Final Scientific/Technical Report (FSR) for DOE/EERE

Project Title:	**Commercial Building Technology Demonstration.**
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I. Executive Summary

The background for this project was a unique and innovative concept that had been proposed and demonstrated by enVerid Systems, reducing the energy consumption in HVAC systems in commercial and public buildings by up to 50% at peak loads. The concept involves selective scrubbing of gas contaminants from indoor air as a practical substitute for outside air ventilation, the latter being the conventional practice today. This scrubbing enables recycling of most of the indoor air and significantly decreasing the amount of outside air, resulting in a reduced HVAC load and commensurate energy savings for the facility. Key to our approach is low cost scrubbing of all gas contaminants from indoor air using novel, efficient and regenerable sorbent materials. The total solution, labeled **HLR** (**H**VAC **L**oad **R**eduction) is implemented by means of compact modules that can be retrofitted onto virtually any building, and utilizes novel sorbents that have been developed and brought to scale production by enVerid. Although the technology had been deployed and demonstrated, the US commercial building and HVAC markets, famously conservative with respect to innovation and new technologies, had yet to embrace the idea or the product.

The overarching **goal of the project** was to help overcome market hesitancy and enable widespread adoption, by creating a critical mass of success stories across different regions and building types, all under oversight and verification of the DOE and NREL, to ensure credibility and accuracy.

The project, overall, was a resounding success. Several installations were deployed and tested comprehensively for the impact on both energy consumption and indoor air quality, and results were not only excellent, but *quantitatively* in line with expectations. A total number of eight (8) installations were attempted, with 2 aborted due to building issues. Of the six *successful* installations, however, complete M&V was performed by NREL on 2 (Miami and NYC) and partial analysis on a third site (ArcBest), and these three, along with their results, were therefore presented from a financial and reporting standpoint. Although the number of case studies fell short of the original target of 10, we nevertheless had excellent demonstrations in vastly different climate zones: Southeast, Northeast and Midwest, and in very different building types. This included a modern high-rise office building in New York City and a University Campus health center in Miami, and a mid-rise high-density office in Arkansas.

The cooling load reduction was shown to be significant, ***averaging* 37%** during the final cooling season in the Miami site. In the NYC site, the cooling energy savings were generally less, at around 12%, as expected. While this is a lower number for average/total savings, two comments are important to note: (i) the outside airflow (OA) reduction was not consistent during the data collection period, at least in part understating the attainable savings through incorrect measurement of the “high energy” reference state; and (ii) the peak impact in NYC is almost certainly as high as Miami, with critical ramifications for peak load reduction and equipment downsizing ability.

Importantly, the measured energy savings in all locations were related to the outdoor climate conditions and the actual achievable reduction in outside air, very much in line with models and calculations; this leaves us with increased confidence in our

understanding of the interaction between the technology and the building, and our ability to project the impact of this innovation in the future, through broad adoption. Simply put: **the energy savings and load reduction impact of the HLR solution has been confirmed quantitatively**.

The results also confirmed the **air quality objective**. This may be even more significant, in that air quality is more complex and harder to measure and quantify, and the performance of the HLR as an air scrubber is the linchpin of the entire solution. In all sites, indoor air quality met or exceeded the required parameters, in terms of achieving the target (low) levels of indoor pollutants. Furthermore, the concentrations of outdoor sourced pollutants were markedly lower, as expected, mostly due to the reduction in outside air intake although in part also due to the scrubbing.

The success was not immediate nor easy, and early challenges with the systems, especially (but not only) around controls and communication, caused delays in commissioning and undermined some of our M&V schedules. The good news is no fundamental issues were encountered and the number of such glitches was declining quickly by the end of the project. Other challenges had to do with coordinating the control of the building OA dampers, which the HLR needs to have in order to deliver the load reduction, but which the facility manager controls regularly and independently. This is not necessarily a problem for normal HLR operation but interferes with accurate M&V, where switching OA settings back and forth on a precise timetable is essential for clean data.

The project provided valuable experience in retrofitting buildings that had been originally designed to operate with less recirculation and more outside air, and some key learnings related to the cyclical regeneration of the sorbents in the operational environment of the building. Some of these learnings gave already been incorporated into ongoing improvements in the design of the HLR module as well as the software that is used to control its operation. The cost and time of retrofit installations is much better understood; so is the test and balance procedure of the building that determines the available range of outside air reduction, which in turn determines the amount of load reduced. We had also implemented at least one annual cycle of sorbent cartridge replacement in the field, after which we tested the used sorbent to assess the rate of degradation of sorbent potency – an important factor affecting the long-term economics of HLR deployments.

A notable shortfall of the project, other than the fact that the number of sites was below target, was that we had not (yet) completed testing to measure and verify (M&V) the **winter energy savings**. This is primarily due to late start on the NYC sites (Miami does not portend any heating savings associated with reduced outside air), combined with the issues of OA damper control. It is by no means suggested that such savings cannot be captured, only that the M&V with respect to winter in NYC has been incomplete.

The value of this project and its interest to the general public are **hard to overstate**. The case studies created from Miami and especially from NYC have, without a doubt, opened up the interest of the broad HVAC industry to HLR in the past year. Major manufacturer reps have signed up to represent and promote the product, and dozens of top tier engineering consultants have introduced HLR as a base of design in upcoming

construction and renovation projects – precisely the overarching goal of this project. These would not have happened without the highly visible installation in NYC and its ultimately satisfied customer. Furthermore, the DOE itself issued a report in late 2017 analyzing *hundreds* of candidate technologies for reducing energy consumption in HVAC; remarkably, the budding HLR solution ranked among the top 3(!); no doubt, its status as a viable and significant contender on this list is informed by the success of these demonstrations. And furthermore, in the wake of these demos, several major energy utilities, led by ConEdison in NYC, have endorsed the HLR solution and now routinely provide substantial cash rebates for customers choosing to incorporate the HLR in their buildings and reap the benefit of the reduced peak load as well as reduced cumulative energy demand. Last but not least, in January of 2019, as this report was being written, the HLR module won the **AHR Expo Innovation Award** for Green Buildings and, remarkably, the prestigious and only **Product of the Year 2019,** being selected by an independent professional panel of judges from AHR and ASHRAE.

Given the confirmation of the enormous energy saving potential of HLR in widescale deployment, as well as ancillary but significant benefits in terms of equipment downsizing and indoor air quality, the benefit of this effort to the public speaks for itself. Accelerating adoption of HLR, without dependence on subsidies and driven by the private sector, is well under way. There is still much work to be done in terms of educating the HVAC and construction ecosystems and improving the product's robustness and simplicity, to further facilitate the adoption of this technology and the capture of its potential value. But the American public will greatly benefit both directly and indirectly in the immediate future and beyond.

II. Comparison of Goals and Accomplishments

The original statement of the project's objective was to "install and operate modular (HLR®) retrofits in multiple and diverse buildings, monitor their performance, analyze the energy savings, overall economics, and verify IEQ/IAQ with specific tests for CO_2 and other contaminants of concern. The set of buildings selected for demonstration should collectively represent target markets based on market and commercialization analyses and strategies. The demonstrations will result in the creation of a body of validating case studies and data to encourage and enable widespread adoption around the country".

The biggest challenge of the project turned out to be the acquisition of suitable sites (buildings), in terms of technical suitability and owner consent and cooperation. Not enough candidate buildings were obtained, and expectations of help from partners like Johnson Controls or others were overly optimistic. As a result, the program took quite a bit longer and achieved fewer demo sites.

A second significant challenge was inconsistent cooperation and meddling of facility managers during M&V, where changing the outside air damper settings in a quantitatively precise and coordinated manner is the key to the comparison between HLR and conventional ventilation. Facility managers routinely, if unofficially, modulate

OA settings based on outside conditions, and were understandably reluctant to cede control of the OA damper settings. These problems were eventually overcome in some sites, after being identified and "renegotiated" with the facility managers; but much of the data collected during the intended M&V periods was partially or wholly compromised due to changed settings of the OA dampers that were not known to our team at the time, and precious time was lost repeating tests or worse, waiting for the next summer cooling season.

Despite the above, the main goals of the program were achieved with much success. From a deployment and technological standpoint, we note:

1. Permitting was initially a major concern but in the end successfully achieved, even with the notoriously tough NYC Department of Buildings.
2. Mechanical and electrical installation was successful. Although some labor costs exceeded initial estimates on the first few installations, these have been brought under control over the course of the program.
3. Solutions for ducting regeneration exhaust were found in each site; in some cases, adding an external booster fan was necessary. An important learning.
4. All units were commissioned and after initial issues, worked continuously and as designed, including of course regular regeneration – the key to the technology's performance.
5. The systems were shown to work with both ducted return air configurations as well as non-ducted plenum configurations.
6. Cartridges showed good stability over many cycles.
7. Cellular communication initially had glitches but was eventually stabilized.

From a performance and demonstration point, the achievements were generally very good:

1. Load reduction and energy savings, when OA dampers were correctly controlled, was excellent.
    a. In Miami, where after initial damper management issues we did achieve good damper control we measured load reduction between 35 – 40% with an average of 37%. In fact, this is most likely an underestimate of the actual impact because in the open damper (conventional) setting, even with the higher energy usage, the building still failed to achieve its desired humidity setpoint. It did so easily with the help of the HLR, while using less than 2/3rd s of the energy.
    b. At ArcBest, the building systems were fundamentally unable to cool the building with conventional OA setting, despite the fact that the building was originally designed to those set points. But with the HLR and the reduced OA, the HVAC did absolutely fine. While this limited our ability to perform a true comparison of energy savings (operating in the reference mode was unacceptably uncomfortable to the occupants), the impact and value were qualitatively established and all the more critical, and the customer was delighted.
    c. In NYC, damper setting management was not consistent, and together with the generally more variable summer weather in the Northeast, made it more difficult to collect as much data as we wanted. Still we were able to

show 5% average load reduction within the limited days where the data was relatively reliable. The lower number (compared with Miami) is not necessarily disappointing, in that it had good agreement with models for the specific climate conditions on the days this data was collected.

2. Air quality
    a. Indoor air quality was tested comprehensively in all sites, including electronic IAQ sensors as well as collection of air samples that were then shipped to an independent analytical lab for complete trace chemical analysis.
    b. Measured contaminant concentration levels from all sites showed IAQ was improved with respect to baseline IAQ conditions, despite the reduction in OA. In other words, the HLR capabilities, and the number of modules designed and deployed, provided a fully satisfactory solution for IAQ, as hoped and as intended.
    c. In NYC it was also shown that IAQ was exceptionally good with respect to outdoor pollutants such as Ozone and PM2.5, in fact so good that we were mostly at the detection threshold of the instrumentation.
3. In terms of spanning geographical variety and building-type variety, we achieved some if not all our goals:
    a. As already pointed out, we did have installations in multiple locations including Miami, Arkansas, and NYC. Outside the scope of this program, we have deployed more systems in these and other locations including Boston, Chattanooga, San Antonio, and outside the US. This is positive but admittedly incomplete.
    b. In terms of building type, we had both high-rise office towers, several mid-rise buildings, a college campus building, a library. It would be desirable to expand the functional type of buildings to include retail stores and classrooms, two important market segments. Similarly, low rise buildings with rooftop based packaged HVAC systems represent a large market segment and it would be desirable to expand the demonstration set to include representation from this category.
4. Related to both these topics is the question of winter/heating load reduction.
    a. While heating load reduction is rather complicated and not a necessary condition for validation of HLR, it remains desirable to have a demonstration of this benefit at least in the areas subject to cold winters, and to establish how it varies across different types of buildings. This work is under way and expected to be completed in the coming year, outside the timeframe and budget of the DOE program.
    b. IAQ management with HLR in winter is not a concern, as the issues are not really any different, and certainly no more challenging, in winter than in summer. The question of energy is more nuanced, as buildings often require cooling of the core while heating the perimeter, and if the former can be achieved with “free” cooling from outside air, there is less benefit in maximum reduction of OA.

III. Summary of Work

Obtaining Sites

Numerous sites were evaluated and ultimately 8 were chosen for installation, though of these 8 only the first 3 were accepted as part of this program and funded by it. The remaining sites did in fact proceed to installation by enVerid but were not funded by this work nor verified by NREL and are therefore considered outside the scope of this report.

Included sites:

Site	Location	Initial Installation
1. UMH Wellness Center	Miami, FL	3Q 2015
2. ArcBest HQ	Fort Smith, AK	1Q 2016
3. Morgan Stanley HQ	New York, NY	2Q 2017

Technical details about each of these sites are well-covered in the independent NREL report and the case studies and are not repeated here.

Installed but excluded sites:

1. University of Miami (UM) Richter Library
2. Diplomat Conference Center
3. U.S. Custom House in downtown Houston, TX
4. Google Boston Office Building

Manufacturing & Installation

The HLR modules for the UMH installation were the third-generation design, HLR-500C, manufactured for enVerid at Cox Engineering in Canton, MA; the units delivered to ArcBest and Morgan Stanley were the fourth-generation design, HLR-1000E, manufactured for enVerid by Cambridgeport Air systems in Salisbury, MA.

Sorbent and cartridges were produced by enVerid at its partner site in Mars, Pennsylvania.

Electronics, sensors and controls were assembled for enVerid at Elreha Printed Circuits in St. Petersburg, FL.

enVerid staff managed all three installations with the use of local subcontractors. Commissioning was performed by enVerid staff engineers in all three sites.

Operation, M&V & Results

1. UMH Wellness Center

The Building: Located at the University of Miami Miller School of Medicine in downtown Miami, this 13-story building opened in October 2006. The UHealth Fitness and Wellness Center occupies the top two stories and spans 60,000 ft^2. The facility includes a 15,000 ft^2 fitness floor with over 100 pieces of state-of-the-art cardio and strength equipment, four group fitness instructional classrooms including a dedicated studio cycling room, and Central Table Restaurant which serves fresh and healthy cuisine daily.

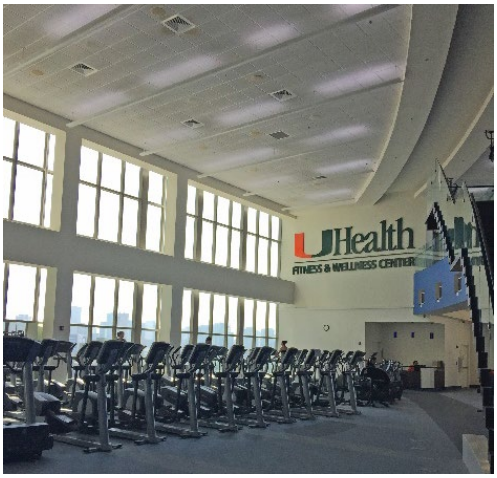

Figure 1. UHealth Fitness and Wellness Center

The challenge: The indoor air quality (IAQ) was not at the level the facilities management team desired. Fitness centers generate a lot of carbon dioxide (CO_2) from people exercising, and the equipment and mats can off-gas formaldehyde and volatile organic compounds (VOCs). Using increased outside air ventilation to improve the air quality inside was attempted, but it made it difficult for the HVAC systems to maintain a comfortable indoor temperature and humidity. Further, the energy consumption of the HVAC equipment was already quite high and adding more hot, humid outside air ventilation would cause a significant increase in utility costs.

The Project: The center is served by four air handling units (AHUs) and a pool dehumidification system. The AHUs are connected to a central chilled water system that serves the medical campus. The scope of the HLR installation excluded AHU-1 and the pool area since this area requires special handling and is served by a separate AHU. In June 2015, enVerid and Johnson Controls installed three of enVerid's HLR modules in the mechanical rooms serving the Wellness Center.

The impact: Improved Energy Efficiency and Indoor Air Quality (IAQ):

- 36% average reduction in cooling energy consumption (Figure 3)
- 41% peak HVAC capacity reduction
- 75% average reduction in outside air

• Per HLR module savings each year
»» $6,500 energy savings
»» $3,100 water savings
»» 19-ton reduction in peak HVAC load
• Better indoor comfort: Relative humidity decreased 10% and air temperature reduced 2.5 °C (Figure 4)
• Improved air quality: Reduced TVOCs to 780 μg/m^3, average formaldehyde to 29 μg/m^3, CO2 to 753 ppm, and reduced particulate matter from the neighboring highway (see Figure 5).

Figure 2. HLR module installed at the university of Miami.

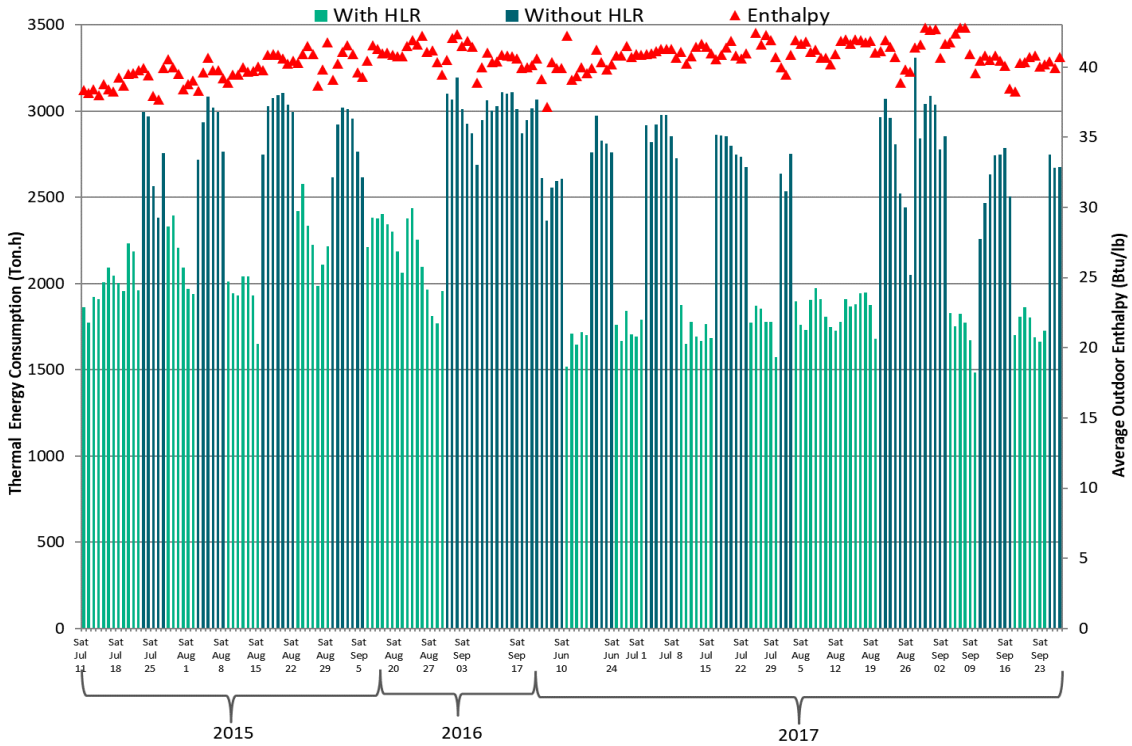

Figure 3. Daily HVAC energy consumption

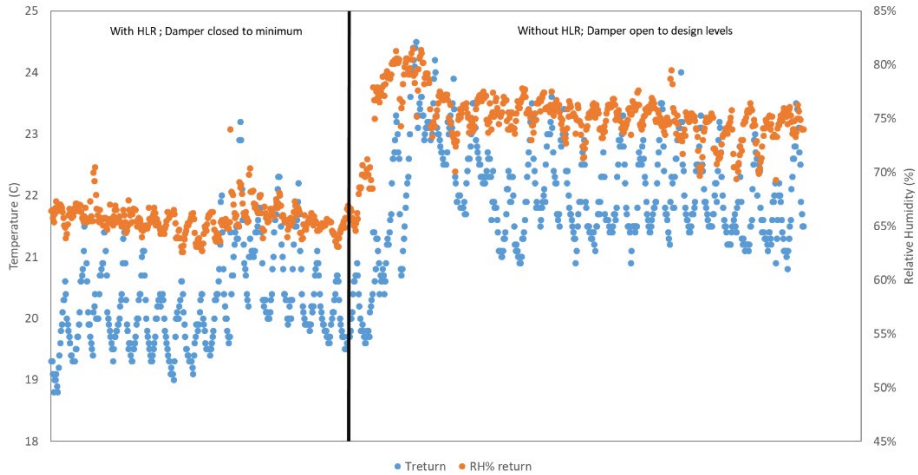

Figure 4. Average hourly indoor temperature and relative humidity from August 14th – September 21st, 2016. HLR system was turned Off on August 30th, represented by the vertical black line.

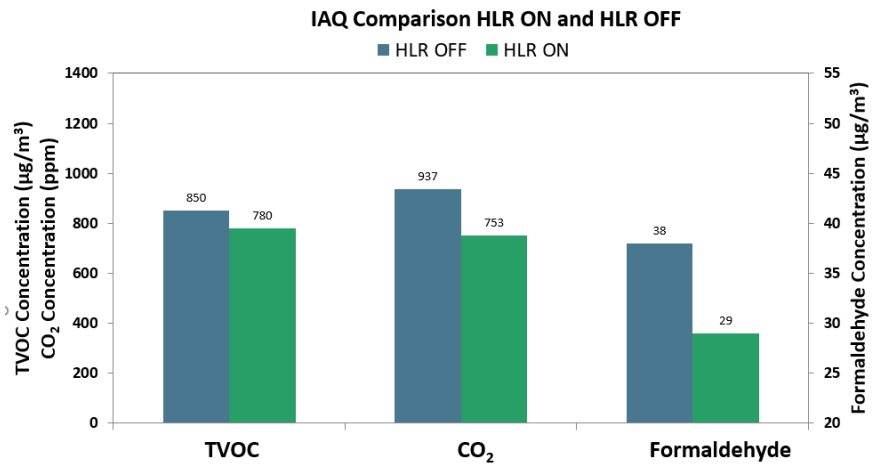

Figure 5. Comparison of total VOCs, CO_2, and formaldehyde with and without HLR technology.

As a result of this successful implementation, enVerid has been selected for three additional projects at the University of Miami: a library, an administrative office building, and a medical office and classroom building.

2. ArcBest Headquarters

The Building: The Corporate Headquarters Building is in Fort Smith, Arkansas, a warm and humid city in the Southeastern United States. The 190,000 ft^2 building has five floors of office space separated into two wings (east and west primary zones). Each wing is served by a dedicated air handling unit (AHU).

Figure 6. The five-story ArcBest Corporate Headquarters Building.

The challenge: Originally designed to support an occupancy level of 850 people, the corporate headquarters has grown to now have 1,085 people plus visitors. Ten percent of the people work at night, requiring 24/7 conditioning of air. The increase in occupancy

drove a need to introduce more outside air to maintain air quality. All of this outside air had to be conditioned, increasing electrical energy costs.

The Project: 10 HLR modules installed in each of the building's mechanical rooms, will cover all spaces within the building. A slip-stream of return air from AHU is ducted through the HLR module to be cleaned. Outside air used for regeneration and regeneration exhaust from the HLR are ducted to the louvered outside air in each mechanical room.

Figure 7. Installation of an HLR module in a mechanical room at ArcBest.

The impact: Reduced HVAC capacity, Improved Energy Efficiency and Indoor Air Quality (IAQ)

- 273 tons reduction in HVAC cooling peak load: At the start of the project, the building's central plant on the ground floor had two packaged hermetic centrifugal liquid single-speed chillers (375 tons each). On warm days, the second 375-ton chiller was required, but now with the HLR modules they typically only need a single chiller as the peak HVAC cooling capacity has been reduced by about 273 tons.
- $63,709 energy cost savings annually
- 65% average reduction in outside air (IAQP using HLR vs VRP)
- $11,535 in water and wastewater savings
- $66,900 utility rebate
- Extended particulate filter life
- All COC and MOC are maintained at a healthy level (Figure 9)
- Eliminated overhead of DCV system: Using IAQP, HLR modules enable reduction in outside air, a feature not available with DCV, because it provides IAQ management for all contaminants, not just people-related contaminants.

Consequently, ArcBest is using the HLR modules to control outside air dampers, thereby bypassing the DCV system. Additionally, by using the HLR and IAQP, ArcBest is now managing ventilation based on all COC instead of just CO2.

- Better indoor air comfort

In addition, when ArcBest replaces the HVAC equipment in the future, the peak capacity required will be 36% less, providing significant savings in capital expense.

BUILDING INFORMATION

Project	Arcbest Existing HQ Building	
City	Fort Smith, AR	
Tariff	Fixed	
Outside Air Reduced	CFM	26640
Operating Hours	from	0:00
	to	24:00
Weekly Schedule	7 Day	
Heating System	Electric ($/kWh)	

ANNUAL SAVINGS SUMMARY

Energy Savings		
Cooling	401,406 kWh	
Heating	545,335 kWh	0 kBTU
Total	**946,741 kWh**	**0 kBTU**
Cost Savings		
Electricity (Usage)	$ 37,870	
Electricity (Demand)	$ 25,839	
Non-Electric Heating	$ -	
Total	**$ 63,709**	

Figure 8. A VRP-compliant design requires 41,240 CFM of outside air. The HLR IAQP-compliant design.

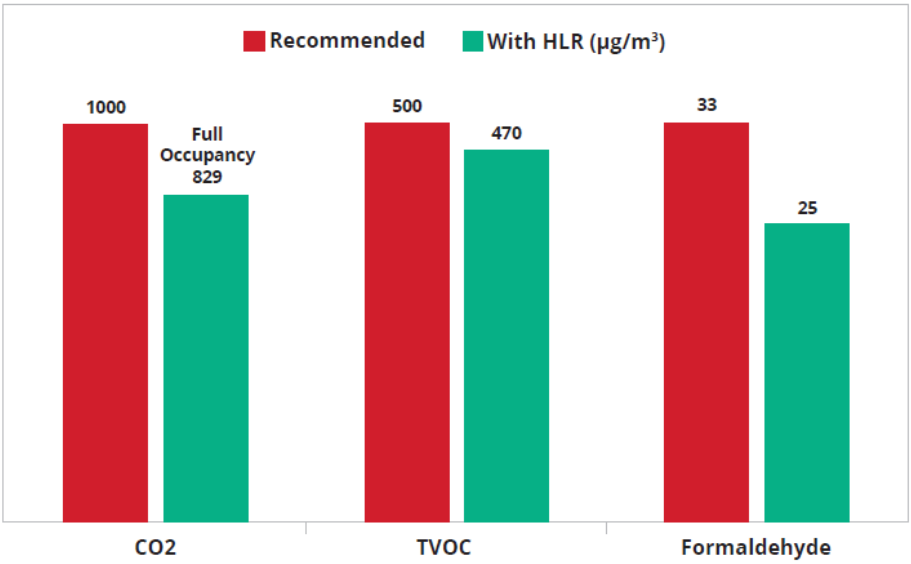

Figure 9. The HLR Systems maintained safe levels for key COC, CO2, TVOC, and formaldehyde.

3. Morgan Stanley Global Headquarters

The Building: Constructed in the 1980s, the global corporate headquarters building is located in the heart of Manhattan, New York, NY. The 1.35 million square foot building has 44 floors of office space and a maximum occupancy of 6,863. Considered Class A office space, the building achieved a LEED Gold rating in 2013, and is Energy Star certified. Critical banking activities occur inside, and so excellent indoor air quality is important to ensure maximal cognitive performance. New York City is considered a non-attainment zone by the EPA and ASHRAE, which means it often has a high concentration of unhealthy ozone. In addition, this area of New York has a lot of traffic, which generates ultrafine particles and combustion gases. Reducing the intake of these outdoor pollutants is highly desirable.

Figure 10. The 44-story Global Corporate Headquarters Building located in Times Square.

The challenge: Hines manages the global headquarters in New York City for a major financial institution. This client has been spending significant money cooling and heating outside air for ventilation, all while knowing that the outside air could no longer be considered “fresh air” due to high levels of air pollution. In addition, Given the important financial decisions being made in the building, not to mention the health benefits, maintaining good air quality is a high priority.

The Project: 40 HLR modules in total were installed in the building's mechanical rooms. A slip-stream of return air from the plenum is drawn into the HLR module by its integrated fans, and after going through the sorbent cartridges, the scrubbed air goes back into return air plenum. Air from the plenum is also used for regeneration. Regeneration exhaust from the HLR is ducted to existing exhaust duct or pressure relief in each mechanical room.

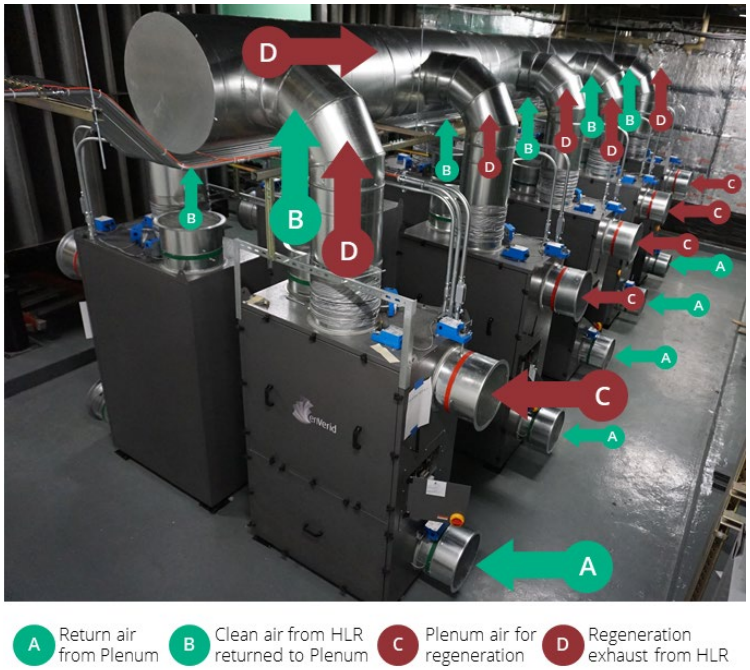

Figure 11. HLR modules were grouped in clusters of 10 each, with a shared exhaust duct.

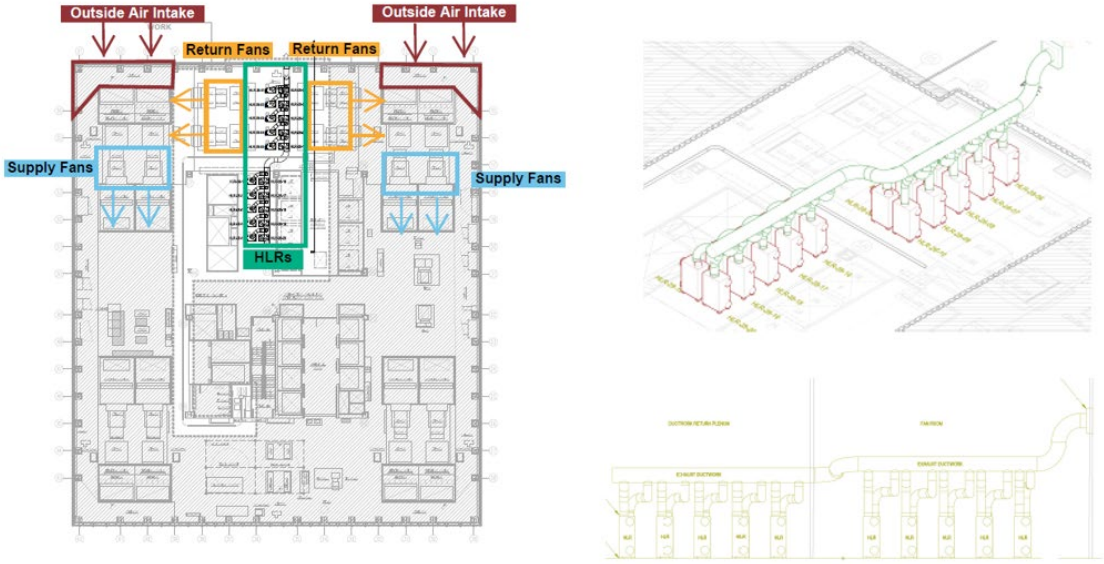

Figure 12. Design diagrams of 10 HLR modules on the 7th floor South, and 10 modules on 7th floor North.

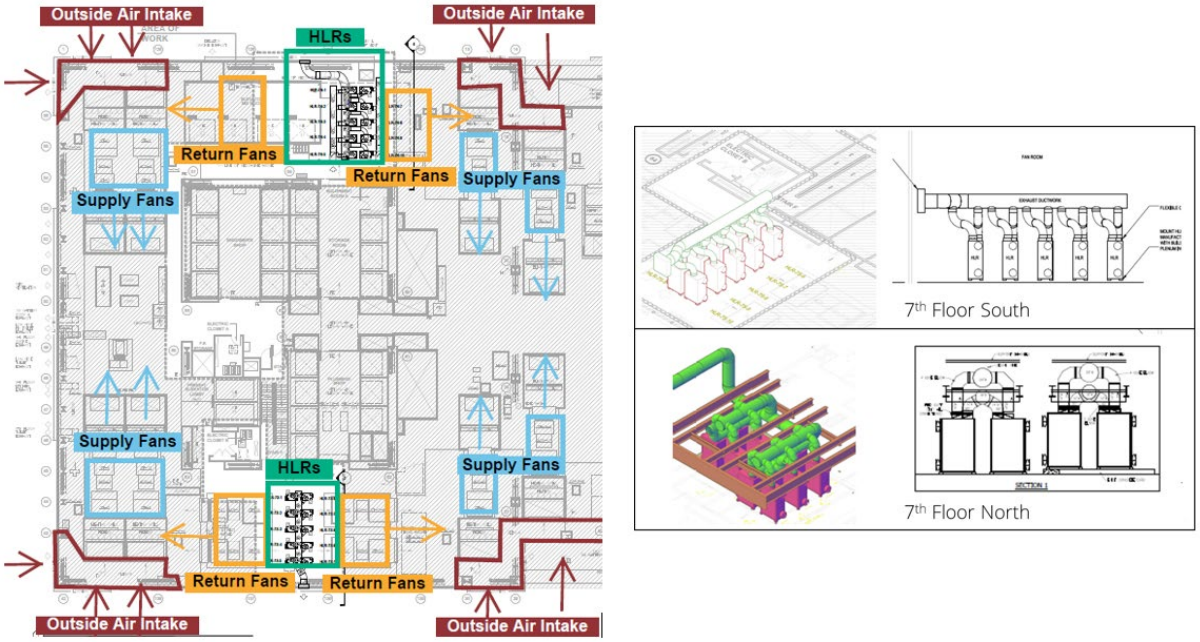

Figure 13. Design diagrams of 20 HLR modules on the 28th floor.

The impact: reduced HVAC capacity, improved energy efficiency and Indoor Air Quality (IAQ)

- 803 tons reduction in HVAC cooling peak load (Figure 14)
  - Calculated based on outside airflow reduction and 5-year historical weather data.
- $403,000 energy cost savings annually
  - Calculated based on actual electric rates (consumption + demand), steam rates, water rates, heating / cooling efficiencies, outside airflow reduction, outside air enthalpy, and hours of HVAC operation.
- 85% reduction in outside air (IAQP using HLR technology vs VRP)
- 592 metric tons annual reduction in greenhouse gases
- $54,370 utility rebate
- Extended particulate filter life
- All COC and MOC are maintained at a healthy level (Table 1)
- Reduced influx of outside pollution (Figure 16)
- Better indoor air comfort

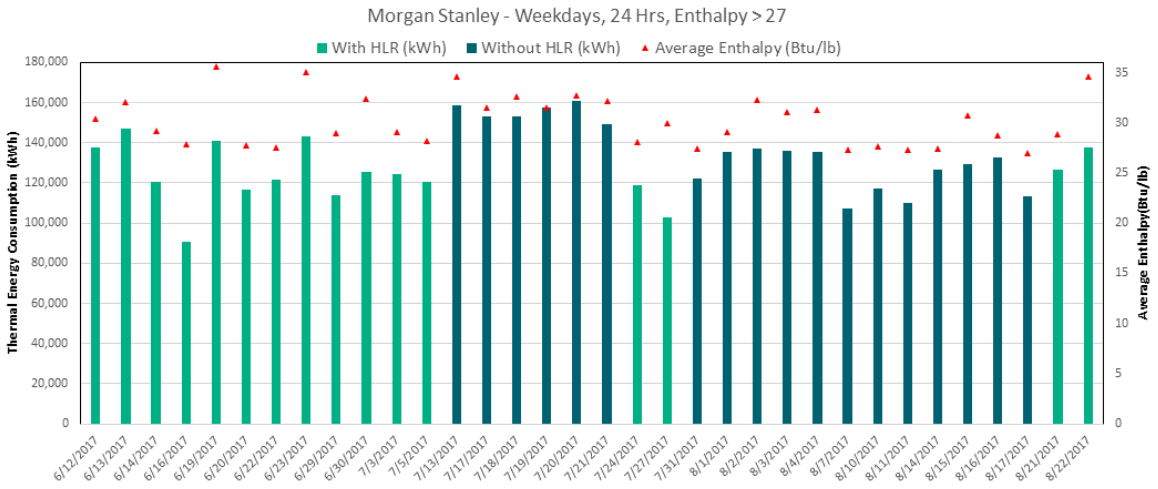

Figure 14. Daily HVAC energy consumption comparison, excluding days when the building was in economizer mode due to enthalpy less than 27. Average daily savings was 11,056 kWh with only a 55,000 CFM reduction in outside air.

Inorganic Compounds and Particulates	Limit	Average Measured Result With HLR
CO (ppm)	9	0.0047
CO_2 (ppm)	1,150	848
PM_1 (μg/m^3)	-	0.3
$PM_{2.5}$ (μg/m^3)	12	0.5
PM_4 (μg/m^3)	-	1.5
PM_7 (μg/m^3)	-	2.1
PM_{10} (μg/m^3)	150	3.7

Table 1. HLR modules maintained low levels of inorganic compounds and particulate matter. Reduced outside air puts less particulate load on outside air filters and extends their life.

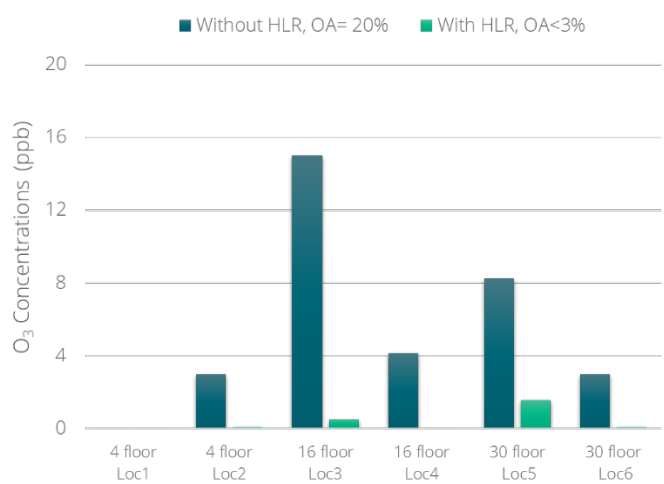

Figure 15. Without HLR, the building brings in significantly higher concentrations of ozone from outside air. Particle filters do not remove ozone, so the reduction in outside air enabled by HLR technology creates a major improvement.

Publications and Recognition

The sites resulted in very good case studies which have been shared broadly with the HVAC engineering community and customers. These case studies include installation details as well as performance results, and are attached herein as a reference and a resource, including:

1. University Campus Health Center in Miami
2. High-rise office tower in NYC
3. Mid-rise office in Arkansas

The HLR solution has received increasing recognition in the recent past, including:

1. A recent study commissioned by the EERE/BTO, authored by Navigant consulting, highlighted HLR as one of the top 3 energy saving technology opportunities for HVAC in the USA, with detailed quantitative analysis of tits overall potential impact.
2. ASHRAE and AHR, the leading trade group for the industry, awarded HLR its highest honor in January 2019 as the AHR Expo Product of the Year. The independent judging panel described the technology as “visionary” and “game changing”.
3. Multiple utility companies have evaluated and endorsed HLR technology, making HLR installations eligible for substantial rebates. These include ConEdison of New York, the MassSave utility consortium in Massachusetts, and Commonwealth Edison in Chicago.
4. HLR has also been qualified by the Massachusetts Clean Energy Center as a “Market Ready Technology” for the DeployMass Program.
5. Independently, the Massachusetts Department of Energy Resources has recently approved a $700,000 grant to install HLR at Harvard University.

IV. Conclusion

The HLR solution was successfully deployed in a small but very diverse set of buildings, and the results provided confirmation of the promise and practicality of this technology. Not only did the performance establish the magnitude of the energy savings and the required air quality metrics achieved in such variable settings, it also presented a rich set of learnings on some of the practical challenges and creative solutions associated with retrofitting buildings of all types with HLR-based ventilation. These important lessons are of foundational value to the continues deployment of HLR on a large scale, nationwide.

To appreciate the success of this endeavor, it is important to keep perspective on the scale of its potential impact, as well as the inherently ambitious goal of changing mainstream HVAC design layout. In this regard, we believe that the program was exceptionally valuable and impactful: the demonstrations supported and independently verified by this program have truly “cracked open” the larger market in many parts of the country. Furthermore, during the 3-4 years of this effort, the market has evolved in ways that only further raise the value of HLR technology, in terms of awareness of air quality, support of electric utility companies for HVAC energy savings, evolution of ASHRAE guidelines and industry awareness of the potential positive impact of reduced outside air intake in commercial buildings.