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Demand Controlled Heat Recovery for Residential Applications

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ABSTRACT

Heating and cooling for residential buildings consumes a lot of energy in the United States every year, which leads to Energy Recovery Ventilator (ERV) systems becoming more common for residential applications. An ERV is a relatively simple air to air heat exchanger with supply and exhaust fans. The supply fan pulls outdoor air into the house while the exhaust fan pulls stale air from the house. The ERV preheats outside air during cold weather and cools/dehumidifies outside air during warm weather. These systems are a good investment because they typically achieve a simple payback of 2 years or less based on energy savings. ERV's also have an important role for Indoor Air Quality (IAQ) in modern energy efficient homes that are carefully sealed to minimize the infiltration. One challenge is determining an optimal strategy for when to turn on the fans for the ERV. Unnecessary run time wastes energy by running equipment when it is not necessarily needed for IAQ.

This paper explores a demand controlled ventilation strategy that has been deployed in a net zero energy home which was designed and built by Purdue University for the 2011 Solar Decathlon. The control strategy only runs the ERV when direct measurements for IAQ indicate that fresh outside air is needed. CO_2, VOC, and relative humidity levels are monitored in the home on a continuous basis. When any of these measurements rise above a specified threshold, the heat recovery system turns on and continues to run until the IAQ levels return to healthy levels. This paper summarizes the results of several years of demand controlled ERV performance in terms of IAQ and energy savings. The results clearly show that this optimized control strategy should be considered in more ERV installations.

1. INTRODUCTION

Data from the U.S. Energy Information Administration (EIA) shows that residential buildings consume approximately 20% of the primary energy used in the United States. Roughly 1/2 of that total is for Heating, Ventilating, and Air Conditioning (HVAC) and the amount of energy for HVAC is increasing. The unit cost of energy is also increasing and that, along with concerns about climate change, have led to increased attention for energy saving opportunities. Residential houses are increasingly being built airtight in order to decrease infiltration and HVAC energy consumption. An unintended sided consequence is that a well-insulated and tightly sealed building envelope can have a negative effect on Indoor Air Quality (IAQ). To counter this trend, an HVAC system must bring in a certain amount of fresh air while taking out exhaust air to meet IAQ and residential health. Both the demands of indoor air quality and energy savings led to Energy Recovery Ventilation (ERV) systems becoming more common in residential applications.

An ERV is a heat exchanger that transfers heat between exhaust air and fresh air in an HVAC system. It is designed to provide fresh air into the building while exhausting an equal amount of stale air to the outside. Energy, sometimes including latent loads due to moisture, is transferred between the airstreams. This reduces the loads on the heating and cooling equipment while delivering the air comfortably and quietly into the space. ERV systems also have an important role for indoor air quality in modern energy efficient homes that are carefully sealed to minimize the infiltration by providing a consistent amount of fresh outside air to maintain healthy living conditions. Although ERV's are not common in residential applications in the U.S., they have been widely used in many European countries, especially in the high latitude nations such as Germany and Sweden, where ERV systems have become a requirement in residential buildings.

Figure 1 is the schematic of an ERV system that highlights the energy transfers taking place. Suppose the season is winter and outside air is cold. One duct of the ERV system carries cool (blue: from outside to inside) outside air (T_1) into the home and through the system, where the air will be pre-heated to state point T_2. The warm (red: from inside to outside) air from the home at state point T_3 is exhausted through the ERV and is cooled to T_4 before it is delivered outside. The red and blue streams exchange energy such that the outside air is heated before entering the home.

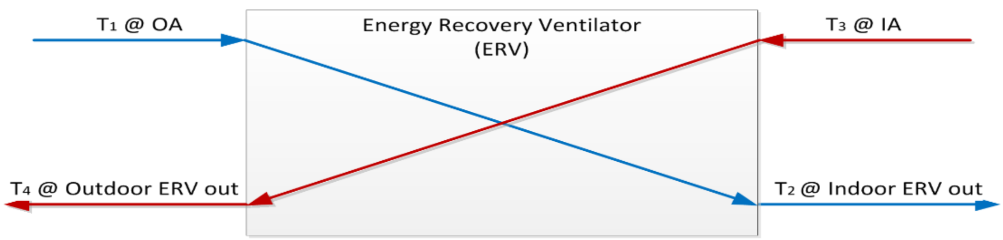

Figure 1. ERV schematic of heating outdoor air in the winter.

During the summer, the process works in reverse. Warm air from outdoors enters at T_1 and is cooled by the air T_3 that is being exhausted. This process saves energy by using less cooling from the HVAC system. At the same time the contaminated indoor air can be moved out while the fresh outdoor air can supply to the house to maintain high levels of IAQ and a comfortable environment.

Effectiveness is one parameter to evaluate the performance of an ERV system. The effectiveness (ε) of an ERV system is the ratio of the sensible energy transferred to the outside air as compared to the total energy transported through the heat exchanger. From the temperatures shown in Figure 1, the effectiveness of an ERV system can be calculated as shown in equation 1:

$$\varepsilon = \frac{T_2 - T_1}{T_3 - T_1} \tag{1}$$

For this equation, T means temperature, and T_1 is the temperature of outside air, T_2 is for supply air to indoors, T_3 is for return air and T_4 is for the exhaust air. In this paper, effectiveness is used to quantify the sensible energy performance of the ERV in sample house. Effectiveness values for common residential ERV systems range from 60% to 80%.

Some ERVs also transfer moisture (latent heat) between the supply and exhaust streams. The latent performance of ERV can be significant in humid climates because the ERV reduces the humidity of the fresh air entering the building. When latent energy is considered, other indices like Coefficient of Performance (COP) or Recovery Efficiency Ratio (RER) can be used to evaluate the performance of ERV system. The determination of whether a sensible or total ERV is appropriate is largely dependent on the weather conditions as a specific geographic location.

A number of researchers have modelled and evaluated the performance of residential ERV's. Zhang*et al* (2006) analyzed ERV efficiency with different factor and developed an equation for Coefficient of Performance (COP). Liu *et al* (2007) simulated the performance of an ERV in different weather conditions and compared the energy savings. Some studies have shown that ERV systems can decrease the annual heating energy consumption significantly. Apart from heating and cooling, an ERV also provides moisture control. Also, some studies have compared the performance of ERV systems in different locations and given suggestions about choosing the type of ERV (sensible or total energy) based on climate conditions.

There is also one practical challenge for ERV system operation in terms of determining when to turn on the fans. Most ERVs use a simple timed schedule that runs the supply and exhaust fans on a 25%, 50%, 75% or 100% duty cycle, which wastes energy by running equipment when it is not necessarily needed for IAQ. It is also possible that the room

needs fresh air while the ERV is not running according to its time cycle. Although some research has been conducted on optimal ERV systems, it has been mostly limited to theoretical modelling. The purpose of this paper is to propose a potential solution for improving the efficiency of an ERV system using a smart controller that makes direct measurements of CO_2, VOC and relative humidity. This control strategy can improve ERV operation by determining when the system is on or off, which means that it only works
when it is necessary to improve IAQ.

2. SMART HOME LAYOUT

A student team from Purdue University designed and built a home for the 2011 Solar Decathlon. Called the INhome (short for Indiana Home) at that time, it earned a 2nd place finish in this international competition. After the competition, the home was moved to Lafayette, IN and became a private residence. The home includes many smart features, including an ERV that has operated on a smart demand controlled strategy. It was also designed to be net zero in terms of its demand for energy all from the electric grid using a 9 kW solar array located on its roof.

The INhome was designed with the intention of proving that attractive, practical, and efficient housing is available at an affordable price. Figure 2 shows that the house was designed for a typical Midwestern consumer, with a contemporary style that would fit in a typical neighborhood. The home was competitive in terms of in today's cost expectations for a new home. The total cost of construction was $250,000, including the solar array that provides all the electricity for the home. Based on the size of the home, the cost translates to $250/ft^2, which includes the cost of the solar array that provides all the electricity. The goal was to show people that the transition to solar powered living could be a smooth and financially realistic one, while maintaining the familiar comforts of home.

Figure 2. Front view of INhome.

The INhome is a new generation of smart house. It is connected to local electric grid but can provide all of its electricity from solar panels. Apart from solar energy, the INhome has passive and active features to minimize energy consumption. It uses high levels of insulation and air sealing and also has large south-facing windows that make daylighting possible. A web-based controller monitors HVAC and security in this house. All of these features combine to fulfill the goal of a net zero energy house.

3. ERV SYSTEM FOR INHOME

Figure 3 is a three-dimensional view that highlights the HVAC system of the INhome that was designed to provide high thermal comfort and exceptional indoor air quality. The green ducts show supply air from outside the house and the orange ducts show return air moving inside the house. The key components of the HVAC system are numbered ① through ④ in Figure 2. ① is a biofilter that was located in the living room to provide natural filtration for house but was recently decommissioned. ② is the Air Handling Unit that modulates air flow throughout the house through carefully placed ductwork within the INhome's conditioned space. The highly insulated duct also conserves the heated or cooled air as it is distributed throughout the home.

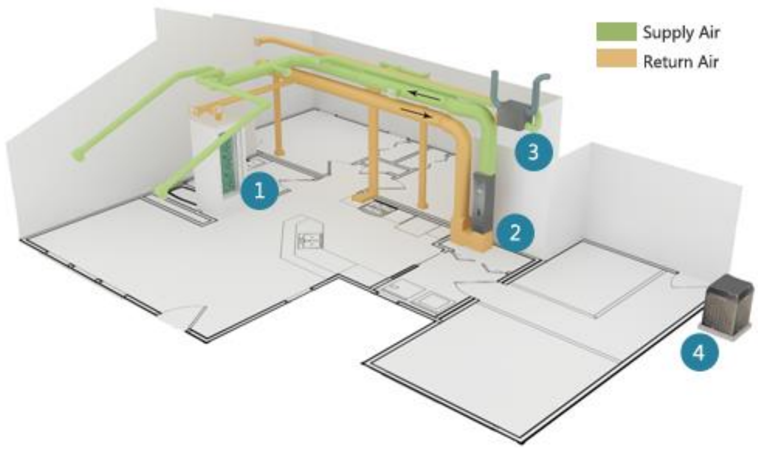

Figure 3. Routing of supply and return ductwork in the INhome.

An ERV was incorporated into the mechanical design to regulate the ventilation air brought into the home. The total cost of the ERV was approximately $1,000, which includes $500 for the ERV itself and $500 for installation. In Figure 3, ③ is the ERV that is located in the utility closet. The ERV is ducted to draw return air from the bathroom and also works as a bathroom vent. Outside air is routed through the ERV and delivered to the space through a grill located high on a wall of the kitchen. ④ is an air source heat pump, which serves as the primary source of heating and cooling for the INhome.

The default operation for a typical ERV is a simple timed cycle. Under this mode of operation, an ERV operates at least 30 minutes out of every hour, regardless of occupancy or the need for fresh air. This is potentially wasteful because the HVAC system has to operate to provide conditioning for the outside air.

Instead of a timed cycle, the INhome used a more sophisticated demand controlled ventilation strategy. This approach was made possible by the automation and control used in the home. An advanced web-based building automation system monitored and controlled the performance of the ERV. It allowed researchers to remotely monitor VOC, CO_2 and relative humidity levels in the home and turn on/off the ERV accordingly. Despite all the automation, the homeowners also had a local over-ride in the bathroom to manually turn on the ERV. In addition to the building automation system, a separate web-based system for monitoring electricity use provided component level energy data, including data on the energy consumption of the HVAC system and the ERV. Taken as a whole, the level of automation in the home provided a basis for this research into demand controlled ventilation for residential applications.

Equation 1 in this paper shows how to compute effectiveness (ε) based on temperature data. The effectiveness of an ERV is similar to efficiency because it measures how well the device is pre-heating and pre-cooling air. Using data from the web-based control system in the home, the outside air, supply air, and return air temperature were monitored while the ERV was running and used to compute effectiveness. An average effectiveness of 87% was then computed from these individual readings. The ERV in the INhome has a typical effectiveness of 60-80% which is better than the typical ERV that is used in a residence. The effectiveness is essentially constant over the whole year, so this 87% value was used as the basis for further computation and analysis.

Table 1 lists the sensors that the ERV uses as triggers for the demand controlled ventilation along with the range and accuracy of each sensor. All of these devices are commercial-grade sensors for general HVAC use and are not as accurate as research-grade sensors. The VOC sensor detects Volatile Organic Compounds (VOCs) from human respiration, building materials, perfume, colognes and furniture off-gassing and is calibrated in ppm of CO_2 equivalent. The CO_2 sensor primarily measures human respiration, so the reading tends to increase with more people or higher activity levels in the home. The range for both the VOC and CO_2 are 0-2000ppm. The relative humidity sensor records moisture levels in the home from 5% to 95%.

Table 1. Sensors for smart control of ERV.

Sensor	Accuracy	Range	On/Off thresholds
Volatile Organic Compounds (VOC)	±5% ppm	0-2000 ppm	1000/900 ppm
Carbon Dioxide (CO_2)	±3% ppm	0-2000 ppm	900/800 ppm
Relative humidity	±5% RH	0%-95%	60/55 %

The building automation system turns on the ERV when direct measurements from one of the three sensors in Table 1 indicates that fresh outside air is needed. These thresholds were based on recommendations from ASHRAE Standard 62.2, Ventilation for Acceptable Indoor Air Quality in Residential Buildings. To minimize short cycling of the ERV, each sensor has an initial higher set point to initially turn on and then a second lower set point to turn off. Table 1 shows that a CO_2 level above 1000 ppm turned on the ERV and it continued to run until the level went below 900 ppm. VOC readings above 900 ppm turned on the ERV and it continued to run until the level went down to 800 ppm. Sensors in both the restroom and living room would trigger the ERV if the relative humidity level rose above 60% and remain on until the level dropped to 55%.

The ERV system in the INhome also has manual control. A timer switch located in bathroom allows the house owner to turn it on whenever it is needed. Apart from maintaining and improving indoor air quality in the whole house, the ERV also works as the bathroom exhaust fan. When the residents take a shower or want fresh air of bathroom they can operate the ERV system manually. This means even though the level of CO_2, VOC and relative humidity all may be below thresholds, the ERV system may run based on the requirements of the homeowners. So the manual control needs to be considered when analyzing the performance of ERV system.

An analysis of the data collected for the ERV shows that the demand control algorithm turned “on” the ERV for about 3000 hours out of 8760 total hours in a year. This means that the ERV had a 34% duty cycle to maintain IAQ in the home. This estimate does not include a small amount of time when data was inadvertently lost due to disruptions in internet connectivity. The 34% ERV duty cycle is significantly less than the 50% to 100% duty cycle that is common for time-operated ERVs. The reduction in runtime also translates to significant energy savings due to decreased loads on the HVAC system in the house and decreased ERV fan run time.

Figure 4 summarizes the energy savings of the ERV system during its run time. The horizontal axis (independent variable) is the cumulative number of hours in one year when the ERV operated. The vertical axis (dependent variable) is the temperature of the outdoor air before and after the ERV in degrees Fahrenheit. The horizontal boundary shows the constant 70˚F room air temperature that is essentially constant. The lower boundary of the curve (green) shows outdoor air temperature on an hourly basis when ERV was running. The middle curve, at the boundary of the two color zones, shows the beneficial impact on air temperature from a heat recovery system with an effectiveness of 87%.

In Figure 4, the colored zones illustrate heat recovery performance. The area of the green zone is proportional to the energy recovered. When the temperature is cold, the green zone is pre- heating energy. During warmer weather it means pre-cooling of outside air. The area of red zone is the additional energy required from heating or cooling the space using the air source heat pump. So the building benefits from pre cooling and heating with the ERV system. Figure 4 illustrates that heat recovery is more beneficial during cold winter weather, but it also helps reduce the cooling loads during hot summer weather by a small amount.

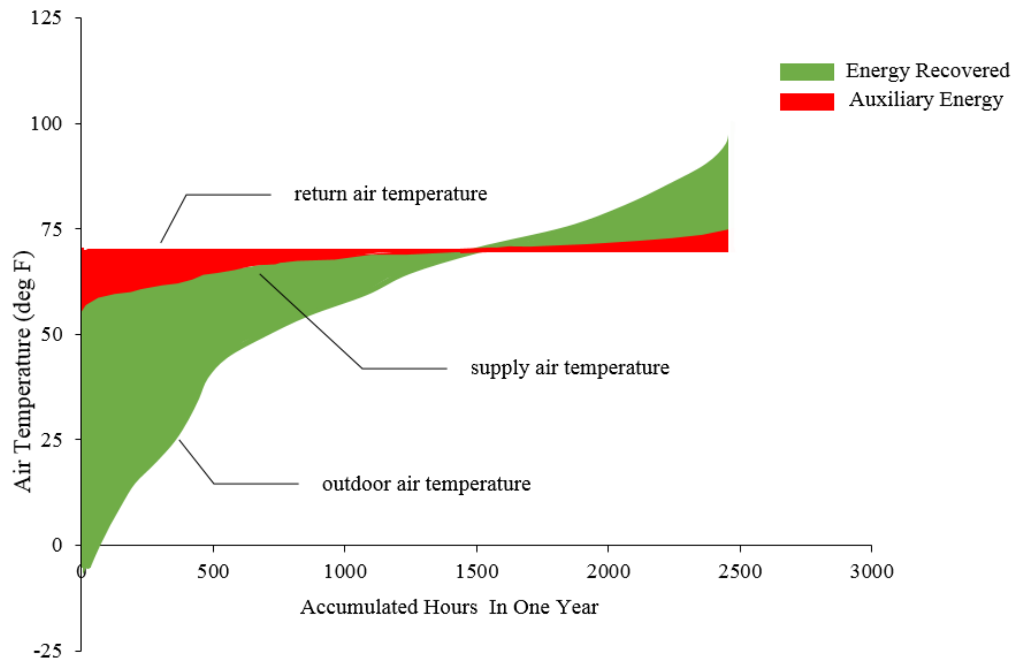

Figure 4. Annual benefit of the ERV system.

4. RESULTS

4.1 Indoor Air Quality Result

Although the INhome has been occupied since 2013, that first year had many disruptions. During 2013, the house was painted and custom furniture was installed. Considering all the decoration work in 2013, the CO_2 and VOC data for 2013 does not accurately reflect IAQ levels for a common residential house. This paper analyzes data from 2014 and 2015. In addition, there were several disruptions in data collection in 2014 and 2015 so that data is not 100% complete for any one year. The data disruptions occurred when the web-based control system turned itself off while performing maintenance or due to disruptions in internet service. As the data for these two years covered most of the time, the data can accurately represent the annual indoor air quality from the demand controlled ERV system.

Table 2 is a summary of the percentage of time that the data collected from IAQ sensors were above the limits for acceptable IAQ using the thresholds described above. Table 2 shows that the VOC exceed the limitation about 21% of the time, while CO_2 and relative humidity exceeded only about 5%. Most of the time these parameters were below the preset threshold levels, indicating acceptable IAQ in the INhome. Table 2 also shows that the zone VOC exceeded its threshold value most often, indicating that VOC is the main index that influenced IAQ.

Table 2. Percentage of parameters above limitation

Sensor	Zone VOC	Zone CO_2	Bathroom RH
Percentage of Time Above IAQ Threshold	21.1%	6.2%	4.6%

The author chose a long time period without interruption and a constant sampling rate when analyzing the relationship between different signals and ERV operation. However, a software update inadvertently took the data acquisition system offline and prevented data logging for a period of time. To counter this gap the paper will present the weighted average of available data to represent the annual performance of the signals and sensors.

Figure 5 shows the percentage of time that multiple triggers turned on the ERV. There are four cases to turn on the ERV. One option has no sensor above the threshold, indicating that the homeowner turned on the ERV manually. This case accounts for about 25% of the measuring time. Another case is when one sensor is above its threshold, which takes more than 50% of the time. Two sensors above their threshold occurred about 20% of the time. All of three sensors were above their limits only about 3% of the time, which is the least common option. Figure 5 shows that just one sensor energized the ERV on and about 1/2 the time. About 25% of the time, the ERV was operated by hand.

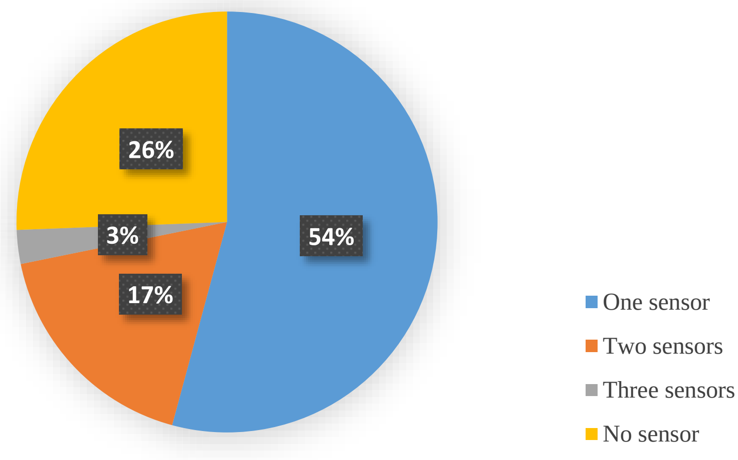

Figure 5. Number of sensors above limitation when ERV works

Through Figure 5, it can be seen that this system can fulfill smart control. The ERV in the INhome was always controlled by indoor air quality sensors. As the percentage when more than one signal energized ERV is 20%, so there was always one or no poor signal to influence air quality. When combined with smart control strategies, the indoor air quality is acceptable for the INhome. Notice that the system can operate manually, so the ERV system may save more energy if it is just controlled by VOC, CO_2 and RH signals in this house.

Figure 6 is the weighted percentage of measured time when a parameter energized the ERV system. The ERV operates about 35% of the time each year. As mentioned above, the number of sensors that drive the ERV in INhome is varied. For this figure, it counts for all cases of ERV worked without manual. It takes indices of VOC, CO_2 and relative humidity of bathroom. It is easy to see that VOC is main source that energized ERV system, since it took 65% of possibility to trigger ERV while RH is about 20% and CO_2 is 15%. This result is similar to Table 2.

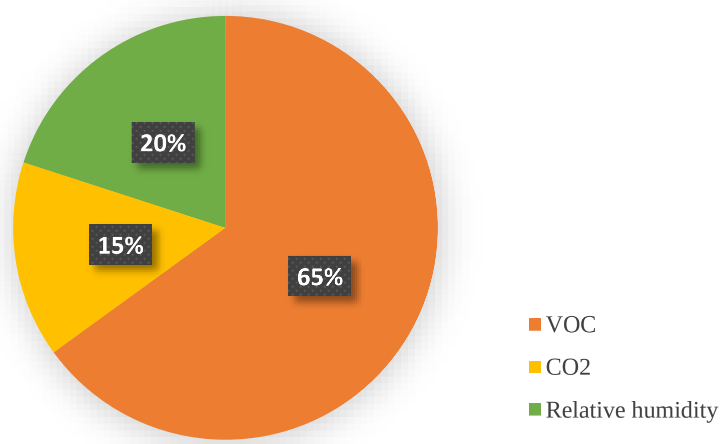

Figure 6. Sensor which energized ERV system.

4.2 Savings for Smart Control ERV

A demand controlled ERV can save energy cost compared with a common ERV. From Emonitor, a website to record energy consumption of the INhome, the annual energy usage of the ERV system is 110kWh. This is based on an instantaneous power consumption of 30 to 40 Watts by the fans. It takes a very small part of the whole house annual energy consumption and less than 1% of the total energy consumption for the home. The residential electricity rate in Lafayette is about 0.12 $/kWh and suppose the ERV system is used in a residential house without smart control. In this instance, the ERV works the whole year for a total of 8760 hours. The annual energy cost can be calculated using equation (2). In this equation, η represents percentage of annual work time of ERV system, and t is working time with unit of hour, here is 8760 hours. The cost of electrical energy is around $42.

$$C = P \times t \times electic\ rate * \eta \tag{2}$$

For the smart control ERV system used in the INhome, the annual cost was about $13, which means residents can save $30 each year on fan energy. A detailed comparison is shown below.

Figure 7 shows the monthly electrical consumption of the ERV system in the INhome compared with a traditional house that has an ERV system running all the time. The traditional house used the same model of ERV equipment as the INhome but without smart control. This means that the ERV was not controlled by IAQ and operated 24 hours per day. In this figure, a traditional house using an ERV for 24 hours will have a constant energy consumption from month to month, while electric usage of ERV in INhome varied with time and more less than traditional houses.

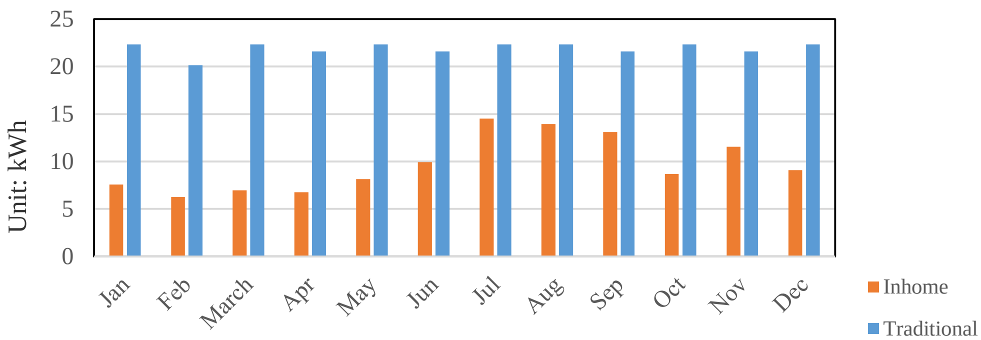

Figure 7. Monthly energy consumption of ERV system.

Figure 7 shows how the ERV energy consumption varied through time for the INhome, which also can reflect smart control of ERV system. During in summer and winter, energy consumption is higher, which means there is a need for more air exchange at that time. One potential reason for this is the residents used heat pump and air handling unit at that time which leads to increased use of the ERV. Consider that the ERV in the INhome also works the vent in the bathroom which can save money on the installation of a vent.

This analysis does not account for the HVAC energy savings avoided from not having to heat or cool outside air unnecessarily. The potential savings from avoided heat and cooling should be substantially larger than the fan electricity savings discussed here. The computations to quantify this additional savings potential is ongoing.

5. CONCLUSIONS

The INhome is a new generation of net zero energy residential house because the cost of ownership is affordable for a typical US family. One challenge with this type of home is that it is tightly sealed and has the potential for poor indoor air quality. The INhome uses an ERV system to save energy and maintain comfort while providing fresh outdoor air. A smart control strategy to make the ERV system more efficient was developed. By setting thresholds for VOC, CO_2 and Relative Humidity, the ERV system only operated when it was needed for IAQ. An analysis of several years' worth of data showed that indoor the air quality in INhome was acceptable most of the time. VOC's were the main contaminant that energized the ERV in the INhome. Through smart control in the INhome, the homeowners saved $30 per year in fan electricity as compared to a traditional ERV that operates continuously. So this optimized control strategy should be considered in more heat recovery installations in residential houses.

NOMENCLATURE

ERV	Energy Recovery Ventilation	
INhome	Indiana Home	
ε	Effectiveness of ERV	
C	Electric cost	$
P	Power	kW

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