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Focus on Energy Cold Climate Variable Refrigerant Flow Program Study

slipstream

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Executive Summary

Background and Objective

Variable refrigerant flow systems are viable for use in Wisconsin. They provide building owners with a highly efficient electric heating system that also provides superior comfort (thermal and acoustic) to occupants. These systems historically have had challenges providing sufficient heating capacity in cold climates without the use of supplemental or secondary heat (often gas fired). However, the newest generation of systems released circa 2017 are rated to -22°F, making them a viable option for many projects in Wisconsin. Few projects in Wisconsin have adopted the new cold climate VRF technology and as a result, limited field data or independent studies exist to confirm the energy, economic and comfort performance of these systems in Wisconsin.

Slipstream, along with the Center for Energy and Environment have completed a study on VRF systems in Wisconsin to understand the market barriers, the typical energy and cost savings and to develop a program framework for Focus on Energy to implement. To accomplish these tasks, we interviewed stakeholders (VRF manufacturers, contractors, energy efficiency program staff), developed energy and economic models, and assessed five sites in the state with VRF systems.

The program framework was developed based on lessons learned regarding applying VRF in Wisconsin. The framework outlines the steps Focus on Energy should take to develop an impactful VRF offering in Wisconsin, to further drive energy savings from these systems and grow the VRF market.

Results

Stakeholder Interviews

Our interviews found that VRF is currently being adopted in Wisconsin. Based on sales data, we estimate approximately 30-50 projects per year in Wisconsin across new construction, major renovations, and retrofits. Historically, projects in Wisconsin most frequently utilized a heated-penthouse approach to solve capacity drop off at low ambient temperatures. This strategy is still utilized today, even with the availability of the cold climate VRF systems. Manufacturers have stated that VRF is growing in popularity with 15% year-over-year growth in sales.

While VRF is growing in popularity, there three key barriers which have hindered the growth. First, VRF is frequently not the lowest cost option. As this research has shown through modeling and analysis, VRF currently has paybacks that are outside of the desired range for most projects, ranging from 10-20 years for most projects. However, pricing is extremely variable, and it is difficult to fully capture all scenarios in an economic analysis. Much of the long payback is currently driven by the expense of electricity as opposed to natural gas, which policy or regulation may impact in the near future.

Second, VRF has advanced rapidly in the past 5 years, causing many in the design community to be unaware of the most recent features. Our research found that most stakeholders (owners, designers, engineers, contractors) are familiar with VRF systems, however, this experience is most frequently driven by past projects featuring older generation VRF systems. As a result, many stakeholders are unaware of the latest technology advancements and the current cold climate capabilities of VRF systems.

Lastly, little field data exists to verify the energy performance of these systems in cold climates. For many stakeholders (designers, engineers, owners, operators), having independent field data to verify the performance and operation of VRF systems in cold climates will provide confidence that these installations will be successful in Wisconsin.

Energy and Economics

We were able to develop energy savings estimates for several common building types through modeling. We found that VRF systems can save energy in Wisconsin, compared to both an electric baseline (heat pump) or gas fired baseline system. The following Table 1 summarizes the estimated energy savings for VRF systems in Wisconsin.

Table 1: Summary of energy savings for VRF over traditional baseline systems.

		VRF Savings over baseline system			
Building Type	**Baseline System**	**kWh/ft²**	**therm/ft²**	**% kWh**	**% therms**
Education	PVAV HW	0.41	0.20	5%	53%
	PVAV Elec	3.00	0.02	27%	9%
	PVAV HW w/ Def	1.44	0.27	15%	61%
	PVAV HP w/ Elec RH	4.57	-0.06	37%	-47%[1]
Hotel	PTAC	2.51	0.00	23%	0%
	PTAC w/ Elec DOAS	3.69	-0.08	31%	-111%[3]
Multifamily	Furnace/DX	2.29	0.16	19%	37%
	WSHP	1.45	0.06	13%	17%
	PTHP	1.81	0.01	15%	2%
Office	PVAV HW	0.49	0.18	5%	74%
	PVAV Elec	4.01	-0.02	32%	-33%
	PVAV HW w/ Def	1.10	0.26	11%	80%
	PVAV HP w/ Elec RH	4.64	-0.05	35%	-228%[3]

One key metric that many stakeholders are interested in is the simple payback for VRF. We used our energy modeling savings estimates combined with energy costs for Wisconsin to calculate payback. We were able to attain HVAC first cost data from both sales representatives and contractors. Table 2 presents these economic findings.

[1] These runs shift the ventilation load from electric heating in the baseline to gas heating (DOAS) in the proposed VRF case, resulting in an increase in therms. The therm increase is relatively small (<0.1 therm/ft²)

Table 2: Summary of economic findings.

		VRF Savings over baseline system		
Building Type	**Baseline System**	**First Cost Increase $/ft2**	**Annual Energy Cost Savings $/ft2**	**Simple Payback years**
Education	PVAV HW	2.50	0.16	15
Education	PVAV Elec	6.00	0.33	18
Education	PVAV HW w/ Def	2.50	0.31	8
Hotel	PTAC	13.50	0.27	50
Multifamily	Furnace/DX	3.70	0.34	11
Office	PVAV HW	2.50	0.16	15
Office	PVAV Elec	6.00	0.47	13
Office	PVAV HW w/ Def	2.50	0.27	9

This research found that VRF systems in Wisconsin typically have a payback of 8-15 years, depending on the building type and baseline system. For certain building types, such as hotel, the baseline system (PTAC) was likely not an ideal comparison for VRF, as VRF is a higher quality HVAC system. As a result, the simple payback was much longer than expected (50 years).

Site Interviews

We interviewed five sites to understand the energy and comfort performance of these system. In addition, we were interested in hearing any other feedback or general knowledge that owners or operators had on their systems. The five sites we assessed were:

- Office, Madison – new construction
- Elementary School, Monroe – major renovation
- NHC Office, near Green Bay – retrofit
- Hotel, Madison – new construction
- Vyron Corporation, Waukesha – retrofit

We found that all five sites were satisfied with their VRF systems and would consider VRF again in the future. From a comfort standpoint, we relied on feedback from building operators. Across the sites, there were occupants were satisfied with the comfort provided by the VRF systems. However, most sites had some initial issues to work through, either from a capacity standpoint (setpoints not being maintained) or a controls setpoint (system not responding quickly enough to occupant's inputs). From an energy performance standpoint, the sites reported reduction in gas usage or utility bills. However, at the elementary school, a utility bill analysis found that utility bills went up significantly. Unfortunately, this analysis was complicated by several factors including a simultaneous LED lighting retrofit and the existing HVAC system not providing sufficient ventilation or meeting setpoints.

One challenge with site assessments was the ongoing pandemic. As most buildings were vacant or had substantial changes to occupancy from March 2020 through spring 2021, it was challenging to assess the performance of these systems. We relied on historic data and the feedback from building operators on comfort issues.

Program Framework Recommendations

Prior to developing recommendations for Focus on Energy, we completed a nationwide review of VRF programs. This review was focused on identifying programs and the basic characteristics of the offering. There was a specific focus on program offerings in cold climates. We took the information gathered during this nationwide program review, along with the lessons learned through this study of VRF systems in Wisconsin and evaluated them against the current Focus on Energy program offerings. Our primary consideration was how to develop a customer-friendly program that would integrate into Focus on Energy's current portfolio and result in both increasing savings for VRF projects and growth in the number of VRF projects in Wisconsin's market. The following list is a set of actionable next steps that Focus on Energy should execute to develop an offering for VRF systems in Wisconsin:

- **Formalize baseline** - 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). Alternatively, a gas-fired HVAC system baseline can be assumed. In this scenario, gas (therm) savings are also claimed in addition to kWh savings. As shown below in the energy modeling and savings potential sections (*Results* and *Savings Potential*), a gas-based fuel baseline will yield more program savings for a VRF measure as compared to an electric baseline.
- **Develop savings calculation** – Create a savings calculation for a new prescriptive VRF measure as part of the *Business Offering* program. The savings calculation will utilize the baseline approach determined by Focus on Energy (gas or electric). A next step would involve developing a workpaper that would provide the basis for a TRM entry or other prescriptive calculation.
- **Offer incentives to projects which implement VRF** – Focus on Energy should include VRF as a prescriptive measure in their *Business Offering - HVAC Catalog*. Incentives should be downstream and 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.
- **Create criteria for eligibility which ensures project success** – To ensure stakeholder satisfaction and program savings, a set of eligibility criteria should be developed. These criteria will be focused on creating successful outcomes for projects installing VRF systems. An example of criteria could include using qualified contractors or implementing a manufacturer recommended installation and start up process.
- **Increase market awareness of VRF** –Focus on Energy can further accelerate VRF adoption through both incentives, marketing, and outreach. We recommend that Focus on Energy develop basic marketing materials to inform the public of the availability of VRF incentives. Focus on Energy should ensure that programs 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 (e.g. K-12 schools), increased education should

be provided to staff to empower them to provide suggestions to potential projects which may be a fit for VRF. Focus on Energy should target the following building segments and project types as defined in Table 3.

Table 3: Summary of target market for VRF systems.

Building Types	Education, Office, Multifamily, Lodging, Buildings with many thermal zones/rooms where individual thermostat control (Police Stations, Nursing Homes, Clinics, etc)
Project Type	New Construction, Retrofit/Renovations
Project Characteristics	Small to mid-sized buildings (5,000 – 100,000 ft^2), existing buildings without existing ductwork, Buildings with energy efficiency targets/goals, Buildings looking to add air conditioning, Institutional buildings

Variable Refrigerant Flow Technology

Background

Variable refrigerant flow (VRF) systems are electric, refrigerant-based heating and cooling systems for commercial and multifamily buildings. They are related to heat pumps but have one outdoor condensing unit and multiple indoor evaporator units, with piped refrigerant to deliver cooling and/or heating to each of these different interior zones as needed. The term VRF 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 piping (CED Engineering 2019).

VRF systems contain many of the same components as traditional heat pump systems. In cooling, the indoor refrigerant fan coil units are the evaporator. The outdoor unit contains the refrigerant compressor, expansion valve, and condenser. In heating, the indoor fan coil becomes the condenser, while the outdoor unit becomes the evaporator. 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 of between 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 1 below shows a similar building configured in heat pump and heat recovery. The heat recovery configuration requires an additional branch selector between the outdoor and the indoor unit, as shown in Figure 2. 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.

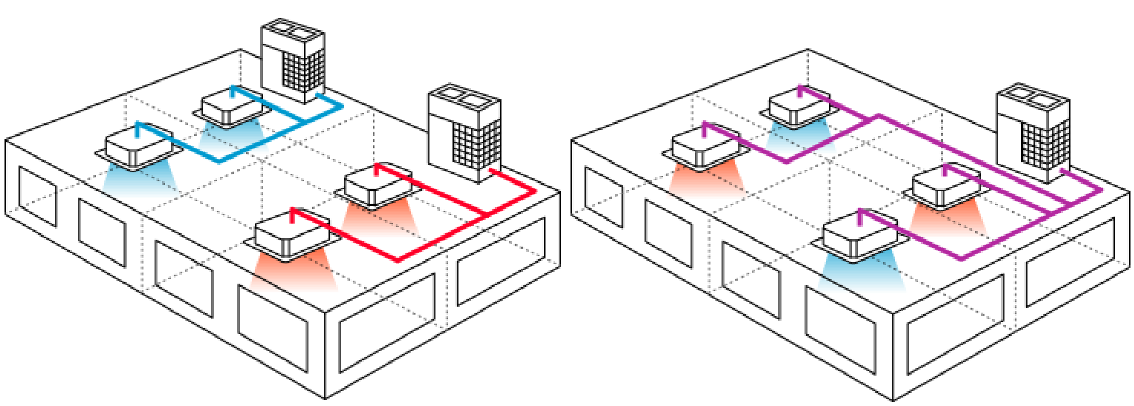


Figure 1: Left - two VRF units in heat pump configuration. Right - one VRF unit in heat recovery configuration (Daikin 2019).

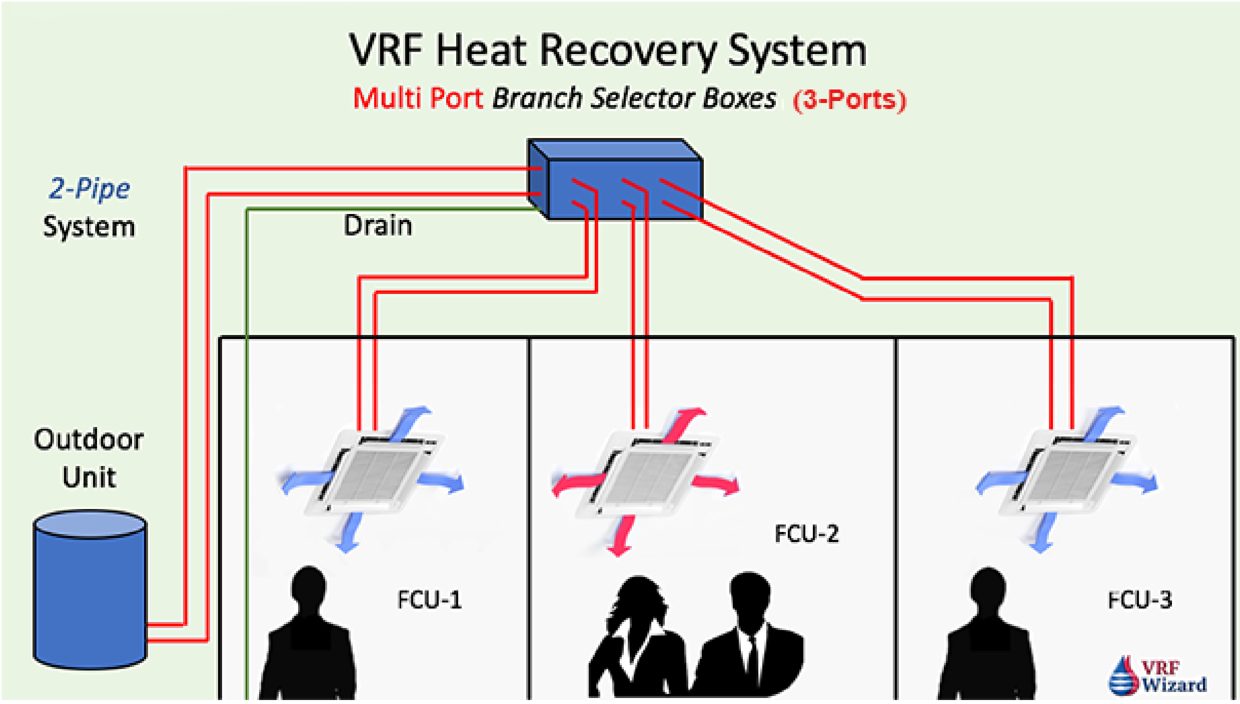


Figure 2: An example of a heat recovery VRF system with the branch selector between the outdoor and indoor fan coil units (VRF Wizard 2017).

VRF Advantages and Benefits

VRF has several advantages over traditional systems:

- The variable compressor in the outdoor unit gives it high part-load efficiency in both heating and cooling.
- Heat recovery improves efficiency further and allows for individual zoning.
- Running refrigerant from the outdoor units to indoor units takes up less space than air systems (ducted) and hydronic systems (piped). This makes VRF particularly attractive for buildings with little ceiling space such as historic buildings. It also eliminates energy required for central fans.
- Indoor units are often quieter than other indoor units like Packaged Terminal Air Conditioners (PTACs).
- Slipstream has found owners have few comfort complaints once they learn to leave the thermostat within recommended ranges (“set it and forget it”).
- Systems are easy to maintain. Only require filter changes and inspection.
- Room air is not returned to a central air handler and recirculated to other spaces, which reduces the chance for spreading pollutants and contagions across the building.
- Comes with proprietary controls and does not require a separate building control system.
- Because it efficiently heats with electricity, it is one of the best options for beneficial electrification.

Some disadvantages of a VRF system include:

- Reduced heating capacity and efficiency at very low outdoor air temperatures (see below).
- Each manufacturer's VRF systems are intricate, and each manufacturer's system has their own unique design requirements. Engineers should performance specify systems or use a sole-source manufacturer.
- Because of the intricate design and the amount of refrigerant piping, VRF systems need trained installers, careful installation, and strong quality control to ensure operation. Manufacturers and their representatives provide installer training and pre-startup services.
- Service requires support of the manufacturer or manufacturer representative.
- Because the system is not as quick to react as traditional air-conditioning and heating systems, there is an adjustment period for occupant comfort and to not adjust the thermostat as frequently.

Design Challenges and Solutions

Challenges. Historically, one of the challenges 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 outdoor coil. Frost buildup is thawed via a defrost cycle, which further degrades system performance.

Wisconsin is of course in a cold climate and features heating design temperatures from -10°F to -25°F (15% of US residents live in climates with heating design temperatures lower than -4°F). These have been divided into three zones shown in Figure 3. These winter design temperatures are mandated by the State of Wisconsin's Commercial Building Code, which has more aggressive winter design temperatures than what is set by ASHRAE 90.1. Table 4 presents additional statistics for these zones, including population and representative city.

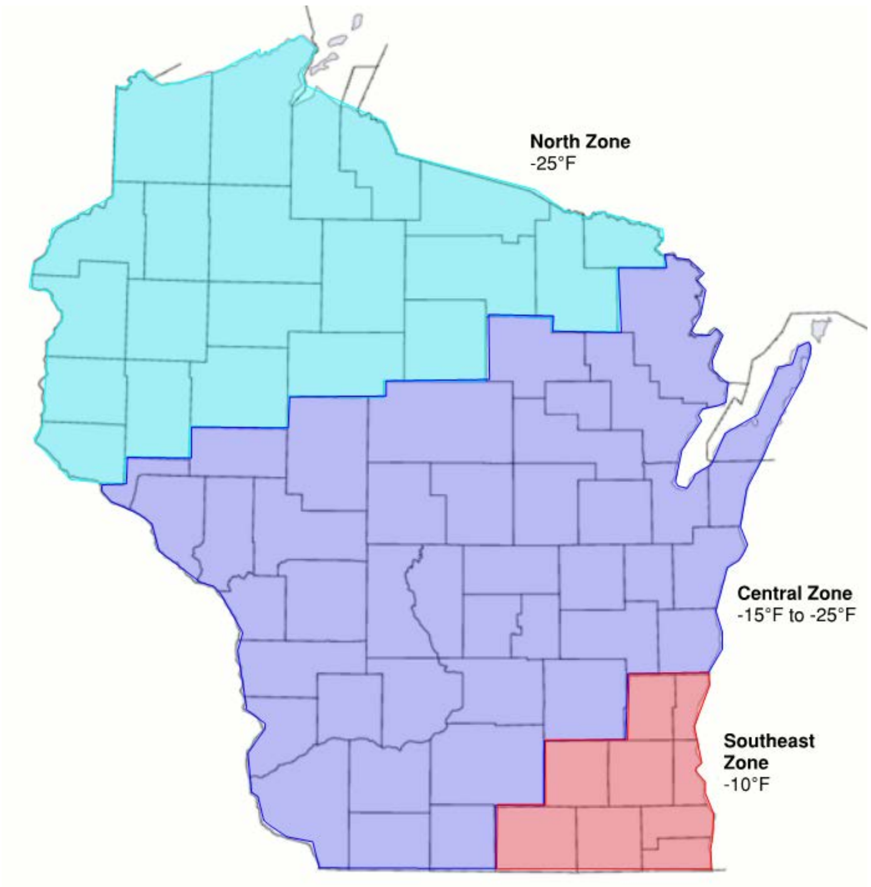


Figure 3: Plot showing the heating design temperatures for Wisconsin.

Table 4: Summary of zones in Wisconsin.

		Heating Design Temperatures		
Zone	Representative City	Wisconsin Code	ASHRAE 99.6%	ASHRAE 99%
North	Phillips, WI	-25°F	-18.3	-12.2
Central	Green Bay, WI	-15°F to -25°F	-2.2 to -13.3	2.8 to -8.5
Southeast	Milwaukee, WI	-10°F	-1.4	3.2

Zone	Representative City	% of Population	Cool Design Days 65°F	Heat Design Days 55°F
North	Phillips, WI	10%	305	8834
Central	Green Bay, WI	50%	470	7684
Southeast	Milwaukee, WI	40%	684	6674

Conventional Solutions. In the past, several approaches have been used for deploying VRF in these climates:

- air-source VRF system with the outdoor unit installed in a heated penthouse
- air-source VRF system with an oversized DOAS or other secondary heating system
- water-source or ground-source VRF system

These approaches have been, and still are, successfully used in Wisconsin to address capacity issues inherent with older generation VRF systems at low ambient temperatures. The first approach, and most popular, 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 atmosphere. At low temperature operation, when capacity would typically be reduced due to cold outdoor 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 4. This workaround proved effective, however, the supplemental heater typically used fossil fuels and ran frequently when temperatures were below 30-40°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.

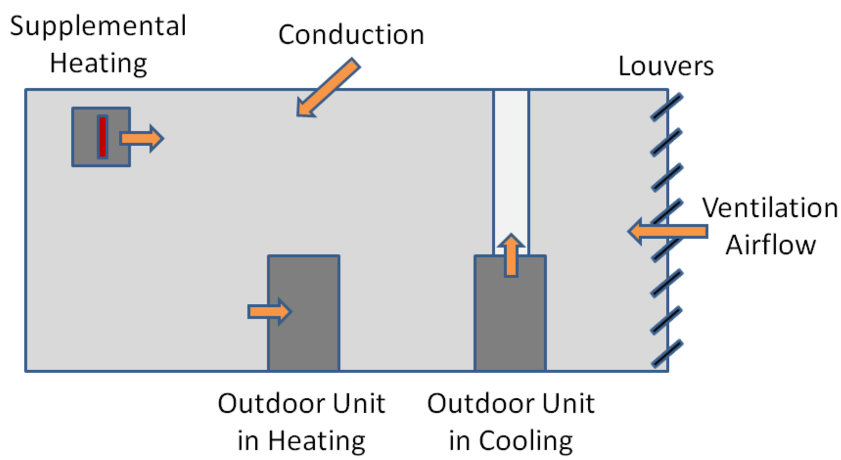


Figure 4: Energy balance of mechanical room featuring supplemental heat and operable louvers.

The second approach is to pair the VRF system with a secondary heating system, such as baseboard heat. Alternatively, the DOAS system, can be oversized to provide non-neutral ventilation air. In both cases, a secondary system provides additional capacity to offset the capacity drop off experienced by the VRF system at low ambient temperatures. A drawback to this approach is that the secondary system (or DOAS) is typically gas-fired or in some cases, such as baseboard heaters, may be inefficient electric resistance heat. In addition, with two HVAC systems present for heating (VRF and a secondary system), operators must ensure the controls are set up and operating correctly. Frequently, operators lack experience in optimizing the operation of the system, leading to the inefficient secondary systems handling more of the heating load than necessary.

The last approach is to use a water-source or ground-source VRF system. Unlike air source systems which this report focuses on, a water source system exchanges energy with a water loop, not the ambient environment. The water loop is most frequently conditioned with a fossil fuel boiler during the heating season and fluid cooler during the cooling season. If a ground heat exchanger (i.e. geothermal) loop is used, a boiler and fluid cooler are often not installed if the building heating and cooling loads are balanced. As a result of using a fossil fuel boiler (or ground heat exchanger), this system should not experience capacity drop off at low ambient air temperatures. However, these systems are typically more expensive than an air-source VRF system.

VRF technology has advanced rapidly in the past 5 years, resulting in new technology which allows for VRF units to be placed outdoors without using a conventional design approach (louvered mechanical penthouse or supplemental heating system). The next sections describe this new solution in detail and how to apply VRF systems in Wisconsin.

Cold Climate Technology

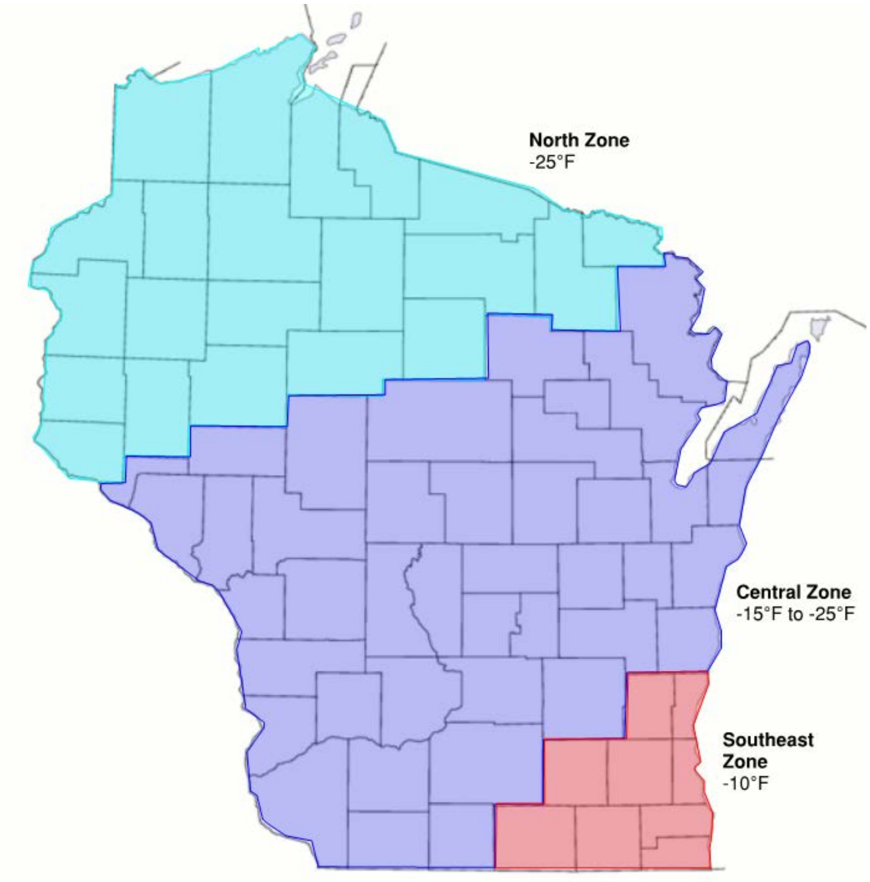
To expand the market for VRF systems to colder climates, manufacturers have been developing “Cold-climate” VRF (ccVRF) technology that can operate without supplemental heat in these regions. These systems use a special outdoor unit to maintain capacity and efficient performance for space heating even at low outdoor temperatures 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. 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. This is a significant advancement, as these units are now capable of operating at the heating design day conditions which cover most of the state of Wisconsin.

However, even with lower operating capabilities, ccVRF systems still have a capacity drop off at low temperatures. To meet the capacity drop off, systems are oversized which results in a performance penalty at all other operating conditions and potentially lower energy savings. The units also have a 10-20% cost premium compared to other VRF systems, depending on the manufacturer.

Applying Variable Refrigerant Flow in Cold Climates

Research conducted thus far through interviewing manufacturers, sales representatives and contractors has outlined how VRF systems are currently installed and operated in Wisconsin. The preliminary conclusions are that there are actually a few different design and installation practices currently used, and they vary *roughly* depending on location in the state. We can use the three winter design temperature zones, shown previously in Figure 3, to categorize these practices. Based on preliminary conversations with the design community and manufacturers, it seems these temperature zones correspond somewhat to three VRF design paradigms. These paradigms are defined in Figure 5 below.



Wisconsin VRF Solutions:

North
- **Water-source VRF systems**
- **Air-source VRF systems with penthouse or auxiliary heating source**

Central
- **Air-source ccVRF systems**
- **Air-source VRF systems with penthouse or auxiliary heating source**

Southeast
- **Air-source VRF systems**

Figure 5: Different design strategy regions in Wisconsin for VRF systems.

The north zone has a design temperature of -25°F which is colder than the -22°F limit for cold climate VRF technology. As a result, cold climate VRF systems cannot be installed without heating capacity issues. Water-source VRF, air-source VRF utilizing penthouses, or air-source VRF with a separate heating system are required in this zone. The central zone has design temperatures suitable for cold-climate VRF, VRF installed in penthouses, or VRF with supplemental heat. The southeast zone has winter design temperatures which are warm enough to allow for the use of high-efficiency VRF technology (-13°F), and cold-climate technology is not required.

As summarized in Table 4 above, approximately 90% of the population in Wisconsin resides in the central and southeast design zones. As a result, a significant majority of Wisconsin's population and building stock can benefit from stand-alone air-source VRF installations (either standard or cold-climate technology). The minority of the population and building stock resides in the north design region which requires a penthouse or auxiliary heating system for air source VRF systems or a water source VRF system.

Product, Supply Chain and Trade Ally Network Review

Literature Review

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. But there are some lessons learned.

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 used a utility bill analysis to quantify energy savings potential, finding a reduction ranging from 10-80% (total energy – BTUs). 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 commissioned by Focus on Energy in 2014 identified VRF projects in Wisconsin and reviewed their energy usage, owner satisfaction and economics (FOE 2014). A brief case study was also presented. Three buildings, two offices and one warehouse, were identified and analyzed, including a site visit. The installed VRF systems were unable to reliably operate below 0°F and had unknown efficiencies between 0°F and 35°F – typical of early generation VRF systems. As a result, each building utilized the penthouse and supplemental heat approach (with varying penthouse set points of -10°F, 28°F and 50°F). This report found typical simple payback to range from 7-9 years.

The report also developed a case study of a subsidized housing building. This facility had both pre-VRF install utility data and post-VRF install utility data. The system was installed around 2010. This install used the penthouse paired with supplemental gas heat approach. Table 5 summarizes the energy savings and cost savings.

Table 5: Energy and cost savings for VRF install at subsidizing housing project.

	PRE-UPGRADE	POST-UPGRADE	% SAVINGS
SITE ENERGY USE [kBtu/ft^2/yr]	92.8	69.7	**24.8%**
SOURCE ENERGY USE [kBtu/ft^2/yr]	168.9	158.2	**6.3%**
COST [$/ft^2/yr]	$1.18	$1.12	**5.5%**

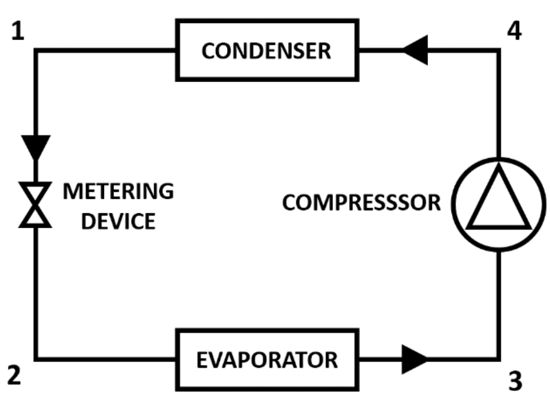
Product Offerings

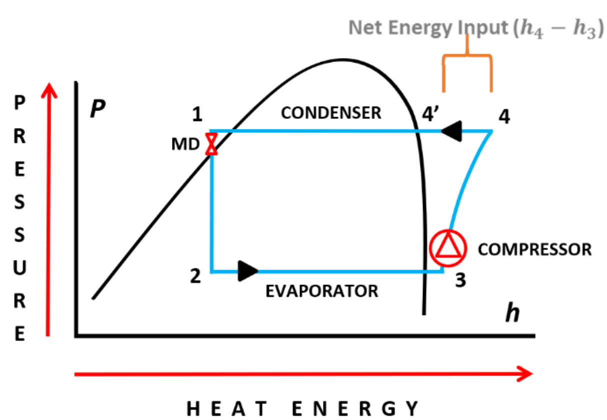
There are currently almost 20 manufacturers of VRF systems on the market, another indication of the growing popularity and success of this HVAC system. There are three manufacturers with the largest share of the VRF market in the United States: Daikin, LG, and Mitsubishi. Slipstream interviewed representatives from these three manufacturers about their products. The primary goal was to understand how ccVRF systems work in comparison to traditional VRF systems.

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

The Daikin Aurora, Mitsubishi Hyper Heat, and LG Multi V5 models all 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 7, a portion of the refrigerant is diverted after the condenser and expanded (Figure 6 shows a traditional VRF cycle for comparison). This diverted refrigerant passes through a heat exchanger to pre-cool the





remaining refrigerant 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 6: Left: Traditional VRF refrigerant flow diagram. Right: Traditional VRF pressure and enthalpy thermodynamic diagram.

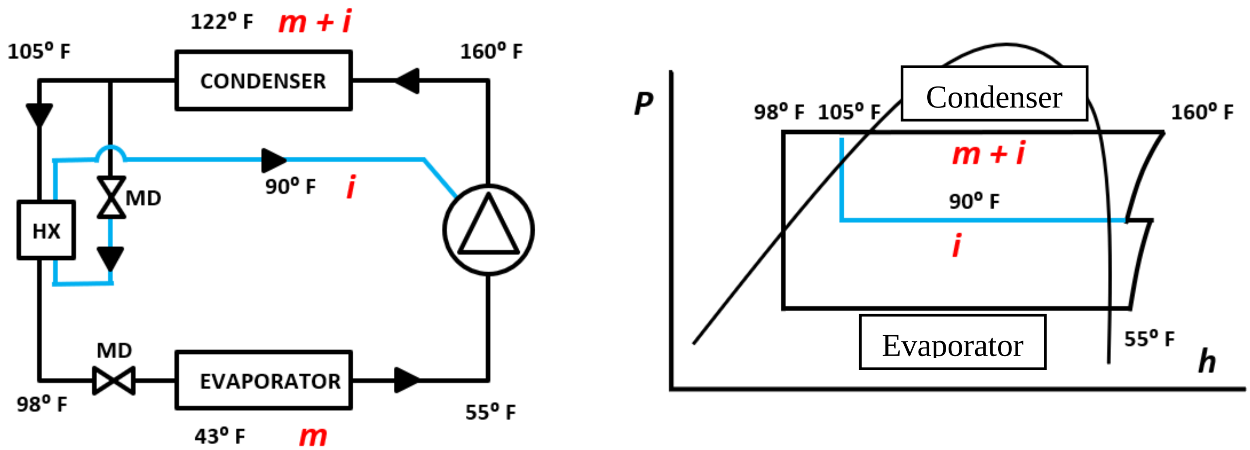


Figure 7: Left: Daikin Aurora VRF refrigerant flow diagram with vapor-injection compressor. Right: Daikin Aurora VRF pressure and enthalpy thermodynamic diagram.

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. In all cases, the technology and approaches which allow for lower temperature negatively impacts part load efficiency.

With any VRF or heat pump system in heating mode, ice buildup on the outdoor unit must be defrosted, and 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.

Manufacturer and Sales Representative Interviews

All three 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 Wisconsin market for VRF increased 15% while another claimed a 50% increase in the last year. They also are projecting double digit year over year increases for the next 5 to 10 years.

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 felt that VRF is cost competitive with traditional HVAC systems that are less than 200 tons of cooling, and that below 100 tons VRF is the best choice for energy efficiency. In addition to 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.

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 budgets to address their uncertainties as to how long installation and commissioning will take. All three manufacturers have noted that over the last five years the pool of mechanical contractors installing VRF systems has grown considerably, leading to more cost competitive pricing compared to other commercial HVAC systems. 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 refrigerant piping compression fittings such as Zoom Lock. Traditionally, copper refrigerant piping had to be brazed together, which is labor-intensive and requires skilled trades workers. Compression fittings are an alternative for many brazed joints, using 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 recommend insuring successful operation.

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 currently help designers and contractors with system selection, sizing, and configuration on their projects.

All three also noted that requirements in ASHRAE Standard 15, a standard for safe use of refrigerants, can impact the refrigerant piping and VRF design. ASHRAE Standard 15 limits refrigerant usage to 26 pounds 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 have been successfully installed to meet these standards and manufacturers assist contractors and designers in overcoming design challenges.

When summarizing these interviews, we should note the inherent bias of manufacturers whose goal is to sell their product. All three representatives noted there is little to no independent field studies on the performance of the latest ccVRF 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.

Trade Allies and Contractor Interview Results

Slipstream interviewed several contractors in Wisconsin to understand how VRF systems are installed in Wisconsin. All the contractors we interviewed have more than five years' experience installing VRF systems and some have as much as ten years' experience with them. All are headquartered in Wisconsin and primarily serve the commercial market except for the HVAC contractor who primarily serves the residential market. Table 6 summarizes the contractors interviewed.

Table 6. Contractors interviewed and general firm characteristics.

Contractor	Type	Employees	Area	VRF systems installed	Building types	Project type
1	Mechanical	360	Southeast WI	10	80% commercial	Design build
2	Mechanical	260	WI, IA, MN, MI	15	Labs, hospitals, retail, commercial	60% design bid build, 40% design build
3	Mechanical	350	WI	125	Office, healthcare, K-12, some manufacturing	Design build or design assist
4	HVAC	80	Dane County	6	Primarily residential including multifamily	Both

Product and Building Types

These contractors are installing VRF systems in nursing homes, multifamily apartments, offices, and some K-12 and retail buildings. These building types align with the research we are conducting in the Midwest and other conversations we have had with manufacturers and contractors. Typically, ideal building candidates have many thermal zones or rooms which require individual thermostat control. By its distributed nature, VRF meets this design criteria. Building candidates may also be seeking a high quality HVAC system which provides precise comfort control and minimal acoustic noise.

The three mechanical contractors represent Daikin, LG, and Mitsubishi. The HVAC contractor represents Daikin and LG. One contractor is doing their first Samsung system. One of the contractors indicated they prefer LG systems because they are less costly, and they have good local support from the manufacturer.

Only two of the contractors have installed cold-climate VRFs (one install in Madison, WI and one in Glendale, WI). However, both contractors expressed uncertainty in their cold weather performance. In particular, one contractor had moisture freeze on the coils on a cold-climate VRF that they installed—they added a shroud to keep freezing rain off the coils and put heat tape on the coils to solve the problem.

Some reasons they were concerned about installing cold-climate VRFs include:

- capacity decreases because they must be upsized to account for the really cold days
- upsized condenser limits the ability to zone the interior of the building

Rather than installing cold-climate VRFs (without supplemental or auxiliary heat), contractors installed the VRF outdoor units in penthouses, added supplemental heat or used water source systems.

Installation and Maintenance

One contractor noted that building load calculations needed to be accurate when specifying a VRF system because they are less forgiving than other HVAC systems. Another notable difference cited by these contractors when comparing VRF installation to other HVAC systems was the reduction in space required and the ease of accommodating other systems. Also, there is more pipe fitter work than sheet metal work in VRF installations.

The contractors also said that the differences in installation protocols between manufacturers could be confusing. They noted that installation protocols are not interchangeable among manufacturers and that it was essential to complete each manufacturers' training. We will investigate these differences further as the project progresses.

Third-party commissioning is not standard practice for these contractors. Typical practice is to include the manufacturer representative at the time of system startup (one contractor purchases the manufacturer startup package), or, if they do third party commissioning, the building owner contracts the service.

Most of these contractors agreed that recharging the refrigerant in a VRF system is not necessary (or typical) unless there is a leak, or when adding or replacing an indoor head. Of the contractors interviewed, none indicated significant issues with leakage on their systems. This will be a more challenging datapoint to extract as these groups are less likely to openly provide information on installations that have not gone as planned. We will work to attain this data as the project moves forward.

Finally, only one of these contractors indicated no difference in the number of service callbacks for VRFs compared to other HVAC systems. Three contractors said they have more callbacks during the first year a VRF system is operating than they do with other HVAC systems. These callbacks centered around software issues, recovery time, and occupant and facility staff education.

Barriers, Challenges, and Solutions

The upfront cost continues to be the single issue these contractors face in selling VRF systems. While some contractors feel they can provide a very compelling energy cost analysis, building owners still balk at the higher price. Beyond price, these contractors cited lack of understanding or knowledge of VRF systems, shorter shelf life (15 years), and safety concerns (refrigerant spills) as barriers to selling more systems.

To overcome these barriers, the contractors suggested:

- provide incentives--$2 - $3/sq. ft. or $250 - $300/ton
- offer case studies of Wisconsin installations that show costs and benefits in this climate
- encourage engineers to recommend VRF systems

Impact of Increased Refrigerant Usage

Refrigerants in VRF Systems

One of the biggest contributors to climate change are refrigerants that leak into the atmosphere (Drawdown 2017). Refrigerants themselves have a much larger global warming potential (GWP) by volume than carbon dioxide. which is the pollutant reduced as energy is saved by the VRF systems. Therefore, understanding and properly managing the refrigerant in VRF systems is critical to their future success as a sustainable energy system. 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 will only increase. But this increase can be mitigated by selecting refrigerants with lower GWP, and by managing refrigerant to ensure it does not leak into the atmosphere. As we'll discuss, these same steps can also provide life safety benefits.

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. The shift to R-32 or other new refrigerants could have significant impacts on reducing GWP as shown in Figure 8. Daikin claims R-32 can reduce electricity consumption by 10% compared to R-22 while also having a global warming potential that is one third of R-410A.

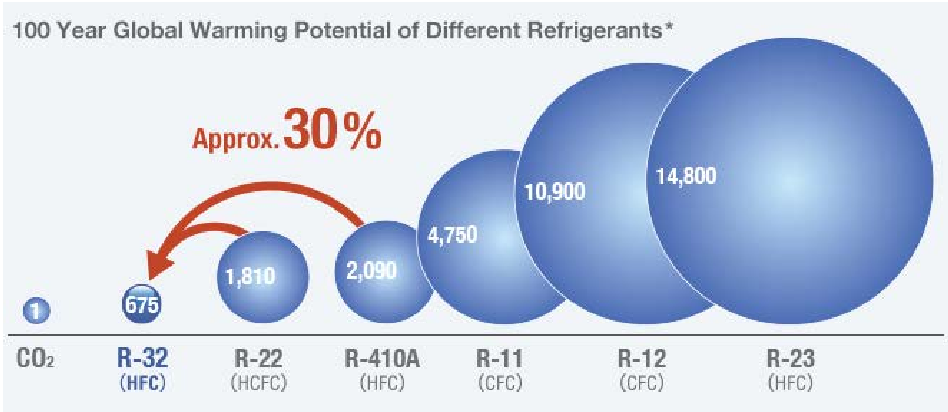


Figure 8: Credit Daikin. Values for 100 year global warming potential (GWP) from IPCC Fourth Assessment Report. Comparative 100 year GWP: HFC410A, 2,090; HFC32, 675.

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 both 1) much larger in volume and 2) not contained in a single appliance (e.g. chiller or air conditioner) but rather it is piped around the building to various spaces. Many of those spaces are occupied, so refrigerant leakage is not just a climate change consideration but also a human safety concern.

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 (values over 100% indicate a system that is recharged and continues to leak). 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).

According to VRF manufacturers, VRF systems that are properly installed should not leak. But refrigerant leaks do occur due to poor installation practice. 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. In fact, ASHRAE Standard 15 requires a detector in some extreme cases for life safety reasons. 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 the BAS. 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 automation and 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 best practices during installation:

- Semiannual maintenance is 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).
- 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).

Site Assessment

As discussed previously, two of the primary benefits of VRF systems are energy efficient operation and superior occupant comfort. During our interviewing of stakeholders, we asked questions related to system efficiency and comfort. Responses to these questions were mostly generalized across multiple experiences with VRF systems. To further investigate and quantify efficiency and comfort, our project team conducted a detailed assessment of five sites which had VRF systems.

Sites were identified with the help of VRF manufacturer representatives and contractors, with the goal of understanding the energy performance and comfort performance of VRF systems in Wisconsin. Our team found it was difficult to find sites which had air-source VRF installed with no supplemental heat (i.e. without the penthouse approach). Three of the sites interviewed have VRF units installed in a mechanical room with supplemental heating, and the fourth site uses hot water heating as the primary heat source. These four sites have Mitsubishi systems. A fifth site, the Vyron Corporation office in Waukesha has an LG system and is not installed in a penthouse with supplemental heat. The five sites we identified are listed below:

- Office, Madison – new construction

- Elementary School, Monroe – major renovation
- NHC Office, near Green Bay – retrofit
- Hotel, Madison – new construction
- Vyron Corporation, Waukesha – retrofit

At each site, our team gathered drawings for review to understand the system and building design. In addition, our team collected utility bills from most sites. Our team interviewed owners and discussed topics related to the VRF system including, but not limited to, operation, installation process and overall satisfaction. A summary table of all five sites is found in at the end of this section (Table 7), while a thorough review of each site is found in *Appendix A*.

Energy Performance

One of the key considerations for most owners when selecting a VRF system is the energy efficient operation. As discussed throughout this report, VRF systems are highly efficient HVAC systems, featuring variable speed equipment and the ability to recover heat between zones. As a result, one of our focuses for the site assessment was understanding the energy performance of the five sites. One challenge to for this was the COVID-19 pandemic, as none of the buildings were regularly occupied during the pandemic, from summer 2020 through spring 2021, making the energy consumption of these facilities irregular as compared to a typical year.

Comfort Performance

Given the COVID-19 pandemic, none of the buildings were regularly occupied during the heating season, making surveying occupants difficult. To quantify the comfort of VRF systems, the building operator was interviewed in lieu of submitting a survey to occupants. The building operator was able to provide a more detailed account of occupant comfort based on typical number of cold calls or other comfort related complaints from the occupants.

The primary takeaway from our comfort surveying is that at all five sites, system operators have reported positive experiences related to system comfort. Occupants are satisfied with the individualized temperature control, setpoint maintaining capability and low noise level of the VRF system. As a result, all five of the projects stated that they are pleased with the operation of their system and would install VRF again on future projects.

However, in several cases, there were initial system startup issues to work through which resulted in dissatisfaction with comfort. We identified two primary categories which can lead to dissatisfaction with comfort: the ability to maintain desired setpoint from lack of capacity and the ability to control the desired setpoint from poor system controls. These experiences are discussed in further detail in the following sections.

Capacity Challenges

Only one site had issues maintaining the desired set point because of limited system capacity. The hotel in Madison, WI reported guest comfort issues, particularly in the corner rooms with large glazing areas and longer distances between the VRF grille and the farthest edges of the units. The grilles in the units came through soffits. In units with a single window this worked fine, but in the corner units, the distance that had to be covered by the airflow was too great for the fan coils. This resulted in the need to add perimeter electric resistance heat in those units, which has rectified the comfort issues. Our project team noted that this could have also been rectified by reducing the amount of glazing in corner units during the design process.

Another issue related to capacity is setback recovery. Commercial buildings often utilize a nighttime setback when the building will be unoccupied. In the morning, several hours before the building will be occupied, the system initiates a warm-up cycle to bring the building to the desired occupied setpoint. However, with VRF systems (and heat pumps in general), there is frequently a lack of capacity to quickly bring a building back to the occupied setpoint. The office building operators experienced this issue. The facility operators recommend reducing the amount of setback. In our interviewing in the Midwest, this was a relatively common issue for VRF systems. The consensus solution is to limit or minimize the amount of setback. Reducing the setback does result in a small energy penalty, but due to the efficiency of the VRF system, is minimized in the annual operation.

Control Challenges

Most of the sites had some small controls issues to work through at start up. At the hotel, temperature dead bands in the units also caused some complaints. Guest perceptions were higher than the system could meet as the VRF system and the building automation system had a minimum temperature setting of 67°F. Many guests wanted them set cooler during the cooling season. In addition, the operators fielded some complaints due to the confusion over whether the system was operational. Hotel guests are most familiar with hearing the loud fans and PTAC-style systems running. The VRF system is much quieter, and guests questioned whether it was turning on to respond to their control of the thermostat. To that end, messaging was added to thermostats to alert guests of the quieter operation of these systems.

For the elementary school, occupants had minimal complaints specifically around the delayed response time to a user-prompted setpoint change (2°F–4°F adjustments). Occupants have not noticed the fan noise or system sounds, especially compared to the much louder on/off blower noise of the previous furnace-based system.

The office in Madison, WI also had issues with occupied space temperature dead band. Initially, the space temperatures were allowed to drift 7°F before the VRF system called for conditioning. This is an ongoing issue that the site is working through with the manufacturer. Manufacturer technicians have been on-site to improve performance, but the system is still not fully meeting expectations.

The VRF system was initially designed with some shared zones on the executive floors. This led to some disagreement over setpoints, comfort complaints, and over- and under-conditioning. The system was modified to allow each office to have its own control and zone. The reconfiguration required significant downtime as zones were added to remedy the setpoint disagreements.

Comfort Satisfaction Based on Project Type

Our site assessment also captured both new construction and retrofit projects. Qualitatively, satisfaction seemed more positive in the retrofit projects, where occupants were pleased with the operation of the system compared to existing HVAC system that was replaced. Conversely, the new construction projects had more complaints to work through (specifically from a controls standpoint).

Utility Bill Analysis

We completed a utility billing analysis at the sites which would provide utility bill data. From March 2020 to Spring 2021, many of the sites were not occupied or experienced highly irregular occupancy, making a utility bill analysis difficult. However, the elementary school had historic data, including VRF data from 2019 (pre-pandemic). At this site, we used gas and electric bills from March 2017 to Feb 2021. The billing analysis was complicated be several factors (Figure 19). Due to the class schedule at the site, occupancy and setpoint scheduling was not consistent across heating and cooling seasons. The COVID pandemic further complicated occupancy and scheduling. The VRF system was retrofitted between the 2018 and 2019 school years. An extensive lighting upgrade was also completed at the same time, complicating the electric use disaggregation.

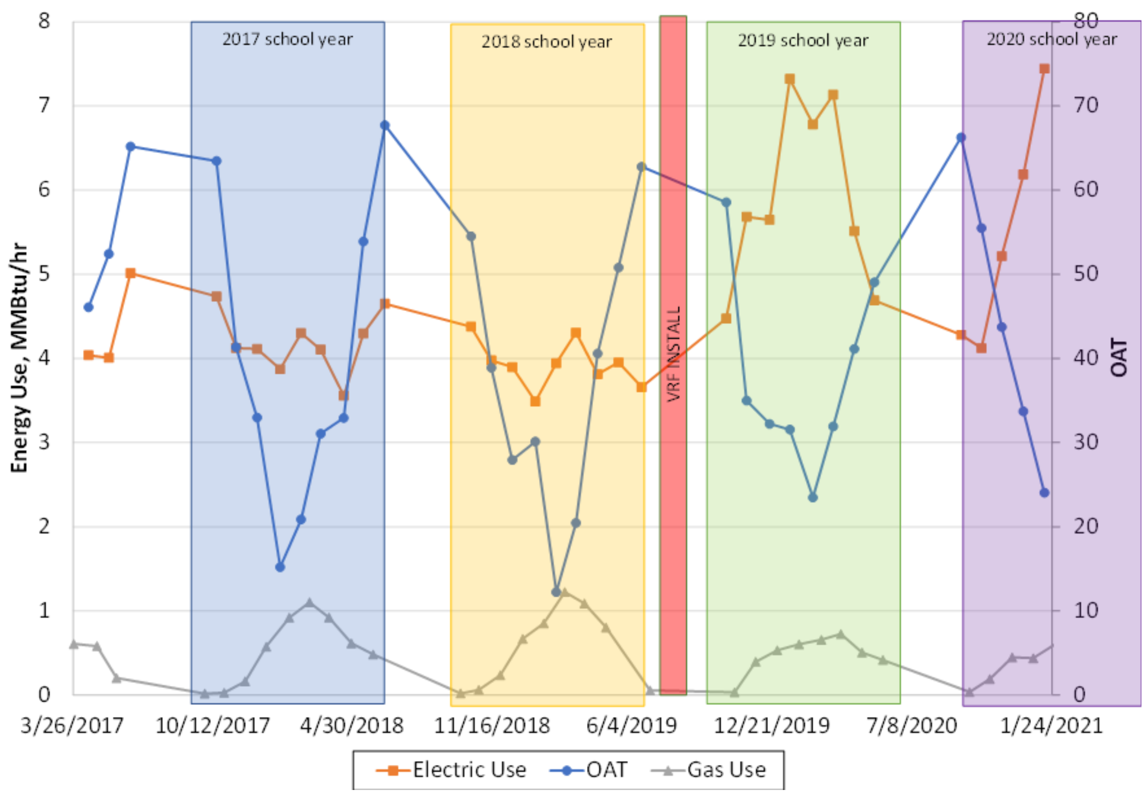


Figure 9: Utility bill data and time periods at the elementary school.

Despite these impacts, the site operators were aware of reduced natural gas bills. The billing analysis found a 23% reduction in total heating gas usage. This reduction was significant, but the presence of natural gas heating in the dedicated outdoor air system and also in the penthouses which the VRF outdoor units are housed, likely limited the gas savings. The electrical use in the property also increased by about 40% during the heating season.

The substantial increase in electrical usage is surprising and largely unexplained based on available data. A LED lighting upgrade would have reduced the site electrical usage (unless the lighting usage drastically increased). From discussions with the mechanical contractor, the previous HVAC system was a residential style system, and was not providing sufficient ventilation to the space to meet code. In addition, the systems were frequently unable to maintain setpoints. A utility bill analysis is unable to capture the specific data points to quantify these changes. However, if the building was underconditioned and under ventilated with the existing system, an increase in electricity usage could be expected as more conditioning (to meet setpoints) and ventilation is provided in with the new VRF and DOAS.

Table 7: These tables summarize the key details for the 5 sites interviewed.

Building	VRF Approach	Reasons for installation	Comfort
Office in Madison	ccVRF using a penthouse install with supplemental gas heat.	Needed high efficiency HVAC to meet code.	Control dead bands have caused occupant discomfort.
Elementary School	ccVRF using a penthouse install with supplemental gas heat through the DOAS.	Cost competitive retrofit solution for improved zone control.	Has solved the zone control issues.
Hotel in Madison	ccVRF using a "outdoor" mechanical room install and supplemental gas heat.	Code allowable and cost competitive.	Most rooms have had minimal complaints. Issues in corner rooms with inefficient envelops and long airflow paths.
NHC Office	ccVRF with outdoor install and gas boiler primary heating.	Improved zone control.	No complaints. Has solved previous over and under cooling issues.
Vyron Office	ccVRF with outdoor units outside and no auxiliary heat.	Improved zone control and efficiency.	90% satisfaction.

Building	Maintenance	Overall Performance	Cost
Office in Madison	Concerns about the impacts of a possible refrigerant leaks. Have not experienced maintenance or leak issues to date.	Energy performance has been great. Controls issues are improving. Contractors (install and maintenance) are getting more comfortable. Concerns over flexibility of the system. Overall, would consider VRF again.	Comparable to traditional hydronic systems.
Elementary School	System requires little operations input and has minimal maintenance needs.	Positive experience for operators, owners, and occupants. They are considering VRF for other buildings.	Cost effective retrofit option.
Hotel in Madison	Concerns over an outdoor unit failure requiring taking a large number of units offline.	Satisfied with performance after initial adjustments. VRF is likely to be used in two properties currently in development.	VRF was a cost premium option when compared to PTAC units, but cost competitive when PTAC were not possible.
NHC Office	System requires little operations input and has minimal maintenance needs.	Very positive opinion of VRF. Systems are being planned for additional buildings. They are interested in using VRF for more heating applications as well.	Cost-effective retrofit option.
Vyron Office	Minimal maintenance, but structure plan (i.e. following recommended maintenance schedule) is key.	Very satisfied. Have installed another system in Green Bay, WI as a result.	N/A

Program Baseline

A key component to calculating energy savings from VRF is determining the baseline. In Wisconsin, most commercial buildings use primarily natural gas-fired heating systems.

For buildings that currently heat with natural gas (or other fossil fuels), VRF may result in an increase in electricity consumption, as the heating load is shifted from fossil fuels to electricity. In cases of purely gas heat, switching to an all-electric heating system like VRF includes some amount of fuel switching, which to this point has not been explicitly incorporated in Focus on Energy measures. This will require consideration.

But there are other scenarios. When compared to buildings that currently heat with electricity - either with resistance heat or heat pumps - VRF systems will always provide electricity savings. In Wisconsin, fully electric buildings are not a large market segment, however, in certain building types they are more common (such as hotels with PTACs). While fully electric heating systems are not commonly used, there are many buildings in Wisconsin which use systems with *both* gas and electric heating sources. A common example of this is packaged variable air volume (PVAV) systems with a gas fired heat exchanger in the main air handler, but electric reheat at the zone level VAV boxes. This is a common arrangement as it typically has lower upfront costs when compared to a system using hot water reheat – requiring extensive hydronic piping for hot water to each zone level VAV box. Other instances may be electric baseboard or electric unit heaters in significant spaces. In these common scenarios with electric heat, it is very possible that a VRF system will result in an overall reduction in electricity consumption.

Given these different scenarios, and after conversations with various stakeholders, we base our analysis here on three different potential baselines:

- Baseline is gas-fired heating equipment (or combination of gas and electric)
- Baseline is all-electric heating source baseline (e.g. resistance heat or heat pumps)
- Cooling only savings

Gas-Fired (or Combination) Equipment Baseline

This scenario assumes a gas-fired (or combination of gas-fired and electric) baseline system type. Wisconsin is dominated by fossil-fuel based heating sources, primarily gas, which makes this approach very applicable. The efficiency for this baseline system type is defined by IECC 2015, the current energy code in Wisconsin.

From a savings perspective, as this heating load is shifted from gas to electric, there may be increased electricity usage on the grid. However, if there is significant electric heat (i.e. electric reheat, baseboard electric heat, etc.) supplementing the gas system, switching to VRF may yield electricity savings. Savings can be calculated in two different ways. First, the total *site* energy savings can be calculated by comparing the baseline gas and electric site energy usage to the VRF site energy usage. This yields the total *site* energy savings.

An alternative approach is to implement a *source* energy savings verification step. Source energy multiplies site energy by a factor to account for the additional energy required to produce and deliver energy to the building. For electricity, the source factor is 3.35 for Wisconsin, while for natural gas, the source factor is 1.05. This method has been proposed for the Illinois Technical Resource Manual for residential heat pumps, allowing savings to be claimed over an existing gas fired furnace. This measure has a source energy savings verification step, which compares the baseline system gas and electric source energy usage to the heat pump source electric usage. If the system shows positive *source* energy savings, then a utility can then claim *site* energy savings (kWh and therms) for the project. For a utility that provides both gas and electricity, the site energy savings that can be claimed are:

- kWh = [Cooling and heating efficiency savings over code compliant system]
- therm = [heating therm savings from elimination of gas heating system] – [increase in kWh for heating from heat pump system]*[kWh to therm conversion]

While this TRM measure was developed for residential heat pumps, a similar approach could be used for commercial VRF systems.

All-Electric Heating Source Baseline

This scenario defines the baseline system as electric (resistance, heat pump, etc.) when switching to a VRF system. Through our interviewing in the Midwest, we have found this approach to be used in both new construction cases and in retrofit cases (even when the existing equipment being replaced was gas-fired). One drawback with this approach is it results in lower total claimed savings (BTU), as savings cannot be claimed from the elimination of gas usage.

The electric baseline system itself is not easily defined. For some building types, such as hotels, inefficient electric resistance heat is commonly installed, and an argument can be made for that being a valid system baseline to compare and measure VRF savings against. For multifamily spaces, heat pumps may be more common. Heat pumps are more efficient than electric resistance heat and would result in reduced savings.

The baseline system selection could be also defined by modeling methodologies applied by LEED, ASHRAE 90.1 Appendix G or some other standard as well. ASHRAE 90.1 Appendix G indicates that if the proposed system is electric then the baseline system shall also be electric. It provides an outline of potential system types based on building characteristics, summarized in Table 8.

Table 8: Summary of baseline systems defined in ASHRAE 90.1, Appendix G when the proposed system utilizes electric heat – such as VRF.

Building Type	System Type
< 3 floors, <25,000 sqft	Packaged Single Zone w/ Resistance heat
4 or 5 floors, < 25,000 sqft OR 5 floors 25,000-150,000 sqft	Packaged VAV w/ Electric reheat
More than 5 floors or > 150,000 sqft	VAV w/ electric boiler and electric reheat

Cooling Only Savings

In other regions of the United States, some utility programs have neglected the heating side of VRF and claimed savings only from the cooling side. This typically works well in regions with mild heating loads – in Wisconsin this would leave out a potentially large component of VRF's impact.

Energy Modeling

Methodology

To understand the impact that VRF could have in Wisconsin with broader adoption, our team developed energy models of Wisconsin building types where VRF is most likely to be applied. These models featured typical HVAC systems and building characteristics for Wisconsin. Energy savings were then calculated over the baseline system by switching the HVAC system to VRF.

We analyzed these building types in two different climates, since Wisconsin covers a significant range of climates from an HVAC standpoint. In previous reports, we presented three zones for consideration – North, Central and Southeast. Based on the heating design day temperatures, the North zone (-25°F heating design temperature) is not a fit for stand-alone air source cold climate VRF. However, both the Central and Southeast zones, with heating design day temperatures above -20°F represent a fit for cold climate VRF or standard (non-cold climate) VRF systems. As a result, we focused our energy modeling on the Central and Southeast zones, using Green Bay and Milwaukee as representative locations for our models.

Baseline cases

We developed energy models in eQUEST 3.64 for the following building types: multifamily, office, hotel and education (K-12). This set of building types were based on interviewing and research conducted and reported in the previous report; these building types were cited as the most common candidates for VRF systems. We also assumed ASHRAE 90.1-2004 for building energy code compliance to represent an existing building scenario where VRF would be retrofitted. This is important as the retrofit market is larger than the new construction market.

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). We checked our model end uses (e.g. lighting, plug loads) against the Commercial Building Energy Consumption Survey (CBECS 2012) to verify that our model usage was representative of the building stock in Wisconsin. We made input adjustments in the hotel and education models to bring the lighting and plug load end uses in closer alignment with CBECS.

For each building type, we developed a baseline HVAC system based on our professional experience informed by previous market characterizations, the DOE Commercial Building Prototype models and ASHRAE 90.1, Appendix G. Table 9 summarizes those HVAC choices.

Table 9: Summary of baseline HVAC systems investigated.

Building Type	Baseline system (Gas-Fired Equipment)	Baseline system (Electric Heating)	Alternate System
Multifamily	Split System AC w/ gas furnace	Packaged terminal heat pump	N/A
Education	PVAV[2], Gas heated coil in air handler, gas boiler HW reheat.	PVAV, Heat pump air handler, electric reheat.	PVAV, gas heated coil in air handler, electric reheat
Hotel	N/A	Packaged terminal AC with electric resistance heat	N/A
Office	PVAV, Gas heated coil in air handler, electric reheat.	PVAV, Heat pump air handler, electric reheat.	PVAV, gas heated coil in air handler, electric reheat

The choice of HVAC system plays a role in the amount of energy savings that are realized. Specifically looking at the Education building type, a baseline system that is Packaged VAV with hot water reheat will consume only natural gas for heating. Alternatively, the Packaged VAV with electric reheat has a primary gas fired coil in the air handler, however, the system is still dominated by the electric reheat. As a result, this system consumes a significant amount of electricity for heating (with an inefficient COP of 1.0).

One specific consideration for PVAV systems (used in the education and office models) is that PVAV system controls often do not perform as well as intended. Often PVAV systems can have higher air terminal minimum airflows, poor or disabled temperature and pressure reset sequences, and other control and air balance issues that result in more energy usage than the best practice PVAV system. VRF systems may have issues with controls, but VRF systems come prepackaged with proprietary controls and should perform closer to the design operation than the custom controls of a traditional PVAV system. To quantify the impact of PVAV deficiencies on the savings of switching to VRF, we included additional modeling runs around PVAV with deficiencies.

Variable Refrigerant Flow cases

After developing the baseline energy models, we then implemented a VRF system. We left all major buildings inputs unchanged (equipment loads, occupancy schedules, etc). When implementing the VRF system, we also implemented an accompanying dedicated outdoor air system (DOAS) to handle the ventilation load for the building. For some building types, this has little deviation from the baseline building design (hotel and multifamily) as they typically feature

[2] PVAV - Packaged Variable Air Volume. For all PVAV systems, we simulated additional cases which included system deficiencies.

a DOAS. However, for the education building types, these buildings use an integrated ventilation approach, where the PVAV systems both heats and cools the building while also handling the ventilation.

The DOAS system has multiple options for conditioning the neutral ventilation air. It is possible for this system to utilize a heat pump, and when paired with an all-electric VRF system, making the building fully electric. However, in Wisconsin, based on our interviewing and previous experience, it will be far more common for design teams to utilize a gas fired DOAS. For our energy modeling, we assumed that the DOAS would be gas fired.

Results

This section will summarize the energy modeling results for our baseline and VRF cases. Key outputs are energy use intensity (EUI – kBtu/ft^2), and kWh and therm savings, per square foot. The first set of results looks at building energy use intensity EUI for the K-12 education model. Figure 10 summarizes the site EUI results.

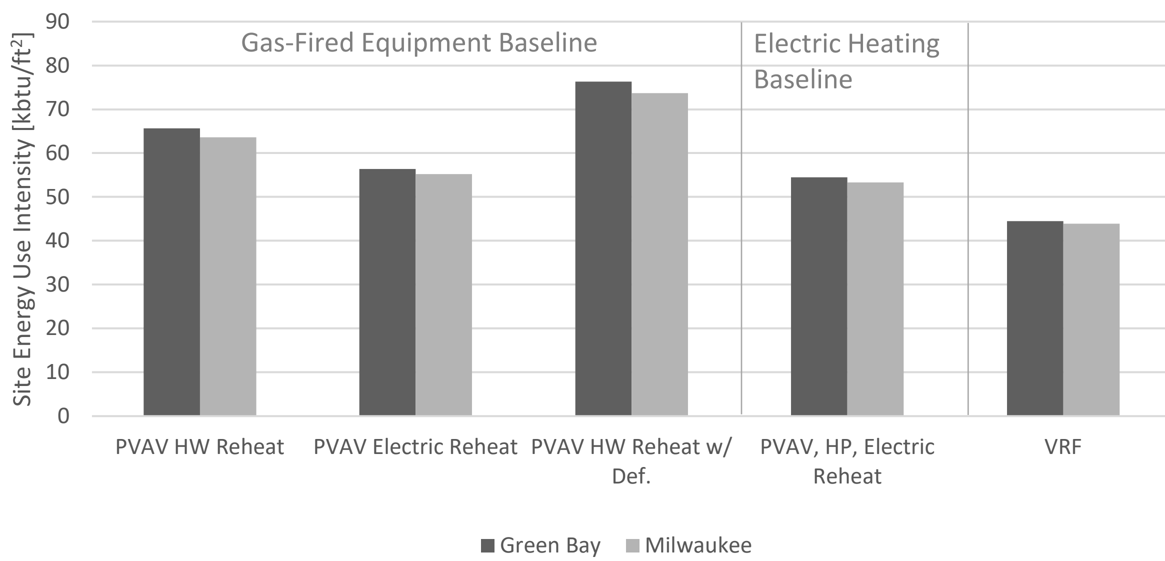


Figure 10: This figure shows the site EUI for the education modeling runs.

Three different baseline systems were modeled for this building – packaged VAV with hot water reheat, packaged VAV with electric reheat and packaged VAV with a heat pump primary heating section and electric reheat (all electric system). In addition, we also ran a 4th analysis, looking at typical deficiencies in packaged VAV systems that impact energy usage. Some of these deficiencies include VAV box minimums set too high (resulting in too much flow), imperfect temperature resets and increased fan power. We saw surprisingly little difference between the two locations, Green Bay and Milwaukee, from an energy perspective. VRF results in a lower site EUI (approximately 44 kBtu/ft^2) when compared the other HVAC cases (ranging from 53 to 76 kBtu/ft^2).

As our offices models the same baseline system type, we expected the EUI results to be relatively similar when compared to education. For office, we saw similar results between Green Bay and Milwaukee as well, as shown in Figure 11.

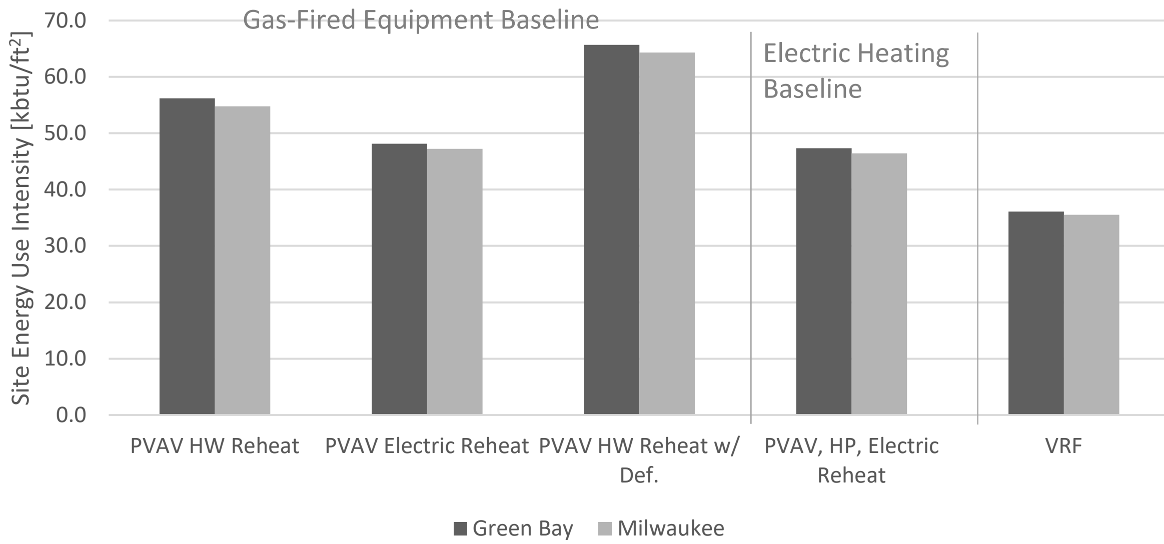


Figure 11: This figure shows the EUI results for the office model.

We also simulated both multifamily and hotel facilities. These building types have different baselines, as previously discussed. Figure 12 plots the site EUI. Like the education case, the VRF system results in a lower EUI than the baseline HVAC systems.

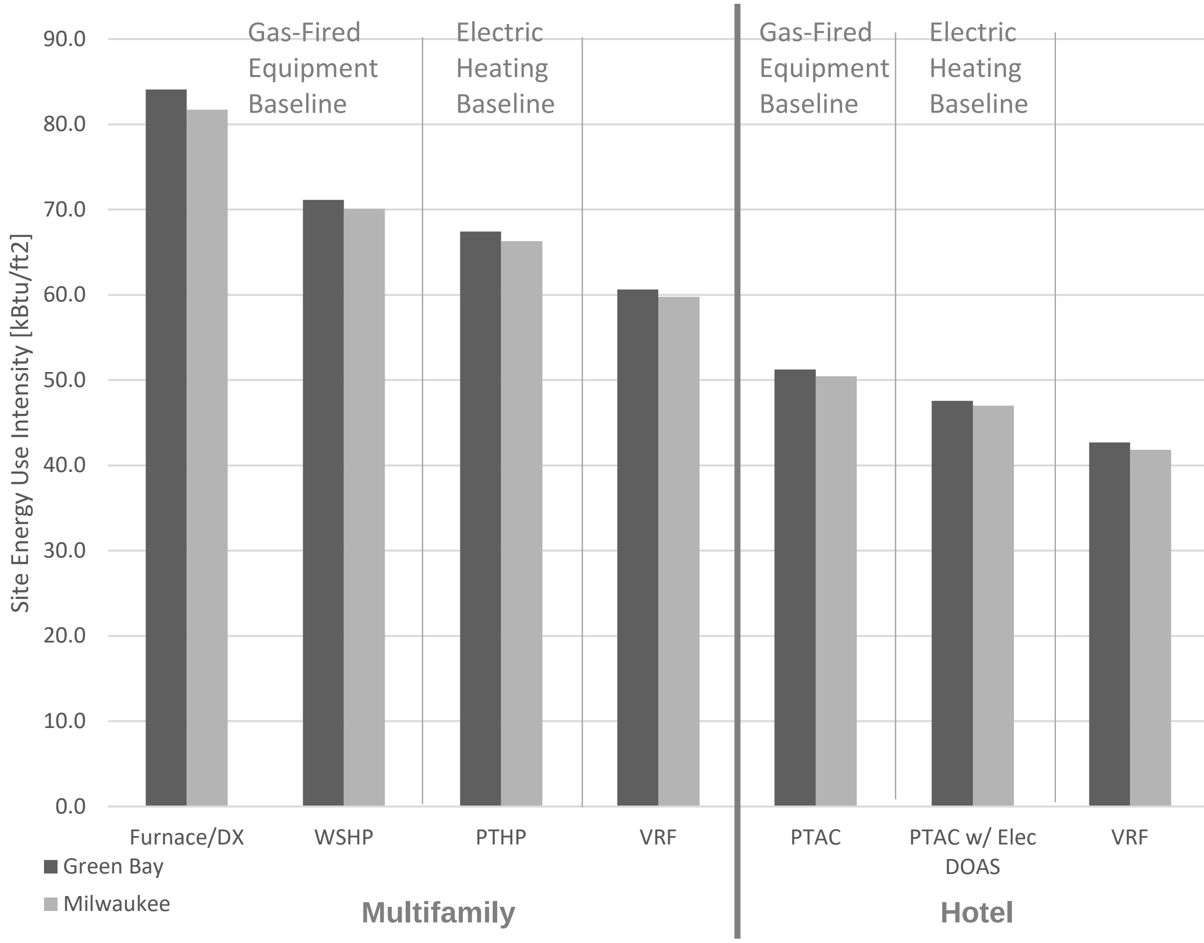


Figure 12: This figure shows the site EUI for the multifamily and hotel modeling runs.

Another finding was the difference between the Milwaukee and the Green Bay results. We had anticipated seeing more energy consumption for buildings located in Green Bay, compared to Milwaukee. Our modeling confirmed this, with annual energy use approximately 1-3% higher for the Green Bay buildings. However, the difference is so small that moving forward we will present only the Green Bay results.

Another important result to consider is both the gas and electric usage of the systems.

Figure 13 shows the electric consumption of each system on a per square foot basis for the Green Bay, WI simulation. Switching to VRF results in a kWh savings of 0.5 to 4.5 kWh/ft^2, with savings being highest when compared to electrically heated baseline systems. VRF natural gas savings for natural gas heated baselines range from 0 to 0.2 therms/ft^2. Note that for the PVAV with electric reheat case, natural gas consumption *increases* by 0.05 therms/ft^2 when switching to VRF. This increase is driven by shifting much the ventilation load from electric reheat in the PVAV baseline to a gas fired DOAS in the proposed VRF scenario. The results for the Milwaukee location were similar, with kWh savings ranging from 0.5 to 4.3 kWh/ft^2 and therms savings of 0.2 therms/ft^2.

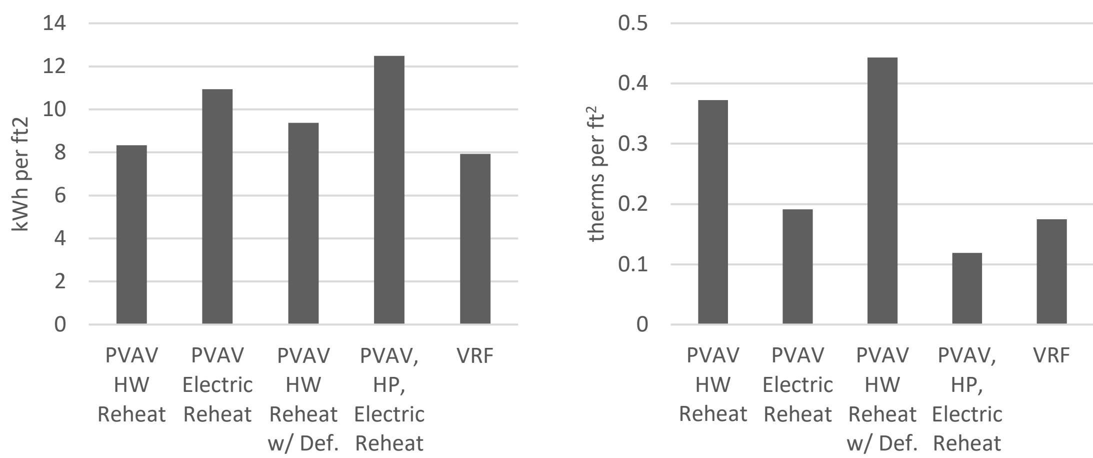


Figure 13: These figures show the kWh/ft2 and therms/ft2 consumption of each system for the education facility.

To succinctly summarize the modeling, we compiled the savings per square foot results into Table 10 below.

Table 10: VRF savings per square foot over baseline HVAC systems for various building types.

Building Type	Baseline System	VRF Savings over baseline system kWh/ft²	therm/ft²	% kWh	% therms
Education	PVAV HW	0.41	0.20	5%	53%
	PVAV Elec	3.00	0.02	27%	9%
	PVAV HW w/ Def	1.44	0.27	15%	61%
	PVAV HP w/ Elec RH	4.57	-0.06	37%	-47%[3]
Hotel	PTAC	2.51	0.00	23%	0%
	PTAC w/ Elec DOAS	3.69	-0.08	31%	-111%[3]
Multifamily	Furnace/DX	2.29	0.16	19%	37%
	WSHP	1.45	0.06	13%	17%
	PTHP	1.81	0.01	15%	2%
Office	PVAV HW	0.49	0.18	5%	74%
	PVAV Elec	4.01	-0.02	32%	-33%
	PVAV HW w/ Def	1.10	0.26	11%	80%
	PVAV HP w/ Elec RH	4.64	-0.05	35%	-228%[3]

Another key set of data is source energy savings, which is critical from a from a fuel switching standpoint. Under some fuel switching approaches, projects must show positive source energy savings for fuel switching to be allowed. These results are summarized in Table 11. In all cases, the VRF system shows positive source energy savings over the standard system.

Table 11: VRF source energy savings per square foot over baseline HVAC systems.

Building Type	Baseline System	VRF source energy savings over baseline system Source kBtu/ft²	% Source kBtu
Education	PVAV HW Reheat	24.9	20%
	PVAV Electric Reheat	32.0	25%
	PVAV HW Reheat w/ Def.	42.7	30%
	PVAV, HP, Electric Reheat	40.1	29%
Hotel	PTAC	25.2	20%
	PTAC w/ Elec DOAS	29.0	23%
Multifamily	Furnace/DX	39.5	24%
	WSHP	20.4	14%
	PTHP	18.8	13%
Office	PVAV HW Reheat	24.3	21%
	PVAV Electric Reheat	38.6	29%
	PVAV HW Reheat w/ Def.	38.2	29%
	PVAV, HP, Electric Reheat	41.9	31%

Economics and Emissions

One of the key questions for owners or potential adopters of VRF is how the system compares to traditional HVAC systems from an economics standpoint. While a small segment of the market will pay more solely for the increased efficiency and comfort, many customers use cost

[3] These runs shift the ventilation load from electric heating in the baseline to gas heating (DOAS) in the proposed VRF case, resulting in an increase in therms. The therm increase is relatively small (<0.1 therm/ft²)

as a primary deciding metric for HVAC selection. As a result, if VRF systems are not cost competitive with traditional systems, uptake of this system will be challenging.

Methodology

To analyze the economics of VRF systems, we calculated a simple payback for VRF over the baseline system type. We also used source energy factors and emissions factors to determine the emissions impact of these systems. This section outlines key economic inputs for the analysis.

Wisconsin manufacturers, manufacturer representatives, and mechanical contractors provided rough cost estimates for VRF systems. Most costs were given in dollars per square foot. Heat Pump VRF systems ranged from $14 to $19 per square foot and Heat Recovery systems ranged from $18 to $28 per square foot, with most estimates between $20 and $24 per square foot. Estimates include cost for DOAS ventilation unit. The cost increase between heat pump and heat recovery systems is significant. As the research progresses, we will gather feedback from manufacturers on the main drivers for that cost increase. Costs for baselines systems were received from Contractors and other data Slipstream has from similar buildings. These baseline systems were assumed to be energy code compliant. Overall, VRF typically represents a significant price increase over lesser quality systems (PTAC, etc). However, for similar systems such as packaged VAV with hot water reheat or a four-pipe fan coil system, VRF will be cost competitive. Table 12 lists cost estimates per square foot per system.

Table 12: Low, Median and High price points for the baseline HVAC systems and VRF systems. Costs are listed on a per square foot basis. We were unable to gather cost data for certain systems such as PVAV HP with electric reheat. As a result, they were excluded from the economic analysis.

	Low	Median	High
PTAC	$7	$8.50	$10
Furnace / DX	-	$12.67	-
DX RTU w/ HW Reheat	$17	$19	$22
DX RTU w/ Elec. Reheat	$15	$17	$19
VRF Heat Pump	$14	$17	$19
VRF Heat Recovery	$18	$21	$28
ccVRF	10% to 20% increase in equipment first cost		

Electric and gas rates are commercial rates per the US Energy Information Administration (EIA) reporting for utility rates. Gas rates are averaged annually. Source Factor and Emission data is from the EPA and averaged for Wisconsin. Refer to Table 13 below for energy cost and emissions data for Wisconsin.

Table 13: Energy costs, source factors and emissions factors for Wisconsin.

	Electric	Gas	Source
Cost – Commercial	$0.1073 / kWh	$0.5937 / therm	EIA Power 2020, EIA Gas 2020
Source Energy Factor	2.95	1.05	EPA eGrid 2018
Equivalent CO2	1.3963 lbs/kWh	11.698 lbs/therm	EPA eGrid 2018

Results

We found that in both locations, the economic results were similar. As a result, we are presenting the economic outcomes for just the Green Bay location. Our economic scenario considers a retrofit building comparing two new HVAC system alternatives: a baseline HVAC system representative of typical building construction in Wisconsin, and a VRF system.

Table 14 summarizes the key economic outputs for comparing VRF to several different energy code compliant HVAC baselines. Note that first costs are an increase over the baseline system cost (in all cases the VRF system first costs were more expensive).

Table 14: Economic data for comparing various baseline HVAC systems to VRF.

		VRF Savings over baseline system		
Building Type	**Baseline System**	**First Cost Increase $/ft2**	**Annual Energy Cost Savings $/ft2**	**Simple Payback years**
Education	PVAV HW	2.50	0.16	15
	PVAV Elec	6.00	0.33	18
	PVAV HW w/ Def	2.50	0.31	8
Hotel	PTAC	13.50	0.27	50
Multifamily	Furnace/DX	3.70	0.34	11
Office	PVAV HW	2.50	0.16	15
	PVAV Elec	6.00	0.47	13
	PVAV HW w/ Def	2.50	0.27	9

We found that the VRF system had simple paybacks ranging from 8 to 15 years for the education and office buildings, depending on the assumed baseline system. While VRF and PVAV have similar installed costs (both systems require extensive piping), the energy cost savings for VRF still take some time to pay back. The primary driver of this is the low cost of natural gas.

The shortest payback was over the PVAV system which assumed the previously described system deficiencies. We believe these payback figures likely represent the current market well. If payback ranges were substantially lower, adoption rates of VRF would be much higher. If payback ranges were significantly longer, far fewer projects would be adoption VRF than what the market is bearing currently.

The hotel and multifamily model results presented longer payback periods of 50 and 11 years, respectively. From our interviewing and market research, there are two challenges in the multifamily market. The first is that tenants may pay their own utility bills. This results in the building owner, who makes the upfront investment in the more expensive VRF system, unable to see an investment return on lower utility bills. The second challenge is that VRF is not a single zone system. As a result, it is not possible for the electric utility to meter the heating/cooling electricity usage for each individual tenant. There are solutions offered from the VRF manufacturers to submeter the usage – but current public service commission regulation prevents building owners from charging energy fees based on sub-metered data. In our experience in the Midwest market, we have seen VRF installed in multifamily buildings; either in affordable housing (with required energy goals) or other high-end residential projects. For buildings with lower energy or comfort goals, VRF is less likely to be installed due to the higher upfront costs.

Hotel presented a much longer payback of 50 years, which was unexpected. The main driver for this result is the PTAC baseline HVAC system that VRF is compared against. This system is extremely inexpensive, but is also a low quality HVAC system (noise, thermal comfort). From our interviewing and market research, we have often found hotel listed as a fit for VRF. In addition, we are currently monitoring two different hotels with VRF systems in Michigan. Further investigation is needed into the costs and energy savings for these facilities. VRF sales in this building sector may also be driven by the significant increase in guest comfort from VRF (as compared to PTAC). It is possible that for facilities that adopt VRF systems, the baseline system used in their economic analysis is not PTAC, but a much higher quality (and higher cost) alternative like water source heat pumps.

Emissions

In addition to analyzing the energy and economics, we also looked at the emissions impact of implementing a VRF system. This is an important metric as carbon targets are being adopted by more private and public entities on local, state and national levels. We found that switching from the baseline HVAC system to VRF saved 2.9 to 6 lbs of CO_2 equivalent per square foot. Table 15 shows the savings, and percent savings by adopting VRF over the defined baseline system types.

Table 15: Emissions data for the baseline and VRF systems. Emissions data is presented in lbs of CO_2 equivalent per square foot.

Building Type	Baseline System	Baseline Emissions	VRF Emissions	% Savings
Education	PVAV HW	16.0	13.1	18%
	PVAV Elec	17.5	13.1	25%
	PVAV HW w/ Def	18.3	13.1	28%
Hotel	PTAC	16.7	13.2	21%
Multifamily	Furnace/DX	22.0	17.0	23%
Office	PVAV HW	15.7	12.8	18%
	PVAV Elec	18.8	12.8	32%
	PVAV HW w/ Def	17.4	12.8	26%

These savings figures represent a snapshot in time. Moving forward, the grid will become cleaner and VRF systems will also become more efficient. As this happens, the amount of CO_2 reduced/saved by switching away from fossil fuel-based systems will increase.

Wisconsin VRF Market Assessment

Methodology

Slipstream conducted a preliminary market assessment using building data from the 2012 Commercial Building Energy Consumption Survey (CBECS 2012) and the Residential Energy Consumption Survey (RECS 2015). Further energy modeling in later tasks will refine these results.

This data was normalized for the state of Wisconsin. The market assessment was conducted for the north, central and southeast zones. To accomplish this segmentation, the CBECS and RECS building survey data was separated into each zone in proportion with the population data from the U.S. Census data for each county (USCB 2010). The zone was then normalized for a typical city within the zone. Refer to Table 4 above for more information. The resulting data set provided the total square footage and energy usage by end use for all building types for the north, central and southeast zones. Based on our interviews with contractors and manufacturers, we narrowed the building types to those most applicable for VRF systems. Figure 14 shows the total square footage of these VRF applicable building types in Wisconsin. To determine the impact of broad implementation of VRF in Wisconsin, typical energy savings and adoption rates can be applied to this dataset.

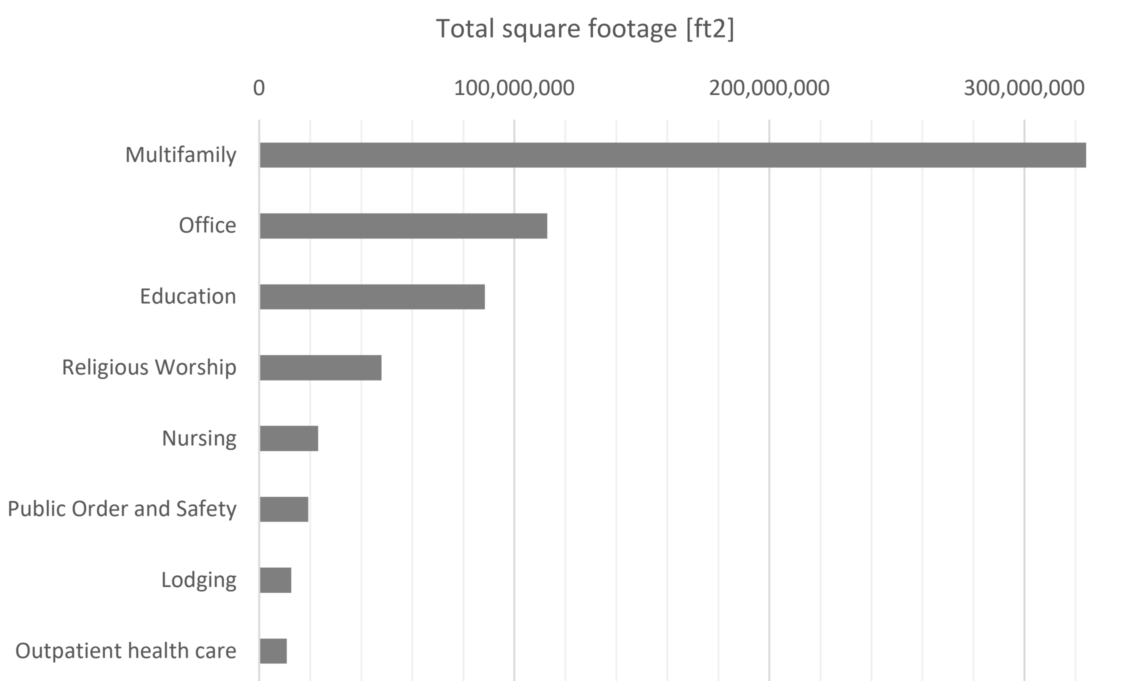


Figure 14: Summary of total building square footage in Wisconsin, sorted by building type.

Preliminary energy savings potential was calculated based on Slipstream energy models. Separate energy models were developed for each building type including office, multifamily, lodging and education. Public order and safety, outpatient healthcare, religious worship utilize the savings estimates from the office model while nursing utilizes the savings estimates from the multifamily model.

Lastly, year over year market projections from manufacturers were compiled as well as reviewing interview results with contractors and manufacturers on the typical number of VRF projects in Wisconsin each year. Based on these data sources, Slipstream estimates between 30 and 40 VRF projects were completed in 2019. Per contractor interviews, about 2% of all construction projects are VRF. Per manufacturer interviews, the estimated HVAC sales growth is around 2% in typical years while VRF system sales are growing at 15% year over year. This early market assessment assumes that Focus on Energy incentives could increase growth for VRF to 20%.

Baseline Impact on Savings

Table 16 on the following page shows the how the potential savings claimed by the program change depending on the baseline used. Using a gas-fired baseline allows 80% of the energy savings to be captured. This method reallocates savings between the electric and gas utilities using source energy factors. Using an electric heating source baseline captures approximately 70% of the savings.

Table 16: Summary of energy savings and potential program savings based on baseline selection.

Building Type	Gas Savings [therms]	Electric Savings [kWh]	Gas-Fired Equipment Baseline [Therms]	Gas-Fired Equipment Baseline [kWh]	Savings Captured [%]	All Electric Heating Baseline [Therms]	All Electric Heating Baseline [kWh]	Savings Captured [%]
Office	65,500	265,000	38,600	533,000	76%	0	1,767,000	81%
Public Order and Safety	11,300	41,000	6,700	87,000	76%	0	301,000	81%
Outpatient health care	3,000	79,000	400	105,000	70%	0	167,000	100%
Religious Worship	29,000	91,000	17,600	205,000	77%	0	750,000	80%
Education	55,600	161,000	36,300	353,000	79%	0	1,392,000	78%
Nursing	13,200	56,000	7,700	111,000	76%	0	361,000	82%
Lodging	1,200	81,000	-700	100,000	70%	0	110,000	95%
Apartment Building with 5+ Units	50,900	1,089,000	32,900	1,269,000	87%	0	1,060,000	41%
Total Annual Savings	229,700	1,863,000	139,500	2,763,000	80%	0	5,908,000	69%
10-year Cumulative Savings	4,660,000	37,820,000	2,830,000	56,090,000	80%	0	119,950,000	69%

Savings Potential

Applying the market share, growth rate projections, and energy savings estimates to the CBECS data results in predicted energy savings for the VRF technology. Figure 15 shows the predicted energy savings over the next 10 years for VRF systems installed in commercial buildings (excluding multifamily). In 10 years, it is estimated that this technology could save a total of 5 million mmBtu when fuel switching is allowed (therms saved are claimed) and 5 million mmBtu if an electric heating baseline is used.

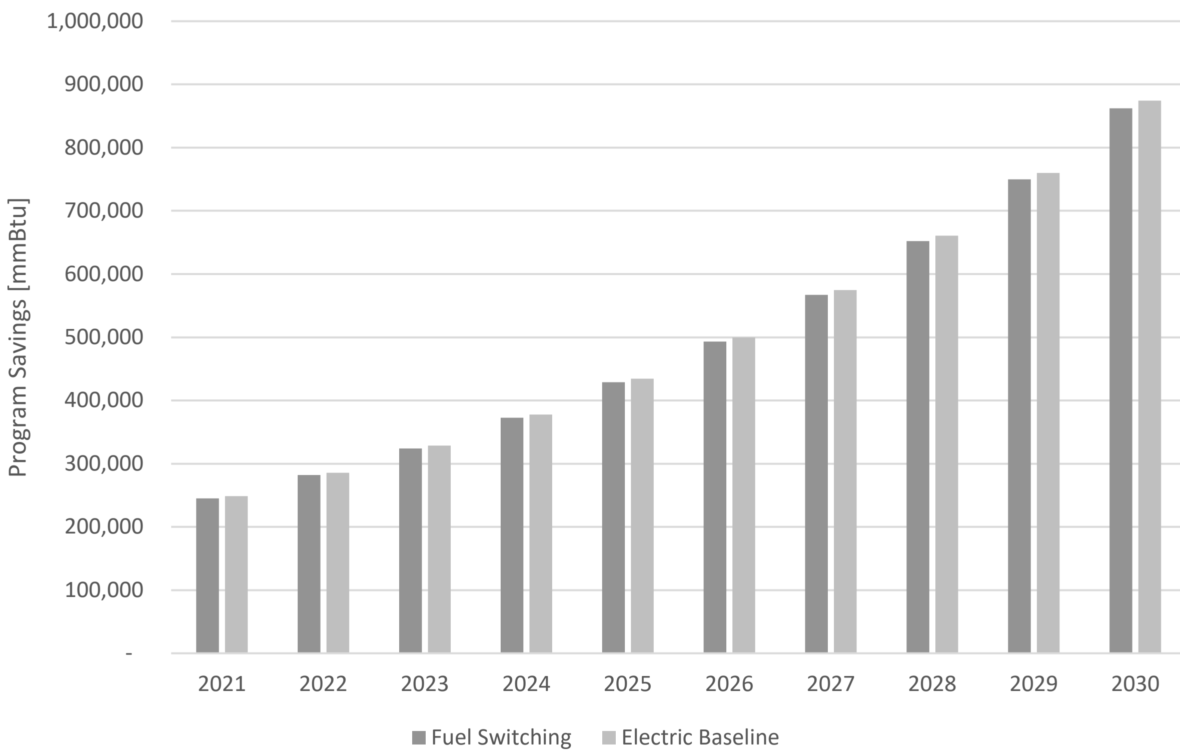


Figure 15: Ten-year cumulative estimated lifetime program savings from VRF systems in commercial buildings (excluding multifamily).

As most heating in Wisconsin is done with natural gas, shifting to electric based heating (VRF) will result in an increase in electricity usage for most building types. The increase in heating electricity consumption is offset by the reduced cooling and fan energy from the more efficient VRF system.

VRF shows potential to save energy for multifamily buildings with more than 5 units as well. Multifamily buildings have higher a prevalence of electric heat, so we predict higher overall electric savings. Figure 16 shows the predicted energy savings over the next 10 years for VRF systems installed in multifamily buildings. Over this period, it is estimated that this technology could save 2.4 million mmBtu when fuel switching is allowed and 1.1 million mmBtu when an electric heating baseline is used. Figure 17 combines the commercial and multifamily savings potential, where a fuel switching baseline could save 7.3 million mmBtu and an electric baseline could save 6.1 million mmBtu.

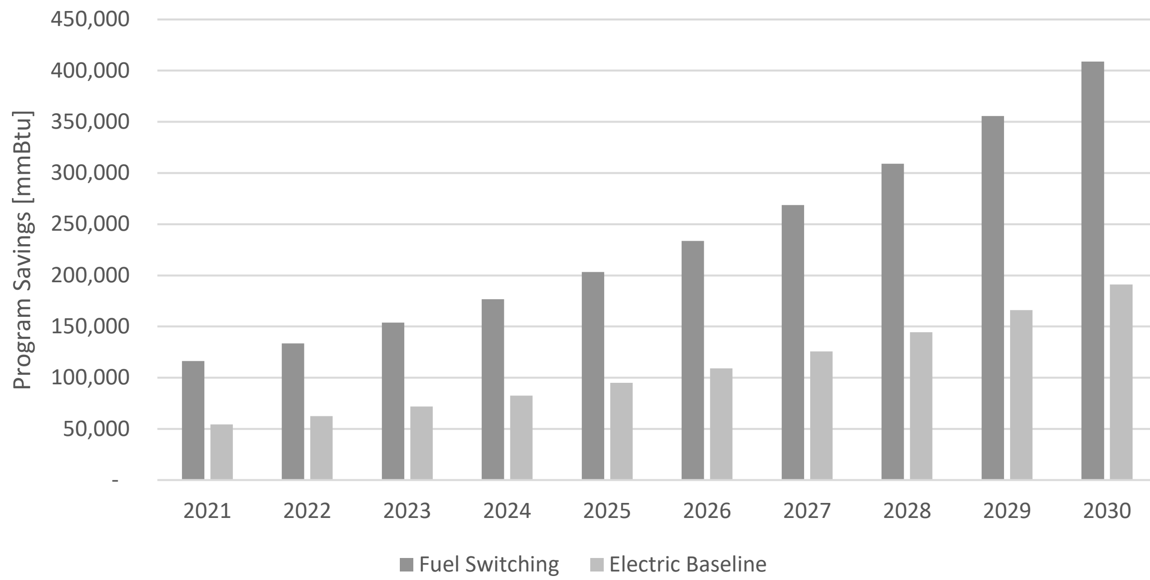


Figure 16: Ten-year cumulative estimated lifetime program savings from VRF systems in multifamily buildings.

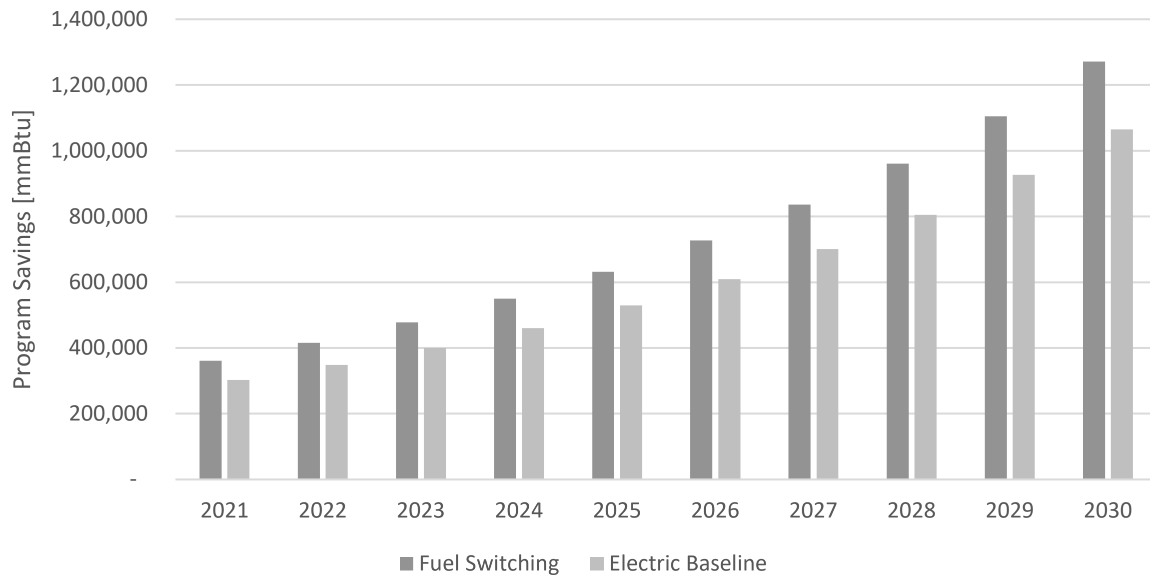


Figure 17: Ten-year cumulative estimated lifetime program savings from VRF systems in both multifamily and commercial buildings.

One of the key inputs to the fuel switching savings calculation is the source energy factor for electricity. In Wisconsin, approximately 55% of electricity is generated from coal, resulting in a higher source energy factor for electricity of 2.95. Utilities have resource plans to shift to cleaner fuel sources which will decrease the source energy factor for electricity. As the source energy factor is reduced, the fuel switching baseline will see increased savings potential.

Figure 18 combines the savings predictions to show which building types contribute the most to the overall site energy savings. Multifamily buildings have the potential to be the largest contributor at 30% of the total savings. After that office and education produce the next most savings. This is driven by two factors – the first that these facilities are typically more energy intense and require more HVAC energy input than other building types. The second factor is that we predict education facilities to be more likely to adopt VRF systems. These facilities typically select higher quality equipment (are less driven by first cost). In addition, our interviewing qualitatively found office and education installations were common with contactors.

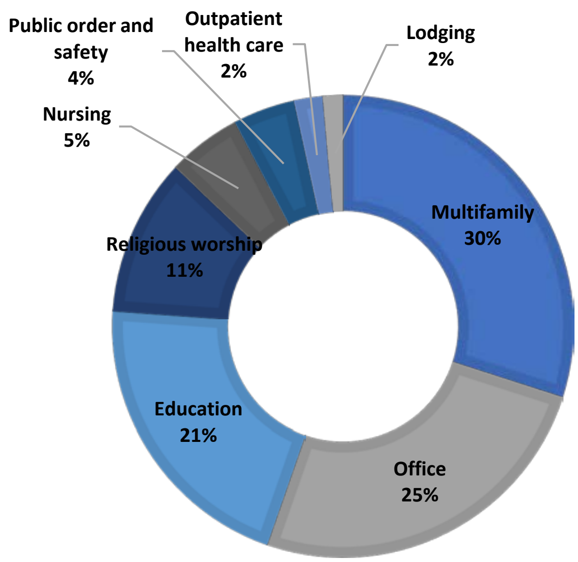


Figure 18: Percentage of total energy savings in Wisconsin by building type.

Programmatic Calculation

Through our discussions with various stakeholders, we have identified several methods for calculating savings within an energy efficiency program. This section will summarize these strategies and provides some general benefits and drawbacks to each.

Custom energy model

The approach that is currently the most common across multiple efficiency programs in the Midwest is a custom-built energy model of each project. The model calculates the annual savings between the baseline system and the proposed VRF system. This approach provides significant flexibility for representing the actual project and specific parameters of the building and systems. The advantages and disadvantages of this approach are outlined in Table 17.

Calculator or TRM measure

Another approach is a spreadsheet-based calculation for energy savings. This has been used in Texas and likely elsewhere as well. Note that Texas has very little heating load, resulting in primarily a cooling-based calculation.

An alternate approach is to develop a TRM measure and associated standard incentive, much like some of the existing offerings from Focus on Energy. This would take a much simpler form, making it easy for contractors and owners to determine early in the process what the incentive impact would be. The advantages and disadvantages of this approach are outlined in Table 17.

Energy modeling tool

A hybrid approach between the first two strategies discussed would be to develop a dedicated VRF calculation tool that utilizes an easy-to-use interface with an energy modeling software running in the background. Examples of this already exist in the market, such as OpenStudio, which is a user interface for EnergyPlus. A customer facing web-based tool could be developed which would allow easy and fast calculations of incentives and energy savings by both program staff and customers (contractors, owners). The advantages and disadvantages of this approach are outlined in Table 17.

Table 17: This table summarizes the advantages and disadvantages of various program savings calculation methods.

	Custom Energy Model	Calculator or TRM Measure	Energy Modeling Tool
Advantages	Flexibility to represent project and specific project parameters. Energy savings calculations are accurate for a given project. Works well for projects which are pursuing certification which requires modeling to certify savings (i.e. LEED).	Results (savings, incentives) can be generated to assist contractors and owners in the decision-making process. Low cost to implement after initial investment of developing the tool. Can utilize empirical data for improved accuracy. A standard incentive rate ($/ton) is easy to use.	Results can be generated faster than using a custom energy model. Calculations based on an energy model which can provide accurate results.
Disadvantages	Complex, time intensive, and costly to develop energy model. Modeling VRF correctly can be difficult. Energy models are slow to respond to quick turnaround which is demanded by projects.	Spreadsheet calculations and TRM measures often rely on significant assumptions to represent large groups of buildings. This can lessen the accuracy of the energy savings results. Generating empirical data can be expensive.	Requires upfront investment to develop tool.

Focus on Energy VRF Program Framework

This section will outline the recommended path for the development of a Focus on Energy VRF offering. The program framework was developed by reviewing the lessons learned during this research regarding the current market and application of VRF systems in Wisconsin. In addition to the review of VRF in Wisconsin, other programs around the country as well as the current Focus on Energy program offerings were considered in an effort to develop a measure that would be easy to incorporate into the existing portfolio.

Nationwide VRF Program Review

There are active incentive programs for VRF in a few colder climate locations in the country. In the Northeast active programs are largely driven by regulatory and policy frameworks that aim to reduce carbon emissions reductions through electrification of space and water heating end uses. Incentive offerings are also well-established in the Pacific Northwest. Few energy efficiency programs in the Midwest are currently explicitly incentivizing VRF.

Table 18 includes a matrix comparing incentive levels and eligibility requirements from selected programs. Prescriptive rebates are widely available in the Northeast and Northwest, while some of the Midwest programs we reviewed are currently addressing VRF through custom incentive offerings. This may be due to a lack of Midwest-specific data on system performance and savings. Some prescriptive incentives reference the advanced performance specifications developed by the Consortium for Energy Efficiency (CEE) and ENERGY STAR, which specify efficiency thresholds that step down with increasing system size. One consideration here: according to Northeast Energy Efficiency Partnerships (NEEP), “the [CEE and ENERGY STAR] performance specifications can introduce additional variance and confusion in the market for establishing a uniform set of performance levels for VRF." (Badger 2019)

Table 18: Summary of VRF offerings in the United States.

Program administrator	State	Format	Incentive structure
Focus on Energy	WI	Custom, Retrofit, New Construction, Downstream	$0.04/kWh; $100/kW
SMMPA	MN	Custom, Retrofit, Downstream	$0.045/kWh
Austin Utilities (SMMPA)	MN	Custom, Retrofit, Downstream	$0.045/kWh
Polk County Rural Public Power District	NE	Prescriptive, Retrofit, New Construction	$30-220/ton
Guthrie County REC	IA	Prescriptive, Retrofit, Downstream	Air source: $200/ton up to 40 tons & $50/ton after that
Efficiency Maine	ME	Prescriptive, Retrofit, New Construction, Downstream	New construction: $3.25/sf with heat recovery (HR); $2.75/sf w/out HR Retrofit: $6.00/sf with HR; $4.00/sf without HR
Mass Save and National Grid RI	MA/RI	Prescriptive, Retrofit, Midstream	$125/ton
Energize Connecticut	CT	Prescriptive, Retrofit, Downstream	$200/ton
ConEdison	NY	Custom, Retrofit, Downstream	$0.45/kWh
Snohomish Public Utility District	WA	Prescriptive, Retrofit, Downstream	$1500/ton
Puget Sound Energy	WA	Prescriptive, Retrofit, New Construction, Downstream	$3/sf conditioned space
Energy Trust of Oregon	OR	Prescriptive, Retrofit, Downstream	$1/sf conditioned space
Tennessee Valley Authority	TN, GA, KY, VA	Prescriptive	$175-200/ton
PSEG Long Island	NY	Custom, Retrofit, Downstream	$.55/kWh
Energy Save Pennsylvania	PA	Custom, Retrofit, New Construction, Downstream	$60-$75/ton
Public Service of Oklahoma	OK	Prescriptive, Retrofit, Midstream, New Construction	$350/ton
LADWP	CA	Prescriptive, Retrofit, Midstream	$125-$400/ton
Burbank Water and Power	CA	Prescriptive, Retrofit, Midstream	$250-$400/ton
New York Clean Heat Program (National Grid territory)	NY	Custom, Retrofit, Midstream, Downstream, New Construction	$80/mmBtu (for projects in National Grid territory)

We found a wide range of prescriptive incentive rates, typically ranging from $30/ton to $400/ton, with the highest incentive we found at $1500/ton. We worked to determine the drivers of the highest incentive numbers. Snohomish County Public Utility (Everett, WA) offers a $1500/ton incentive. Eligible projects for this incentive must be retrofits switching from electric resistance heat. No other existing heating sources qualify.

Focusing on states with climates similar to Wisconsin, we identified several different incentive approaches. The Mass Save program administrators are offering midstream discounts of $150/ton through participating HVAC distributors (Mass Save 2020). Efficiency Maine is offering a straightforward incentive per square foot with different tiers for retrofit ($4-6/sf) versus new construction ($2.75-3.25/sf), and a higher incentive level for systems with heat recovery (Efficiency Maine 2021). ConEd specifically targets VRF for multifamily buildings, offering a custom incentive of $150/MMBTU (ConEd 2021). Commercial buildings can receive VRF incentives of $0.45/kWh (ConEd 2020). Several programs, including Efficiency Maine and Energy Trust of Oregon, require customers to work with a qualified contractor to receive VRF incentives. Efficiency Vermont[4] and Efficiency Maine[5] have sponsored trainings to educate customers about VRF systems as well as contractor training to support high quality installation practices. Figure 19 plots the incentive offerings from various utilities.

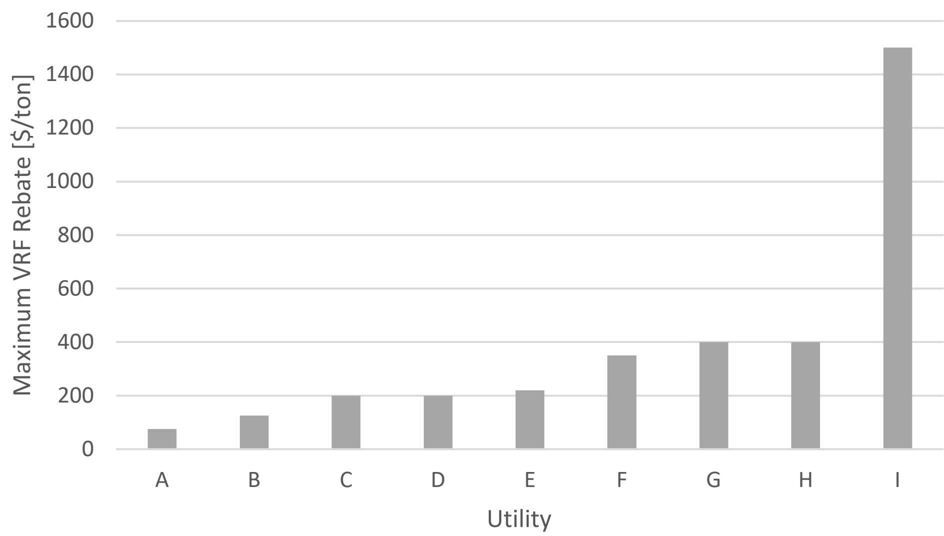


Figure 19: This figure summarizes the current prescriptive VRF incentive offerings from a variety of different programs around the United States.

One of the most successful programs we reviewed was a pilot in Massachusetts administered by MassCEC. MassCEC's two-year (2017-2019) VRF pilot saw participation from a diverse

[4] Efficiency Vermont (March 2021). *Fujitsu AirState VRF Training (J-Series Installer Qualification).* Available at: https://www.efficiencyvermont.com/events/2021/03/09/fujitsu-airstage-vrf-training-j-series-installer-qualification-7

[5] Efficiency Maine (2020). *Emerging Role of VRFs in Maine's Commercial Properties*. Panel presentations at 2020 IAQ & Energy Conference. Available at: https://www.efficiencymaine.com/docs/IAQ%20_VRF_Presentation.pdf

range of market segments: public/nonprofit (43%), private sector (35%) and affordable housing (22%). Owner motivations for selecting VRF included sustainability goals, cooling savings and improved temperature control via room-to-room zoning. Daikin and Mitsubishi/Trane supplied the products that were installed in 70% of the projects participating in the MassCEC VRF pilot, with other manufacturers representing a much smaller share (Samsung, LG, Toshiba/Carrier, Fujitsu, and Lennox). MassCEC required proof of manufacturer-assisted startup as part of their QA/QC strategy. The interviews we conducted with manufacturers' reps confirmed that they are actively involved in providing installation standards for contractors to follow. This pilot saw 106 projects, with a total of 3.78 million ft^2 of building area. (McPhee 2019).

Program Interviews

From our nationwide review of programs, we selected several programs which closely aligned with a potential future VRF offering from Focus on Energy. We considered geography, program delivery type and participation criteria when selecting specific programs to interview. The primary purpose of the program interviews was to understand what challenges or successes that existing VRF programs had.

Public Service Company of Oklahoma

The first interview was with the Public Service Company of Oklahoma (PSCO), which serves eastern Oklahoma (including Tulsa, OK) as well as southwestern Oklahoma. Our interview was conducted with an ICF program account manager, who is the program administrator for PSCO. PSCO has offered incentives for VRF for several years now.

Initially, the offering was custom, using the Arkansas Technical Reference Manual (TRM) VRF calculation for estimating savings. This approach uses heat pumps as a baseline (electric baseline), regardless of the existing system type. Incentives were paid directly to the customer. The custom calculation approach was slower and less transparent for the customers who the program serves. As a result, this was a barrier to participation. When the commercial program underwent a redesign to a midstream approach in 2019, VRF was added as an official measure. Initially the incentive rate was $250/ton, offered to the distributor. Later, the incentive was increased to $350/ton, which has received positive feedback. The measure savings are still determined using the Arkansas TRM (electric baseline), but there is some consideration of reviewing that calculation in further detail in the future. ICF did an analysis and found that VRF is one of the most cost-effective measures (from an energy efficiency program savings perspective) in the PSCO business portfolio.

Participation requires meeting the minimum VRF specifications (18 SEER, 3.3 COP), which is slightly improved over the energy code baseline (IECC 2015). While there are no specific criteria for the customer, as a midstream incentive, there are criteria that must be met by the distributors such as following proper installation practices, etc. As the distributors are closely tied to the manufacturers (or in some cases are the manufacturer), proper installation practices are pushed by the manufacturer to installers.

The program did not develop specific marketing or educational materials around VRF. Instead, the approach for VRF is like any other HVAC measure. The portfolio puts on promotional events or releases marketing materials which highlight all the HVAC measures. Similarly, there is no specific outreach approach for VRF driven by ICF. As a midstream measure, distributors and manufacturers push the measure through their sales and outreach process. Most of the projects which apply for the VRF measure are new construction. It is unclear whether that is because the market for VRF is mostly new construction or if the program is missing many of the smaller retrofit projects. The program sees a wide variety of projects including multifamily, hotels, event spaces, multi-use facilities. The customers who install VRF and participate in the program are often energy-efficiency minded.

New York State Clean Heat – National Grid

The New York Clean Heat program is a statewide program framework for electric heating systems (including VRF) which utilities within New York can adopt and offer to their customers. The outcome is utilities can assist customers in making energy and emission conscious decisions, which will result in moving New York closer to the statewide energy and emissions targets. This newly developed framework allows utilities to claim both therm and kWh savings for systems which switch from fossil fuel baselines to electric systems. The program provides criteria and guidelines for implementation, but it is up to each individual utility to administer the program to their customers. Utilities set their own incentive structures, develop marketing campaigns, educational materials, or other program related literature. We interviewed National Grid, which serves upstate New York, including Albany and Buffalo. They launched their VRF measure (as part of New York State Clean Heat) in early 2020. Limited data was available driven by the recent launch and limited participation. In the upstate New York territory, National Grid sells natural gas and electricity to customers.

As a fuel switching measure, a combined mmBtu is used as the energy savings metric (combining both therms and kWh) and the incentive is based on those savings. This same approach is used for other similar technologies like heat pumps, etc. The baseline system which savings are calculated against is the alternate system that a participant is considering, which can be gas or electric. For the savings calculation, this baseline system is assumed to be energy code compliant. The measure is a custom calculation, based on the heating load, cooling load and VRF system efficiency. The heating and cooling load is typically determined from an energy model. The choice for using a custom calculation is driven by evaluation.

National Grid offers an incentive of $80/mmBtu. Incentives are paid either to the contractor (in which the contractor can offer a lower price to the customer) or directly to the customer. The contractor also receives a $500 incentive for bringing a project to the program. The program has an approved contractor list, which helps ensure that contractors are qualified. The program will do a pre- and post-inspection of commercial projects to verify that the final product reflects what was submitted on the application.

This offering is still new for National Grid. The biggest barrier to participation was the lack of clarity for customers around what the potential incentives are for installing VRF. This is driven by the custom calculation. In response, one of the key efforts moving forward is the development of more customer facing tools to increase the visibility of VRF. The program plans to develop a calculator for estimating incentives (but will still require the custom approach outlined about for actual incentive payout) which will help customer understand early on what is available for VRF. In addition, online guides and other materials around VRF will be developed to help customers understand VRF and the benefits. In addition to these efforts, the New York State Energy Research & Development Authority (NYSERDA) is playing a role in the New York State Clean Heat program and has funding to educate the market and further develop the workforce around clean heat technologies (not limited to VRF).

Program Lessons Learned for Wisconsin

Supply Chain. One key takeaway from our review is that building an informed contractor and designer network is one of the biggest implementation hurdles that programs must overcome. Most engineers and contractors are familiar with VRF systems, though only some from first-hand experience with their own projects. Furthermore, this experience is often based on the earlier generation VRF systems which had significant challenges in cold climate heating performance. These engineers and contractors are often unaware of the latest advancements in the technology, specifically the newest cold climate VRF systems, which are rated to heat at Wisconsin's heating design day conditions. As a result, engineers and contractors are likely to default to traditional system types. Since VRF system performance depends on good design, precise sizing, and quality installation, program support for training and quality control can be critical to ensuring good customer experience.

Another key lesson was how critical the distributors are to ensuring adequate stocking of VRF products and support of requisite training. Since distributors work on a regional basis, a program design and incentive strategy that is coordinated with other Midwest utilities would likely benefit a program's engagement of important market actors. Other key takeaways related to the supply chain in Wisconsin:

- Contractors that are actively promoting air source heat pumps in the residential and small commercial market may be open to adding VRF to their menu of offerings.
- Market development will be challenging in rural areas with limited contractor coverage and exposure to the latest developments in VRF technology. In rural parts of the state, resources should be focused on small towns and cities where there is a more diverse stock of commercial buildings.
- It will be critical to invest and support supply chain development in Wisconsin. This means supporting contractor training on quality installation practices and engagement with manufacturer's representatives. Supporting representatives and distributors is beneficial for contractor training, recruitment, and other adoption drivers.

Current Market Status. The stage is set for growth of this measure in Wisconsin. VRF is currently being adopted in the state without a defined offering from Focus on Energy to support these projects and promote further adoption and market growth, though a few VRF projects have received incentives through either a custom approach or the Energy Design Assistance offering. Stakeholder interviews indicate that this technology is beginning to move beyond the "early adopter" stage (current estimates suggest 30-40 VRF projects in Wisconsin annually).

Focus on Energy has the opportunity impact the existing VRF market in Wisconsin by maximizing energy savings and increasing the persistence of savings. Interviews conducted with VRF system manufacturers indicated the importance of system sizing and design to overall performance. The existing VRF market would benefit from program support to encourage projects to follow manufacturer recommend design practices and sizing procedures. In addition, with installation, system commissioning, and system operation being critical to the long term success and energy performance of VRF projects, a Focus on Energy program offering verify that projects are using certified contractors who are trained to install and commission VRF systems. To improve project success, program materials and education around successful operating procedures (i.e. minimized nighttime setback, etc) for VRF can be provided to building operators. Combined, these efforts will increase the energy savings and persistence of savings for VRF projects within Wisconsin.

The research and current market trends for VRF systems suggest a simple prescriptive measure for program implementation coupled with a marketing plan could also result in significant growth in VRF adoption in the state. This could lead to additional HVAC savings as estimated in our *Wisconsin VRF Market Assessment* section. VRF is still a new technology and has significant room for an independent utility program to ensure customers that the technology will save energy and be successful for their application, in addition to providing financial support as motivation. Many stakeholders are also not aware of the newest product offerings for VRF or many projects forgo VRF due to its increased upfront cost compared to traditional systems. A defined program offering can work to overcome these barriers and increase adoption while ensuring projects are successful.

Existing Focus on Energy Program Structure. Manufacturers' representatives noted that prescriptive incentives for VRF are critical to scaling up adoption of the technology. Most of the prescriptive incentives currently being offered by other programs are on a per ton basis. This incentive system is easy for customers and contractors to utilize and assist with decision making. Projects should be encouraged to right size equipment as it leads to improved operation, decreased energy consumption, and reduced first costs. A prescriptive incentive offering will fit within Focus on Energy's current program design, specifically the *Business Offering*.

Another critical consideration is baseline determination, including stakeholder agreement on that baseline. Focus on Energy could utilize one of two paths for baseline development: an electric-to-electric approach or a fuel switching approach. Both would result in significant program savings, but with some differences as described in *Wisconsin VRF Market Assessment* section.

Currently, Focus on Energy can serve dual-fuel projects. A midstream program was launched which includes a measure to serve ductless heat pumps. In 2020, the ductless heat pump measure was updated in the TRM to include application to both natural gas and electrically heated buildings, resulting in claimed natural gas savings and an electric penalty. In 2021, the ductless heat pump measure was used as the basis for a centrally ducted dual-fuel air source heat pump measure as well. This measure offers an incentive of $1,000 for dual-fuel systems utilizing a natural gas furnace and heat pump efficiency of at least SEER 15/HSPF 8.5[6]. Like those dual-fuel systems, VRF systems provide the opportunity to implement highly efficient electric HVAC technology which also results in saving a significant amount, though not necessarily all, of the gas used for heating. Focus on Energy should consider input and future projections from regulatory staff specific to Wisconsin's approach to these types of measures with fuel switching components; approaches and regulatory considerations are rapidly changing on this topic in the Midwest.

Pathway to Focus on Energy VRF program

This research has developed a specific list of steps for Focus on Energy to pursue to implement a VRF offering into their portfolio. We recommend leveraging the existing *Business Offering* program and developing a prescriptive VRF measure to be included in the *HVAC Catalog*. This strategy will be cost effective to implement and will also be familiar to stakeholders.

The following list is a set of actionable next steps that Focus on Energy should execute to develop an offering for VRF systems in Wisconsin.

Formalize baseline

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). Alternatively, a gas-fired HVAC system baseline can be assumed. In this scenario, gas (therm) savings are also claimed in addition to kWh savings. These program baseline scenarios were discussed in further detail in the *Program Baseline* section.

The selection of the program baseline will directly impact the total program savings for a VRF measure. As shown in the energy modeling and savings potential sections (*Results* and *Savings Potential*), a gas-based fuel baseline will yield more program savings for a VRF measure as compared to an electric baseline. If the current evaluation paradigm allows for this type of baseline for VRF, then Focus on Energy should select 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. Using an electric resistance baseline would increase VRF savings.

Develop savings calculation

Create a savings calculation for a new prescriptive VRF measure as part of the *Business Offering* program. The savings calculation will utilize the baseline approach determined by

[6] SEER - Seasonal Energy Efficiency Ratio, HSPF - Heating Seasonal Performance Factor

Focus on Energy (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). A logical next step to streamlining the approach for VRF savings calculations would involve developing a workpaper that would provide the basis for a TRM entry or other prescriptive calculation.

Offer incentives to projects which implement VRF

Focus on Energy would then include VRF as a prescriptive measure in their *Business Offering - HVAC Catalog*. Incentives should be downstream and be an easy-to-calculate metric such as $/ft^2 or $/ton. This simplified approach will increase customer satisfaction and participation, while also decreasing the development time to bring the measure to market. During our interviews with stakeholders, both in Wisconsin and in the Midwest, a simplified incentive calculation was preferred by manufacturers, contractors, and owners. Incentives which are easily defined ($/ton, $/ft^2) creates certainty early in the process on what incentives would be available for VRF and enables early budgeting and planning. Once the downstream program is offered, Focus on Energy could work to transition the VRF program to a more cost-effective midstream offering.

Create criteria for eligibility which ensures project success

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

- utilizing qualified contractors
- following the VRF manufacturer recommended installation and start-up process
- pressure testing protocol to mitigate leakage
- other lessons learned discussed in *Appendix B*

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 market awareness of VRF

While our research has found that VRF is currently being adopted in Wisconsin, Focus on Energy can further accelerate that adoption through both incentives, marketing, and outreach. We recommend that Focus on Energy develop basic marketing materials to inform the public of the availability of VRF incentives. As this research has outlined, in addition to energy benefits, VRF systems also have many non-energy benefits. Focus on Energy should also work to increase the awareness of both the energy and non-energy benefits.

Focus on Energy should ensure that programs 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 (e.g. K-12 schools), increased education should be provided to staff to empower them to provide suggestions to potential projects which may be a fit for VRF. Focus on Energy should target the following building segments and project types as defined in Table 19.

Table 19: This table outlines project characteristics which are typically a good fit for VRF systems. Project staff should consider pushing VRF for these projects.

Building Types	Education, Office, Multifamily, Lodging, Buildings with many thermal zones/rooms where individual thermostat control (Police Stations, Nursing Homes, Clinics, etc)
Project Type	New Construction, Retrofit/Renovations
Project Characteristics	Small to mid-sized buildings (5,000 – 100,000 ft^2), existing buildings without existing ductwork, Buildings with energy efficiency targets/goals, Buildings looking to add air conditioning, Institutional buildings

Conclusions

This research has shown that while a growing number of stakeholders in Wisconsin are familiar with VRF, there is a general lack of understanding and market activity on the newest generation of cold climate VRF systems. Preliminary modeling shows energy savings and payback periods of 10-20 years, which will vary widely depending on specific project parameters. Stakeholder interviewing shows generally positive reception of VRF systems.

Next steps and Future work

To push the existing VRF market to deeper savings and increase adoption of VRF, Focus on Energy should work to develop a program offering. Specific steps for this offering were outlined in the *Pathway to Focus on Energy VRF program* section.

Additional work around VRF would further stakeholder's understanding of this technology in Wisconsin. The primary area of need is independent verification of cold climate VRF systems in Wisconsin. Currently, no independent field data exists in Wisconsin to confirm the energy performance of VRF systems. We would recommend a field study that would monitor the energy performance of 2-3 VRF systems in Wisconsin. The resulting data from this monitoring study would help inform the savings estimates for a TRM measure and be useful for detailed case studies which could be used to push VRF adoption in Wisconsin. One of the biggest barriers found during this research is lack of independent research to verify savings and typical economic outcome. Many prospective projects are hesitant to rely solely on energy modeling estimates.

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Appendix A

Site Name: Office in Madison

Building Information and Profile

This office is a large office building with approximately 169,000 square feet of conditioned interior floor space. The building contains executive offices, a conference center, a fitness center, and a dinning center that can be converted to an auditorium.

The building was designed with the assumption that it will be owned and operated by the owners of the office for a long term period. This design approach represented sustainability for the owners and allowed them to justify longer paybacks when selecting equipment during the design process.

HVAC Design Criteria

The key metrics for selecting HVAC systems at this site were operating costs (annual energy costs); first costs; maintainability (maintained costs, lifetime, and durability); and sustainability. Greenhouse gas emissions and comfort were also important considerations.

Consistency in system performance was a key HVAC decision point. Operators wanted comfort levels to be the same year-round so occupants could expect consistency on any given day. A stated example of this was to keep indoor temperatures constant allowing occupants to wear the same level of clothing regardless of the time of year.

This property put effort into energy modeling and making decisions based on lowest achievable costs. They started with baseline code compliance and, from there, looked for cost-effective methods to reduce energy spending. The goals of sustainability and long-term ownership allowed them to consider options with longer paybacks than would shorter-term owners of similar buildings.

The project relied heavily on designers to suggest options and make high-level decisions early in the process. As a design came together, specific options were sent out for bid and first costs were weighed against modeled performance.

VRF System Specifications

A cold-climate variable refrigerant flow (VRF) system was installed utilizing supplemental heat, wherein outdoor units are installed in a penthouse. The penthouse has exterior dampers that close when temperature goes below 50 degrees Fahrenheit (°F). As the temperature in the penthouse continues to drop, auxiliary natural gas heaters are activated to warm the penthouse.

The VRF system is has 10 total outdoor units with a nominal total of 26 tons of heating capacity (312 MBtu/hr).

VRF Planning

A VRF system was suggested at the design phase of construction for this property. There were concerns over the performance of the envelope due to the large amount of glass used in the design. Designers felt it was necessary to install a high-efficiency heating and cooling system to meet code requirements.

Comfort of the occupants was also considered. The design process required the building models to show an 80% occupant comfort level. This criterion was used as one measure for balancing building design choices and energy use. For example, the designers had to determine how to ensure occupant comfort despite the higher thermal loses due to the glass exterior. Energy models were used to evaluate options such as hydronic heating at the perimeter of the building and increasing interior space temperatures.

VRF Installation

The VRF installation was simplified due to the building being a new construction project, and VRF had been selected early in the project. New construction avoids complications with indoor unit placement and running refrigerant lines, which can be barriers in retrofit applications.

This installation did have a few concerns about the appearance of the VRF indoor components. Interior designs had open ceilings with exposed mechanics. Designers preferred to run VRF refrigerant lines in conduit or trays that hide the tubing from occupant view. Additionally, cassette-style indoor units were avoided due to their aesthetics.

VRF Operation

Thermal comfort

This site has had issues with occupied space temperature dead band. Initially, the space temperatures were allowed to drift 7°F before the VRF system called for conditioning. This is an ongoing issue that the site is working through with the manufacturer. Manufacturer technicians have been on-site to improve performance, but the system is still not fully meeting expectations.

The VRF system also takes longer to recover from setback. Operations staff would prefer a method of control that allowed occupants to adjust setpoints over a small range (e.g. 71°F to 75°F) and then reset all controls points to default at night (e.g. 73°F).

The VRF system was initially designed with some shared zones on the executive floors. This led to some disagreement over setpoints, comfort complaints, and over- and under-conditioning. The system was modified to allow each office to have its own control and zone. The reconfiguration required significant downtime as zones were added.

Performance and Energy Costs

Energy costs were much lower than expected. The building compares well in terms of energy use per square foot to other buildings of a similar type. It is using less than half of the forecasted energy budget. However, occupancy levels have been very low with staff working remotely. They are spending around $15,000 to $20,000 per month on utility bills for this facility. This equates to approximately $1.5 per square foot, which is about half the assumed consumption for this building type ($3/ft^2).

Occupant Experience Survey

Survey potential was limited. Construction on the building was completed in February 2020. The building was occupied when the COVID-19 pandemic forced many employees to work from home, so occupancy has been inconsistent, which makes surveying difficult. However, building operations keeps complaint logs. Those logs and build operator interviews have been used to represent occupant experience.

The majority of comfort complains are around the dead band on occupied space temperatures. Things are improving, but the building is still well short of the 80% comfort satisfaction goal.

Occupants are also pleased with the acoustic comfort of the system. The VRF system is very quiet, and there have been no issues with noise.

Overall takeaways

The property has had issues with the VRF system since startup, mostly related to controls as previously discussed. They have been working to improve system performance and would not avoid VRF in the future due to these issues.

However, there are a few concerns and barriers to VRF that will be evaluated before selecting for future buildings:

Flexibility. The building was designed around a specific need for the space at the time of construction, but needs within the space can change. Some areas of the building were designed for offices but have since been converted to laboratory space. The VRF system has been difficult to modify in response to such changes. Our project team notes that this is less of a concern in a traditional office building, where the building layout may change but not the building use type (i.e. converting from office to laboratory).

Maintenance. To date, the system has needed little to no maintenance work. There was a concern over refrigerant leaks and the ramifications for the building if a leak was found. These concerns led to increased care for durability in system design, particularly around refrigerant line connections.

Utility Bills

We did not pursue utility bill data due to the limited amount occupancy (less than 2 months before occupants started working remotely).

Focus on Energy

This building was part of Focus on Energy's new construction design guidance program and received an overall rebate around $50,000 for the entire building.

Site: Elementary School

Building Information and Profile

This elementary school is a 70,000 square foot building and serves approximately 350 students from pre-k to 5th grade. It is owned and operated by the public school district in Monroe, Wisconsin.

HVAC Design Criteria

For the school district, first costs and operating costs are high priority when considering HVAC systems. Occupant comfort and ease of operation are also very important. As an institutional building, longer payback periods are typically acceptable.

VRF System Specifications

The elementary school features an air-source variable refrigerant flow (VRF) system paired with a dedicated outdoor air system with gas heat. The VRF system consists of four outdoor units with a total rated capacity of 102 tons. The outdoor units are installed in mechanical rooms on the second floor. The mechanical room has gas heaters. The mechanical rooms also have dedicated outdoor air systems with natural gas heating. The dedicated outdoor air system's gas heat has a total output capacity of 640 MBtu/hr.

VRF Planning

VRF was suggested by the long-time contractor for the property, NAMI, as a solution to ongoing zonal control issues and the properties desire to decrease energy usage and energy costs.

The school district and contractor viewed VRF was an attractive option early in planning because the first cost was the same or slightly less than a retrofit to a boiler/chiller system. VRF also delivered lower energy costs and a preferred maintenance schedule with lower costs.

VRF Installation

The VRF system was a retrofit installation in 2019 and used a design-build process. The VRF system replaced a large number of residential style natural gas forced air furnaces. The building originally had 28 individual furnaces — the total number of systems was reduced to 22 through shell improvements and other efficiency work. The school district used energy modeling to make system selection decisions.

In addition to retrofitting the new VRF system, the school district also did lighting upgrades (LED), fire/sprinkler system upgrades, and Cat5 improvements at the same time. VRF distribution and cassettes were hidden in the ceiling. This work was packaged for efficiency while the drop ceiling was open.

During installation, there were a few minor issues, including a refrigerant line leak and several water condensates lines that did not have enough slope to drain properly. The school district highlighted that these issues were minor and quickly rectified. The school district did note that as dehumidification occurs at each indoor unit, some units had a particularly long condensate line length to the nearest drain. This added additional cost and installation time but wasn't significant enough to result in large additions to the project budget.

VRF Operation

One major benefit to the VRF system was that it allowed control of the setpoints for individual classrooms. Previously, multiple classrooms had shared a thermostat and furnaces, which limited control to a small group of classrooms and teachers, often leading to comfort issues.

The operator indicated that VRF is a "set and forget" style of HVAC system. This is a benefit over the previous, more hands-on boiler system. Additionally, a VRF system installed with a dedicated outdoor air system, like the one at this site, guarantees that fresh outdoor air requirements are met. This system design also allowed for much higher filtration and improved air quality over the previous system.

Performance and Energy Costs

The site has noticed a significant reduction in gas usage. Electrical performance attributed to the VRF system is harder to determine, given the simultaneous lighting improvement.

Occupant Experience Survey

Teacher's schedules have been inconsistent due to the ongoing COVID-19 pandemic. Their schedules and increased workloads limited the potential for and usefulness of occupant surveys. Building operations staff were interviewed instead about complaint logs and their experiences interacting with building occupants on comfort issues.

Occupants have been overwhelmingly happy with the building's heating and cooling performance. The only comfort complaints, and they have been very minimal, have been about the delayed response time to a user-prompted setpoint change (2°F–4°F adjustments).

Occupants have not noticed the fan noise or system sounds, especially compared to the much louder on/off blower noise of the previous furnace-based system.

Overall takeaways

The system has yielded a positive experience for operators, owners, and occupants. They are considering VRF for other buildings, including for replacement of a traditional boiler/chiller system.

Utility Bills

A utility billing analysis was conducted at this site using gas and electric bills from March 2017 to Feb 2021. The billing analysis was complicated be several factors (Figure 20). Due to the class schedule at the site, occupancy and setpoint scheduling was not consistent across heating and cooling seasons. The COVID pandemic further complicated occupancy and scheduling. The VRF system was retrofitted between the 2018 and 2019 school years. An extensive LED lighting upgrade was also completed at the same time (resulting in energy savings for lighting), complicating the electric use disaggregation. The electrical use in the property increased by about 40% during the heating season. While a slight increase in electric use would not be unexpected when converting from gas heat to electric heat, a 40% increase is significant. Unfortunately, insufficient data was available to fully explain this discrepancy.

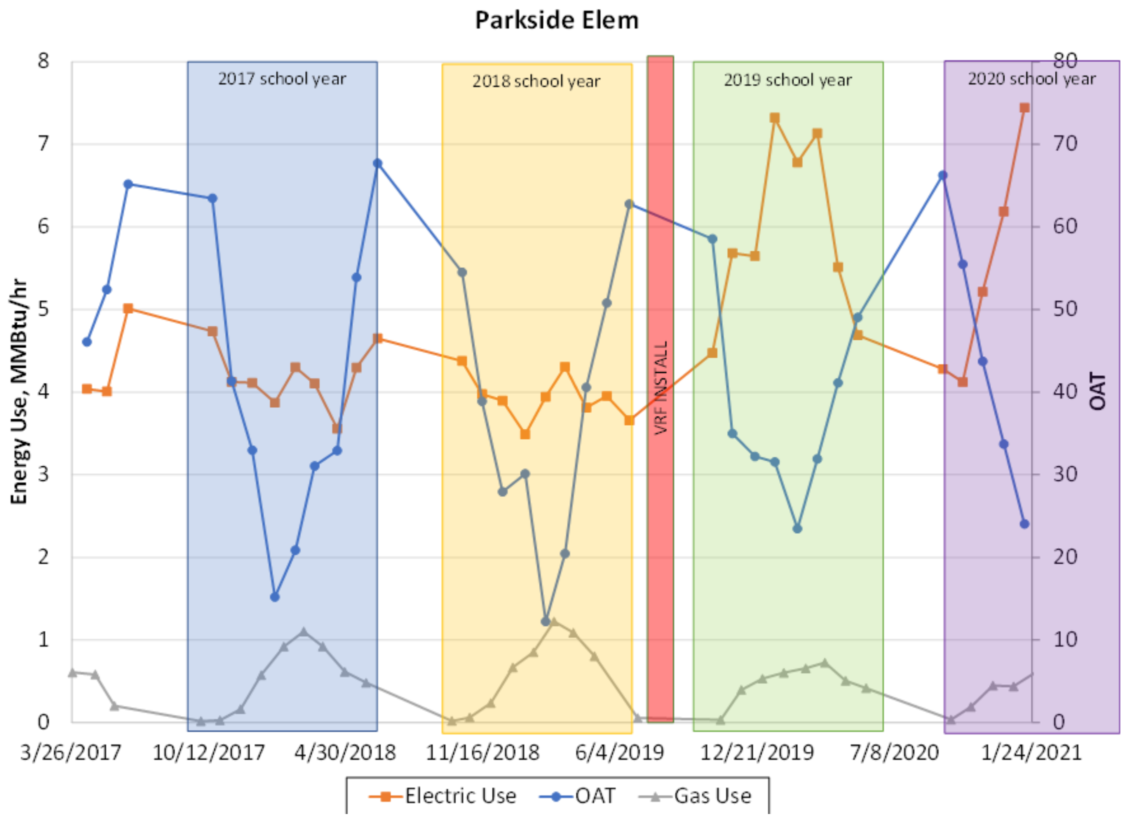

Figure 20. Utility bill data and time periods at elementary school.

Despite these impacts, the site operators were aware of reduced natural gas bills. The billing analysis found a 23% reduction in total heating gas usage. This reduction was significant, but the presence of natural gas heating in the dedicated outdoor air system, likely limited the gas savings. In addition, the outdoor units for the VRF system were placed in a penthouse which was supplied with gas heat.

Focus on Energy

The school district did not receive a rebate for their VRF system. However, they did receive a significant lighting rebate, which was all handled by the installer who passed on the savings to the elementary school.

Site: Hotel in Madison

Building Information and Profile

A 165-guest room hotel with on-site dinning and fitness center. The building consists of 10 stories above ground and two below-ground parking levels. This hotels is part of a hotel chain with properties around the world.

HVAC Design Criteria

The management group undertook this variable refrigerant flow (VRF) project to try to understand more about VRF systems and determine the role these systems could have across all their properties. This hotel was their first with a VRF system and is being used as a "pilot site".

Packaged terminal air conditioners (PTACs) have traditionally been the HVAC system of choice for this hotel chain and for hospitality buildings in general. They are used in in this hotel chains' major markets (Midwest and Phoenix areas). PTACs are reliable and have low first costs. Replacements are easy and can be completed by operations staff already on-site. Maintenance issues can also be addressed with only the individual room experiencing any downtime.

Capital costs and occupant comfort are the most important metrics when deciding on HVAC systems. Operating costs are also important, but a secondary priority.

VRF System Specifications

A VRF system was installed at the time of building construction. Outdoor units are located in mechanical rooms on the first floor, which serves the space on the ground through third floors. Outdoor units are also located on the second floor, which serves floors four and above. Mechanical rooms are enclosed spaces but are treated as outdoors. Louvers in these rooms remain open until temperatures drop below 50°F outdoors. Once louvers close, the mechanical rooms are conditioned by two gas unit heaters in each room.

The height of the building prevented VRF outdoor units being installed on the rooftop. The City of Madison regulates building height, preventing additional levels on this building that would been required for a traditional penthouse design. In addition, the potential roof mounted scenario may have resulted in long refrigerant piping runs from the VRF outdoor unit to guest rooms, which would have presented an additional hurdle.

This system is a hyper-heat Mitsubishi install with heat recovery between indoor units. Each guest room has a VRF indoor unit and its own thermostat. Indoor units are fan coil design installed in the soffit on the interior side of the guest room.

VRF Planning

The VRF system was suggested by the design-build team for this property. It was compared to a traditional four pipe system that had a similar initial cost. The VRF system had several potential benefits for this property. First, it allowed the design team to add additional window space. In some units, windows were installed within 12 inches of the floor. Traditional PTAC or boiler systems place heating components below the windows preventing floor to ceiling window installs. Second, VRF systems have less noise transfer through the guest room envelopes. PTAC shells are a penetration through the building envelope and are not noise-tight. Eliminating this envelope penetration is a significant benefit for properties with high exterior ambient noise (in this case, a nearby freeway). The site contact also indicated that the City of Madison would not allow PTAC units at this site due to aesthetics.

VRF Installation
No major installation issues were reported at this site. The building operator did not provide details on any specific lessons learned for their installation. Our project team will attempt to follow up to see if additional commentary can be provided on the install.

VRF Operation
The site is satisfied with the VRF system. There were several lessons learned during the initial operation of the system. These lessons will be used to improve the approach of any future installations. Lessons learned include:

- Fan coil indoor units had some airflow issues. These are not VRF specific, but they remain important for fan coil units to understand the length from the discharge grille and the edge of the occupied space. There are concerns on whether or not the fan coil throw will cover that distance.
- VRF systems take longer to recover from setback. For this hotel, it has led to a default strategy of reducing or eliminating typical occupancy-based temperature setbacks.
- Room layouts and distribution design is important. This led to a need for supplemental heat in only the corner units in this property.
- From a maintenance perspective, when a compressor goes down, any unit conditioned by that system will be impacted. VRF systems have less ongoing maintenance, but failures are likely to result in longer downtimes impacting multiple rooms.

Thermal comfort
This property had guest comfort issues, particularly in the corner rooms with large glazing areas and longer distances between the VRF grille and the farthest edges of the units. The grilles in the units came through soffits. In units with a single window this worked fine, but in the corner units, the distance that had to be covered by the airflow was too great for the fan coils. This resulted in the need to add perimeter electric resistance heat in those units. Our project team noted that this could have also been rectified by reducing the amount of glazing in corner units during the design process.

Temperature dead bands in the units also caused some complaints. Guest perceptions were higher than the system could meet. The VRF system and the building automation system had a minimum temperature setting of 67°F. Many guests wanted them set cooler during the cooling season.

Performance and Energy Costs
Building has much lower energy costs than anticipated, due in part to high performance of the VRF system. The building owner and operator were pleased with this outcome.

Occupant Experience Survey
Initially there were guest complaints around comfort, primarily in units located on the building's corners (with significant glazing). Those reduced as supplemental heat was added.

The owners fielded some complaints due to the confusion over whether the heating system was operational. Hotel guests are most familiar with hearing the loud fans and PTAC-style systems running. The VRF system is much quieter, and guests questioned whether it was actually on. To that end, messaging was added to thermostats to alert guests of the quieter operation of these systems.

Overall takeaways

There is still some skepticism from the owners, but they have found enough satisfaction with the building operation now that VRF will be considered for a couple urban midrise buildings where height restrictions and exterior noise concerns make VRF systems especially attractive.

Site: NHC Office

Building Information and Profile

The NHC Office is an office building located near Green Bay. The building owner has a large number of buildings with a wide range of uses. Many of their commercial spaces are converted residential (mostly multifamily) buildings. They hold a unique perspective in that they anticipated owning these properties and their associated systems for a long time. Since properties will not be sold, the economic concerns are over the lifetime of the buildings and systems, which increases the importance of performance and durability.

HVAC Design Criteria

This site indicated that total operational costs, system performance, and reliability are their primary drivers in HVAC system design. They plan to own these buildings for the long term, so short paybacks are not nearly as important as operating costs and total lifetime costs.

Occupant comfort and environmental performance are important as well.

VRF System Specifications

A cold climate variable refrigerant flow (VRF) system was installed as a retrofit measure. The system was installed prior to the 2019–2020 heating season. A Mitsubishi hyper-heat system was installed with outdoor units on the roof. The VRF system was installed to meet the cooling load in a portion of the building. The building retained the gas boiler hydronic system for heat. The VRF system is operated to provide heat for the zones in which it is installed at outside temperatures at or above 55°F. However, while the VRF system does not handle the full heating load, it was designed to carry the full load of the zone if necessary, but due to inexpensive gas costs and concerns over frost protection in the hydronic distribution system that runs along the exterior of the building, VRF heating operation is limited to the shoulder season. Our project team did discuss with the Norbert Hill building operators that lowering the VRF phase out temperature from 55°F to approximately 30-40°F may lead to reduced utility bills. However, a more detailed energy analysis would be required to confirm the optimized lower phase out temperature.

VRF Planning

The VRF system was installed due to poor zonal control of the cooling system. The existing cooling system used residential-style split air conditioners. Each of these systems delivered cooling to multiple rooms with only one thermostat. This led to over- and under-cooling and occupant discomfort.

VRF Installation

The VRF installation was straightforward. The most significant barriers were around drilling into the concrete building structure for refrigerant piping and getting makeup air ducts to each room.

Integration of controls with the building automation system took some troubleshooting with the building controls team and the VRF manufacturer to get operating correctly.

VRF Operation

VRF systems run without the need for operational staff oversight. This is especially important when building staff are responsible for multiple buildings.

Thermal comfort

Building operators have been happy with the thermal performance of the system. Improved zone controls have reduced occupant complaints and disagreements over thermostat settings.

Performance and Energy Costs

The site is happy with the VRF operational costs. There was considerable interest in learning more about how the VRF system would perform if asked to meet more of the heating load. The system can meet the load at lower ambient temperatures, but the cost and environmental impacts of changing the VRF operating points is unknown without an energy/carbon analysis.

Occupant Experience Survey

Occupancy has been limited since the COVID-19 pandemic. The building operations team is exploring options for comfort surveys.

Overall takeaways

They are actively looking at more opportunities to add VRF systems. Another retrofit installation would likely be underway if not for impacts of the COVID-19 pandemic. It is an especially attractive solution for older buildings where adding ductwork is cost prohibitive or technically difficult.

Utility Bills

The building owner has provided utility bill data dating back to 2010. Analysis of the utility bills was inconclusive for this property. The VRF system was only installed for one zone of the conditioned space. Additionally, the VRF only provides heating at temperatures greater than 55°F. Therefore, the expected natural gas savings would be small compared to the variance in monthly energy bills as shown in Figure 21.

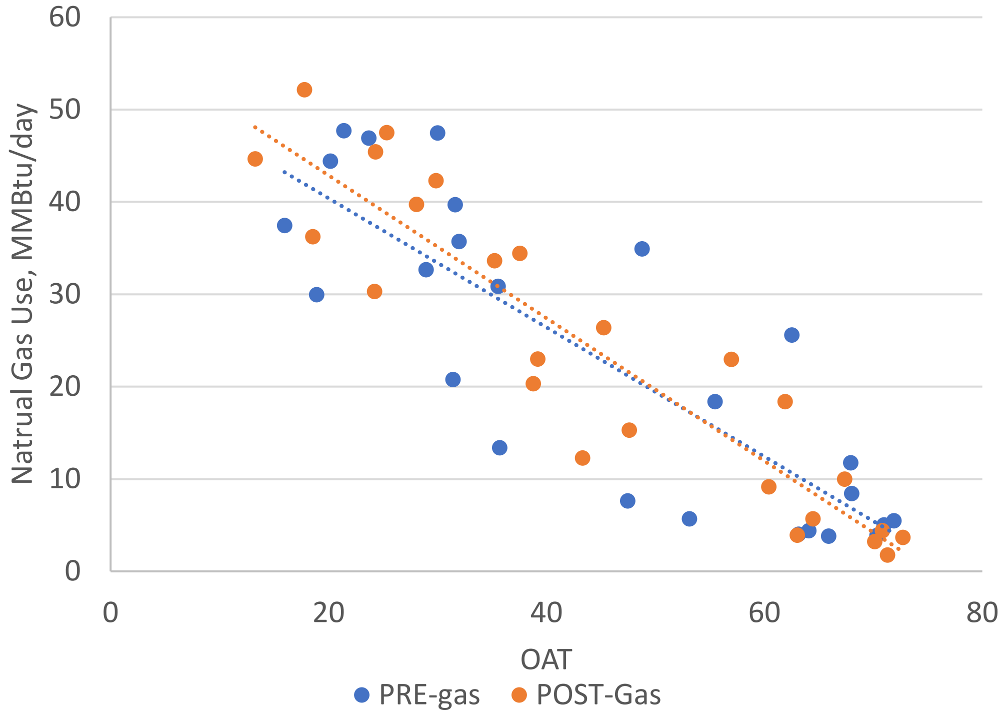

Figure 21: Natural gas usage from utility bills at NHC.

Site: Vyron Corporate Headquarters

Building Information and Profile

The Vyron corporate headquarters in Waukesha, WI is a corporate office with larger training and demonstration areas and smaller office spaces. It is a one-story facility with VRF systems serving two of the property's suites. The site is owned and operated by an HVAC manufacturer's representative business, so high-quality HVAC performance is a top priority. Vryon is a manufacturer sales representative for LG VRF systems.

HVAC Design Criteria

This site prioritizes energy efficiency, effective zoning, and comfort above all other criteria for selecting an HVAC system to retrofit for the space. Previously, the property had constant-volume RTUs that were old and could no longer sufficiently heat the space.

This site underwent a VRF retrofit to replace the existing RTUs. An LG VRF system was selected. First cost was not as significant a consideration for this site as it normally is for this site[7]. The building operators said VRF was a good fit for the needs of this building and this space.

VRF System Specifications

Two separate VRF systems, one for each suite (Suite A and Suite B). Both systems have the outdoor unit installed outside the envelope and are rated for performance down to -13°F. One outdoor unit is mounted to an exterior wall. The second was originally installed in a semi-penthouse. Since then, the penthouse was disassembled, and only an always-open louvered down remains. This unit is essentially outdoors as well. There is a wider range of indoor units installed for this application. They have two-by-two cassettes, three-by-three cassettes, standard wall-mounted units, a floor unit, a picture-frame unit, and high-static ducted units. Systems were installed in 2015 and 2018.

The VRF systems provides full heating and cooling to the occupied space with no supplemental heating or cooling systems. Outdoor air is provided to the space with a simple ERV wheel. The VRF system also provides year-round cooling for the IT service room.

VRF Planning

A VRF system was selected due to the high efficiency and energy savings potential, as well as being a good fit for the space. The lack of ductwork and simplicity of the design of the system were notable benefits of the space. Additionally, with a large amount of open area and many small offices, the zoning and control options of VRF were very attractive.

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[7] Vyron is a representative for LG VRF products. However, at the time of the retrofit, an official business relationship between the site and LG was not in place (though at that point the relationship was in its early stages).

VRF Installation

The installation of the VRF system for this building was straightforward. One design change that would be made is adding increased snow guards for the outdoor units. The heavy snow load and high humidity has forced the site to run more aggressive defrost cycles (longer and more frequent). Increased defrost cycles increases system energy consumption and decreases overall system performance

VRF Operation

The site is very happy with the performance of their VRF system. They have installed sole source air source VRF with outdoor units outside at this corporate headquarters, and subsequently at another property in Green Bay, WI. The system was able to keep the building at setpoint through the polar vortex this last winter and also delivered cooling to IT services at the same time.

Thermal comfort

Occupants are happy with the space temperatures and minimal noise levels from the system. Building operations estimates 90% occupant satisfaction.

Performance and Energy Costs

Since Vyron occupied the site with a previous HVAC system, a direct comparison between the pervious HVAC system and the new VRF system is possible. Operators have seen significant energy savings at this building. In addition, their previous system was underserving the space, resulting in the use of many space heaters in office spaces.

Overall takeaways

This site is in full support of VRF. They would not hesitate to install additional VRF systems on properties they own or operate. Their biggest concern or barrier with VRF is quality installation — a lot of early adopters have poorer quality installations. The biggest installation issues they encounter are: (1) Accurate measurement of piping diameter and lengths. These are very important to measure accurately, so that the system can be charged and monitored properly. Without proper charge, the system can lose control of subcooling and superheating, which reduces system performance. (2) Good electrical design and service. Over-amping a compressor adds stress and can lead to early failure. (3) A high-quality certified installer. Such installers know the systems and its benefits and drawbacks. (4) Sufficient maintenance. Maintenance plans are not used as frequently as they should be. Maintenance on these systems is minimal, but necessary. The site operators were recently working with another property the VRF had only been installed for 1.5 years and it had a compressor fail. The system was installed well, but the maintenance had been neglected. Filters had been removed and the coils and whole system internals were covered in dust. This led to early failure.

Appendix B

This appendix summarizes some of the key lessons learned and best practices for VRF systems in Wisconsin.

Ideal Project Types

VRF has been successful installed in both new construction and retrofit/renovations. The economics in each scenario can vary significantly from project to project. Typically, for existing buildings undergoing a retrofit or renovation, if the existing HVAC system can be replaced with the exact same system type (i.e. PVAV, replacing only the RTU and retaining the ductwork), VRF will likely end up being a more costly option.

VRF is a good fit for the following building types:

- Education
- Office
- Multifamily
- Lodging
- Buildings with many thermal zones/rooms where individual thermostat control (Police Stations, Nursing Homes, Clinics, etc)

Other key project characteristics:

- Small to mid-sized buildings (approximately 5,000-100,000 ft^2)
- Existing buildings where running ductwork will be challenging (masonry walls, low ceiling heights, etc).
- Buildings with energy efficiency targets/goals
- Buildings looking to add air conditioning
- Institutional buildings

Design and Installation Best Practices

Design strategy is dependent on project location. Based on Figure 5, the following design recommendations are made for VRF projects in Wisconsin:

- **North Zone:** design temperature -25°F, water-source VRF, air-source VRF with penthouse, or air-source VRF with secondary heating system
- **Central Zone:** design temperatures between -15°F and -25°F, cold climate air-source VRF rated to -22°F, air-source VRF with penthouse, air-source VRF with secondary heating system
- **Southeast Zone:** design temperature -13°F, air-source VRF rated to at least -13°F

Other key design and installations recommendations:

- Avoid significantly oversizing the VRF system

- Ensure that engineers and designers are familiar with the specific VRF system that has been selected. Each VRF manufacturer has unique design requirements which engineers and designers need to be aware of.
- VRF systems are unique to each manufacturer, and often are required to be designed by a manufacturer representative. Engineers and designers need to coordinate load calculations and other design aspects with the VRF manufacturer.
- Contractors/Installers should be educated in the installation of the specific system that has been selected. Each manufacturer has specific criteria and installation practices which will result in success. Manufacturers offer training for installers which is highly recommend.
- The electronics on VRF units are sensitive to power surges and voltage drops. Consult with the manufacturer if the building experiences power variations from the electric grid.

Operation Best Practices

Based on interviewing manufacturers, contractors and owners/operators, the following list of operational recommendation was compiled:

- VRF systems and heat pumps are different than heating systems that most owners, operators, and occupants are familiar with. As a result, some learning and education is required.
- VRF systems often respond slowly to changes in setpoints. Stakeholders should be aware of this. Nighttime setbacks should be limited, and warmup time periods should be extended.