# ASSESSMENT OF EFFECTIVE ENERGY RETROFIT STRATEGIES AND RELATED IMPACT ON INDOOR ENVIRONMENTAL QUALITY

## A case study of an elementary school in the State of Maryland

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## 1.0. INTRODUCTION

In the United States, K–12 school buildings spend more than $8 billion each year on energy—more than they spend on computers and textbooks combined [1]. Most occupied older buildings demonstrate poor operational performance—for instance, more than 30 percent of schools were built before 1960, and 53 percent of public schools need to spend money on repairs, renovations, and modernization to ensure that the schools' onsite buildings are in good overall condition. And among public schools with permanent buildings, the environmental factors in the permanent buildings have been rated as unsatisfactory or very unsatisfactory in 5 to 17 percent of them [2]. Indoor environment quality (IEQ) is one of the core issues addressed in the majority of sustainable building certification and design guidelines. Children spend a significant amount of time indoors in a school environment. And poor IEA can lead to sickness and absenteeism from school and eventually cause a decrease in student performance [3]. Different building types and their IEQ characteristics can be partly attributed to building age and construction materials. [4]

Improving the energy performance of school buildings could result in the direct benefit of reduced utility costs and improving the indoor quality could improve the students' learning environment. Research also suggests that aging school facilities and inefficient equipment have a detrimental effect on academic performance that can be reversed when schools are upgraded. [5] Several studies have linked better lighting, thermal comfort, and air quality to higher test scores. [6, 7, 8] Another benefit of improving the energy efficiency of education buildings is the potential increase in market value through recognition of green building practice and labeling, such as that of a LEED or net zero energy building. In addition, because of their educational function, high-performance or energy-efficient buildings are particularly valuable for institution clients and local government. More and more high-performance buildings, net zero energy buildings, and positive energy buildings serve as living laboratories for educational purposes. Currently, educational/institutional buildings represent the largest portion of NZE (net zero energy) projects. Educational buildings comprise 36 percent of net zero buildings according to a 2014 National New Building Institute

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report. Of the 58 net zero energy educational buildings, 32 are used for kindergarten through grade 12 (K–12), 21 for higher education, and 5 for general education. [9]

Finally, because educational buildings account for the third largest amount of building floor space in the United States, super energy-efficient educational buildings could provide other societal and economic benefits beyond the direct energy cost savings for three reasons: 1) educational buildings offer high visibility that can influence community members and the next generation of citizens, 2) success stories of the use of public funds that returns lower operating costs and healthier student learning environments provide documentation that can be used by others, and 3) this sector offers national and regional forums and associations to facilitate the transfer of best design and operational practices.

**KEYWORDS:**

school buildings, school facility management plans, retrofit strategies, indoor environmental quality, energy efficiency

## 2.0. RESEARCH METHODOLOGY AND APPROACH

The research methodology is a combination of 1) occupancy survey and field measurement, 2) visual inspection and construction documents review, 3) literature review, and 4) energy modeling and simulation. The research examines the energy efficiency and indoor environment quality simultaneously.

### 2.1. Occupancy survey and field measurement—IEQ

Regarding IEQ, occupancy survey and field measurement are used to establish the existing building performance baseline. The occupancy survey was conducted to determine occupant satisfaction and the evaluation of existing school indoor environment's comfort level. Filed measurement was conducted to collect quantitative physical environmental indicators: temperature, humidity, light level, acoustic level, carbon dioxide level against regulations, and code requirements. The data from the occupancy survey and field measurement were compiled and analyzed first separately, and then the data were aggregated and compared to establish the correlation or opposite trend between survey results and physical measurement. The primary problematic areas and crucial factors of IEQ were identified. In addition, the major discrepancies between the occupancy survey and the field measurement were identified and possible explanations were provided.

### 2.2. Visual inspection and construction documents review—energy efficiency

The research team conducted visual inspections of the studied building twice, in the fall and winter. Photos of the exterior face and the interior were taken and analyzed. The original construction documents are provided by the county along with other building operating information, such as utility bills and an energy data book. For energy performance, the detailed utility bills and annual energy data book for last five years were used to establish the actual baseline performance.

### *2.3. Literature review—energy benchmark*

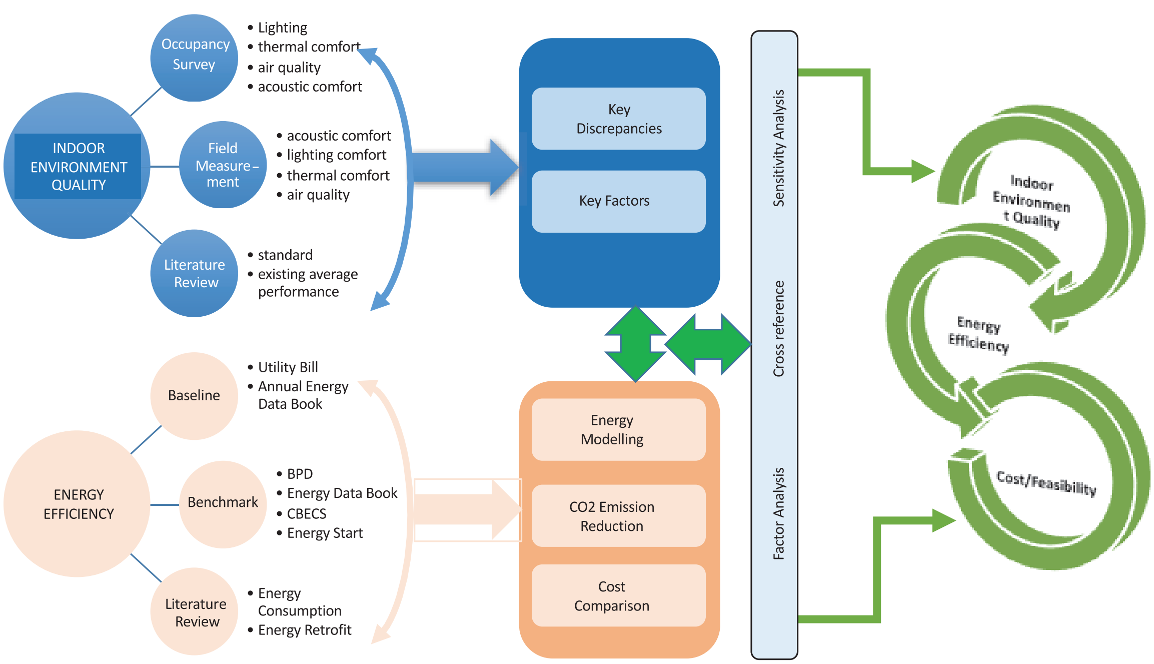
Over 125 research papers were reviewed to gain an overall understanding of existing educational building energy performance in school buildings worldwide, and through the reviews, several vital factors have been identified that have an effect on energy efficiency and IEQ. And the crucial factors recognized through research paper reviews are correlated to the findings from the occupancy survey, the field measurements, and the existing building energy data book.

### *2.4. Energy modelling and simulation*

Based on the previous steps: occupancy survey, field measurement, visual inspection, construction documents review and literature review, the two most effective energy retrofit and indoor environment quality improvement strategies were identified: space heating load reduction and air quality improvement. Based on original construction documents and on-site measurement, a virtual BIM (building information model) was constructed; then energy modeling and simulation were conducted using a BIM model to compare the effectiveness of retrofit strategies against the baseline building. Finally, conclusions and recommendations are made based on the simulation and analysis results.

### *2.5. Assessment framework*

**FIGURE 1.** Research Methodology Diagram.




## 3.0. LITERATURE REVIEW ON ENERGY CONSUMPTION AND INDOOR ENVIRONMENT QUALITY IN SCHOOL BUILDINGS

A vast amount of research was conducted on school buildings regarding both energy performance and indoor environment quality (IEQ). A number of studies demonstrated the high potential for energy savings by retrofitting school buildings. Thewes and colleagues demonstrated the potential energy savings for sixty-eight schools in Luxebourg. The energy-consumption analysis reveals that some simple solutions could have a significant effect on energy reduction, such as adding insulation. They concluded that the overall energy saving of school buildings could account for 1 percent of the nation's annual fuel oil and gas consumption. [8] Butla and Novak conducted an investigation on twenty-four old school buildings in Slovenia regarding indoor environment quality and energy efficiency. They found that 60 percent of the buildings are high-energy consumers and have poor indoor air quality, and the heat losses of the school buildings due to insufficient building envelope insulation are 89 percent higher than are the recommended values. [10] Daslacki and team analyzed different energy retrofit solutions while ensuring that the indoor environment quality was acceptable based on standards; the studies were conducted in three distinct climate zones, and the results showed that performing envelope refurbishments are most commonly used and the most effective retrofit strategies. [14] Duzgun conducted research on twenty-four buildings at the University of Florida and suggested that the blanket sustainability policy and building certification requirement have no significant effect on building energy efficiency. Rather, they recommend focusing on building functionalities and on $CO_2$ emissions from the building. [11] Overall, the building exterior envelope retrofit has been identified as one of the most effective renovation strategies.

Indoor environment is a primary concern in the education building sector: it is perhaps more important than energy efficiency. The US General Accountability Office (GAO) has determined that approximately fifteen thousand schools have poor indoor air quality, which affects more than eight million students, or, out of every five students, one student will be affected. The effects include but are not limited to dizziness, headache, fatigue, nausea, or sleepiness, known as "sick building syndrome" [12]. A large body of research recognized the effects of indoor environment quality on teachers and on student health conditions and learning outcomes. [13, 14, 15] Rosen and team found that improving air quality would reduce students' absenteeism. The experiment was conducted in two Swedish day-care centers using electrostatic air cleaning technology. The implementation of the new technology had a positive impact on indoor air quality and decreased the absenteeism rate. The researchers showed that when indoor fine particles caused by outdoor air pollution were reduced by 78 percent, the absenteeism rate decreased by 55 percent. [16] Smedje and Norback found airborne bacteria and mold could be related to asthma, thereby increasing the absenteeism rates. [17] Toyinbo and team found that ventilation is associated with thermal comfort and students' learning outcomes and that lower mathematic scores could be related to the lack of a recommended ventilation rate. [18] MacNaughton and team conducted research in five US cities and found occupants in green-certified buildings scored 26.4 percent higher on cognitive function tests, controlling for annual earnings, job category, and level of schooling, and had 30 percent fewer sick building symptoms. [19]

Several consensuses about deficiencies in school building energy efficiency and indoor environmental quality that were derived from these studies include the following: 1) a high percentage of school buildings have poor energy performance and often have poor IEQ [20, 21]. Energy inefficiency is correlated to the age of the building. More than 30 percent of schools were built before 1960 in the United States, existing building envelopes do not have sufficient thermal insulation, and space heating is a major energy consumer. In addition, there is a lack of homogeneity of protocols and consistent benchmarks of school building energy performance, particularly K–12 [22, 23]. 2) A large number of schools do not have adequate ventilation, especially during the wintertime. This is mainly due to older schools not having mechanical ventilating systems; when CO2 level reaches higher than 1000 PPM (parts per million), headaches, drowsiness, and the inability to concentrate ensue. [5] 3) Even though a variety of researchers and government agencies published guidelines for school retrofitting, most guidelines are still too generic and not tailored to school buildings' unique operating schedule and users' profile [24].

Based on these findings the case study will pay particular attention to three areas: building exterior envelope construction, building a ventilation system, and indoor environment quality.

## 4.0. CASE STUDY—THE QUARTERFIELD ELEMENTARY SCHOOL

### *4.1. Background of the study*

In 2015, the Anne Arundel County Public School System (AACPS) in Maryland updated the Strategic Facilities Utilization Master Plan that intended to address the long-term (10-year) facility needs of the district. AACPS is the 46th largest in the United States, with more than 80,000 students and 5,000 teachers [25]. ACCPS has 79 elementary schools, 19 middle schools and 12 high schools. [28]

Assessments of AACPS's educational facilities were conducted to determine existing deficiencies as measured against the district's facility standards for new schools. The assessments included building and site conditions, educational suitability, and technology readiness. Each assessment resulted in a score based on a 100-point scale with the four scores weighted to create a "combined score" for each facility.

"Cut-points" were developed for the assessment scores to group and to make the facility needs a priority. In addition, the four facility assessment scores were weighted to develop a combined score that would facilitate comparisons of the facilities. The weighting, developed by consulting with the district and county staff, was 55 percent for building conditions, 35 percent for educational suitability, and 5 percent each for site condition and technology readiness. Anne Arundel County commissioned a consultant-conducted survey and gathered data about community's input on quality of education and the environment of education. More than 70 percent of respondents feel the quality of education is "excellent" or "good" [26]. However, nearly 40 percent of respondents feel the environment for education is "fair" or "poor." Many respondents cited leaking roofs or HVAC issues as examples. There were also concerns about open concept schools that lack walls between classrooms, making instructional spaces too noisy. These survey data show that 42 percent of respondents thought the school buildings were inequitable, and 44 percent of respondents recommended that building condition deficiencies should be rated highest. A majority of respondents (61 percent) identified the general classroom spaces as "poor" and indicated that they should be given the highest priority for improvement. [28]

### *4.2. General Information about Quarter Field Elementary School*

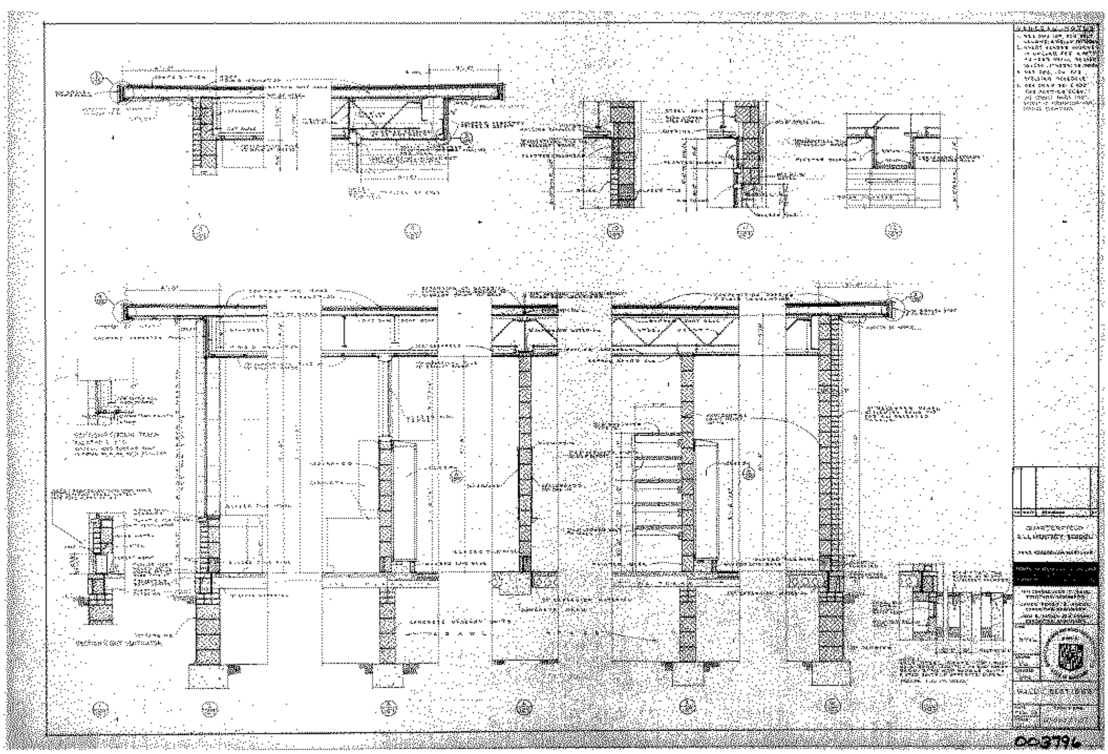
The current building condition was scored as 64.37 out of 100. [28] Total student enrollment in 2015 is 411. Quarterfield Elementary School is one-story masonry of 44,267 gross square feet, located at 7967 Quarterfield Rd., Severn, Maryland (39.1340° N, 76.6546° W). The general shape of the building is a U-shape that is 30 degrees from the east-west axis. The original building was constructed in 1968; there were several renovations and revisions done after initial completion to the present. The medical center was renovated and expanded in 1992, and an additional partition wall was added in 2015. Another renovation included the reconfiguration of the health room in 2008.The remainder of and the majority of the buildings and the primary building system remained in the same condition as it was originally constructed.

**FIGURE 2.** Quaterfield Elementary School Existing Condition.

### *4.3. Exterior Envelope*

The original exterior wall is composed of composite brick veneer with CMU (concrete masonry unit) backup and no insulation or air space in between, which provides very limited R-value to the exterior walls—estimated at R value of 1.90 hr.ft$^2$ F/Btu (national concrete masonry association). The existing wall construction does not meet the current code for R-value based on the ASHRAE 2013 edition with an R-value of 19 for the exterior wall. The exterior brick units are in fair to good condition in general; there are only few areas in which minor damage to the mortar can be seen. At the top course right beneath the roof, some mortar and sealant are missing, which could be easily repaired.

**FIGURE 3.** Existing wall section based on original construction document.



The original roof is made of poured gypsum slab on open-web steel joists with insulation board and composition roofing over it. The composition roofing has a warranty of 20 years, so presumably the roofing has been replaced sometime between 1968 and now; however, no detailed documents have been found. Based on the original construction of the roofing system, the estimated R value could be 5.0 hr.ft$^2$ F/Btu. The existing roof construction does not meet current code for an R-value of 30 based on the ASHRAE 2013 edition. Overall, the existing roof appears to be in fair shape. There does appear to be some ponding issues on the roof due to the low slope for drainage, which is common in buildings built around the same time.

The existing windows are the original units composed of sing-pane un-insulated glass with painted steel frames. Each unit of windows for each room has one or two window-mounted air conditioning units, and currently all window and door units are operable. The existing doors generally have hollow metal frames. The current R-value of window and door units does not meet current energy efficiency standards as well.

In general, through the on-site visual inspection, we could summarize that the existing building exterior envelope is in good condition considering the building's age. The primary problem is that the existing building envelope does not meet current building energy code; in fact, it is far below the current minimum requirement. For instance, the R-value of the exterior wall is only 1/10 of the minimum requirement, and the R-value of the roof is only 1/5 of the minimum requirement. Adding additional insulation is one of the least costly but effective strategies for undertaking renovation and retrofit.

## *4.4. Building System*

### 4.4.1. Structural System

The original structure is composed of steel frame, open web joists supporting a high and low roof, precast floor plank, cast-in-place concrete, and load-bearing masonry. In the original construction, documents date back to 1968; the structure was designed for a live load of 60 pounds per square foot in a classroom and 100 pounds per square foot, which still complies with existing code. However, in the gymnasium and the media room, the load is unknown. The concrete has a compressive strength of 3,000 pounds per square foot, and soil-bearing pressure is 4,000 pounds per square foot. In general, the structure system in Quarterfield Elementary school complies with the current and most up-to date code requirements. Based on a visual investigation, it appears that all major structure elements are in good condition and no immediate and foreseen conditions exist that could undermine the structural integrity.

### 4.4.2. Mechanical System

The current mechanical system includes two fire/oil/gas steam boilers located in the boiler room. The second boiler is redundant, which is available as fuel if needed. Hot steam is fed from the boiler through unit ventilators to the entire building and each unit ventilator has an outside air griller opening for ventilation air. The existing building uses window air conditioning units instead of central air conditioning units. The individual units might be less efficient; however, they do give individual control. There is no mechanical ventilating system in the existing building, and the supply of fresh air is through the operable openings, which could be the reason for the poor indoor air quality that the classrooms in particular are experiencing. (Refer to section 4.5.2)

### 4.4.3. Lighting System

The lighting system was updated. Currently, most classrooms are equipped with 1′ × 1′ fluorescent fixtures with T8 lamps. And the classroom lights are controlled by two toggle switches near the door, and each switch controls one half of the classrooms. Occupancy and daylight sensors are not installed per current AACPS guidelines. In the corridor, 1′ × 2′ fluorescent light fixtures with T8 lamps are used and spaced at 2′ apart. Currently all corridors must rely on electrical lighting to meet minimum lighting level requirements, which is 30-foot candle per the Illuminating Engineering Society (IES) guidelines, even during sunny days with plenty of daylight. In general, the lighting fixtures used meet current standards. By installing and integrating daylight sensors and occupancy sensors, Quarterfield Elementary school could achieve some energy savings from a smart lighting system.

**FIGURE 4.** Existing Interior Condition (lighting and layout).

### *4.5. Indoor environmental quality*

The research team conducted a field measurement to collect environmental data for each room, such as CO2 density, humidity, temperature, lighting intensity, and acoustic levels using several different indoor quality detectors. Meanwhile, an anonymous survey was sent out to teachers and staff in Quarterfield Elementary school. Out of 45 full-time and part-time employees, 19 responded. Overall, thermal comfort and air quality received the lowest scores. A great deal of improvement is needed, and both elements directly relate to current mechanical systems, particularly the ventilation system.

#### 4.5.1. Lighting

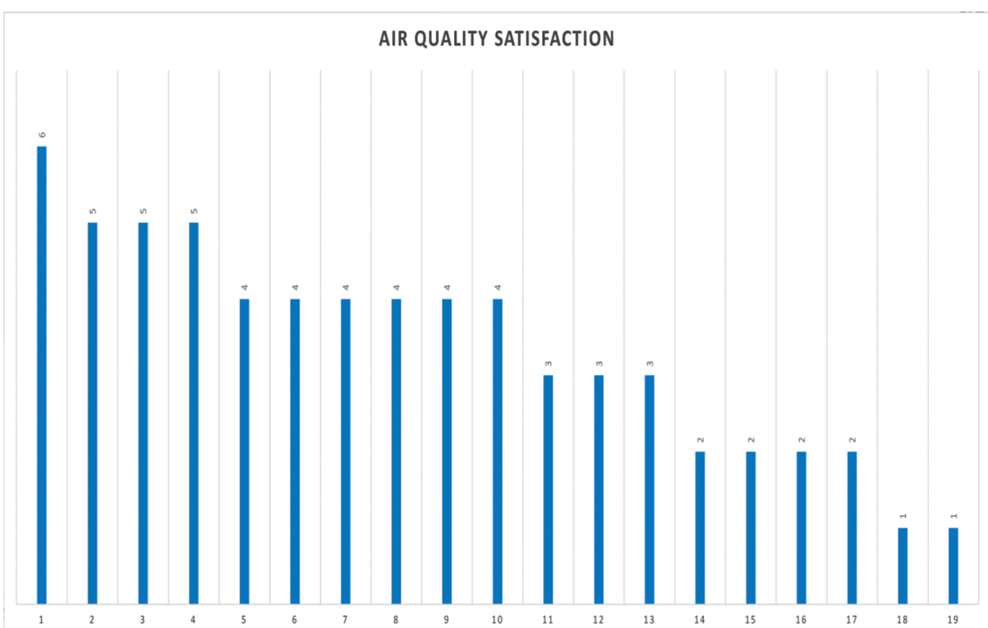
Teachers and staff are content with the amount of daylight, window views, amount of electric lights, and light control; however, teachers are discontented with visual comfort (glare) and do not have access to dimmer switches. The most used lighting control devices are the window shades. During the site investigation, it was observed that 90 percent of the window shades are down while all the electric lights are on during a sunny day. According to survey data, lighting rates constitute one of the lowest satisfactory items, and visual comfort tends to rank as the lowest factor in the lighting comfort category.

#### 4.5.2. Air quality

Air quality trended lowest among survey categories in terms of stuffiness, stale air, cleanliness, and odors. The average $CO_2$ ppm measured in 34 rooms at Quarterfield Elementary was found to be 991 ppm. ASHRAE recommends that $CO_2$ levels should be lower than 800 ppm for offices and 1,000 ppm in schools. Of the 34 rooms surveyed, 19 boast a $CO_2$ level lower than 800, whereas only 7 of these rooms are non-classroom spaces. Every room measured as having more than 800 ppm was a classroom, with 12 of these rooms measuring between 1,001 and 2,300 $CO_2$ ppm. This is directly related to the current mechanical system; as mentioned in

**FIGURE 5.** Air quality data ($CO_2$ level) per room.

| Room # | $CO_2$PPM |
|---|---|
| 180 | 540 |
| 103 | 570 |
| Confereence Rm | 585 |
| 122(window open) | 596 |
| Read Room | 618 |
| 181 | 676 |
| Guide Room | 696 |
| Main Office | 702 |
| Mens | 708 |
| Womens | 740 |
| Group 2 hall way | 742 |
| Health Room | 747 |
| Group 3 corridor | 752 |
| 101 | 772.5 |
| 101-104 corridor | 791 |
| Storage | 792 |
| 106 | 792 |
| 107 | 795 |
| Teacher's room | 800 |
| 105-women bath | 801 |
| 111 | 894 |
| 104 | 899.5 |
| 106-111 corridor | 963 |
| 110 | 970.5 |
| 112 | 1021 |
| 102 | 1034 |
| 109 | 1062 |
| 115 | 1142 |
| 105 | 1250 |
| 108 | 1252.5 |
| 1251 | 1300 |
| 125 | 1356 |
| 123 | 1521 |
| 114 | 1726 |
| 124 | 1871 |
| 113 | 2307 |



section 4.4.2, there is no mechanical ventilating system in the existing building, and the supply of fresh air is supplied via the operable openings and air infiltration. The amount of fresh air being circulated through openings is not controlled and regulated. To increase the air quality, mechanical ventilation and other passive renovation strategies could be considered. Passive strategies include using sorbent for gaseous pollutants, constructing an indoor living wall, and using air filtration. As $CO_2$ levels were found to be higher in nearly all classrooms than in offices, it is clear that a priority must be placed on classrooms in terms of ventilation.

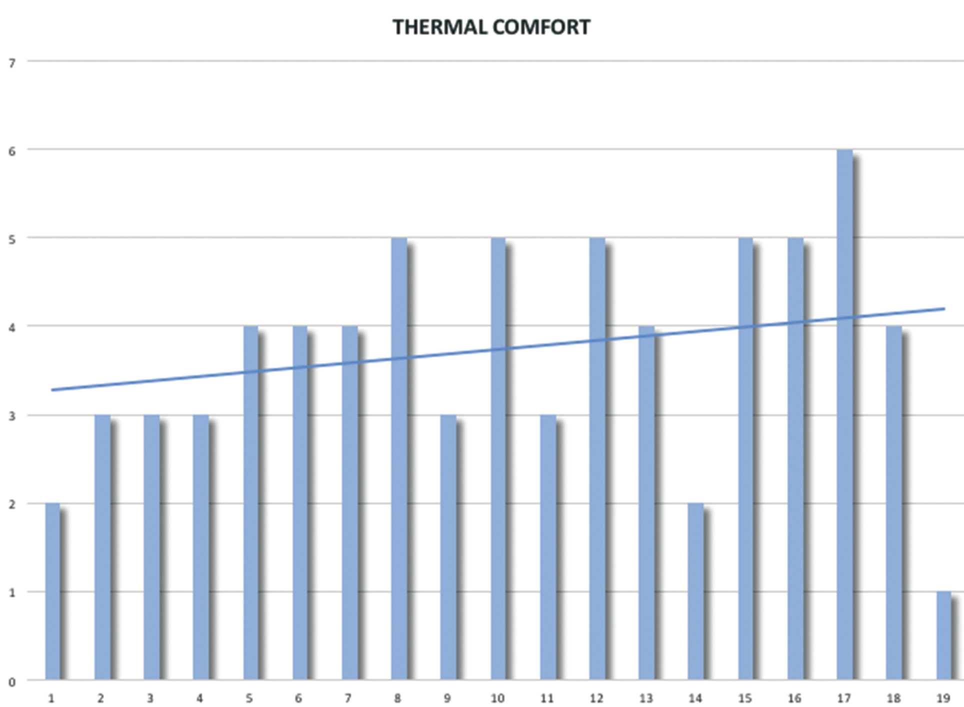
#### 4.5.3. Acoustic

Teachers and faculty were generally content with acoustic quality with the perceived overall noise level trending slightly higher than acoustic privacy, which is a known problem in open classroom layouts.

#### 4.5.4. Thermal comfort

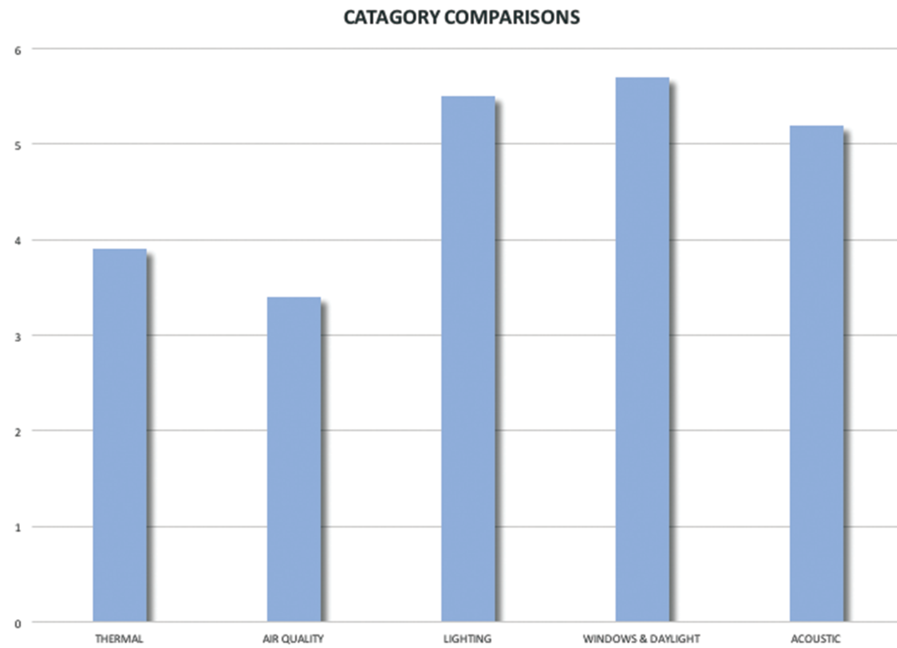
Regarding thermal comfort, according to the survey, teachers and staff are generally dissatisfied with existing conditions (during winter a mean value of 3.88 out of 7 was recorded). Teachers and faculty felt they have limited access to thermostats, portable fans, and adjustable vents and no access to ceiling fans, adjustable floor vents, or portable heaters. However, through the data collected, it can be seen that temperature, humidity, all room conditions are within a prescriptive comfort range based on ASHRAE 90.1. The temperature ranges between 23° C to 26° C, and the humidity ranges between 30.6 and 38 percent. The dissatisfaction from the occupants is largely due to the lack of personal control. This clearly shows the gap between designed thermal comfort based on the prescriptive building code and how the occupants perceive thermal comfort.

**FIGURE 6.** Thermal comfort satisfaction.



### 4.5.6. Summary

**FIGURE 7.** Overall indoor environment quality(IEQ) satisfaction.




Teachers and staff of Quarterfield Elementary were surveyed to identify areas of concern regarding lighting, windows and daylight, air quality, thermal comfort, and acoustic quality. With a few exceptions, survey data were rated on a satisfaction scale of 1–7 where 1 is the least satisfied and 7 is the most satisfied. Within these satisfaction ratings, it was found that (in terms of mean score) air quality is considered to be in the poorest state with a mean score of 3.4 out of 7, followed by thermal comfort at 3.9. Windows and daylight scored highest at 5.7 out of 7, followed by lighting at 5.5, and acoustic at 5.2.

## 5.0. BUILDING RENOVATION STRATEGIES AND SIMULATION

After conducting building performance auditing, which is based on the current utility bill, the annual energy data book, and a visual inspection along with an indoor environment quality analysis based on an occupancy survey and site measurement, two primary problematic areas were identified: high space heating demand coupled with thermal comfort dissatisfaction and poor indoor air quality. Therefore, the chief focus was placed on these two areas, and potential renovation strategies were evaluated.

### *5.1. Energy reduction*

#### 5.1.1. Energy database—benchmarking

Regarding the energy consumption dataset, several datasets are commonly used in United States: the EIA's (Energy Information Administration) Commercial Building Energy Consumption Survey (CBECS) [27], the DOE's (Department of Energy) Building Performance Energy Databook, and the DOE's Building Performance Database. The CBECS comprises 389 education buildings, including those of universities, colleges, and K–12 schools, and the average EUI for school buildings is 89KBtu/sqft. [8]. The DOE's Building Performance Database includes 25 primary school buildings with a median EUI of 48 KBtu/sqft for schools in the 4A climate zone. [28] The Building Performance Energy Databook [29] shows a median EUI of 100 KBtu/sqft for school buildings in the Mid-Atlantic region, including K–12 and college buildings. The varying dataset collection and aggregation methodologies' variations result in the differing values, which make it hard to find a reliable benchmark. Instead of setting up a fixed-target EUI (energy use intensity) as a benchmark, a percentage of energy savings is a more appropriate indicator for measuring and comparing building retrofit and renovation options [3]. It is more useful and appropriate to conduct energy measurement and auditing of the existing building to understand current building performance.

### 5.1.2. Energy profile of Quarterfield Elementary School

School buildings have a unique energy profile that do not align with that of typical commercial buildings. Based on 2015 CBECS, in school buildings, space heating accounts for 36 percent of the overall energy consumption, followed by cooling (11 percent) and ventilating (8 percent). (Refer to Figure 8.) The energy behavior of schools is more similar to that of a residential building than to a commercial building. This could be due to the operational schedule of schools; in particular, primary and secondary schools are largely different from regular commercial buildings that operate on a year-round schedule, as most K–12 buildings are closed during the summer. Quarterfiled has extremely high space heating consumption, 68 percent of overall energy consumption. The cooling load is 15 percent, close to the national average of 11 percent; the water heating load is 3.2 percent, lower than the national average of 8 percent; electrical lighting load is 8.4 percent, comparable to the national average of 9 percent. (Refer to Figure 9.) A reduction in the space heating load by 50 percent could result in an overall energy consumption reduction of 34 percent. Therefore, a focus is placed on space heating load reduction in the proposed renovation strategies.

**FIGURE 8.** 2015 School building energy use profile based on 2015 CBECS data [4].

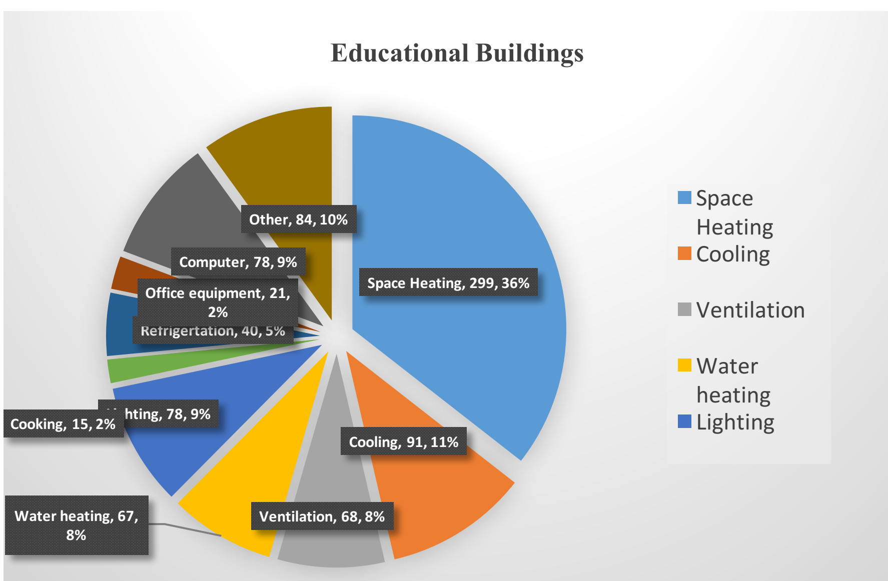
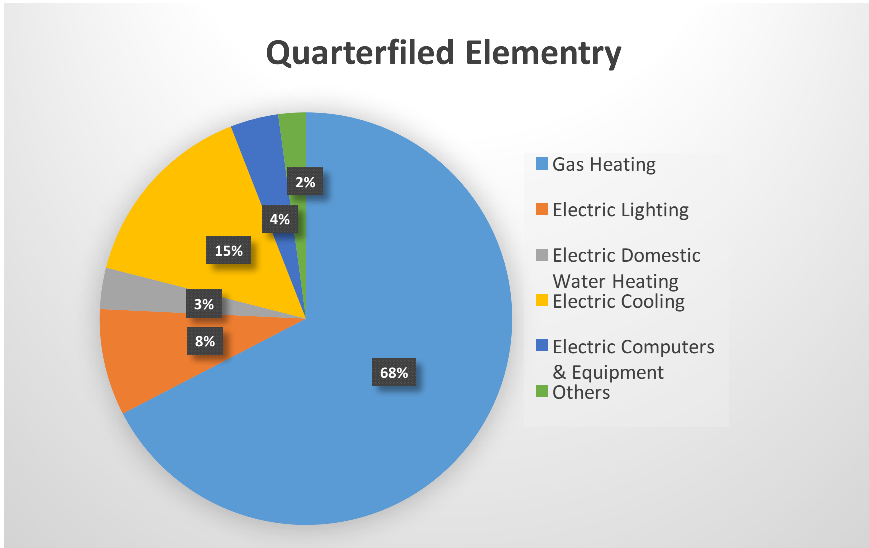


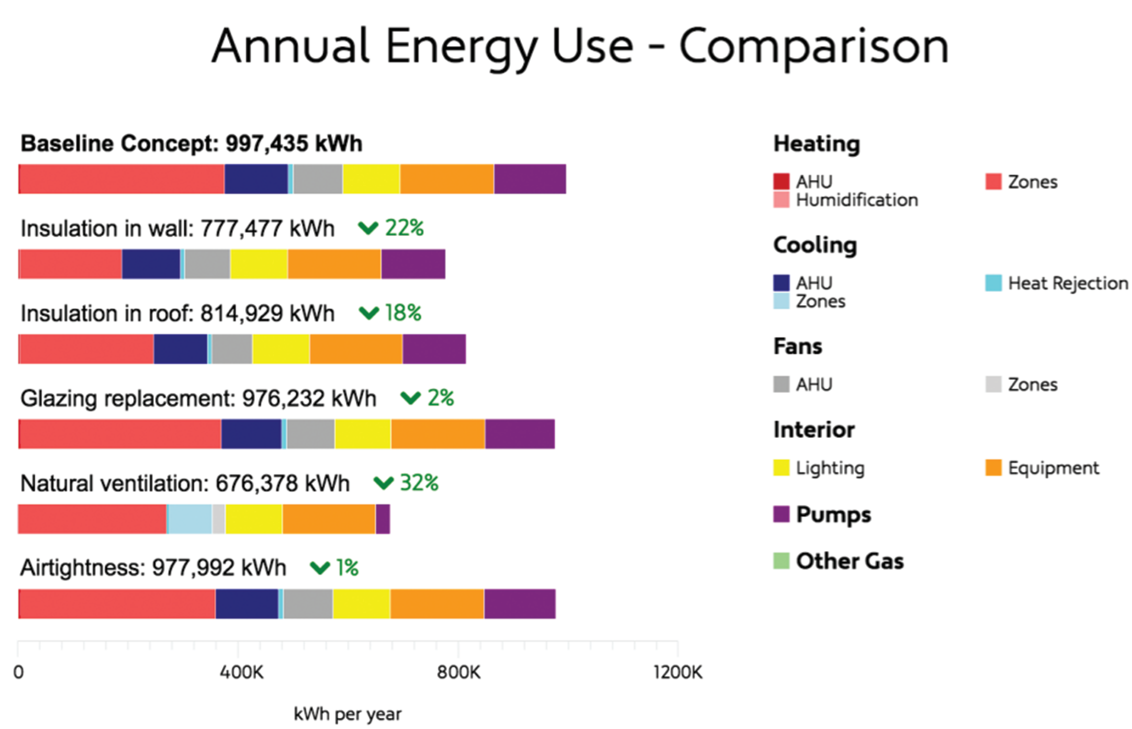
FIGURE 9. Quarterfield Elementary school energy use profile (Provided by AAPC).




### 5.1.3. Energy reduction and simulation

Based on the findings from current utility bills, original construction documents, and visual inspection, we find that three primary problematic areas could potentially be causing high space heating demand. They were identified as the following: lack of sufficient insulation in existing building façade, a poorly performed exterior glazing, and a poorly sealed building envelope.

FIGURE 10. Design retrofit packages/strategies comparison.



A building energy model of the case study was first constructed in Sefaira [30] plug-in Revit [31], the massing, orientation, and location from the model were uploaded onto the web version. The baseline is the existing building. Different envelope retrofit strategies were tested and compared using cloud simulation. Five models were created and calculated to measure the energy reduction effect of each renovation package, and results are illustrated in the Table 1. The five models are obtained under the same constraint such as temperature, humidity, actives and HVAC systems. The different envelope retrofit packages are 1) additional insulation in the exterior wall, (4-inch-thick stone wool layer), which should be added within the exterior inside face of the exterior wall to increase the R-value to 19; 2) additional insulation in roof (8-inch-thick stone wool layer) to increase the R-value to 40; 3) replacement of all exterior glazing with glazing of a U value of 0.28 $BTU/h.ft^2.F$, solar heat gain coefficient (SHGC) of 0.26 $BTU/h.ft^2.F$; and 4) a decrease in the air infiltration rate to 0.1ACH (ASHRAE standard is 0.35 ACH).

**TABLE 1.** Design retrofit strategies comparison.

| Package | Relative energy consumption reduction | Heating load reduction | Cost reduction | $CO_2$ emission reduction |
|---|---|---|---|---|
| Additional insulation in exterior wall (R19) | 22% | 50% | 11.9% | 50% |
| Additional insulation in roof (R 40) | 18% | 35% | 12.3% | 35% |
| Replacement of exterior glazing | 2% | 2% | 2% | 2% |
| Change air tightness to 0.1 ACH | 1% | 1% | 1% | 1% |

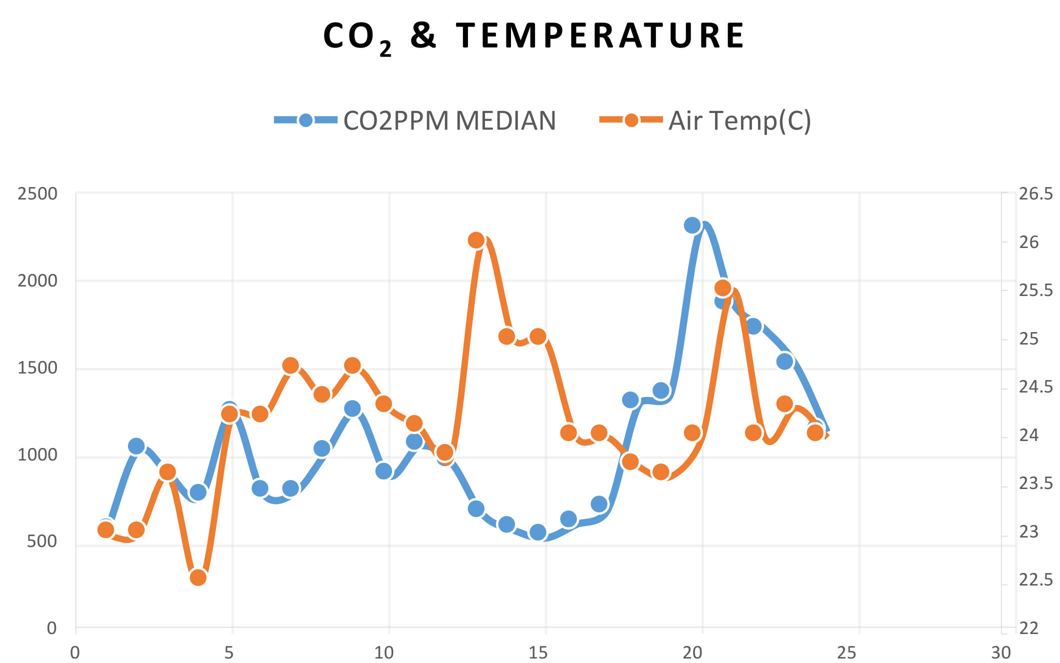
From the comparison, we observed that a significant overall energy consumption reduction of 22 percent can be achieved by adding additional insulation in the exterior wall alone. Quarterfield Elementary school is a one-story building with a large exposed exterior façade area, and a great amount of heat loss occurs through the existing exterior wall. This also could explain why Quarterfield has such a high percentage of space heating load. Because space heating accounts for 68 percent of overall energy consumption, adding additional wall insulation could be the most effective energy-saving and retrofit strategies. Adding additional insulation per current energy code requirement could save on space-heating energy consumption by 50 percent, adding insulation onto the roof could save 35 percent on heating energy, and replacing all exterior glazing could save 2 percent on heating energy. Also, adding insulation to the inner face of the exterior wall is more economical than is replacing the exterior glazing. Making the entire building envelope airtight only results in a 1 percent energy reduction.

### *5.2. Indoor environmental quality improvement*

The principal findings from Section 4.5 are that thermal comfort and air quality have been scored the lowest among all environment quality indicators. Thermal comfort analysis also revealed overheating and poor air quality in most classrooms. Based on a literature review, we see that other studies have proved that the air exchange rate is not sufficient for a classroom when mechanical ventilation is exclusively used. [11, 32, 33] The combination of the two dissatisfaction factors could lead to a need for additional ventilation, particularly in the classroom during wintertime. Considering the budget constraints and construction feasibility, adding a mechanical ventilating system in the existing school would be difficult, time consuming, and costly; therefore, passive renovation strategies should be given full consideration first. Each indoor microenvironment is uniquely characterized, which is determined by the local outdoor air, specific building characteristics, and indoor activities. [34] The high $CO_2$ concentration and overheating are related to room use and occupancies. When most classrooms are occupied, it is assumed that teachers' offices will not be fully used. As seen in Figure 11, there is a correlation between classroom temperature and $CO_2$ density; in other amenity rooms such as in the storage and health room, there is no clear correlation.

Several passive renovation strategies could be considered. They are as follows: 1) Dilute $CO_2$ concentration through natural ventilation, 2) absorb $CO_2$ by implementing an indoor living wall as a bio-filter, and 3) stack ventilation to reduce the CO2 concentration. Strategies 2 and 3 would require certain building alternation to integrate a living wall or stack vents. Solution 1 might have the least impact on the existing building. While classrooms are occupied, they experience most thermal gains from human heat, which could compensate for the heating need; therefore, natural ventilation could be used in a controlled way in classrooms even during the winter to decrease the $CO_2$ concentration without an increase to the heating energy demand. The control of natural ventilation could occur through the controlled and automated opening of the window system.

**FIGURE 11.** Temperature and $CO_2$ correlation.




An alternative retrofit strategy is to regulate heating system distribution in offices differently from those in the classroom. The corridor could be set at a lower temperature; the temperature difference could help increase the cross ventilation to help dilute $CO_2$ concentration.

## 6.0. CONCLUSION

The second largest expenditure for school buildings is on energy spending following payroll, so the education building itself offers a great deal of opportunity for cost cutting through energy savings. [11] In the United States, school buildings cost around $8 billion annually in energy-related spending. [35] Due to a unique operating schedule and occupancy character, school buildings would require particular attention to energy management and on a monitoring system. In fact, several studies demonstrated that energy savings directly relate to monitoring systems [36]. Meanwhile, there is growing interest in indoor environment quality for occupancy in schools, which includes thermal, visual, lighting, and acoustic comfort, as an integrated evaluation criterion. Indoor environmental quality is inevitably linked to energy performance. Viewed from this perspective, the operation and maintenance of a building are as important as the design phase because energy efficiency and comfort are strictly related to the building's operating conditions. [37] School buildings represent a special case due to their unique occupants, activities, and operating schedules. Students spend about 25 percent of their time at school and mostly indoors [38]; as such, education buildings have tremendous potential to improve their indoor environmental quality and thereby provide a healthy environment for students and teachers. [39, 40].

Through the site measurement, survey, indoor environment comfort analysis, and energy retrofit simulation, this case study provides insights into practical building retrofit strategies for a K–12 building in Anne Arundel County, Maryland. Another important goal of this case study is to identify the major indoor environment quality issues based on a variety of environmental indicators and several improvement strategies are proposed. In summary, here are some important conclusions:

- Increasing the thermal insulation for the exterior wall will have the biggest effect on total energy consumption reduction (22 percent) by decreasing space-heating energy consumption by 50 percent.
- Replacing exterior glazing will have a minimal effect on overall energy consumption reduction.
- There is a gap between designed thermal comfort based on prescriptive setting by code and how occupants perceive thermal comfort. The dissatisfaction is largely due to the lack of personal control.
- In existing K–12 buildings more than 50 years old, poor indoor air quality and overheating is caused by a lack of sufficient ventilation.
- A potential conflict could exist between making buildings airtight and increasing ventilation through air infiltration.

These results, in the context of the project could be used to facilitate the long-term facility management planning by Anne Arundel County. Achieving overall high-performance design in K–12 buildings demands concurrent assessment of the synergy effect of energy-efficient building envelope design and assessment of indoor environment quality. In the course of this paper, potential energy savings of practical envelope retrofit options were investigated through case study analysis. In the existing literature, such buildings have been studied under an energy retrofit perspective; however, this was primarily in a context that did not address the need to improve indoor environment quality simultaneously. The present study focuses on both perspectives. Future research efforts should concentrate on further verification of the simulation outcome. To this end, the data from Sefaira will be transferred to EnergyPlus, and further simulation will be undertaken to calibrate the model and document lessons learned. In addition, as this study identified a significant problem with indoor air quality, further passive and active ventilation strategies will be measured and studied using simulation tools.

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