March 2020

Very High Efficiency HVAC Systems for Small and Medium-sized Commercial Buildings

Executive Summary

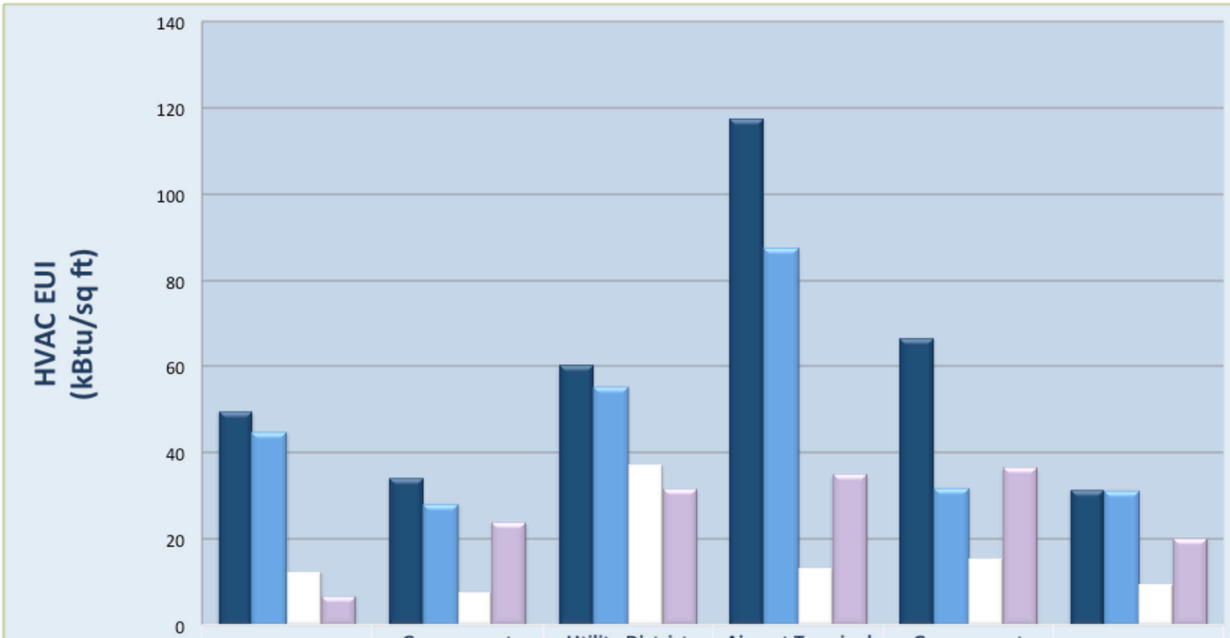
One of the largest HVAC loads in commercial buildings results from the combining of ventilation air with that of heating and cooling air. With the arrival in the North American market of a line of very high efficiency commercial HRVs and ERVs, it is now possible to radically reduce commercial HVAC system energy use and GHG emissions (including reducing natural gas use for space heating to zero) while significantly improving indoor air quality. If the right systems are chosen, it is also possible to provide the most sophisticated and reliable controls available today for the smallest commercial building spaces as part of the system conversion process. This is possible because these 21st century controls cost about one-tenth as much per square foot as typical Direct Digital Control (DDC) systems while far outperforming them.

This approach to HVAC system conversion was successfully demonstrated in smaller existing commercial buildings in a pilot project conducted by the Northwest Energy Efficiency Alliance (NEEA), from the fall of 2014 through the end of 2019. The project separated the heating and cooling functions from the ventilation functions in the buildings, and optimized both the heat pump-based heating and cooling (typically VRF or ducted/ductless heat pump) and HRV-based ventilation systems. The results were significant and consistent. Some of the most important findings included:

1) In office occupancies, ***HVAC savings almost always exceeded 75 percent on an EUI basis***. This included the elimination of all natural gas use for space heating where it was present in the existing building as found. ***Ending office HVAC EUIs ranged from 8-14 kBtu/sq ft, regardless of where they started.*** None of the building envelopes were particularly efficient.
2) ***Electricity demand savings tended to range from 20-40 percent, in many cases with little or no increase in winter demand when space heating was electrified.*** The actual demand savings for each project was somewhat variable, depending on the demand performance of the existing systems as found.
3) ***If the conversion system design and specifications were truly optimized, the cost of conversion was not very high – typically $15-20 per square foot.*** In one project that exceeded this range (~$35/sq ft), the project team was not able to influence the design and specifications and the systems were not fully optimized, except for optimizing revenue to the project engineers and contractors.
4) ***System heating and cooling capacities were typically reduced by 40-60 percent as part of the conversions***, in large measure through the near-elimination of the ventilation loads.
5) While no retail buildings were recruited for the project, the results are robust enough to conclude that ***similar savings to those achieved in the office occupancy are likely for retail occupancies of any size.*** In fact, most occupancies will achieve similar savings, with the notable exception of restaurants. ***But even in restaurants, where base loads usually significantly exceed HVAC loads, significant heating and cooling savings can be achieved.***
6) ***In some projects, indoor air quality improved to such an extent that building occupants commented on this outcome, unprompted.*** However, the project also revealed that the performance of the ventilation system is highly sensitive to good design and installation, which was not always achieved.
7) ***System conversion will work very well in almost all commercial occupancies – office, retail, schools, outpatient healthcare, assembly, restaurants, etc., and works especially well and***

inexpensively where the incumbent system is based on packaged rooftop units (RTUs). The conversion concept is especially easy and cost-effective to implement in large retail buildings, particularly those that are designed by formula for franchised or company-owned stores.

These are the results of the pilot projects that are not restaurants; base loads are included to show their variability and their scale relative to HVAC loads:



	Law Office	Government Office	Utility District Office	Airport Terminal Building	Government Dormitories	Seattle Office
Pre-Conversion	49.5	34.2	60.4	117.7	66.7	31.4
Code Minimum	44.6	28	55.1	87.3	31.7	31.2
Post-conversion	12.2	7.7	37	13.3	15.3	9.6
Base Load	6.8	23.7	31.3	34.8	36.2	20.1

The enabling technology for these system conversions is a ***very*** high efficiency heat recovery ventilation (HRV) system derived from European equipment. By a "very high efficiency HRV" we mean one where the temperature difference between the exhaust and supply air is so small that the supply air does not need to be tempered at all before introducing it to the space, and the electricity use of the fans is less than about 0.3 Watts/cfm.[1]

Until recently, such very high efficiency HRV/ERV systems have not been available in North America, but they are now. Sensible Effectiveness ratings of 85 percent or higher are needed to reduce the exhaust/supply temperature differentials to the point where the relatively high cost of tempering the supply air can be avoided, even under more extreme outside ambient conditions. The new product line also has very high efficiency continuously variable speed fans and sophisticated on-board control and data collection functions. The HRV/ERV efficiency for heating ventilation air is greater than COP 30 (thirty) and for cooling ventilation air, greater than COP 20 (twenty). At present, HRV/ERV capacity ranges from the 500 cfm school classroom unit to 3,000 cfm.

[1] The product line is from Portland, OR-based Ventacity Systems. All are Passiv Haus-certified. See www.ventacity.com .

The Conversion Proposition

This level of HRV/ERV system performance enables existing packaged HVAC systems in commercial building occupancies to be converted to very high efficiency ventilation systems with ductless or ducted heat pump-based heating and cooling. It should also work very well with hydronic systems, though this has not yet been demonstrated and documented in North America. The types of occupancies in the target market include retail stores, small and medium-sized office buildings (at least up to 100,000 sq ft), restaurants, churches, medical & dental clinics, smaller service businesses, most schools, and light industrial spaces. Such occupancies are found in strip malls, small office or retail developments, light industrial parks, and "main street" businesses in buildings of two stories or less. The ductless heating and cooling systems could be ducted or ductless heat pumps (DHPs) or variable refrigerant flow (VRF)-type systems, or ceiling radiant heating and cooling systems.

Nationally, according to the 2012 CBECS data,[2] more than half of commercial building floor area is heated and cooled with packaged equipment, heat pumps, or furnaces, in every size category. It includes 70 percent of office square footage, two-thirds of education square footage, and almost all mercantile space. This means that the target market, and the potential for system decarbonization, is very large – ***more than 75 billion square feet of existing building square footage.*** The savings for any given building of a particular occupancy (such as office or retail, the two largest commercial occupancies in terms of square footage), are fairly easily estimated. If the building base load is known, and this is easily and accurately estimated with an appropriate billing analysis, then the savings is the difference between the starting HVAC EUI and the ending HVAC EUI. The ending HVAC EUI will fall into a very narrow range for most occupancies, with any inaccuracy amounting to no more than 1,000 or 2,000 Btu/sq ft – inconsequential.

Conclusion

The most important conclusion to be drawn from the project is that there is no reason to delay converting most commercial building systems. The process is not difficult and it's not expensive if done optimally. Every new gas-pack RTU placed on a building, new or existing, is a 20-year lost opportunity, and we may not have more than 20 years to get this done. This suggests that a system conversion team should be present whenever the owner of an existing building is considering an HVAC system replacement.

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[2] See Table B39 at www.eia.gov/consumption/commercial/data/2012 .

Significant Savings Potential in an Underserved Market Segment

In the Beginning

In 2010, conversations with a number of Pacific Northwest regional energy efficiency stakeholders about the state of *existing commercial building* energy performance made a few things very clear:

- Aside from lighting programs, there were almost no utility, NEEA, or other programs focused on significantly reducing the energy use in this sector, especially in the smaller buildings that primarily use packaged HVAC systems.
- The Energy Use Index (EUI, in Btu/sq ft/year) values for these buildings are all over the map, with the worst often using 5 times more energy per square foot than the best. Energy performance benchmarking work in the cities of Seattle and Portland was making this much more obvious at the time.
- Based on best HVAC practices common in Europe, involving heating/cooling systems that are completely separate from *very* high efficiency ventilation systems, the savings potential is quite large in all but the best of these buildings.
- The amount of building square footage involved is very large, with NEEA's CBSA data suggesting that more than half the commercial building square footage in the region could be targeted for HVAC system conversion on the European model, delivering very large regional savings and radically lower building EUIs, at very reasonable cost.

There were also some related marketplace trends that were in the early stages of changing the visibility of commercial building energy use. Climate change response policies in certain states and local jurisdictions were starting to focus attention on these buildings, generating building EUI benchmarking initiatives by a growing number of cities as they attempted to quantify carbon footprint contributions from building energy use. Early data showed not only that our best buildings were outperforming our worst buildings by a factor of as much as 10, but that some of our best-*rated* new buildings were using a lot more energy than they were modeled to use.

The best buildings (often built to Passive House Institute specifications) always use a combination of a very high efficiency ventilation system, separate from a very high efficiency heating and cooling system, with the overall system designed to maximize the time that HVAC systems are simply off,[3] using greatly simplified controls and control strategies.

The worst performing buildings tend to use complicated HVAC systems that combine space conditioning and ventilation air flows, exhibiting large numbers of hours in a simultaneous heating and cooling mode, often by system design, using very complicated and expensive DDC control systems that might or might not be working properly.

As is often the case, Europe has been well ahead of these recent North American market changes and many of the technologies needed to significantly reduce building energy consumption have been in widespread use there for many years. The key technology required

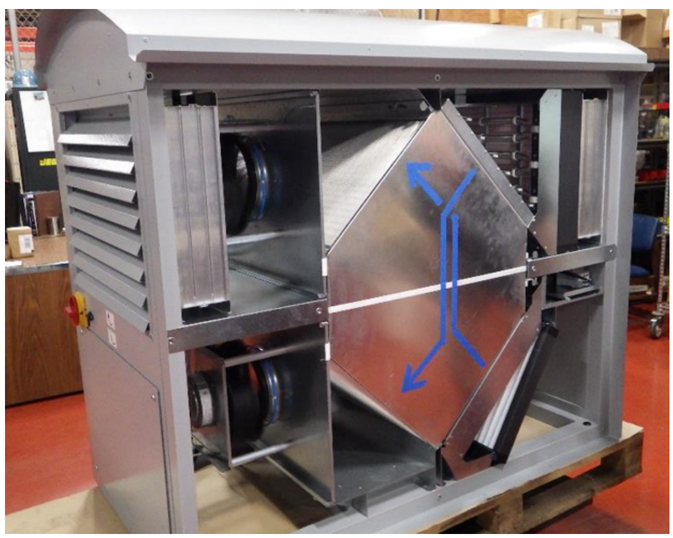
[3] This means heating and cooling systems have no load to meet to maintain setpoint, and ventilation is off when spaces are not occupied, barring other reasons for running the HRV/ERV, such as for economizing.

for enabling significant HVAC savings – a very high performance heat or energy recovery ventilator (H/ERV) and its associated distribution system and controls – is available in a wide range of capacities, from multiple manufacturers, but only in the European market.

A high-level NEEA analysis in 2011 suggested that the installed cost of a less efficient built-up ERV system[4] would be as high or higher than using a more expensive packaged European technology, but the savings would be half or less than those possible with the European equipment, in part because the lower HRV efficiencies would impose the need to heat and cool the ventilation air before delivering it, and in part because of the dismal efficiencies of the standard fans in the North American models. In other words, conversions using the available technologies would not be cost-effective at all by NEEA and utility program standards. Some ERVs at the low end of the efficiency scale would use more energy than they recovered when paired with a very efficient heating and cooling system.

So the notion of a pilot project to demonstrate how one might use very high efficiency Dedicated Outside Air Systems (DOAS), in combination with very efficient heat pump systems to provide the heating and cooling functions (such as VRF/VRV systems) was put on the shelf until an appropriate H/ERV technology arrived in the market.

In late 2014, that opportunity arrived in the form of a local Portland entrepreneur with an interest in solving the problem, and a business track record that made success highly likely. After a period of due diligence and technology licensing activity, a partnership between Cinagro Ventures and NEEA was formed to enable the start of a regional market transformation program, and later national product line distribution and adoption. Early work would involve redesigning a selected HRV product line from well respected manufacturer *2VV* in the Czech Republic, adaptable to the needs of the North American market, lab-testing to validate performance, UL-listing, and finding a number of early pilot conversion projects to demonstrate the savings potential of using such systems in smaller existing commercial buildings. Product redesign mostly had to do with developing a product variant that could be installed on existing rooftop curbs, with downward supply air flow and upward exhaust air flow – something not done in Europe. Because of the particular expertise of the Cinagro Ventures design team, the project also ended up involving radical improvements in the HVAC control systems required to optimize whole-system performance.



[4] An HRV transfers sensible energy only, while an ERV transfers both sensible and latent energy (humidity). The Pacific Northwest climate calls for HRV use rather than ERVs, but there were hardly any HRVs available in the market, most likely because the entire American HVAC industry is focused primarily on the cooling function, and has little demonstrated interest in heat pump technology.

The Pilot Project

By mid-2015, a new company had been formed (Ventacity Systems) and three units of the first product in the line – the VS1000RT – were in the U.S. and undergoing the UL-listing process, which was completed by January 2016. Lab testing to verify efficiency performance was also completed in the fall of 2015, concurrent with recruiting for pilot project buildings. By late 2015, planning and construction of the first pilot project was underway – a gut-remodel of a historic building in downtown Portland, OR that would be a law office when finished. That was followed quickly by two projects in Corvallis, OR (a state government district office and a pizza restaurant), and two projects in Seattle – another gut remodel in a historic mixed use building and a major HVAC system overhaul for a 1930 airport terminal building – were also underway.

Three years later there were three products in the line, all UL-listed, nine pilot projects in the field in three PNW states, HRV and ERV product being sold across the country, and a relatively inexpensive but very sophisticated control system and zoning system had been added to the line. All of Ventacity's products are Passiv Haus (PHI)-certified, and they produce the *only commercial capacity ERVs that are PHI-certified* (300 cfm and larger).

The design details for each project were unique (not at all surprising in the existing commercial building market), and the design and specification work was performed for the various projects by a combination of VRF system distributor personnel, HVAC contractors, and mechanical engineers. Five of the eight early projects are office occupancies, two are restaurants, and one is a set of four dormitories at a Montana federal government training center. Much later a middle school library and classroom project was added to the list.[5] Systems were tested in two climate zones, with the coldest being in Darby, MT and the more moderate being in the Portland, OR area and in the Puget Sound area in WA State.

All but one of the projects used either a VRF/VRV system[6] or a multi-zone DHP system for heating and cooling. Because of federal "buy American" requirements (which actually isn't possible, in fact, in the case of heat pump systems), the Darby, MT project used multiple conventional split system heat pumps for space conditioning. The other Montana project left in place an electric boiler to provide back-up for the heat pump system during the coldest hours. The multi-zone DHP systems, which are very appropriate for smaller projects, can lower costs significantly relative to a VRF installation. The smaller systems are also inherently more efficient.

The first eight projects used the separate control systems that come with the Ventacity HRVs combined with whatever VRF/VRV or DHP system controls came with the system. The relatively recent school project was the first to use an integrated Ventacity control system that manages both the heating/cooling and ventilation systems. In most projects, this HRV/VRF combination will replace one or more packaged or split systems of 10 tons or less in capacity – systems that combine space conditioning and ventilation air and suffer from all of the myriad system inefficiencies of these mid-twentieth century technologies. Ceiling radiant hydronic

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[5] An HRV and a Fujitsu VRF system were installed for this project, but other major renovations in the same school wing interrupted data collection early enough that no analysis could be accomplished.

[6] Daikin calls their system a VAV, or Variable Refrigerant Volume, system, but it's the same thing as a VRF system.

heating/cooling systems, now the standard of practice in Europe, are also an ideal heating/cooling system type for such conversions, but the pilot project did not find any project owners who were ready to invest in that amount of change in their systems.

One of the early questions asked as a pilot was being considered was, “Is it a good idea to put a high performance heat recovery ventilation system on a building that leaks a lot of air?” The next [obvious] question was, “How leaky are smaller commercial buildings?” There were virtually no answers to that question; hardly anyone had ever systematically tested such buildings with a blower door. So that work became an element of the pilot project. The answer turned out to be “not that leaky,” so not a barrier to the pilot project.

Recruiting participants was ad hoc, with utility partners finding some sites, serendipitous conversations turning up others, and some were brought by contractors or clients that wanted to do a project. Not all of the potential sites assessed ended up in the pilot, for various reasons. In the end, the first 8 buildings in Table 1 were the projects that were completed:

Building Type	Location	Project Floor Area (sq ft)	Existing System Type	Conversion System Type	Starting/Ending Whole-Building EUIs
Law Office	Portland, OR	11,615	Gas/Elec RTUs	VRF	**56.3 / 19.0**
Pizza Restaurant	Corvallis, OR	1,730	Gas/Elec RTU	Multi-zone DHPs	**1,515 / 1,352**
Government District Office[7]	Corvallis, OR	3,770	Gas/Elec RTUs	Multi-zone DHPs	**48.9 / 43.4**
Utility District Office	Libby, MT	5,681	Elec Boilers + HP RTU	Multi-zone DHPs w/boiler	**91.7 / 68.3**
Airport Terminal Building	Seattle, WA	26,200	Gas/Elec RTUs	VRF	**152.5 / 48.1**
Government Dormitories (4)	Darby, MT	~11,000, each building	Elec Res Forced Air	Split System HP	**102.9 / 51.5**
Engineering Office	Seattle, WA	6,100	Elect Res RTU	VRF	**51.5 / 29.7**
Restaurant	Portland, OR	1,147	Gas/Elec RTU	Multi-zone DHP	**924 / 701**
Middle School	Hillsboro, OR	6,266	Steam/Elec RTU	VRF	**Incomplete data**

Table 1 – Project Characteristics Summary

Goals, Activities and Findings

[7] This project converted 2 of 5 zones (3,770 sq ft of 13,200 sq ft). The other zones were converted in a later project, based on the excellent results of the pilot.

The overall goal of the pilot project was to demonstrate significant energy and demand savings in smaller existing commercial buildings in a handful of occupancy types – the ones that comprise the vast majority of commercial building square footage in the Pacific Northwest[8] while maintaining or improving indoor air quality (IAQ) and occupant comfort. The activities required to achieve this goal were several:

- Accomplish system conversion in several buildings of a few occupancy types (office, retail, school, restaurant) to validate the concept. Offices were the majority of the projects (5 of 9). The school project arrived at the very end and post-conversion data collection was interrupted by some major renovation work at the site, resulting in there being insufficient data with which to analyze the outcomes from the project. No retail projects were successfully recruited.
- Determine building HVAC loads, conduct billing analyses, and sub-meter HVAC end uses to quantify HVAC and non-HVAC energy use and demand.
- Monitor indoor temperature and CO_2 levels to document system comfort and indoor air quality performance.
- Model each project, and calibrate the models with field metering and energy bill data. Model a consistent base case to compare against conversion system energy use and demand. The base case is a simple code-minimum replacement of existing systems with the latest version of the same.
- Blower door-test each project space to determine air leakage rates. Use results to eliminate an assumption in the models and begin to collect data on smaller commercial building air leakage rates.
- Collect as much pre-conversion HVAC system energy use at the component level, and as much indoor temperature and CO2 data as possible before the conversions take place. Six months of pre-conversion data was preferred, backed up by at least a year of pre-conversion energy bill data.
- Follow the supply chain analysis, design, proposal and decision-making processes to understand how such conversions might take place in the absence of program specifications and guidance. Document lessons learned as project team members use the project specifications and guidelines to accomplish system conversions. Document permitting, installation, and set-up issues.
- Document system installed costs and gather information on alternative system costs.
- Commission new systems and verify performance.
- Collect at least 13 months of post-conversion HVAC and whole-building energy use, and indoor air quality and temperature data. Model the pre- and post-conversion systems and estimate energy and demand savings.
- Document lessons learned during the course of each project.
- Gather a limited amount of feedback from building occupants and project owners regarding their satisfaction with the performance of the new systems.

[8] Based on the results of NEEA's Commercial Building Stock Assessment (CBSA).

To a greater or lesser degree with each building conversion, these goals have largely been achieved. Taken as a whole, the pilot projects achieved all of the most critical goals – the ones that would inform a decision to go ahead with a program, or not. Certain results (such as the final HVAC energy use per square foot in the office occupancy type) have proven to be remarkably consistent.

General findings can be characterized as follows, in no particular order:

1. Building *base loads* (non-HVAC loads) are quite variable, and in restaurants overwhelmingly dominate whole-building energy use.
2. On the other hand, in office occupancies, in any given climate zone, the post-conversion HVAC energy use per square foot will fall into a very narrow range (8-14 kBtu/sq ft). This made HVAC energy use a much smaller than expected fraction of whole-building use.
3. As found, the range of starting EUIs was huge (less than 50 to more than 150, not counting the restaurants). This means that a "percent savings" metric is nearly useless in describing system conversion outcomes – the range is so large as to be meaningless, especially to predict outcomes. However, once a base load (non-HVAC) EUI is known, the ending EUI for an office is predictable within a very narrow range.
4. Smaller commercial buildings aren't as leaky as we imagined – 0.25 to 0.50 cfm/sq ft, typically. This was good news for the prospects of managing building air change with a very high efficiency heat recovery ventilation system.
5. Accurate system modeling for the project was very difficult and time-consuming. Without the field monitoring data collected during the project for model calibration, none of the models would likely have accurately predicted system energy use, for the base case or conversion systems.
6. Considerable design guidance will be necessary in the early years of a roll-out of this type of conversion process. Most engineers, designers and contractors have no experience with HVAC systems with this level of capability and performance. Most will:
    a. oversize the heating/cooling system (we generally downsized system capacity by half in the conversion process);
    b. specify too many zones (this maximizes revenue to project's industry stakeholders);
    c. assume the ventilation air has to be heated and cooled (except in the very coldest and hottest climates, it doesn't);
    d. will assume the ventilation air has to be "mixed" in the space (it doesn't);
    e. will often place the supply and extract ventilation duct terminations within feet of each other in a space (supply air must be introduced on one side of the space and extracted from the other side, in order to benefit the people in the space);
    f. as a matter of routine, throw in a very large amount of budget for unspecified "controls" (in general, there are no controls required, except what comes with the equipment; the Ventacity Smart Building Control system tends to be about one-tenth of the installed cost of traditional DDC control systems).

7. In general, the project was highly successful, many important lessons were learned, and it is now much more clear that very large amounts of energy can be fairly easily and relatively inexpensively saved in most existing commercial buildings.

The eight fully completed pilot projects are depicted below. The individual case study reports provide the details for each, but several of the lessons learned are common to most or all of them, and must be taken into account in any organized effort to promote this type of system conversion in commercial buildings, new or existing.

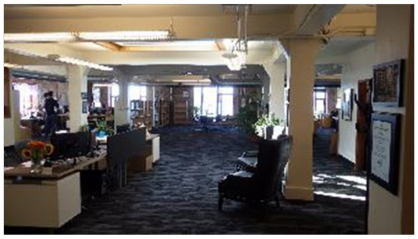
Law Offices – Portland

State Offices – Corvallis

Pizza Restaurant – Corvallis

Utility Field Office – Libby, MT

Job Corps Dorms – Darby, MT



Offices – Seattle (historic bldg.)

Airport Terminal – Seattle (historic bldg.)

Restaurant – Portland

Performance Results

Tables 2 and 3, and Figures 2 and 3 summarize the performance of the eight fully monitored and analyzed conversion projects in the pilot. There are a few things to note carefully as you study the data:

- The results vary a lot by occupancy type. This wasn't a surprise but one must be careful about comparisons from type to type.
- Note the wide range of base loads (the non-HVAC-related energy use). In the office occupancy, these range from 6.8 Btu/sq ft per year in a very lightly loaded law firm to 34.1 for the airport terminal building, which has the airport runway lighting controls in the basement. In several cases, the base load EUI is far larger than the final HVAC EUI (see Figure 2 below). This is why both whole-building and HVAC EUI results are presented. While the base loads and the pre-conversion EUIs vary a lot, the final HVAC EUIs don't vary much at all for the office occupancy. While there are no retail projects in the pilot, as hoped, it's likely that a narrow range of final HVAC EUIs will hold true for that occupancy type as well. This raised an important question – if, for any given occupancy, the final HVAC EUI falls into a very narrow range, do these projects really need to be modeled? Or can a simple billing analysis that separates base and HVAC loads, provide sufficient information with which to make a conversion decision? This type of analysis was done for most projects and seemed very promising as a way to project the outcomes of a conversion project. Figure 1 is an example of the results of this type of analysis, in this case for the pre-conversion systems in the Airport Terminal Building project. Base loads are clearly depicted (they total about 2.9 W/sq ft), as is the enormous amount of simultaneous heating and cooling going on, even during the summer months.

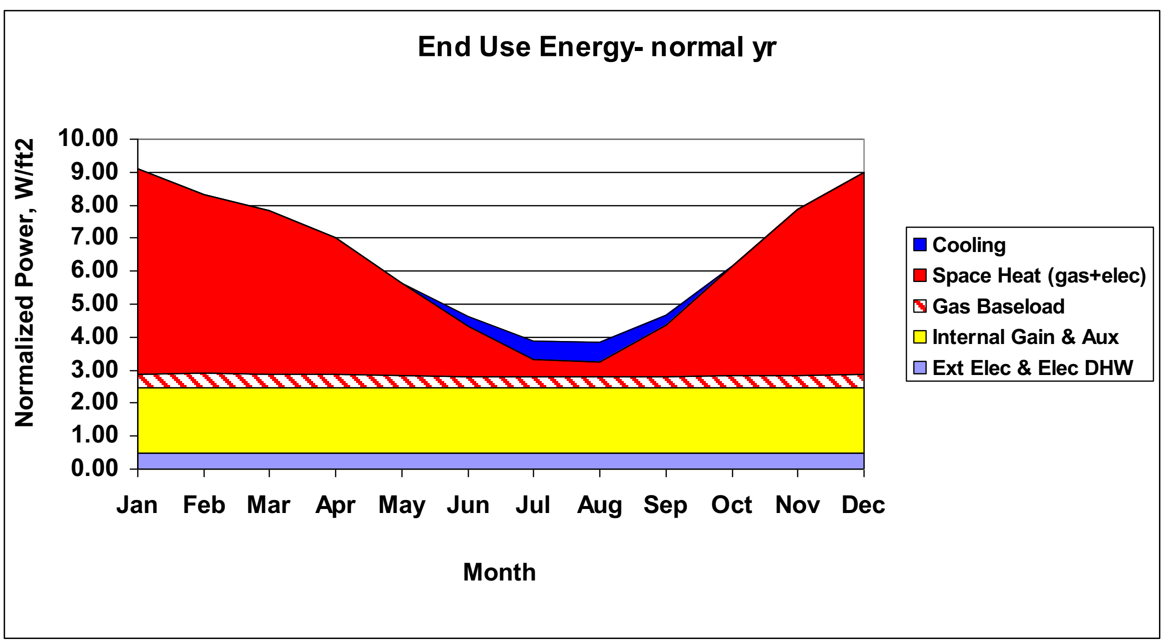


Figure 1 – Billing analysis models for the Airport Terminal Building Project

- While there are percentages given for savings, the data make it pretty clear that this metric is inappropriate for predicting energy use reductions. A far better indicator of savings will be how bad the building is to start with. In the office occupancy, starting with the whole-building EUI, subtract the base load, subtract the estimated final HVAC EUI (about 11 kBtu/sq ft, plus or minus 3), and the result will be a reasonable savings estimate. The range of answers will be large. If the final HVAC EUI is off by 25 percent (14 instead of 11), the savings estimate will be off by a much smaller percentage (e.g., 6-7 percent), and not worth worrying about. Table 2 has the final HVAC EUI results for the office occupancies highlighted in red. They range from a low of 7.7 to a high of 13.3, excluding the Utility District Office where the existing large electric resistance boiler was left in place for back-up heating; this unit substantially increases the heating energy use in the Montana climate zone.
- There are three cases analyzed and documented for each building in the project – pre-conversion (as found), code minimum (the alternative replacement equipment option of simply the latest version of what's already there), and post-conversion. All were modeled to Typical Meteorological Year (TMY) conditions in Energy Plus, calibrated with detailed field monitoring data. Be careful as you compare outcomes that you're comparing the right cases.
- Conversion systems in the office occupancy type seem to show a correlation between HVAC system energy performance and the number of square feet of conditioned floor area served per HVAC zone. The more square feet per zone, the lower the HVAC EUI. However, the two lowest post-conversion office EUIs in the project were also served by multi-zone mini-split systems of under 4 tons of capacity each, which may also have contributed to their relatively exceptional performance. More data will be needed to confirm some of the early observations.
- Electric demand impacts were recorded, modeled and analyzed, but only a sample is provided here. Each project produced its own set of demand impacts, largely based on the electric demand behavior of the system in place, as found. The conversion systems all produced a much less variable seasonal demand pattern, and a generally lower level of demand. In the cases where winter demand increased, the increase was modest, and was the result of relatively lower pre-conversion fan power and the addition of heat pump heating.

Energy Performance

The modeling results for the energy performance of the three cases for each of the 8 completed projects are shown in Table 2. All of the models were calibrated with at least a year of detailed post-conversion field monitoring of the installed systems and at least a few months of pre-conversion monitoring, along with at least a year's worth of pre- and post- billing data in all but two projects. A few projects did not have a year of pre-conversion billing data - the first one (the Law Office), as the space was vacant for more than 2 years prior to its conversion, the Government Dormitory project, where the energy use for individual buildings could not be separated from the energy bills for the whole facility, and the Seattle office, where multiple spaces in the building were on the same meter and the space had been vacant for some time prior to the major tenant improvement project beginning.

Energy Performance Results									
Project	**Climate Zone**	**Project Floor Area (sq ft)**	**Base Load EUI (Btu / sq ft)**	**Pre-conversion EUI (Btu / sq ft)**		**Code Minimum Replacement EUI (Btu / sq ft)**		**Post-Conversion EUI (Btu / sq ft)**	
				Bldg.	HVAC	Bldg.	HVAC	Bldg.	HVAC
Law Office	4	11,615	6.8	52.8	46.0	51.4	44.6	**19.1**	**12.3**
Pizza Restaurant	4	1,730	1,193	1,515	322	1,470	277	**1,352**	**159**
Government District Office[9]	4	13,200	23.7	57.9	33.1	51.7	26.9	**31.4**	**7.7**
Utility District Office	5	5,681	31.3	91.7	60.4	86.4	55.1	**68.3**	**37.0**
Airport Terminal Building	6	26,200	34.1	152.5	117.7	122.0	87.3	**48.1**	**13.3**
Government Dormitories (4)	5	~11,000, each building	36.2	102.9	66.7	67.9	31.7	**51.5**	**15.3**
Seattle Office	6	6,100	20.1	51.5	31.4	51.3	31.2	**29.7**	**9.6**
Restaurant	4	1,147	636	924	289	875	239	**701**	**65**

Table 2 – Energy performance results (EUIs)

As mentioned earlier here, estimating savings based on percentages turned out to be largely meaningless as a metric for predicting the *whole-building* outcome of any given conversion project, even for one occupancy type. However, when looking just at the HVAC energy use – the part addressed by the HVAC system conversion – some consistent outcomes were evident. **Not only were the end-point HVAC EUI results quite consistent, but the HVAC energy percentage saved was most often greater than *two-thirds*.** The data in Table 3 should help make this conclusion clear.

[9] This project converted 2 of 5 zones (3,770 sq ft of 13,200 sq ft). The numbers here are for the whole-building model (all 5 zones converted) in order to make this project comparable to the other office projects. The other 3 zones were converted in a later project, based on the excellent results of the pilot and the analysis results presented here.

Project	Pre-conversion HVAC EUI (Btu / sq ft)	Code Minimum HVAC EUI (Btu / sq ft)	Post-Conversion HVAC EUI (Btu / sq ft)	Pre-conversion to Code HVAC Savings	Code to Post-Conversion HVAC Savings	Pre-conversion to Post-conversion HVAC Savings
Law Office	46.0	44.6	**12.3**	10%	73%	**75%**
Pizza Restaurant	322	277	**159**	14%	43%	**51%**
Government District Office[10]	33.1	26.9	**7.7**	18%	73%	**77%**
Utility District Office	60.4	55.1	**37.0**	9%	33%	**39%**
Airport Terminal Building	117.7	87.3	**13.3**	26%	85%	**89%**
Government Dormitories (4)	66.7	31.7	**15.3**	52%	52%	**77%**
Seattle Office	31.4	31.2	**9.6**	1%	69%	**69%**
Restaurant	289	239	**65**	17%	73%	**77%**

Table 3 – Percent ***HVAC*** savings for each of the three modeled cases

Figure 2 shows the HVAC EUI results for the three modeled cases (pre-conversion in blue, code minimum in red, and post-conversion in chartreuse). Base loads, in purple, are shown for comparison. Note that in four of the six cases, HVAC EUIs end up well below base loads after conversion. Typical offices (like the Government and Seattle cases here) have base loads of about 20 kBtu/sq ft, and will have post-conversion HVAC EUIs of 10-12 kBtu/sq ft in Climate Zone 4. Added together, an average whole-building EUI of around 30 kBtu/sq ft will result from the kind of system conversions conducted in the office pilots, *if done well.*

[10] This project converted 2 of 5 zones (3,770 sq ft of 13,200 sq ft). The numbers here are for the whole-building model (all 5 zones converted) in order to make this project comparable to the other office projects. The other 3 zones were converted in a later project, based on the excellent results of the pilot and the analysis results presented here.

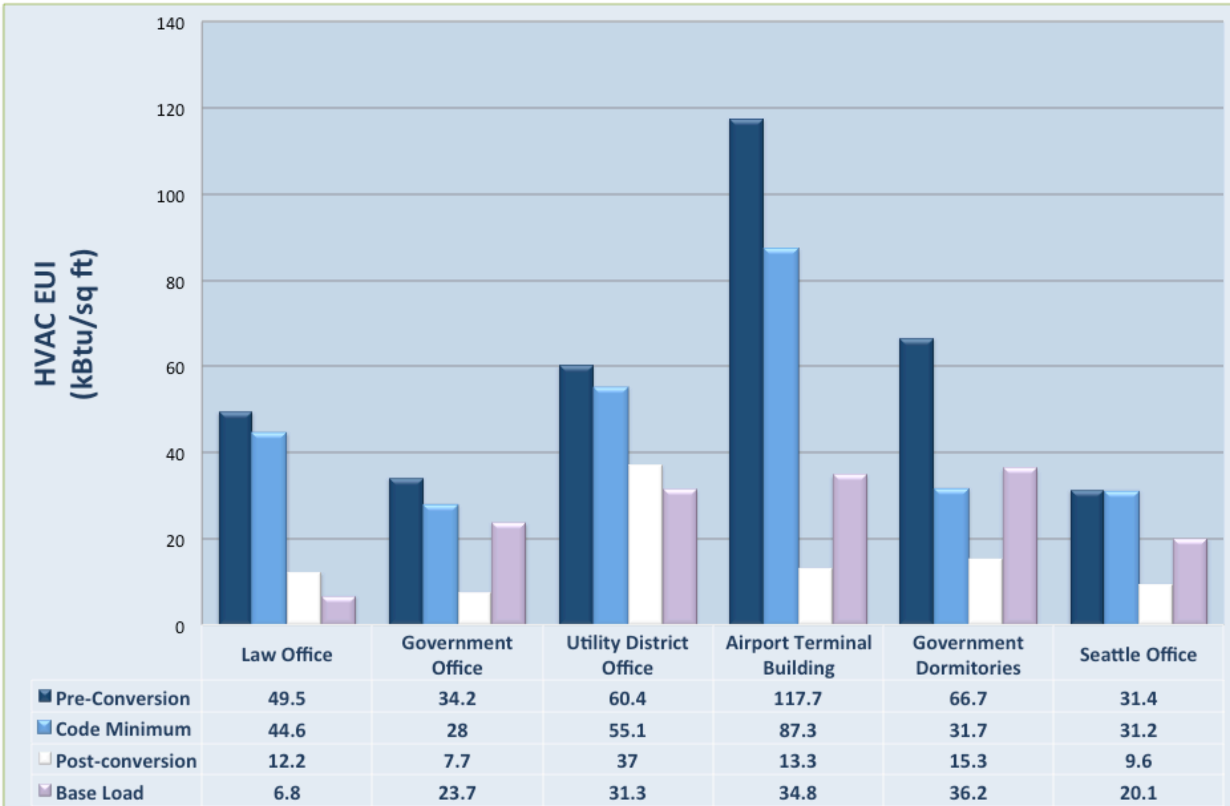


Figure 2 – HVAC EUIs for the three modeled cases in the office and dormitory occupancies

The large code minimum savings in the Airport Terminal Building are due to the elimination of the grossly inefficient existing dual-deck RTU systems that resulted in a significant amount of simultaneous heating and cooling during many hours of the year. In the Government Dormitory project, the large code minimum savings come from the elimination of the existing electric resistance heating in the pre-conversion case, substituting minimum efficiency heat pump systems for the Code Minimum case. In most buildings, the Code Minimum step will not result in a lot of energy savings.

The savings from the code-minimum to the conversion systems come primarily from the near-elimination of the conditioning loads for ventilation air. Some additional savings come from the improved efficiency of the heating and cooling systems, and the downsizing of system capacities. Smaller systems tend to be inherently more efficient when properly sized.

The electricity demand outcomes are not easily summarized here because of the complexity of providing meaningful information in a condensed fashion. However, **it became clear during the course of the project that it is often possible to convert the heating function from a natural gas-fired system to a heat pump system without any significant (or even *any*) increase in winter electric demand.** This is especially true for the least efficient as-found systems, where inefficient and oversized fans and/or large amounts of simultaneous heating and cooling cause significant wintertime electricity demand and energy use. A typical example is shown in Figure 3, where the demand reductions are very clear. Note that the scales are slightly different in the upper graphs.

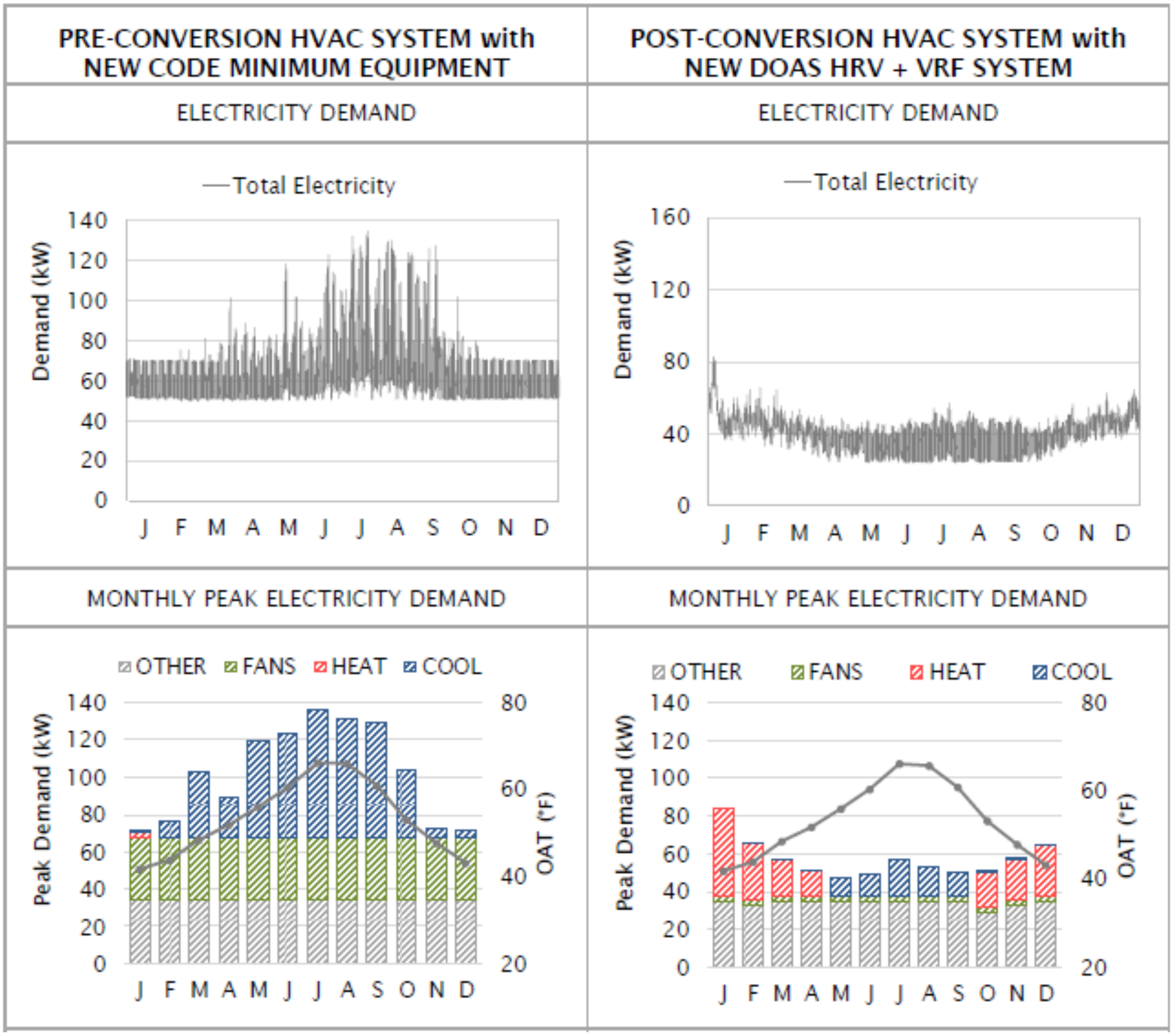


Figure 3 – Demand reductions in the Airport Terminal Building project

In the office occupancies (5 of the 8 projects), cooling demand during the peak summer cooling months (July and August) can most often be reduced by a third or more. Actual outcomes ranged from 13 to 59 percent, but three of the five fell into the 25 to 40 percent range. Consult the individual case studies for the demand reduction outcomes for each project.

Project Lessons

While not all lessons applied to all projects, many or most projects shared key findings. The project characteristics in Table 4 are key metrics for assessing whether or not a project proposal is developed using current industry rules-of-thumb, or whether the project team has actually gone to the trouble to properly calculate building loads, design and specify an optimal design for the conversion system, and proposed a reasonable cost for the project. In most projects this won't happen without the dogged insistence on adherence to specifications and guidelines by a knowledgeable project owner or their technically savvy representative. Table 4 provides the background project information that underlies some of the lessons discussed here.

Project	Floor Area (sq ft)	Installed System Capacity (tons)	Conditioned Floor Area / Ton (sq ft / ton)	Number of System Zones	Conditioned Floor Area per Zone (sq ft / zone)	Project Cost	Project Cost per Square Foot
Law Office	11,615	16	**726**	8	**1,452**	$181,256	**$15.61**
Pizza Restaurant	1,730	9	**192**	4	**433**	$37,400	**$21.62**
Government District Office[11]	3,770	8	**471**	2	**1,885**	$43,238	**$11.47**
Utility District Office	5,681	8	**710**	8	**710**	$125,528	**$22.10**
Airport Terminal Building	26,200	24	**1,092**	37	**708**	$928,500	**$35.44**
Government Dormitories (4)	~11,000, (each building)	16	**688**	5	**2,200**	$106,000	**$9.64**
Seattle Office	6,100	14	**422**	12	**508**	$99,500	**$16.83**
Restaurant	1,147	3	**382**	3	**382**	$35,550	**$30.99**

Table 4 – Key project metrics

The lessons learned, gathered from all projects, include the following:

- **Contractors and distributors want to sell equipment, and engineering fees are typically based on the HVAC budget, which almost always leads to system oversizing, needless added system complexity, and much higher project costs than for an optimally designed and specified system.** Large numbers of indoor units (zones) also inflicts much higher maintenance costs on the owners or occupants of the building – every VRF/VRV indoor unit has a condensate pump (which often fails), and a filter that has to be cleaned or changed at least twice a year. The VRF/VRV system filters are relatively expensive.

[11] This project converted 2 of 5 zones (3,770 sq ft of 13,200 sq ft). The numbers here are for the whole-building model (all 5 zones converted) in order to make this project comparable to the other office projects. The other 3 zones were converted in a later project, based on the excellent results of the pilot and the analysis results presented here.

One project metric that is an indicator of too much equipment and too many heating/cooling zones is the "conditioned area per zone" metric in Table 4. A typical 4-ton, *single-zone* RTU, using the longtime industry standard 400 sq ft per ton of cooling capacity rule-of-thumb, will serve about 1,600 square feet of office floor area. For project purposes, we regarded values lower than 1,000 sq ft per zone as an indicator that the system likely has too many indoor units, and more first costs and maintenance costs than necessary. This doesn't apply to the restaurants where loads per square foot are often double or more that for office or retail occupancies. In restaurant systems, in rough terms, double the capacity needed per square foot yields half the per-zone floor area that one would expect for an office.

- **System design is really important for optimal performance, but contractors and engineers don't yet know how to design with this equipment, especially the *very* high efficiency HRV.** Lots of rules-of-thumb are in use in the HVAC and mechanical engineering world, and almost none of them are relevant to the systems used in this sort of conversion project.

  For example, **in older buildings, proper conversion system sizing is in the range of 700-800 sq ft of conditioned area per ton of cooling system capacity, not the typical 300-400 sq ft per ton.** Table 4 has the floor area served by each ton of cooling system capacity in the conversion system for each project. In the office occupancies and the dormitory project, all but two of the projects (the Government Office and Seattle Office), system sizing was within the project guidelines. The two outliers were clearly designed with the industry standard 400 square feet per ton of capacity rule-of-thumb. Both are in Climate Zone 4, so have a considerable amount of excess capacity (and some additional cost) in the systems.

  The other major design challenge for contractors and engineers is the proper design of the ventilation system, using highly capable and efficient HRV or ERV technology. Most engineers and contractors are unfamiliar with packaged HRV or ERV systems that perform the cooling season economizing function, without any connection to or control provided by the heating and cooling system, or other building controls. The unit must be sized properly if economizing is to be carried out effectively in the building. **This generally means sizing the ventilation capacity for any given zone or zones being served by a unit such that the ASHRAE 62.1 air flows are between 40 and 60 percent of the full rated flow of the unit (i.e., for a 1,000 cfm unit such as those used in the pilot project, 400-600 cfm for maximum ventilation air flow requirements).** If this is done properly, the performance of the HRV or ERV will dramatically increase the number of cooling season hours per day that the cooling system is off – a large source of cooling energy savings. The excess HRV or ERV flow capacity also allows for boosting air flows when a zone experiences higher occupancy levels than planned for. In addition, ventilation air must be delivered to one side of the space being ventilated and exhausted from the other side, so the occupants in the middle receive the benefits of the fresh air, and no "mixing" of the air is required. And in all but the most extreme climates, the ventilation air does not need to be conditioned, ever. These are *not* the assumptions behind typical design strategies.

In the case of the Airport Terminal Building project, the NEEA project team had little or no influence on the design and specifications for the systems. The ventilation system is sized such that all 3 HRV units must run at near maximum flow rates simply to meet ASHRAE 62.1 requirements. Aside from compromising the economizing function and the energy efficiency of the units during most operating hours, there is no additional ventilation capacity to spare for boost. When it became apparent that the facility conference room was routinely exceeding 1,000 ppm CO_2 concentrations whenever it was used by more than a few people, there was nothing that could be done about the problem. The NEEA project team strongly recommended a total ventilation capacity of 5,000 cfm, but the contractor simply pointed at the engineer's specifications for the project and declined to consider any changes. Unfortunately, this will likely be the most common response to such a design guideline recommendation.

- **Energy models don't yet accurately model the impacts of such system conversions, either in the base case or the conversion case.** Sometimes this is because the individual system performance data in the models, for both base case and high performance systems, is based on test and rating methods that do not reflect field performance at all. In most cases the performance of the systems (especially the HRV system) simply can't be accurately represented, in even the best of the models, due to the form of inputs required or the lack of inputs altogether. The ranges of typical modeling outcomes are shown in Figure 4 below.

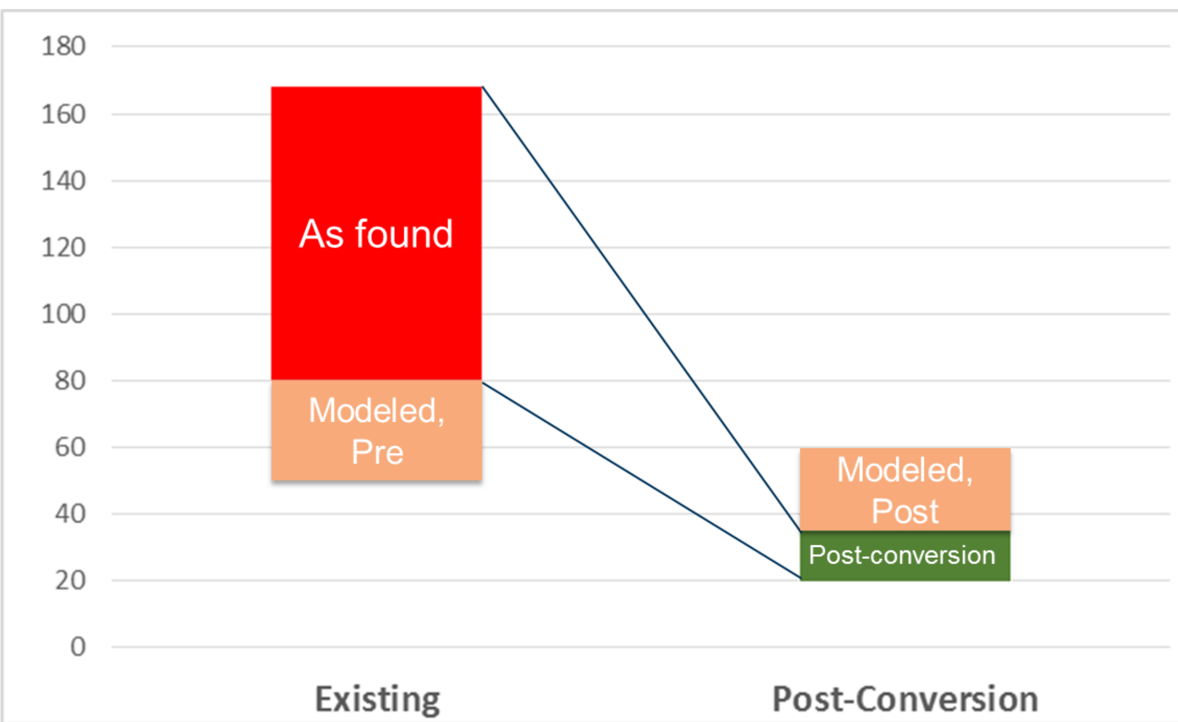


Figure 4 – Typical modeling outcomes

Packaged H/ERVs have their own characteristic (and non-linear) performance curves based on flow rates and external static pressures. Flow rates in sophisticated ventilation systems, especially those using demand-based controls programming, are highly variable, on an hourly basis, for each building. The power used by the project HRV model (1,000 cfm nominal maximum flow rate) is, on average, over a day of operation, lower than expected – **about 0.1 W/cfm, or 10 cfm/W**, which is needed for the simplistic inputs that most energy models allow. This radical simplification compared to the actual operating characteristics of the system may or may not deliver a reasonable estimate of H/ERV performance.

VRF modeling in Energy Plus has improved a bit, according to many modelers, but there are still deficiencies, some stemming from uncertain real performance curves and refrigerant piping loss assumptions that are not based on any field validation. And the larger the number of zones, the larger the losses, and the larger the error in loss estimates. There is also the matter of sizing, which most models assign based on inappropriately applied rules-of-thumb. Absent strong guidance for designers and specifiers, most systems will be significantly oversized. Standard model zoning conventions may or may not apply. VRF distributors, who design most systems, will usually have many more zones than necessary, and whole-system behavior under low-load conditions is not reflected in the performance curves used in the models.

Temperature setback, assumed by the models to save energy, may actually not save any energy at all, due to the nature of how variable capacity heat pump systems handle large discrepancies between space temperature and setpoint. Because of the non-linear efficiency curve of the systems (fan laws are exponential), it is most often more efficient to leave setpoints alone than to prompt operation in high power modes by varying the setpoint by more than a degree or two.

Figure 5 shows how far off the mark a good energy model can be when attempting to model the conversion system in the Law Office project. The models quite consistently over-predict actual energy use, sometimes by a large percentage.

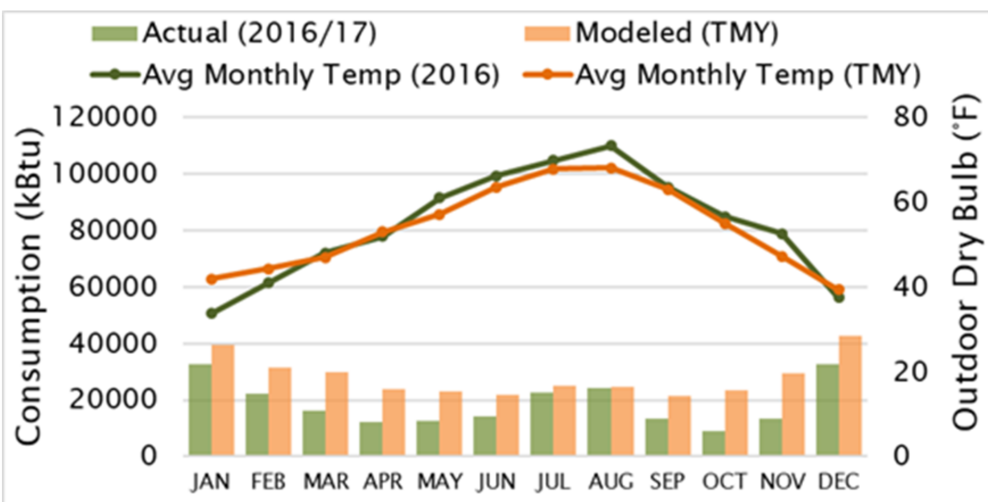


Figure 5 - Early energy modeling results for the Law Office project

Obviously some important conversion system characteristics cannot be well represented in the models, but they definitely impact system energy use. With good field data for calibration, and with the right work-arounds, models can made to be more representative. In the end, modeling improved as knowledge was gained over the course of the project, and was important for allowing valid comparisons among the three cases modeled (pre-conversion, code minimum, post-conversion).

- **In most buildings, the "heat recovery" option for VRF/VRV systems will seldom save anywhere near enough energy to justify its cost, which is substantial.** If the option is purchased, the zoning ***must*** be specified in a way that that allows excess energy in one zone to be utilized in another. While some building layouts and orientations may lend themselves to this type of strategy, we were not witness to any sort of analysis as a part of the decision-making process in the several project buildings that have the heat recovery option. And in the first project building, the contractor zoned the system in such a way that it could never utilize this installed capability, combining core and perimeter spaces on both sides of the building into individual zones. This added considerable cost to the project and saves no energy. This will often be the case.
- **Refrigerants matter** – HFCs are on the way out, due to their serious impact on the climate. The "drop-in" replacements for HFCs favored by manufacturers are scarcely an improvement from a 20-year GWP perspective.[12] **VRF/VRV systems currently use large amounts of HFC refrigerants – hundreds of pounds, and the more zones a system has, the more refrigerant there is, and the more potential exists for refrigerant losses.** Future-proofing these systems (and optimizing performance overall) requires minimizing the number of zones, and setting systems up to use natural refrigerant-based systems in the future, such as reverse-cycle chiller-based hydronic systems, which would substitute air-to-water heat pumps for the VRF/VRV outdoor unit, and hydronic air handlers for the refrigerant-based AHUs.
- **Many existing buildings that use packaged HVAC systems such as RTUs aren't actually ventilated as found.** Heating and cooling ventilation air can be expensive, so building occupants or owners have often taken steps to minimize outside air flow into the system, in many cases simply locking or taping the outside air dampers shut. In such cases the savings that come from the conversion system eliminating almost all of the conditioning of ventilation air will not materialize. But indoor air quality is certain to improve, at almost no cost.
- **Fully optimized controls for the ventilation and/or the heating/cooling systems are still in development, but there is significant potential for dramatic simplification, better system integration and performance optimization, and much lower controls costs.** Typical DDC system costs were found to be $5-7/sq ft during the course of the pilot project. In contrast, the integrated whole-system controls now available as part of the Ventacity Systems line cost about one-tenth as much, while being simpler and far more user-friendly. Installation consists of simply connecting the control modules of the

[12] The GWP numbers cited today are 100-year values. Given the urgent nature of our collective climate predicament, only the 20-year GWP values are relevant, and are the ones underlying the discussion here.

ventilation system and the heating/cooling system. In projects such as the pilots, this consists of running a single CAT 5 cable.

- **Project costs in the pilot were most often quite reasonable – typically well under $25/sq ft.** In typical office occupancies, this kind of project, in Pacific Northwest markets, should be possible for **$15-20/sq ft**. However, this isn't how most projects were initially proposed. Several were proposed at $25-35/sq ft. In one case where a cost breakdown was requested, the proposal contained $5/sq ft for "controls." When the contractor was asked "What controls?" the answer was "we're told to just put that in there for whatever the controls for the system will be." When asked "Told by whom?" the answer was, "By the controls company or distributor." When the contractor was informed that the project would not require any such controls, it's not clear that this cost was ever removed from the proposal. But the proposed controls costs encountered during the course of the pilot (including for many projects that did not become part of the pilot) consistently ran **between $4.50 and $7 per square foot** (taken from 11 different proposals). The control systems described in the section immediately above virtually eliminate this cost, by replacing the typically complex, opaque, unreliable, and very expensive DDC control systems typically specified with a superior system that costs about one-tenth as much. *Every project owner should consider moving to a 21st century control system as part of a conversion project.*

  All four of the projects in Table 4 with costs above $20/sq ft had circumstances that explained the high costs, except for the Airport Terminal Building project. In spite of the ventilation system under-capacity, this system had the highest costs per square foot, by far, in the pilot, and came in at just about exactly the price being quoted for just about every VRF project in the pilot project urban markets - $35/sq ft. Six engineering studies for other building projects were reviewed during the course of the project and shortly after. All six, by five different engineering firms, priced the standard three types of HVAC systems - an upgraded RTU-based system, VRF, and VAV – within a dollar per square foot of the same number - $25/sq ft for the RTU-based system, $35/sq ft for VRF, and $40/sq ft for a VAV system. The buildings were of varying ages, of varying sizes (9,000 sq ft to 80,000 sq ft), but all were offices.

  Based on the pilot project costs, there is clearly the potential for building owners to save a lot of money if the right specifications and design guidelines are followed, the right controls are used, and if there is any real competition in the marketplace. The first two can be insisted upon, but the last is in some doubt.

- **HRV/ERV system efficiency is very sensitive to the characteristics of the ventilation duct system.** Elevated external static pressures, on either side of the unit, will notably increase fan power, especially at higher air flow rates. Duct leakage, especially if on the exhaust intake side of the unit from unconditioned spaces, can seriously impact the temperature of the exhaust air entering the unit. In a very efficient HRV or ERV, this then impacts the temperature of the fresh air stream on the other side of the heat exchanger. During the heating season, in addition to increasing the heating load, fresh air temperatures may even be reduced enough to affect thermal comfort conditions.

During the cooling season, both the sensible and latent cooling load will increase and reduce comfort conditions in the space.

This is especially a problem for ducting above the roof, where both duct leakage and insufficient insulation can combine to seriously lower system efficiency and thermal comfort while increasing space conditioning loads. In conventional HVAC systems where ventilation air and space conditioning air are combined, the heating and cooling components of the systems are simply sized with enough capacity to overcome the thermal losses of the ducting and maintain delivered air temperatures within the comfort range. While the ventilation system can be designed to add or subtract energy to or from the delivered fresh air to maintain comfort, such system requirements can add significant cost and impose significant system efficiency penalties. This was evident in more than one of the pilot projects. **In general, outdoor ducting should be avoided whenever possible. In most projects this will not be an issue, but where outdoor ducting must be used, attention must be paid to the airtightness of the ducting, and added insulation for ventilation ducting is strongly advised.**

- **Restaurants are difficult.** Most restaurants have one or more powerful range hood systems serving the kitchen. These systems, with their make-up air units, dominate the airflow and building pressure regime for this type of occupancy, so much more attention must be paid to the interaction of the balanced ventilation system that serves the dining area and the exhaust vent system that serves the kitchen. It's not that easy to do well in existing buildings. In order to maximize the effectiveness of the ventilation system, the balance between the vent hood and make-up air fans must be carefully calibrated, leaving the kitchen slightly depressurized relative to the dining area. As difficult as this can be to accomplish, the Portland restaurant pilot project did this very well and the results were exemplary.

  The guidelines for space conditioning system design and sizing are also necessarily different than for other occupancies – the peak loads per square foot are inherently larger. This is another reason for extra care when designing and specifying conversion systems for this occupancy.

Conclusions

The overall goal of the project was to demonstrate the potential for substantial energy and demand savings in smaller existing commercial buildings while maintaining or improving indoor air quality and occupant comfort. The pilot project clearly achieved that goal. In the end, if the project specifications and guidelines were followed, it was neither difficult nor expensive to dramatically reduce energy use and moderately reduce electric demand, generally while improving indoor conditions for the building occupants.

The smaller existing commercial buildings sector was also targeted because it would be the most difficult to address. All of the work done in the pilot buildings will be much easier and much less expensive to accomplish in new buildings, of any size, and in larger existing commercial buildings.

It was also evident that the HVAC industry, in general, either lacks interest in providing systems like those in the pilot for their clients, or simply lacks the expertise to do so. Today's energy models and the inputs and assumptions they use are not yet up to the task of accurately predicting commercial building energy use, but this has been the case for quite some time. Modeling capabilities are only very slowly improving.

System simplification turned out to be the primary tool for producing the best results. Today's conventional HVAC systems are inefficient, overly complex, too expensive, not very reliable, and poorly controlled. Typical DDC controls for these systems are themselves too complex, opaque, expensive (in general unaffordable for smaller buildings), and unreliable.[13] Toward the end of the pilot project a far simpler, far less expensive, and much more transparent control system became available as part of the Ventacity Systems line. Unfortunately, the project was too close to completion to incorporate this 21st century control system in any of the first eight projects, but early deployments in the last year have substantially raised the bar for control system performance and cost - value.

Given the outcomes of the pilot projects, the energy and demand savings potential is enormous, not only for smaller existing commercial buildings, but for the vast majority of commercial buildings, new or existing, large or small.

Given the lessons learned during the project, the need for a programmatic approach to acquiring these savings is obvious. The only big question remaining is, who will run the programs?

[13] One of the people in charge of the City of New York's public school system's buildings stated that at any given time, about one-half of their control systems are wholly or substantially inoperable. And for this they pay their controls contractor about $30 million per year. They claim this is not unusual for organizations with a large portfolio of buildings.