these standards and manufacturers assist contractors and designers in overcoming design challenges.

Contractors

Slipstream interview two contractors in MECA territory to gain additional feedback on VRF systems and barriers from a contractor’s perspective. Both contractors had experience installing VRF systems and had been working on mini-split installations for the past few decades. These firms see VRF as the right tool for certain applications, but not a ‘one size fits all’ technology.

Between the two contractors, they have installed VRF at hospitals, schools, churches, hotels, resorts, and municipal buildings. One contractor said they often use the system for historical work because of the ease of installing refrigerant pipe compared to air or water systems. One contractor mostly focused on installations in the Detroit area, and said there were not many installations outside of Detroit, although he has done VRF work as far as Traverse City and Grand Rapids. The other contractor installed most of their systems in southwestern lower peninsula. One contractor stated that there were not as many contractors in western Michigan as there were some poor installs in the early 2010s that pushed contractors and engineers away from VRF technology.

Both contractors felt that most owners they have installed VRF systems for are happy with their systems. The contractors’ concerns with VRF was service if the system went down. Losing a condensing unit means that the section served by that unit are without heating or cooling as long as that unit is down. If the install is done correctly, as both contractors said their companies always do, there usually aren't issues.

Both contractors stressed the importance of training. One contractor makes sure all his workers are trained and certified to the fullest extent by the manufacturers, although he does state most installers are only required to take a four day training course. Mitsubishi requires more training to become a Diamond Contractor which gives contractor's access to a better Mitsubishi warranty.

Both Contractors offer training to owners on the use and maintenance of the VRF system, similar to training for any other HVAC system. The contractors take a day to go through physical systems, the controls, operation, and maintenance. One contractor noted they tell owners, "don't touch things you don't understand" as the VRF systems are complicated. Both said maintenance was easy as it's just changing filters. However, servicing for a VRF system is more expensive.

Some of the main barriers identified for VRF were:

Technological knowledge required by installers. VRF systems are complex and require error-free installation to be successful. Installers must be familiar with the technology and the specific manufacturer's system that is being installed. One contractor felt "99% of issues" are due to poor install. He indicated in his experience, the most common reasons for VRF system issues are due to poor purging of refrigerant lines and other installation issues.

Troubleshooting and Diagnosing Problems. VRF systems can be challenging to diagnose and troubleshoot. These systems are complicated and "black box" by nature, making traditional diagnosing and troubleshooting procedures less effective. This often means that manufacturer representative must diagnose the system, and that can lead to delays in service and more time for replacement, especially in rural Michigan. Because of this, time spent troubleshooting can be significantly longer than most traditional HVAC systems. In addition, should a system be non-operational, there is no heating or cooling for the areas served by that system.

Upfront costs. As identified in interviews of all stakeholders, VRF systems can carry a premium cost in some building types and sizes (though not all). For these applications, this limits the customer base to those willing to wait for longer paybacks or those that have a significant preference for one of the functional features of VRF (like small form factor or flexibility). To help reduce the high upfront costs, one manufacturer tries to install cold-climate systems to eliminate the need for supplemental heat which adds supplemental cost.

OWNER AND OCCUPANT SATISFACTION

Neither site wanted Slipstream to ask questions or survey guests, but each site did provide their experience with occupant satisfaction in their interviews.

Stafford's Perry Hotel's primary goal with the VRF system was to provide a new HVAC system that hotel guests could control room temperature. Stafford's Perry Hotel's vice president, Reginald Smith, stated he was "very satisfied" with how the system has performed in terms of occupant comfort. With their previous rooftop unit system, their were frequent guest complaints that it was too hot, too humid, or too cold. The number of guest complaints have gone down significantly. "We solved the problem, from my standpoint, [VRF] was a home run".

In addition to the reduction in hot and cold calls, Stafford's Perry hotel staff also note that the system is very quiet compared to their existing system, something guests also like compared to traditional noisy wall or window A/C units.

Mr. Smith noted that the staff and guests have had to adjust to the controls of the VRF system. The thermostats provided offer a number of ways to control the heating, cooling, and fan for the room. Mr. Smith says that all those options overwhelm guests, and guests don't want the other functions, just "hot or cold". As Slipstream was leaving the hotel, a guest told staff he was having difficulty setting the heat higher at the thermostat.

Another learning process was that the VRF system is a bit slower to respond then a traditional PTAC hotel unit. Guests are used to the system starting right away. The VRF system offers better temperature stability but not necessarily that confirmation that's it's on. Mr. Smith noticed that guests are happiest when they explain to operate the system, you just "set it and forget it."

Gregg Boyer, the director of maintenance at Drury Hotels, noted their Grand Rapids hotel has not had any issues with hot or cold calls, even in winter, which is somewhat surprising as the Grand Rapids hotel is their northernmost chain with an air-source VRF system. "Inability to heat has never been an issue in Grand Rapids".

THERMAL PERFORMANCE

One of the key questions surrounding VRF systems in cold climates is their ability to maintain desired set points during the coldest periods of the year. In this section, we use our temperature data to analyze the ability of the VRF system to maintain set point temperatures.

As outlined in the *Measurement* section, we measured temperature and relative humidity in each guest room, typically behind a fixed piece of furniture at 3' from the floor. One drawback to this strategy is that it does not provide a true average of the temperature in the room, as multiple points locations in the room would need to monitor, including at multiple heights. However, even with a single temperature measurement point, insights can be drawn into the system's ability to keep space temperatures at generally levels. In addition to our single data logger, we utilized the Mitsubishi Maintenance tool to trend guest room temperatures as a secondary point (measured from the thermostat, typically located on an interior wall at 4-5'). We found a significant difference in the measurement of temperature between our sensor and the Mitsubishi wall thermostat, as shown in Figure 24. Based on differences between the sensors and locations, we found on average a difference of 2-3°F between our sensor and the Mitsubishi wall mounted thermostat. As Mitsubishi wall thermostat controls the VRF system, we will use that temperature reading when analyzing how closely the room was being held to desired setpoints.

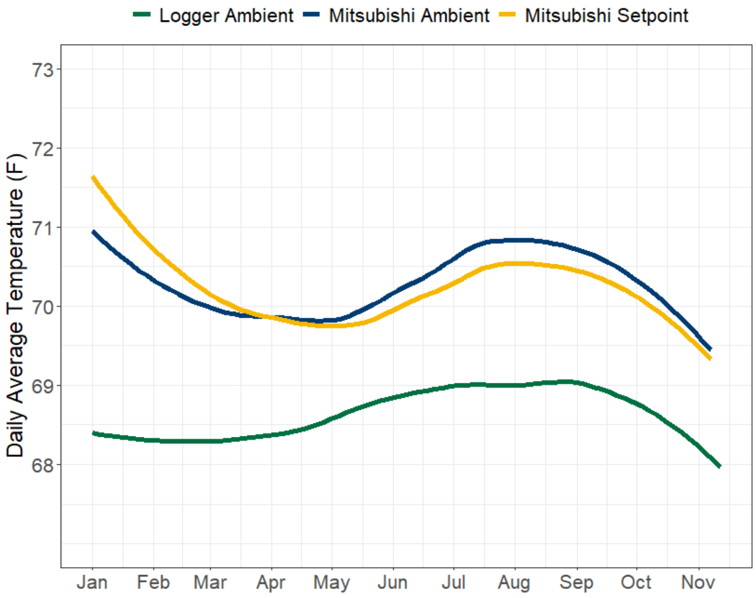

Figure 24: Comparison of our temperature measurements and Mitsubishi wall thermostat measurements.

At Perry, in the eight rooms monitored on VRF-1, indoor air temperatures generally range between 68°F and 75°F over the course of the year, regardless of outdoor temperature, as shown in Figure 25. We did not see a significant correlation between space temperatures and outdoor temperatures, an indication that the system is able to maintain desired setpoints.

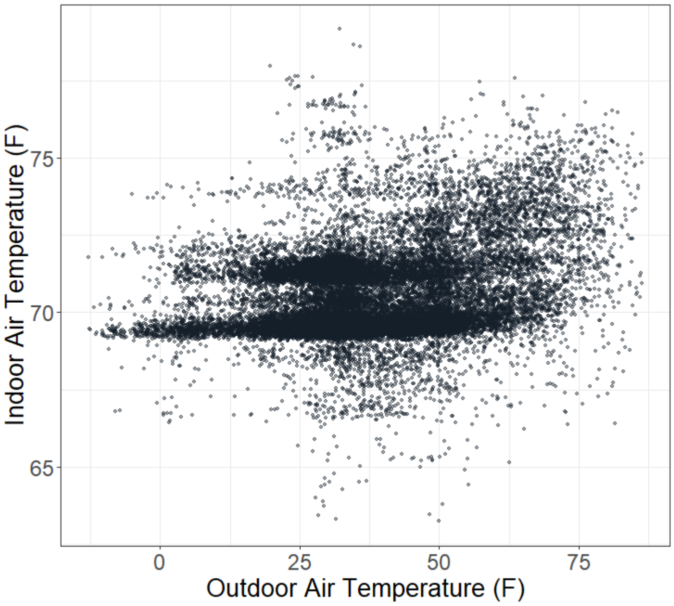

Figure 25: Guest room temperatures plotted against outdoor air temperature at the Perry. Time resolution is 1 hour.

While most hours fell between 68°F and 75°F, our data also found several hours which fell below 65°F. We investigated these moments individually to determine if this was a result of user input or system limitations. We found that these cases were most frequently caused by infrequent low thermostat setpoints. To further look at the ability of the system to maintain setpoints, we looked at the difference between the room temperature and thermostat setpoint, shown in Figure 26.

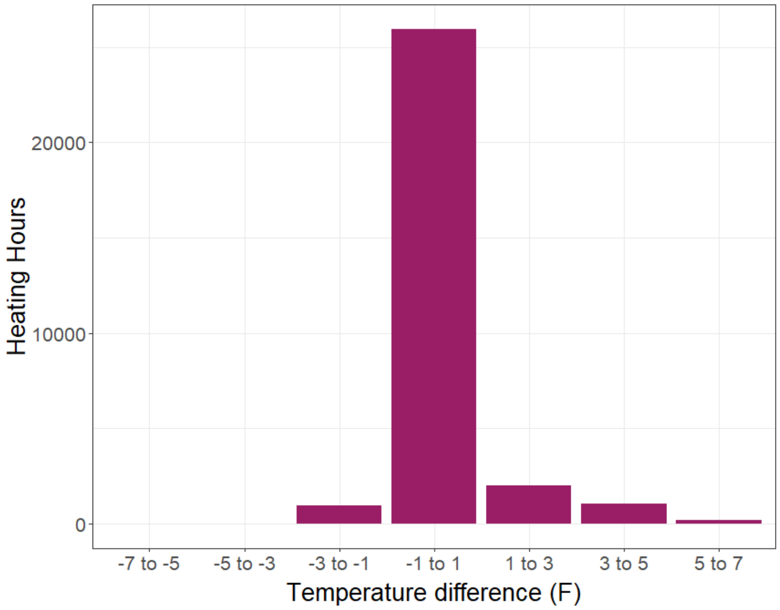

Figure 26: This figure shows the difference between thermostat setpoint and room temperature during heating operation (measured with Mitsubishi thermostat) at Perry. Data is binned by temperature difference based on hourly intervals.

Our data found at Perry, the difference between the thermostat setpoint and thermostat reading was most frequently +/- 1 degree of the desired setpoint during the heating season. Note that the above graph excludes times when the setpoint was changed.

Daily Temperature Profiles

In addition to looking at the heating season as a whole we also looked at several select days of the year. Figure 27 shows the VRF operation for room 311 at Perry on February 15th, when it was 5°F outside for nearly 6 hours. The supply air temperature spikes show when the VRF unit activated to heat the space. At outdoor air temperatures of 5°F, the supply air temperature is approximately 15°F colder than when the outdoor air temperature is 15°F. As VRF system suffer reduced capacity at the coldest ambient conditions, the direct result is reduced supply air temperatures. However, even with reduced supply air temperatures, the room is kept at the desired setpoint throughout the day. In addition, at approximately 10:00 AM, there is a 4°F increase in thermostat setpoint. The VRF system brings the room temperature to within 0.5°F of the setpoint over the course of 80 minutes.

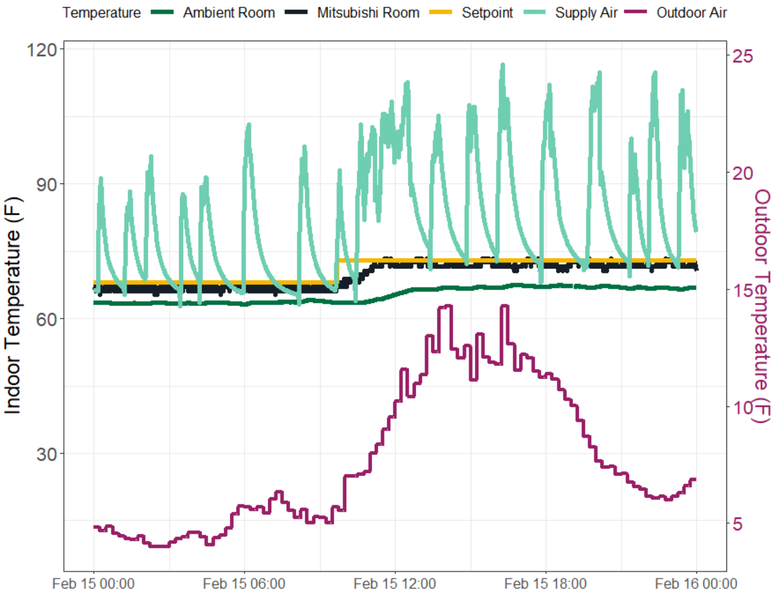

Figure 27: Temperatures in Room 311 on February 15th at Perry. Outdoor temperatures ranged from 3°F to 14°F.

We also looked at day when outdoor temperatures were milder. Figure 28 shows the temperature profiles in Room 311 on March 16th. We found that the VRF system was able to control the room temperature to the desired setpoint of 67°F until an occupant made a setpoint change at approximately 10:00 AM to 72°F. The system took approximately 80 minutes to raise the room temperature from 67°F to 72°F.

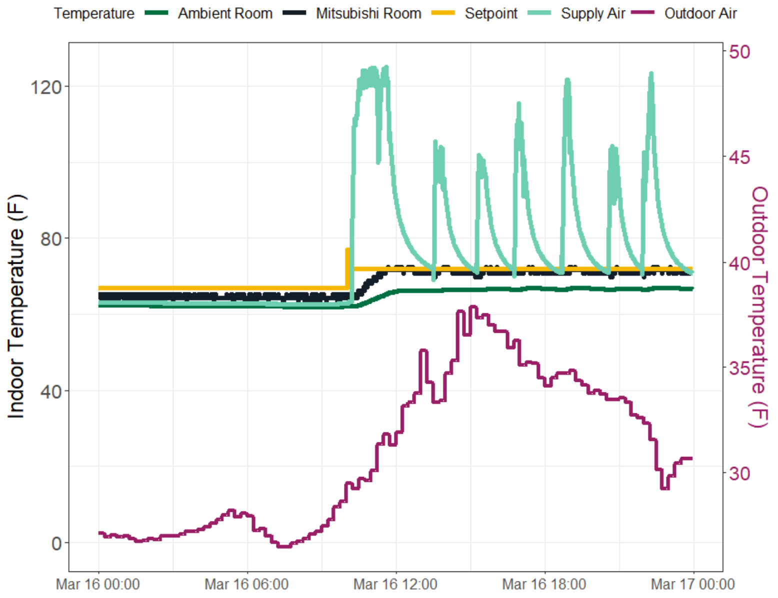

Figure 28: Temperatures in Room 311 on March 16th at Perry. Outdoor temperatures ranged from 30-40°F. Room setpoint temperature was 67° and 72°F.

The VRF system at Perry does not utilize supplemental heat at the outdoor unit or auxiliary heat in the guest rooms. However, the Makeup Air unit serving the hallway (not directly serving each room) was sized to provide additional heat in an emergency. Figure 29 shows the temperatures within the corridors are below 75 degrees for most heating hours. As corridor temperatures are close to the room temperatures (generally between 65 and 75), we expect that the corridor/MAU system is not contributing significant heating to the guest rooms; the VRF system is providing a vast majority of the guest room heat.

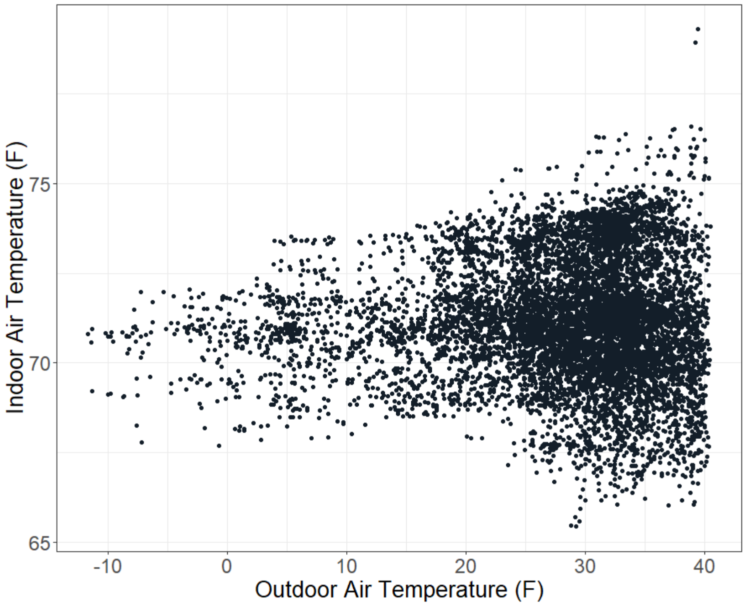

Figure 29: Temperatures in the hallway on floors 3 and 4 of Perry that are served by the VRF systems.

We also looked at more temperate days, when outdoor temperatures were between 40-70°F, typical of a shoulder season day. Figure 30 shows the temperature profiles in Room 311 on October 1st. On this day, Room 311 was operating in cooling mode (with a set point of 69°F), evident by supply air temperatures near 45-50°F. For a short period of time, the setpoint was reduced to 67°F. During the middle of the day, the setpoint was set to 72°F, allowing the room temperature to slowly drift upward without the use of the VRF system. At approximately 4:00 PM, the system ran intermittently to maintain the setpoint of 72°F. At approximately 5:00 PM, the setpoint was reduced to 69°F and the system responded to meet that input over 40 minutes. Similarly to the two heating days, we see the VRF system tightly controlling the room temperature to the setpoint.

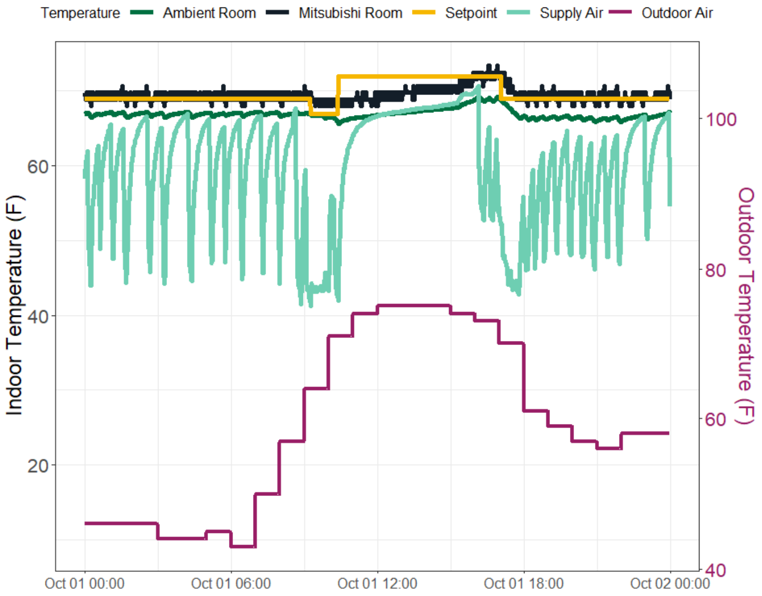

Figure 30: Temperatures in Room 311 on October 1st at Perry. Outdoor temperatures ranged from 43°F-75°F.

We also looked at day when outdoor temperatures reached as high as 85°F. Figure 31 shows the temperature profiles in Room 311 on June 6th. On this day, the setpoint begins at 72°F before being increased to 73°F followed by 74°F. In all cases, the VRF system operates as needed to maintain the desired setpoint.

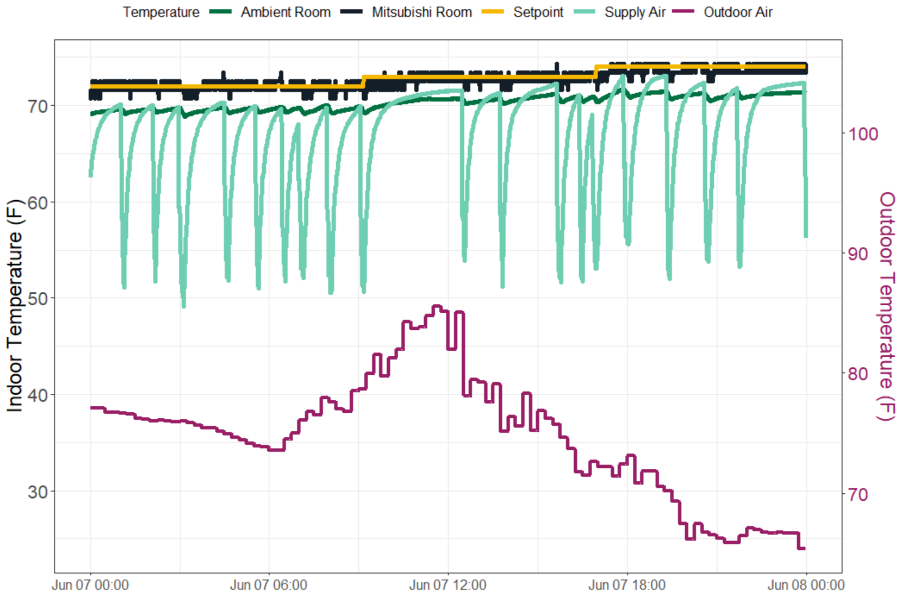

Figure 31: Temperatures in Room 311 on June 6th at Perry. Outdoor temperatures ranged from 65°F-86°F.

We also looked at room by room temperature data for Drury. These rooms followed similar trends to Perry. Slipstream did not have access to the VRF control system to verify temperature setpoint, thermostat reading or system operation. However, Figure 32 shows the temperature for a guest room maintaining between 65 and 70 degrees. The Drury makeup air unit, which is ducted directly to the room, is providing neutral air at 70 degrees, and at 35 cfm, is not significantly contributing to heating the space.

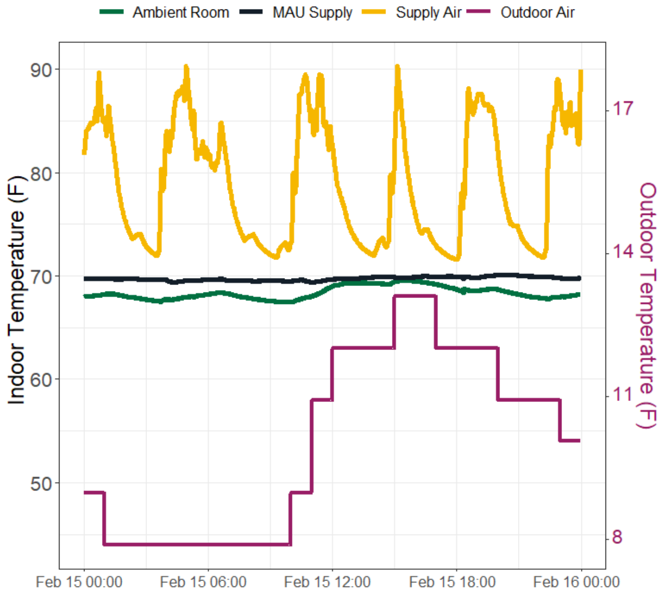

Figure 32: Temperatures for Room 614 at Drury. Three days are shown, February 15th.

ENERGY AND DEMAND CONSUMPTION

We used our data to look at the energy and demand characteristics of the VRF systems monitored at Perry and Drury. The first view of the data is the total system energy consumption over the course of the monitoring period, shown in Figure 33. At Perry, the dominating trend is that as temperatures decrease during the heating season, energy consumption by the system increases to maintain setpoints. This is intuitive, as the difference between the setpoint and outdoor ambient temperature in winter could be as much as 70°F, while in the summer the difference can be as little as 30°F (albeit summer loads also include a latent component and internal gains). At Drury, the VRF system shows a much flatter usage profile over the course of the monitoring period.

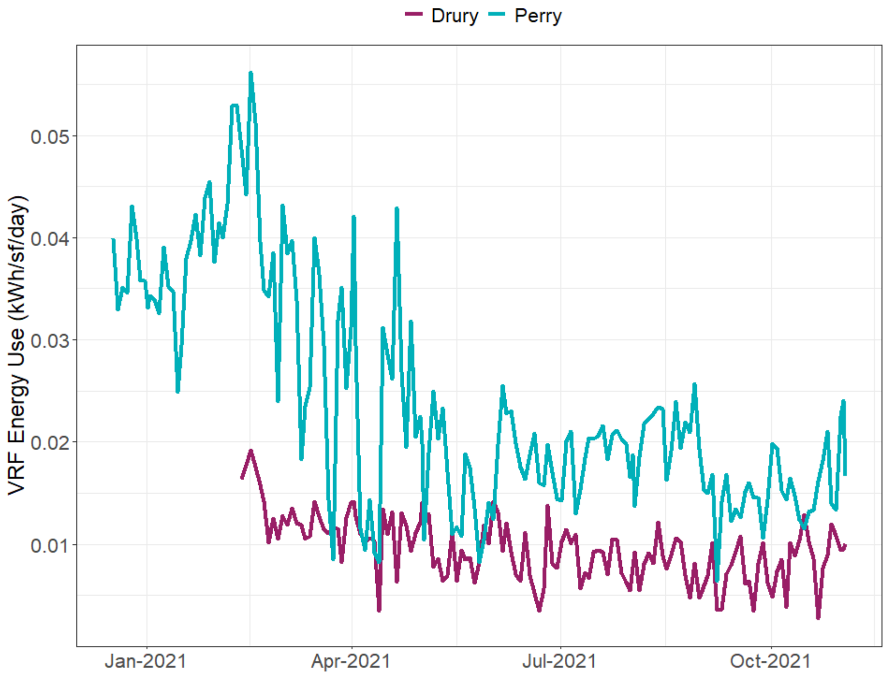

Figure 33: Total daily energy usage (kWh) for VRF systems at Perry. Drury data represents VRF system serving floor 6.

We also plotted the system energy consumption versus outdoor air temperature, to further analyze the impact of outdoor air temperature on system energy consumption. Figure 34 shows this trend for Perry and Drury, respectively. At Perry, we saw a very distinct trend between heating and cooling. As temperature decreases below 50°F, overall system energy use increases to meet the heating load. As temperature increases beyond 60°F, energy consumption increases to meet the cooling load. At Drury, the trend was less clear. Below 35°F, energy consumption does increase with decreasing temperature. However, above 35°F, there is no discernable energy consumption trend as a function of increasing outdoor temperature. We believe this could be for several reasons. First, the building construction is newer and should have greatly reduced heating and cooling loads driven by outdoor conditions. Second, much of the data was recorded during the COVID-19 pandemic, where hotels saw significantly reduced occupancy.

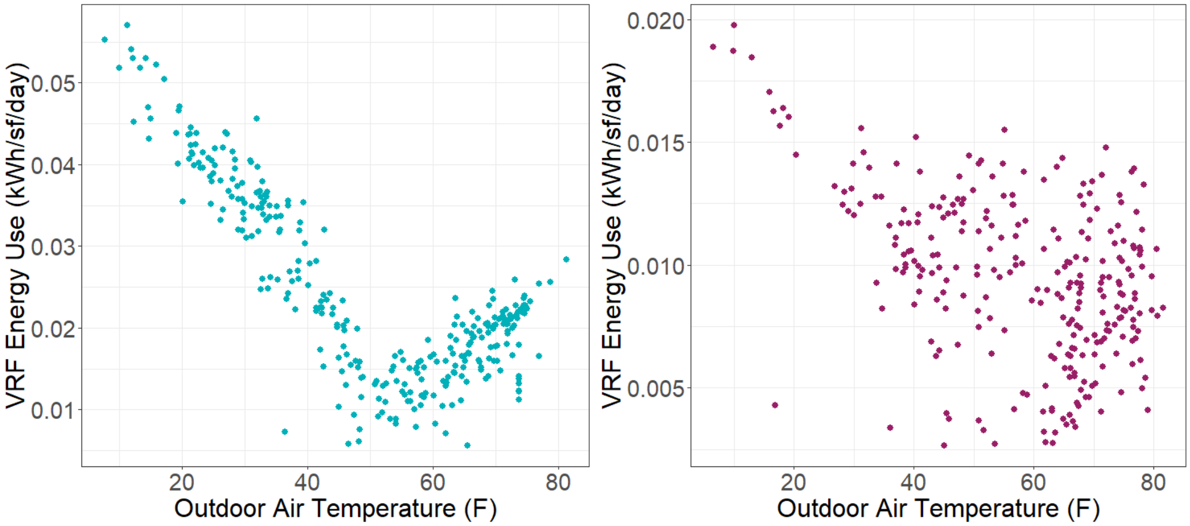

Figure 34: Daily energy usage of VRF systems at Perry (left) and Drury (right) versus average daily outdoor air temperature. As temperature decreases, energy usage increases.

Component Energy Use

We also looked at the impact of each component of the VRF system, including the outdoor condenser, indoor fan coil units and defrost. Figure 35 shows the daily average energy use per square foot over the monitoring period.

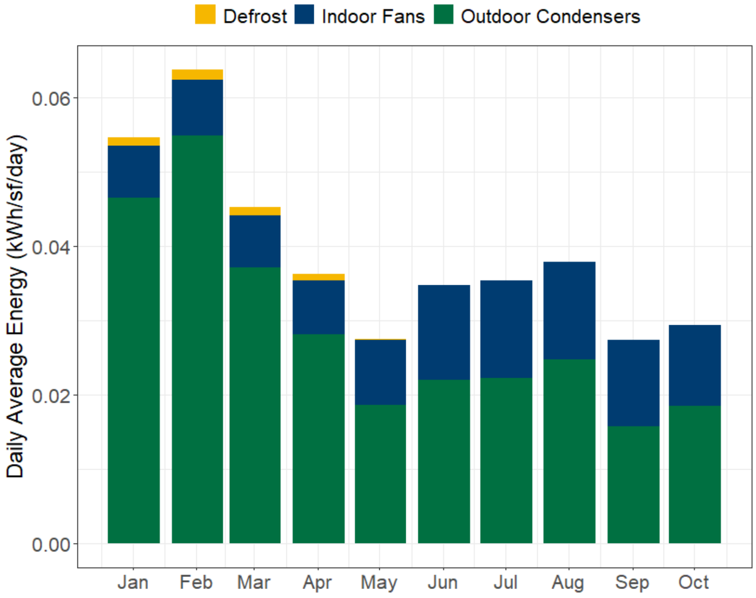

Figure 35: Energy use by VRF component during each month at Perry.

Utility Bill Analysis

At both sites we attained historic utility bill data for both gas and electric usage. The utility bill data was weather-normalized to account for the effect of year-to-year temperature variation on building energy use. Weather normalization models are fit to each building to capture their unique energy-temperature relationship. These models disaggregate predicted heating, cooling, and baseload energy consumption for each site, which informs building energy models.

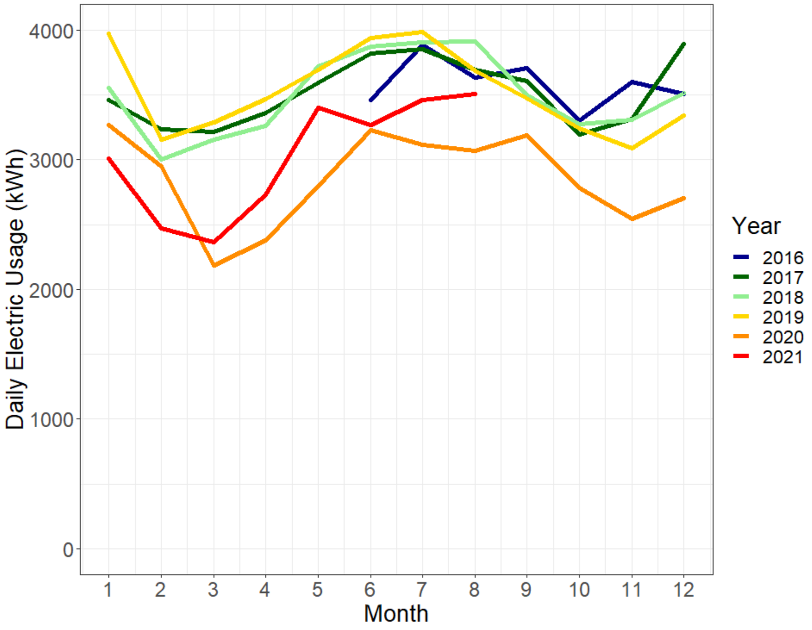

Figure 36: Utility bill analysis (electricity) at Drury for years 2016-2021. 2020 and 2021 show the impact of the COVID-19 pandemic on usage.

Our analysis of the electricity usage (Figure 36) at Drury found consistent usage from 2016 – 2019. In March of 2020, the COVID-19 pandemic had an impact on usage, continuing through August of 2021. The estimated reduction in daily electric bills due to the pandemic was 617 kWh. The percent reduction of normalized electric usage due to the pandemic was 15-19% of total usage.

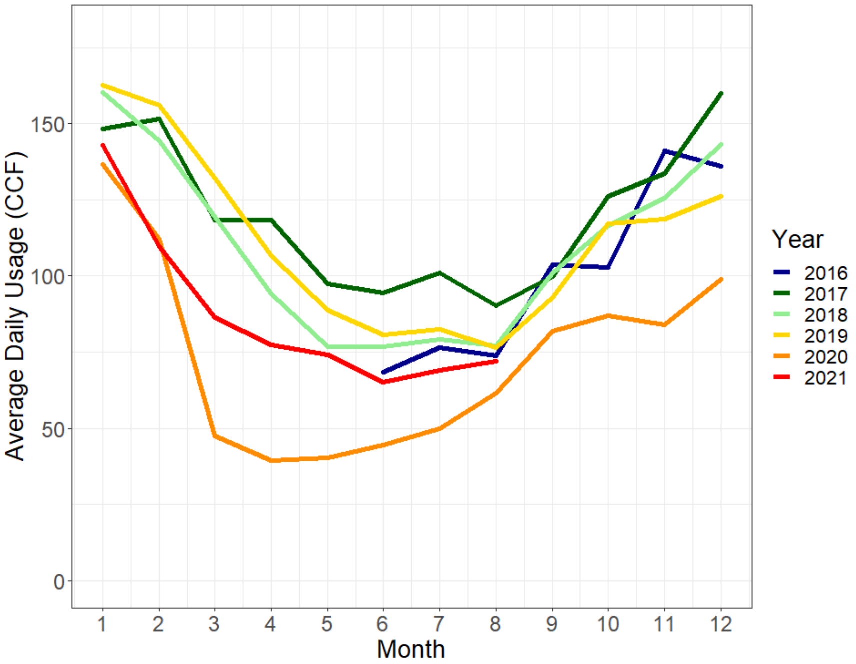

Figure 37: Utility bill analysis (natural gas) at Drury for years 2016-2021. 2020 and 2021 show the impact of the COVID-19 pandemic on usage.

Our analysis also reviewed the gas usage (Figure 37) at Drury for the DOAS. Like the electric usage, we found relatively consistent gas usage from 2016 – 2019. In March of 2020, the COVID-19 pandemic had an impact on usage, continuing through April of 2021. The estimated reduction in daily gas bills due to the pandemic was 31 CCF. The percent reduction of normalized gas usage due to the pandemic was 18-36% of total usage.

Figure 38: Utility bill analysis (electric) at Perry for years 2015-2021. 2020 and 2021 show the impact of the COVID-19 pandemic on usage.

Our analysis of the electricity usage (Figure 38) at Perry found consistent usage from 2016 – 2019. The estimated reduction in daily electric bills due to the pandemic was 285 kWh. The percent reduction of normalized electric usage due to the pandemic was 14-22% of total usage. Unlike Drury, which was a new construction site, Perry completed a VRF retrofit in Spring and Fall of 2016. We were unable to determine any significant impact of the VRF system, but the VRF system only serves only 1/3 of facility.

Peak Demand

Another area of significant interest is the impact that VRF will have on peak demand. Currently, most buildings with gas-fired HVAC equipment experience peak demand during the summer, driven by the peak cooling load. However, by transferring the heating load from gas to electric, peak could occur in the winter in some building types. Table 6 summarizes the peak 15-minute kW between May-September (cooling months) and that for October-April (heating months). At Perry, the VRF systems studied experienced a winter peak kW approximately 2.5 times higher than the summer peak. At Drury, the winter peak was less substantial but was still 25% higher than the summer peak.

Table 6: Peak W/ft^2 for heating and cooling at each site.[3]

Month	Drury	Perry

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[3] To calculate peak demand, we took the average power draw over 15-minute intervals. Perry (system VRF-1) and Drury (VRF 6A/6B) are 11,202 and 14,363 ft^2, respectively.

	Peak (W/ft2)	*Time*	*Peak (W/ft2)*	*Time*
Jan	-	-	0.77	18:15
Feb	**0.38**	**10:15**	**1.03**	**7:15**
Mar	0.37	8:30	0.75	13:45
Apr	0.34	8:30	0.72	8:45
May	0.31	8:00	0.57	3:30
Jun	0.26	9:00	0.40	14:30
Jul	0.28	9:00	0.41	14:15
Aug	**0.31**	**Midnight**	**0.42**	**15:15**
Sep	0.31	8:45	0.39	11:00
Oct	0.29	5:15	0.46	13:00
Nov	0.29	7:45	0.60	23:45
Dec	-	-	0.78	18:15

ENERGY AND DEMAND SAVINGS

We also considered the energy and demand savings impacts over traditional HVAC systems. For lodging buildings, we assumed two common code compliant[4] HVAC system types for our energy savings calculation. The first was a packaged terminal air conditioner system (PTAC) with electric resistance heat. This system is commonly used in hotels and has very low upfront costs. However, it is typically associated with lower occupant comfort and being energy intensive (resistance heat). A second baseline system of water-source heat pump (WSHP) was also selected. This system features gas heating for the water loop and has *higher* upfront costs compared to VRF. Like VRF, WSHPs are considered a premium quality HVAC system in this building type. We calculated energy cost, electricity, gas, and demand impacts at both sites, against both baselines.

Percent energy savings. We first calculated the percent energy savings by end use (heating, cooling, fan and total) for each site, over each baseline. Table 7 shows these results. As a highly efficient heating and cooling system, VRF yields significant energy savings over PTAC systems. When compared to a PTAC with resistance heat, VRF results of 50% savings of heating energy. This aligns with our seasonal COP findings (*Seasonal Performance* section), showing the seasonal heating COP to be 2.2 (versus resistance heating COP of 1.0). Over the water-source heat pump system, energy savings are also significant (62%), driven by the elimination of the gas boiler which provides significant input for the water loop at 80% efficiency (compared to the VRF seasonal heating efficiency of 220%). Total HVAC energy savings are approximately 50% for both baseline cases.

Table 7: Percent energy savings for VRF systems over traditional systems.

	Perry

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[4] Current Michigan energy code is IECC 2015 or ASHRAE 90.1-2013

Baseline	Cooling	Heating	Fan	Heat Rejection / Pumping	Total
	%	*%*	*%*	*%*	*%*
PTAC	11	50	33	n/a	42
WSHP	15	62	-102	100	58

	Drury				
Baseline	Cooling	Heating	Fan	Heat Rejection / Pumping	Total
	%	*%*	*%*	*%*	*%*
PTAC					
WSHP					

Savings per square foot. We also looked at the savings expected per square foot, shown in Table 8. Compared to a PTAC baseline, VRF shows 4.9 kWh/ft^2 of savings. Ninety percent of these savings are from space heating. For the WSHP, the VRF system consumes slightly more kWh, driven by space heating. However, the WSHP system also consumes an additional 0.33 therms/ft^2 for space heating. The WSHP system also utilizes a heat rejection system (e.g. fluid cooler or cooling tower) and pumps for the condenser loop, which consume additional kWh. Savings from this end use amount to 2.2 kWh/ft^2.

Table 8: Energy savings per square foot for VRF systems over traditional systems.

	Perry						
Baseline	Cooling	Heating	Heating	Fan	Heat Rejection / Pumping	Total	Total
	kWh/ft^2	*kWh/ft^2*	*therm/ft^2*	*kWh/ft^2*	*kWh/ft^2*	*kWh/ft^2*	*therm/ft^2*
PTAC	0.23	4.38	0.00	0.30	0.00	4.92	0.00
WSHP	0.33	-2.68	0.33	-0.31	2.20	-0.46	0.33

	Drury						
Baseline	Cooling	Heating	Heating	Fan	Heat Rejection / Pumping	Total	Total
	kWh/ft^2	*kWh/ft^2*	*therm/ft^2*	*kWh/ft^2*	*kWh/ft^2*	*kWh/ft^2*	*therm/ft^2*

PTAC		
WSHP		

Peak demand. At both locations, compared to a PTAC system, VRF results in slightly lower summer peak demands, as well as significantly lower winter peak demands. However, compared to a WSHP system, VRF results in a higher winter demand. It is important to note that for a VRF system the winter peak is larger than the summer peak; this is a winter peaking system. These results are summarized in Table 9.

Table 9: Demand impacts for VRF systems over traditional systems.

	Perry		**Drury**	
Baseline	Summer Demand Reduction *W/ft²*	Winter Demand Reduction *W/ft²*	Summer Demand Reduction *W/ft²*	Winter Demand Reduction *W/ft²*
PTAC	0.08	6.19		
WSHP	0.39	0.36		

Emissions. VRF systems offer an opportunity for owners to reduce the amount of CO2 generated. We used emissions factors from Portfolio Manager[5] to calculate the CO2 savings which are summarized in Table 10.

Table 10: Summary of emissions factors.

Electric	159.12 kg/MBtu
Natural Gas	53.11 kg/MBtu

We then applied these emissions factors to our calculated energy savings. Table 11 summarizes the potential CO2 savings for VRF systems. While VRF saves approximately the same amount of *energy* over both baseline systems (48% and 52%), the emissions saved is significantly different. This difference is driven by the current composition of electricity generation in Michigan. On the current grid, electricity used on site produces more CO2 than burning natural gas on site. In the future, if additional clean energy sources are added to the grid, the emissions factor for electricity will decrease.

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[5] Direct Emissions factors from ENERGY STAR Portfolio Manager - https://portfoliomanager.energystar.gov/pdf/reference/Emissions.pdf

Table 11: Emissions impacts for VRF systems

Baseline	**Perry** Emissions Savings *kg/ft²*	**Drury** Emissions Savings *kg/ft²*
PTAC	2.67	
WSHP	1.52	

COEFFICIENT OF PERFORMANCE

In addition to the ability of VRF systems to maintain heating capacity, there is also interest in their ability to maintain efficiency in the field during different outdoor conditions, particularly at very low outdoor temperatures. Slipstream measured the parameters to calculate COP as outlined in the *Analysis and Calculation of Energy Usage, Savings and Coefficient of Performance* section. Hourly average COP is plotted over the course of the monitoring period, shown in Figure 39. We found that VRF-1 at Perry operated, on average, between a COP of approximately 2 and 5 during our data collection period (represented by the orange line). There are two gaps in the data set, in February and April where room temperature and humidity data was missing and we were unable to calculate the COP.

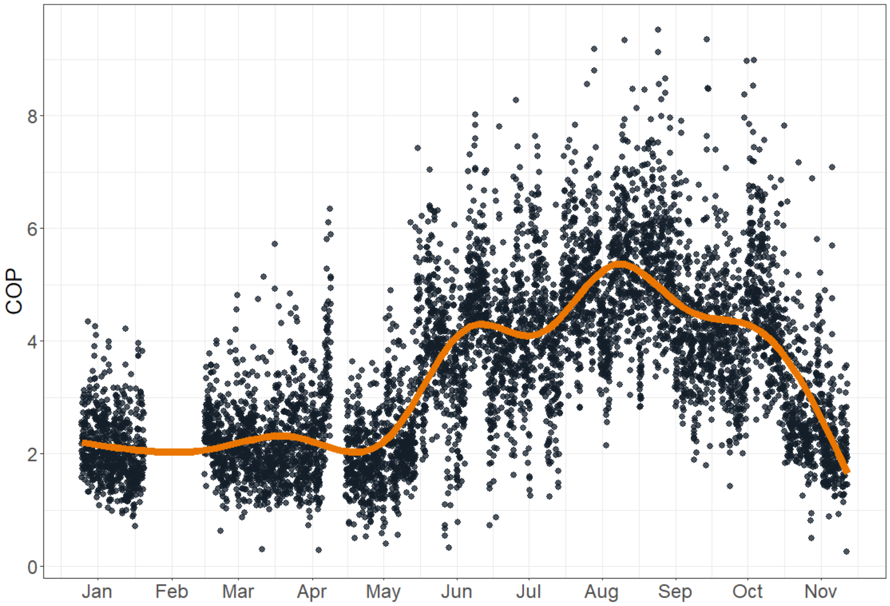

Figure 39: Coefficient of Performance for VRF-1 at Perry. Listed COPs are hourly averages throughout the monitoring period.

We also looked at different temperature bands to see the impact of outdoor temperature on COP. Figure shows the average hourly COP during the coldest periods of the year. Our data shows that below 25°F, the heating COP ranges from 2-2.5. Our data also found that very few hours are spent below 5°F. Counterintuitively, as the outdoor air temperature drops, the COP *increases*. Many factors can be contributing to this, including (but not limited to) system loading and indoor conditions or defrost. In addition to defrost, it could also be due to decreasing load on the system, the VRF system is forced to operate at a minimum compressor speed. This part-load minimum could result in decreasing heating output at a higher power input.

There are significantly more hours of the year between 25 and 40°F. The hourly average COP operates slightly below 2, as shown in Figure 40. This temperature range is when defrost is typically required – where there is moisture in the air with the potential to freeze on the coils. Defrost can have a significant negative impact on the system performance.

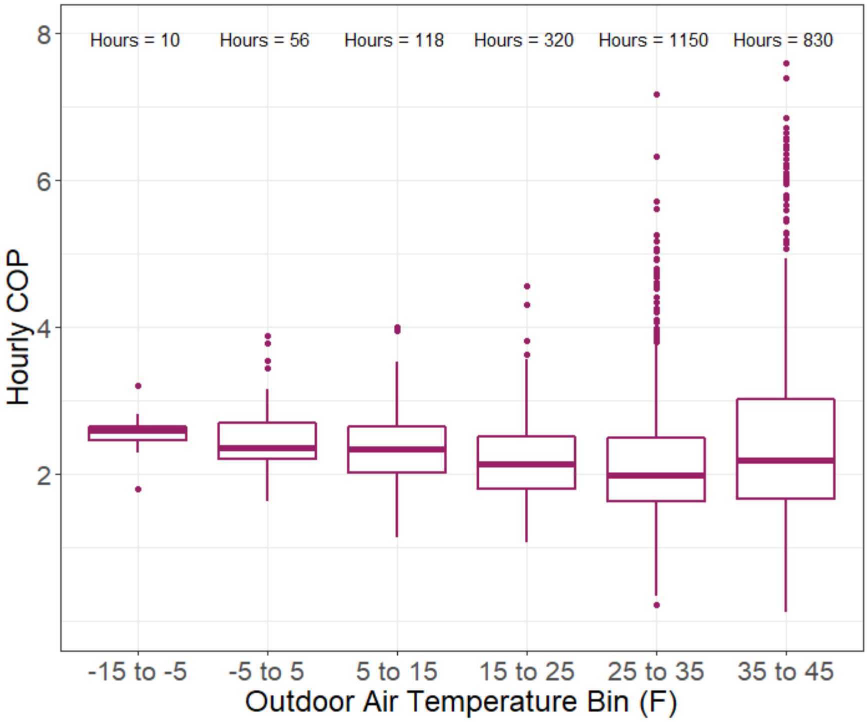

Figure 40: System COP for temperatures below 45°F.

As outdoor conditions further warm, between 45°F and 70°F, the COP begins to increase, shown in Figure 41. This likely indicates that there are few hours between 50 and 70 degrees where the system needs to run at substantial load and is spending a lot of these warm months running at favorable part load conditions. In addition, heat pumps typically operate at their highest efficiencies within the 30-60°F range (NESEA 2021).

As the outdoor air temperature increases beyond 70°F, to the highest temperatures of the year, the COP continues to increase. We are surprised by this behavior, as typically there is an efficiency drop off as temperature continue to increase. However, VRF systems are complex, and part load operation among other variables can impact the system efficiency. There are also very few operating hours above 80°F making the sample size of that measurement small.

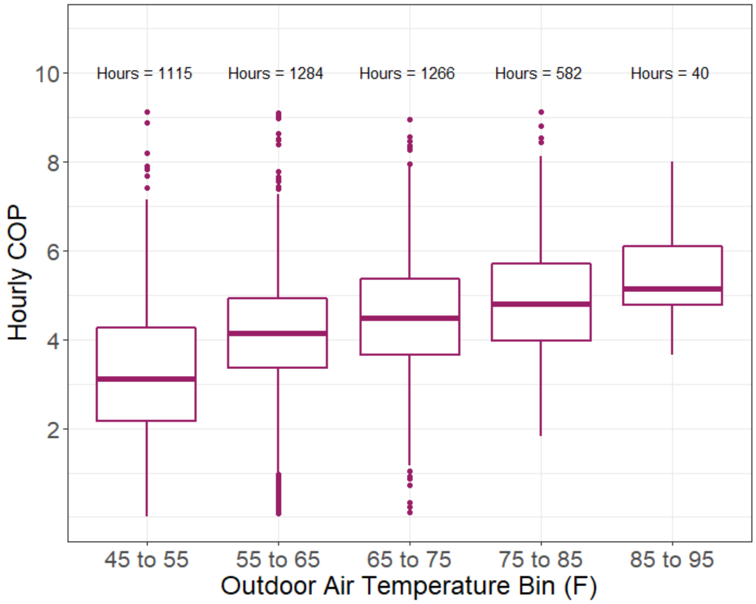

Figure 41: System COP for temperatures between System COP for temperatures above 45°F.

Seasonal Performance

While the individual point in time measurements of the COP shown above shed light on performance of the system at specific conditions, the most critical measurement is the *seasonal* COP as this indicates the total performance of the system over hundreds of hours of operation, at various loading and ambient conditions. We calculated the season and annual average COPs for VRF-1 at Stafford's Perry Hotel. This data is summarized in Table 12.

There are known sources of error that add uncertainty around these COP estimates. First, TrueFlow meters have a minimum flow accuracy of ± 7%. Although previous field studies have shown typical TrueFlow measurement errors between 2-3%, this application may have lower accuracy because it required many low flow measurements and there may have been air leakage in the box used to direct air to the meter. Additionally, HOBO loggers report accuracy of ± 0.38°F for temperature and 2% for relative humidity[6]. This measurement error, along with sources of error that are not observable with our collected data lead to our approximation of 10% uncertainty surrounding the COP estimates.

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[6] https://assets.omega.com/manuals/HOBO%20MX1101%20Manual.pdf

Table 12: This table summarizes the heating, cooling, shoulder, and annual average COPs for Stafford's Perry Hotel VRF-1. Seasonal COP is the total load delivered divided by the energy consumed (raw average).

	COP[7]
Heating Season (below 40°F)	2.2 ± 0.22
Cooling Season (above 50°F)	4.6 ± 0.46
Shoulder Season (between 40 and 50°F)	2.8 ± 0.28
Annual	3.3 ± 0.33

The seasonal performance findings for this system are significant. VRF-1 at Stafford's Perry Hotel was able to achieve a seasonal heating COP of 2.2 and a seasonal cooling COP of 4.6. The heating COP is of particular interest, it verifies the efficiency as much greater than resistance heat. In addition, heat pump systems which achieve a heating COP of greater than 2.5 are typically able to show *source* energy savings when compared to traditional gas fired HVAC systems.

ECONOMICS

VRF Capital Costs

Slipstream asked manufacturers and contractors to provide what they use to estimate the cost of a VRF system. These estimates generally included Dedicated Outdoor Air Systems for ventilation.

Table 13: Summary of first cost data.

Source	Location	Cost	Notes
VRF manufacturer representative	MI	\$300/ton	Equipment only
Michigan VRF manufacturer representative	MI	\$22-\$24/ft^2	Mechanical cost (labor + equipment), retrofit hotel
VRF manufacturer representatives, various	MI U.P. and WI	\$17-\$28/ft^2	Mix of retrofit and new construction
VRF manufacturer	National	\$14-\$16/ft^2	Heat Pump style VRF
VRF manufacturer national costs	National	\$18-\$21/ft^2	Heat Recovery style VRF

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[7] We estimate between 10% error around COP estimates due to measurement error from the TrueFlow meter, HOBO loggers, and unobserved system dynamics that may impact performance.

ACEEE Study[8]	National	$2,863/ton or $18/sf	Retrofit VRF systems.
VRF manufacturer representatives, various	IL	$19-$33/ft^2	Mix of retrofit and new construction
Average Cost of VRF systems	Midwest	$24/ft^2	Average of all upper Midwest sources[9]
Average cost of water-source VRF systems	WI	$27/ft^2	
PTAC, Michigan TRM	MI	$694/ton	
PTAC, Illinois TRM	IL	$1,047/ton	
PTAC	WI	$6,500/room	Estimated cost for installing PTAC with electric heat for Multifamily Buildings

Table shows the collected installed cost data from interviews with manufacturers and general research. Most air-source VRF estimates were a range of cost per square foot or cost per cooling ton. All data was collected between the fall of 2020 through the spring of 2021. In addition to costs from Michigan representatives, costs for VRF collected from VRF manufacturers in neighboring states such as Wisconsin and Illinois are included for comparison. Costs per square foot include the cost for dedicated outside air system to provide building ventilation.

The average cost for a VRF system in Michigan is $22 to $24 per square foot. This is similar to the average cost for VRF systems collected from four upper Midwest states, which is $24 per to square foot.

Demonstration Site Economic Analysis

Our analysis uses the following energy costs for MECA and Michigan, as reported by the EIA (Table).

Table 14: Assumed fuel costs for analysis, reported from the EIA for Michigan.

Electric	0.123 $/kWh
Natural Gas	0.663 $/therm
Propane	1.592 $/gallon

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[8] Nadal, Steven, and Perry, Chris. “Electrifying Space Heating in Existing Commercial Buildings: Opportunities and Challenges”. Page 77. American Council for an Energy-Efficient Economy (ACEEE). October 2020. https://www.aceee.org/sites/default/files/pdfs/b2004.pdf

[9] Michigan, Illinois, Wisconsin, Minnesota – Sample size of 7.

Based on the energy savings calculated in the *Energy and Demand Savings* section, we can calculate the approximate costs, savings, and simple payback period for installing a VRF system. Utility costs are summarized in Table .

Table 15: Estimated costs for Perry.

System	Electricity Cost $	Natural Gas Cost $	Total Cost $	Electricity Cost $/ft^2	Natural Gas Cost $/ft^2	Total Cost $/ft^2
VRF	22,147	3,043	25,190	1.79	0.25	2.03
PTAC	29,636	3,043	32,679	2.39	0.25	2.64
WSHP	21,628	5,773	27,401	1.75	0.47	2.21

We also determined the expected cost savings for the VRF system over the traditional systems. Table shows the electricity, natural gas, and total cost savings. The VRF system saves approximately 0.60 $/ft2 of energy costs compared to the PTAC system. Due to the low costs of natural gas, the cost savings for VRF over WSHP is only 0.18 $/ft2. This is typical for comparing most electric heating systems against natural gas-fired heating systems. For sites that utilize propane as a fuel source, the cost savings for VRF are even more substantial due to higher costs of propane. If the WSHP system were using propane as a fuel source, the total cost savings of the VRF system would be $0.50 $/ft^2.

For Perry, utility bill costs were between 2.0-2.6 $/ft2 – indicating that the calculated VRF savings over WSHP (natural gas) are 10% of the total utility bill.

Table 16: Estimated cost savings for VRF over traditional HVAC systems at Perry.

System	Electricity Cost Savings $	Natural Gas Cost Savings $	Total Cost Savings $	Electricity Cost Savings $/ft2	Natural Gas Cost Savings $/ft2	Total Cost Savings $/ft2
PTAC	$7,489	$0	$7,489	0.60	0.00	0.60
WSHP	($519)	$2,730	$2,211	-0.04	0.22	0.18

Table 17: Estimated simple payback over traditional HVAC systems for Perry. The installed cost of the VRF system was $24/ft^2 or $297,240.

System	Installed Cost	VRF Incremental Cost	VRF Annual Utility Cost Savings	Simple Payback
PTAC	$208,000	$89,240	$7,489	12 years
WSHP	$334,395	-$37,155	$2,221	Immediate

Table shows the VRF system's estimated payback for Perry against common alternative HVAC systems. Based on our collected cost data, the VRF cost is \$24/ft^2, the PTAC cost is \$6,500 per hotel guest room (approximately \$16.80/ft^2) and the WSHP cost is \$27/ft^2.

The VRF system pays back in approximately 12 years over the PTAC system. While the VRF system showed significant energy savings over the PTAC system (\$0.60/ft^2), the inexpensive upfront cost of the PTAC system results in a longer payback period for the VRF system. It is difficult to make a direct comparison between the PTAC and VRF systems as VRF is a much higher quality HVAC system from an occupant comfort and experience standpoint. Compared to the WSHP system, the VRF system pays back immediately because the air-source VRF system is less expensive. The additional boiler, pumps, and water cooler add more cost than the air-source VRF system. In addition, the VRF system saves more energy than the WSHP system.

CONCLUSIONS AND DISCUSSION

This research set out to answer several key questions. The primary outcomes for these questions are summarized below:

- Our research found that VRF systems save approximately 48-52% of HVAC energy and 0.2-0.6 \$/ft^2 over traditional HVAC systems. We also found VRF systems save 2.67 kg/ft^2 over PTAC systems and 1.52 kg/ft^2 over WSHP systems.
- The two VRF systems we monitored – without a backup heating source – were able to maintain setpoints throughout the year, including at the coldest hours in Climate Zones 5 and 6.
- We found that there are several key metrics that drive decisions in selecting a VRF system. First cost and energy costs and often drive the final HVAC selection. However, some owners place a premium on aesthetics and occupant experience and comfort. These owners are often looking at higher end HVAC systems (not just VRF) and are willing to pay a premium.
- We interviewed stakeholders in Michigan (owners, manufacturers, contractors, etc) to understand the current state of VRF and market barriers. Cost is, as always, a barrier; as is lack of confidence in heat pump technology in cold climates.

We used all of our results to create recommendation and guidance for two groups: utility programs staff and building owners. These are discussed in the following two sections.

VARIABLE REFRIGERANT FLOW SYSTEMS FOR UTILITIES AND PROGRAMS

The results of our field study indicate that VRF systems save energy and energy cost over electric HVAC systems. They also save energy over gas-fired HVAC systems such as WSHP. VRF systems also provide a premium HVAC experience for building occupants. To foster adoption of these systems in MECA territory, we have identified several key barriers and suggested interventions:

Increase market awareness in VRF

Interviews with Contractors and building owners in western Michigan showed both a lack of awareness of VRF systems and some distrust in its operation in cold climate. In our interviews, only four owners of nine that did not have VRF systems were not aware of VRF systems before the interview.

MECA can further accelerate VRF awareness through both incentives, marketing, and outreach. We recommend that MECA develop basic marketing materials to inform the public of the availability of VRF incentives and their strong energy performance and positive occupant experiences. Case studies highlighting the most common opportunities in the EO-Collaborative service territory would be beneficial. Individual utilities may reference the "2017 MECA EO Collaborative Customer Characterization Report" for information on prevalence of different business types in their territory. As described earlier, one building operator would only consider VRF once seeing a case study from their own city where the system handled the cold-climate and wind effect from the lake smoothly. As this research has outlined, in addition to energy benefits, VRF systems also have many non-energy benefits. MECA should also work to increase the awareness of both the energy and non-energy benefits.

MECA should ensure that program personnel are able to connect potential customers to sources of information or industry contacts, such as manufacturers sales representatives or local qualified contractors. For programs staff which work in building sectors which are prime candidates for VRF, such as hotels, staff should be trained to better understand typical market concerns and solutions for VRF. Our *Market Segment* section provided a detailed list of common applications which VRF has typically been successful, outlined below:

Retrofit
- Older or Historic Buildings
- Buildings with Electric Heat

New Construction
- Hotels and Lodging
- Multifamily
- Schools and Offices
- Multi-Zone Mid-Sized Buildings
- Electrification and Sustainability Goals (also applies to retrofits)

Increase market confidence in VRF

In addition to increasing the awareness of VRF, MECA should also focus on increasing the confidence in VRF systems. Through our interviewing we found that some contractors in Western Michigan distrust VRF systems. Both contractors interviewed stated that installs in the early 2010's had issues and VRF gained a negative reputation. This is a barrier that needs to be focused on, as our owner interviews indicated many owners and building developers rely on mechanical engineers and contractors to recommend system options. If engineers and contractors are not confident in VRF systems, they will be unlikely to recommend them to owners.

Throughout our interviewing in the Midwest, including Detroit, the available installers for VRF systems are typically less common in rural areas as compared to urban areas (like Detroit). This decreased availability of installers ultimately results in a lack of awareness and confidence in these systems. To help increase designer and installer awareness and confidence, MECA should help promote buildings where VRF is operating successfully (such as Perry and Drury) to not just owners, but contractors and engineers as well.

The primary reason for system issues identified by both manufacturer representatives and contractors is the quality of the install. VRF installation has some key distinctions from more typical split systems that can lead to the failure of the VRF system down the line. Installers nation-wide have more experience and manufacturers provide better training and startup services, helping address many of these issues in new installations. The major VRF manufacturers offer training for their systems and at least one certifies installers in exchange for a better warranty period.

To help promote VRF systems, MECA should support VRF training for contractors or make training certifications from VRF manufacturers a prerequisite to receiving VRF incentives. This will help ensure that every VRF install is a quality installation that won't saddle owners with repairs or lead to a poor reputation for VRF. It will also help increase the pool of installers in western Michigan.

Overcome high first costs

Variable Refrigerant Flow systems are premium HVAC systems which carry higher first costs when compared to basic HVAC alternatives (RTUs, PTACs, etc). As a result, it is often challenging for building owners and developers to pursue VRF in an industry that is often driven by first costs. There are several interventions that can address these higher first costs.

First, target building segments where VRF systems are most effective (both in terms of cost and energy). As previously discussed, VRF is not a one size fits all solution. Certain building segments may be better served by other HVAC system types (RTUs, PTACs, etc). Program staff should target applications where owners are either looking for, or will at least consider, premium HVAC solutions. Staff should recognize that as a premium HVAC system, VRF offers significant benefits beyond just energy efficiency, including occupant comfort benefits, including quiet operation and stable control of desired setpoints.

Second, to help offset potential increased upfront costs, offer downstream prescriptive incentives in near-term and consider midstream incentives in the long-term. Incentives should be an easy-to-calculate metric such as $/ft^2 or $/ton. This simplified approach will increase customer satisfaction and participation, while also decreasing the development time to bring the measure to market. During our interviews with stakeholders, both in Michigan and in the Midwest, a simplified incentive calculation was preferred by manufacturers, contractors, and owners. Prescriptive incentives which are easily defined ($/ton, $/ft^2) creates certainty early in the process on what incentives would be available for VRF and enables early budgeting and planning.

While we recommend beginning with downstream incentives, there are benefits to moving incentives midstream so contractors receive an instant discount at participating distributor locations. First, the headache of paperwork from multiple parties is avoided and assuming there is sufficient volume, associated program administration costs are lowered. Second, distributor stocking practices may be affected and could make VRF equipment more widely available. Due to the need for scale, any single EO-Collaborative member utility is unlikely to deploy this model successfully own their own and a collaborative approach by multiple utilities would be important just like how the EO program pooled 5 EO-Collaborative utilities as part of the residential midstream HVAC offering. The feasibility for midstream VRF incentives would be much greater as well if there was cooperation with other major utilities in Michigan. To our knowledge, no other Michigan utilities are yet offering VRF incentives in a midstream program design. The most successful midstream programs across the country were designed as statewide offerings and distributors were approached with one single program design and incentive levels.

Overcome increase operational costs versus gas-fired systems

As found in our energy and costs savings results (*Energy and Demand Savings* section), depending on the baseline HVAC comparison, VRF is near breakeven on utility cost impact where the alternative HVAC system is gas fired. This is one of the most significant barriers to electric heating technologies. Program staff should target segments and use cases where the increase in utility costs is minimized. We have identified the most common segments in the *Increase market awareness in VRF* section. Typically, new construction buildings or existing buildings with resistance heat or without air condition can be opportunities for VRF. In addition, areas This is most common for areas where gas rates are more expensive and electric rates are cheaper. Alternatively, cases where VRF has a lower first cost may also alleviate potentially higher utility bills in an economic analysis.

Some utilities also have tariffs for fully electric buildings or those with electric heat. These reflect how the utilities electricity assets are more efficiently utilized in such buildings. This approach can help make the shift to electric heating much more cost competitive. Strategies like this will also spur the adoption of VRF and could be another consideration for EO-Collaborative utilities that do not already have a special rate. Great Lakes Energy and Presque Isle Electric & Gas (PIE&G) both offer $.03/kWh space heating discounts. Great Lakes Energy (GLE) offers this rate to residential and general service commercial (<200kW peak demand) when a member installs a submeter provided by the utility and has a qualifying air source heat pump. According to a few residential members, the cost for the necessary wiring and to have this meter installed by a licensed electrician is approximately $700 so GLE member savings aren’t quite realized until approximately 23,000 kWh have been discounted.

Develop a formal program baseline

Prior to discussing programmatic baselines, it is important to note that beginning in 2022, the EO-Collaborative utilities will no longer be required to operate within the “Energy Waste Reduction” paradigm regulated by the Michigan Public Service Commission. As a result, future utility program offerings may be developed that allow fuel switching. This section suggests two different baseline approaches.

VRF lacks a standardized programmatic baseline to calculate savings. Programmatic savings can be calculated in two different ways: an electric HVAC system baseline can be assumed (such as a code compliant heat pump or resistance heat) or a gas-fired HVAC system baseline can be assumed. In the latter scenario, gas (therm) savings are also claimed in addition to kWh savings.

The selection of the program baseline will directly impact the total program savings for a VRF measure. As shown in the *Energy and Demand Savings* section, a gas-based fuel baseline will yield more program savings for a VRF measure as compared to an electric baseline. If the evaluation paradigm allows for this type of baseline for VRF, then we recommend selecting that as the baseline. Alternatively, if an electric baseline must be utilized, careful consideration should be taken when selecting the electric baseline system. Heat pumps are commonly specified as the baseline to measure VRF savings against, however, in certain building types, market trends show that a more common baseline may be electric resistance heat. For example mid-sized multi-zone commercial buildings that would use VAV systems with electric reheat or hotels may use PTAC systems with resistance heat. Using an electric resistance baseline would increase VRF savings.

Develop savings calculation

Typically, most VRF projects are incentivized using a custom calculation approach. This method is time intensive and is not straightforward for customers/participants to understand what potential incentives are available. We recommend creating a prescriptive VRF measure with a set savings calculation. The savings calculation will utilize the baseline approach determined by MECA (gas or electric). In addition, the savings calculation should consider a variety of different scenarios which impact the savings potential of VRF, including, but not limited to: building type, VRF efficiency, VRF type (cold climate standalone vs penthouse) and baseline system type (gas-fired, electric heat pump, electric resistance). One approach to developing the VRF savings calculations would involve developing a workpaper that would provide the basis for a prescriptive calculation.

Develop successful path for project delivery

Variable Refrigerant Flow systems are complex and frequently not well understood by designers and contractors. Design and installation needs differ between manufacturers and requires project delivery stakeholders to be well trained and informed on specific manufacturer’s systems. Manufacturers and/or sales representatives are typically engaged and involved in the design, selection, installation and commissioning of their VRF systems.

To ensure stakeholder satisfaction and program savings, a set of eligibility criteria should be developed for projects which pursue VRF systems. These criteria will be focused on creating successful outcomes for projects installing VRF systems:

- following manufacturer recommend design practices and sizing procedures
- utilizing contractors who have completed manufacturer training sessions
- following manufacturer recommended installation and start-up process
- pressure testing protocol to mitigate leakage

The criteria must be carefully considered to avoid being overly onerous for the customer, but also still ensuring projects that are incentivized have quality outcomes.

Increase contractor training and support

We have heard from manufacturers and distributors that a utility can help drive sales by conducting outreach and training to equipment specifiers and highlighting program support that increases the value proposition for heat pump systems like VRF. For installer support, there are several strategies an EO-Collaborative might deploy. First, high-quality manufacturer provided training is typically offered in larger cities and HVAC contractors in EO-Collaborative territory may find it difficult to financially justify travel and the time to take the training. A utility-provided scholarship can help ease this financial burden. Similarly, to encourage an HVAC contractor to complete their first VRF installation and ease financial risk from the extra time to learn how to install a new system, a utility bonus or spiff could be provided. This type of incentive is sometimes provided by equipment distributors but additional support from the utility would help. Finally, if pre-approval of the project is required before installation and rebate delivery, the utility should provide a sufficiently long period of time for the contractor to complete the project that accounts for the potential lag in equipment deliveries.

Shorten operator learning curve

While most owners, operators and occupants are familiar with gas fired heating systems, few are familiar with VRF technology and the differences in its operation compared to traditional systems. Based on our interviewing with various building owners, we have learned that it often takes some time for building operators and staff to become familiar with their VRF system. Some common themes include:

- slower than expected response times
- quiet fan operation that often leads occupants to believe that the system is not responding to their thermostat inputs
- thermostats can be too complicated for some occupants
- complicated diagnostics and troubleshooting for on-site facilities staff
- fine tuning the controls

Many of these differences take little time for occupants and operators to adjust to, and do not cause significant issues over time. But awareness is important. The guidance for VRF systems is to reduce the amount of setback and ensure that warm up periods are long enough. VRF systems (and heat pumps in general) have a general characteristic of requiring more time to recover as compared to gas-fired systems. Owners and operators should also provide feedback to occupants on the system and thermostat operation as most occupants are not familiar with VRF systems. On-site maintenance staff may find VRF systems are challenging to diagnose and trouble shoot. We recommend building operators develop a relationship with their contractor who can provide continued learning and guidance on the operation. This may also include fine tuning the control strategies of the system.

FUTURE WORK

Variable Refrigerant Flow Systems and heat pump technology are rapidly advancing, specifically with their performance in cold climates. As the market demands additional solutions and support for electric heating solutions, we expect these technologies to be further refined for use in cold climates. There are several areas of research that build off what we have accomplished.

We attempted to monitor a diverse building set in this research, but challenges sourcing these buildings ultimately lead to monitoring two hotels. Additional monitoring of other common building types (office, education, etc) would broaden the resulting data set to show the potential and impact of VRF across the commercial building sector in cold climates. In addition, capturing data during a year less impacted by the COVID-19 pandemic would eliminate the need to estimate a typical year of data.

In addition to monitoring, more first cost data and operating cost data needs to be collected. The biggest challenge electric heating systems face is the economic impact of shifting from inexpensive natural gas to electricity for heating. Not enough data exists to fully quantify the first cost and operational cost impacts of VRF systems (and heat pumps in general). In certain building segments, the financial impact of transitioning to efficient electric heat may be negligible.

Lastly, as more entities set emission reduction targets, which ultimately necessitate the shift to electric heating, a thorough investigation of refrigerant leakage is required. No data set currently exists which quantifies the scale of leakage. As we scale up the number and capacity of refrigerant based system in the market, it will be critical to understand the offsetting nature these systems may have on emissions savings. Any study of this nature should also consider the future refrigerants expected to be used in these systems.

GLOSSARY

Body text

REFERENCES

ASHRAE 2013. American Society of Heating, Refrigerating and Air-Conditioning Engineers. ANSI/ASHRAE/IES Standard 90.1-2013 – Energy Standard for Buildings Except Low-Rise Residential Buildings.

ASRHAE Guideline 14 2014. American Society of Heating, Refrigerating and Air-Conditioning Engineers. ASHRAE Guideline 14-2014 – Measurement of Energy, Demand, and Water Savings.

CBECS 2012. Energy Information Administration, Commercial Buildings Energy Consumption Survey (2012). Building Characteristics, "2012 CBECS microdata, June 2015 Release Date". Available: https://www.eia.gov/consumption/commercial/data/2012/index.php?view=microdata. Accessed August 1, 2017.

DOE 2020. US Department of Energy. Commercial Prototype Building Models. Available: https://www.energycodes.gov/development/commercial/prototype_models. Accessed January 31, 2021.

Nadal, Steven, and Perry, Chris. “Electrifying Space Heating in Existing Commercial Buildings: Opportunities and Challenges”. Page 77. American Council for an Energy-Efficient Economy (ACEEE). October 2020. https://www.aceee.org/sites/default/files/pdfs/b2004.pdf

NESEA 2021. Rodriguez, J., Lujan, M., Bridgeland, B., and Beguin, M., A Rational Approach to Large Building Decarbonization: Lessons Learned from New York’s Empire Building Challenge. NESEA Building Energy Magazine, Volume 40, No. 1, Pg. 20-23.

Swanson and Carlson 2015. Swanson, Gary A. and Carlson, Cole A. 2015. "Performance and Energy Savings of Variable Refrigerant Technology in Cold Weather Climates". Conservation Applied Research & Development (CARD), Prepared for the Minnesota Department of Commerce, Division of Energy Resources. Prepared by: Energy Management Solutions, Inc.

APPENDIX A: PRODUCT REVIEW

VRF OVERVIEW

Variable refrigerant flow systems have one outdoor condensing unit and multiple indoor evaporator units that use piped refrigerant to deliver cooling and/or heating to different zones. The term variable refrigerant flow refers to the ability of the system to modulate the amount of refrigerant flowing to the indoor units, which also allows for individualized comfort control. This level of individual control requires installation of a complex network of refrigerant pipes (CED Engineering 2019).

VRF systems contain many of the same components as traditional heat pump systems. The indoor refrigerant fan coil units are the evaporator. The outdoor unit contains the refrigerant compressor, expansion valve, and condenser. The compressor is driven by an inverter to vary the speed of the compressor and therefore vary the refrigerant. A typical condenser unit has a maximum capacity around 36 to 40 tons. Larger systems consist of multiple condenser units. These outdoor units are then connected to several indoor fan coil units which serve the zones.

VRF systems can be configured as heat pumps or in a “heat recovery” configuration that has the capability to recover heat rejected from zones in cooling and use that energy to heat spaces requiring heating, saving even more energy. Figure 30 below shows a similar building configured in heat pump and heat recovery. The heat recovery configuration requires additional branch selector between the outdoor and the indoor unit, as shown in Figure 31. The decision to use a heat pump or heat recovery configuration is dependent on the building application and system zoning. If significant diversity in zone loads is present leading to simultaneous heating and cooling, a heat recovery configuration should be selected. This can be common in many commercial buildings such as offices. For applications where very little diversity in zone loads exists – where the entire building will always be heating or cooling, then a heat pump configuration should be selected.

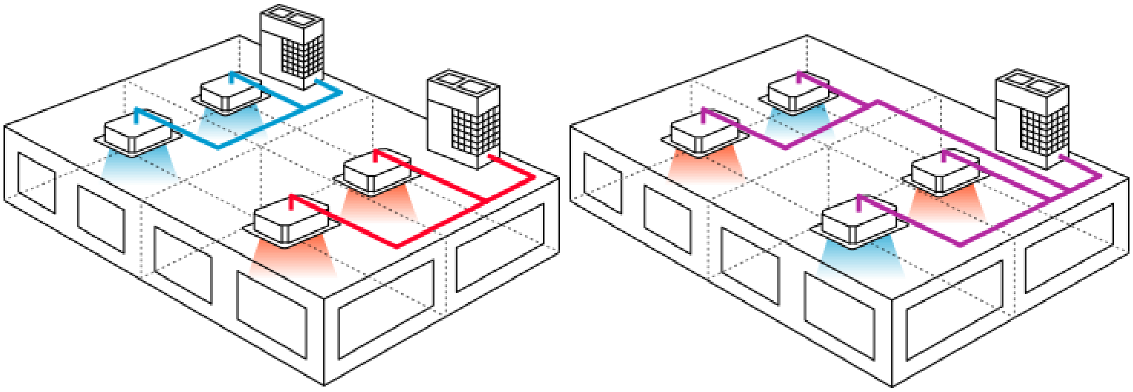


Figure 42: Left - two VRF units in heat pump configuration. Right - one VRF unit in heat recovery configuration (Daikin 2019).

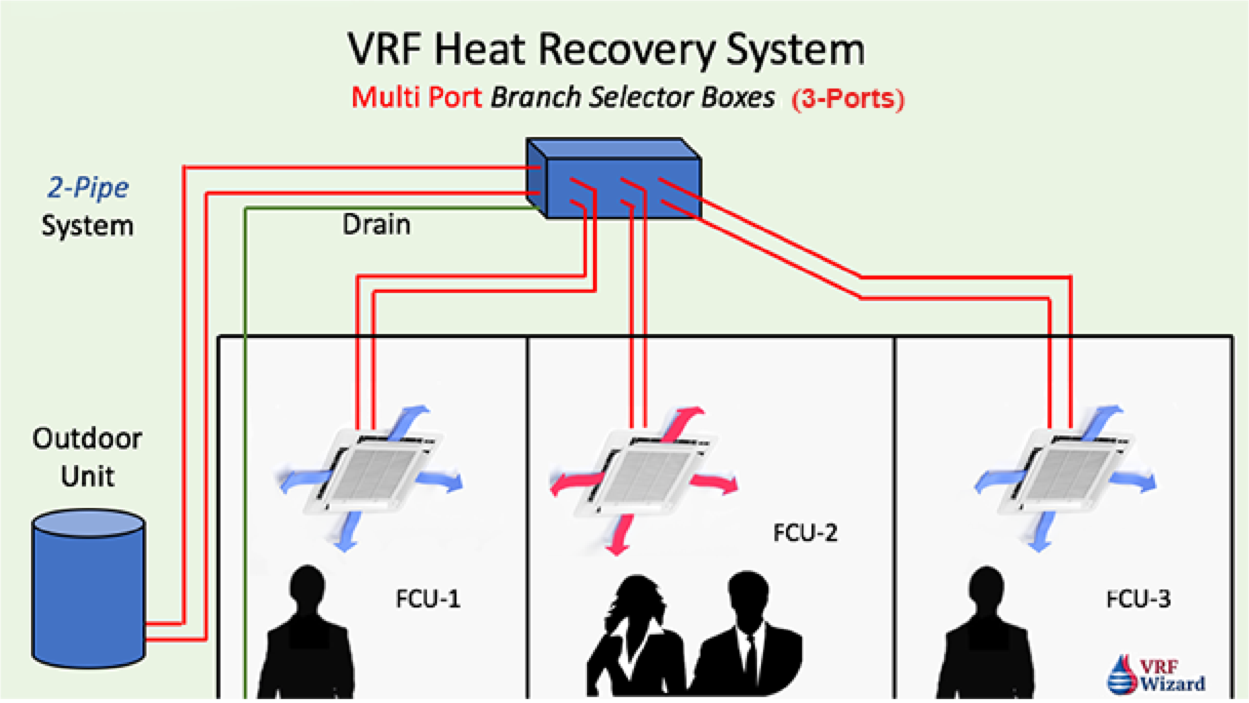


Figure 43: An example of a heat recovery VRF system with the branch selector between the outdoor and indoor units (VRF Wizard 2017).

One of the challenges and criticisms of VRF (and heat pump) systems is cold climate performance and capacity. As the outdoor temperature decreases below 5°F, VRF systems have decreased ability to transfer energy from the outdoor environment to the indoor environment. As a result, capacity decreases and maintaining zone temperature setpoints becomes difficult. Cold weather conditions also lead to freezing on the condenser coil. Frost build up is thawed via defrost cycle, which further degrades system performance. 65% of residents in the United States live in a climate with yearly heating design temperatures lower than 32°F, and 15% of all residents live in climates with heating design temperatures lower than -4°F. Figure 32 summarizes the climate information for MECA's climate zones. While many of these cities do not fall in MECA's territory, their climate and engineering design criteria are representative of the MECA territory.

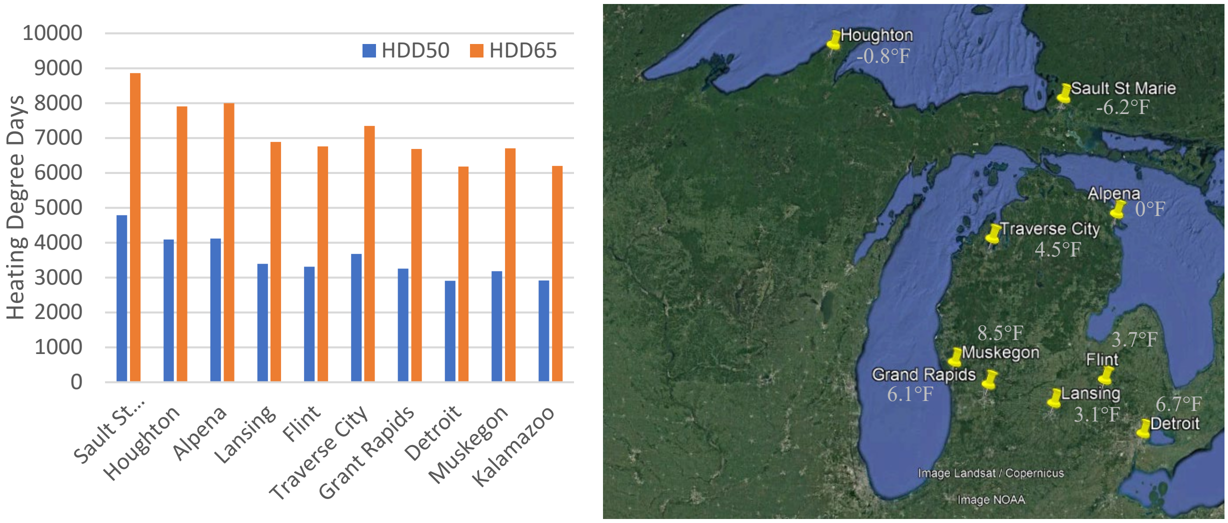


Figure 44: Plot showing the heating degree days for various cities in Michigan that fall near or in MECA territory. A google map shows the heating design day temperature for several of these cities.

One approach that has been used historically in these cold climates is to partially enclose the outdoor units together with supplemental heat. The outdoor unit would be placed in a louvered mechanical room. During standard operation, the louvers would be open, and the outdoor unit would reject and absorb energy from the ambient. At low temperature operation, when capacity would typically be reduced due to cold conditions, the louvers on the mechanical room would close, and a supplemental heater in the mechanical room would operate to increase the temperature. This design is shown in Figure 33. This workaround proved effective, however, the supplemental heater was typically fossil fuel fired and often run when temperatures were below 30°F leading to a significant amount of fossil fuel consumption. The supplemental system cost, additional cost associated with the louvered room, and controls complexity were also barriers to this approach.

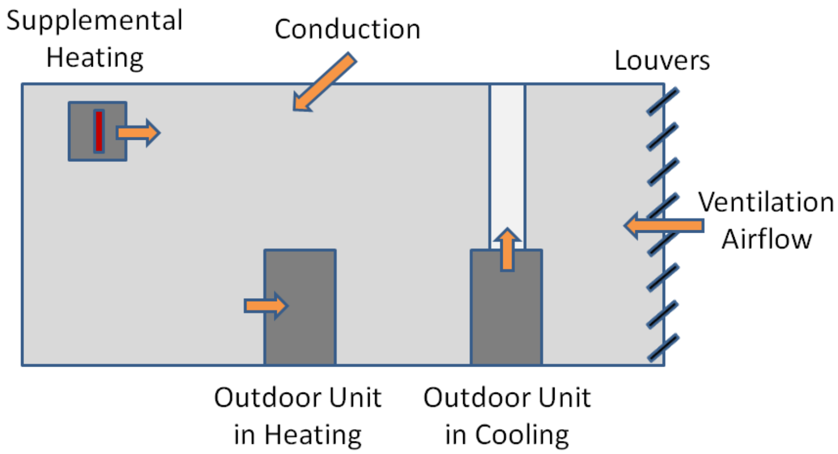


Figure 45: Energy balance of mechanical room featuring supplemental heat and operable louvers.

In order to expand the market for VRF systems to colder climates, manufacturers have been developing “Cold-climate” VRF technology that can operate without supplemental heat in these regions. These systems use a special outdoor unit to maintain capacity and efficient performance for space heating even at low outdoor temperatures. These systems do not require a louvered mechanical room as previously described and can be designed to operate to approximately -22°F. Currently, minimal third-party testing and monitoring exists. However, preliminary test data and case studies published by the manufacturers indicate that ccVRF is feasible for cold climates.

ccVRF has advanced quickly in the last decade. Five years ago, VRF units were only rated to outdoor wet-bulb temperature of -10°F. In the last two to three years, manufacturers now have units rated to perform as low as -22°F.

FIELD STUDIES

The VRF marketplace has been rapidly changing as manufacturers have vastly improved the cold climate performance of their systems in the past 5 years. Due to the recent nature of these improvements, there are no third-party field studies on the performance of these systems in cold climates. One of the most relevant studies for our climate is a report from the Minnesota Conservation Applied Research and Development (CARD) Program (CARD 2014). This CARD report published in 2014 reviewed five VRF installations in Minnesota. Unfortunately, these installations took place circa 2010 and had either electric resistance baseboard heat as backup or placed the outdoor condensing unit in a mechanical room with operable louvers with an electric resistance supplemental heat source. The project did not specifically monitor these systems to analyze the performance and the amount of backup or supplemental energy used. The report concluded that the VRF technology is applicable to cold climates such as Minnesota and that the systems can be cost effective. It should be noted that each building studied was a renovation. The report listed the following challenges: first costs, refrigerant piping design, compliance with ASHRAE standard 15, 34 and 62, personnel training, proprietary components and lack of familiarity and manufacturer support. The VRF industry has been working to address many of these challenges. Since the installation of those systems (circa 2010) and publishing of the report (2014), VRF technology has advanced significantly in terms of industry education, cold climate performance, and first costs.

Another study from Oak Ridge National Laboratory featured a test facility fitted with a VRF system. (ORNL 2016) This building was in Knoxville, TN which is climate zone 4A – a significantly milder region than MECA territory. In addition, this test was from 2015, using a Samsung VRF system. Like the Minnesota CARD VRF study, this test used equipment that predated the recent advancements allowing units to operate far below -10°F. However, this test still reported heating performance data that is worth reviewing, as it should present a lower bound to system performance – we would expect new systems to be superior to the performance found in this study. Figure 34 below shows the heating coefficient of performance (COP) of this system. The COP is defined as energy output (for heating) divided by energy input (to operate the system).

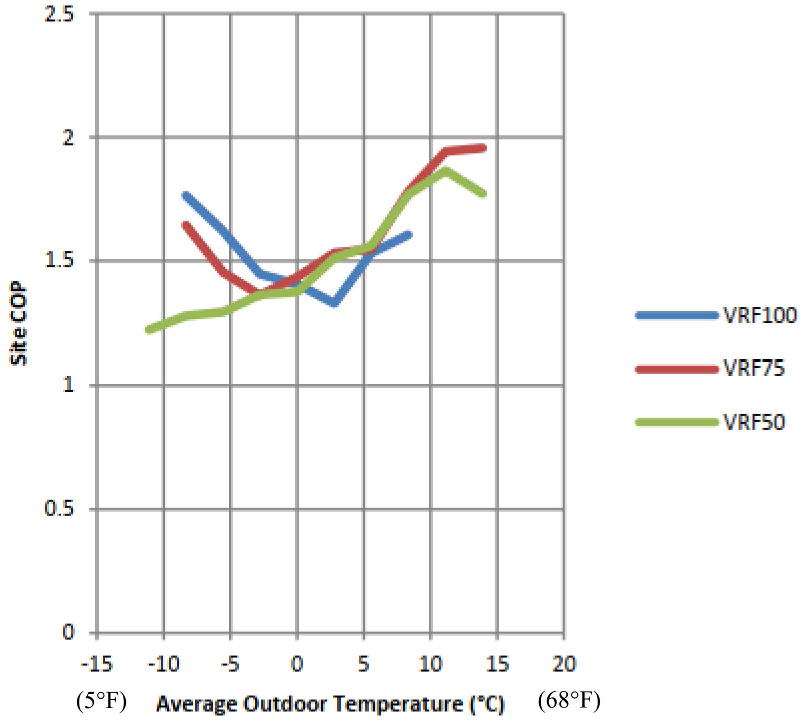


Figure 46: Oak Ridge National Lab test results showing COP over a range of outdoor temperatures during heating operation. Note that temperatures are in Celsius. (ORNL 2016)

PRODUCT REVIEW

There are currently almost 20 manufacturers of VRF systems on the market, another indication of the growing popularity and success of this HVAC system. There are three manufacturers with the largest share of the VRF market in the United States: Daikin, LG, and Mitsubishi. All three manufacturers offer ccVRF options rated to -22°F:

- Daikin VRV Aurora
- LG Multi V5
- Mitsubishi Y Series (Heat Pump) Hyper Heat and the R2 Series (Heat Recovery) Hyper Heat

Both the Daikin Aurora, Mitsubishi Hyper Heat, and LG Multi V5 achieve cold-climate VRF by using inverter-driven vapor injection compressor technology to reach lower evaporator temperatures. In this refrigerant cycle, as shown in Figure 36, a portion of the refrigerant is diverted after the condenser and expanded (Figure 35 shows a traditional VRF cycle for comparison). This refrigerant passes through a heat exchanger to pre-cool it prior to expansion, lowering the refrigerant temperature at the evaporator. After the heat exchanger, the diverted, warmer refrigerant is injected halfway through the compressor cycle.

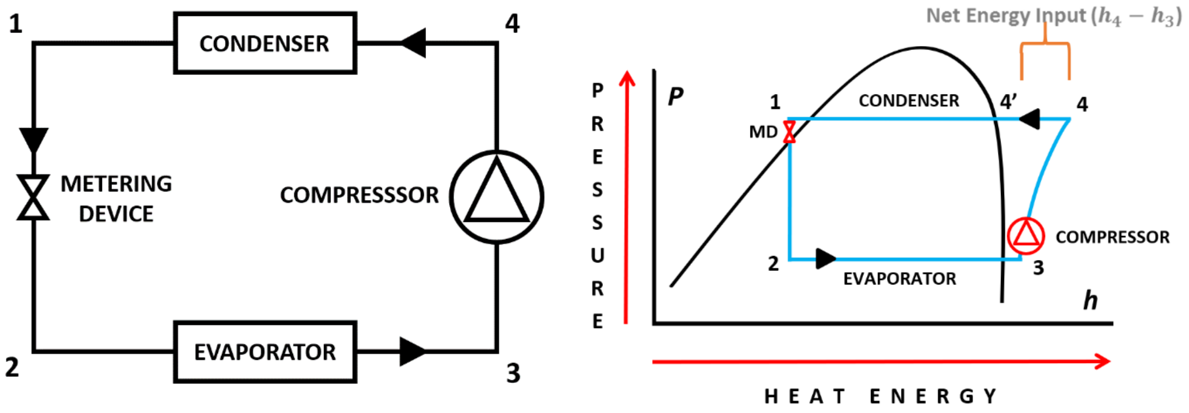


Figure 47: Left: Traditional VRF refrigerant flow diagram. Right: Traditional VRF pressure and enthalpy thermodynamic diagram.

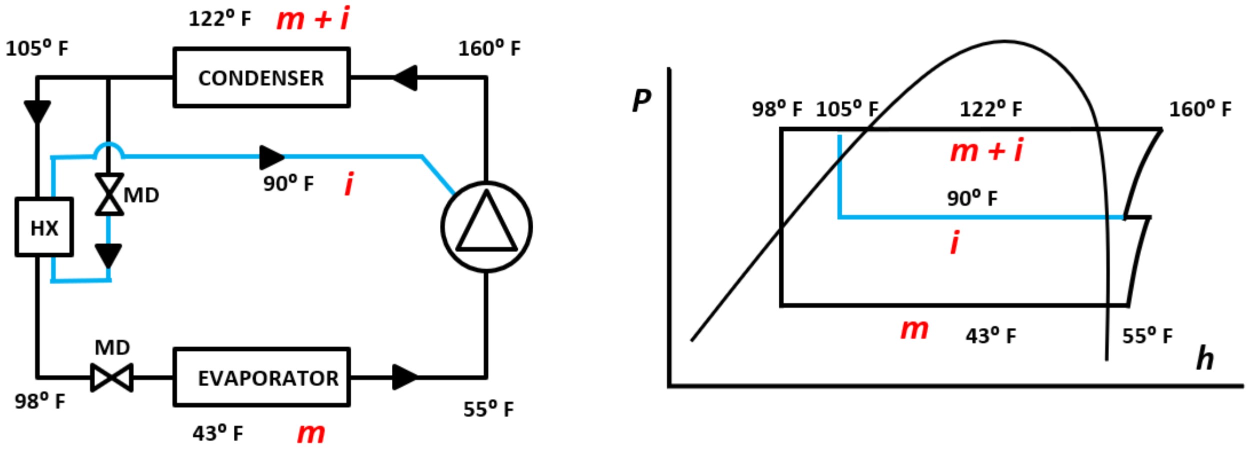


Figure 48: Left: Daikin Aurora VRF refrigerant flow diagram with vapor-injection compressor. Right: Daikin Aurora VRF pressure and enthalpy thermodynamic diagram.

In all three product lines, the use of an inverter-driven compressor adds heat to the refrigerant which needs to be cooled. Each manufacturer has a different way of accomplishing this, which affects the energy consumption and/or the capacity of the system at cold temperatures. As an example, one manufacturer uses a separate refrigerant line to cool the inverter, while another cycles cold refrigerant gas back to cool the compressor and inverter.

With any VRF or heat pump system in heating mode, ice buildup on the condenser must be addressed. This defrost is even more pronounced for ccVRF. Defrost occurs under near freezing conditions with relatively high humidity. Different manufacturers each take their own approach to defrost, each with differing power consumption impacts. One method is to operate the outdoor unit in cooling (rejecting heat to the condenser) for 5 to 20 minutes to melt ice buildup on the condenser. It is recommended that the defrost cycle be operated based on sensors and not on a fixed timer schedule.

Another approach to cold climate operation is exemplified by the Daikin IVX. While only rated to -10°F WB, it has a vapor-injection compressor and an option to be combined with a gas furnace unit, similar to a regular air conditioning unit. This allows the unit to have back-up gas heating and additional flexibility in cold climates.

PRODUCT PERFORMANCE

Table 5 compares the ccVRF outdoor units offered by Daikin, Mitsubishi, and LG. Nominal 10-ton outdoor air units in Heat Recovery mode were used as a basis of comparison. Listed efficiencies are per AHRI Certified Rating data. VRF outdoor units are rated per AHRI Standard 1230 Performance Rating of VRF Multi-Split Air-Conditioning and Heat Pump Equipment.

Table 18: This table summarizes the key features of the Daikin, Mitsubishi and LG ccVRF offerings.

	Daikin VRV Aurora	**Mitsubishi R2-Series Hyper-Heat**	**LG Multi V5**
Model Number	RELQ120TATJU	PURY-HP120TNU	ARUM121BTE5
Capacity			
Capacity	10 ton	10 ton	10 ton
Type	Heat recovery	Heat recovery	Heat recovery
Cooling:			
Nominal capacity (BTUH)	114,000	120000	119700
Input power (KW)	8.1	not listed	7.72
Heating:			
Nominal capacity (BTUH)	129,000	135000	135000
Input power (KW)	9.47	not listed	9.2
Efficiencies (non-ducted/ducted)			
Cooling EER	13.7 / 12.4	13.2 / 12.1	13.1 / 12.5
Cooling IEER	23.4 / 19.6	24.4 / 19.7	29.6 / 24.6
Heating COP (47°F DB)	4.0 / 3.5	3.6 / 4.0	4.0 / 3.5
Heating COP (17°F DB)	2.3 / 2.3	2.3 / 2.3	2.7 / 2.5
SCHE	26.7 / 21.1	29.1 / 25.3	31.0 / 26.4
Operating range			
Cooling (F DB)	23 to 122	23 to 126	5 to 122
Heating (F WB)	-22 to 60	-22 to 60	-22 to 61
Refrigerant			

Refrigerant type	R410a	R410a	R410a
Refrigerant charge (lb)	25.8	23.8	23.3
Connection Capacity			
Max # indoor units	20	30	20
Compressor quantity	1	1	1
Power supply			
Voltage / Hz / phase	208-230/60/3	208-230/60/3	208-230/60/3
MOP	90	47	40
MCA	83.4	70	30.9
Rated load amps	39.3	-	26.3

There are many similarities between all three manufacturer offerings. All three products use similar refrigerant and refrigerant charge, and similar operating ranges. Each 10-ton unit has similar coefficient of performance (COP) of around 3.8 at 47°F which decreases to around 2.3 at 17°F. Figure 37 below shows unit heating performance for all three manufacturers across a range of outdoor temperatures. The graph shows heating capacity and input power at different outdoor air temperatures. When comparing unit performance data, you can see that VRF heating capacity begins to decrease between 5°F to 10°F. Above 10°F, the system maintains capacity and power input begins to decrease. Note that while all manufacturers have decreasing capacity below 5 F, Daikin maintains higher capacity for the majority of the cold climate range.

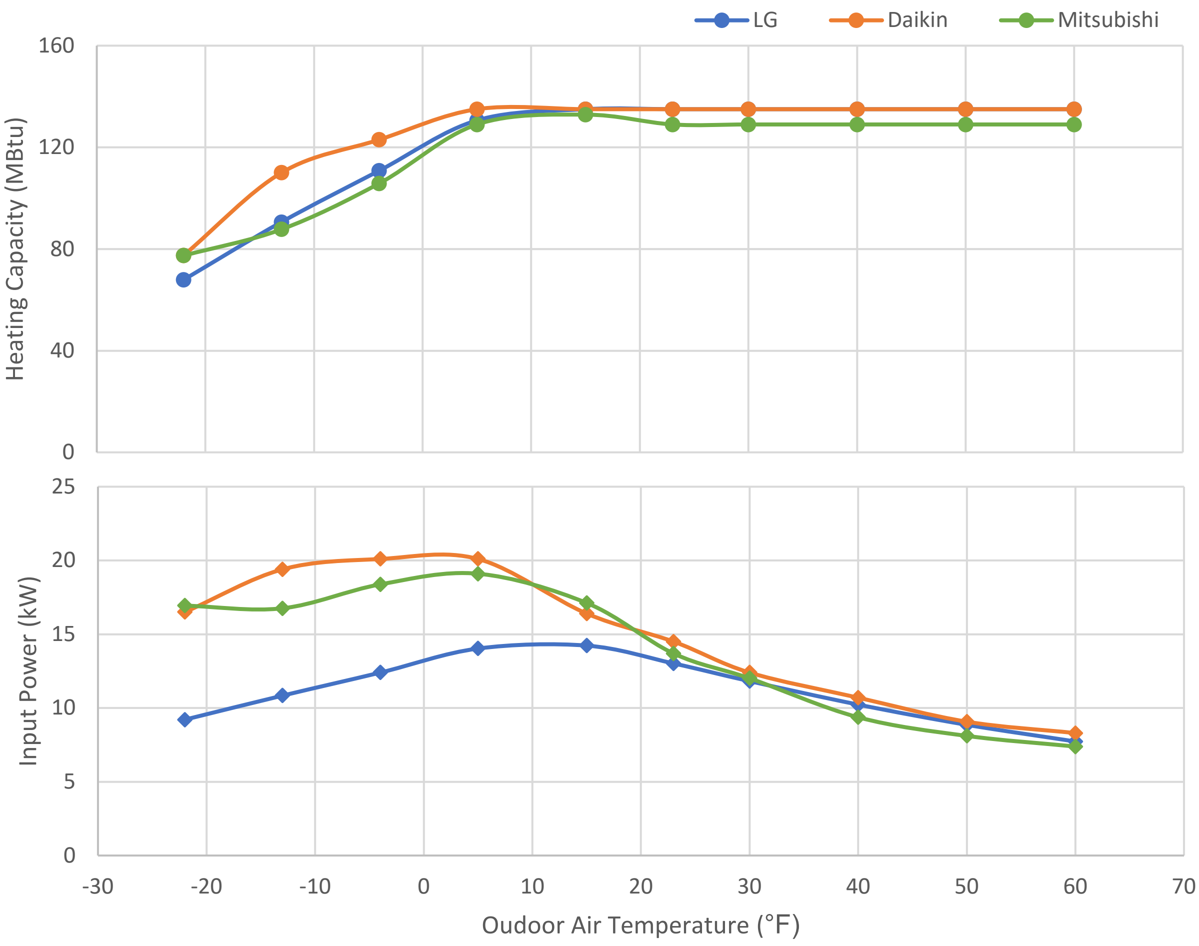


Figure 49: Heating capacity and input power across heating operating range.

Figure 38 shows the COP at different outdoor temperatures. Efficiency for each unit significantly decreases as outdoor temperature decreases. However, this graph also shows the energy saving potential of ccVRF systems, which can output three to five times the energy input when outdoor temperatures are between 25°F and 60°F, and only decreasing below twice the input energy when temperatures are less than 0°F outside. For reference, electric resistance heat has an energy output equal to the energy input or a COP of 1. Even for the very few hours each year when outdoor temperatures fall below -10°F, ccVRF systems will still be at least 30% more efficient than electric resistance heat sources. For the majority of heating hours, VRF systems will be 2-5 times (or 200-500%) more efficient than electric resistance heat.

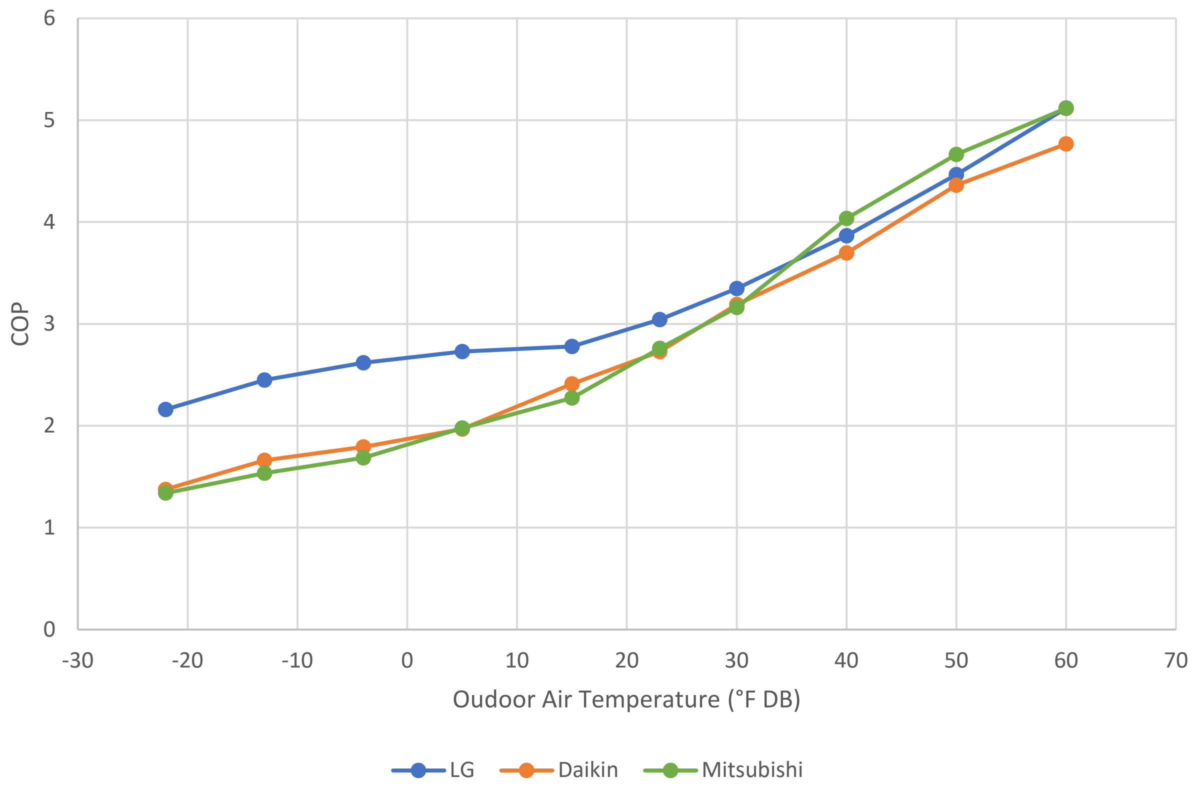


Figure 50: Heating COP across heating operating range.

Although performance declines in cold weather, even in Michigan these hours of poor operation are only for a small portion of the year. To illustrate this, Table 6 summarizes the hours per year in various heating temperature bins for two locations that bracket MECA service territory; Kalamazoo and Sault Ste. Marie. For Kalamazoo the total percentage of the year outdoor temperatures are below zero is 0.2% of the year, and for Sault Ste. Marie it's 2.5%. Per the manufacturer data above, those would be the times of the year that VRF heating capacity would decrease and COP would fall below 2.0. Engineers will still size units to meet the building load at design day temperatures, leading to oversized equipment for all other conditions where the units most frequently operate. So as a result of relatively low operating hours, we should recognize that the design implications of this new cold climate equipment – eliminating supplemental heat, simplifying controls, and allowing VRF to exist in spaces it wouldn't have been able to – are as (or more) important as the *efficiency* of the units at cold temperatures.

Table 19: Hours per year in each temperature bin for both Kalamazoo, MI and Sault St Marie, MI.

	Kalamazoo		Sault Ste Marie		Daikin
Outdoor Air Temperature	Number of Hours	% of Year	Number of Hours	% of Year	Heating COP
-20 to -15	0	0.0%	12	0.1%	1.5
-15 to -10	0	0.0%	25	0.3%	1.6

-10 to -5	5	0.1%	57	0.7%	1.7
-5 to 0	14	0.2%	125	1.4%	1.8
0 to 5	64	0.7%	244	2.8%	2.0
5 to 10	156	1.8%	359	4.1%	2.2
10 to 15	171	2.0%	400	4.6%	2.3
15 to 20	318	3.6%	509	5.8%	2.6
20 to 25	486	5.5%	431	4.9%	2.8
25 to 30	473	5.4%	662	7.6%	3.0
30 to 35	323	3.7%	797	9.1%	3.3
35 to 40	836	9.5%	649	7.4%	3.5
40 to 45	657	7.5%	685	7.8%	3.8
45 to 50	727	8.3%	723	8.3%	4.1
50 to 55	885	10.1%	731	8.3%	4.4
55 to 60	524	6.0%	722	8.2%	4.7

APPENDIX B: REFRIGERANT REVIEW

A critical piece of the future of VRF systems is understanding and managing the environmental impact of the refrigerant that is central to system operation. One of the biggest contributors to climate change are refrigerants (Drawdown 2017), which themselves have a much larger global warming potential (GWP) than carbon dioxide, which is the pollutant that is reduced as energy is saved by the VRF systems. As more HVAC systems transition from fossil fuel-based heating to electric based heating (VRF and heat pumps – refrigerant based), the impact of refrigerants on the climate could increase. This increase can be mitigated by selecting refrigerants with lower GWP, and by managing refrigerant to ensure it does not leak into the atmosphere.

REFRIGERANT SELECTION

Most VRF systems contain between four and six pounds of refrigerant per ton of cooling (Del Monaco 2016). In the United States, R-410A is typically the refrigerant used in VRF systems, while R-32 is used in Europe. R-32 is a near-term next generation refrigerant created by Daikin. It is expected that the United States will shift to using R-32 when legislation is passed to expedite the transition. Currently, the EPA has issued a phase-out of hydrofluorocarbon refrigerants (HFCs), including R-410A, beginning in 2024, and this phase-out may have cost impacts on VRF systems, as R-32 is not a drop in refrigerant for R-410A systems, meaning the piping, outdoor units, and fan coils would eventually need to be replaced (EPA 2018; Xylem Inc. 2018). The phase-out approach would allow this to happen at the convenience of most owners – owners would not be required to switch out equipment that is still operational. The most likely switch over would occur when units are at end of life and new equipment is purchased.

ASHRAE Standard 34 includes a list of over 160 proposed refrigerants that includes safety, toxicity, and flammability information. By this standard, R-410A is classified as non-flammable, nontoxic, and with zero ozone depletion potential (ODP) (Jankovic 2016). However, HFCs, including R-410A, have significant impacts on global warming when released to the atmosphere (DOE 2014). New refrigerants are being rapidly developed, and next-generation non-flammable refrigerants are very attractive as they have a relatively short persistence in the atmosphere. This results in both a low ODP and low GWP. Key players in the next generation refrigerant market include AGC Inc., Arkema SA, ASPEN Refrigerants, Inc., Daikin Industries, Ltd., Global Refrigerants, Harp International Ltd., Honeywell International Inc., SRF Limited, Tazzetti S.p.A., The Chemours Company, and The Linde Group, among others (Research and Markets 2018). Figure 39 shows the global warming potential of several refrigerants, including R-410A and R-32.

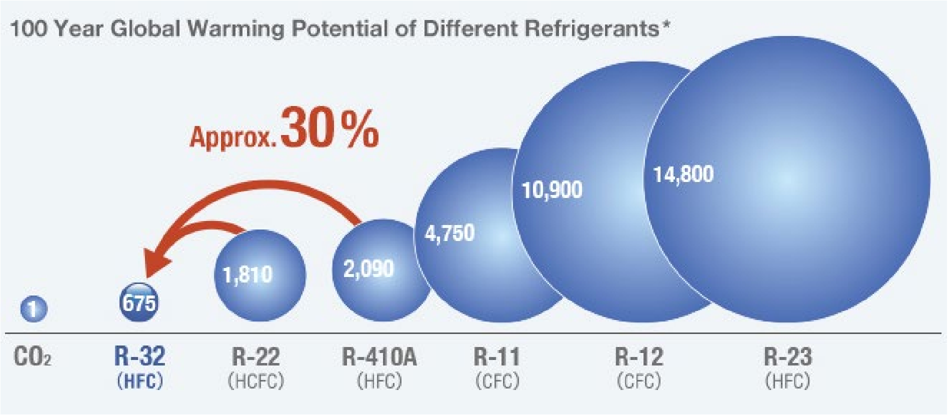


Figure 51: Credit Daikin. Values for 100 year global warming potential (GWP) from IPCC Fourth Assessment Report. Comparative 100 year GWP: HFC410A, 2,090; HFC32, 675.

Hydrofluoroolefins (HFOs) are one class of next generation refrigerants. Examples of HFOs are R513A and R514A, which are already being used in commercial and institutional HVAC equipment (Trane 2018). The other class of next generation refrigerants is "natural refrigerants", which include propane (R-290), ammonia (R-717), and carbon dioxide (R-744). Natural refrigerants are attractive due to their extremely low GWPs and ODPs. For example, carbon dioxide has a GWP of 1 and propane has a GWP of 3, compared to GWPs in the thousands for most HFCs. However, most natural refrigerants (except carbon dioxide) are more toxic and/or flammable than traditional refrigerants (Tatum 2017). Barriers to using natural refrigerants are the up-front system costs, additional contractor training required, and energy performance.

The future of refrigerants in the United States will be driven by federal, state and building codes. Currently, HFCs are being phased out, which indicates that R-410A will be produced to service R-410A equipment that was installed prior to the transition – extending the service life of this equipment (typical service life 15-25 years). Daikin, as the producer of R-32, has committed to this refrigerant to replace R-410A. Mitsubishi and LG have not publicly stated which refrigerant will replace R-410A in their systems. The earliest the market may see R-32 in VRF systems is 2024. At this point, there is no clear link to the use of natural refrigerants in VRF systems.

REFRIGERANT LEAKAGE AND MANAGEMENT

While refrigerant leakage can be a problem for many different HVAC systems, it is particularly relevant for VRF systems because the refrigerant is not contained in a single appliance (e.g. chiller or air conditioner), rather it is piped around the building to various spaces, many of which are occupied. The possibility of a refrigerant leakage is therefore not just a climate change consideration but also must be a human safety concern.

Beginning January 1, 2019, the EPA implemented new rules regarding the regulation of HFC refrigerant (e.g. R-410A) systems. The threshold leak rate was lowered to 10% loss annually, and those systems exceeding that leak rate must be repaired within 30 days or face mandatory shutdown or replacement. While reports of typical leak rates are scarce, in one study the United

States Military Service reported an annual leak rate of approximately 25% in 2017 (DOD 2019). At the state level, the California Air Resources Board's (CARB) Refrigeration Management Program (RMP) requires that all systems containing more than 50 lbs of high-GWP refrigerant conduct and report periodic leak inspections. These inspections must be performed every three months or annually depending on the size of the system (CARB 2019).

Generally, refrigerant leaks in VRF systems are difficult to detect and locate due to the sheer size of most systems and the fact that piping is usually difficult to access. When a leak has occurred, replacement of the refrigerant in the system is often done inadequately because it is challenging to determine exactly how much refrigerant was lost (Sabeer 2016). However, the EPA requires the leak rate to be calculated each time substitute refrigerant is added, and owners must submit reports to the EPA if their systems contain 50 or more pounds of refrigerant and have leaked 125% or more of their full charge in one year. Finally, quarterly or annual leak inspections or continuous monitoring devices are required for systems that have exceeded the threshold leak rate (10% as of January 1, 2019) (EPA 2018).

The VRF manufacturers state that VRF systems that are properly installed should not leak, but refrigerant leaks do occur due to poor installation practices and other factors. For example, in VRF systems, the leaks usually occur at the flare connections at the fan coil unit or in the direct expansion (DX) coil. The flare fitting connections require sufficient torque to prevent leaks (Turpin 2018). Flare fittings are also becoming more popular in the market due to their ability to bring down the overall installed costs of VRF systems.

Several approaches exist for managing leaks. First, refrigerant leak detection monitors can be utilized to identify leaks early-on, and the ASHRAE 15 Standard requires a detector in some cases. These can be hand-held devices that are used to spot-check an installation for leaks or a monitor left in the space to warn occupants if a leak occurs (e.g. Bacharach multizone gas leak monitor). Some can be integrated with any BMS/BAS. Because refrigerant is denser than air, the detector should be placed about a foot from the ground (Burniston 2017). Some VRF manufacturers are even starting to include leak detection and containment systems that provide constant monitoring within the overall VRF system (Cunniff 2013; IOR 2019). Solenoid valves, which can shut off the flow of the refrigerant, can be coupled with a monitoring or detection system for added safety (P.A. Collins P.E. 2016).

Second, careful installation of the systems by a skilled, qualified professional is critical. It has been reported that issues with VRF systems are most commonly caused by contractors who didn't follow industry standards during installation. Semiannual maintenance is also critical to prolonging the life of the systems (Krawcke 2016). As flared joints are a common source of leaks, some manufacturers are moving away from those. During installation, pipes should remain sealed as much as possible in order to minimize entry of moisture into the system. During pipe brazing, pipes should be purged with nitrogen gas to prevent formation of a carbon layer inside the pipe, which will clog the filters over time. It is recommended that isolation valves with service ports are included in the branch lines for each indoor unit so that the unit can be moved or repaired without affecting the operation of the rest of the system (Jacksons 2012).

Finally, after installation, systems must be thoroughly pressure tested to identify leaks. Then, systems must be evacuated to remove air and moisture and to check for additional leaks. Evacuation can take days depending on the size of the system and requires proper use and maintenance of the vacuum pump. Due to the time and money required for a proper triple evacuation procedure of a VRF system, contractors may cut corners. Requiring detailed commissioning sheets may aid with adherence to the proper procedure (Jacksons 2012).

Figure 40 below shows the estimated annual global warming potential (expressed in lbs of CO2 emissions) from switching to a VRF system. The GWP savings are calculated based on the energy model results for a building in Sault Ste. Marie. Refer to Section 3 for more details regarding the energy model. The building is assumed to have a 20-ton VRF system, with an estimated 100 pounds of refrigerant. The green bars show the annual amount of CO2 emissions reduced by switching to the more energy efficient VRF system, while the red bars show the estimated CO2 emissions *increase* due to annual refrigerant leakage compared to a 20-ton rooftop unit.

Using the EPA maximum allowable 10% refrigerant leakage rate, switching to a VRF system would add approximately twice the CO2 to the atmosphere than the CO2 that would be saved through efficiency (reduced gas and electricity consumption). This is a significant finding and impact on the environment for VRF systems. There are multiple ways to improve this outcome. First, if the leakage rate is reduced to 5%, the CO2 emissions from refrigerant leakage will decrease. This is shown in the center set of bars, where, with a 5% leakage rate, the switch to a VRF system results in a net positive CO2 emissions reduction. The second option is to utilize a refrigerant with a lower GWP than R-410A, such as R-32. This scenario is presented in the right set of bars. New lower GWP refrigerants will significantly reduce the impact of refrigerant leakage on the environment.

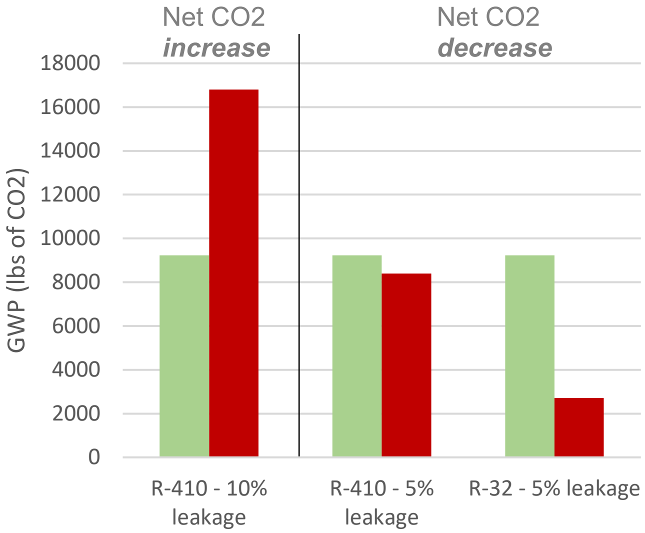
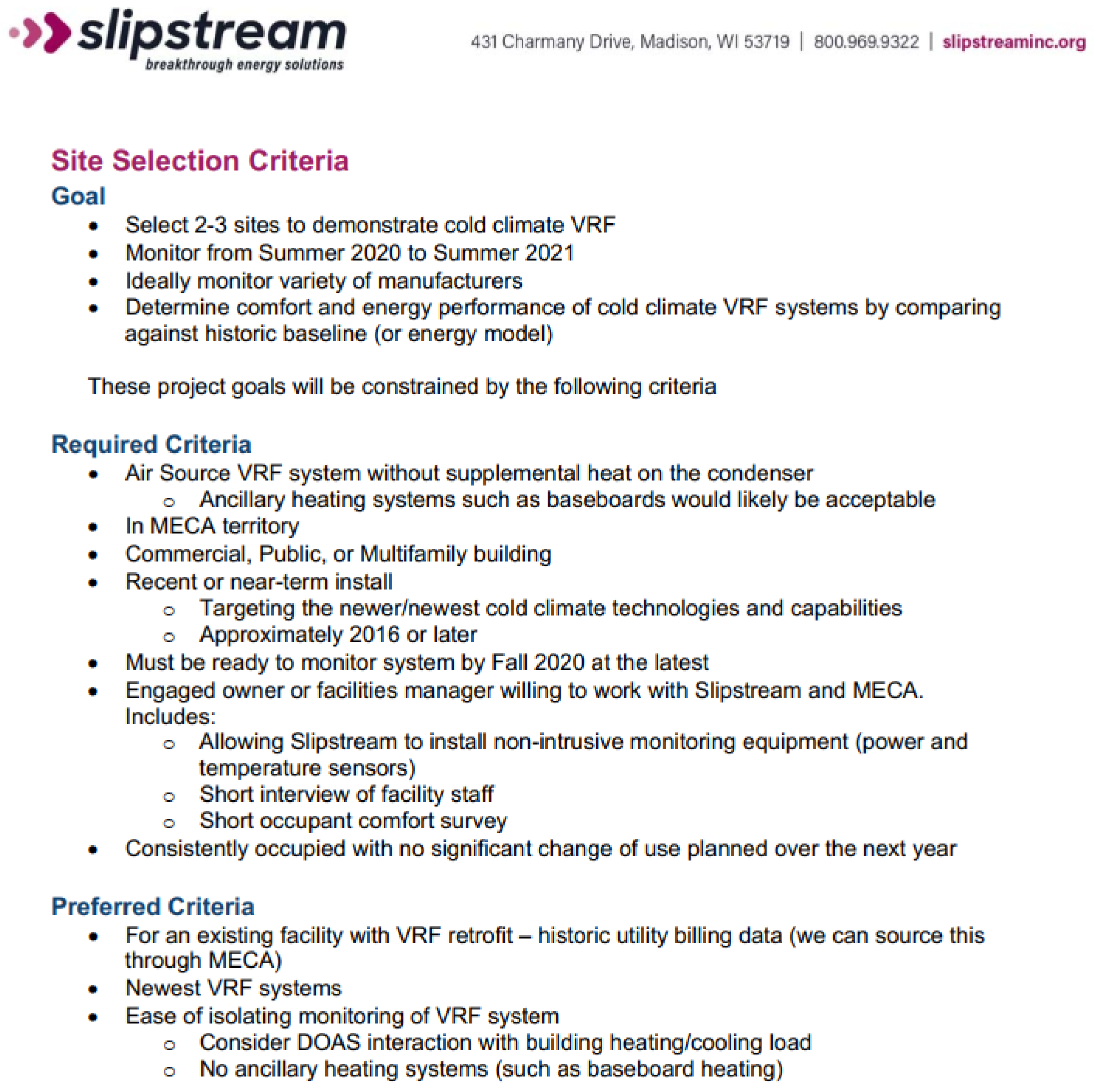


Figure 52: This figure shows the environmental impact of implementing a VRF system. Bars in green represent global warming potential (GWP) in equivalent CO2 emissions reduced through energy savings (in comparison to a traditional RTU). Bars in red represent equivalent CO2 emissions increased due to refrigerant leakage.

APPENDIX C: SITE SELECTION CRITERIA



431 Charmany Drive, Madison, WI 53719 | 800.969.9322 | slipstreaminc.org

Site Selection Criteria

Goal

- Select 2-3 sites to demonstrate cold climate VRF
- Monitor from Summer 2020 to Summer 2021
- Ideally monitor variety of manufacturers
- Determine comfort and energy performance of cold climate VRF systems by comparing against historic baseline (or energy model)

These project goals will be constrained by the following criteria

Required Criteria

- Air Source VRF system without supplemental heat on the condenser
    - Ancillary heating systems such as baseboards would likely be acceptable
- In MECA territory
- Commercial, Public, or Multifamily building
- Recent or near-term install
    - Targeting the newer/newest cold climate technologies and capabilities
    - Approximately 2016 or later
- Must be ready to monitor system by Fall 2020 at the latest
- Engaged owner or facilities manager willing to work with Slipstream and MECA. Includes:
    - Allowing Slipstream to install non-intrusive monitoring equipment (power and temperature sensors)
    - Short interview of facility staff
    - Short occupant comfort survey
- Consistently occupied with no significant change of use planned over the next year

Preferred Criteria

- For an existing facility with VRF retrofit – historic utility billing data (we can source this through MECA)
- Newest VRF systems
- Ease of isolating monitoring of VRF system
    - Consider DOAS interaction with building heating/cooling load
    - No ancillary heating systems (such as baseboard heating)

APPENDIX D: INTERVIEW GUIDES

APPENDIX E: SITE MONITORING PLAN – STAFFORD PERRY

MECA VRF
Hobo installation
Slipstream 12/2020

If any problems/questions, call Allie Cardiel: 608-669-4481 (can text and Facetime, too)

Parts supplied

- MX1101 Temp/RH Hobo **(30)**
- MX2302A ext. Temp/RH Hobo **(1)**
- White radiation shield **(1)**
- Mounting gear: fishing line, zip ties, 3M adhesive, velcro straps, hose clamps

Instructions for Hobo installation (by contractor)

1. Place an MX1101 Hobo device in each of these rooms/locations:
    - Room: 311, 312, 314, 315, 317x2, 320, 328, 3rd fl hallway x2
    - Room: 411, 412, 414, 415, 416x2, 426, library, 4th fl hallway x2
    - Find an inconspicuous/hidden location to place the device in the room (e.g. on top edge of framed art, on top of wardrobe/closet), **away from air register, supply vents, and windows.**
    - Make sure device is securely fastened using something like the following: fishing line, velcro straps, zip ties, 3M adhesive
    - **Take photo** in each room from as far back as possible to show placement of hobo. **Identify the room number** in the photo in some way (e.g. sticky note with room number).
    - **Record room number, Hobo serial number, and location on form.**
2. Place an MX1101 Hobo device on one supply air vent in each of these rooms/locations:
    - Room: 311, 312, 314, 315, 3rd fl hallway
    - Room: 411, 412, 414, 415, 4th fl hallway
    - Use fishing line or zip tie to fasten device to grille of supply vent
    - **Take photo** in each room from as far back as possible to show placement of hobo. **Identify the room number** in the photo in some way (e.g. sticky note with room number).
    - **Record room number, Hobo serial number, and location on form.**
3. Place MX2302A hobo on roof.
    - Find pipe or frame away from vents and heat sources, secure radiant shield in upright position using hose clamps or zip ties.
    - Secure Hobo with zip ties or screws (no hose clamps) so the cable exits the **bottom** of the device to prevent water entry.

    - Make sure blue LED is flashing at about 4 second intervals.

4. Place MXGTW1 (MX Gateway) in attic**.** Plug in power supply. The **light will turn a constant green** (no blinking) once it has successfully connected wirelessly to the AT&T hotspot (may take ~5 min). If blinking green, yellow, or red, call Allie to troubleshoot.
5. Attach a “Do not unplug” tag to the MX Gateway power supply, near the outlet.
6. **Call Allie at 608-669-4481 to confirm the Hobos are successfully online.** We may need to place another MX Gateway depending on the proximity to all the MX1101 devices.
7. **Take photo or scan of installation form and email to acardiel@slipstreaminc.org.**
8. **Email all photos to acardiel@slipstreaminc.org.**

Room number	Hobo serial number	Location in room/hallway

MECA VRF
eGauge installation
Slipstream 12/2020

If any problems/questions, call Allie Cardiel: 608-669-4481 (can text and Facetime, too)

Parts supplied:

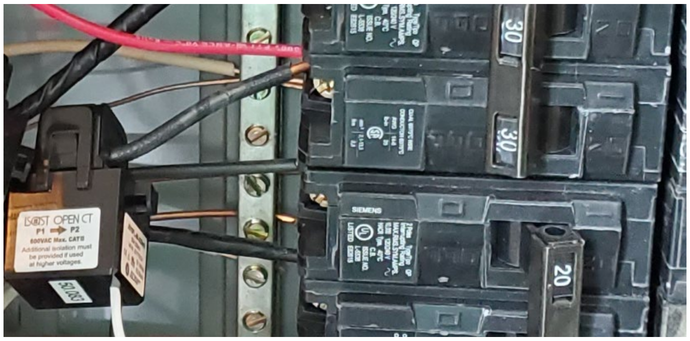
- eGauge device **(5)**: 59360, 59361, 59362, 59363, 59364 **(last two digits are ID #'s below)**
- CTs
    - Whole panel: **(6)** 200A, **(3)** 400A
    - FCUs: **(36)** 50A
    - VRFs: **(12)** 100A
    - A/C: **(1)** 50A
    - MUA: **(2)** 50A
    - ERV: **(1)** 50A
    - Extras: **(1)** 400A, **(2)** 200A, **(3)** 100A, **(5)** 50A
- Switch & power supply: **(1)** Black D-Link with 8 ports
- Wi-Fi client device & power supply: **(1)** White TP-Link
- Hotspot & power supply: **(1)** Black AT&T Unitepro (Netgear) 7W_05
- eGauge voltage connection plugs (Green plug with red, blue, black cables) **(6)**
- Ethernet cables: **(2)** 100 ft, **(1)** 75 ft, **(2)** 50 ft, **(5)** 3 ft

Contractor to supply

- 12-14 ga wire for voltage/neutral taps
- **(9)** circuit breakers for voltage tap lines (1 for each phase at each panel)

Instructions for eGauge installation (by contractor)

9. Open panel, identify circuit breakers that are of interest **according to the form**.
10. Complete steps 3-18 for **one** eGauge **before moving to the next**, so we can check setup.
11. Clip CTs on wires. All CTs should be installed with **manufacturer's label facing circuit breaker (i.e. label faces source of power)**. Ignore arrows, ignore other markings.

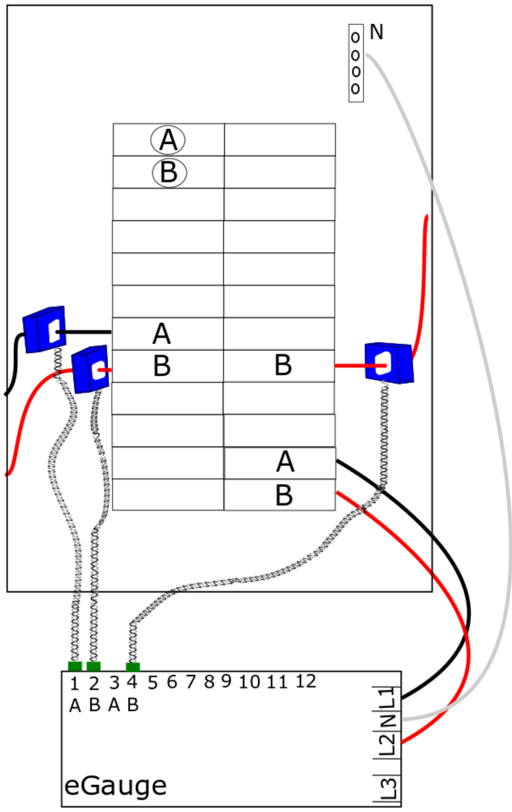


12. J&D CTs have a double-click latching mechanism, and getting the second click can be challenging. **Make sure CTs are double-clicked to close completely**.
13. The wire leads on J&D CTs are susceptible to pulling loose – **handle gently**
14. On the form, **document the CT number that you use for each circuit.**
15. Connect **neutral and voltage** lines on eGauge (located on shorter side of device).
    - If no neutral available, use ground for the N terminal.
16. Connect all voltage phases:
    - The voltage phase feeding breaker #1 will be called Line 1 (or Phase A). Choose a circuit on Phase A to connect that phase to the L1 terminal on the eGauge. **Label that circuit with an "L1-6_" on the form, filling in last digit of eGauge number.**
    - The voltage phase feeding breaker #3 will be called Line 2 (or Phase B). Choose a circuit on Phase B to connect that phase to the L2 terminal on the eGauge. **Label that circuit with an "L2-6_" on the form, filling in last digit of eGauge number.**
    - The voltage phase feeding breaker #5 will be called Line 3 (or Phase C). Choose a circuit on Phase C to connect that phase to the L3 terminal on the eGauge. **Label that circuit with an "L3-6_" on the form, filling in last digit of eGauge number.**
    - Use open circuit breakers if available, or install new breakers, or double-tapping is usually acceptable for a temporary installation.
17. Connect CT leads to eGauge **according to input numbers listed on form**.
18. Turn on circuit breakers to power eGauge.
19. Connect the Ethernet cable to the port on the eGauge.
20. **Take photos of each panel**, some up close and some showing whole panel.
21. Run the ethernet cable through the wall to the attic (where switch & wifi client device are).
22. Plug the ethernet cables from all the eGauges into the black D-Link switch.
23. Plug an ethernet cable into the black D-Link switch and plug the other side of that cable into the white TP-Link device.
24. **Plug in** and **power on** black AT&T hotspot (Netgear). Take photo of screen to show strength of connection (i.e. how many bars).
25. **Plug in** power supplies and **power on** the D-Link switch and TP-Link device.
26. Attach "Do not unplug" tag to power strip, near outlet.
27. **Call Allie at 608-669-4481 to confirm the eGauges are successfully online.**

28. **Take photo or scan of installation form and email to acardiel@slipstreaminc.org.**
29. **Email all photos to acardiel@slipstreaminc.org.**

If any problems/questions, call Allie Cardiel: 608-669-4481 (can text and Facetime, too)

Visual Aids:



Top: CTs
Middle: egauge voltage connections
Bottom: egauge CT connections

Project: MECA VRF **egauge #: 59360 (60) & 59361 (61)**

Site: **Staford Perry Hotel**

Panel: **3rd Fl - Right** **Photos?**

Date:

L1 L2 L3	egauge input #	CT #		Load		Load		CT #	egauge input #	L1 L2 L3
	1 (60)	200.____	A	**Whole Panel**		**Whole Panel**	B	200.____	2 (60)	
	3 (60)	200.____	C	**Whole Panel**						
	4 (60)	50.____	1	FCU 326	A	**FCU 314**	2	50.____	14 (60)	
	5 (60)	50.____	3	FCU 326	B	**FCU 314**	4	50.____	15 (60)	
			5		C	FCU ?	6	50.____	1 (61)	
			7		A	FCU ?	8	50.____	2 (61)	
	6 (60)	50.____	9	FCU 328	B	FCU 312	10	50.____	3 (61)	
	7 (60)	50.____	11	FCU 328	C	FCU 312	12	50.____	4 (61)	
	8 (60)	50.____	13	FCU 320	A	FCU 316	14	50.____	5 (61)	
	9 (60)	50.____	15	FCU 320	B	FCU 316	16	50.____	6 (61)	
	10 (60)	50.____	17	FCU 318	C	FCU 317	18	50.____	7 (61)	
	11 (60)	50.____	19	FCU 318	A	FCU 317	20	50.____	8 (61)	
	12 (60)	50.____	21	FCU ?	B	FCU 324	22	50.____	9 (61)	
	13 (60)	50.____	23	FCU ?	C	FCU 324	24	50.____	10 (61)	
			25		A		26			
			27		B		28			
			29		C		30			
			31		A		32			
			33		B		34			
			35		C		36			
			37		A		38			
			39		B		40			
			41		C		42			

Project: **MECA VRF** **egauge #: 59362 (62) & 59363 (63)**

Site: **Staford Perry Hotel**

Panel: **4th Fl - Right** **Photos?**

Date: **Note: use Ground for eGauge "N" input**

L1 L2 L3	input # (egauge #)	CT #		Load		Load		CT #	egauge input #	L1 L2 L3
	1 (62)	400.____	**A**	**Whole Panel**		**Whole Panel**	**B**	400.____	2 (62)	
	3 (62)	400.____	**C**	**Whole Panel**						
	4 (62)	100.___	1	VRF #1	**A**		2			
	5 (62)	100.___	3	VRF #1	**B**		4			
	6 (62)	100.___	5	VRF #1	**C**	Rooftop A/C	6	50.___	3 (63)	
			7		**A**	Rooftop A/C	8			
			9		**B**		10			
	7 (62)	100.___	11	VRF#2	**C**		12			
	8 (62)	100.___	13	VRF#2	**A**	VRF#4	14	100.___	4 (63)	
	9 (62)	100.___	15	VRF#2	**B**	VRF#4	16	100.___	5 (63)	
	10 (62)	100.___	17	VRF#3	**C**	VRF#4	18	100.___	6 (63)	
	11 (62)	100.___	19	VRF#3	**A**	FCU 417	20	50.___	7 (63)	
	12 (62)	100.___	21	VRF#3	**B**	FCU 417	22			
	13 (62)	50.___	23	FCU 418	**C**		24			
			25	FCU 418	**A**		26			
	14 (62)	50.___	27	FCU 424 etc	**B**	FCU 413	28	50.___	8 (63)	
			29	FCU 424 etc	**C**	FCU 413	30			
	15 (62)	50.___	31	FCU 412	**A**	FCU 415	32	50.___	9 (63)	
			33	FCU 412	**B**	FCU 415	34			
	1 (63)	50.___	35	FCU 414	**C**		36			
			37	FCU 414	**A**		38			
	2 (63)	50.___	39	FCU 416	**B**		40			
			41	FCU 416	**C**		42			

Project: **MECA VRF** **egauge #: 59364**

Site: **Staford Perry Hotel**

Panel: **4th Fl - Left** **Photos?**

Date:

L1 L2 L3	egauge input #	CT #		Load		Load		CT #	egauge input #	L1 L2 L3
	1	200.____	**A**	**Whole Panel**		**Whole Panel**	**B**	200.____	2	
	3	200.____	**C**	**Whole Panel**						
			42		**A**		41			
			40		**B**		39			
			38		**C**		37			
			36		**A**	FCU 419	35	50.____	5	
			34		**B**	FCU 419	33	50.____	6	
			32		**C**	FCU 428	31	50.____	7	
			30		**A**	FCU 428	29	50.____	8	
			28		**B**	FCU 420	27	50.____	9	
			26		**C**	FCU 420	25	50.____	10	
			24		**A**		23			
			22		**B**		21			
			20		**C**		19			
			18		**A**		17			
			16		**B**		15			
			14		**C**		13			
			12		**A**		11			
	4	50.____	10	ERV	**B**		9			
			8		**C**	Make Up Air	7	50.____	11	
			6		**A**	Make Up Air	5	50.____	12	
			4		**B**		3			
			2		**C**		1			

MECA VRF
Rooftop Hobo installation
Slipstream 10/2021

If any problems/questions, call Allie Cardiel: 608-669-4481 (can text and Facetime, too)

Parts supplied

- MX2302A ext. Temp/RH Hobo **(1)**
- White radiation shield **(1)**
- Mounting gear: screws, zip ties, hose clamps

Instructions for Hobo installation (by contractor)

30. Place MX2302A hobo on roof.
    - Find pipe or frame away from vents and heat sources, secure radiant shield in upright position using hose clamps or zip ties. **Can use same location as before.**
    - Secure Hobo with zip ties or screws (no hose clamps) so the cable exits the **bottom** of the device to prevent water entry.
    - Make sure blue LED is flashing at about 4 second intervals.
31. **Call or text Allie at 608-669-4481 to confirm the Hobo is successfully online.**
32. **Take photo and text or email to acardiel@slipstreaminc.org.**

For reference, here is where the logger was placed before, and it's fine to place here again (SE side of roof):

APPENDIX F: SITE MONITORING PLAN – DRURY

MECA VRF - Drury
Hobo installation
Slipstream 2/2021

If any problems/questions, call Allie Cardiel: 608-669-4481 (can text and Facetime, too)

Parts supplied

- MX1101 Temp/RH Hobo **(24)**
- MX2302A ext. Temp/RH Hobo + white radiation shield **(1)**
- Mounting gear: fishing line, zip ties, 3M adhesive, velcro straps, hose clamps
- MX Gateways & power supply **(4)**
- White TP-Link & power supply **(2)**
- Edgerouter & power supply **(2)**
- Netgear cell modem/hotspot & power supply **(2)**
- Ethernet cables: **(1)** 50 ft, **(3)** 25 ft, **(6)** 3 ft
- Power strips **(2)**

Instructions for Hobo installation (by contractor)

33. Place an MX1101 Hobo device in each of these rooms:
    - Room: 611, 613, 614, 616, 618, 619, 620, 621
    - Room: 711, 713, 714, 716, 718, 719, 720, 721
    - Find an inconspicuous/hidden location to place the device in the room (e.g. on top edge of framed art, on back of side table), **away from air register, supply vents, and windows.**
    - Make sure device is securely fastened using something like the following: fishing line, velcro straps, zip ties, 3M adhesive
    - **Take photo** in each room from as far back as possible to show placement of hobo. **Identify the room number** in the photo in some way (e.g. sticky note with room number).
    - **Record room number, Hobo serial number, and location on form.**
34. Place an MX1101 Hobo device on/in the two supply air vents in each of these rooms:
    - Room: 614, 616
    - Room: 714, 716
    - Use fishing line or zip tie to fasten device to grille of supply vent
    - **Take photo** in each room to show placement of hobo. **Identify the room number** in the photo in some way (e.g. sticky note with room number).
    - **Record room number, Hobo serial number, and location on form. Please differentiate the two supply air vents (e.g. large or small).**

35. Place MX2302A hobo on roof.
    - Find pipe or frame away from vents and heat sources, secure radiant shield in upright position using hose clamps or zip ties.
    - Secure Hobo with zip ties or screws (no hose clamps) so the cable exits the **bottom** of the device to prevent water entry.
    - Make sure blue LED is flashing at about 4 second intervals.
36. Place Netgear cell modem in drop ceiling next to elevator hallway**.**
    - Plug Netgear power suppy into power strip, **all lights should turn solid green**
    - Plug ethernet cable from Netgear cell modem to Edgerouter **(port 0)**
    - Plug ethernet cable from TP-Link Access Point SS_0X to Edgerouter (any port)
        - SS_06 = 6th floor
        - SS_07 = 7th floor
    - Plug power supplies for TP-Link and Edgerouter into power strip
    - **Make sure all devices are powered on**
37. Place MX Gateway in drop ceiling next to elevator hallway**.**
    - Plug power supply into power strip.
    - Plug ethernet cable from MX Gateway to Edgerouter (any port)
    - The light on the MX Gateway will turn **a constant green** (no blinking) once it has successfully connected to the internet (may take ~5 min). If blinking green, yellow, or red, call Allie to troubleshoot.
38. Attach a "Do not unplug" tag to the power strip, near the outlet.
39. **Call Allie at 608-669-4481 to confirm the Hobos are successfully online.** We may need to place another MX Gateway depending on the proximity to all the MX1101 devices.
40. **Take photo or scan of installation form and text to 608-669-4481 or email to acardiel@slipstreaminc.org.**
41. **Email or text all photos.**

Room number	Hobo serial number	Location in room
Roof	21004834	
	21006174	
	21006175	
	21006176	
	21006177	
	21006178	
	21006179	
	21006180	
	21006181	
	21006182	
	21006183	
	21006184	
	21006185	
	21006186	
	21006187	
	21006188	
	21006189	
	21006190	
	21006191	
	21006192	
	21006193	
	21006194	
	21006195	
	21006196	
	21006197	

MECA VRF - Drury
eGauge installation
Slipstream 2/2021

If any problems/questions, call Allie Cardiel: 608-669-4481 (can text and Facetime, too)

Parts supplied:

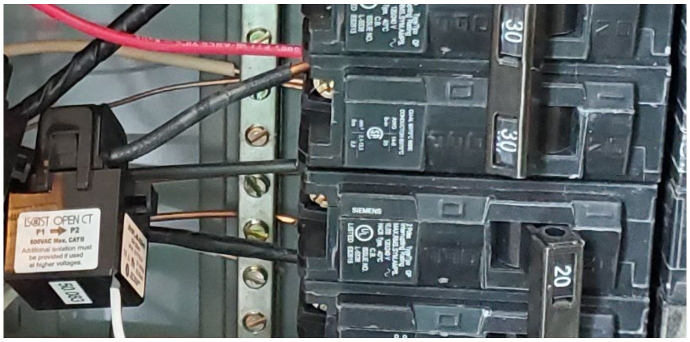
- eGauge device **(4)**: 60237, 60238, 60239, 60240 **(last two digits are ID #'s below)**
- CTs
  - Whole panel: **(6)** 600A
  - FCUs: **(16)** 50A
  - ERUs: **(6)** 50A
  - ERCUs: **(6)** 75A
  - HRs: **(12)** 50A
  - Extras: **(3)** 2775A, **(6)** 100A, **(5)** 50A
- Switch & power supply: **(2)** Black D-Link with 8 ports
- Wi-Fi client device & power supply: **(2)** White TP-Link
- eGauge voltage connection plugs (Green plug with red, blue, black cables) **(5)**
- Ethernet cables: **(2)** 100 ft, **(4)** 50 ft, **(2)** 3 ft
- Power strips **(2)**

Contractor to supply

- 12-14 ga wire for voltage/neutral taps
- **(9)** circuit breakers for voltage tap lines (1 for each phase at each panel)

Instructions for eGauge installation (by contractor)

42. Open panel, identify circuit breakers that are of interest **according to the form**.
43. Complete steps 3-18 for **one** eGauge **before moving to the next**, so we can check setup.
44. Clip CTs on wires. All CTs **except mains** should be installed with **manufacturer's label facing circuit breaker (i.e. label faces source of power)**. <u>Ignore arrows.</u>

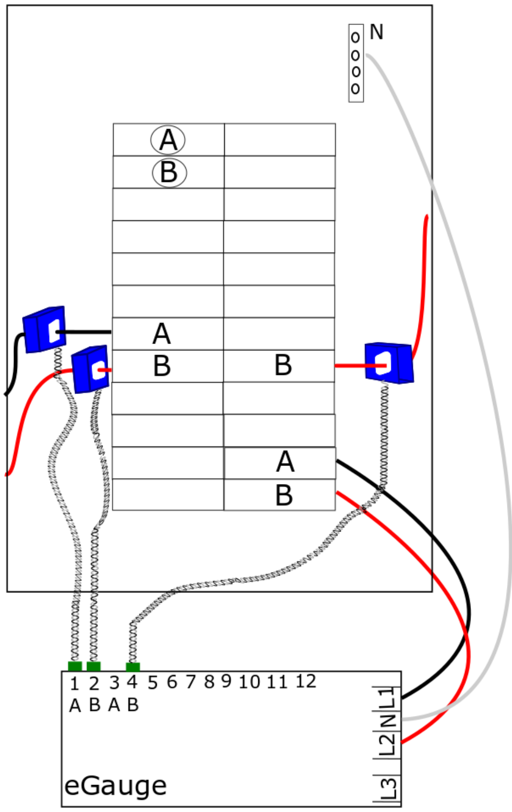


45. J&D CTs have a double-click latching mechanism, and getting the second click can be challenging. **Make sure CTs are double-clicked to close completely**.
46. The wire leads on J&D CTs are susceptible to pulling loose – **handle gently**
47. On the form, **document the CT number that you use for each circuit.**
48. Connect **neutral and voltage** lines on eGauge (located on shorter side of device).
    - If no neutral available, use ground for the N terminal.

49. Connect all voltage phases:
    - The voltage phase feeding 1st breaker will be called Line 1 (or Phase A). Choose a circuit on Phase A to connect that phase to the L1 terminal on the eGauge. **Label that circuit with an "L1-_" on the form, filling in last 2 digits of eGauge number.**
    - The voltage phase feeding 3rd breaker will be called Line 2 (or Phase B). Choose a circuit on Phase B to connect that phase to the L2 terminal on the eGauge. **Label that circuit with an "L2-_" on the form, filling in last 2 digits of eGauge number.**
    - The voltage phase feeding 5th breaker will be called Line 3 (or Phase C). Choose a circuit on Phase C to connect that phase to the L3 terminal on the eGauge. **Label that circuit with an "L3-_" on the form, filling in last 2 digits of eGauge number.**
    - Use open circuit breakers if available, or install new breakers, or double-tapping is usually acceptable for a temporary installation.
50. Connect CT leads to eGauge **according to input numbers listed on form**.
51. Turn on circuit breakers to power eGauge.
52. Connect the Ethernet cable to the port on the eGauge.
53. Run the ethernet cable out of the electrical panel
    - 6th floor: plug ethernet cable into white TP-Link Client SS_06
    - 7th floor: plug the ethernet cables from all the eGauges into the black D-Link switch. Plug an ethernet cable into the black D-Link switch and plug the other side of that cable into the white TP-Link Client SS_07.
54. **Plug power supplies into power strip** and **power on** the D-Link switch and TP-Link devices.
55. Attach "Do not unplug" tag to power strip, near outlet.
56. **Call Allie at 608-669-4481 to confirm the eGauges are successfully online.**
57. **Take photos of each panel**, some up close and some showing whole panel.
58. **Take photo or scan of installation form and text to 608-669-4481 or email to acardiel@slipstreaminc.org.**
59. **Email or text all photos.**

If any problems/questions, call Allie Cardiel: 608-669-4481 (can text and Facetime, too)

Visual Aids:

	  
	Top: CTs Middle: egauge voltage connections Bottom: egauge CT connections

Project: MECA VRF **egauge #: 60237**

Site: Drury Hotel

Panel: 6th Floor L6 **Photos?**

Date: 2/21

L1 L2 L3	egauge input #	CT #		Load		Load		CT #	egauge input #	L1 L2 L3
			A	Whole Panel		Whole Panel	B			
			C	Whole Panel						
			43		A		44			
			45		B		46			
			47		C		48			
			49		A		50			
			51		B		52			
			53		C		54			
			55		A		56			
			57		B		58			
			59		C		60			
			61		A		62			
			63		B		64			
			65		C		66			
			67		A		68			
			69		B		70			
			71		C		72			
			73		A		74			
			75		B		76			
	1	50.___	77	Fan Coils Left	C	Fan Coils Right	78	50.___	5	
	2	50.___	79	Fan Coils Left	A	Fan Coils Right	80	50.___	6	
	3	50.___	81	Fan Coils Left	B	Fan Coils Right	82	50.___	7	
	4	50.___	83	Fan Coils Left	C	Fan Coils Right	84	50.___	8	

Project: **MECA VRF** **egauge #: 60238**

Site: **Drury Hotel**

Panel: **7th Floor L7** **Photos?**

Date: 2/21

L1 L2 L3	egauge input #	CT #		Load		Load		CT #	egauge input #	L1 L2 L3
			A	**Whole Panel**		**Whole Panel**	**B**			
			C	**Whole Panel**						
			43		**A**		44			
			45		**B**		46			
			47		**C**		48			
			49		**A**		50			
			51		**B**		52			
			53		**C**		54			
			55		**A**		56			
			57		**B**		58			
			59		**C**		60			
			61		**A**		62			
			63		**B**		64			
			65		**C**		66			
			67		**A**		68			
			69		**B**		70			
			71		**C**		72			
			73		**A**		74			
			75		**B**		76			
	1	50.___	77	Fan Coils Left	**C**	Fan Coils Right	78	50.___	5	
	2	50.___	79	Fan Coils Left	**A**	Fan Coils Right	80	50.___	6	
	3	50.___	81	Fan Coils Left	**B**	Fan Coils Right	82	50.___	7	
	4	50.___	83	Fan Coils Left	**C**	Fan Coils Right	84	50.___	8	

Project: MECA VRF **egauge #: 60239 (39) & 60240 (40)**

Site:

Panel: DH7 Distribution **Photos?**

Date: 2/21

L1 L2 L3	egauge input #	CT #		Load		Load		CT #	egauge input #	L1 L2 L3
	1 (39)	600.____	**A**	**Whole Panel**		**Whole Panel**	**B**	600.____	3 (39)	
	2 (39)	600.____	**A**	**Whole Panel**		**Whole Panel**	**B**	600.____	4 (39)	
	5 (39)	600.____	**C**	**Whole Panel**						
	6 (39)	600.____	**C**	**Whole Panel**						
	7 (39)	50.____	1a	ERU-1	**A**	ERU-2	2a	50.____	13 (39)	
	8 (39)	50.____	1b	ERU-1	**B**	ERU-2	2b	50.____	14 (39)	
	9 (39)	50.____	1c	ERU-1	**C**	ERU-2	2c	50.____	15 (39)	
	10 (39)	75.____	3a	ERCU-1	**A**	ERCU-2	4a	75.____	1 (40)	
	11 (39)	75.____	3b	ERCU-1	**B**	ERCU-2	4b	75.____	2 (40)	
	12 (39)	75.____	3c	ERCU-1	**C**	ERCU-2	4c	75.____	3 (40)	
			5a	HR-1A	**A**	HR-1A	6a			
			5b	HR-1A	**B**	HR-1A	6b			
			5c	HR-1A	**C**	HR-1A	6c			
			7a	HR-1B	**A**	HR-1B	8a			
			7b	HR-1B	**B**	HR-1B	8b			
			7c	HR-1B	**C**	HR-1B	8c			
			9a	HR-2	**A**	HR-2	10a			
			9b	HR-2	**B**	HR-2	10b			
			9c	HR-2	**C**	HR-2	10c			
			11a	HR-3	**A**	HR-3	12a			
			11b	HR-3	**B**	HR-3	12b			
			11c	HR-3	**C**	HR-3	12c			
			13a	HR-4	**A**	HR-4	14a			
			13b	HR-4	**B**	HR-4	14b			
			13c	HR-4	**C**	HR-4	14c			
			15a	HR-5	**A**	HR-5	16a			
			15b	HR-5	**B**	HR-5	16b			
			15c	HR-5	**C**	HR-5	16c			
	4 (40)	50.____	17a	HR-6	**A**	HR-6	18a	50.____	10 (40)	
	5 (40)	50.____	17b	HR-6	**B**	HR-6	18b	50.____	11 (40)	
	6 (40)	50.____	17c	HR-6	**C**	HR-6	18c	50.____	12 (40)	
	7 (40)	50.____	19a	HR-7	**A**	HR-7	20a	50.____	13 (40)	
	8 (40)	50.____	19b	HR-7	**B**	HR-7	20b	50.____	14 (40)	
	9 (40)	50.____	19c	HR-7	**C**	HR-7	20c	50.____	15 (40)	
			21a	Space	**A**	Space	22a			
			21b	Space	**B**	Space	22b			
			21c	Space	**C**	Space	22c			

APPENDIX G: PRELIMINARY SITE VISIT PLAN

Primary Goal

Review VRF systems and associated electrical systems to help Slipstream understand the layout and configuration.

Key Details of Visit

Slipstream will be monitoring the energy consumption of the VRF system at ______. In order to successfully monitor the VRF system, it is critical for Slipstream to understand various details about the system. The following list has been compiled to provide a guide for items we need to understand.

At each location please call Slipstream (we will provide a number this week). Slipstream will have questions about what is found at each location. Try to use a video conference method (i.e. Microsoft Teams, Apple Facetime, or Google Hangouts).

Rooftop:

1. Photograph each outdoor VRF unit from 2 different angles
2. Is there a 120V outlet on the roof and roughly how far is it from outdoor units?
3. Is there an easy way to run an ethernet cable from the rooftop units into the building?
4. Open up outdoor units and photograph circuit. If possible, show:
    a. Conductors serving whole unit
    b. Conductors serving compressor
5. DOAS Unit (Ventilation Air Handling unit)
    a. Photograph from 2 different angles.
    b. Photograph nameplate.
    c. Photograph gas line and gas train.

4th Floor:

1. Identify panel mounting type
2. Verify that outdoor units are served by 4th floor electrical panel.
    a. Verify that outdoor units are wired to a single room/location.
    b. Is there a 120V outlet close to those panels (i.e. within 10-20 ft) or accessible through a dropped ceiling or otherwise?
3. Determine circuits that serve the outdoor units and DOAS unit
    a. Determine the rated amperage of those circuit(s)
    b. Note conductor size (OD, not wire gauge) of those circuit(s)

4. Verify that the electrical panel also serves indoor units.
5. Determine the circuits that serve the indoor units
    a. Determine the rated amperage of those circuit(s)
    b. Note conductor size of those circuit(s)

6. Determine if the panel has a circuit serving a branch selector
    a. Determine the rated amperage of those circuit(s)
    b. Note conductor size of those circuit(s)
7. Are there spare breaker slots for all 3 phases in panel? If not, will have to double-tap each phase for voltage signal to egauge.

8. Photograph (or video) the inside of the 4th floor panel which these circuit(s) are located and note the physical size of the panel.
    a. Photo of circuit ID table in panel
    b. Verify that there is space for egauge in panel (approx. 2 x 4 x 8 inches)

3rd Floor:

1. Verify that the electrical panel serves indoor units.
    a. Verify that outdoor units are wired to a single room/location.
    b. Is there a 120V outlet close to those panels (i.e. within 10-20 ft)?
2. Determine the circuits that serve the indoor units
    a. Determine the rated amperage of those circuit(s)
    b. Note conductor size of those circuit(s)

3. Determine if the panel has a circuit serving a branch selector
    a. Determine the rated amperage of those circuit(s)
    b. Note conductor size of those circuit(s)

4. Photograph (or video) the inside of the panel which these circuit(s) are located and note the physical size of the panel.
    a. Photo of circuit ID table in panel
    b. Verify that there is space for egauge in panel (approx. 2 x 4 x 8 inches)

5. *If Possible: Photograph indoor unit within a guest room and location of thermostat in guest room.*

APPENDIX F: AIR FLOW MEASUREMENT PLAN – STAFFORD'S PERRY

COP MONITORING PLAN

STAFFORD HOTEL – PETOSKEY, MI

Primary Goal

To measure the coefficient of performance of the VRF system. Due to the difficulty in measuring the COP of VRF systems, we propose measuring the COP using two different methods (via indoor airside and via outdoor airside, both discussed below). Our primary interest is heating season COP, however, any data captured on the cooling season COP will be beneficial.

After measuring the COP using the indoor and outdoor strategies, the results can be compared. Lessons learned from this work will be carried forward for ongoing work in Minnesota and Illinois. We may encounter systems in future work that we are unable to utilize a given method (indoor or outdoor) due to specific constraints. This could be an opportunity to identify any challenges or benefits to these measurement strategies.

If possible, we could consider setting up a test rig in Madison to try out the key pieces of any given strategy. This may prove difficult with the limited time available and lack of similar systems to mock up a test on.

Key Personnel

Hotel

Reg Smith

Business: 231-347-5397
Mobile: 231-348-6016
regs@staffords.com

Electrician

Bear River Electric will be assisting with the install of the monitoring equipment. They were able to successfully use Microsoft Teams to provide Madison staff with a live video of the site/visit.

This firm completed the install of the electric system for the VRF system.

They completed the site install of the primary monitoring equipment in November 2020 and have visited the site several times since for ongoing equipment maintenance.

Mitsubishi

A representative (Dan Marney?) from Mitsubishi (manufacturer of VRF system) may be on site for the COP measurement to assist. Let's figure out exactly what we need to do and then determine if we need Mitsubishi there (i.e. they are mission critical) or if they are not mission critical and having them on site is a only a bonus.

1. Indoor Airside

Primary Goal

6. Map airflow at indoor units to fan power.
    a. Map several indoor units. Look at variation between units to decide if they all need to be measured.
    b. Consider what role air temp/density plays. It shouldn't be a significant factor indoors, but worth double checking.

Measurements at each indoor unit

We may consider measuring a sample of indoor units if possible. Recall, any measurement would need to be replicated for as many indoor units that are selected for monitoring.

1. Measure the airflow using the following strategies, if applicable:
    a. TrueFlow – replaces filter, easiest, question is will it fit in the filter slot
    b. Hot wire anemometer – take this no matter what, good to practice and learn to use. Best to do a traverse at the grill. This device can also record temperatures (a traverse of them). Could do a velocity measurement at the center point of the ductwork.
    c. Flow hood – might be quicker to use than hot wire anemometer
    d. Mitsubishi Data
    e. Pressure matching with Duct blaster makeup air. Accurate but time consuming to set up.
2. Flow measurements must be taken at multiple fan speeds (assuming fan is variable speed). Unit may need to be forced into multiple operating modes (Fan HI, Fan LO, etc).
3. When flow rate measurements are taken, check that the power measurement data is valid. Also recall that power data is 1-minute resolution, so testing must be several minutes long.
4. Measure static pressure drop
    a. Static pressure measurements could adjust the TrueFlow measurement (if TrueFlow is impacting pressure compared to filters)
5. Temperature measurements will be required for the inlet and outlet.
    a. We currently have 1 temperature measurement over the supply grill. We could use a temperature sensor traverse across the grill to verify that our single supply temperature represents a good average value. If it does not, can we develop an adjustment factor?

2. Outdoor Airside

Primary Goal

1. Map airflow of the outdoor unit to fan power.

Measurements at the outdoor unit

1. Measure the airflow using the following strategies, if applicable. One challenge will be how to force the outdoor unit to operate and different fan speeds. Mitsubishi says we cannot simply set the outdoor fan speed. One option is to put the indoor units into different modes and try to get the outdoor fan to react.
    a. Hot wire anemometer traverse – use zip ties with numbers like flags, call out number, record measurement – bring step ladders, check how to get on the roof. ASHRAE may have some guidance on doing a traverse on an open fan.
    ~~b. Flow hood~~
    ~~c. True Flow~~
    d. RPM of fan (using reflective tape on fan blade)
    e. Mitsubishi data
2. Measure the outlet temperature
    a. ?
3. Measure the inlet temperature
4. Measurements must be taken at multiple fan speeds (assuming fan is variable speed). Unit may need to be forced into multiple operating modes (Fan HI, Fan LO, etc).
5. When flow rate measurements are taken, check that the power measurement data is valid. Also recall that power data is 1-minute resolution, so testing must be several minutes long.

COP Calculation

$$COP = {}^{Q}/_{W_{in}}$$

Indoor Airside

1. Calculate energy delivered (Q) from:
    a. Air flow rate (correlated from fan power)
    b. Inlet air temperature
    c. Outlet air temperature
2. System input power (W_{in})
    a. Outdoor unit total power
    b. Branch controller power
    c. Sum of indoor unit power

Outdoor Airside

1. Calculate energy delivered (Q) from:
    a. Air flow rate
        i. For the fan power correlation, we may need to use Mitsubishi data on compressor power and when defrost occurs
    b. Inlet air temperature
    c. Outlet air temperature
2. System input power (W_{in})

a. Outdoor unit total power
b. Branch controller power
c. Sum of indoor unit power

APPENDIX G: OWNER AND OPERATOR INTERVIEW GUIDE

1. How would you describe your role?
2. Do you manage any other buildings than Drury?
3. How did you decide on a VRF system for Drury?
4. Who introduced the concept of VRF to you, and how did they convince you to adopt it?
5. What factors do you prioritize when deciding on the VRF system?
6. Did you have concerns about using a VRF system? Were they addressed?
7. What is the name of the firm that installed your current HVAC system
8. What other systems did you consider?
9. What year was the system installed?
10. Can you share anything about VRF system capital costs for the VRF system?
11. What challenges did you face during design and construction of your VRF system?
12. Are you satisfied with its operation (answer as dissatisfied, neither, satisfied)?
13. What specific features do you like about the VRF system?
14. What specific features do you *not* like about VRF system?
15. Are you happy with the energy performance of the system? Does it save you in energy costs?
    - Can you share utility bills for the hotel?
16. How would you rate occupant satisfaction with the temperature in your building (answer as dissatisfied, neither, satisfied)?
17. Do you or the building occupants perceive the VRF system is louder, quieter, or about the same level of noise as other HVAC systems you’ve had experience with?
18. Would you recommend other building owners install VRF systems?
19. How easy or difficult would say it is to maintain compared to other HVAC systems?
    - Do you have a service contract for regular pre-arranged maintenance to occur?
    - How often do you re-charge the refrigerant for the VRF system?