Sustainable Engineering Group LLC

FOCUS ON ENERGY

ENVIRONMENTAL AND ECONOMIC RESEARCH AND DEVELOPMENT (EERD)

EVALUATION OF ADVANCED HVAC TECHNOLOGIES

FINAL REPORT

April 15, 2014

PREPARED BY:

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EXECUTIVE SUMMARY

Date of Report:	April 15, 2014
Title of Project:	Evaluation of Advanced HVAC Technologies
Investigators:	Amalia Hicks, Ph.D. (Research Director) Svein Morner, Ph.D., PE (Principal) Eric Mueller (Engineer) Jon Evans, PE (Engineer) Andy DeRocher (Engineer) Ken Von Bank, PE (Engineer) Jamie Campbell, PE (Engineer)
Organization:	Sustainable Engineering Group, LLC
Research Priority:	"Further evaluation of advanced HVAC"
Project Period:	March 13, 2013 to April 15, 2014

Research Objectives:

- Gather data on existing advanced HVAC systems to create a database of energy usage for at least five (5) buildings in each of three categories: displacement ventilation; variable refrigerant flow; and radiant systems
- Analyze data gathered to identify patterns of energy usage
- Conduct ASHRAE Level I energy audits of at least two (2) buildings from each technology to find common operational issues
- Perform cost-benefit analysis of the systems and identify the system types that provide the most favorable energy savings relative to first cost in Wisconsin

Summary of Results:

A database of energy usage was created for 19 buildings containing any of three advanced HVAC technologies: displacement ventilation; variable refrigerant flow; and/or radiant systems. This data was then compared to the median energy use of similar buildings (obtained from the CBECS database via Energy Star Target Finder). All but two buildings in the sample exhibited measurable energy savings, broadly suggesting that each of these technologies is capable of increasing the efficiency of building operation in Wisconsin climate conditions.

Buildings containing displacement ventilation showed total energy savings of 34% on average, while those utilizing radiant systems averaged 38% savings and buildings with VRF systems showed 26% energy savings. These are total building energy savings, however, and are complicated by the fact that additional energy conservation measures were present in all buildings. Assuming that energy savings are distributed similarly to typical Wisconsin energy end uses, it can be estimated that approximately 50% of measured savings are attributable to HVAC systems.

One important caveat to mention is that quantitative conclusions drawn by this work are subject to uncertainties associated with small number statistics. The magnitudes of these uncertainties are difficult to estimate when coupled with reporting errors, weather variations, and the inherent complexities of interacting building systems. As a rough approximation, it is estimated that uncertainties on energy benchmarking results are approximately 30%; however, in the case of VRF systems, benchmarking results are also supported by an independent before-and-after case study.

Satisfaction feedback was obtained from building owners via a self-completed survey. Overall, advanced HVAC technologies are viewed as solidly above average in the category of energy performance. Occupant comfort also receives an overall positive rating. Ease of operation is given the lowest rating, considered to be "Average" when compared to traditional HVAC systems.
A majority of respondents (82%) report that they would recommend these advanced technologies to others. Energy Savings and Occupant Comfort are cited as the main motivators for using these technologies, however a statistical treatment of the data reveals that occupant comfort is weakly correlated with whether or not building owners would use the technology again. Perceived energy savings are strongly correlated with technology re-use, even in the case of buildings that are not measurably performing as promised.

Figure 1 shows how each technology performs compared to projected energy savings during design. The dashed line represents the relationship where anticipated savings are exactly met. Points falling above this line exceed expectations, and points below this line fall short of expected savings. The solid line represents the best linear least-squares fit to the data and suggests that, in general, achieved savings are comparable to predicted savings for the sample as a whole.

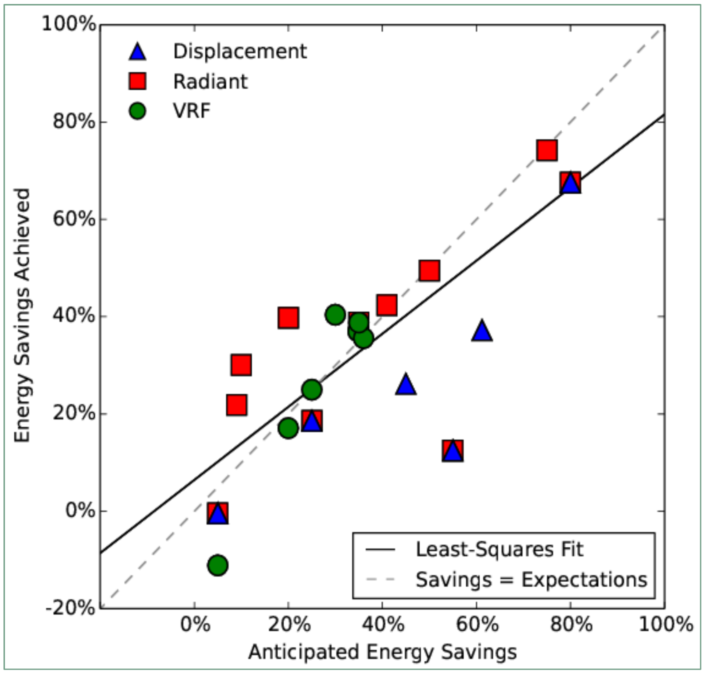

Figure 1. Achieved vs. Anticipated Savings for Advanced HVAC Technologies

ASHRAE Level I energy audits were conducted on three buildings from each technology to identify common performance issues. It was found that displacement ventilation tends to face the most challenges in terms of operation and/or design in Wisconsin climate conditions, possibly due to misconceptions that displacement ventilation is capable of heating spaces. VRF systems are also found to be somewhat challenged by cold climates, because the central unit (intended to pull heat from the outside air in heating mode) does not typically function at temperatures below 0 ^{o}F, and has unknown efficiencies at temperatures between 0 ^{o}F and 35 ^{o}F. With regard to radiant systems, though no condensation problems were uncovered in the course of this study, care should be taken to prevent such issues when designing radiant cooling systems.

Though cost-benefit estimates are complicated by assumptions and uncertainties related to small number statistics, our results suggest that of the three HVAC types studied, radiant systems provide the most favorable energy savings relative to first cost in Wisconsin climate conditions.

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INTRODUCTION

MOTIVATION

Buildings account for 40% of the total energy use in the United States, consuming 72% of the electricity and 36% of the natural gas (e.g., U.S. Department of Energy, 2008). Approximately a third of this energy consumption is due to HVAC needs (e.g., Thornton, 2012). The HVAC fraction is even higher in Wisconsin commercial buildings, with heating, cooling, and ventilation consuming nearly 60% of total building energy use (U.S. Energy Information Administration, 2008, also see Figure 2). These numbers suggest that increasing building HVAC efficiencies would have the potential to make a significant impact on overall energy use.

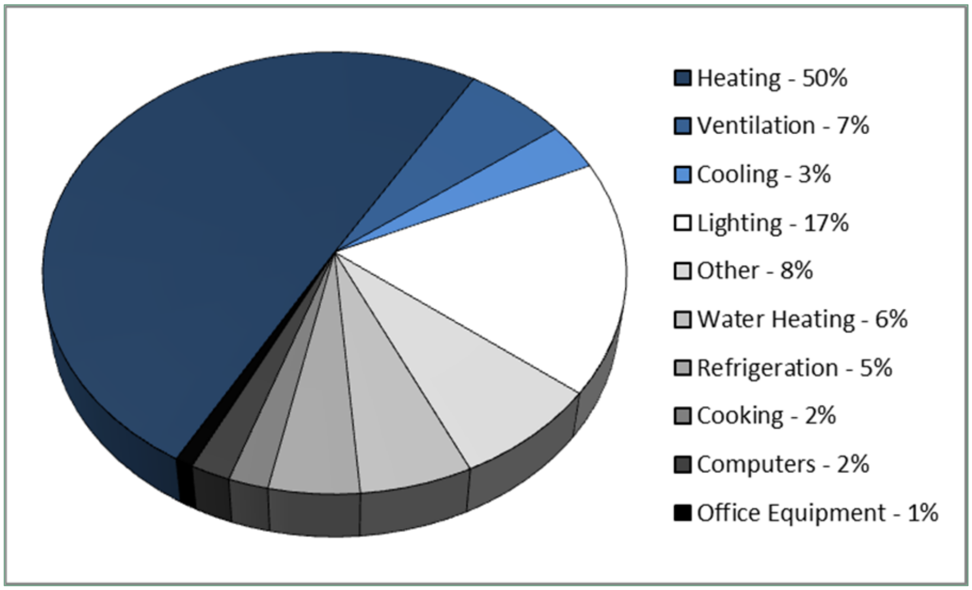

Figure 2. Energy End Use Distribution in Wisconsin Commercial Buildings (CBECS East North Central Region)[1]. HVAC uses (i.e., heating, cooling, and ventilation) are shown in blue tones.

The three major functions of HVAC systems are to heat, cool, and ventilate (deliver fresh air to occupants). Each type of HVAC system has a certain set of advantages and disadvantages which tend to be application-specific. For heating and cooling, most systems rely on transferring heat throughout the building using a combination of air, water and/or liquid refrigerant as media. In terms of ventilation, some systems mix fresh air with conditioned supply airflow, and others have a ventilation system completely separate from the conditioning system.

The most common type of commercial HVAC system mixes return air and outside air for ventilation and conditioning of the space. The air to each zone (e.g., room or space) is supplied by a variable air volume (VAV) box that adjusts flow, depending on zone temperature, down to a minimum level that satisfies ventilation air requirements. A number of zones are usually

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[1] http://www.eia.gov/consumption/commercial/data/archive/cbecs/cbecs2003/detailed_tables_2003/2003set19/2003html/e02.html

assigned to an air handler. Typically the air handlers condition the supply airflow through hot water coils for heating and chilled water or refrigerant coils for cooling before it is routed through ductwork for zones. At times, one room may need heating and others cooling. If a VAV box needs heating for a zone, it can reheat the air with a hot water or electric coil before it exits the diffuser, which is usually located at ceiling level. Although this reheat is a convenient control mechanism, it is relatively inefficient and can prove expensive to operate.

Commercial HVAC systems typically utilize some variation of the system described above, almost always involving mixed air delivery for heating, cooling, and ventilation. In the last few years, however, there have been numerous advances in HVAC technology that have gained significant traction in Wisconsin. In large part this is due to growing trends towards LEED certification, green buildings, and energy efficient building systems. Common among newer systems are claims by manufacturers and designers that significant energy savings can be achieved.

The main objective of our Focus on Energy Environmental and Economic Research and Development study is to evaluate the actual energy performance of three modern building technologies: displacement ventilation, radiant cooling and heating, and variable refrigerant flow. Much of the available literature on these technologies relies on computer simulations and theoretical calculations; this study will provide a field-based complement to the existing knowledge base.

DISPLACEMENT VENTILATION

Of the three major functions of HVAC systems, displacement ventilation focuses on the ventilation of spaces, rather than on heating and cooling. Specifically, displacement ventilation is a technology designed to deliver fresh air more effectively to occupants by taking advantage of thermal air stratification. Fresh air enters the space at floor level in the occupied zone and as it heats and rises, it pulls contaminants up with it to exit at ceiling level. In this fashion, people are in contact with the freshest air in the space, as opposed to more typical systems in which incoming fresh air is mixed with return air.

Displacement ventilation specifically operates by distributing slightly cool air (~65 ^{o}F) near the floor. To ensure that the space remains largely undisturbed, this air must be released at low velocity (~40 feet per minute) through air diffusers. As seen in Figure 3, when cool, low-velocity air enters an occupied zone, it flows horizontally until a warm object causes a natural upward air flow, creating a plume. As the warmed air rises it carries pollutants with it through a ceiling level outlet. When operating correctly, there will be measurable temperature differences between floor and ceiling air. These systems are typically installed in large open spaces with taller ceilings and/or spaces without much occupant movement such as classrooms or office buildings.

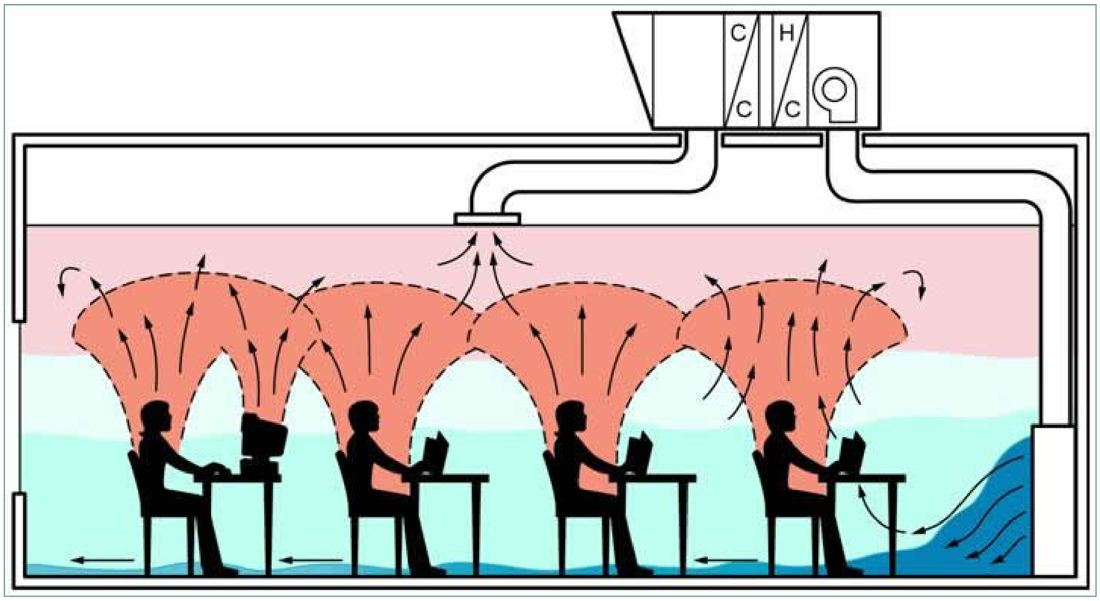

Figure 3. Diagrammatic Representation of Displacement Ventilation (Source: Engineering Design Resources, 2010).

Displacement ventilation has been purported to not only reduce energy use in buildings but significantly improve air quality for occupants (e.g., Holland and Livchak, 2002; Chen and Glicksman, 1999). One energy advantage of displacement ventilation is the higher allowable (cooling) discharge air temperature required by floor-level diffusers compared to traditional mixed-air, variable air volume (VAV) systems.

In cold weather climates it may be possible to provide most of a building's cooling needs with a displacement ventilation system. In general, however, DV systems are primarily meant to ventilate. If system discharge temperatures are turned too low, the stratification of the space and/or upward plumes created may become uncomfortable and disruptive to occupants. The stratification effects of displacement ventilation may offset some cooling loads, but using displacement ventilation as a sole source of cooling will create comfort issues if the supply air temperature is dropped much below ~65 ^{o}F . Although displacement ventilation is typically not designed to meet full heating or cooling loads, it is a strong candidate to supplement other alternative HVAC options like radiant systems (e.g., Roth, 2002).

In their 2002 study, Bourassa et al. find impressive whole building energy savings of 30-60% (compared to a typical VAV system) from utilizing displacement ventilation. The majority of domestic studies of this technology are based on computer simulations, and therefore our knowledge of the true energy benefits of displacement ventilation suffers from a striking lack of field-based research on actual Wisconsin buildings. Although computer models are becoming increasingly accurate in predicting displacement ventilation performance in various building types and climates, it is still difficult to assess the role of building operations and management in simulated environments (e.g., Roth, 2002).

RADIANT SYSTEMS

Radiant cooling and heating provide thermal changes to a zone through exchange of radiation with objects or occupants in the room (Figure 4). Radiation has a net flow from warmer to cooler objects, so in heating mode radiant panels emit thermal radiation, and in cooling mode radiant panels effectively absorb thermal radiation. One of the main benefits of radiant systems is that they typically use hot and cold water to transfer heat to and from occupants rather than air (electric radiant heating is not considered in this study). Water can transport about four times as much energy as air (per weight) and is also much denser, reducing both space and fan power requirements.

Figure 4. Graphic Representing the Use of Radiant Panels for Heating. (Source: TCS, 2010).

According to ASHRAE, a panel or surface is considered radiant if 50% or more of the heating or cooling it provides is through thermal radiation (e.g., ASHRAE, 2008). The heated/cooled surface temperature is controlled to allow a comfortable heat transfer for occupants. Although an additional ventilation system is necessary to supply fresh air, radiant systems require significantly less airflow to a space than a mixed air VAV system. With less airflow required, considerable energy savings are achieved through smaller fans and duct sizes, including a potential reduction of duct pressure losses which can have a significant effect on fan energy use.

While radiant heating is fairly common in Wisconsin, radiant cooling is less common. It is estimated that radiant cooling systems can save 17% of total cooling energy in humid regions, and 42% of cooling energy in dry regions (e.g., Stetiu 1999). The differentiation of energy efficiency between climates is due to a need for prevention of condensation on cold panels or surfaces. Condensation can cause water damage to surrounding spaces, so an additional dehumidifier is necessary in humid climates.

VARIABLE REFRIGERANT FLOW

Variable refrigerant flow (VRF) systems use refrigerant as a medium to transfer heat to and from building zones. These systems can be configured in a variety of ways, however, this study is primarily focused on the performance of outside air-source VRF units, primarily because that is the type of system utilized by the majority of our participants. Similar to radiant systems, VRF systems primarily address the conditioning of spaces, and are typically supplemented with dedicated ventilation systems to satisfy fresh air requirements.

All local units on a VRF system are connected to a central unit which draws heat from the outside air during winter and rejects heat to the outside air during summer. Each zone unit consists of a small fan and coil which produce warm or cold air for the space. This system offers the advantage of high thermal control of many small zones (e.g., apartment buildings, hotels, or office buildings), as it is capable of heating one zone while simultaneously cooling another.

A benefit of VRF systems is that they are able to operate at varying speeds, allowing for energy savings when at partial-load conditions. Traditional compressors have only two options: compressor on or off. It is estimated that partial-load conditions account for 97% of HVAC operations, and due to their ability to operate at variable flow rates, modeling studies have suggested that VRF systems can produce approximately 40% energy savings over other unitary equipment systems (e.g., Abdullah, 2013). VRF systems additionally reduce the sizeable duct losses associated with typical HVAC systems, which can account for 10-20% of total fan power.

Some common concerns with designing these systems are correct sizing of refrigerant loops (since refrigerant piping is present in all conditioned spaces), and controls that can be difficult to integrate into typical building automation systems. In addition, since VRF is a relatively new technology in Wisconsin there is a current lack of experience with these systems in the field.

Figure 5. Diagram Representing the Application of VRF Technology (Source: AIA, 2009).

Figure 5 above illustrates some of the advantages of VRF systems in a typical office space. A full conference room with many occupants and laptops will require cooling to accommodate the thermal loads (shown as blue diffuser air) while a perimeter office space requires heating (shown as red diffuser air). Additionally, the VRF system shown will be able to modulate to lower refrigerant flow at part-load conditions for each unoccupied zone, which increases the energy efficiency of the system as compared to an on/off compressor.

METHODOLOGY

BUILDING IDENTIFICATION

Our search methodology consisted of pointedly reaching out to a diverse network of architects, engineers, building owners, municipalities, and sustainability communities to help us locate buildings that utilized any of the three technologies. Individual communications with approximately 200 contacts, in addition to a Wisconsin Green Building Alliance e-newsletter, resulted in a preliminary list of 150 candidate buildings.

Of the 150 buildings originally identified, 11 were mislabeled and did not utilize any of the target technologies, and 10 were currently under construction. The remaining 129 candidate buildings consisted of 42 with displacement ventilation, 43 with radiant cooling / heating, and 44 with variable refrigerant flow (Appendix A). A breakdown of these buildings by type and location is given in Table 1.

Table 1. Database Breakdown by Technology

	TOTAL IDENTIFIED	NUMBER IN WISCONSIN
DISPLACEMENT VENTILATION	42	18
RADIANT COOLING / HEATING	43	26
VARIABLE REFRIGERANT FLOW (VRF)	44	40
TOTAL[a]	**129**	**84**

Notes: **a** – Some buildings utilize more than one of the targeted technologies, and are therefore represented multiple times in the total.

SURVEY DISTRIBUTION

All building owners were approached for study participation, and surveys were distributed to approximately 40 building owners (an example survey is given in Appendix B). Surveys were completed and returned for 32 total buildings (with 27 located in Wisconsin) however one of the participating buildings was found to not contain any target technologies. Table 2 shows the breakdown of our final participating building sample by technology and location.

Table 2. Participating Building Sample

	TOTAL PARTICIPATING	NUMBER IN WISCONSIN
DISPLACEMENT VENTILATION	8	5
RADIANT COOLING / HEATING	18	16
VARIABLE REFRIGERANT FLOW (VRF)	14	14
TOTAL[a]	**40**	**35**

Notes: **a** – Some buildings utilize more than one of the target technologies, and are therefore represented multiple times in the total.

DATA ANALYSIS AND LIMITATIONS

Surveys were collected and raw data was converted to spreadsheet format for further processing. Data was broken into two categories, energy use (objective) and owner satisfaction (subjective).

Though every attempt was made to verify survey responses where possible, limitations to their accuracy do exist. Site visits uncovered a number of conflicts between reported building characteristics and those that could be verified on site. In most cases these inaccuracies were minor and would not have substantially affected results, however, in one case the building area was misrepresented, which did initially have a significant effect on resulting EUI.

Overall, building area and total energy use were the most reliable response categories, so our analysis remains as close to this raw data as possible. While a more involved, model-informed analysis was considered, it was ultimately not within the scope of this work. Such an approach would also involve a significant number of additional assumptions, and therefore may or may not ultimately improve the accuracy of study conclusions.

Owner satisfaction feedback was also found to contain some discrepancies (primarily via inverting the 1-5 scale values). In all cases where this was suspected, owners were re-contacted to confirm their responses. In the case of buildings that contained more than one of the target technologies, attempts were made to obtain separate satisfaction feedback for each contributing technology. In practice, responses were difficult to separate, particularly in cases where using more than one advanced HVAC technology increased the difficulty of operating the system as a whole.

Quantitative conclusions drawn by this work are subject to the uncertainties associated with small number statistics. The magnitudes of these uncertainties are difficult to estimate when coupled with reporting errors, weather variations, and the inherent complexities of interacting building systems. Standard error of the mean was calculated for each “measurable” quantity, resulting in uncertainties on energy benchmarking results of roughly 30%.

BUILDING ENERGY USAGE

The first page of the survey was designed to gather physical building information such as size, location, fraction utilizing target technologies, supplementary energy saving measures, and utility use data. The requested input was tailored to provide enough information to obtain Energy Star Target Finder[2] savings estimates for each building (based on the Commercial Buildings Energy Consumption Survey, or CBECS, database). The goal of this portion of the analysis was to provide comparisons between predicted energy savings during design, and actual energy savings achieved during operation.

Completed energy use analysis was possible for 19 of the 31 participating buildings. The primary reasons for exclusion from this piece of the analysis were inaccurate physical building data, absent energy savings predictions, and the inability of Energy Star to provide a reliable energy savings estimate. Table 3 shows the technology breakdown of buildings included in energy use analysis. Excluded buildings along with the reason for their exclusion are listed in Appendix C.

Table 3. Buildings Included in Energy Analysis

	TOTAL PARTICIPATING	NUMBER IN WISCONSIN
DISPLACEMENT VENTILATION	5	2
RADIANT COOLING / HEATING	11	10
VARIABLE REFRIGERANT FLOW (VRF)	7	7
TOTAL[a]	**23**	**19**

Notes: **a** – Some buildings utilize more than one of the target technologies, and are therefore represented multiple times in the total.

The Target Finder tool operates by using entered building data to obtain median source energy consumption for buildings of similar type and location. Site energy use is backed out by matching to the site fuel mix ratio of the specific building in question. Therefore if a building uses 100% electricity and is entered into Energy Star Target Finder, site energy comparisons (and subsequent cost and CO_2 comparisons) also assume 100% electricity.

The paradigm for estimation of energy savings in the buildings industry (adopted by LEED and ASHRAE 90.1-2007 Appendix G, among others) is to match primary fuel types in baseline and design modeled energy use. While this may be the most straightforward and/or logical practice, it can have the tendency to overestimate predicted energy savings. This typically occurs when the baseline system is egregiously inefficient, since a system of this type would not likely be put in place in lieu of the advanced system being considered.

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[2] https://portfoliomanager.energystar.gov/pm/targetFinder?execution=e1s1

To investigate technology savings with respect to the median energy use of buildings using typical Wisconsin fuel mixes, we re-entered building data into Energy Star while leaving measured utility use inputs blank. This produces median site energy use, cost, and CO_2 values based on the average fuel mix for that building type in the given location. Examples of both types of Energy Star output are given in Appendix D and Appendix E.

Median building energy use (matched fuel mix) was used to determine the total energy savings percentage achieved by each building. These savings were then compared to the predicted energy savings for each building, and used to create a ratio of savings achieved to savings anticipated. Simple as well as weighted (by the percentage of each building utilizing the target technology) average savings were calculated for each technology subset.

It should be noted that anticipated energy savings may be overestimated if they are deduced from achieved LEED points without supporting energy modeling documentation (i.e., specifically predicted kBTU/year savings). This is due to the fact that for some systems (particularly 100% electric systems) LEED baseline models are more inefficient than the "average" CBECS buildings that are used to evaluate savings in this study, as mentioned above.

OWNER SATISFACTION FEEDBACK

The second page of the survey was used to obtain feedback regarding owner satisfaction and motivations for use of the technology. These data were treated similarly to the energy data, calculating averages and weighted averages for each technology. The answers to yes/no questions were assigned the numerical values of 1 and 0, respectively.

FIELD INVESTIGATION SUBSAMPLE

SELECTION CRITERIA

Primary criteria for field study subsample inclusion were (in rough order): 1) Target technology is utilized in over 50% of total building space; 2) Radiant systems include radiant cooling as well as heating; 3) Building is located in Wisconsin (or very nearby); 4) Overall subsample includes a variety of building types and Wisconsin climate conditions; 5) Owner is willing to allow building access, and is responsive to queries for additional information. Buildings selected for field study are listed in Table 4.

Displacement ventilation was the most difficult technology to locate in Wisconsin. Many of the buildings that were suggested to us turned out to actually utilize underfloor air distribution, and this same phenomenon also occurred with some owners who originally reported that their buildings incorporated displacement ventilation technology. Of the buildings that did use displacement ventilation, most only included the technology in a small fraction of the building (generally in large spaces such as auditoriums, church sanctuaries, etc.)

Although radiant heating is not particularly difficult to find in Wisconsin, identifying buildings that utilize true radiant cooling poses a larger challenge. Some of the buildings that were recommended to us turned out to be active chilled beam systems, which do not operate on the same physical principles as radiant cooling.

Variable refrigerant flow (VRF) technology is comparatively easy to find, despite its more recent introduction to the Wisconsin building community. VRF also tends to be utilized building-wide, therefore this technology category provided us with the most flexibility in terms of choosing a field study subsample. In addition to the more general selection criteria detailed above, we attempted to avoid choosing buildings that also incorporated geothermal well fields, as an overlap of technologies tends to complicate the isolation of target technology contributions to overall building energy savings.

While selection of the site visit subsample may have had minor effects on field-derived results, the most common operational issues are likely to be present in any given subset of the buildings studied.

Table 4. Buildings Selected for Field Inspection

ID	SPACE TYPE	CITY	STATE	EUI [kBtu/ft^2]	TECHNOLOGY USAGE [%][a]
DV-1	Library	Elk River	Minnesota	50.6	100%
DV-2	Office	Maple Grove	Minnesota	69.2	100%
DV-3	K-12 School	Clintonville	Wisconsin	66.7	100%
RAD-1	Library	Hartford	Wisconsin	46.9	100% (100%)
RAD-2[b]	Mixed Use	Baraboo	Wisconsin	14	85% (85%)
RAD-3	Worship Facility	Madison	Wisconsin	61.5	75% (75%)
VRF-1	Office	Dodgeville	Wisconsin	49.3	100%
VRF-2	Office, Warehouse	Stoughton	Wisconsin	37.3	100%
VRF-3	Office	Stevens Point	Wisconsin	54	100%

Notes: a – Usage of both radiant heating and radiant cooling shown (with radiant cooling in parentheses). **b** – Also contains Displacement Ventilation

SITE VISIT PROCEDURE

Prior to visiting a building, engineers contacted a member of the design team (usually a mechanical engineer) to confirm that the building contained the target technology and obtain information about the motivations behind the building design.

The procedure for on-site visits was designed based on a combination of: 1) ASHRAE Level 1 Energy Audits; 2) Energy Star Certification Procedures; and 3) Initial Retro-commissioning visits. The purpose of the site visits was to investigate the performance of the target technology and verify that building energy usage was not inflated due to operational inefficiencies (such as 24/7 operation) or deflated due to extreme savings measures (such as closing the OA intake).

The site visit procedure document is listed in Appendix F, along with supplementary design team interview questions.

COST / BENEFIT ANALYSIS

Operational cost savings for each technology were estimated using average electric ($0.12/kWh, $11.20/source MMBTU) and gas ($0.81/therm, $7.70/source MMBTU) rates for the entire building sample. Weighted average median EUI for each technology was split into electric and gas components using average fuel mix percentages, and then converted into cost per square foot of building area. This number was then multiplied by the average energy savings to determine overall cost savings. A similar calculation was done to estimate cost savings with respect to a median building with a typical Wisconsin fuel mix.

Savings estimates obtained in this way possess two caveats. First, this method assumes that energy is conserved in the same fuel mix proportion as the building uses. For example a system that uses 90% electricity is assumed to be primarily saving electric energy, whereas in truth it may be mostly offsetting gas use (as in the case of VRF systems).

The second caveat is related to the estimated fraction of energy savings due to the advanced HVAC technology (as opposed to other energy conservation measures). For this purpose the assumption was made that savings were spread equally across the various energy end uses. Specifically, in Wisconsin heating and cooling make up 53.7% of total energy end use (Figure 2), therefore total cost savings were multiplied by that percentage.

In the case of displacement ventilation this assumption is almost certainly an overestimation, since it includes the percentage of energy use attributable to heating, a function that displacement ventilation has little effect on. Therefore attributing 53.7% of total building savings to displacement ventilation technology should be regarded as an upper limit. An estimate of the lower limit of savings attributable to displacement ventilation could be achieved by multiplying whole building energy savings by 9.6%, which is the contribution of cooling and ventilation to total energy end use in typical Wisconsin buildings (Figure 2). For the sake of consistency, the upper limit of 53.7% is perpetuated throughout the analysis. Significant improvement of these estimates would require either a before-and-after retrofit case study, or supplementary detailed energy modeling.

Additional first cost estimates for each technology were obtained from literature sources as well as local field contacts, when possible. These estimates were then divided by cost savings to produce simple payback timescales for each scenario. If errors calculated for mean energy savings are propagated through this piece of the analysis, expected errors on payback timescales are of the order 30%.

DISPLACEMENT VENTILATION

Displacement ventilation buildings are rare in Wisconsin. In part this is due to very limited exposure to the technology. More than half of the buildings which were suggested to us as displacement ventilation candidates were found not to contain the technology, often due to mislabeling or misinterpretation of under-floor air distribution (UFAD) systems. Our final participants for this technology are the eight buildings listed in Table 5.

Table 5. Participating Displacement Ventilation Buildings

ID	SPACE TYPE	CITY	STATE	TECHNOLOGY USAGE[a] [%]
DV-1	Library	Elk River	MN	100%
DV-2	Office	Maple Grove	MN	100%
DV-3	K-12 School	Clintonville	WI	100%
DV-4	Mixed Use	Baraboo	WI	100%
DV-5	K-12 School	Hudsonville	MI	25%
DV-6	Worship Facility	Middleton	WI	17%
DV-7	Performing Arts	Madison	WI	10%
DV-8	Casino	Milwaukee	WI	6%

Notes: a – Percentage of building area served by the technology, as reported on owner surveys.

DV-3 was selected to be part of the site visit subsample. Upon examining this building it was determined that it did not contain true displacement ventilation, therefore DV-3 was removed from all further analysis.

SURVEY DATA

ENERGY USE BENCHMARKING

Five of the buildings in this category were eligible for inclusion in energy use benchmarking analysis. EUIs in this group ranged from 19 to 66 kBTU/ft^2/yr, with an average (weighed by the percent of building area served by the technology) of 46±9 kBTU/ft^2/yr. Median comparison buildings covered a range of 39 to 89 kBTU/ft^2/yr, with a weighted average of 67 kBTU/ft^2/yr.

Buildings in this study that utilize displacement ventilation technology achieve weighted average energy savings of 34±6% over median buildings. That number is the overall savings for the entire building, and includes contributions from additional energy savings measures (envelope, lighting, etc.) as well as the HVAC contribution. Though significant savings are measured, these buildings tend to fall somewhat short of expected savings, achieving an average of 61% of total savings anticipated.

The average fuel mix of participating buildings was approximately 93% electric, whereas a more typical Wisconsin fuel mix for existing buildings of similar type came in at about 44% electric. This is reflected in a somewhat diminished average cost savings (22% cost savings vs. 34% energy savings), due to current discrepancies in cost per kBTU between electric and gas. Though nearly all of the buildings exhibited some energy savings, due to the (currently) high cost of electricity, two of the buildings report a net loss in cost savings.

Numerical results of the energy use benchmarking analysis are shown in Table 6.

Table 6. Displacement Ventilation Energy Use Benchmarking

ID	SITE EUI [kBtu/ft^2/y]	MEDIAN SITE EUI[a] [kBtu/ft^2/y]	SITE FUEL MIX[b] [% Electric]	AVERAGE FUEL MIX[c] [% Electric]	COST SAVINGS[d] [%]	CO_2 SAVINGS[e] [%]	PREDICTED SITE ENERGY SAVINGS [%]	MEASURED SITE ENERGY SAVINGS [%]	SAVINGS RATIO [Act. / Est.]
DV-1	48.3	77.0	96.9%	36.4%	17.3%	30.9%	61.2%	37.2%	0.61
DV-2	65.6	88.9	91.8%	55.6%	22.6%	22.6%	45.0%	26.2%	0.59
DV-4[f]	19.9 (12.7)	39.2	100.0%	43.6%	40.0% (64.1%)	50.7% (70.4%)	80.0%	49.3% (67.6%)	0.85
DV-5	63.9	63.7	50.1%	31.2%	-1.6%	-5.9%	5.0%	-0.4%	0.00
DV-6	35.9	41.0	91.4%	43.6%	-33.6%	7.5%	55.0%	12.5%	0.23
AVERAGE	**47±9**	**62.0**	**86.0%**	**42.1%**	**8.9%**	**21.2%**	**49.2%**	**25±9%**	**0.45**
WEIGHTED AVERAGE	**46±9**	**66.7**	**92.6%**	**44.1%**	**21.6%**	**30.4%**	**57.5%**	**34±6%**	**0.61**

Notes: a – Using CBECS Database, assumes same fuel mix as participant building. **b**– Percentage of total site energy use by kBTU. **c**– Typical fuel mix based on building type, location, etc. (CBECS). **d** – Operating cost savings, assuming average fuel mix. **e**– CO_2 emissions savings, assuming average fuel mix. **f –** Numbers in parenthesis show energy use and savings when significant PV contributions are included. Averages and weighted averages are calculated with PV savings removed.

OWNER SATISFACTION

Owner satisfaction feedback was analyzed from all seven participating displacement ventilation buildings (Table 7). Overall, the technology is viewed as above average in the categories of energy performance and occupant comfort, but closer to average in terms of ease of operation.

Six out of seven respondents (85.7%) report that they would recommend this technology to others. Motivations for using the technology were, in order of frequency, Occupant Comfort (85.7%), Air Quality (57.1%), and Energy Savings (42.9%).

Table 7. Owner Satisfaction Results for Displacement Ventilation[a]

ID	ENERGY PERFORM	OCCUPANT COMFORT	SAVINGS ACHIEVED	RECOMMEND TECHNOLOGY	USE AGAIN	EASE OF OPERATION	MOTIVATION FOR USE[b]
DV-1	2.0	3.0	YES	YES	2.0	2.0	
DV-2	2.0	3.0	YES	YES	3.0	3.0	1,2,3
DV-4	1.0	2.0	YES	YES	2.0	2.0	1,2,3
DV-5	4.0	1.0	NO	NO	3.0	4.0	2,3
DV-6	1.0	1.0	YES	YES	1.0	1.0	2,4[c]
DV-7	3.0	2.0	NO	YES	2.0	3.0	1,2
DV-8	1.0	1.0	YES	YES	1.0	2.0	1,2,4[d]
AVG	**2.0**	**1.9**	**0.7[e]**	**0.9**	**2.0**	**2.4**	
WEIGHT AVG	**1.8**	**2.4**	**0.9**	**0.9**	**2.3**	**2.4**	

Notes: a - Scale of 1=Excellent/Definitely, 2=Good/Probably, 3=Average/Neutral, 4=Fair/Somewhat Unlikely, 5=Poor/Unlikely. **b** – 1=Air Quality, 2=Occupant Comfort, 3=Energy Savings, 4 =Other (described in additional footnotes). **c**– Quiet operation. **d**- Evacuation of second-hand cigarette smoke. **e** – Numerical values assigned to yes/no answers are 1/0 respectively.

SITE VISIT FINDINGS

The three buildings in this category which were investigated on site were a library, an office building, and a school. Each of those building types represents an appropriate application of this technology, since there should be low enough occupant movement to maintain air temperature stratification (i.e., not a lot of air mixing).

In general, it was found that this technology tends to be challenging in terms of operation and/or design in Wisconsin climate conditions. This may be due to misconceptions that displacement ventilation is capable of heating spaces. Only one of the three buildings seemed to possess enough perimeter heating to keep occupants comfortable in the wintertime. Discomfort during cold months led to adjustments to the DV systems (e.g., increasing air discharge temperatures) which eliminated stratification, decreased ventilation effectiveness, and ultimately resulted in increased frustration on the part of owners and operators. These types of adjustments were also implicated as possible contributors to the failure of one of the DV-1 compressors.

When used correctly as a ventilation system, displacement ventilation has the capability to operate effectively and efficiently. Suggested supplemental design criteria for this technology are: 1) Ensure that an adequate heating system is in place (radiant heating seems to work well in this capacity); and 2) Since diffusers are located in the occupied zone, careful consideration of where to place them is necessary to avoid drafts and cold complaints from occupants.

COST / BENEFIT ANALYSIS

Average additional first costs for installing DV systems (compared to traditional VAV systems) are estimated at \$1-2/ft^2 by the California Public Utilities Commission[3]. Though multiple attempts were made to procure local cost estimates, they were ultimately stymied by the low market penetration of this technology in Wisconsin. Assuming a maximum estimated value of \$2.00/ft^2 and distributing savings according to typical Wisconsin energy end use, the lower limit on payback is in the range of 5-8 years. The true payback timescale is likely longer, and could be more accurately constrained using before-and-after case studies, or supplementary energy modeling. Errors on payback timescales are carried over proportionately from estimated energy savings errors (Table 6), and should be viewed as coarse approximations. Results of this analysis are shown in Table 8.

Table 8. Displacement Ventilation Cost/Benefit Analysis

	ESTIMATED SAVINGS[a]	
	Cost Savings [\$/ft^2]	Simple Payback[b] [yrs]
TYPICAL DV FUEL MIX (93% Electric)	\$0.40	5.0 ± 0.9
AVERAGED WI FUEL MIX (44% Electric)	\$0.27	7.4 ± 1.3

Notes: a– Assuming 53.7% of total measured savings are attributable to the advanced HVAC system. **b -** Assuming additional first costs of \$2.00/ft^2.

TECHNOLOGY EVALUATION SUMMARY

In general, displacement ventilation is found to produce measureable energy savings, stemming primarily from decreased fan energy use in the buildings it serves. It has the capability of providing enhanced air quality to occupants by delivering fresh air at head height and removing contaminants more efficiently than other HVAC systems, possibly resulting in less school or work absence due to illness.

DV systems are expected to have similar life expectancy to more typical systems, but this could be impacted by incorrect operation. There should be no additional maintenance required. It is

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[3] http://energydesignresources.com/media/1723/EDR_DesignBriefs_displacementventilation.pdf?tracked=true, 2005, \$1-2/ft^2.

crucial for designers and O&M staff to understand that this is primarily a ventilation system, and that no heating should be provided by it.

Currently in Wisconsin displacement ventilation has a tendency to be operated inefficiently, however this would be largely remedied with the installation of complementary systems with sufficient heating capacity, as well as increased operator education.

RADIANT SYSTEMS

While it was relatively easy to find buildings which utilized some amount of radiant heating in Wisconsin, radiant cooling technology was much more difficult to find. This is partially due to the tendency for buildings to contain radiant heating as a supplement to a separate cooling technology. In addition, owners or designers may be concerned about the possibility of condensation in using radiant cooling systems.

In some cases chilled beam systems were misinterpreted as radiant cooling. Though there may be little difference in practice between ceiling panel radiant cooling and passive chilled beam systems, active chilled beams operate on a completely different set of physical principles, and were therefore excluded from this study.

Our final participants for radiant heating and cooling are the eighteen buildings listed in Table 9. Seven of them included some amount of both radiant heating and cooling. Eleven buildings were radiant heating only systems, with four of these having radiant systems in 100% of the building and the others at reduced percentages.

Table 9. Participating Radiant Cooling / Heating Buildings

ID	SPACE TYPE	CITY	STATE	TECHNOLOGY USAGE^{a,b}[%]
RAD-1	Library	Hartford	WI	100% (100%)
RAD-2	Mixed Use	Baraboo	WI	85% (85%)
RAD-3	Worship Facility	Madison	WI	75% (75%)
RAD-4	Mixed Use	Plain	WI	100% (100%)
RAD-5	Office	Montreal (Canada)	QC	90% (90%)
RAD-6	K-12 School	Hudsonville	MI	100% (5%)
RAD-7	Mixed Use	Madison	WI	6% (6%)
RAD-8	K-12 School	Clintonville	WI	100%
RAD-9	Performing Arts	Madison	WI	100%
RAD-10	Residence Hall / Dormitory	Plymouth	WI	100%
RAD-11	Residence Hall / Dormitory	Madison	WI	100%
RAD-12	K-12 School	Wausau	WI	95%
RAD-13	Worship Facility	Middleton	WI	80%
RAD-14	Multifamily Housing	Madison	WI	67%
RAD-15	Office, Repair Services	Madison	WI	60%
RAD-16	Museum	Madison	WI	36%
RAD-17	Mixed Use	Monona	WI	30%
RAD-18	Office	Neenah	WI	10%

Notes: a – As reported on owner surveys. **b** - Usage of both radiant heating and radiant cooling shown (with radiant cooling in parentheses). Omission of a number in parentheses indicates that the building utilizes radiant heating only.

SURVEY DATA

ENERGY USE BENCHMARKING

Eleven of the eighteen buildings in this category were eligible for inclusion in energy use benchmarking analysis. EUIs in this group ranged from 19 to 64 kBTU/ft^2/yr, with an average (weighed by the percent of building area served by the technology) of 45±5 kBTU/ft^2/yr. Median comparison buildings covered a range of 41 to 124 kBTU/ft^2/yr, with a weighted average of 79 kBTU/ft^2/yr.

Buildings in this study that utilize radiant heating and/or cooling technology achieve weighted average energy savings of 38±9% over median buildings. That number is the overall savings for the entire building, and includes contributions from additional energy savings measures (envelope, lighting, etc.) as well as the HVAC contribution. In general, these buildings tend to meet or even exceed expected savings, exceeding anticipated savings by 30% on average (using weighted averages).

The average fuel mix of participating buildings was approximately 70% electric, whereas a more typical Wisconsin fuel mix for existing buildings of similar type came in at about 43% electric.

This is reflected in a somewhat diminished average cost savings (29% cost savings vs. 38% energy savings), due to current discrepancies in cost per kBTU between electric and gas. Though all but one of the buildings exhibited energy savings, due to the (currently) high cost of electricity, three of the buildings report a net loss in cost savings.

Numerical results of the energy use benchmarking analysis are shown in Table 10.

Table 10. Radiant System Energy Use Benchmarking

ID	SITE EUI [kBtu/ft^2/y]	MEDIAN SITE EUI[a] [kBtu/ft^2/y]	SITE FUEL MIX[b] [% Electric]	AVERAGE FUEL MIX[c] [% Electric]	COST SAVINGS[d] [%]	CO_2 SAVINGS[e] [%]	PREDICTED SITE ENERGY SAVINGS [%]	MEASURED SITE ENERGY SAVINGS [%]	SAVINGS RATIO [Act. / Est.]
RAD-1	45.4	89.9	75.2%	36.4%	46.5%	45.9%	50.0%	49.5%	0.99
RAD-2[f]	19.9 (12.7)	39.2	100.0%	43.6%	40.0% (64.1%)	50.7% (70.4%)	80.0%	49.3% (67.6%)	0.85
RAD-3	33.7	43.2	100.0%	28.9%	-3.5%	11.8%	9.0%	21.9%	2.44
RAD-4	31.7	123.1	46.4%	43.6%	46.9%	43.4%	75.0%	74.2%	0.99
RAD-5	60.0	99.6	76.0%	84.0%	55.1%	8.9%	20.0%	39.8%	1.99
RAD-6	63.9	63.7	50.1%	31.2%	-1.6%	-5.9%	5.0%	-0.4%	0.00
RAD-8	64.0	78.6	37.9%	31.2%	22.9%	17.2%	25.0%	18.6%	0.74
RAD-11	56.0	91.4	58.4%	40.9%	35.2%	37.1%	35.0%	38.8%	1.11
RAD-12	60.3	86.3	36.0%	31.2%	20.5%	29.0%	10.0%	30.1%	3.01
RAD-13	35.9	41.0	91.4%	43.6%	-33.6%	7.5%	55.0%	12.5%	0.23
RAD-18	42.4	73.5	99.8%	55.6%	30.4%	39.6%	41.0%	42.4%	1.03
AVERAGE	**47±5**	**75.4**	**70.1%**	**42.7%**	**23.5%**	**25.9%**	**36.8%**	**34±10%**	**1.2**
WEIGHTED AVERAGE	**45±5**	**78.8**	**69.5%**	**43.4%**	**28.8%**	**27.6%**	**40.2%**	**38±11%**	**1.3**

Notes: **a** – Using CBECS Database, assumes same fuel mix as participant building. **b** – Percentage of total site energy use by kBTU. **c** – Typical fuel mix based on building type, location, etc. (CBECS). **d** – Operating cost savings, assuming average fuel mix. **e** – CO_2 emissions savings, assuming average fuel mix. **f –** Numbers in parenthesis show energy use and savings when significant PV contributions are included. Averages and weighted averages are calculated with PV savings removed.

OWNER SATISFACTION

Owner satisfaction feedback was analyzed from all eighteen participating radiant buildings (Table 11). Overall, the technology is viewed as above average in the categories of energy performance and occupant comfort, but closer to average in terms of ease of operation.

Fifteen out of eighteen respondents (83.3%) report that they would recommend this technology to others. Motivations for using the technology were, in order of frequency, Energy Savings (72%), Occupant Comfort (72%), and Air Quality (17%).

Table 11. Owner Satisfaction Results for Radiant Systems[a]

ID	ENERGY PERFORM	OCCUPANT COMFORT	SAVINGS ACHIEVED	RECOMMEND TECHNOLOGY	USE AGAIN	EASE OF OPERATION	MOTIVATION FOR USE[b]
RAD-1	2.0	2.0	YES	YES	2.0	3.0	3
RAD-2	1.0	2.0	YES	YES	1.0	2.0	2,3
RAD-3	2.0	2.0	YES	NO	3.0	5.0	3
RAD-4	2.0	1.0	YES	YES	1.0	5.0	3
RAD-5	2.0	2.0	YES	YES	2.0	4.0	2,3
RAD-6	4.0	1.0	NO	NO	3.0	4.0	2,3
RAD-7	1.0	3.0	YES	YES	1.0	1.0	1,2,3
RAD-8	2.0	2.0	YES	YES	2.0	1.0	1,3
RAD-9	3.0	2.0	NO	YES	2.0	2.0	2
RAD-10	2.0	3.0	NO	NO	5.0	4.0	2,3
RAD-11	2.0	2.0	YES	YES	1.0	4.0	2
RAD-12	1.0	2.0	YES	YES	1.0	2.0	3
RAD-13	1.0	1.0	YES	YES	1.0	1.0	2
RAD-14	1.0	1.0	YES	YES	1.0	3.0	2,3
RAD-15	1.0	1.0	YES	YES	1.0	1.0	2
RAD-16	1.0	5.0	NO	YES	1.0	5.0	2
RAD-17	2.0	3.0	YES	YES	1.0	1.0	2,3,4[c]
RAD-18	3.0	3.0	NO	YES	2.0	2.0	1,2,3
AVG.	**1.8**	**2.1**	**0.7**[d]	**0.8**	**1.7**	**2.8**	
WEIGHT AVG.	**1.9**	**1.9**	**0.8**	**0.8**	**1.8**	**3.2**	

Notes: **a** - Scale of 1=Excellent/Definitely, 2=Good/Probably, 3=Average/Neutral, 4=Fair/Somewhat Unlikely, 5=Poor/Unlikely. **b** – 1=Air Quality, 2=Occupant Comfort, 3=Energy Savings, 4=Other (described in additional footnotes). **c** – Environmental Impact. **d** – Numerical values assigned to yes/no answers are 1/0 respectively.

SITE VISIT FINDINGS

The three buildings in this category which were investigated on site were a library, an office/museum, and a house of worship. There are no appreciable constraints on where this technology could successfully be applied, in terms of building type or size. One application which is particularly well-suited to under floor radiant systems is areas where young children may spend lots of time near the floor such as daycares or the children's sections of libraries.

In general, it was found that once radiant systems are optimized (e.g., via building commissioning) they tend to require less maintenance than typical systems. They are also relatively easy to operate, when not complicated by additional technologies or systems. Two of the three buildings that were visited were comfortable despite low outside air temperatures, the third became too cool when outside temperatures dropped below 10 °F. Generally, owners reported few complaints in either heating or cooling seasons, and none of the buildings reported problems with condensation during summer operation.

Radiant heating and cooling were found to achieve significant energy savings while providing comfortable conditions for occupants. The primary design recommendation for this technology is to ensure that an adequate humidity control system is in place when designing radiant cooling systems.

COST / BENEFIT ANALYSIS

Additional first costs for radiant (floor) systems (as compared to traditional VAV systems) are estimated at \$1-2/ft^2 based on a combination of estimates from the Department of Energy[4], Smith Group JJR[5] and Green Globes[6]. The most current source, Smith Group JJR (2013), reports that first costs for a radiant system were actually lower than a standard VAV system; however, because that study represents only one building, a source-combined estimate is used in the analysis. Assuming a value of \$2.00/ft^2, and distributing savings according to typical Wisconsin energy end use, payback is in the range of 4-7 years. Errors on payback timescales are carried over proportionately from estimated energy savings errors (Table 10), and should be viewed as coarse approximations. Results of this analysis are shown in Table 12.

Table 12. Radiant System Cost/Benefit Analysis

	ESTIMATED SAVINGS[a]	
	Cost Savings [\$/ft^2]	Simple Payback[b] [yrs]
TYPICAL RAD FUEL MIX (70% Electric)	\$0.44	4.6 ± 1.3
AVERAGED WI FUEL MIX (43% Electric)	\$0.32	6.2 ± 1.8

Notes: a – Assuming 53.7% of total measured savings are attributable to the advanced HVAC system. **b** - Assuming additional first costs of \$2.00/ft^2.

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[4] http://www.pnl.gov/main/publications/external/technical_reports/pnnl-19004.pdf, 2009, approx. \$3/ft^2.
[5] http://www.esmagazine.com/articles/96111-the-cost-of-doasradiant, 2013, first cost savings (i.e., <\$0/ft^2).
[6] http://www.greenglobes.com/advancedbuildings/_frames/fr_t_heat_radiant_heating.htm, 2008, approx. 20% more than conventional air based system (~\$4/ft^2).

TECHNOLOGY EVALUATION SUMMARY

Radiant systems are found to be a cost effective energy efficiency choice for heating and cooling buildings in Wisconsin. Transferring heat via water is inherently more efficient than using air as a transfer medium. In addition, separating the heating/cooling system from the ventilation system allows for additional savings in reheat energy. Radiant systems provide thermal comfort to occupants, tend to require less maintenance than traditional HVAC systems, and last at least as long (if not longer). While operation can become complicated in buildings that contain additional technologies, most respondents find the difficulty level of operating these systems similar to that of more common forced air systems.

VARIABLE REFRIGERANT FLOW

The use of variable refrigerant flow systems in Wisconsin buildings has been increasing over the last several years, therefore they were comparatively easy to find. In addition there was very little mislabeling of this technology in the community. VRF systems tend to serve the entire building rather than just a portion, which also renders the technology conducive to detailed field study.

Our fourteen VRF participant buildings are listed in Table 13. Nine of the fourteen buildings are entirely served by VRF.

Table 13. Participating Variable Refrigerant Flow Buildings

ID	SPACE TYPE	CITY	STATE	TECHNOLOGY USAGE[a] [%]
VRF-1	Office	Dodgeville	WI	100%
VRF-2	Office, Warehouse	Stoughton	WI	100%
VRF-3	Office	Stevens Point	WI	100%
VRF-4	Senior Care Facility	Rice Lake	WI	100%
VRF-5	Museum	Madison	WI	100%
VRF-6	Mixed Use	Madison	WI	100%
VRF-7	Senior Care Facility	Oshkosh	WI	100%
VRF-8	Mixed Use	Madison	WI	100%
VRF-9	College / University	Milwaukee	WI	100%
VRF-10	Residence Hall / Dormitory	Madison	WI	90%
VRF-11	Office	Madison	WI	65%
VRF-12	Office	Port Washington	WI	50%
VRF-13	Office, Repair Services	Madison	WI	40%
VRF-14	Office	Madison	WI	31%

Notes: a – As reported on owner surveys.

SURVEY DATA

ENERGY USE BENCHMARKING

Seven of the fourteen buildings in this category were eligible for inclusion in energy use benchmarking analysis. EUIs in this group ranged from 39 to 57 kBTU/ft^2/yr, with an average (weighed by the percent of building area served by the technology) of 52±3 kBTU/ft^2/yr. Median comparison buildings covered a range of 48 to 92 kBTU/ft^2/yr, with a weighted average of 73 kBTU/ft^2/yr.

Buildings in this study that utilize VRF technology achieve average energy savings of 26±8% over median buildings. That number is the overall savings for the entire building, and includes contributions from additional energy savings measures (envelope, lighting, etc.) as well as the HVAC contribution. In general, these buildings fall just slightly short of expected savings, achieving an average of 87% of total savings anticipated.

The average fuel mix of participating buildings was approximately 77% electric, whereas a more typical Wisconsin fuel mix for existing buildings of similar type came in at about 49% electric. This is reflected in a somewhat diminished average cost savings (12% cost savings vs. 26% energy savings), due to current discrepancies in cost per kBTU between electric and gas. Though nearly all of the buildings exhibited some energy savings, due to the (currently) high operational costs associated with switching from gas to electric as a primary heating fuel, two of the buildings report a net loss in cost savings.

Numerical results of the energy use benchmarking analysis are shown in Table 14.

Table 14. VRF System Energy Use Benchmarking

ID	SITE EUI [kBtu/ft^2/y]	MEDIAN SITE EUI[a] [kBtu/ft^2/y]	SITE FUEL MIX[b] [% Electric]	AVERAGE FUEL MIX[c] [% Electric]	COST SAVINGS[d] [%]	CO_2 SAVINGS[e] [%]	PREDICTED SITE ENERGY SAVINGS [%]	MEASURED SITE ENERGY SAVINGS [%]	SAVINGS RATIO [Act. / Est.]
VRF-1	39.1	62.0	95.3%	55.6%	39.8%	33.7%	34.8%	37.0%	1.06
VRF-3	56.7	88.0	92.4%	55.6%	7.0%	12.3%	36.0%	35.6%	0.99
VRF-4	56.3	75.1	77.9%	40.9%	44.7%	19.8%	25.0%	25.0%	1.00
VRF-6	53.9	48.5	71.2%	43.6%	-53.1%	-16.1%	5.0%	-11.1%	0.00
VRF-10	56.0	91.4	58.4%	40.9%	35.2%	37.1%	35.0%	38.8%	1.11
VRF-12	52.0	87.2	64.5%	55.6%	8.3%	40.3%	30.0%	40.4%	1.35
VRF-14	52.4	63.2	53.1%	55.6%	-20.0%	18.7%	20.0%	17.1%	0.85
AVERAGE	**52±2**	**73.6**	**73.3%**	**49.7%**	**8.8%**	**20.8%**	**26.5%**	**26±8%**	**0.91**
WEIGHTED AVERAGE	**52±3**	**73.4**	**76.7%**	**48.6%**	**11.9%**	**19.1%**	**26.9%**	**26±8%**	**0.87**

Notes: **a** – Using CBECS Database, assumes same fuel mix as participant building. **b** – Percentage of total site energy use by kBTU. **C** – Typical fuel mix based on building type, location, etc. (CBECS). **d –** Operating cost savings, assuming average fuel mix. **e –** CO_2 emissions savings, assuming average fuel mix.

OWNER SATISFACTION

Owner satisfaction feedback was analyzed from all fourteen participating VRF buildings (**Error! Not a valid bookmark self-reference.**). Overall, the technology is viewed as above average in the categories of energy performance, occupant comfort, and ease of operation.

Eleven out of fourteen respondents (78.6%) report that they would recommend this technology to others. Saving energy was the main motivator for using this technology as reported by 79% of respondents, followed by Occupant Comfort (64%), and Air Quality (14%).

VRF-6 was the only building in this subsample that did not achieve measured energy savings. The building owner reports that VRF technology was used primarily because of space considerations. This owner gives the technology average marks in all categories, and indicates that they would recommend it to others. This is the only scenario in the study where the technology is recommended despite negative energy savings, however it should also be noted that predicted energy savings for this building were modest to begin with (5%).

Table 15. Owner Satisfaction Results for VRF Systems[a]

ID	ENERGY PERFORM	OCCUPANT COMFORT	SAVINGS ACHIEVED	RECOMMEND TECHNOLOGY	USE AGAIN	EASE OF OPERATION	MOTIVATION FOR USE[b]
VRF-1	1.0	2.0	YES	YES	1.0	1.0	3
VRF-2	4.0	4.0	NO	NO	2.0	4.0	3
VRF-3	2.0	2.0	YES	YES	2.0	2.0	2,3
VRF-4	1.0	2.0	YES	YES	1.0	1.0	2,3,4[c]
VRF-5	3.0	5.0	NO	NO	5.0	5.0	2,3
VRF-6	3.0	3.0	YES	YES	3.0	3.0	4[d]
VRF-7	2.0	1.0	YES	YES	1.0	1.0	2,3
VRF-8	1.0	3.0	YES	YES	1.0	1.0	1,2,3
VRF-9	3.0	3.0	NO	YES	2.0	2.0	2
VRF-10	2.0	2.0	YES	YES	1.0	4.0	2
VRF-11	3.0	3.0	NO	NO	3.0	5.0	3, 4[e]
VRF-12	1.0	1.0	YES	YES	2.0	2.0	1,2,3,4[f]
VRF-13	3.0	1.0	YES	YES	3.0	3.0	3
VRF-14	1.0	1.0	YES	YES	1.0	1.0	2,3
AVG.	**2.1**	**2.4**	**0.7[g]**	**0.8**	**2.0**	**2.5**	
WEIGHT AVG.	**2.2**	**2.5**	**0.7**	**0.8**	**2.0**	**2.5**	

Notes: **a** - Scale of 1=Excellent/Definitely, 2=Good/Probably, 3=Average/Neutral, 4=Fair/Somewhat Unlikely, 5=Poor/Unlikely. **b** – 1=Air Quality, 2=Occupant Comfort, 3=Energy Savings, 4=Other (described in additional footnotes). **c** – Simultaneous cooling/heating. **d** – Space considerations. **e** – Most cost effective based on building construction. **f** – Showcase high efficiency technologies. **g** – Numerical values assigned to yes/no answers are 1/0 respectively.

SITE VISIT FINDINGS

The three buildings in this category which were investigated on site were two offices and an office/warehouse. There are no appreciable constraints on where this technology could successfully be applied, in terms of building type or size. However, care should be taken to keep the refrigerant volume small enough relative to the individual space volumes such that a refrigerant evacuation system is not required in case of a leak in the refrigerant piping (as explained in ASHRAE standard 15).

One particularly suitable application for VRF systems is in buildings that require simultaneous heating and cooling (such as office buildings or buildings containing data centers). VRF technology can experience difficulties with temperature setbacks during unoccupied hours, so buildings which are in constant operation are another good match for VRF systems.

Cold climates present somewhat of a challenge to the performance of this technology. The central unit, which is intended to pull heat from the outside air in heating mode, does not typically function at temperatures below 0 ^{o}F, and has unknown efficiencies at temperatures between 0 ^{o}F and 35 ^{o}F. This results in a need for supplemental heating of the air surrounding the unit in low temperatures. The buildings that were visited each chose a different setpoint for this outside air heating (-10 ^{o}F, 28 ^{o}F, and 50 ^{o}F) and it is unclear which setpoint temperature is ultimately the best choice. These concerns are eliminated if the VRF system is coupled with a geothermal ground loop, therefore this combination (VRF/geothermal) likely represents the most ideal configuration for this technology in Wisconsin climate conditions.

In general, it was found that though VRF systems may initially be challenging to optimize, once they are in operation they do not require much adjustment or maintenance. Because this is a relatively nascent technology in Wisconsin, its precise longevity is unknown.

VRF systems were, on average, ultimately found to produce measurable energy savings while providing comfortable conditions for occupants. Suggested supplemental design and operation criteria for this technology are: 1) Take care to size refrigerant loops in larger buildings so that refrigerant evacuation systems are not needed; 2) Remain cognizant of the potential for simultaneous heating/cooling in spaces that contain supplementary perimeter heating (high electric use in shoulder seasons could indicate this); 3) Avoid altering VRF system settings once the system has been professionally configured; and 4) Couple with geothermal ground loops when possible to reduce complexity and maximize energy savings.

COST / BENEFIT ANALYSIS

Additional first costs for VRF systems (compared to traditional VAV systems) were estimated at \$1-2/ft^2 based on up-to-date estimates by local contractors[7]. Historically estimates have been somewhat higher, averaging at \$4/ft^2 (e.g., Pacific Northwest Laboratory[8]) however as the technology and the market evolves, first costs for this type of system have decreased.

Assuming the maximum value of \$2.00/ft^2 and distributing savings according to typical Wisconsin energy end use, payback is in the range of 6-10 years. Errors on payback timescales are carried over proportionately from estimated energy savings errors (Table 14), and should be viewed as coarse approximations. Results of this analysis are shown in Table 16.

Table 16. VRF System Cost/Benefit Analysis

	ESTIMATED SAVINGS[a]	
	Cost Savings [\$/ft^2]	Simple Payback[b] [yrs]
TYPICAL VRF FUEL MIX (77% Electric)	\$0.29	6.8 ± 2
AVERAGE WI FUEL MIX (49% Electric)	\$0.22	9.3 ± 3

Notes: **a** – Assuming 53.7% of total measured savings are attributable to the advanced HVAC system. **b** - Assuming additional first costs of \$2.00/ft^2.

VRF CASE STUDY

One of the retrofitted buildings in our VRF sample (VRF-7) had utility records spanning back to 2000, which made it an excellent candidate for a before-and-after case study. The building is a subsidized housing establishment, which does not yet have an available category in Energy Star Target Finder, so this building is not included in our existing VRF energy benchmarking sample and can therefore be viewed as an independent data point.

Prior to the upgrade to VRF, this building was centrally heated only (perimeter radiant fin tube). Approximately half of the residents had window air-conditioning units, while the other half did not. Although a detailed treatment of historical utility data was beyond the scope of this work, a brief analysis of the data was possible.

Average monthly electric and gas use were calculated over the pre-upgrade period of July 2000 to June 2008. The same was done for post-upgrade utility data from May 2011 to June 2013. To correct for the increase in cooling provided by the VRF system, differences between pre-upgrade summer electric load and pre-upgrade electric base load (58,655 kWh/month) were doubled in the months of June, July, August, and September (to coarsely simulate air

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[7] Phone conversation with General Heating and Air Conditioning, Madison, WI, 2014, \$1-2/ft^2.
[8] http://rtf.nwcouncil.org/subcommittees/vchp/VRF%20Life%20Cycle%20Cost%201-23-2013.pdf, 2011, \$4/ft^2.

conditioning window units in the remaining half of the apartments). Table 17 lists the resulting energy use for each scenario, which is presented visually in Figure 6 and Figure 7.

Table 17. VRF-7 Monthly Utility Use Pre- and Post-Upgrade

	PRE-UPGRADE[a]		POST-UPGRADE	
	ELECTRIC [kWh]	GAS [Therms]	ELECTRIC [kWh]	GAS [Therms]
JAN	58,145	8,475	88,417	3,778
FEB	55,843	7,681	92,125	3,570
MAR	55,461	6,279	79,879	2,732
APR	59,034	4,050	77,962	2,107
MAY	56,477	2,156	81,825	1,125
JUN	87,811	929	80,822	652
JUL	115,376	680	97,826	568
AUG	104,711	688	90,872	646
SEP	80,316	1,413	79,955	1,127
OCT	62,439	3,957	75,933	1,773
NOV	59,765	5,711	82,057	3,020
DEC	62,078	8,052	92,043	3,755
ANNUAL	**857,456**	**50,069**	**1,019,715**	**24,854**

Notes: a – Summer months of June, July, August and September have been adjusted to account for additional cooling post-upgrade (see text).

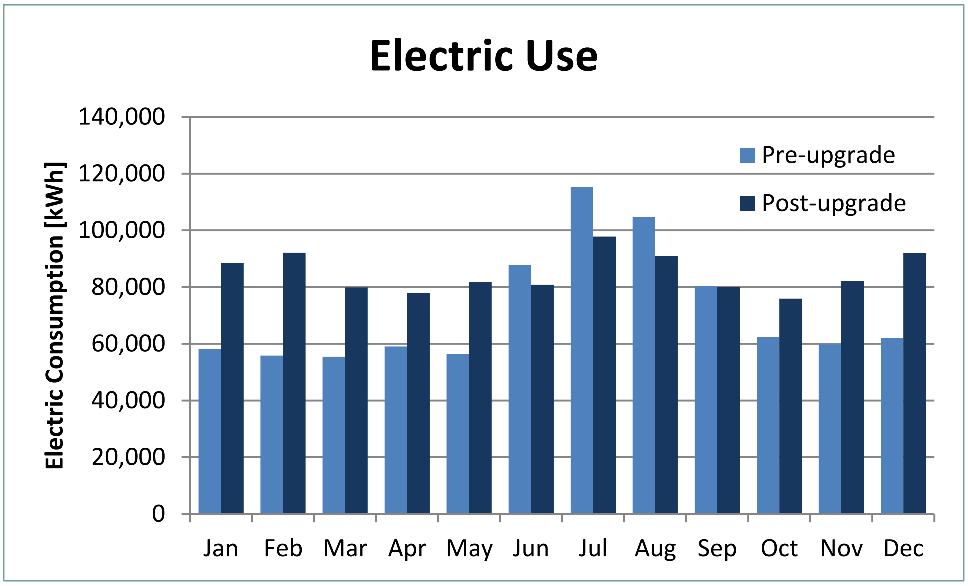

Figure 6. VRF-7 Monthly Electric Use Pre- and Post-Upgrade

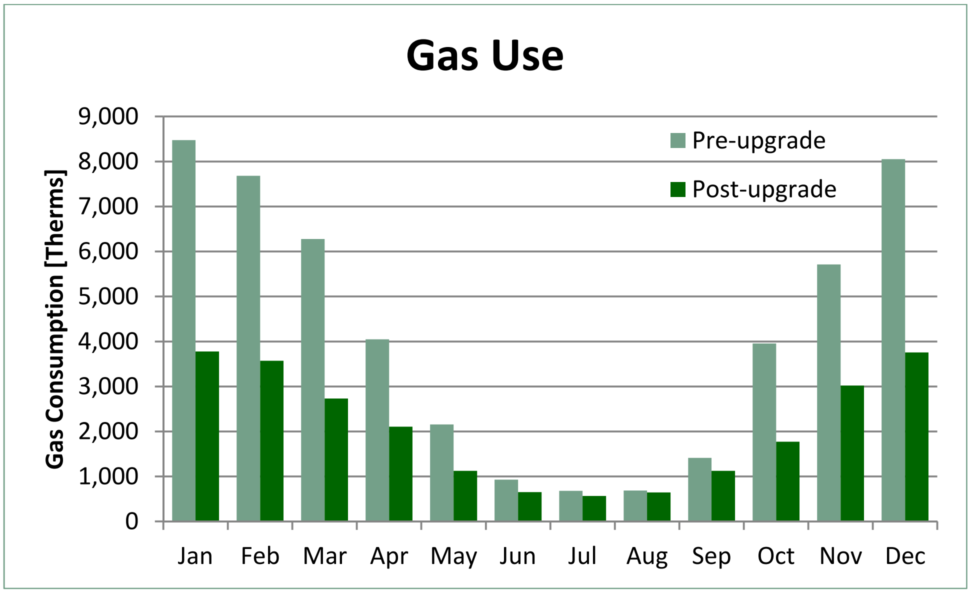

Figure 7. VRF-7 Monthly Gas Use Pre- and Post-Upgrade

From Figure 6 and Figure 7 it can be seen that the VRF system causes electricity consumption to increase while gas use is decreased in winter. Overall energy consumption for the two scenarios is shown in Figure 8, which indicates that the majority of energy savings are obtained in the winter months. This analysis is slightly complicated by the fact that window upgrades were completed over the same time period as the HVAC upgrade, therefore some fraction of energy savings should be attributed to envelope improvement as well.

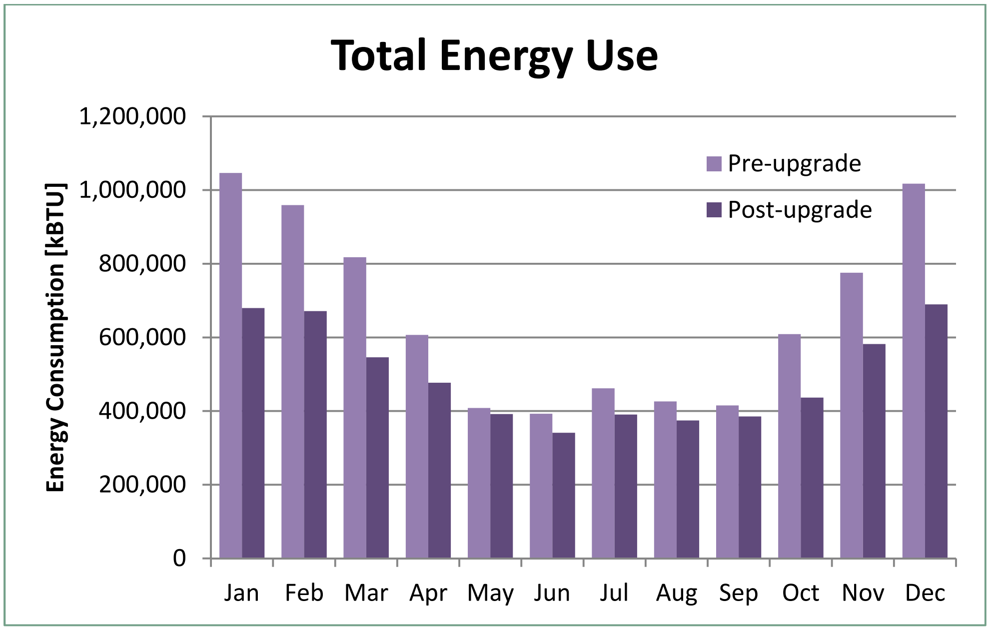

Figure 8. VRF-7 Total Energy Consumption Pre- and Post-Upgrade

Table 18 lists energy and utility cost savings achieved in the upgrade. The results of this case study are consistent with our overall energy benchmarking analysis, indicating that the upgrade has produced site energy savings of 24.8% (compared to 25.7% in our general analysis). Due to the fuel switch from primarily gas to primarily electric, source energy savings are significantly lower, at 6.3%.

Surprisingly, average electric rates (per kWh) and gas rates (per therm) were consistent over the two time periods studied, at \$0.08/kWh and \$0.65-\$0.67/therm, therefore no adjustment for utility rate increase was necessary in this analysis. Because gas prices are currently very low, cost savings for this upgrade are estimated at just 5.5% (or about \$0.06/ft^2/yr). Despite modest cost savings, the building owner reports that he is very happy with the technology, in particular because the occupants are much more comfortable than they were prior to the upgrade.

Table 18. Energy and Cost Savings Resulting from VRF Upgrade

	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%**

TECHNOLOGY EVALUATION SUMMARY

Variable refrigerant flow was found to produce measurable energy savings in participating buildings. These savings can be attributed to the increased efficiency of using refrigerant to transfer heat rather than air, the ability to heat and cool simultaneously, and decreased fan energy use by decoupling heating/cooling from ventilation systems. VRF systems are reported to provide suitable comfort to occupants.

Once optimized, VRF systems are relatively easy to operate. As a nascent technology these systems have unknown longevity, however, there is no current reason to suspect that it is appreciably less than traditional HVAC systems.

It is unclear how efficiently air-source VRF systems perform in below-freezing temperatures. Accurately evaluating the low-temperature performance of these systems and estimating an optimal setpoint temperature for supplemental evaporator intake air heating would be a useful focus of study for future investigations.

COMBINED RESULTS

While the main objective of this study is to determine the individual efficacies of three advanced HVAC technologies in the field, a broader assessment of advanced HVAC technologies can also be executed. The following section briefly revisits the data presented in the previous three chapters to present a more overarching view of advanced HVAC technologies in Wisconsin climate conditions.

SURVEY FINDINGS

ENERGY USE BENCHMARKING

Nineteen total buildings were included in the energy benchmarking portion of this analysis. Of these, five contain more than one of the target technologies. For this reason simple averages rather than weighted averages were utilized in this section. The average EUI of all buildings was 49±3 kBTU/ft^2/yr, compared to an average median EUI of 74.7 kBTU/ft^2/yr.

Buildings that utilize advanced HVAC technologies achieve average energy savings of 31±6% over median buildings. That number is the overall savings for the entire building, and includes contributions from additional energy savings measures (envelope, lighting, etc.) as well as the HVAC contribution. In general, these buildings tend to almost meet expected savings, on average achieving 91% of the savings promised.

The average fuel mix of participating buildings was approximately 74.4% electric, while a more typical Wisconsin fuel mix for existing buildings of similar type came in at only 45.7% electric. This is reflected in a somewhat diminished average cost savings (17% cost savings vs. 31% energy savings), due to current discrepancies in cost per kBTU between electric and gas. Numerical results of this analysis are shown in Table 19.

Table 19. Energy Saving Comparisons

ID	SITE EUI [kBtu/ft^2/y]	MEDIAN SITE EUI[a] [kBtu/ft^2/y]	SITE FUEL MIX[b] [% Electric]	AVERAGE FUEL MIX[c] [% Electric]	COST SAVINGS[d] [%]	CO_2 SAVINGS[e] [%]	PREDICTED SITE ENERGY SAVINGS [%]	MEASURED SITE ENERGY SAVINGS [%]	SAVINGS RATIO [Act. / Est.]
DV-1	48.3	77.0	96.9%	36.4%	17.3%	30.9%	61.2%	37.2%	0.61
DV-2	65.6	88.9	91.8%	55.6%	22.6%	22.6%	45.0%	26.2%	0.59
DV-4, RAD-2[f]	19.9 (12.7)	39.2	100.0%	43.6%	40.0% (64.1%)	50.7% (70.4%)	80.0%	49.3% (67.6%)	0.85
DV-5, RAD-6	63.9	63.7	50.1%	31.2%	-1.6%	-5.9%	5.0%	-0.4%	--
DV-6, RAD-13	35.9	41.0	91.4%	43.6%	-33.6%	7.5%	55.0%	12.5%	0.23
RAD-1	45.4	89.9	75.2%	36.4%	46.5%	45.9%	50.0%	49.5%	0.99
RAD-3	33.7	43.2	100.0%	28.9%	-3.5%	11.8%	9.0%	21.9%	2.44
RAD-4	31.7	123.1	46.4%	43.6%	46.9%	43.4%	75.0%	74.2%	0.99
RAD-5	60.0	99.6	76.0%	84.0%	55.1%	8.9%	20.0%	39.8%	1.99
RAD-8	64.0	78.6	37.9%	31.2%	22.9%	17.2%	25.0%	18.6%	0.74
RAD-11, VRF-10	56.0	91.4	58.4%	40.9%	35.2%	37.1%	35.0%	38.8%	1.11
RAD-12	60.3	86.3	36.0%	31.2%	20.5%	29.0%	10.0%	30.1%	3.01
RAD-18	42.4	73.5	99.8%	55.6%	30.4%	39.6%	41.0%	42.4%	1.03
VRF-1	39.1	62.0	95.3%	55.6%	39.8%	33.7%	34.8%	37.0%	1.06
VRF-3	56.7	88.0	92.4%	55.6%	7.0%	12.3%	36.0%	35.6%	0.99
VRF-4	56.3	75.1	77.9%	40.9%	44.7%	19.8%	25.0%	25.0%	1.00
VRF-6	53.9	48.5	71.2%	43.6%	-53.1%	-16.1%	5.0%	-11.1%	--
VRF-12	52.0	87.2	64.5%	55.6%	8.3%	40.3%	30.0%	40.4%	1.35
VRF-14	52.4	63.2	53.1%	55.6%	-20.0%	18.7%	20.0%	17.1%	0.85
AVERAGE	**49±3**	**74.7**	**74.4%**	**45.7%**	**17.1%**	**23.5%**	**34.8%**	**31±6%**	**0.91**

Notes: a – Using CBECS Database, assumes same fuel mix as participant building. **b** – Percentage of total site energy use by kBTU. **c** – Typical fuel mix based on building type, location, etc. (CBECS). **d** – Operating cost savings, assuming average fuel mix. Average costs for the entire building sample are $0.12/kWh and $0.81/therm. **e** – CO_2 emissions savings, assuming average fuel mix. (0.12/kWh, $0.81/therm on average for sample). **f –** Numbers in parenthesis show energy use and savings when significant PV contributions are included. Averages are calculated with PV savings removed.

Figure 9 shows a plot of achieved vs. anticipated energy savings for buildings in our sample. The buildings are color-coded to indicate which technologies are represented. Five of the buildings use more than one of the target technologies. The dashed line represents the relationship where anticipated savings are exactly met. Points falling above this line exceed expectations, and points below this line fall short of expected savings.

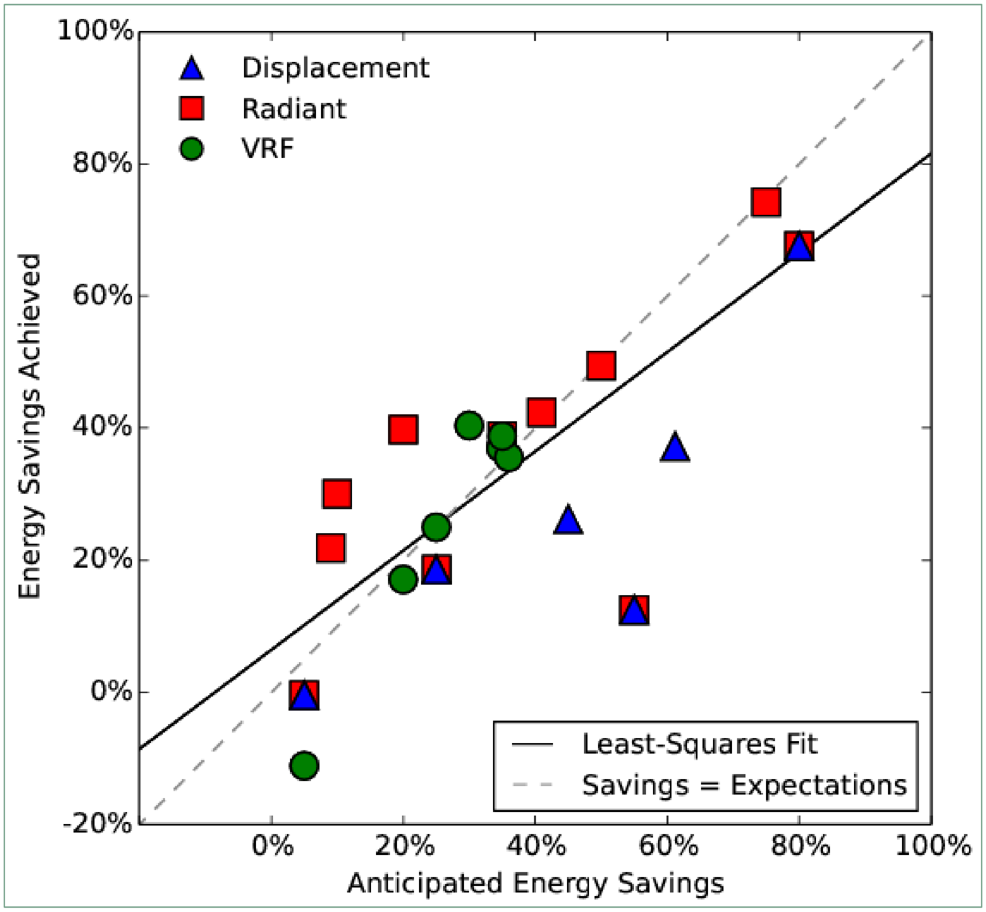

Figure 9. Anticipated vs. Achieved Energy Savings

The solid line represents the best linear least-squares fit to the data, weighted by the percentage of each building served by the advanced technology. For the purposes of this fit, buildings using more than one technology were treated as two separate buildings with two separate weights.

The fitted relationship has the form: *Y* = *mX* + *b*. Best fit parameters were *m* = 0.75 +/- 0.09 and *b* = 6.4 +/- 4.5. The coefficient of determination was R^2 =0.56. This fit shows that, in general, achieved savings are comparable to predicted savings for this sample as a whole, with a tendency for exceeding lower predicted savings and not quite achieving higher predicted savings.

Though a more rigorous treatment of the data is not possible with this sample size, the individual technology data have an appearance that is consistent with earlier analysis.

Displacement ventilation systems tend to fall short of expectations, VRF systems are generally in line with expectations, and independent Radiant systems slightly exceed expectations.

OWNER SATISFACTION

Owner satisfaction feedback was analyzed for 40 individual survey responses which are listed in Table 20. A visual breakdown of this data is given in Figure 10. Overall, advanced HVAC technologies are viewed as solidly above average in the category of energy performance. Occupant comfort also receives an overall positive rating. Ease of operation is given the lowest rating, considered to be “Average” when compared to traditional HVAC systems.

Thirty three out of forty respondents (82.5%) report that they would recommend the advanced technology to others. Energy Savings and Occupant Comfort were the main motivators for using this technology as reported by 70% of respondents. Air Quality was less of a drive, only being selected in 25% of cases.

Table 20. Owner Satisfaction Results for Advanced HVAC Technologies[a]

ID	ENERGY PERFORM	OCCUPANT COMFORT	SAVINGS ACHIEVED	RECOMMEND TECHNOLOGY	USE AGAIN	EASE OF OPERATION
DV-1	2.0	3.0	1	1	2.0	2.0
DV-2	2.0	3.0	1	1	3.0	3.0
DV-4	1.0	2.0	1	1	2.0	2.0
DV-5	4.0	1.0	0	0	3.0	4.0
DV-6	1.0	1.0	1	1	1.0	1.0
DV-7	3.0	2.0	0	1	2.0	3.0
DV-8	1.0	1.0	1	1	1.0	2.0
RAD-1	2.0	2.0	1	1	2.0	3.0
RAD-2	1.0	2.0	1	1	1.0	2.0
RAD-3	2.0	2.0	1	0	3.0	5.0
RAD-4	2.0	1.0	1	1	1.0	5.0
RAD-5	2.0	2.0	1	1	2.0	4.0
RAD-6	4.0	1.0	0	0	3.0	4.0
RAD-7	1.0	3.0	1	1	1.0	1.0
RAD-8	2.0	2.0	1	1	2.0	1.0
RAD-9	3.0	2.0	0	1	2.0	2.0
RAD-10	2.0	3.0	0	0	5.0	4.0
RAD-11	2.0	2.0	1	1	1.0	4.0
RAD-12	1.0	2.0	1	1	1.0	2.0
RAD-13	1.0	1.0	1	1	1.0	1.0
RAD-14	1.0	1.0	1	1	1.0	3.0
RAD-15	1.0	1.0	1	1	1.0	1.0
RAD-16	1.0	5.0	0	1	1.0	5.0
RAD-17	2.0	3.0	1	1	1.0	1.0
RAD-18	3.0	3.0	0	1	2.0	2.0
VRF-1	1.0	2.0	1	1	1.0	1.0
VRF-2	4.0	4.0	0	0	2.0	4.0
VRF-3	2.0	2.0	1	1	2.0	2.0
VRF-4	1.0	2.0	1	1	1.0	1.0
VRF-5	3.0	5.0	0	0	5.0	5.0
VRF-6	3.0	3.0	1	1	3.0	3.0
VRF-7	2.0	1.0	1	1	1.0	1.0
VRF-8	1.0	3.0	1	1	1.0	1.0
VRF-9	3.0	3.0	0	1	2.0	2.0
VRF-10	2.0	2.0	1	1	1.0	4.0
VRF-11	3.0	3.0	0	0	3.0	5.0
VRF-12	1.0	1.0	1	1	2.0	2.0
VRF-13	3.0	1.0	1	1	3.0	3.0
VRF-14	1.0	1.0	1	1	1.0	1.0
AVG.	**2.0**	**2.2**	**0.7**[b]	**0.8**	**1.9**	**2.6**
WEIGHT AVG.	**2.0**	**2.3**	**0.8**	**0.8**	**2.0**	**2.7**

Notes: **a** - Scale of 1=Excellent/Definitely, 2=Good/Probably, 3=Average/Neutral, 4=Fair/Somewhat Unlikely, 5=Poor/Unlikely. **b** – Numerical values assigned to yes/no answers are 1/0 respectively.

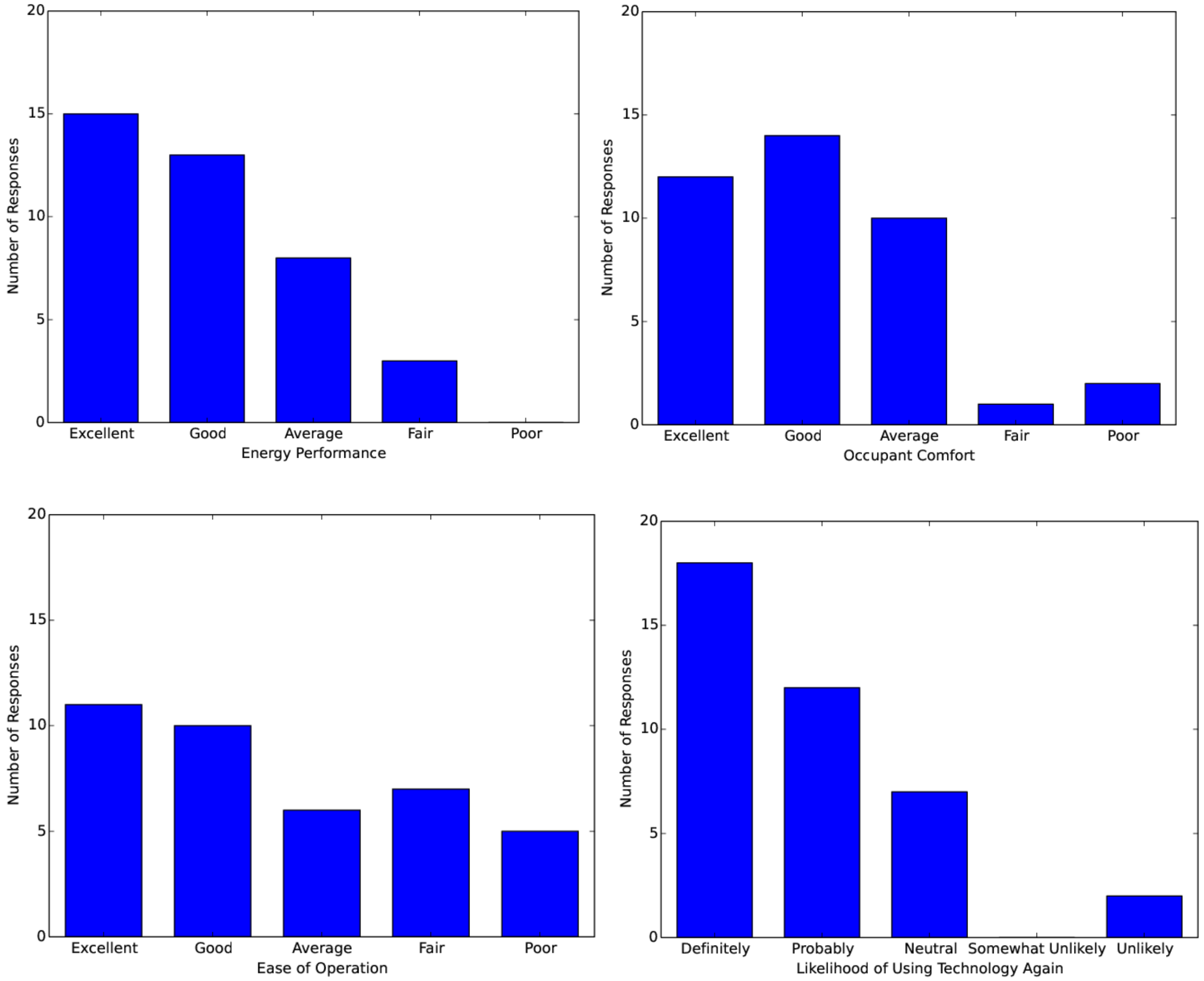

Figure 10. Owner Satisfaction with Advanced HVAC Technologies

To examine potential connections between perceived performance and likelihood of using the technology again, Spearman's Rank Correlation tests were performed on the data (Table 21). Perceived Energy Performance was the most closely tied to whether the owner would be likely to use the technology again, followed by Ease of Operation. Occupant Comfort was very weakly if at all related, which is an interesting finding given that Occupant Comfort was selected just as frequently as Energy Performance as a motivator for use of the technologies.

Table 21. Correlation of Owner Satisfaction Parameters with the Likelihood of Repeated Technology Use

	USE TECHNOLOGY AGAIN		
	Spearman's Rho [r_S]	p-value	Correlation Strength[a]
ENERGY PERFORMANCE	0.66	7.8×10^{-5}	Strong, significant
EASE OF OPERATION	0.53	0.003	Moderate, significant
OCCUPANT COMFORT	0.38	0.04	Weak, less significant

Notes: a – Using a 5-point scale of "very weak" to "very strong" for correlational strength, with p-value<0.05 indicating correlational significance.

SUMMARY

A database of energy usage was created for 19 buildings containing any of three advanced HVAC technologies: displacement ventilation; variable refrigerant flow; and/or radiant systems. This data was then compared to the median energy use of similar buildings (obtained from the CBECS database via Energy Star Target Finder). All but two buildings in the sample exhibited measurable energy savings, broadly suggesting that each of these technologies is capable of increasing the efficiency of building operation in Wisconsin climate conditions.

Buildings containing displacement ventilation showed total energy savings of 34% on average, while those utilizing radiant systems averaged 38% savings and buildings with VRF systems showed approximately 26% energy savings. These are total building energy savings, however, and are complicated by the fact that additional energy conservation measures were present in all buildings. Assuming that energy savings are distributed similarly to typical Wisconsin energy end uses (Figure 2), it can be estimated that approximately 50% of measured savings are attributable to HVAC systems.

One important caveat to mention is that quantitative conclusions drawn by this work are subject to uncertainties associated with small number statistics. The magnitudes of these uncertainties are difficult to estimate when coupled with reporting errors, weather variations, and the inherent complexities of interacting building systems. As a rough approximation, it is estimated that uncertainties on energy benchmarking results are approximately 30%; however, in the case of VRF systems, benchmarking results are supported by an independent before-and-after case study that effectively isolates the contribution of VRF technology to building energy savings.

Satisfaction feedback was obtained from building owners via a self-completed survey. Overall, advanced HVAC technologies are viewed as solidly above average in the category of energy performance. Occupant comfort also receives an overall positive rating. Ease of operation is given the lowest rating, considered to be "Average" when compared to traditional HVAC systems.

A majority of respondents (82%) report that they would recommend these advanced technologies to others. Energy Savings and Occupant Comfort are cited as the main motivators for using these technologies, however a statistical treatment of the data reveals that occupant comfort is only weakly correlated with whether or not building owners would use the technology again. Perceived energy savings are strongly correlated with technology re-use, even in the case of buildings that are not measurably performing as promised.

ASHRAE Level I energy audits were conducted on three buildings from each technology to identify common performance issues. It was found that displacement ventilation tends to face the most challenges in terms of operation and/or design in Wisconsin climate conditions, possibly due to misconceptions that displacement ventilation is capable of heating spaces. VRF systems are also found to be somewhat challenged by cold climates, because the central unit (intended to pull heat from the outside air in heating mode) does not typically function at temperatures below 0 ^{o}F, and has unknown efficiencies at temperatures between 0 ^{o}F and 35 ^{o}F. With regard to radiant systems, although no condensation problems were uncovered in the course of this study, care should be taken to prevent such issues when designing radiant cooling systems.

Though cost-benefit estimates are somewhat complicated by assumptions and uncertainties related to small number statistics, our results suggest that of the three HVAC technologies studied, radiant systems provide the most favorable energy savings relative to first cost in Wisconsin climate conditions.

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ACKNOWLEDGEMENTS

This work was made possible by the contributions and assistance of many individuals and organizations. We are particularly grateful to the building owners and operators that agreed to participate in this study. Those buildings that we were requested to identify by name (whether or not they were ultimately included in the study) are listed below; we are equally appreciative of those that prefer to remain anonymous.

800 University Bay
Aldo Leopold Legacy Center
Aldo Leopold Nature Center
Arboretum Co-Housing
Brentwood Senior Communities, Memory Care
Clintonville Public High School
DNR Northern Region Headquarters
E80 Plus Building
First Unitarian Society
Georgetown Elementary School
Green Technology Training and Enterprise Center
Holy Wisdom Monastery
Iowa County Health & Human Services Building
Jack Russell Memorial Library
Madison Children's Museum
Madison Senior Center
Marian Manor
Overture Center
Plymouth Generations
Sacred Heart School of Theology
USDA Stevens Point
Wisconsin Air National Guard Civil Engineering
YWCA Madison

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APPENDIX A. BUILDINGS DATABASE

Table A-1. Displacement Ventilation Candidate Buildings

IDENTIFIER	SPACE TYPE	CITY	STATE	PARTICIPATING
DV-1	Library	Elk River	Minnesota	✓
DV-2	Office	Maple Grove	Minnesota	✓
DV-3	K-12 School	Clintonville	Wisconsin	✓
DV-4	Mixed Use	Baraboo	Wisconsin	✓
DV-5	K-12 School	Hudsonville	Michigan	✓
DV-6	Worship Facility	Middleton	Wisconsin	✓
DV-7	Performing Arts	Madison	Wisconsin	✓
DV-8	Casino	Milwaukee	Wisconsin	✓
DV-9	Other	Danbury	Wisconsin	
DV-10	Other	Racine	Wisconsin	
DV-11	Other	Madison	Wisconsin	
DV-12	K-12 School	Bayfield	Wisconsin	
DV-13	K-12 School	Green Bay	Wisconsin	
DV-14	Office	Kohler	Wisconsin	
DV-15	Office	Milwaukee	Wisconsin	
DV-16	Other	West Bend	Wisconsin	
DV-17	K-12 School	Maple	Wisconsin	
DV-18	House of Worship	Milwaukee	Wisconsin	
DV-19	Other	Madison	Wisconsin	
DV-20	Office	Whitewater	Wisconsin	
DV-21	Office	Milwaukee	Wisconsin	
DV-22	Other	Akron	Ohio	
DV-23	K-12 School	New Brighton	Minnesota	
DV-24	Other	Minneapolis	Minnesota	
DV-25	K-12 School	Brainerd	Minnesota	
DV-26	K-12 School	Chaska	Minnesota	
DV-27	K-12 School	Cloquet	Minnesota	
DV-28	K-12 School	New Brighton	Minnesota	
DV-29	K-12 School	New Brighton	Minnesota	
DV-30	K-12 School	Shoreview	Minnesota	
DV-31	K-12 School	Silver Bay	Minnesota	
DV-32	Other	Duluth	Minnesota	
DV-33	Other	Duluth	Minnesota	
DV-34	K-12 School	St. Paul	Minnesota	
DV-35	Other	Maple Grove	Minnesota	
DV-36	K-12 School	Brainerd	Minnesota	
DV-37	K-12 School	New Brighton	Minnesota	

DV-38	K-12 School	Moundsview	Minnesota	
DV-39	Other	Plymouth	Minnesota	
DV-40	K-12 School	Two Harbors	Minnesota	
DV-41	K-12 School	Elk River	Minnesota	
DV-42	Residence Hall	Chicago	Illinois	

Table A-2. Radiant System Candidate Buildings

IDENTIFIER	SPACE TYPE	CITY	STATE	PARTICIPATING
RAD-1	Library	Hartford	Wisconsin	✓
RAD-2	Mixed Use	Baraboo	Wisconsin	✓
RAD-3	Worship Facility	Madison	Wisconsin	✓
RAD-4	Mixed Use	Plain	Wisconsin	✓
RAD-5	Office	Montreal	Canada	✓
RAD-6	K-12 School	Hudsonville	Michigan	✓
RAD-7	Mixed Use	Madison	Wisconsin	✓
RAD-8	K-12 School	Clintonville	Wisconsin	✓
RAD-9	Performing Arts	Madison	Wisconsin	✓
RAD-10	Residence Hall / Dormitory	Plymouth	Wisconsin	✓
RAD-11	Residence Hall / Dormitory	Madison	Wisconsin	✓
RAD-12	K-12 School	Wausau	Wisconsin	✓
RAD-13	Worship Facility	Middleton	Wisconsin	✓
RAD-14	Multifamily Housing	Madison	Wisconsin	✓
RAD-15	Office, Repair Services	Deforest	Wisconsin	✓
RAD-16	Museum	Madison	Wisconsin	✓
RAD-17	Mixed Use	Monona	Wisconsin	✓
RAD-18	Office	Neenah	Wisconsin	✓
RAD-19	Other	Oshkosh	Wisconsin	
RAD-20	Other	Madison	Wisconsin	
RAD-21	Other	Madison	Wisconsin	
RAD-22	Office	Milwaukee	Wisconsin	
RAD-23	Other	Appleton	Wisconsin	
RAD-24	Office	Madison	Wisconsin	
RAD-25	Other	Madison	Wisconsin	
RAD-26	K-12 School	Shawano	Wisconsin	
RAD-27	Hospital	Appleton	Wisconsin	
RAD-28	Office	Whitewater	Wisconsin	
RAD-29	Other	Akron	Ohio	
RAD-30	Office	Lakeville	Minnesota	
RAD-31	Office	Detroit	Michigan	
RAD-32	Other	Ann Arbor	Michigan	
RAD-33	K-12 School	Allendale	Michigan	

RAD-34	K-12 School	Caledonia	Michigan	
RAD-35	Hospital	Oak Park	Illinois	
RAD-36	Other	Chicago	Illinois	
RAD-37	Other	Chicago	Illinois	
RAD-38	Other	Chicago	Illinois	
RAD-39	Other	Chicago	Illinois	
RAD-40	Hospital	Chicago	Illinois	
RAD-41	Office	Toronto	Canada	
RAD-42	Office	Winnipeg	Canada	
RAD-43	Office	Montreal	Canada	

Table A-3. Variable Refrigerant Flow Candidate Buildings

IDENTIFIER	SPACE TYPE	CITY	STATE	PARTICIPATING
VRF-1	Office	Dodgeville	Wisconsin	✓
VRF-2	Office, Warehouse	Stoughton	Wisconsin	✓
VRF-3	Office	Stevens Point	Wisconsin	✓
VRF-4	Senior Care Facility	Rice Lake	Wisconsin	✓
VRF-5	Museum	Madison	Wisconsin	✓
VRF-6	Mixed Use	Madison	Wisconsin	✓
VRF-7	Senior Care Facility	Oshkosh	Wisconsin	✓
VRF-8	Mixed Use	Madison	Wisconsin	✓
VRF-9	College / University	Franklin	Wisconsin	✓
VRF-10	Residence Hall / Dormitory	Madison	Wisconsin	✓
VRF-11	Office	Madison	Wisconsin	✓
VRF-12	Office	Port Washington	Wisconsin	✓
VRF-13	Office, Repair Services	Madison	Wisconsin	✓
VRF-14	Office	Madison	Wisconsin	✓
VRF-15	Office	Madison	Wisconsin	
VRF-16	Office	Milwaukee	Wisconsin	
VRF-17	Multifamily Housing	Oshkosh	Wisconsin	
VRF-18	Multifamily Housing	Oshkosh	Wisconsin	
VRF-19	Multifamily Housing	Oshkosh	Wisconsin	
VRF-20	Other	Racine	Wisconsin	
VRF-21	Other	Madison	Wisconsin	
VRF-22	Other	Madison	Wisconsin	
VRF-23	Residence Hall	Madison	Wisconsin	
VRF-24	Other	Madison	Wisconsin	
VRF-25	Office	Prairie du Chien	Wisconsin	
VRF-26	Other	Chenequa	Wisconsin	
VRF-27	Hotel	Delafield	Wisconsin	
VRF-28	Hotel	Burlington	Wisconsin	

VRF-29	Hotel	Sturgeon Bay	Wisconsin	
VRF-30	Courthouse	Prairie du Chien	Wisconsin	
VRF-31	Office	Fond du Lac	Wisconsin	
VRF-32	Office	Madison	Wisconsin	
VRF-33	Other	Milwaukee	Wisconsin	
VRF-34	Residence Hall	Milwaukee	Wisconsin	
VRF-35	Office	Green Bay	Wisconsin	
VRF-36	Other	Madison	Wisconsin	
VRF-37	Medical Office	Madison	Wisconsin	
VRF-38	Hospital	Tomah	Wisconsin	
VRF-39	Office	Madison	Wisconsin	
VRF-40	Office	Madison	Wisconsin	
VRF-41	Other	Gladstone	Michigan	
VRF-42	Senior Care Facility	Gladstone	Michigan	
VRF-43	K-12 School	Belvedere	Illinois	
VRF-44	Retail	Geneva	Illinois	

APPENDIX B. EXAMPLE SURVEY

Focus on Energy Buildings Research – Owner Survey

Part I: Building Data

1. How would you prefer your building to be referenced in research publications?

   ☐ Name of Building ☐ Anonymous Identifier ☐ No Preference

2. Building name

3. Year of completion

4. Address

5. City, State, Zip

6. Air conditioned (heated/cooled) square footage

7. Percentage or square footage of building served by these systems [% or sqft]

   Displacement Ventilation Variable Refrigerant Flow
   Radiant Heating Radiant Cooling

8. Additional energy conservation measures included in building [please check all that apply]

   ☐ Daylight Sensors
   ☐ Solar Hot Water
   ☐ High Efficiency Windows
   ☐ LED Lighting
   ☐ Wall Insulation Thickness
   ☐ Spray Foam Insulation
   ☐ Geothermal Bore Field
   ☐ Energy Recovery
   ☐ Lighting Occ. Sensors
   ☐ Condensing Boiler
   ☐ Solar Panels (indicate kW)
   ☐ Wind Energy (indicate kW)
   ☐ Ventilation Occ. Sensors
   ☐ Roof Insulation Thickness
   ☐ Other (please indicate)

9. Additional energy uses [please provide quantity]

   Cooking Facilities Walk-in refrigerators Computers Parking lot (area)
   Pool(s) MRI Machines Other (please indicate)

10. Operating schedule [days of week and hours of day]

11. Number of occupants / workers / students

12. Please provide total annual (12-month) utility use and cost below or attach utility bills (preferred)

    Electric Company Gas Company
    Date Range [mm/yy] From To Date Range [mm/yy] From To
    Annual Electric Usage [kWh/yr] Annual Gas Usage [Therms/yr]
    Annual Electric Cost [$/yr] Annual Gas Cost [$/yr] [OVER]

Part II: Performance Feedback

Please fill out a separate page for each technology used

RATING SYSTEM: 1 – Excellent / Very Likely 2 – Good / Somewhat Likely
3 - Average / Neutral 4 - Fair / Somewhat Unlikely 5 – Poor / Unlikely

1. Please indicate technology (radiant heating and cooling may be selected together)
   ☐ Displacement Ventilation ☐ Radiant Heating ☐ Radiant Cooling ☐ Variable Refrigerant Flow

2. What were the main reason(s) for implementing this technology
   ☐ Air Quality ☐ Occupant Comfort ☐ Energy Savings
   ☐ Other (please explain)

3. How would you rate the energy performance of this system? ○1 ○2 ○3 ○4 ○5

4. How would you rate occupant satisfaction compared to a typical building? ○1 ○2 ○3 ○4 ○5

5. What percentage of energy savings were anticipated from using this technology?

6. Do you feel the building is achieving the anticipated level of energy savings? ○YES ○NO

7. Would you recommend this technology to other building owners? ○YES ○NO

8. How likely are you to use this technology again in a future building? ○1 ○2 ○3 ○4 ○5

9. How would you rate the ease of operation / operation training with respect to this technology? ○1 ○2 ○3 ○4 ○5

10. In your own words, please indicate the main benefit(s) and drawback(s) of this system

11. Would you be willing to provide more information as necessary? ○YES ○NO

12. Additional comments / feedback

Research Director: Amalia Hicks, Ph.D., LEED GA • Phone: 608-836-4488 x22 • Email: AHicks@sustaineng.com

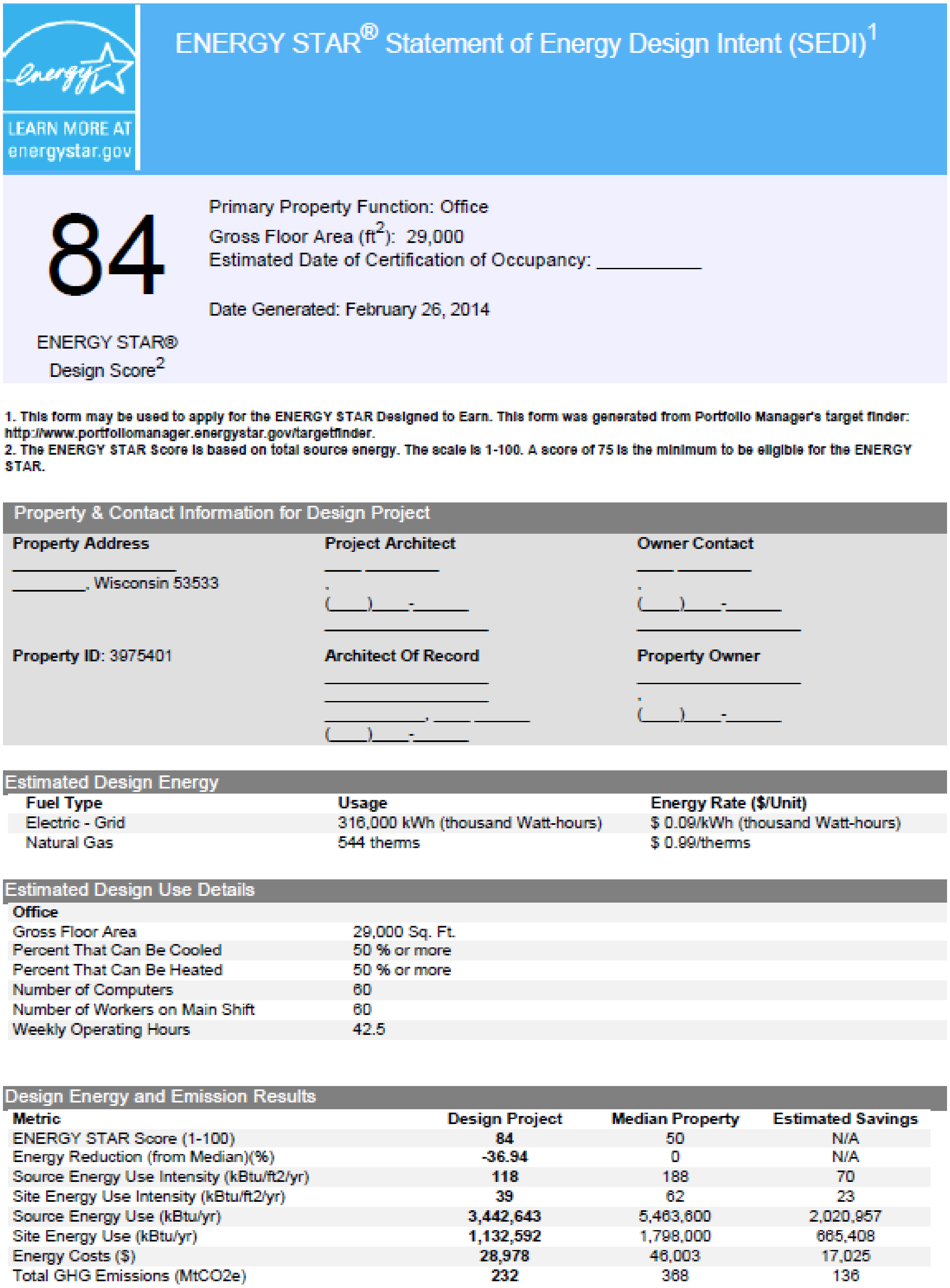
APPENDIX C. BUILDINGS NOT INCLUDED IN ENERGY ANALYSIS

Table C-1. Participating Buildings Not Included in Energy Analysis

ID	EUI [kBtu/ft^2/yr]	REASON
DV-7, RAD-9	107.7	1
DV-8	386.1	2, Casino plug loads underrepresented
RAD-7, VRF-8	48.5	2, Additional Greenhouse
RAD-10	101.0	1
RAD-14	26.6	2, Multifamily
RAD-15, VRF-13	49.4	1
RAD-16, VRF-5	64.1	1
RAD-17	45.9	1
VRF-2	31.8	1
VRF-7	69.7	1
VRF-9	207.9	3, inaccurate building area
VRF-11	58.6	1

Key: **1** – No savings estimate provided. **2** – Unable to accurately represent building with existing Energy Star tools. **3** – Known inaccuracies in building data.

APPENDIX D. SAMPLE ENERGY STAR TARGET FINDER OUTPUT



LEARN MORE AT energystar.gov

ENERGY STAR® Statement of Energy Design Intent (SEDI)[1]

84

ENERGY STAR® Design Score[2]

Primary Property Function: Office
Gross Floor Area (ft^2): 29,000
Estimated Date of Certification of Occupancy: __________

Date Generated: February 26, 2014

[1] This form may be used to apply for the ENERGY STAR Designed to Earn. This form was generated from Portfolio Manager's target finder: http://www.portfoliomanager.energystar.gov/targetfinder.
[2] The ENERGY STAR Score is based on total source energy. The scale is 1-100. A score of 75 is the minimum to be eligible for the ENERGY STAR.

Property & Contact Information for Design Project

Property Address ________________ ________, Wisconsin 53533	**Project Architect** ____ _______ . (____)____-______ ________________	**Owner Contact** ____ _______ . (____)____-______ ________________
Property ID: 3975401	**Architect Of Record** ________________ ________________ __________, ____ ______ (____)____-______	**Property Owner** ________________ . (____)____-______

Estimated Design Energy

Fuel Type	Usage	Energy Rate ($/Unit)
Electric - Grid	316,000 kWh (thousand Watt-hours)	$ 0.09/kWh (thousand Watt-hours)
Natural Gas	544 therms	$ 0.99/therms

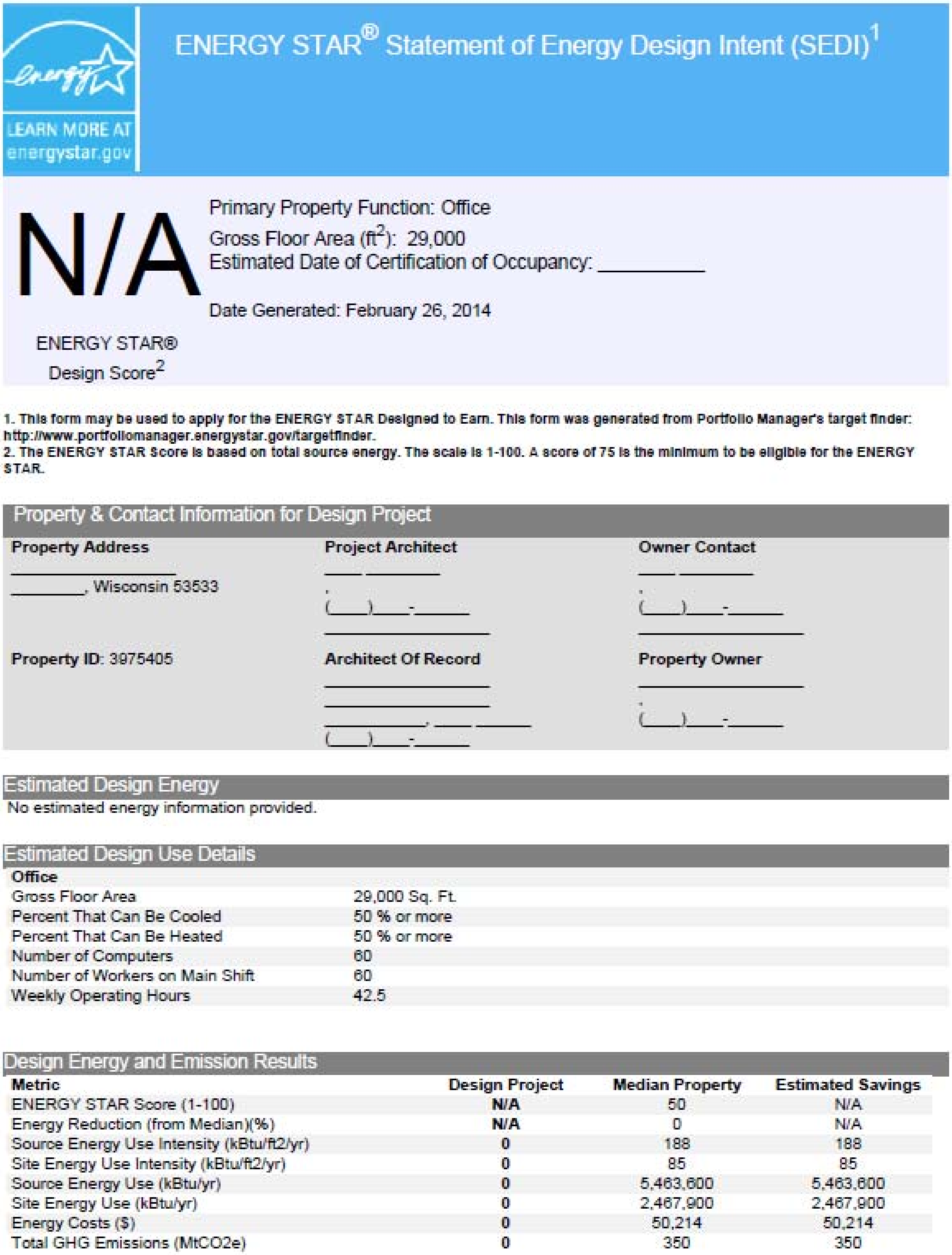
Estimated Design Use Details

Office	
Gross Floor Area	29,000 Sq. Ft.
Percent That Can Be Cooled	50 % or more
Percent That Can Be Heated	50 % or more
Number of Computers	60
Number of Workers on Main Shift	60
Weekly Operating Hours	42.5

Design Energy and Emission Results

Metric	Design Project	Median Property	Estimated Savings
ENERGY STAR Score (1-100)	**84**	50	N/A
Energy Reduction (from Median)(%)	**-36.94**	0	N/A
Source Energy Use Intensity (kBtu/ft2/yr)	**118**	188	70
Site Energy Use Intensity (kBtu/ft2/yr)	**39**	62	23
Source Energy Use (kBtu/yr)	**3,442,643**	5,463,600	2,020,957
Site Energy Use (kBtu/yr)	**1,132,592**	1,798,000	665,408
Energy Costs ($)	**28,978**	46,003	17,025
Total GHG Emissions (MtCO2e)	**232**	368	136

APPENDIX E. TYPICAL FUEL MIX ENERGY STAR TARGET FINDER OUTPUT



LEARN MORE AT energystar.gov

ENERGY STAR® Statement of Energy Design Intent (SEDI)[1]

N/A

ENERGY STAR®
Design Score[2]

Primary Property Function: Office
Gross Floor Area (ft^2): 29,000
Estimated Date of Certification of Occupancy: __________

Date Generated: February 26, 2014

1. This form may be used to apply for the ENERGY STAR Designed to Earn. This form was generated from Portfolio Manager's target finder: http://www.portfoliomanager.energystar.gov/targetfinder.
2. The ENERGY STAR Score is based on total source energy. The scale is 1-100. A score of 75 is the minimum to be eligible for the ENERGY STAR.

Property & Contact Information for Design Project

Property Address	**Project Architect**	**Owner Contact**
__________________ ________, Wisconsin 53533	____ ________ , (____)____-______ __________________	____ ________ , (____)____-______ __________________
Property ID: 3975405	**Architect Of Record**	**Property Owner**
	__________________ __________________ ___________, ____ ______ (____)____-______	__________________ , (____)____-______

Estimated Design Energy

No estimated energy information provided.

Estimated Design Use Details

Office	
Gross Floor Area	29,000 Sq. Ft.
Percent That Can Be Cooled	50 % or more
Percent That Can Be Heated	50 % or more
Number of Computers	60
Number of Workers on Main Shift	60
Weekly Operating Hours	42.5

Design Energy and Emission Results

Metric	Design Project	Median Property	Estimated Savings
ENERGY STAR Score (1-100)	**N/A**	50	N/A
Energy Reduction (from Median)(%)	**N/A**	0	N/A
Source Energy Use Intensity (kBtu/ft2/yr)	**0**	188	188
Site Energy Use Intensity (kBtu/ft2/yr)	**0**	85	85
Source Energy Use (kBtu/yr)	**0**	5,463,600	5,463,600
Site Energy Use (kBtu/yr)	**0**	2,467,900	2,467,900
Energy Costs ($)	**0**	50,214	50,214
Total GHG Emissions (MtCO2e)	**0**	350	350

APPENDIX F. SITE VISIT PROCEDURE

OVERVIEW

The main purpose of EERD site visits is to investigate the performance of the three target technologies (VRF, displacement ventilation, or radiant cooling/heating). Site visits will allow us to determine whether the technology is installed, how much space is served by it, and if it is operating correctly. The secondary purpose of these visits is to verify that building energy usage is not inflated due to operational inefficiencies (such as 24/7 operation) or deflated due to extreme savings measures (such as closing the OA intake) and that the reported usage and square footage of the facility is as reported. Typical effort is 4-6 hours on site.

Benefits of participation for building owners:

1) Assessment of the actual energy performance of their building
2) Opportunity to participate anonymously in buildings research
3) Possible complimentary Energy Star Certification (if eligible)
4) A copy of the final paper when completed

PROCEDURE

PREPARATION

1. Contact design team (mechanical engineer, architect) to determine anticipated energy savings and motivation for including target technology in the design (see Supplement 1)
2. Contact building owner/representative in advance regarding the following information:
   a. Scheduling (see if building manager / operator can be there for a portion of visit)
   b. Provide estimate of time for site visit and personnel involved
   c. Monthly utility bills for the past year if possible (may already have this for some)
   d. Building drawings and any recent TAB reports
   e. A room in which to review the building drawings and documentation.
3. Determine whether the building might qualify for Energy Star certification. If so, gather the small amount of additional information required for certification.

REQUIRED MATERIALS

1. Light Meter
2. Pressure Meter
3. Humidity Meter
4. Thermometer, air and infrared (Fluke IR Meter, including T/C)
5. CO_2 Sensor
6. Cordless Drill / Tape
7. Camera
8. Tape Measure
9. Flashlight
10. Engineering Scale
11. Vane anemometer
12. Bring completed survey to confirm answers

SITE VISIT CHECKLIST

1. Verify the recorded physical characteristics of the building:
    a. Building name & address
    b. Owner name
    c. Primary contact
    d. Year of primary construction
    e. Gross floor area
    f. Swimming pool?
    g. Parking structure?
    h. Renewable energy sources?
2. Review the technology investigated: Radiant Cooling/Heating (RCH), Variable Refrigerant Flow (VRF), or Displacement Ventilation (DV)
    a. What percentage of the conditioned space is utilizing the target technology
    b. Is the technology applied and utilized correctly, e.g.
        i. RCH: Is cooling used (not just heating), are there issues with condensation, etc. Measure floor temp.
        ii. VRF: Is heat recovery used (if applicable), is OA system running, etc.
        iii. DV: Is the air introduced at occupant level at low velocities (measure with vane anemometer?) is there enough ceiling height to maintain stratification, is the exhaust up high, etc.
    c. Record notes on any obvious performance risks, recommended design criteria (i.e., what works, what doesn't)
3. Obtain building photos:
    a. Exterior of building
    b. Components of technology of interest (in mechanical rooms and/or spaces)
4. Verify the recorded operating characteristics (using completed survey)
    a. Number of occupants
    b. Average weekly occupancy hours
    c. Months in use per year
    d. Number of personal computers
    e. Presence and extent of data center/large server room
    f. Percentage of gross floor area mechanically cooled/heated
    g. Whether the building is mechanically ventilated
    h. Presence of cooking facilities in operation
5. Verify recorded energy consumption
    a. Monthly consumption for all energy sources in building are accounted for
    b. Any other fuels used in the building?
    c. At least 11 concurrent months of utility data is recorded
    d. Monthly recorded data has contiguous start and end dates

6. Use the site visit log (see attachment) to document findings for the following space conditions:
    a. Verify thermal comfort levels
        i. Observe spaces for signs of discomfort
        ii. Measure temperature and humidity levels in a sampling of spaces

	HEATING MODE	COOLING MODE
DRY BULB TEMPERATURE RANGE [F]	68 - 74	73 - 79
RELATIVE HUMIDITY RANGE [%]	30 - 60	30 - 60

    b. Verify illumination levels
        i. Measure illumination levels in a sampling of spaces
    c. Verify outside air ventilation (ASHRAE 62 – 1999)
        i. Measure/calculate the amount of OA provided by each air handling unit and compare with requirements.
    d. Verify control of indoor air pollutants (ASHRAE 62 – 1999)
        i. Verify proper exhaust (negative pressurization) of rooms such as cooking facilities, restrooms, mechanical rooms, and chemical storage areas
        ii. Verify that the building is free of visible signs of mold and mildew
        iii. Combustion sources are exhausted directly outside
7. Review to see if there are any obvious energy savings measures such as:
    a. High light level
    b. AHU schedules and zone schedules
    c. AHU dampers and valves
    d. HW/CW/AHU temp resets
    e. Excessive static pressure settings (hydronic and air)
    f. Over-ventilation
    g. CO_2/relative humidity sensors not calibrated
    h. Economizer changeover temp
    i. Humidification setpoints and scheduling of humidification if units run 24/7
    j. OA dampers open during unoccupied mode
    k. AHU's running to cool one highly loaded room
    l. CRAC units not running right, too tight of temp and humidity setpoints, short circuiting of air, 2 units running when only one is needed
    m. Simultaneous heating/cooling, especially in open areas
    n. Bad economizer control, cooling with econ then heating with hw coil
    o. No temperature reset during winter mode (reduce reheat)
    p. Minimum VAV terminal airflow settings are too high
    q. Large spaces with no scheduling on airflow or outside air (e.g., always ventilating for 1000 occupants but this only happens twice each year

SUPPLEMENT 1: DESIGN TEAM INTERVIEW QUESTIONS

Explain to design team members that we're conducting Focus on Energy research on advanced HVAC technologies, and that all gathered responses will be anonymous, including the use of anonymous building identifiers (when requested by owners).

Benefits of participation for design teams:

1) Documentation of the enhanced energy performance of a building they designed
2) Opportunity to participate anonymously in buildings research
3) A copy of the final paper when completed

Please take detailed notes of answers!

1. Does this building contain the target technology?

2. What were the overall projected energy savings for the building?

3. What did you assume for additional first costs for the technology?

4. What was your motivation for using this technology?

5. Has the system met your expectations?

6. What would you do differently?

7. Would it be possible to obtain LEED (energy credit) documentation and/or energy modeling reports?

APPENDIX G. SITE VISIT REPORTS

DV-1

BACKGROUND

Displacement Ventilation Building 1 is a ~16,800 sq-ft public library in Central MN. Figure G-1 shows the interior and exterior of the building. Library construction was completed in 2007. The building includes offices, stacks, reading rooms, an employee break room, and a community meeting room. The library employs 1 full-time person and 12 part-time people. The building is open 6 days per week, 5-10 hours per day, and closed on Sundays.

Figure G-1. DV-1 Interior and Exterior

Project design goals included exceeding ASHRAE Standard 90.1-2007 (IECC 2009) energy performance requirements by greater than 62% while meeting the indoor air quality requirements of ASHRAE Standard 62.1-2007 and thermal comfort requirements of ASHRAE Standard 55-2007. LEED Gold certification was pursued using LEED NC 2.2 criteria. The building includes high efficiency windows, daylight sensors, a geothermal bore field, and energy recovery along with the advanced HVAC system. Although the library is ineligible for an Energy Star rating, the building is using significantly less energy than the Minnesota B3 Benchmark and is ranked in the 88th percentile amongst 107 similar sites.

DESIGN INTENT

Ventilation: Ventilation is provided from a single, 100% Dedicated Outdoor Air Handler with an energy recovery wheel. The unit provides ~2,090 cfm of ventilation, which can be reduced to ~700 cfm after hours to only serve the Community Meeting Room and Lobby. This air handling unit – located in the mechanical room on the southeast side of the building – contains no supplemental heating or cooling. The outside

Figure G-2. DV-1 AHU-1 (100% OA)

ventilation air is distributed to air handling units AHU-2 and AHU-3, where the air is mixed with return air and distributed to the building spaces.

Primary Heating and Cooling: Heating water and chilled water are generated by three geothermal water to water heat pumps located in the mechanical room. The heat pumps deliver heating water up to ~110°F in the heating mode, and chilled water down to ~45°F in the cooling mode. The source water to/from the heat pumps comes from a closed loop geothermal piping system consisting of a field of 36 connected vertical loops (3 circuits of 12 bores per circuit) buried south of the building. Fin tube heating is used to offset perimeter heat losses in the winter.

Figure G-3. DV-1 Water to Water Heat Pump (Typical of 3)

Terminal Heating and Cooling: The heating and chilled water generated by the heat pumps is distributed to air handling unit coils, VAV box reheat coils, and unit heaters. Two air handling units (AHU-2 and AHU-3) deliver conditioned air to VAV boxes located throughout the building. From the VAV boxes, the air is then distributed to the displacement ventilation system.

Figure G-4. DV-1 AHU-2 (AHU-3 similar)

Displacement Ventilation: Conditioned air in the range of 60°F to 65°F is discharged at low velocities – typically 50 to 70 feet per minute – through customized perforated supply air diffusers located at the occupant level, low on walls and columns. The intent of this type of system is that the cool air is negatively buoyant compared to air in the space, and drops after discharge, spreading across the floor. Heat sources around the room transfer heat to the cooler air creating a plume around and above the heat sources. At a certain height – typically over 9 feet – the plume spills horizontally. Two distinct zones are formed: a lower occupied zone with little recirculation flow, and an upper zone with recirculation flow. It is also at the upper zone that the air is drawn back to the air handling equipment.

Figure G-5. DV-1 Low Velocity Supply Air Diffusers (Round and Flat)

We discussed the building design with the mechanical engineer. Their motivation for using the displacement ventilation technology included more efficient energy performance, decreased air distribution, and increased ventilation effectiveness. They feel the system is performing well and meeting their expectations with the exception of fan and air noise at the supply diffusers, especially in the open stacks area.

ENERGY CONSUMPTION

Table G-1 and Table G-2 summarize Displacement Ventilation Building 1 utility information for the last 12 months. Average utility costs for the library are $0.10/kWh and $1.02/therm. The building was compared to an average building in Energy Star Target Finder, which predicts that it is performing ~40% better than the median.

Table G-1. DV-1 Benchmarking Performance

	ELECTRIC	GAS	DV-1 TOTAL	MEDIAN LIBRARY[a]	% SAVINGS
ENERGY USE [kBtu/ft^2/yr]	46.3	2.0	48.3	77.0	**37.2%**
COST [$/$ft^2$/yr]	$1.42	$0.02	$1.44	$2.31	**37.6%**

Notes: a – Using CBECS Database, assumes same fuel mix as participant building.

In addition the building's actual bills were compared to design team projections, shown in Table G-2. Individual predictions for electricity and gas use were not available, so EUI was used. The actual consumption of the building is significantly greater (~60%).

Table G-2. DV-1 Design Team Energy Use Projections

	PROJECTION	ACTUAL
ELECTRICITY [kWh/yr]	--	228,463
GAS [therms/yr]	--	331
Total [kBTU]	502,858	812,646
EUI [kBTU/ft^2]	29.9	48.3

BUILDING PERFORMANCE

Displacement Ventilation Building 1 was visited in early January, 2014. We met with the building maintenance staff. Air temperature, humidity, and light levels were measured throughout the building (Table G-3). Humidity levels in the spaces were low (~8.4%) likely due to a combination of very low outside air temperatures and no existing building humidification system. We verified that displacement ventilation was being used in 100% of the building.

Table G-3. DV-1 Site Visit Log

SPACE	TEMPERATURE [°F]	RELATIVE HUMIDITY	LIGHT LEVEL [FC]	CO_2 [PPM]	NOTES
Children's Stacks (S)	66.4[a]	23% / 8.4%[b]	45.6	530	3 people
Children's Stacks (N)	66.3	--	67.4	527	3 people (windows)
NE Corner Stacks	66.2	--	89.0	566	2 people (windows N and E)
SE Corner Stacks	66.7	--	105.5	546	1 person
Study 2	67.4	--	22.1	544	Unoccupied
Circulation Desk	68.3	--	31.1	561	2 people
Main Entrance	69.3	--	77.3	522	Unoccupied
Vestibule	70.5	--	63.5	510	Unoccupied; Sunny; Glass
Outside Conditions	9.3	47.9%	--	--	Sunny

Notes: **a -** Temperatures were measured low in the space, and generally reflect typical DV distribution temperatures. **b -** Relative humidity was shown as 23% (return air) on the Building Automation System but measurements indicated a much lower humidity level (8.4%) in the space.

The maintenance staff is relatively pleased with the displacement ventilation features of the project. The project goals for energy and air quality are being met with few issues. However, while we were touring the mechanical room, the maintenance staff pointed out that the compressor from one of the three water to water heat pumps was recently replaced due to failure. Although the cause of the failure is not clear, the maintenance staff speculates that attempts to increase the heating water temperature above 120 deg. F to improve occupant comfort may have contributed.

Although the current heat pumps are operating as intended and producing heating water at design conditions, occupant comfort still remains somewhat of an issue during the heating season. Any comfort issues they may be experiencing were not noticed during the site visit as the outside air temperature was -9 deg. F and the majority of the space temperatures ranged from the mid to upper 60s.

SUMMARY

This is a successful project and an aesthetically pleasing application of displacement ventilation. The customized supply air diffusers wrapped around columns and installed low in walls integrate well into the overall building structure, and although some air noise is noticeable as one walks past the diffusers, the sound is similar to white noise and does not distract. The very low air flow velocity from the diffusers prevents drafts, but the supply air temperatures inherent to a well-designed displacement ventilation system can and do create space temperatures that may be too low for some occupants.

DV-2

BACKGROUND

Displacement Ventilation Building 2 (DV-2) is a 166,000 ft^2 office facility in east central Minnesota. Figure G-6 shows the interior and exterior of the building. Construction began in 2006 and occupancy began in April of 2008. The building includes open and individual offices, conference rooms, kitchen, fitness center, lower level parking garage, and numerous mechanical rooms. The facility currently employs approximately 250 people. Normal business hours are 8am to 5pm, Monday through Friday. However, up to eight employees occupy the building 24 hours a day every day as needed for specific business and building operations.

Figure G-6. DV-2 Exterior and Interior

Project design goals included exceeding ASHRAE Standard 90.1-2007 (IECC 2009) energy performance requirements by 45% while meeting the indoor air quality requirements of ASHRAE Standard 62.1-2007 and thermal comfort requirements of ASHRAE Standard 55-2007. The building achieved LEED Platinum certification using LEED NC 2.2 criteria and is the first building in Minnesota to receive Platinum status. The building includes multiple energy conservation measures that include 72 kW solar panels, a 200 kW wind turbine, daylight sensors, lighting occupancy sensors, energy recovery, high efficiency windows, and a closed loop lake geothermal system, along with the advanced HVAC system.

DESIGN INTENT

Ventilation: Ventilation is provided from two packaged 100% outdoor air handling units with 2 stages of energy recovery (enthalpy wheel and static plate heat exchanger) located in the Penthouse. The two units are scheduled to provide ~10,700 cfm and 5,300 cfm of ventilation air respectively, which can be reset based on feedback from CO_2 sensors. The make-up air handlers also contain a heat pump coil, reheat coil, and hot gas reheat coil for dehumidification in the summer months.

Figure G-7. DV-2 Make Up Air Handler

Primary Heating and Cooling: Heating water and chilled water are generated by five geothermal water to water heat pumps located in the penthouse mechanical rooms. These heat pumps are scheduled to deliver heating water up to ~120°F in the heating mode, and chilled water down to ~45°F in the cooling mode. The source water to/from the heat pumps comes from a closed loop lake type geothermal piping system submerged in a lake north of the building. Perimeter heating is supplied by water to air heat pumps.

Figure G-8. DV-2 Geothermal Pumps

Terminal Heating and Cooling: The heating and chilled water generated by the water to water heat pumps is distributed to fan coil units and water to air heat pumps located throughout the building. From these units, the air is then distributed to the displacement ventilation system to approximately 80% of the building. The majority of the supply air is delivered through floor mounted circular diffusers.

Figure G-9. DV-2 Fan Coil Unit

Figure G-11. DV-2 Supply Diffusers

Figure G-11. DV-2 Heat Pump

We discussed the building design with the mechanical engineer, who feels that the design was generally a success. The engineer's motivation for using the displacement ventilation technology was primarily the potential for energy savings. Occupant comfort and indoor air quality were also cited as motivators for including displacement ventilation.

When asked if this system met their expectations, the engineer made these points:

- The system is performing well. People like fresh air.
- Energy performance did fine.
- Regarding occupant comfort: the Owner is making improvements in certain areas of the building to increase occupant comfort in the heating season.
- Displacement ventilation at the perimeters tends to result in zones which are too cool in some occupied areas, especially in the winter months.
- Having tighter control over perimeter heating is critical to grab heat losses.

ENERGY CONSUMPTION

Table G-4 and Table G-5, and Figure G-12 and Figure G-13 summarize Displacement Ventilation Building 2 utility information, averaged over the last 5 years. Average utility costs are $0.09/kWh and $0.82/therm. The building was compared to an average building in Energy Star Target Finder, which predicts that it is performing ~30% better than the median.

Table G-4. DV-2 Monthly Utility Use

	ELECTRIC [kWh]	GAS [therms]
JAN	284,400	2,446
FEB	237,200	2,161
MAR	230,900	1,123
APR	212,250	640
MAY	212,500	356
JUN	235,000	246
JUL	251,250	227
AUG	249,750	234
SEP	220,917	234
OCT	217,667	299
NOV	214,417	809
DEC	287,333	2,233
ANNUAL	**2,853,583**	**11,006**

Table G-5. DV-2 Benchmarking Performance

	ELECTRIC	GAS	DV-2 TOTAL	MEDIAN BUILDING	% SAVINGS
ENERGY USE [kBtu/ft^2/yr]	58.9	6.7	65.6	88.9	**26.2%**
COST [$/ft^2/yr]	$1.51	$0.05	$1.56	$2.18	**28.2%**

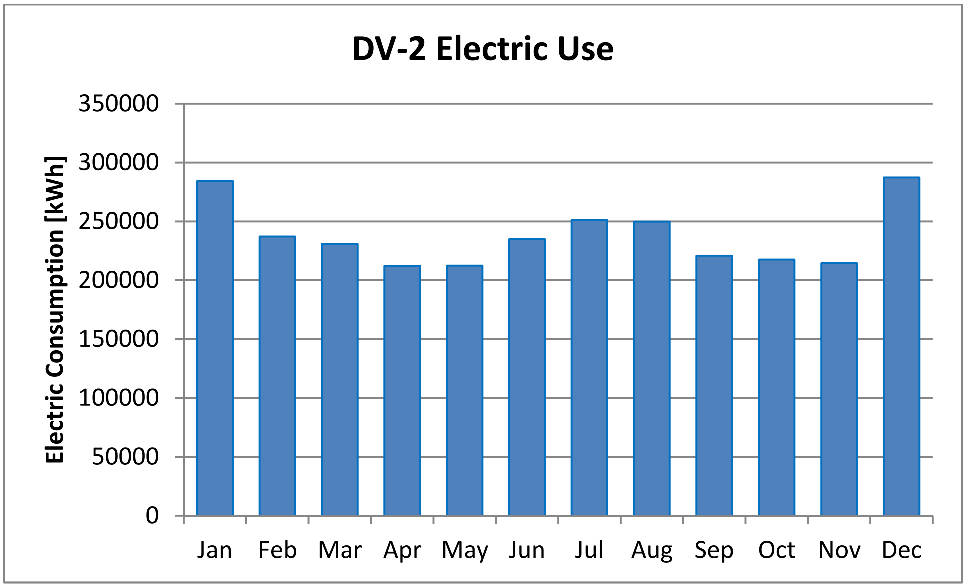


Figure G-12. DV-2 Monthly Electric Consumption [kWh]

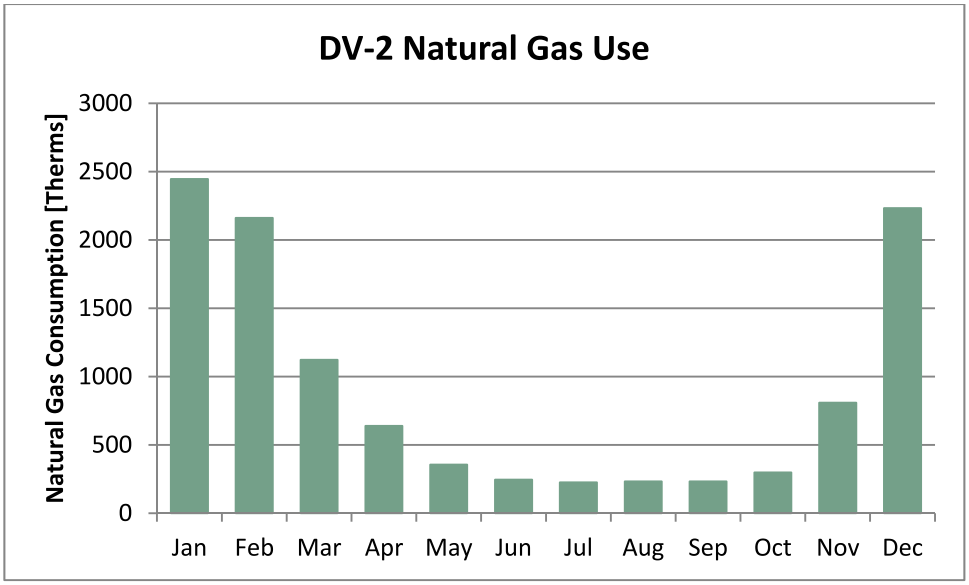


Figure G-13. DV-2 Monthly Gas Consumption [Therms]

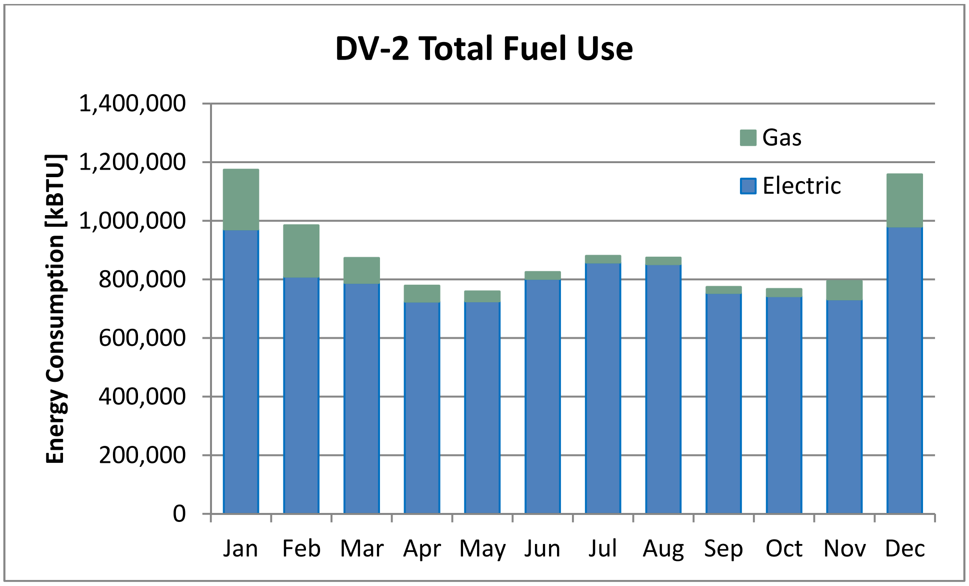


Figure G-14. DV-2 Total Monthly Energy Consumption [kBTU]

In addition the building's actual bills were compared to design team projections, shown in Table G-6. Individual predictions for electricity and gas use were not available, so EUI was used. The actual consumption of the building is greater than predicted by about 30%.

Table G-6. DV-2 Design Team Energy Use Projections

	PROJECTION[a]	ACTUAL
ELECTRICITY [kWh/yr]	--	2,853,583
GAS [therms/yr]	--	11,006
Total [kBTU]	9,178,000	10,838,201
EUI [kBTU/ft^2]	55.5	65.6

Notes: **a** – From LEED credit documentation.

BUILDING PERFORMANCE

Displacement Ventilation Building 2 was visited early in January 2014. We met with building users and maintenance staff. Air temperature, humidity, and discharge air velocities through diffusers were measured on the first and third floors (Table G-7). We verified that displacement ventilation technology was being used in approximately 80% of the building.

Table G-7. DV-2 Site Visit Log

Heat Pump	AIR DISCHARGE TEMPERATURE [°F]	TEMPERATURE [°F]
HP1-4	91.1	68.6
HP1-10	90.0	61.4
HP1-17	71.8	74.1
HP1-21	73.4	77.4
HP3-4	92.7	73.7
HP3-5	80.0	73.4
HP3-10	103.4	72.0
HP3-16	69.8	70.5
Outside Conditions	--	-3.0

The maintenance staff and stakeholders are somewhat pleased with the project in terms of energy savings and indoor air quality. However, it was stressed that thermal comfort in many areas of the building has been challenging and somewhat disappointing since the building was first occupied in 2008. The following are issues and observations that were discussed related to the displacement ventilation system:

- Conference rooms are a challenge for displacement ventilation. Even at low air velocities, people complain of cold ankles, feet, and legs especially where the supply air diffusers are adjacent to or under chairs. The ductwork for one of the first floor conference rooms is being reconfigured so the supply air will discharge at the ceiling.
- The majority of complaints are from occupants being too cold in the heating season.
- Cooling is generally good in the summer. Complaints are rare in the cooling season compared to the heating season.
- When the building was first occupied, discharge air temperatures ranged from mid to high 60s. Due to comfort complaints, the discharge air temperature has been increased to around 70 deg F at perimeters and in some conference rooms. This practice is likely to eliminate air stratification and subsequently reduce ventilation effectiveness.
- Due to the placement of the floor diffusers, furniture layouts are limited.
- Free-cooling coils were added to approximately 25 heat pumps by the Owner after occupancy to help further improve system efficiency and occupant comfort. The coils were added to heat pumps that primarily serve the south side of the building.
- Perimeter heating comes from water to air heat pumps, but is not always effective.

SUMMARY

This project is generally a good example of displacement ventilation design and application in terms of laminar flow air velocities, supply air temperatures, and cooling effectiveness. However, some aspects of this design have led to unfortunate drawbacks, due mainly to the lack of effective perimeter heating in the winter months, and the placement of floor mounted diffusers in sensitive occupied areas. There were lessons learned related to occupant comfort when utilizing displacement ventilation in cold climates, including the need for better control of perimeter heat losses. This could mean the difference between a "fussy building" – as described by a staff member – and a building that provides year-round comfort and energy savings.

DV-3

BACKGROUND

Displacement Ventilation Building 3 is a 212,000 sq-ft high school in Central WI. Figure G-15 shows the entrance of the school. It was designed and built in 2000-2002. The building includes classroom, gymnasiums, aquatic center, library, cafeteria/kitchen, performing arts center, offices and conference rooms. The school employs 50 teachers and administrators and has about 450 students. The school is open 7 days per week, 6-8 hours per day. The activity varies – regular school and teaching activities during the week and sporting activities and events on Saturdays and Sundays. The school is also lightly occupied and air-conditioned in summer with the same daily schedule as in winter.

Figure G-15. DV-3 Main Entrance

Project design goals included creating a comfortable and energy efficient school. The school was willing to invest some additional capital for a system that was more energy efficient than average and reviewed a few technologies until they found one that they were comfortable with.

The building envelope and lighting system were designed as in typical buildings with advanced, untraditional HVAC systems. This HVAC system consisted of radiant hot water strip heating above the windows, ventilation system only with hot and cold deck, numerous heat exchangers (air and water), indirect and direct evaporative coolers, and ice storage.

DESIGN INTENT

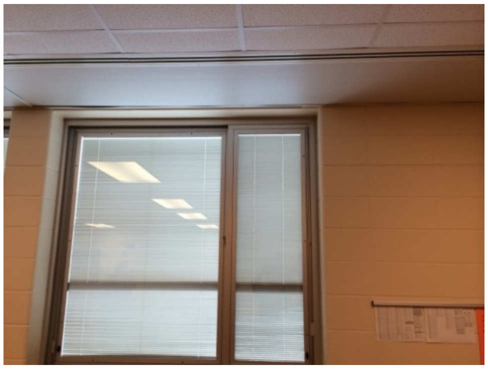


Figure G-16. DV-3 Radiant Heating Panels and Slot Diffuser.

Ventilation: Ventilation is provided from two, 100% Dual Duct (cold and ventilation) Dedicated Outdoor Air Handlers with energy recovery. The units provide ~40,000 and 31,500 cfm of ventilation. Supplemental heat from a direct-fired gas burner is provided to the exhaust air stream when needed in the winter, to heat exchange with the ventilation deck and incoming air. The exhaust also has an evaporator that is used to cool the outgoing air in summer to cool the incoming outside air. The air handlers have cooling coils for space cooling and humidity control in the summer. The air handlers are located in a second floor mechanical room. These units have no recirculating air and the O&M manager feels that this has resulted in considerably less sick days than other area schools. There is a pool in this high school with a separate AHU.

Figure G-17. DV-3 Boilers

Primary Heating and Cooling: Primary cooling consists of (2), water cooled ice making chillers with heat recovery. The ice storage is primarily used for electric demand management. The chilled water is provided to the air handler cooling coil. Heat of rejection is primarily used for pool heating and secondarily ejected through a cooling tower. The heating is provided by four natural gas fired boilers for the ceiling radiant panels and ceiling mounted radiators. The AHU heating is provided by natural gas direct fired air units to heat the ventilation deck and to preheat the incoming outdoor air.

We discussed the building design with both the O&M manager and mechanical engineer. Both speak highly of the building.

ENERGY CONSUMPTION

Table G-8 and Table G-9, and Figure G-18 and Figure G-19 summarize Displacement Ventilation Building 3 utility information for the last 12 months. Average utility costs are $0.10/kWh and $0.69/therm. The building was compared to an average building in Energy Star Target Finder, which predicts that it is performing ~20% better than the median.

Table G-8. DV-3 Monthly Utility Use

	ELECTRIC [kWh]	GAS [therms]
JAN	114,000	15,414
FEB	118,500	12,377
MAR	103,500	11,837
APR	109,500	8,440
MAY	117,000	3,732
JUN	133,500	1,720
JUL	148,500	1,233
AUG	129,000	1,041
SEP	162,000	2,241
OCT	112,500	5,503
NOV	109,500	9,560
DEC	109,500	12,490
ANNUAL	**1,467,000**	**85,588**

Table G-9. DV-3 Benchmarking Performance

	ELECTRIC	GAS	DV-3 TOTAL	MEDIAN LIBRARY	% SAVINGS
ENERGY USE [kBtu/ft^2/yr]	23.6	40.4	64.0	78.6	**18.6%**
COST [\$/ft^2/yr]	\$0.67	\$0.28	\$0.94	\$1.19	**20.9%**

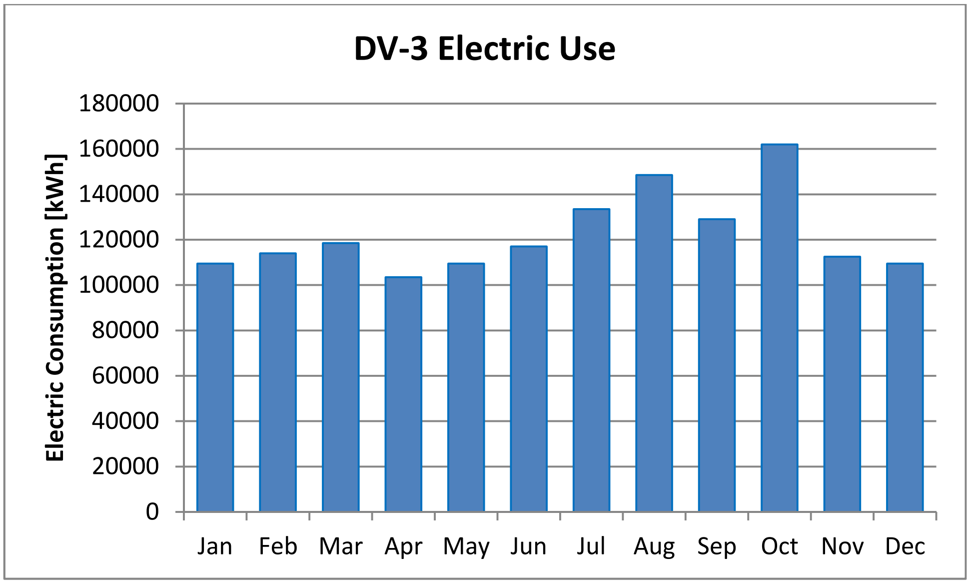


Figure G-18. DV-3 Monthly Electric Consumption [kWh]

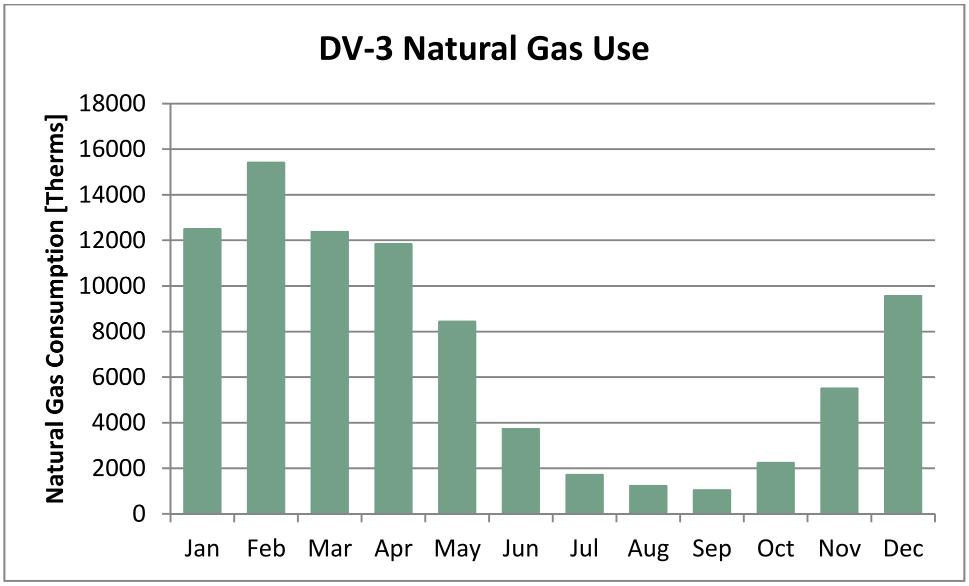


Figure G-19. DV-3 Monthly Gas Consumption [Therms]

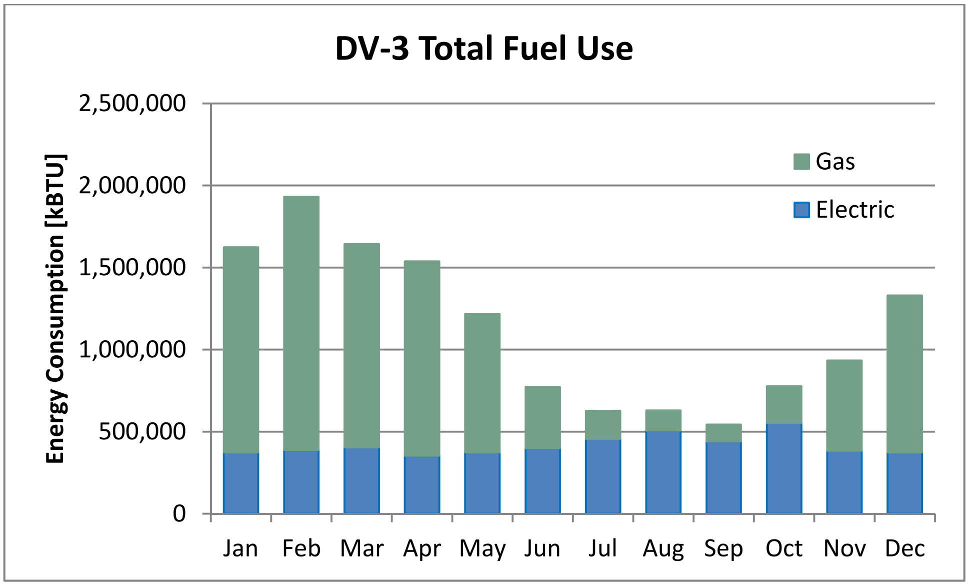


Figure G-20. DV-3 Total Monthly Energy Consumption [kBTU]

In addition the building's actual bills were compared to design team projections, shown in

Table G-10. Individual predictions for electricity and gas use were not available, so EUI was used. The actual consumption of the building is slightly more (~8%).

Table G-10. DV-3 Design Team Energy Use Projections

	PROJECTION	ACTUAL
ELECTRICITY [kWh/yr]	--	1,467,000
GAS [therms/yr]	--	85,588
Total [kBTU]	12,508,000	13,568,000
EUI [kBTU/ft^2]	59.0	64.0

BUILDING PERFORMANCE

Displacement Ventilation Building 3 was visited in early January 2014. We met with the operation and maintenance manager. Air temperature, floor temperature, humidity and light levels were measured throughout the building in different types of spaces (Table G-11).

Table G-11. DV-3 Site Visit Log

SPACE	TEMPERATURE [°F]	RELATIVE HUMIDITY	LIGHT LEVEL [FC]	CO_2 [PPM]	NOTES
Cafeteria	70.7	12%	45	875	Lights off when unoccupied
Gym	69.9	12%	33	936	T5, High output
Pool	80.0	55%	46	956	--
Library	72.9	9%	53	810	--
Classroom E137	73.1	10%	55	945	--
Comp Lab	70.0	12%	--	1020	--
Classroom E002	70.2	9%	60	710	--

Table G-12. DV-3 Air Stratification Temperature Measurements

SPACE	FLOOR TEMPERATURE [°F]	CEILING TEMPERATURE [°F]
Cafeteria	68.0	71.0
Gym	66.0	66.0
Pool	80.0	81.0
Library	72.4	76.0
Classroom E137	69.8	71.0
Comp Lab	70.4	73.0
Classroom E002	67.0	68.0

Displacement ventilation was not utilized in the traditional sense. While this term was used by the engineer and staff to describe the ventilation strategy, it did not appear to function as displacement ventilation, with the possible exception of the performing arts center. In the classrooms and cafeteria air was introduced from ceiling diffusers near the windows, and our temperature measurements did not show any stratification; floor and ceiling temperatures were very close to each other as measured by an infrared thermometer. We believe that the school is not utilizing true displacement ventilation, in particular in the heating mode but also not likely in the cooling mode. For this reason, DV-3 was not included in energy benchmarking or owner satisfaction analysis.

The operations and maintenance manager is very happy with the HVAC aspect of the project, and it is believed that the number of sick days reported by the school are considerably lower than surrounding schools due to the 100% outside air system.

Over the years there have been a few energy efficiency and operational improvements within the school:

1. The lighting for the school has been upgraded to more efficient lighting
2. A cooling tower has been added to enable the building to dump heat in summer, avoid overheating the pool, and reduce draining of the cooling tower sump when it overheats.
3. The chilled water/ice storage systems have been fine-tuned and the summer peak demand has been reduced from 630 kW to 491 kW over the last two years.

SUMMARY

While this is a successful school from an energy and comfort point of view, with many innovative technologies and relatively low energy usage, it does not technically utilize the displacement ventilation technology that we are targeting. We believe there is a misconception in the engineering community about the term displacement ventilation, and that it is regularly used for systems that do not necessarily qualify as displacement ventilation as defined by ASHRAE (AHSRAE Handbook, 2011 chapter 57) and other HVAC organizations.

RAD-1

BACKGROUND

Radiant Building 1 (RAD-1) is a ~36,000 sq-ft public library in Southeastern Wisconsin. Figure G-21 shows the interior and exterior of the building. It was designed in 2008-2009 to replace an existing facility that was about 1/3 the size. The building includes offices, stacks, reading rooms and conference rooms. The library employs 13 people and is open 6 days per week, 7-12 hours per day. Patron activity varies greatly – the building is generally busier after school and on Saturdays, and is more heavily used in the Summer than the Winter.

Figure G-21. RAD-1 Exterior and Interior

Project design goals included exceeding ASHRAE Standard 90.1-2007 (IECC 2009) energy performance requirements by greater than 50% while meeting the indoor air quality requirements of ASHRAE Standard 62.1-2007 and thermal comfort requirements of ASHRAE Standard 55-2007. The building owner participated in the Focus on Energy and WPPI New Construction Programs. While LEED certification wasn't sought, LEED NC 3.0 criteria were used as a guideline. It was built in 2010-2011 and occupied in October 2011. The building includes a high performance envelope and lighting system along with the advanced HVAC system. The total construction cost of the project was ~$8.0 M ($222/sq-ft), with an HVAC system cost of ~$1.1M (~$30/sq-ft). The efficiency improvements to the HVAC system were projected to have a 10-year payback over a more conventional system.

DESIGN INTENT

Ventilation: Ventilation is provided from a single, 100% Dedicated Outdoor Air Handler with 2-stage energy recovery. The unit provides ~10,000 cfm of ventilation, which can be reset based on feedback from CO_2 sensors. Supplemental heat from a direct-fired gas burner is provided to the exhaust air stream when needed in the winter. The air handler also has a cooling coil for humidity control in the summer. The air handler is located in a basement mechanical room.


Figure G-22. RAD-1 Air Handler

Primary Heating and Cooling: Primary cooling consists of (2), 30-ton water cooled ice making chillers with heat recovery. Ice storage is primarily used for electric demand management. The coldest chilled water is provided to the air handler cooling coil. "Warmer" chilled water is provided to the radiant floor system to avoid condensation issues. Heat of rejection is stored and used with the radiant floor system or rejected through a HX to city water ("pump and dump"). If there isn't enough waste heat available, two small condensing boilers supplement.


Figure G-23. RAD-1 Chillers

Terminal Heating and Cooling: The radiant heating and cooling system are integrated into the mass floors. Cooling water is provided at no lower than 55 °F to prevent condensation. Floor temperature is controlled via thermocouples imbedded in the floor. Perimeter fin tube heating is used to control envelope heat loss and supplement the radiant floor system in heating mode (fin tube is in series with the radiant floor loops). The primary chilled water and hot water is distributed via pumps and heat exchangers. We discussed the building design with both the architect and mechanical engineer. Both speak highly of the building and have made some effort the monitor the performance of the facility.


Figure G-24. RAD-1 Radiant Floor HX

The following is the architect's feedback on the project:

> *"One of the successes of the project is the integration of the HVAC system into the skin and bones of the building. The system developed used very small ductwork because so much of the heating / cooling was integrated into radiant floor systems. The smaller ducts allowed us higher ceilings, which meant deeper penetration of natural light. We even got to use some simple light shelves and tops of casework to bounce light further because of the ceiling height. The live floor also helped us capture heat load from sun / people /*

> *computers and move it to places that needed it, or stored it for later use. In the end we realized we were trying to answer the question "what would I do if I had waste heat to deal with?" Since a building like this *always* has waste heat it turned into many interesting evenings of discussion. And lead to some surprising realizations about designing for passive heat loss instead of pumping it out of the building, or capture of the energy for other uses. Another interesting point was how we integrated the 2nd floor supply air into the building skin, and how we bridged the entry area to feed the administration area. And, this is all done with 100% outside air which, with our location of the vapor barrier and insulation on the exterior of the wall systems, should provide very good IAQ. So, lots of subtleties." – Project Architect via email*

The following is the mechanical engineer's feedback on the project via an ASHRAE Publication:

> *"The use of radiant heating and cooling systems employing PEX tubing embedded in the floor resulted in a nearly maintenance free terminal heating and cooling system. Controls employ 2-position ball valves. Other than damper actuators, the air handling system contains only 4 motors and air filters. Only the heat wheel and tower fan have belts, which are readily accessible. Pumps are direct-drive. There are only two coils in the air handler and neither have the potential to freeze. No reheat is employed anywhere in the building." – excerpt from ASHRAE Technology Award Application written by Mechanical Engineer*

ENERGY CONSUMPTION

Table G-13 and Table G-14, and Figure G-26 and Figure G-27 summarize Radiant Building 1 utility information. Average utility costs for the library are $0.10/kWh and $0.82/therm. Water consumption is also reported to illustrate increased summer usage due to the building's open-loop heat rejection system. Conservatively assuming that all water use above the minimum monthly usage (700 cubic feet) is associated with heat rejection, and using an average cost of $0.01/gallon, water consumption due to heat rejection contributes less than 2% to annual operating costs.

This building was compared to an average building in Energy Star Target Finder, which predicts that it is performing ~50% better than the median.

Table G-13. RAD-1 Monthly Utility Use

	WATER[a] [100 ft^3]	ELECTRIC [kWh]	GAS [therms]
JAN	8	17,040	865
FEB	12	30,960	820
MAR	7	25,080	112
APR	7	22,200	118
MAY	13	31,080	43
JUN	26	31,800	33
JUL	30	45,600	52
AUG	21	31,200	102
SEP	24	39,240	167
OCT	16	31,680	251
NOV	9	28,680	490
DEC	8	27,600	891
ANNUAL	**181**	**362,160**	**3,944**

Table G-14. RAD-1 Benchmarking Performance

	ELECTRIC	GAS	RAD-1 TOTAL	MEDIAN LIBRARY	% SAVINGS
ENERGY USE [kBtu/ft^2/yr]	34.4	11.0	45.4	89.5	**49.2%**
COST [$/ft^2/yr]	$1.01	$0.09	$1.10[a]	$2.17	**49.3%**

Notes: **a -** Not including minor contributions (<2%) from water use.

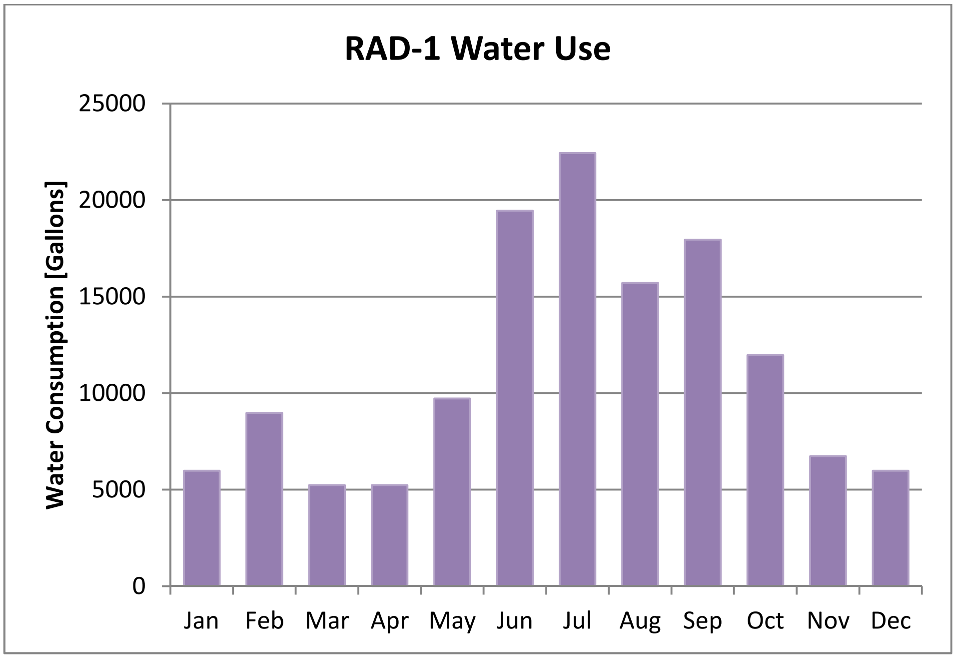


Figure G-25. RAD-1 Monthly Water Consumption [Gallons]

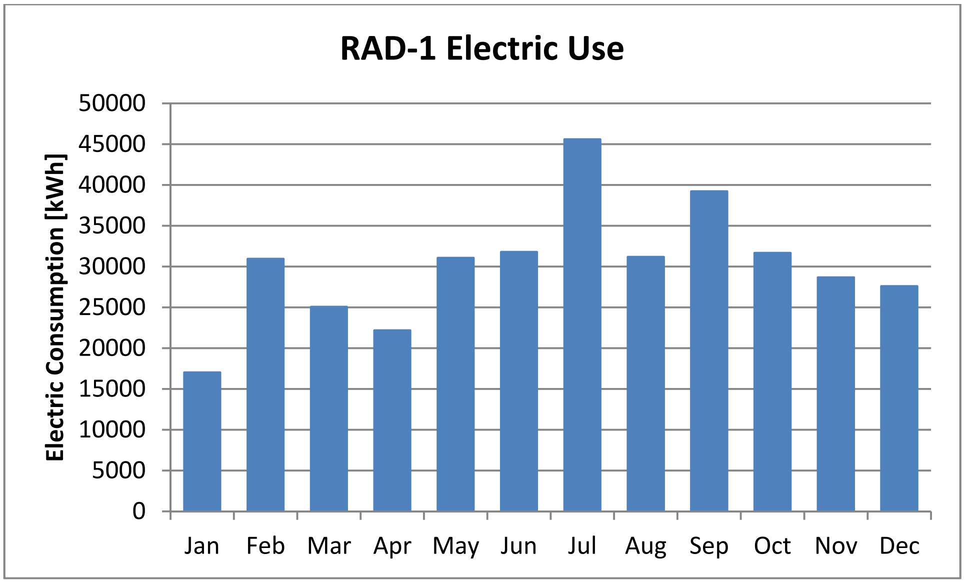


Figure G-26. RAD-1 Monthly Electric Consumption [kWh]

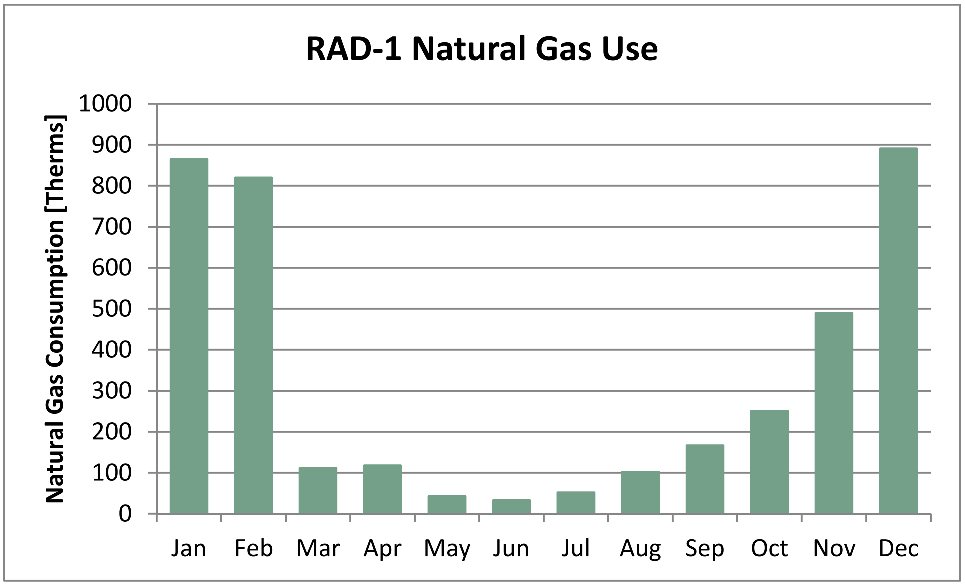


Figure G-27. RAD-1 Monthly Gas Consumption [Therms]

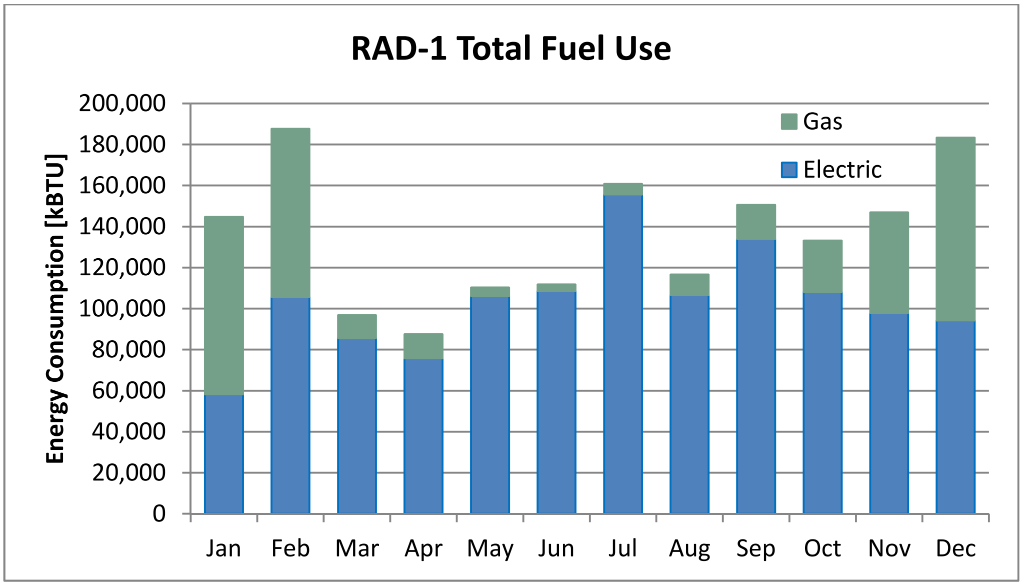


Figure G-28. RAD-1 Total Monthly Energy Consumption [kBTU]

In addition the building's actual bills were compared to design team projections, shown in Table G-15. The actual consumption of the building is significantly less (~25%).

Table G-15. RAD-1 Design Team Energy Use Projections

	PROJECTION	ACTUAL
ELECTRICITY [kWh/yr]	449,913	362,160
GAS [therms/yr]	5,795	3,944
Total [kBTU]	2,115,055	1,630,405
EUI [kBTU/ft^2]	58.9	45.4

BUILDING PERFORMANCE

Radiant Building 1 was visited mid December 2013. We met with both building users and maintenance staff. Air temperature, floor temperature, humidity and light levels were measured throughout the building (Table G-16 and Table G-17). We verified that radiant floor heating and cooling was being used– 100% of the building utilizes this technology.

Table G-16. RAD-1 Site Visit Log

SPACE	TEMPERATURE [°F]	RELATIVE HUMIDITY	LIGHT LEVEL [FC]	CO_2 [PPM]	NOTES
Children's Stacks	68.8	27.5%	68.9	505	3 people
Sitting Area	68.6	25.8%	55.4	536	No occupants
Young Adult	68.9	24.2%	35.9	502	3 people, 1 staff
Main Lobby	68.8	22.0%	45.0	520	2 staff
Community Room	68.3	26.7%	26.3	449	2 people, lights off
Periodicals	68.7	22.8%	47.8	498	2 people
Upstairs Stacks	69.6	22.1%	25.4	514	5 people
Conference	70.0	24.9%	56.0	445	Lights on; no people
Outside Conditions	12.0	40.9%	--	430	Sunny

Table G-17. RAD-1 Radiant Conditions

SPACE	SLAB TEMPERATURE [°F]	SPACE TEMPERATURE [°F]
Storytime 128	66.7	70.8
Community Room 130	79.0 (West), 72.4 (East)	69.9
Vestibule 100	78.0	61.6
Entry Lobby 101	62.9 (South), 62.8 (North)	--
Toilets 102/103	77.4	68.2
Storage 108	83.3	66.8
Staff Room 106	77.8 (SE), 65.6 (SW), 66.4 (NW), 80.1 (NE)	66.9
Information Desk 103	66.1	67.2
Break Room 112	81.7	66.2
Director's Office 114	79.8	67.4
Youth Office 126	69.1	70.0
Storytime Storage 129	67.9	--

The maintenance staff and users are very happy with the radiant cooling and heating aspect of the project. It is very comfortable and their project goals for energy, air quality and thermal comfort are being met. When reviewing the HVAC system with the maintenance staff, several key issues were uncovered, some unrelated to the radiant floor system:

1. The mechanical portion of the project was design-build.
2. There are two sets of PEX tubing in the floor – blue for cooling and red for heating. There is no cross-over between the systems. Individual zones can either be in heating or cooling depending on the thermostat feedback.
3. Gaps in the roof insulation and a lack of a vapor barrier caused significant issues with ice dams the first year of operation. The entire roof was replaced in Summer 2012. This is no longer an issue for them.
4. The radiant floor cooling system uses a significant amount of city water to reject heat during cooling mode. Staff told us it is 200-300 gallons during peak summer days. In addition the water filtration and softening system has not worked properly and causes the maintenance staff significant headaches. The maintenance staff in hindsight would have preferred a "closed-loop" heat rejection system and is looking to retrofit the system.
5. A special cooling tower was designed for this facility that is located in the air handling unit – the ventilation air is used to cool. While this type of cooling tower is very common in hot, humid climates it is not very common for cold climates. Maintenance staff have had significant issues with leaks and condensation in the mechanical room. They are looking to disable the cooling tower function of the air handler and install a more typical cooling tower for a cold climate (i.e. outdoor and disabled in the winter).
6. The humidification system was just started in Fall 2013. It hadn't worked previously.

7. While the system is simple on the terminal side, it is quite complicated in the mechanical room and requires sophisticated controls to operate efficiently. Maintenance Staff have learned how to fine tune and operate the system over the past 2 years with a lot of trial and error. They have been well supported by their HVAC service contractor.
8. The project could have benefited from 3rd party commissioning during the design and construction phases. This may have avoided issues with the roof, city make-up-water for cooling, cooling tower configuration and controls.

This is what the library director told us:

> *"We were promised that our new electric bill would be NO higher than our existing facilities electric bill (existing was ~1/3 the size of the new building). We more than doubled our square footage, but our electric bill is the same. We didn't have a gas bill before and now we only have a small, manageable one." – Library Director*

SUMMARY

This project represents a successful application of radiant cooling and heating. Although a number of aspects of the building design contribute to reduced energy use, the majority can be attributed to the radiant heating/cooling technology. The radiant cooling system reportedly handles the load effectively during summer months without producing any condensation problems.

RAD-2

BACKGROUND

Radiant Building 2 is a 10,000 sq-ft office/museum in South Central WI. Figure G-29 shows the entrance of the center. It was completed in 2008. The building includes museum, offices and conference rooms. The center employs 15 employees and has a varying amount of visitors who often are K-12 students and teachers. The center is open Monday through Saturday from 9 am to 5 pm all year.

Figure G-29. RAD-2 Exterior

Project design goals included creating a comfortable and highly energy efficient center at net zero energy usage. The center was willing to invest additional capital for a system that created a highly energy efficient building and worked diligently through the design to come up with the most energy efficient design.

The building envelope is well insulated with traditional operable windows. The building takes full advantage of daylighting with a clerestory along the center (operable). The HVAC system consisted of radiantly heated and cooled floor, displacement ventilations system, ability to take advantage of natural ventilation when conditions are advantageous and a buried outside air intake (earth tubes) to preheat/cool the incoming air. One attached meeting room uses a separate heat pump and ERV to heat, cool and ventilate the space without radiant heating/cooling. In addition there is a wood stove that supplements the heating in winter (average usage of 1 cord of wood, 4x4x8 ft^3 per year) in the main building. The staff noted that the building is slightly cool when the outside air temperature drops below 10°F.

DESIGN INTENT

Ventilation: Ventilation is provided from one main air handling unit with preconditioning in “earth tubes” and supplied to the space at slightly below room temperature. The diffusers are mostly located low on the wall and occasionally in the floor and the air is supplied at low velocities to the space. This configuration allows the ventilation air to stay in the “breathing zone” until heated by a pollution source (people or other heating sources) when it will rise to the ceiling and get exhausted out of the space. The bathrooms and kitchen are exhausted to the outside.

Figure G-30 RAD-2 Diffusers in Offices (On Wall Under Desk) and in Kitchen (in Floor).

Primary Heating and Cooling: Heating and cooling is provided by a geothermal heat pump system that either heats or cools the water for the radiant floor and for the preconditioning of the ventilation air. The domestic hot water is heated by a solar hot water heating system with supplement by the heat pump system. There is also a wood burning stove in the kitchen that supplements the heating of the main space in the winter.

Figure G-31. RAD-2 Heat Pump and Cold/Hot Water Storage.

Power Generation: The building has a 40 kW PV system that is generating electricity. The PV system is generating less energy than was projected.

Lighting: The lighting in Radiant Building 2 revolves around daylighting and task lighting. The general light levels in the building are relatively low with 10-25 foot candles (fc), but higher on work surfaces with task lights (40 to 100 fc).

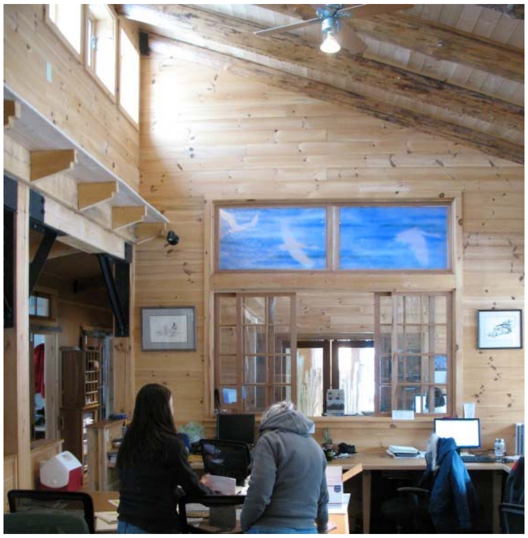


Figure G-32. RAD-2 Clearstory and Work Surface Light.

ENERGY CONSUMPTION

Table G-18 and Figure G-33 and Figure G-34 summarize Radiant Building 2 utility information. Average utility costs for the building are $0.13/kWh. The building was compared to an average building in Target Finder, which predicts that it is performing ~65% better.

Table G-18. RAD-2 Monthly Utility Use

	ELECTRIC USE [kWh]	PV PANEL PRODUCTION [kWh]	NET ELECTRIC CONSUMPTION [kWh]	WOOD[a] [Cord]
JAN	9,040	360	8,680	0.2
FEB	7,920	320	7,600	0.2
MAR	6,920	1,000	5,920	0.2
APR	5,120	1,440	3,680	--
MAY	1,760	3,320	-1,560	--
JUN	880	3,080	-2,200	--
JUL	2,400	3,160	-760	--
AUG	3,000	2,920	80	--
SEP	1,080	3,040	-1,960	--
OCT	3,160	1,400	1,760	--
NOV	5,200	920	4,280	0.2
DEC	5,920	80	5,840	0.2
ANNUAL	**52,400**	**21,040**	**31,360**	**1**

Notes: **a** – Assuming even distribution of wood consumption during coldest winter months.

Table G-19. RAD-2 Benchmarking Performance

	ELECTRIC	WOOD[a]	RAD-2 TOTAL	MEDIAN BUILDING	% SAVINGS
ENERGY USE [kBtu/ft^2/yr]	10.7	2.0	12.7	39.2	**67.6%**
COST [$/ft^2/yr]	$0.39	--	$0.39	$1.49	**73.6%**

Notes: a - Assuming 20 MMBtus per cord

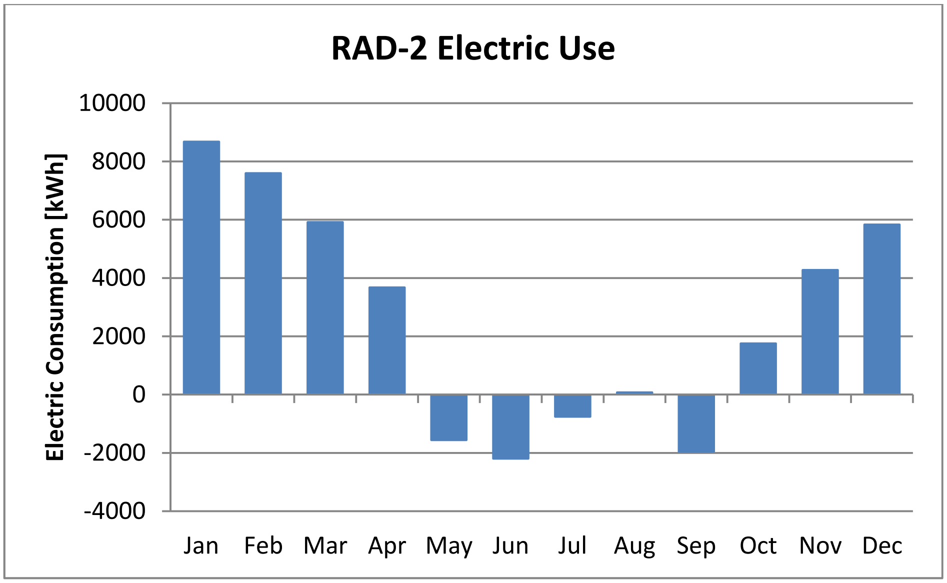


Figure G-33. RAD-2 Monthly Electric Consumption [kWh]. Negative values indicate times when the solar panels generate more than what is consumed.

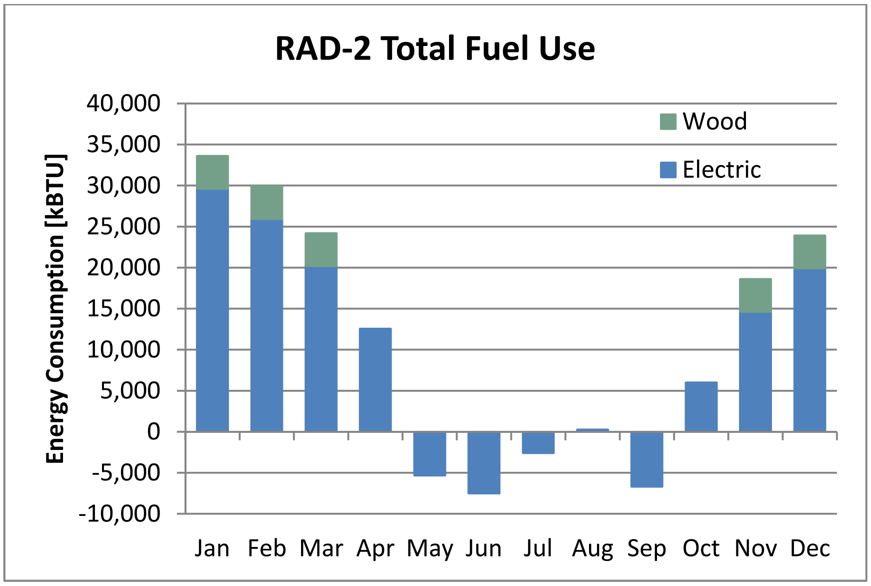


Figure G-34. RAD-2 Total Monthly Energy Consumption [kBTU]

In addition the building's actual bills were compared to design team projections, shown in Table G-20. Individual predictions for electricity and wood use were not available, so EUI was used. The actual consumption of the building is approximately 60% greater than predicted, however that number represents a comparatively small amount of energy.

Table G-20. RAD-2 Design Team Energy Use Projections

	PROJECTION	ACTUAL
ELECTRICITY [kWh/yr]	--	362,160
WOOD [cords/yr]	--	1
Total [kBTU]	78,000	127,005
EUI [kBTU/ft^2]	7.8	12.7

BUILDING PERFORMANCE

Radiant Building 2 was visited early January 2014. We met with the operation and maintenance manager who summarized the comfort level and operation of the building. Air temperature, floor temperature, humidity and light levels were measured throughout the building in different types of spaces (Table G-21).

Table G-21. RAD-2 Site Visit Log

SPACE	TEMPERATURE [°F]	LIGHT LEVEL [FC]	NOTES
Main, Kitchen Bench	72.0	99	Spotlights on bench
Main, Kitchen Counter	71.0	22 – natural light	Radiant heat from wood fireplace
Office 1	67.0	14 – natural light 54 – with task light	--
Cubicle	70.0	11 – Desk 46 – work table	--
Fireplace	68.0	7	--
Next to fire	69.0	17	--
Exhibition	70.0	12	--
Outside Conditions	9.0	--	Partly sunny

Table G-22. RAD-2 Radiant Conditions

SPACE	SLAB TEMPERATURE [°F]	SPACE TEMPERATURE [°F]
Main, Kitchen Counter	72	74
Office 1	72	69
Exhibition	78	70
Overall	72-79	--

Displacement ventilation was utilized in the traditional term with diffusers near or in the floor introduced to the space at low velocities. While the temperature of the ventilation air was set to slightly below room temperature, this loop was unstable and the supply air temperature varied between 60 and 80°F on the day of the visit. The spaces had relatively low lighting levels that were mostly provided by daylight with task lights for desks and other work spaces.

In general the staff is happy with the performance of the building except when the outside air temperature drops below about 10°F when the main space gets slightly cold. The conference space is rarely utilized and therefore not fully heated or cooled when not in use. This space also recovers slowly and might not have sufficient capacity to keep it comfortable at extreme temperature so it is often uncomfortable.

There have not been any major improvements to the building after it was constructed.

SUMMARY

The energy consumption of the building is extremely low and generally meets the energy consumption expectations set forth by the engineers. The PV system does not perform as well as expected which would have made the building energy consumption at or very close to net zero energy. While there are some minor operational issues it is believed that none of them significantly impacts the performance of the building, the displacement ventilation or the radiant floor technologies.

RAD-3

BACKGROUND

Radiant Building 3 (RAD-3) is a ~36,000 ft^2 church in South Central Wisconsin. Figure G-35 shows the interior and exterior of the building. An addition/remodel was completed and occupied in September of 2008 replacing a 3,100 ft^2 section of the building with a 20,000 sq-ft addition that includes a 500-seat auditorium, offices, kitchen, meeting, fellowship, and music rehearsal spaces. Extensive repairs and restoration were also made to the historic building. The new building was awarded LEED-Gold certification in 2009.

This report focuses on this new addition in order to evaluate the benefits and challenges of radiant heating and cooling systems. The energy modeling carried out in support of the LEED^{TM} process was limited to the single story C-wing remodel (1,984 ft^2) and the D-wing new addition (15,412 ft^2 on the lower floor and 3,581 ft^2 on the upper floor). The C-wing consists of four classrooms and a corridor. The D-wing consists of three additional classrooms that adjoin the C-wing classrooms. The largest fraction of the D-wing is made up of an auditorium whose south façade is exposed and two stories tall. Grading on the site is such that the balcony at the rear of the auditorium is at ground level.

Figure G-35. Left: RAD-3 Exterior A & B Wings. **Right:** RAD-3 Exterior C & D Wings

The church is occupied seven days a week from 8 a.m. until 9 p.m. The building accommodates approximately 400 attendees at each of two services on Sunday and 150 during the Saturday Service. The B-wing classrooms serve about 210 during the week while the rest of the building provides office space for about 15.

The new portion of the building is designed to transfer thermal loads via radiant floor heating and cooling, instead of through conventional forced-air systems. A high-efficiency, multiple-stage, water-to-water geothermal heat pump transfers heat to and from a geothermal vertical bore ground circulation loop.

The HVAC system treats and supplies only the code-required amount of outdoor air to occupied spaces. The reduction in air volume transferred around the building means less ductwork and appreciably lower fan energy costs. The decision to transfer thermal loads via radiant floor heating and cooling, instead of through conventional forced-air systems, was a significant factor contributing to the energy performance of the addition.

DESIGN INTENT

Figure G-37. RAD-3 Air Handler AHU-2

Figure G-36. RAD-3 AHU-3 with Energy Recovery Ventilation Wheel

Figure G-38. RAD-3 Underfloor Air Diffuser

Ventilation: There are three ventilation systems in the C and D wings. The first ventilation system (AHU-1) primarily serves the zones along the north side of the lower crossing (restrooms, kitchen, library, and storage). It also provides approximately half of the ventilation air that goes to the lower crossing and a small amount of air to the upper crossings. The AHU-1 air handler delivers 26.7C (80F) air in heating season and 16.7C (62F) air in cooling season. Only the required amount of outdoor air is provided to these spaces; AHU-1 does not have any return air. The thermal loads in these spaces are handled by a radiant floor that heats in winter and cools in summer. AHU-1 is a constant volume device and is located in the north mechanical room (along the north side of the lower crossing). It consists of an outdoor air inlet, a water coil that is hot in winter and cold in summer, and a constant speed supply fan.

The second ventilation system (AHU-2) serves the seven classrooms (four in the C wing and three in the D wing). The air handler delivers 32.2C (90F) air in heating season and 12.8C (55F) air in cooling season. This ventilation system does have a return air side. AHU-2 is a constant volume device.

The third ventilation system (AHU-3) serves the auditorium, balcony, and music suite with 16.7C (62F) air. It also provides the other half of the lower crossing ventilation air. AHU-3 is a variable volume (demand controlled) device, its fan speed modulating based on carbon dioxide sensors. The exhaust side of AHU-3 takes air from the upper portion of the auditorium and passes it across the exhaust side of an energy recovery wheel; the exhaust fan is variable speed. On the supply side, outdoor air first passes through the variable speed supply fan and over the supply side of the energy recovery wheel. The air then passes across a changeover water coil (hot in winter and cold in summer). The coil is supplied with water from the main loop. The supply air is then mixed with an amount of return air (also drawn from the upper portion of the auditorium). In summer, if the mixed air is cooler than 16.7C (62F), an electric reheat coil warms it to 16.7C (62F). Air is delivered to the auditorium via an underfloor air distribution system. During the site visit we measured discharge air flow rates from the auditorium underfloor diffusers at between 2.2 ft/sec and 4.3 ft/sec. No temperature stratification was observed in the auditorium during the site visit.

Primary Heating and Cooling: Two separate heating and cooling systems serve the C and D wings. The classroom zones are heated and cooled exclusively by the AHU-2 ventilation system as described above.

In the public areas (auditorium, lower crossing, music suite, storage, library, kitchen, and restrooms), thermal loads are met by means of radiant floors that are heated in winter and cooled in summer with liquid from the centralized heat pump (WHP-1). The building manager switches the building manually from heating to cooling mode in the early summer and back again in fall. WHP-1 also serves the coils in the various air handlers. The heat pump is a three-stage water-to-water heat pump that can run at either 20 tons, 40 tons, or 60 tons. The temperature of the liquid depends on the heat pump's current capacity given the conditions in the building and on the source side of the heat pump. A constant speed pump (P-2) serves the radiant floors, and the water coils in AHU-1, AHU-2, and AHU-3. WHP-1 takes its source energy from a vertical bore ground circulation loop that consists of 16 boreholes. A constant speed pump (P-1) circulates water through the source loop.

Terminal Heating and Cooling: The radiant heating and cooling system are integrated into the mass floors. Floor temperature is controlled via thermocouples imbedded in the floor.

ENERGY CONSUMPTION

Determining the energy consumption of the new C and D wings required some analysis to separate out the electricity consumed by the old sections of the building. Because no natural gas is supplied to the C and D wings, only electricity is of concern here. The building is supplied through a single electric meter. To separate the electricity attributable to the old portion of the building the pre-construction annual kWh (123,560 kWh, averaged over two years) was divided by square footage (21,800 ft^2) to determine the energy intensity of the original building (5.67 $kWh/ft^2/yr$). This intensity was multiplied by the post-construction square footage of the remaining original building (16,700 ft^2) to determine the electricity attributable to it (94,647 kWh). This amount was then subtracted from the average post-construction annual consumption of the whole building (302,162 kWh) to determine the amount used in the new C and D wings (207,515 kWh). Using data from the pre-construction energy model to further break this down indicates that the HVAC system in the C and D wings (21,000 ft^2) requires approximately 112,000 kWh/year.

Average electricity costs for the church are $0.12/kWh. The new portion of the building (C and D wings only) was compared to an average worship facility in Energy Star Target Finder, which predicts that RAD-3 is performing ~22% better than the median.

Table G-23. RAD-3 Monthly Electricity Use of Whole Building

	PRE-CONSTRUCTION AVERAGE ELECTRIC[a] (2005 & 2006) [kWh]	POST-CONSTRUCTION AVERAGE ELECTRIC (2012 & 2013) [kWh]	ATRIUM NET AVERAGE ELECTRIC USE [kWh]
JAN	10,142	32,471	22,329
FEB	9,667	32,901	23,234
MAR	9,146	28,027	18,880
APR	9,131	27,848	18,717
MAY	8,135	24,151	16,016
JUN	5,852	22,325	16,473
JUL	5,898	21,367	15,468
AUG	5,730	17,909	12,179
SEP	6,833	21,333	14,500
OCT	6,634	18,680	12,046
NOV	8,043	25,127	17,084
DEC	9,437	30,026	20,588
ANNUAL	**94,647**	**302,162**	**207,515**

Notes: a – Corrected for differences in area post-construction (please see text).

Table G-24. RAD-3 Benchmarking Performance

	RAD-3 TOTAL	MEDIAN BULIDING	% SAVINGS
ENERGY USE [kBtu/ft^2/yr]	33.7	43.2	**21.9%**
COST [$/ft^2/yr]	$1.19	$1.52	**22.0%**

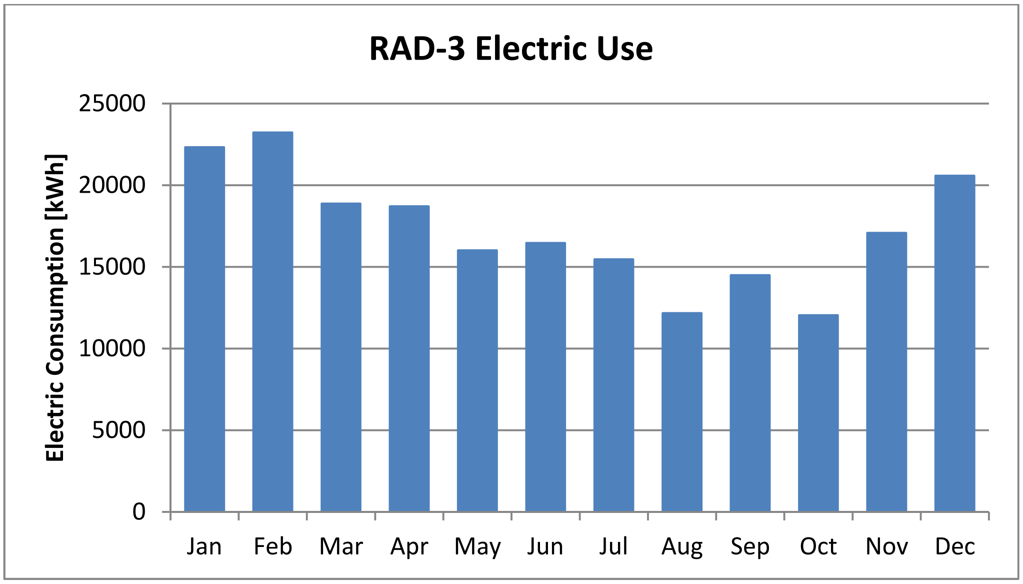


Figure G-39. RAD-3 Monthly Electric Consumption [kWh]

In addition, the actual consumption for the new portion of the building was compared to design team projections, shown in Table G-25. The actual consumption of the building is somewhat less (~15%).

Table G-25. RAD-3 Design Team Energy Use Projections

	PROJECTION	ACTUAL
ELECTRICITY [kWh/yr]	242,550	207,515
TOTAL [kBTU]	827,615	708,071
EUI [kBTU/ft^2/yr]	39.4	33.7

BUILDING PERFORMANCE

Radiant Building 3 was visited mid-January 2014. We met with both building users and maintenance staff. Air temperature, humidity, CO_2 levels and light levels were measured throughout the building (Table G-26). We verified that radiant floor heating and cooling was being used. The building systems consistently maintain temperatures in most spaces between 68 and 72 degrees F. (see exceptions noted below). Light levels were excellent throughout the building with most spaces benefitting from daylighting.

Table G-26. RAD-3 Site Visit Log

SPACE	TEMPERATURE [°F]	RELATIVE HUMIDITY	LIGHT LEVEL [FC]	CO_2 [PPM]
Corridor	68	20%	--	622
Auditorium	72	16%	26 – Natural light	550
Upper Balcony	69	19%	--	543
Director	64	25%	--	880
Gaebler	66	--	--	627
Office 1	69	--	--	666
Office 2	70	--	--	627
Old Landmark	70	--	--	550
B-wing Classroom	71	--	--	1052
B Entry	70	--	--	1127
Classroom	69	--	--	1172
Kitchen	68	31%	--	726
Childcare Class[a]	69	18%	50	547
C-wing Class 1[a]	70	18%	87	602
C-wing Class 2[a]	69	18%	--	609
Radiant Floor Temps	66-87	--	--	--

Notes: **a** – AHU-2, no radiant floor in these areas.

The maintenance staff and users are reasonably happy with the radiant cooling and heating aspect of the project (see exceptions noted below). It is generally comfortable and most of their project goals for energy, air quality and thermal comfort are being met. The site visit and discussions with the building manager yielded several points worth noting:

1. During periods of extreme cold, the multi-stage heat pump compressors (WHP-1) can overheat and trip their thermal protection switch. The spaces can drop to 63 degrees under these circumstances. This should be investigated further. In the past some engineers have suggested that the addition of a buffer tank for the supply water loop could help.
2. Night setback has not been implemented because the radiant floor system has a slow response time to setpoint and load changes.
3. The building manager must manually control the outdoor air ventilation dampers in the auditorium wall if additional ventilation is desired during periods of favorable weather. This is rarely done and the dampers leak cold air in the winter suggesting that they are of questionable benefit.

4. The CO_2 levels in the C & D wings were consistently between 500 and 750 ppm except for the B wing classrooms where readings as high as 1200 ppm were observed. The air handler for this zone has a history of problems with rusting ducting to the OA intake.
5. During cold weather the connecting upper corridor between the D wing and the B wing is very cold (64 degrees measured). The space is heavily glazed and has uninsulated steel beams that are very cold.
6. AHU-1 serving the kitchen, restrooms, library, and storage was not enabled at the time of the site visit. The building seems to be meeting these loads with the radiant floor and AHU-3 due to the open floor plan of the building.

SUMMARY

This is a successful project and a good application of radiant cooling and heating. Many aspects of the building design contribute to the reduced energy use, but a significant portion can be attributed to the radiant heating/cooling technology. While there are definitely some open issues related to temperature control under changing and very cold conditions, the building is meeting or exceeding energy and air quality goals. The building would likely benefit from a re-commissioning of the radiant heating system and control sequences to address the thermal comfort problems. The radiant cooling system reportedly handles the load during the summer months without significant floor condensation problems.

VRF-1

BACKGROUND

VRF Building 1 is an approximately 29,000 ft^2 office building in southwest Wisconsin. This building is 100 percent heated and cooled by a VRF system. Figure G-40 shows the exterior of the building. The building was designed in 2007 and constructed in 2010. The office space includes a combination of open and private offices, conference rooms, kitchenettes/break rooms, IT rooms, and miscellaneous spaces. There is also a 2,500 ft^2 community room that is used for large meetings and public gatherings. The building is occupied by approximately 60 people 8:00a – 4:30p, M – F.

Figure G-40. VRF-1 Exterior

DESIGN INTENT

Figure G-41. VRF-1 Rooftop Unit With ERU

Ventilation: Ventilation is provided from two, 100 percent Dedicated Outdoor Rooftop Units with energy recovery. One unit is for the main building (3,400 cfm) and the second is for the community room (1,500 cfm). The units operate continuously 24/7. The units have gas-fired heating and DX cooling. The ventilation air is generally ducted to the return side of the fan coil units, but there are some dedicated ventilation air diffusers as well. The rooftop units are located in two penthouses, where the air-cooled condensing units are.

Figure G-42. VRF-1 Air-Cooled Condensing Units

Primary Heating and Cooling: Primary heating and cooling consists of six 10-ton and one 12-ton air cooled condensing units with 3-pipe heat recovery. The condensers are located inside a mechanical room with one ducted exhaust louver and one intake louver. There are no motorized dampers installed on the louvers, so the louvers are always open to the outside air. There are gas-fired unit heaters to maintain the penthouse room temperature. The setpoints are anywhere between 0 and -20°F.

Figure G-43. VRF-1 Ductless Fan Coil Unit

Terminal Heating and Cooling: The VRF terminal units are a mix of ductless and ducted fan coil units distributed throughout the building. Typical fan coil units supply heating and cooling to two to three offices and are controlled by wall mounted control panels.

The mechanical engineer for the project commented that a VRF system was selected for its predicted energy savings (modeled to be 30 percent better than a baseline system with traditional VAV reheat system), which lined up with the client’s goals. Additionally, the difference in the proposed and baseline system costs was almost negligible because refrigerant pipes are smaller than ductwork, and the floor-to-floor height was reduced. So although the VRF system cost slightly more than the baseline system, the structure and envelope savings offset the costs.

> *“The two systems (baseline and proposed) were virtually identical in cost because the VRF system allowed us to decrease the floor-to-floor height by 8 inches per floor and this resulted in envelope cost savings that offset the added VRF costs.”*
>
> - *VRF Building 1 Mechanical Engineer*

ENERGY CONSUMPTION

Table G-27 and Figure G-44 and Figure G-45 summarize VRF Building 1 utility information. The building was evaluated in Energy Star Target Finder, which calculates a site energy use intensity of 39.1 kBTU/sf/yr. This indicates the building is performing approximately 37 percent better than a median comparable property. The Target Finder score was 84 out of a possible 100.

Table G-27. VRF-1 Monthly Utility Use

	ELECTRIC [kWh]	GAS [therms]
JAN	41,520	148
FEB	40,080	150
MAR	32,800	30
APR	24,640	27
MAY	19,760	25
JUN	18,560	22
JUL	19,760	23
AUG	20,240	23
SEP	18,160	21
OCT	19,120	23
NOV	26,000	26
DEC	35,360	29
ANNUAL	**316,000**	**544**

Table G-28. VRF-1 Benchmarking Performance

	ELECTRIC	GAS	VRF-1 TOTAL	MEDIAN LIBRARY	% SAVINGS
ENERGY USE [kBtu/ft^2/yr]	37.18	1.88	39.1	62.0	**37.0%**
COST [$/ft^2/yr]	$1.02	$0.02	$1.04	$1.60	**34.7%**

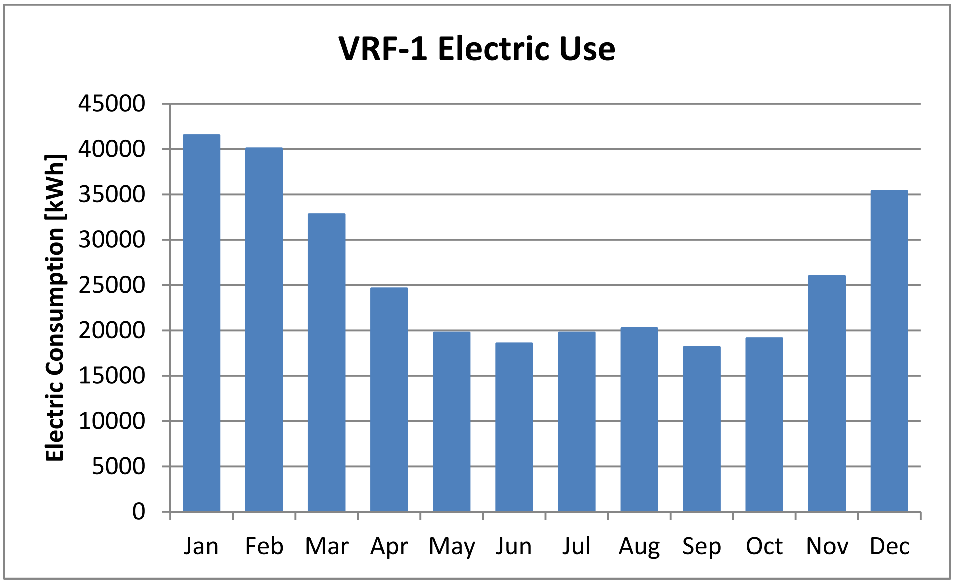


Figure G-44. VRF-1 Monthly Electric Consumption [kWh]

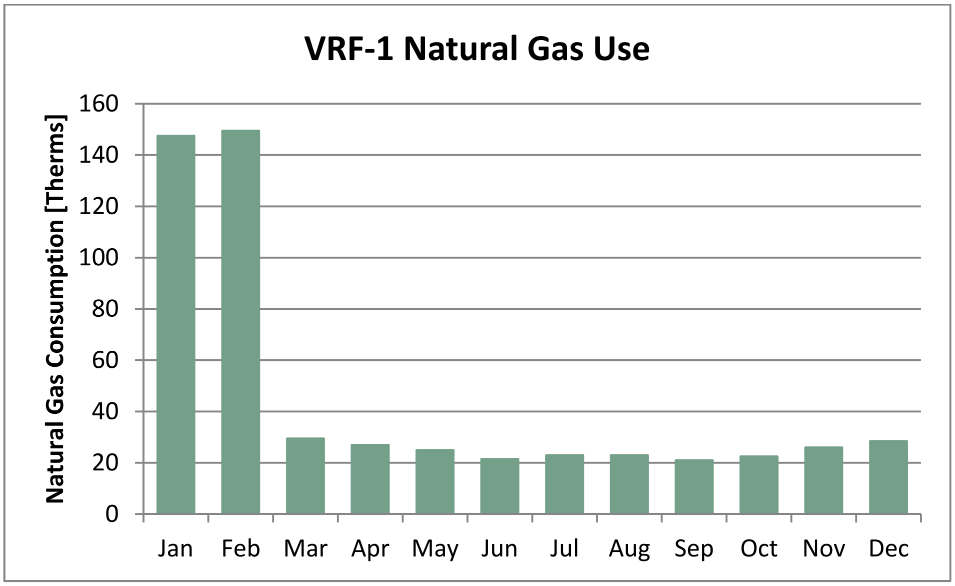


Figure G-45. VRF-1 Monthly Gas Consumption [Therms]

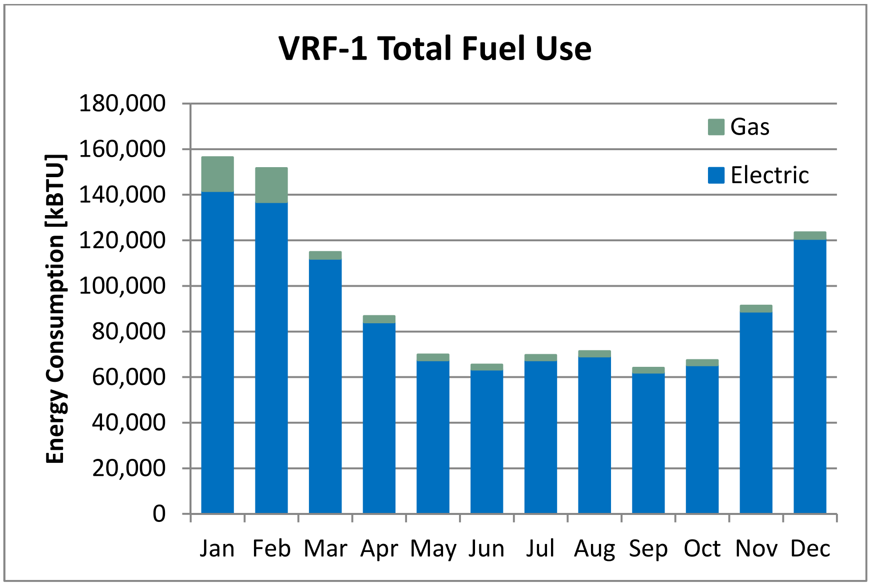


Figure G-46. VRF-1 Total Monthly Energy Consumption [kBTU]

In addition the building's actual bills were compared to design team projections, shown in Table G-29. The actual consumption of the building is slightly less (~3%).

Table G-29. VRF-1 Design Team Energy Use Projections

	PROJECTION	ACTUAL
ELECTRICITY [kWh/yr]	280,333	316,000
GAS [therms/yr]	2,135	544
Total [kBTU]	1,170,179	1,132,673
EUI [kBTU/ft^2]	40.4	39.1

BUILDING PERFORMANCE

VRF Building 1 was visited early January 2014. We met with building occupants and the operator. Air temperature, humidity, CO_2, and light levels were measured throughout the building (Table G-30). We verified that 100 percent of the building utilizes VRF for heating and cooling, with the exception of a few electric heaters in vestibules, stairways, and mechanical/storage rooms.

Table G-30. VRF-1 Site Visit Log

SPACE	TEMPERATURE [°F]	RELATIVE HUMIDITY	LIGHT LEVEL [FC]	CO_2 [PPM]	EXHAUST?
1024 – Kitchenette	69.0	20%	60	500	Y
2326 – Office	72.5	17%	70	775	N
2312 – Office	72.8	16%	95	735	N
2002 – Conference	73.4	15%	155	610	N
2004 – Kitchenette	73.0	15%	70	560	Y
2001 – Conference	72.2	15%	70	550	N
2011 – Storage	71.8	16%	30	610	N
2207 – Work Space	71.8	16%	70	660	N
1002 – Conference	71.3	16%	125	550	N
1203 – Office	70.9	16%	75	590	N
1206 – Storage	71.1	16%	35	630	Y
1211 – Office	70.8	19%	60	585	N
1015 – Copy	71.0	16%	45	560	Y
1101 – Exterior Community Room	70.6	16%	105	500	Y
1101 – Interior Community Room	70.7	16%	145	510	Y
1004 – Conference	70.7	15%	30	480	Y
1303 – Office 1301	70.9	17%	80	565	N
Outside Conditions	36.0	35%	--	--	--

The operator and occupants are generally content with the VRF system overall in terms of comfort, maintenance requirements, and operating costs. This operator's experience was that very little maintenance was necessary. Routine filter changes (every 3 to 4 months) and cleaning the condenser coils have been the biggest maintenance items. The key findings regarding the VRF system include:

1. The building operator noted that it took about a year after construction to get the setpoints in a good spot for year-round occupant comfort, especially as some building envelope issues were fixed in the first year (such as better air sealing around window sills). It is generally cooler near windows and warmer in the interior, but space temperature measurements showed this variance was a reasonable level.
2. The mechanical rooftop penthouse where the air-cooled condensing units are located does not have motorized dampers installed on the outside air louvers, so the space is essentially maintained at the outside air temperature. There are gas-fired unit heaters to maintain the penthouse temperature with setpoints between 0 and -20°F, while the condensers appear to have a minimum ambient operating temperature of 0°F. As a result, the unit heaters rarely run (this area of Wisconsin experiences approximately 4%

of its total annual hours less than 0°F according to TMY data), increasing electrical use and decreasing natural gas use. Further investigation on the proper setpoint for the penthouse space temperature is suggested.

The following are performance recommendations for VRF Building 1:

1. **Implement an occupancy schedule or controls on the rooftop/energy recovery ventilation units.** The rooftop/energy recovery ventilation units are currently operating continuously 24/7. Since these are dedicated outside air units, these only need to operate when the building is occupied. The main building with offices is typically occupied 8:00a – 4:30p, Monday through Friday. The community room is occupied about half the time during the normal weekdays, and is sometimes used during evenings and weekends. The original design specifications suggest operating the main building ventilation unit on an occupancy schedule, and the community room ventilation unit based on a signal from the A/V control panel. This would save significant amounts of energy due to reduced heating/cooling of the ventilation air and reduced fan runtime.

Figure G-47. Panoramic View of the VRF-1 Community Room that is Typically Ventilated Continuously.

2. **Investigate the cause of rooftop/energy recovery ventilation unit trip-outs.** During our site visit, both ventilation units were tripped out and the operator acknowledged that they do need to be reset occasionally. It was not evident what caused this during the site visit.

3. **Install motorized dampers on the outside air louvers in the penthouse.** This measure would close the dampers when the outside air temperature is below a setpoint (perhaps 5 to 10°F warmer than the gas-fired unit heater setpoints). A recirculation damper would open and create a closed room for the air-cooled condensing units to operate in. When the gas-fired unit heaters operate, the heated air would

Figure G-48. Outside Air Intake Louvers in the VRF-1 Penthouse.

be conserved in the space instead of allowing some of it to escape through the louvers. In this building, one important aspect that would have to be done is to extend the energy recovery unit exhaust ductwork. This exhaust duct currently terminates inside the penthouse. It would need to be routed to an appropriate location outside of the penthouse.

Figure G-49. VRF-1 Thermostat Located Behind a Copy Machine that Emits Significant Heat.

4. **Investigate fan coil unit operation and thermostat locations.** During the site visit, a review of the setpoints, space temperatures, and heating/cooling modes at the main control screen revealed that fan coil units appear to be overshooting setpoints by 5°F or more in several spaces. It was unclear whether the fan coil units were being controlled by the wall thermostat temperature sensors or the return air temperature sensors. This type of VRF system can be configured to use either the wall sensor or the return air sensor, and there seem to be instances throughout the building where each gets used. The ductless units seem to recirculate some supply air back into the return air stream, which might be a good case for the wall sensors. However, some wall thermostats were observed in poor locations (for example, behind a large copy machine), which may lend a benefit to using the return air sensors in some spaces.

5. **Investigate correct operation of existing lighting controls and install lighting controls in areas with ample daylight.** The lighting throughout the building is generally T-8 fluorescent or compact fluorescent, which are both efficient options, and most offices and conference rooms utilize occupancy sensors. However, the occupancy sensors in the community room did not seem to turn off the lights when unoccupied during the visit, and some private office occupancy sensors were vulnerable to activation by passersby in the hallway. Another area of possible improvement is that many areas throughout the building were observed with abundant daylight and the lights were on. Light levels in these areas were measured to be 100 to 150 foot-candles, which is pretty high. The addition of daylighting controls would reduce this lighting energy.

SUMMARY

Office buildings tend to be prototypical applications for VRF systems with 3-pipe heat recovery due to the natural simultaneous heating and cooling conditions that can exist. Given that this VRF system was designed in 2007 and the overall energy utilization intensity is 37 percent better than a median comparable building, this office building has been a successful application of VRF technology. There are still some improvements that can be made to reduce energy consumption (as outlined in the building performance recommendations), but the operator reports that operation and maintenance costs have been very low and occupants are generally comfortable.

VRF-2

BACKGROUND

VRF Building 2 is an approximately 47,500 sq-ft mixed use office and warehouse building in south-central Wisconsin. This building includes approximately 11,000 sq-ft of office space heated and cooled by a VRF system. The remainder of the building is warehouse (material storage, garage space, and shop space) heated by gas-fired unit heaters (no cooling). Figure G-50 shows the exterior of the building. The building was originally built in the 1940s, and the interior has been renovated for new uses over the years. The office renovation involving the VRF system was constructed in 2009. The remainder of the mechanical systems serving the warehouse and garage spaces are from the previous renovation in 1995. The office space includes a combination of open and private offices, conference rooms, kitchenettes/break rooms, a central filing/mail room, IT/computer rooms, and miscellaneous spaces. The office space is occupied by approximately 22 people 7:00a – 5:00p, Monday – Friday.

Figure G-50. VRF-2 Exterior

DESIGN INTENT

Ventilation: Ventilation is provided from a single, 100 percent Dedicated Outdoor Air Handler with energy recovery. The unit provides a constant volume of approximately 1,300 cfm of ventilation, and is controlled on an occupancy schedule. There was initially an electric duct heater for supplemental heat, but the operator has disabled it. The ventilation air is generally ducted to the return side of the fan coil units. The air handler is located in the basement mechanical room.

Figure G-51. VRF-2 Air Handler

Primary Heating and Cooling: Primary heating and cooling consists of two 10-ton air cooled condensing units with 3-pipe heat recovery. The condensers are located inside a mechanical room with one ducted exhaust louver and one intake louver. Motorized dampers were retrofitted to the louvers after construction. These dampers are open to the outside air when the outside air temperature is above 55°F. The intake and exhaust dampers close and a recirculation damper opens when the outside air temperature is below 55°F. The mechanical room is maintained at 50°F by a gas-fired unit heater.

Figure G-52. VRF-2 Air-Cooled Condensing Units

Terminal Heating and Cooling: The VRF terminal units are a mix of ductless and ducted fan coil units distributed throughout the office space. Typical fan coil units supply heating and cooling to two to three offices and are controlled by wall mounted control panels. The control panels have been locked out for adjustment by the occupants and only the building operator can adjust heating, cooling, and airflow setpoints. Perimeter heating is supplemented by electric baseboard heaters with on-board thermostats.

Figure G-53. VRF-2 Ductless Fan Coil Unit

ENERGY CONSUMPTION

Table G-31 and Figure G-54 and Figure G-55 summarize VRF Building 2 utility information. A 6.8 kW solar photovoltaic system produces about 8,000 kWh per year for the building. The building was evaluated in Energy Star Target Finder, which calculates a site energy use intensity of 31.8 kBTU/sf/yr. This indicates the building is performing approximately 45 percent better than a median comparable property (23% office / 77% warehouse). The Target Finder score was 85 out of a possible 100. This optimistic result is likely influenced by the large (uncooled) warehouse floor area relative to the office area.

Table G-31. VRF-2 Monthly Utility Use

	ELECTRIC [kWh]	GAS [therms]
JAN	24,000	1,931
FEB	20,840	1,840
MAR	19,480	1,398
APR	15,080	676
MAY	11,840	125
JUN	9,640	79
JUL	10,560	51
AUG	10,960	43
SEP	10,160	61
OCT	12,160	302
NOV	14,520	1,083
DEC	22,480	1,330
ANNUAL	**181,720**	**8,919**

Table G-32. VRF-2 Benchmarking Performance

	ELECTRIC	GAS	VRF-2 TOTAL	MEDIAN BUILDING	% SAVINGS
ENERGY USE [kBtu/ft^2/yr]	13.1	18.8	31.8	54.9	**42.0%**
COST [$/ft^2/yr]	$0.52	$0.13	$0.65	$1.12	**42.0%**

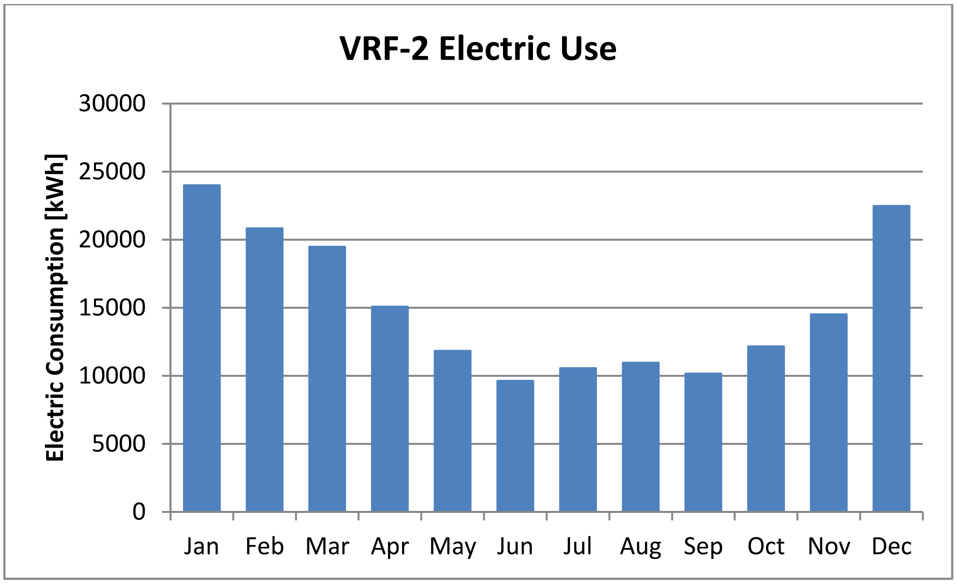


Figure G-54. VRF-2 Monthly Electric Consumption [kWh]

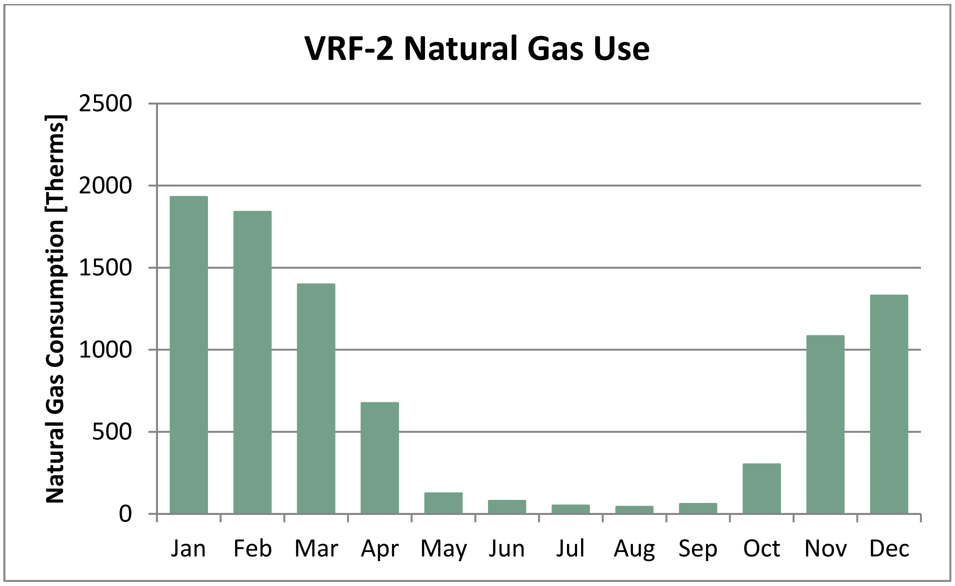


Figure G-55. VRF-2 Monthly Gas Consumption [Therms]

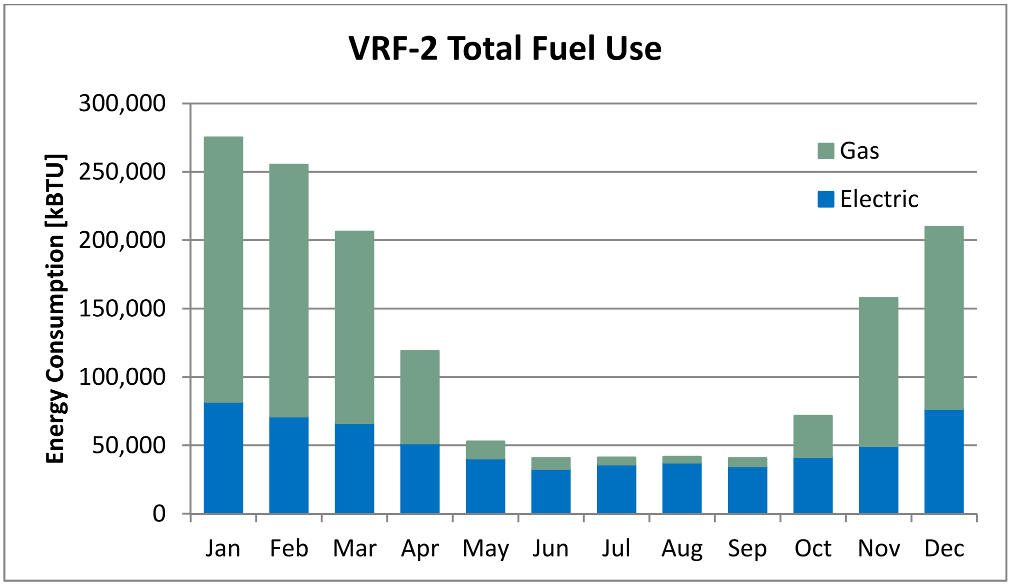


Figure G-56. VRF-2 Total Energy Consumption [kBTU]

BUILDING PERFORMANCE

VRF Building 2 was visited early January 2014. We met with building occupants and the operator. Air temperature, humidity and light levels were measured throughout the building (Table G-33). We verified that 100 percent of the office space utilizes VRF for heating and cooling.

Table G-33. VRF-2 Site Visit Log

SPACE	TEMPERATURE [°F]	RELATIVE HUMIDITY	LIGHT LEVEL [FC]	EXHAUST?	COOLING?
121 – Mall Rm	71	14%	30 - general 110 - table	N	Y
103 – Mech Rm	52 – 60	10%	--	N	N
122 – Open Office	70 - 73	10-15%	48	N	Y
111 – Kitchenette	67	12%	90	N?	Y
113 – Men's Bathroom	68	10%	70	Y	Y
119 – Staging	70	13%	30	N	Y
128 – Locker Room	68	13%	60	Y	Y
135 – Office	64	10%	80	N	Y
Material Warehouse	60	25%	10	N	N
Small Truck Rom	53	20%	5	Y	N
Large Truck Room	60	24%	12	Y	N
108 – Office	70	13%	70	N	Y
133 – Office	70	13%	70	N	Y
127 – SCADA	77	11%	--	N	Y
125 – Community Room	70	11%	--	N	Y
Outside Conditions	0.0	10%	--	--	--

The operator and occupants are generally content with the VRF system overall in terms of comfort, maintenance requirements, and operating costs. When reviewing the VRF system with the staff several key findings were uncovered:

1. The VRF portion of the mechanical work was design-build, and the building operator reported that the design-build mechanical contractor's startup/commissioning did not result in optimal operation. The operator's experience with a VRF system working efficiently and as intended is that correct startup and commissioning in construction and ongoing outside assistance (a knowledgeable service contractor and/or engineer) during operation are needed. This results in some operating savings turning into maintenance costs.
2. The mechanical room where the air-cooled condensing units are located are being maintained at the outside air temperature when in cooling mode (when outside air temperature is above 55°F) and maintained at 50°F by a gas-fired unit heater when in heating mode (when outside air temperature is below 55°F). This is probably warmer than the ideal temperature for the condensers to operate the most efficiently or cost effectively (it does not appear this was calculated or specified during design). However, this mechanical space contains domestic water piping (this piping pre-exists the VRF

renovation) and there has been a case in the past of freeze damage. This freeze event initiated the installation of the dampers on the outside air louvers, a temperature-controlled heat trace system on the domestic water piping, and the unit heater setpoint of 50°F. Although operating the mechanical space cooler than 50°F may be more efficient or cost effective, it would result in greater energy use from the heat trace and increase the risk of another freeze event. This is an example illustrating that domestic water piping should not be located in the same mechanical room as condensing units. In this case, the domestic water piping pre-exists the mechanical work and would have had to be re-located to enable the condensers to operate at a cooler temperature. Where domestic piping is necessary in the mechanical space for periodically cleaning the condenser coils, a frost-free hydrant can be used.


Figure G-57. VRF-2 Domestic Water Piping with Heat Trace and Controls.

Performance Recommendations for VRF Building 2 are:

1. **Electric perimeter baseboard heating should be used as minimally as possible.** A pair of private offices on one VRF fan coil unit were examined and it was found that there was some simultaneous heating and cooling as the electric perimeter baseboard heaters were interfering with the operation of the VRF fan coil units. One office was warm (74°F) and the other was cool (68°F). The warm office is where the fan coil unit thermostat was located, and this office had its electric baseboard heater turned to maximum heat on its independent thermostat. This caused the office to become warm and the fan coil unit to shift into cooling mode. The cooler office had its electric baseboard unit turned to medium heat and the fan coil unit subsequently over-cooled that space.


Figure G-58. Typical Electric Baseboard Heater in VRF-2 with Onboard Thermostat.

2. **Investigate air balancing and thermostat locations and calibration.** A private office in the front of the building was found to be cold (64°F) during the site visit. The discharge air temperature of the diffuser was measured at 64°F. The occupant runs an electric space heater under the desk. Upon review of the balance report, it appears the ventilation air to this space was not balanced. This office is relatively close to the

energy recovery ventilator and could be receiving too much ventilation air. With the outside air temperature at 0°F during the visit, this could explain the space becoming over-cooled beyond what the fan coil unit was able to capacitate. A thermostat location or calibration issue could be a likely explanation for this as well.

3. **Repair energy recovery unit wheel.** The energy recovery unit was discharging 0°F air during our visit (the outside air temperature was 0°F). This was causing occupant discomfort and so the ERV typically gets turned off during this type of weather. It was observed that the wheel was stopped while the fans were running. The operator was notified. With the wheel running, ventilation air should be discharged to the building at a much more moderate temperature.
4. **Investigate jogging control for energy recovery unit.** The energy recovery unit normally runs during occupied hours and during this time the wheel runs at 100% speed. It was observed that the manufacturer of this unit offers an optional jogging control for economizing. An office building like this can see significant cooling loads when outside air temperatures are approximately 40 to 60°F. When the wheel runs at 100%, the unit's discharge air temperature may be warm enough that it is missing the opportunity to add free cooling to the building that it could have achieved by jogging the wheel.
5. **Adjust CRAC unit setpoint.** The computer room air conditioning (CRAC) unit serves an IT room with a fair amount of server equipment. The current cooling setpoint is 68°F, which results in a measured temperature of 75°F at the warmest point in the room. An email alarm to the IT manager is generated when the space temperature reaches 85°F. Since a lower setpoint does not necessarily result in more notice or more time for the IT manager to respond to a possible problem, it is suggested to adjust the cooling setpoint to approximately 72 to 75°F.
6. **Use warehouse unit heaters for heating when ventilation is not required.** The warehouse space gets used as vehicle storage, material storage, and general shop space for the facility's operations. It was observed that a gas-fired ventilation unit was running to heat part of the warehouse where an employee was working. Heating ventilation air consumes much more energy than heating the indoor air, so it is suggested that unit heaters are used for keeping the space heated. The ventilation units should only run when ventilation is needed, such as when vehicles are running and producing exhaust, or fumes are produced from work being performed in the shop (such as painting, etc.). To assist with this, automatic controls could be added to the ventilation units to update them with modern control strategies, such as NO_2 and CO sensors. The existing controls are basically manual.
7. **Install a dedicated exhaust fan in office kitchenette.** Significant food odors were produced in the office kitchenette, and these odors spread quickly throughout other spaces in the office. Occupants confirmed this was typical. Upon reviewing the drawings, it appears this space was intended to be exhausted by sharing the exhaust system with the women's bathroom, which is immediately next to the kitchenette. The women's bathroom would be under a negative pressure, and the kitchenette air would be drawn into the bathroom via a door grille. However, this door grille was never

installed, and given the air balancing questions in other parts of the building, it is recommended that a dedicated exhaust fan is installed. There is an existing exhaust grille in the ceiling of the kitchenette, but the operator believes this is a remnant from previous renovations, and this was abandoned in 2009.

SUMMARY

With the persistence of the building operator and service contractor, this has turned into a successful project and a good application of VRF cooling and heating. There are still some improvements that can be made to reduce energy consumption (as outlined in the building performance recommendations), but the building seems to be functioning reasonably well considering it was one of the first of its kind in the region when it was installed in 2009.

VRF-3

BACKGROUND

Variable Refrigerant Flow Building 3 (VRF-3) is a ~16,000 sq-ft single story office building in central Wisconsin. Figure G-59 shows the exterior of the building. It was completed in 2012 and occupied in the fall of that year. The building includes a reception area, open and private offices, conference rooms, storage rooms, a break room, and restrooms. Approximately 43 people work in this office five days per week, 10 hours per day. The building is pursuing LEED Silver certification and includes a high performance envelope and lighting system along with the advanced HVAC system.

Five different technologies were considered for space conditioning including geothermal. The VRF system was selected for its cost competitiveness (within \$1/ft^2 of rooftop VAV with hot water reheat) and its efficiency.

Figure G-59. VRF-3 Exterior

DESIGN INTENT

The primary means of heating, cooling, and ventilating the building is provided by a Variable Refrigerant Flow (VRF) system served by two 18-ton heat recovery units HR-1 and HR-2, combined with an Energy Recovery Ventilator (ERV). Figure G-60 below is a general schematic of the mechanical systems serving the building and illustrates how the air distribution system is connected to the other mechanical systems.

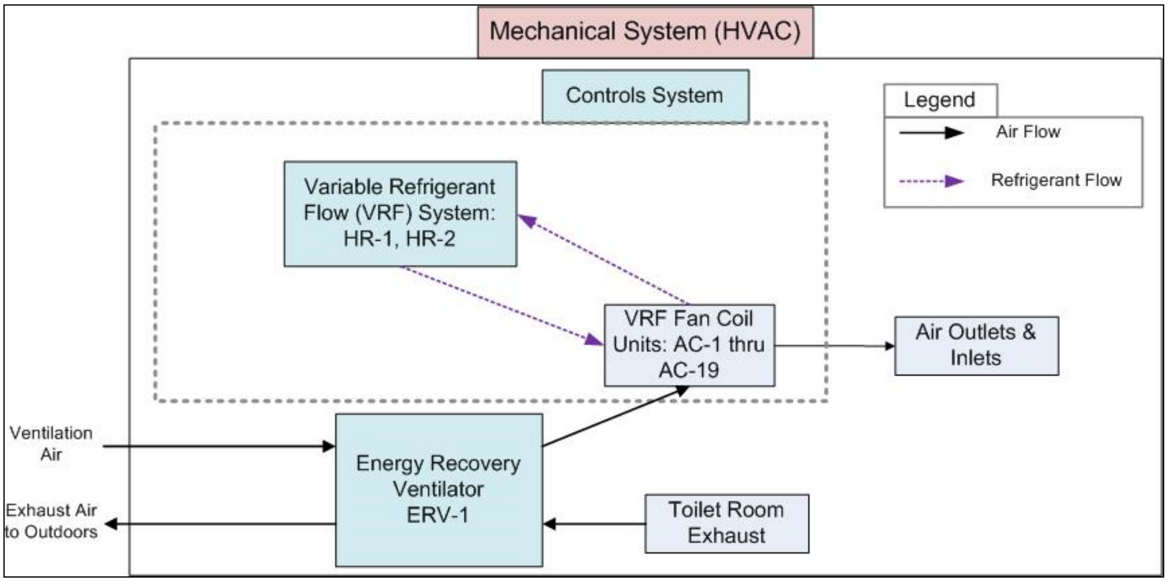


Figure G-60. VRF-3 Overview of Mechanical System

Ventilation: The Energy Recovery Ventilator (ERV-1) provides ventilation air to the entire building, exhausts toilet room air to the outdoors, and recovers a significant portion of the heat energy from the exhaust air to the ventilation air (Figure G-61).

This unit is provided with a belt driven supply air fan, belt driven exhaust air fan, and a static plate heat exchanger. The fan motors are connected to variable frequency drives (VFDs) that regulate fan speeds as necessary to maintain the proper amount of ventilation air and a slightly positive building pressure. The duct-mounted static pressure sensor is used to determine when the fan speed can be reduced. As duct static pressure increases, the fan speed is decreased to maintain a constant duct static pressure setpoint.

Figure G-61. VRF-3 Energy Recovery Ventilator (ERV-1)

The ERV is also provided with 2-inch thick filter banks in both the supply and exhaust air streams to remove particulates and keep the heat exchanger media clean.

The energy recovery ventilator is programmed to operate only during occupied times.

Primary Heating and Cooling: Two 18-ton heat recovery units HR-1 and HR-2 (Figure G-62) are located in the semi-conditioned Mechanical Room 28A. These units reject heat in the cooling mode, and add heat in the heating mode via refrigerant lines connected to indoor fan coil units. In the winter, heat is provided to the mechanical room via two suspended gas-fired unit heaters to maintain the space at 28 degrees F.

Figure G-62. VRF-3 Heat Recovery Unit

There are two roof-mounted exhaust fans (EF-2 and EF-3) that serve the Mechanical Room. These exhaust fans along with the air intake damper and the exhaust air dampers are controlled to reject heat to the outdoors as the space temperature climbs above the various space temperature setpoints. Figure G-64 below is a one-line diagram of the VRF system.

Figure G-63. VRF-3 Typical Ducted Fan Coil Unit

Terminal Heating and Cooling: After leaving the energy recovery ventilator, the ventilation air flows through ducts to various zones served by fan coil units (Figure G-63) that operate continuously during occupied times. Before being delivered to the spaces, the ventilation air is mixed with return air and then passed through fan coil units equipped with variable refrigerant coils. The coils are capable of both heating and cooling. The purpose of the fan coil units is to further adjust the volume and temperature of the air entering the spaces to meet the zone thermostat setpoints while also delivering the required ventilation air to the spaces. When the zone space is warmer than the setpoint, the BC Controller box – located above the ceiling in Storage Room 21 – will energize to allow refrigerant flow in the cooling mode. When the zone space is cooler than the setpoint, the BC Controller box will energize, enabling the fan coil unit to the heating mode. Each fan coil unit is served by wall mounted thermostat.

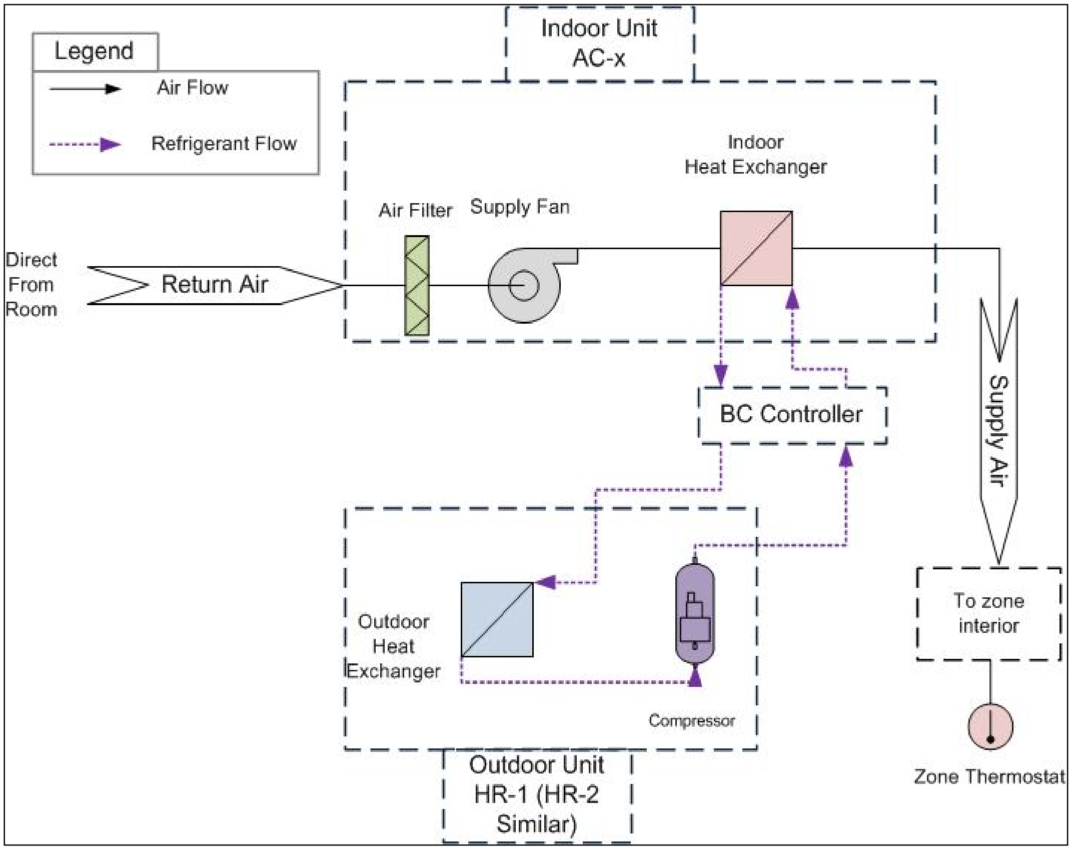


Figure G-64. One Line Diagram of the VRF-3 System

ENERGY CONSUMPTION

Table G-34 and Table G-35, and Figure G-65 and Figure G-66 summarize VRF Building 3 utility information. Average utility costs for the office are $0.11/kWh and $1.07/therm. The building was compared to an average building in Energy Star Target Finder, which predicts that it is performing ~14% better than the median.

Table G-34. VRF-3 Monthly Utility Use

	ELECTRIC [kWh]	GAS [Therms]
JAN	26080	143
FEB	24960	211
MAR	23600	138
APR	22240	80
MAY	20320	7
JUN	15280	2
JUL	14560	1
AUG	17920	1
SEP	18400	1
OCT	16800	2
NOV	18160	3
DEC	25360	73
ANNUAL	**243,680**	**663**

Table G-35. VRF-3 Benchmarking Performance

	ELECTRIC	GAS	VRF-3 TOTAL	MEDIAN OFFICE	% SAVINGS
SITE ENERGY USE [kBtu/ft^2/yr]	52.5	4.2	56.7	67.8	**16.4%**
COST [\$/ft^2/yr]	\$1.69	\$0.04	\$1.73	\$2.07	**16.4%**

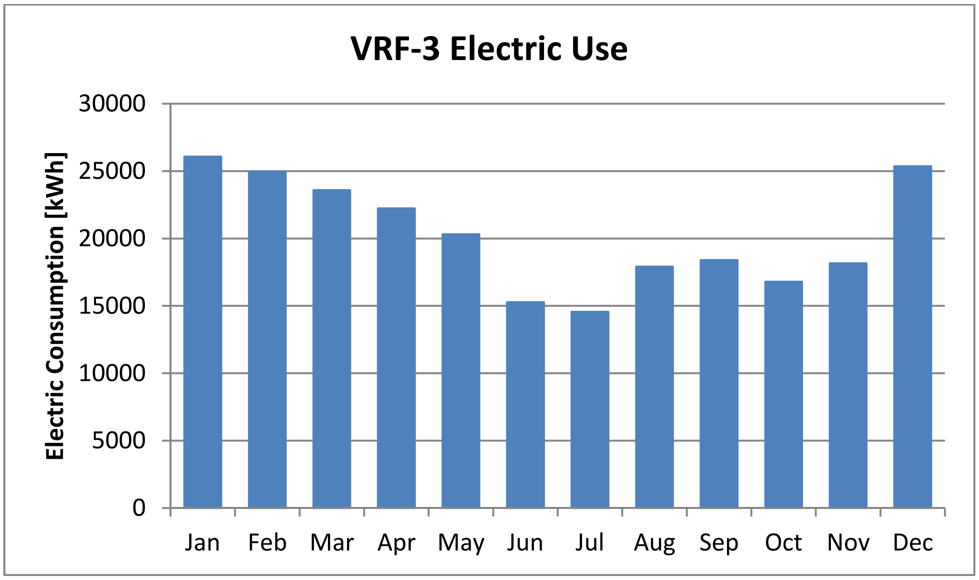


Figure G-65. VRF-3 Monthly Electric Consumption [kWh]

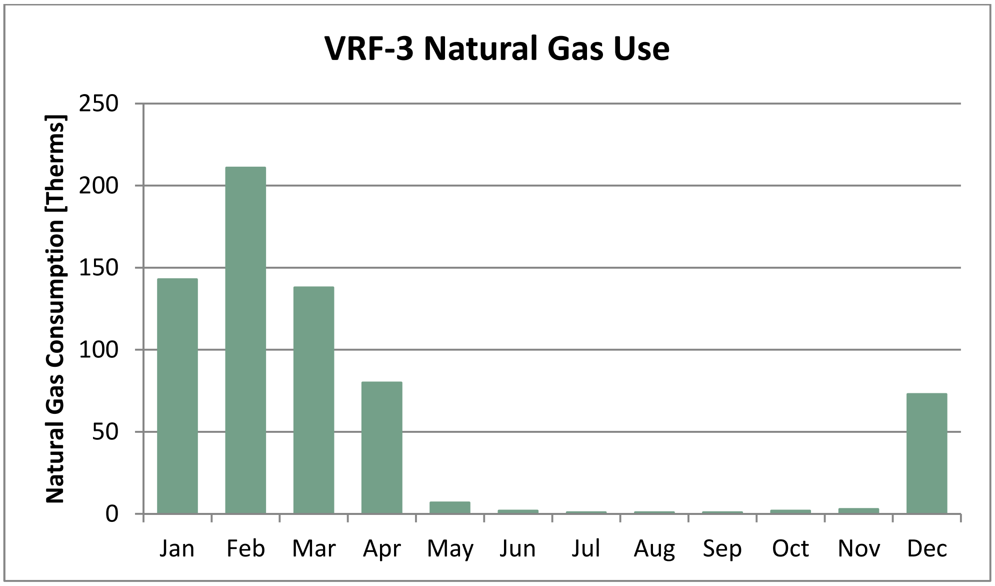


Figure G-66. VRF-3 Monthly Gas Consumption [Therms]

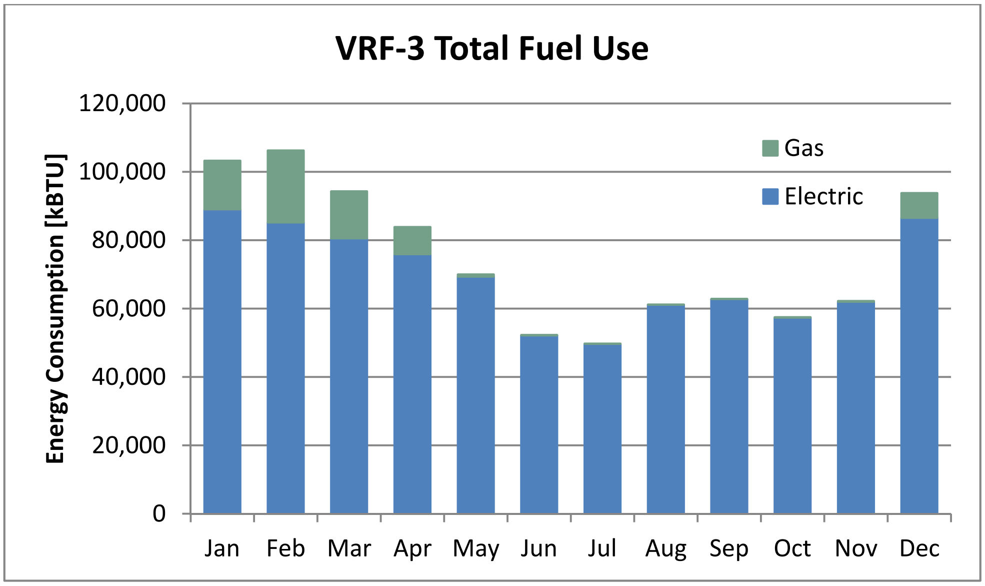


Figure G-67. VRF-3 Total Energy Consumption [kBTU]

In addition the building's actual bills were compared to design team projections, shown in Table G-36. While the actual electricity consumption of the building is a bit higher than projected (particularly during the winter months) the natural gas consumption is significantly lower than projected (~45%).

Table G-36. VRF-3 Design Team Energy Use Projections

	PROJECTION	ACTUAL
ELECTRICITY [kWh/yr]	228,000	243,680
GAS [therms/yr]	1,177	663
Total [kBTU]	895,747	897,715
EUI [kBTU/ft^2]	56.5	56.7

BUILDING PERFORMANCE

VRF Building 3 was visited mid-January 2014. We met with both building users and maintenance staff. Air temperature, humidity, CO_2 levels and light levels were measured throughout the building (Table G-37). The VRF system heating and cooling system was 100% operational throughout the building. The building systems consistently maintain temperatures between 70 and 74 degrees F. Light levels were excellent throughout the building. Task lighting is provided at workstations and occupancy sensors control the general lighting. The building is very comfortable and the project goals for energy, air quality and thermal comfort are being met.

Table G-37. VRF-3 Site Visit Log

SPACE	TEMPERATURE [°F]	RELATIVE HUMIDITY	LIGHT LEVEL [FC]	CO_2 [PPM]
Corner Conf. Room	71	9.5%	108	550
Cubes	72	11%	45	555
Office	73	11%	94	565
Office	73	11%	57+	562
Filing Room	73	8%	33+	472
Storage Ctr.	72	10%	34+	496
Bathroom	72	11%	49	560
Lg. Central Conf.	71	10%	50+	561
Break Rm.	71	12%	100	610
File Rm.	71	12%	55	635
IT	71	12%	47	635
Cubes	71	12%	64	638
Cubes	72	12%	46	657
Corridor	72	12%	56	660
Perimeter Conf. Room	73	12%	52	550/481
Reception	74	12%	65	630
Mail	74	12%	62	620
Outside Conditions	36.0	35%	--	--

The site visit and discussions with the building manager yielded several points worth noting:

1. The occupants of the building are very happy with the comfort of the building, especially the temperature control and air quality provided by the VRF system.
2. The VRF system was selected for its potential to achieve high energy efficiency and comfort levels while reducing required maintenance and saving ductwork space in the building design.
3. Overall, the building manager is pleased with the operation, energy consumption, and comfort of the building. He would consider using the technology again in the future. The system costs were roughly in-line with expectations, however the building overall was more costly due to other LEED requirements.
4. The relay setup used to control the temperature in the mechanical room where the condensing units are located is complicated, requiring many relays. Simplifying this control system is something that the engineer would consider doing differently.
5. One surprise was that while the building is meeting expectations for energy use, it only achieves a score of 65 using the Energy Star Portfolio Manager software.

The following are some observations made during the site visit that could yield additional energy savings:

1. During the site visit the mechanical room that houses the heat recovery units HR-1 and HR-2 was at 22 degrees F. This should have sequenced the operation of the gas-fired heaters to maintain 28 degrees in the mechanical room. However, the heaters were not operating. We observed icicles on the exhaust ducting of the heaters (see Figure G-68) and this freezing may have prevented the heaters from firing (frozen damper?). The colder room temperatures would cause the heat recovery units to work harder, increasing electric consumption. If this has been an on-going problem, it might explain the surprisingly low gas consumption and the higher than expected electricity consumption observed during the winter months.

Figure G-68. VRF-3 Freezing Observed on Heater Exhaust Ducting

2. The initial control sequence for the energy recovery ventilation calls for the system to be on M-F from 7 a.m. until 6 p.m. According to the building manager, the building is only occupied until 5 p.m. If the setpoint hasn't been adjusted to reflect this shorter occupancy period, this may be an opportunity for some energy savings.
3. During the site visit we observed a flow meter on the ERV showing 5,600 cfm of OA. This is more than double the flow specified in the drawings (2,340 cfm OA). This should

be checked for possible energy savings. (CO2 levels measured: 500-650 ppm -- in good agreement with the building sensors)

4. The scheduling and sequencing of the six electric wall mounted heaters in the building should be reviewed to ensure that they are not competing with the fan coil units for control of the space temperatures. Also, while the VRF system is currently not scheduled for unoccupied setback, some energy savings might be realized by incorporating a setback for these electric space heaters.

SUMMARY

This is a successful project and a good application of a variable refrigerant flow system. It is realizing significant energy savings compared to a similar building using a more conventional HVAC system. Further refinement and adjustments to the operation of the VRF system have the potential to provide additional energy savings and possible Energy Star certification. Many aspects of the building design contribute to the reduced energy use, but a significant portion can be attributed to the variable refrigerant flow technology.

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