Energy Retrofit Evaluation of a Naturally Ventilated Historic Building in a Hot and Humid Climate

Layla Iskandar
The University of Texas at San Antonio, San Antonio, Texas

Antonio Martinez-Molina
Drexel University, Philadelphia, Pennsylvania

Saadet Beeson
The University of Texas at San Antonio, San Antonio, Texas

ABSTRACT: *Successful energy retrofits of historic buildings are those that take into consideration energy savings, thermal comfort, and the conservation of cherished heritage values. This study proposes passive energy efficiency measures that abide by historic preservation standards and evaluates their impact on a wood-frame heritage residential building in a hot and humid environment. It also assesses the efficacy of natural ventilation in those conditions. The approach is structured according to the following steps: (a) the building performance assessment through onsite monitoring; (b) the numerical studies by energy simulations; (c) the selection of adequate passive energy efficiency measures; (d) the investigation of potential energy savings of the chosen energy efficiency measures; (e) the investigation of the efficacy of natural ventilation. The achieved results reveal that high energy savings can be attained through the selected solutions, with some measures better than others. However, natural ventilation proved to be ineffective without being paired with the package of energy measures. The findings of this research are replicable to numerous similar historic buildings in hot and humid conditions.*

KEYWORDS: Historic buildings, Energy retrofit, Building simulation, Natural ventilation, Passive energy efficiency measures

INTRODUCTION

Based on literature reviews on databases like Scopus (Elsevier 2022), Web of Science -former Web of Knowledge- (Web of Science 2022), Google Scholar (Google Scholar 2022), and ResearchGate (ResearchGate 2022), research investigating cooling and dehumidification of indoor environments has grown considerably in the past decade, reaching hundreds of highly ranked publications. Additionally, countless historic buildings have been retrofitted with energy savings and occupants' comfort as the main motivations. In many cases, the building envelope conditions were very dire, and mechanical systems were non-existent or causing damage to the building's materials and features (Martinez-Molina and Dupont 2020). The severity of ASHRAE climate zones 1A, 2A, 2B, 3A, and 3B exacerbates the situation by increasing the difficulties in controlling the indoor hygrothermal conditions (air temperature and relative humidity) of these structures. Moreover, before the installation of air conditioning became regulated in historic buildings, cooling systems were selected with only occupant comfort in mind, conclusively overlooking the sustainable conservation of the historic building and its cultural values. A detailed literature review by Lidelöw et al. (2019) examined the connection between energy efficiency and the historic preservation of heritage buildings. Their outcomes expose that research in this field mainly focuses on the energy aspect while hardly dealing with the valued architectural and cultural values. Nevertheless, a successful retrofit of a historic structure can only be performed by balancing the goals of energy efficiency with those of historic conservation. As shown in Preservation Brief 3 of the National Park Service (Hensley and Aguilar 2011), planning must holistically consider the building envelope, its systems and components, site, and environment, as well as a systematic assessment of all the procedures to be implemented.

Natural ventilation is also considered crucial to the overall historic building's performance. While natural ventilation contributes to reaching enhanced thermal environments, the effectiveness of using wind-driven flow depends on multiple factors. For example, investigations on the use of natural ventilation in residential buildings in Thailand (a hot and humid climate) demonstrate that an indoor air velocity of as little as 0.04 m/s is sufficient to increase occupants' thermal comfort (Aflaki et al. 2015). A study conducted by Bay et al. (2022) in Texas also concluded that natural ventilation can achieve the acceptable range for user comfort in a number of summer days. However, natural ventilation solutions are not sufficient to maintain comfortable indoor conditions throughout the cooling period, and mechanical cooling systems are necessary to reach not only thermal comfort but also required conservation standard levels (Ahmed, Kumar, and Mottet 2021). Hot and humid climate zones experience extremely high temperatures and humidity values at times during the year, even at night, making natural ventilation ineffective. However, in these areas, a thorough and methodical evaluation of natural ventilation opportunities and optimization remains important to decrease the use of mechanical cooling systems. This saving in operation time of the mechanical cooling system will reduce the above-mentioned conservation issues that could be resulting from the forced indoor conditions that are created. Past publications have revealed a research gap regarding naturally ventilated historic buildings in hot and humid climates which this research aims to address through a case study under the adverse environmental circumstances of the Cfa-Humid Subtropical Climate (Institute for Veterinary Public Health 2011).

Passive retrofit measures alone can achieve great energy savings in historic buildings retrofits. However, relevant research revealed that retrofit strategies usually applied to new buildings are not always appropriate for heritage structures due to the requirement to keep their historic value unaltered. For example, almost all publications in the literature do not mention the use of exterior insulation due to its harmful impact on historic facades. However, applying insulation on the interior of the historic external walls is recommended when adequate (Webb 2017). New approaches must therefore be comprehensively assessed before implementing them to prevent permanent damage to valuable architectural features, materials, and the building's surroundings. Numerous strategies and passive energy approaches (Martinez-Molina and Alamaniotis 2020) nevertheless can considerably increase the energy savings of a building without invasive and intrusive interventions (Bay, Martinez-Molina, and Dupont 2022). The goal of this research is to analyze the impact of commonly used passive energy efficiency measures that could be adopted for wood-frame historic buildings in a hot and humid climate in addition to the efficacy of natural ventilation in these particular conditions.

1. METHODOLOGY

As known, the energy refurbishment of historic buildings offers ample prospects for enhancing occupants' comfort, reducing global greenhouse gas emissions, and extending the life of heritage assets. By means of a case study, this research would accentuate the necessity of suitable retrofit measures that can achieve great energy savings without compromising cultural and historical values.
The suggested approach can be structured according to the following steps:

- The building's current energy performance evaluation through onsite monitoring.
- Numerical energy simulation of the building with a calibration of the model using the measured data.
- Proposal of potential energy efficiency solutions tailored to the building's needs and that abide by historic preservation principles.
- Evaluation of the energy savings yielded by the selected measures.
- Evaluation of the impact of natural ventilation.

1.1 The case study: The Kelso House

The Kelso House, a 1907 wood-frame residence, was selected for the purposes of this study. It is located in San Antonio, Texas, and is listed on the National Register of Historic Places as a contributing structure in the Monte Vista National Historic District (National Archives Catalog 1998). The area has a Cfa-Humid Subtropical Climate according to the Köppen-Geiger climate classification (Kottek et al. 2006) and an average annual temperature of 70°F with summer temperatures reaching 100°F (US Department of Commerce 2022). The property is owned by the Power of Preservation Foundation (PoP), which completed an exterior restoration of the structure while opening it as a learning laboratory for trades education. The foundation aims to rehabilitate the currently deteriorated interior and improve the energy performance of the Kelso House without compromising its heritage values.

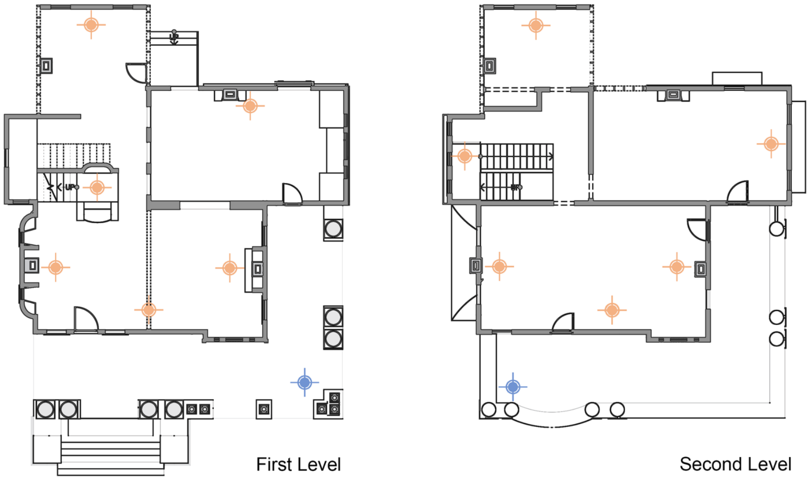
The structure was constructed in the simplified Neoclassical style with Craftsman and Queen Anne influences (Ahlquist et al. 2021). Neoclassical features include elaborate Doric columns, wood-trimmed entablature and frieze, dentils, and curved cornice. Queen Anne influences include asymmetrical facades, a two-story porch wrapping the primary south and east facades, a front-facing gable roof, and textured cladding. The irregular and asymmetrical plan arrangement, unenclosed eave overhangs with exposed roof rafters, and divided-light windows reflect Craftsman influence. In addition to its architectural significance, the Kelso House is also renowned for being designed by famous architect Atlee B. Ayres and for having the prominent civic leader and Judge Winchester Kelso as its owner (Huddleston 2022).


Figure 1: The exterior of the Kelso House (left) and the interior (right) in its current state. Source: (Huddleston 2022)

1.2 The onsite monitoring

Temperature (°F) and relative humidity (%) conditions of the Kelso House were monitored to evaluate the environmental conditions and explore any specific thermal issues in the building. The monitoring campaign was performed from the 1st of May to the 30th of September of 2022, as cooling is the main concern of this study taking place in a hot and humid climate. Figure 2 shows the deliberate positioning of 13 indoor and 2 outdoor data loggers throughout the building. Data was logged in 15 minutes intervals and averaged hourly to ensure a thorough acquisition of the thermal conditions.

The obtained data, displayed in Figure 3, showed that indoor temperatures were very elevated during the monitoring period. In fact, a maximum of 107°F was recorded in July and temperatures surpassed 100°F in June and August as well. Great temperature differences were also observed. For instance, while the maximum temperature in June was 104°F, the minimum temperature was 72°F, exceeding a 30°F difference. It can also be noted that the indoor temperatures were higher than the outdoor temperatures throughout the entire study period due to the high air infiltration and absence of mechanical ventilation and air conditioning. Finally, the indoor and outdoor relative humidity values were linearly correlated, with the outdoor relative humidity remaining higher than the indoor value during the five months.



First Level

Second Level

Figure 2: Arrangement of the indoor data loggers (orange) and outdoor data loggers (blue) on the first and second levels of the building. An additional indoor logger is located on the attic level. Source: Drawings by (UTSA School of Architecture 2019) and edits by (Authors 2022)

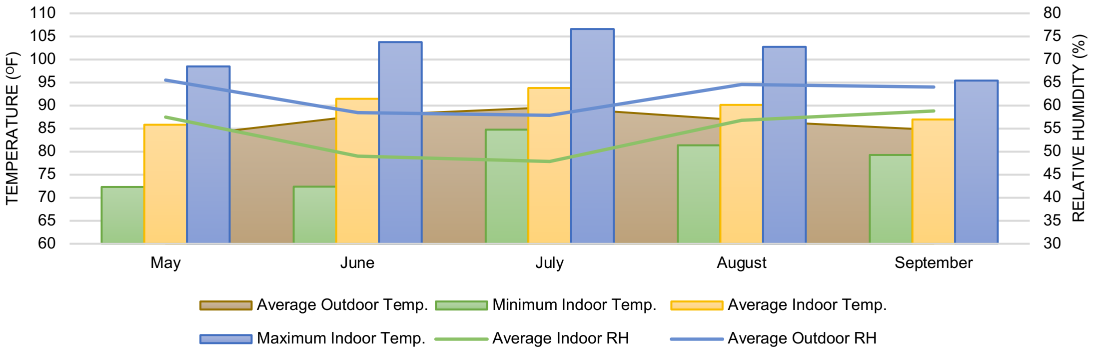


Figure **3**: Indoor minimum, average and maximum temperatures, outdoor average temperatures, and indoor and outdoor relative humidity throughout the period of study. Source: (Authors 2022)

1.3 Numerical simulation of the building and calibration of the model

The energy simulation of a building is an effective tool to estimate and quantify the energy savings of different solutions for energy retrofits. In order to simulate dependable energy performances, a detailed energy model of the Kelso House was developed using DesignBuilder. The geometrical and thermal characteristics of the building were defined. Table 1 presents the most significant envelope properties in the as-in-state calibrated model. The building is very leaky due to the wood-frame construction with low thermal mass as well as the deteriorated state of the envelope on the interior. According to Cho et al. (2022), the airtightness performance of historic buildings ranges between 0.8 ACH to 10 ACH (air changes per hour). Moreover, Tiberio and Branchi (2013) classify that detached houses have a low airtightness level when values exceed 10 ACH. Accordingly, the air infiltration rate in the model was fixed at 10 ACH.

After assigning the input data to the model and running the simulation for the selected study period, the temperatures evaluated by the energy simulations were compared to the measured temperatures. To assess the ability of the model in forecasting the actual building performances, the two main uncertainty indices recommended by ASHRAE Guideline 14 (2014), mean bias error (NMBE) and coefficient of variation of the root mean square error CV(RMSE), were used. Models are typically considered to be calibrated if NMBE and CV(RMSE) do not exceed ± 10% and 30% respectively for hourly calibration (Pachano and Bandera 2021). Two representative summer days, July 15th and August 19th, were chosen to validate the model. NMBE values were 0.9% and -0.4% for the two days respectively and CV(RMSE) values were 11.3% and 2.5%. These comparisons reveal a convergence completely satisfactory according to the literature indications. Figure 4 and Figure 5 show the results of the comparison between the measured and simulated indoor temperatures for the two days.

Table 1: Envelope properties in the as-in-state calibrated model. Source: (Authors 2022)

Component	Characteristics	Thermal transmittance (Btu/h.ft2.F)
Exterior walls	Wood-frame with wood shingle cladding	0.235
Roof	Pitched roof clad with composite asphalt shingles	0.259
Floor	Wood joists and hardwood	0.311
Windows	Single-glazed wooden windows	0.93

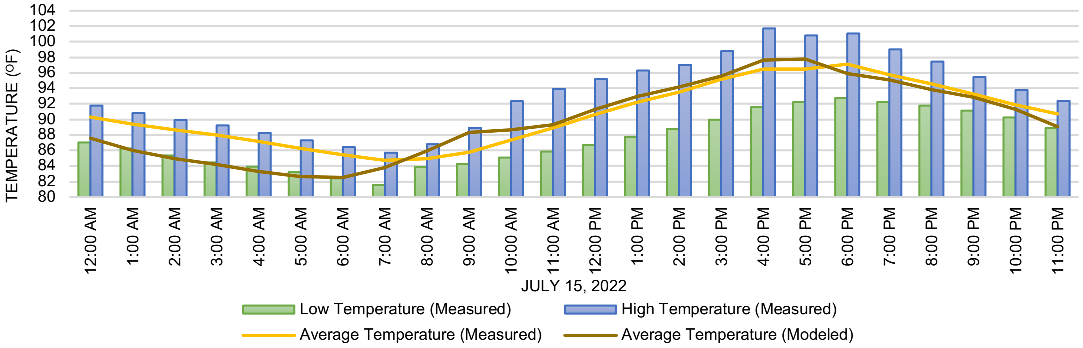


Figure 4: Hourly indoor temperatures (°F) measured onsite compared to those simulated in DesignBuilder on July 15th. Source: (Authors 2022)

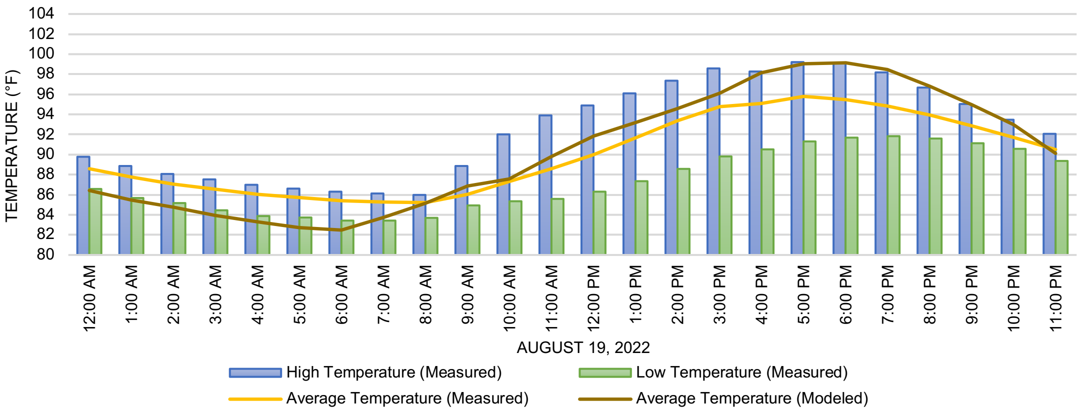


Figure 5: Hourly indoor temperatures (°F) measured onsite compared to those simulated in DesignBuilder on August 19th, 2022. Source: (Authors 2022)

1.4 Selection of the passive energy efficiency measures

The compromise between energy performance and the requirements of historic preservation is necessary and thus reduces the selectable energy efficiency measures greatly (Ascione et al. 2015). In fact, the energy retrofit is restricted by certain conservation principles and guidelines that ensure the protection of valuable historic materials and features. In the United States, the rehabilitation of historic buildings is guided by the Secretary of the Interior’s standards for rehabilitation (U.S. Department of the Interior National Park Service 1995; U.S. Department of the Interior and National Park Service 1997). According to these standards, the basic principles that need to be taken into account are the following:

- Retention of the materials, features, finishes, and construction techniques that are important to defining the building’s historic character;
- Minimal intervention;
- Protection of archeological resources;
- Compatibility of new materials and features used to replace deteriorated materials or features;
- The distinction of any additions;
- Reversibility of the interventions.

For the presented case study, the following set of passive energy efficiency solutions was selected following the abovementioned requirements:

Addition of insulation on the interior of the exterior walls. This process does not impact any historic materials since most walls are already unfinished in the existing state of the building. Moreover, since the wood-frame envelope has low thermal inertia, the addition of insulation can yield great energy savings.

Addition of attic and crawlspace insulation to reduce heat transfer through these surfaces. The installation is simple and has a minimal impact on historic materials in both cases.

- Reducing air infiltration by weatherstripping openings and sealing cracks in the walls, crawlspace, attic, and surrounds of doors and windows.
- Installation of tight-fitting storm windows and doors to increase the thermal performance of the openings without losing any historic fabric.

Furthermore, the building was considered to remain naturally ventilated and the inherent energy concept was retained by avoiding any change in the spatial relationships, placement, and size of the openings and ceiling height, as well as preserving all existing shading devices.

2. RESULTS AND DISCUSSION

Analyses of energy savings that were achieved by the considered energy retrofit measures, in addition to the efficacy of natural ventilation are presented in this section. Since the building’s interior finishes and the envelope are currently in a deteriorated condition, there was no benefit in considering the as-in state as the control model to attain significant results. Therefore, the characteristics of the control model were determined considering that the building was restored to a habitable condition without the addition of any energy efficiency technologies. The materials’ characteristics were acquired from Ahlquist et al. (2021) and onsite surveys, while the thermal transmittance (U-value) of the historic windows was obtained from Myers (1982). Table 2 summarizes the characteristics of the control model. The features of the five retrofit measures applied to the building were acquired from ASHRAE Guideline 34 (2016); The United States Department of Energy (2022); Myers (1982); Tiberio and Branchi (2013); Cho et al. (2022); Hensley and Aguilar (2011) and are displayed in Table 3.

Table 2: Characteristics of the control building energy model. Source: (Authors 2022)

Component	Characteristics
Exterior walls	Wood-frame construction with wood shingle cladding. U-value = 0.267 Btu/h.ft2.F
Roof	Pitched roof with composite asphalt shingles. U-value = 0.259 Btu/h.ft2.F
Floor	Wood joists and hardwood. U-value = 0.366 Btu/h.ft2.F
Windows	Single-glazed wooden windows. U-value = 0.93 Btu/h.ft2.F
Occupancy	5 people
Infiltration	10 ACH

Table 3: Summary of the five retrofit measures applied to the building. Source: (Authors 2022)

Retrofit measure	Content
Wall insulation	R-19 fiberglass batt insulation, applied to the interior of the exterior walls. U-value of the new wall assembly = 0.047 Btu/h.ft^2·F
Attic insulation	R-38 fiberglass batt insulation. U-value of the new attic assembly = 0.026 Btu/h.ft^2·F
Crawlspace insulation	Rigid foam insulation. U-value of the new floor assembly = 0.045 Btu/h.ft^2·F
Air infiltration reduction	Weatherstripping with holes and cracks filling. Infiltration 10ACH → 3ACH
Storm doors and windows	U-value of the new assembly = 0.46 Btu/h.ft^2·F

2.1 Analysis of the retrofit measures' efficiency based on cooling loads reductions

Simulations were performed in DesignBuilder to test and compare the cooling loads in cases when no passive retrofit measures were applied (control model), when each retrofit measure was applied solely, and when all measures were applied simultaneously. According to Dalugoda (2020), cooling load is the amount of energy removal necessary to sustain the indoor environment at a desired temperature and relative humidity. Therefore, the lower the cooling load, the better the energy performance of the house. The total cooling load is the sum of sensible and latent loads. The results of the simulations are presented in Table 4 and Figure 1. Among the applied measures, wall insulation afforded the best savings in sensible cooling (21.9%) while the reduction of air infiltration yielded the most reduction in total cooling (23.8%). Attic and crawlspace insulation also proved to be very effective, yielding respectively 10.7% and 12.4% savings in sensible cooling loads and 17.5% and 9.4% in total cooling loads. However, storm windows and door installation was the least effective of the selected passive technologies. The sensible cooling energy was reduced by 3.0% and the total cooling energy by 3.6%. When all five retrofit measures were applied simultaneously, the savings in sensible cooling loads were equal to 63.6% and those in total cooling loads were equal to 61.8%. Following this analysis, wall insulation, attic insulation, crawlspace insulation, and air infiltration reduction are the measures to be prioritized in the retrofit of the case study, while the addition of storm windows and doors can be overlooked.

Table 4: Comparison of cooling loads under different energy retrofit measures. Source: (Authors 2022)

Retrofit measure	Cooling load (Btu/ft^2)		Energy savings (%)	
	Sensible cooling	***Total cooling***	***Sensible cooling***	***Total cooling***
None	-33,846.4	-44,818.9	-	-
Wall insulation	-26,419.3	-36,990.3	21.9	17.5
Attic insulation	-30,223.5	-40,613.0	10.7	9.4
Crawlspace insulation	-27,952.8	-38,424.5	17.4	14.3
Air infiltration reduction	-28,392.9	-34,174.2	16.1	23.8
Storm doors and windows	-32,837.8	-43,205.2	3.0	3.6

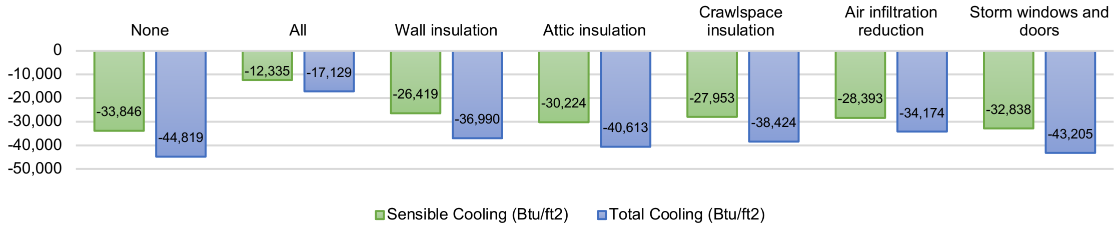


Figure 6: Cooling loads analysis during the study period. Source: (Authors 2022)

2.2 Analysis of natural ventilation's efficiency

The impact of natural ventilation was analyzed by producing two sets of simulations. In the first set, no retrofit measures were applied to the building and the cooling loads were compared in cases where natural ventilation was off and when it was on. Conversely, in the second set of simulations, all retrofit measures were employed. The results of these simulations are displayed in Figure 6. In the first case, natural ventilation contributed to a 0.92% reduction in sensible cooling while increasing the total cooling by 1.39%. In the case where all retrofit measures were in effect, sensible cooling loads were reduced by 13.71% when natural ventilation was in operation and total cooling loads decreased by 6.24%. The results indicate that natural ventilation is not an effective strategy for wood-frame buildings in a hot and humid climate unless it is paired with other passive retrofit measures such as those used in this study. In that case, it contributes to additional energy savings.

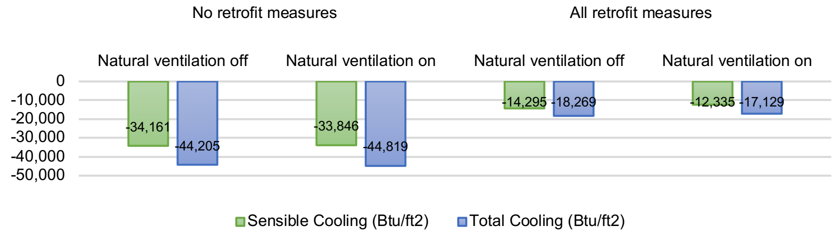


Figure 7: Natural ventilation analysis during the study period. Source: (Authors 2022)

CONCLUSION

This paper investigated the relationship between energy retrofits and conservation requirements in a residential historic wood-frame building in San Antonio, Texas, situated in a hot and humid climate. A set of passive cooling strategies, in addition to using natural ventilation, have been analyzed to control and mitigate indoor air temperature and relative humidity and to reduce the cooling energy load. A set of passive retrofit measures was thoroughly selected and field monitoring and building energy modelling were used to evaluate the impact of these measures in addition to the efficacy of natural ventilation in this case.

The results revealed that the internal insulation of the exterior walls and the reduction of air infiltration were the best strategies to increase energy efficiency. In this particular case study, the addition of insulation to historic walls was possible since the walls are unfinished, which resulted in greater energy savings without compromising any historic materials. The addition of attic and crawlspace insulation was also very effective. However, the addition of storm windows and doors did not yield great energy savings. Moreover, natural ventilation proved to be ineffective without being paired with the other retrofit measures, but its efficacy increased when all the considered strategies were employed.

Some current methodologies promote a combination of building energy retrofits, historic preservation, and occupant satisfaction by optimizing passive systems. Building energy simulation is a crucial tool for determining which interventions affect a heritage building's thermal environment and for figuring out potential energy performance upgrades. While upgrading a building's energy efficiency is an essential approach for delivering indoor thermal comfort, the cultural and heritage significance of the building must be considered to achieve heritage-sensitive management. Lastly, this approach reinforces the sustainability aspect, creating a more resilient historic building stock facing potential future rising temperatures and humidity levels due to climate change. The methodology of this investigation is replicable and the results are adaptable to countless historic buildings in hot and humid climates throughout the world.

ACKNOWLEDGEMENTS

This research would not have been possible without the cooperation of the Power of Preservation (PoP) Foundation.

REFERENCES

Aflaki, Ardalan, Norhayati Mahyuddin, Zakaria Al-Cheikh Mahmoud, and Mohamad Rizal Baharum. 2015. A Review on Natural Ventilation Applications through Building Façade Components and Ventilation Openings in Tropical Climates. Energy and Buildings: Elsevier Ltd. https://doi.org/10.1016/j.enbuild.2015.04.033.

Ahlquist, Tristan, Sydney Burt, Mitchell Ford, Diana Hernández, Lisa Maccora, and Sara Patrick. 2021. Kelso House Materials Analysis Summary Report.

Ahmed, Tariq, Prashant Kumar, and Laetitia Mottet. 2021. Natural Ventilation in Warm Climates: The Challenges of Thermal Comfort, Heatwave Resilience and Indoor Air Quality. Renewable and Sustainable Energy Reviews: Elsevier Ltd. https://doi.org/10.1016/j.rser.2020.110669.

Ascione, Fabrizio, Nicla Cheche, Rosa Francesca de Masi, Francesco Minichiello, and Giuseppe Peter Vanoli. 2015. Design the Refurbishment of Historic Buildings with the Cost-Optimal Methodology: The Case Study of a XV Century Italian Building. Energy and Buildings 99 (May): 162–76. https://doi.org/10.1016/j.enbuild.2015.04.027.

ASHRAE Guideline 14. 2014. ASHRAE Guideline 14-2014: Measurement of Energy, Demand, and Water Savings.

ASHRAE Guideline 34. 2016. ASHRAE Guideline 34-2019: Energy Guideline for Historic Buildings. www.ashrae.org/bookstore.

Bay, Ezgi, Antonio Martinez-Molina, and William A. Dupont. 2022. Assessment of Natural Ventilation Strategies in Historical Buildings in a Hot and Humid Climate Using Energy and CFD Simulations. Journal of Building Engineering 51 (July). https://doi.org/10.1016/j.jobe.2022.104287.

Cho, Hyun Mi, Beom Yeol Yun, Young Uk Kim, Hyeonseong Yuk, and Sumin Kim. 2022. Integrated Retrofit Solutions for Improving the Energy Performance of Historic Buildings through Energy Technology Suitability Analyses: Retrofit Plan of

Wooden Truss and Masonry Composite Structure in Korea in the 1920s. Renewable and Sustainable Energy Reviews 168 (October). https://doi.org/10.1016/j.rser.2022.112800.
Dalugoda, Chandana. 2020. Cooling Load Calculations ASHRAE CLTD/SCL/CLF Method. https://www.ashraebangalore.org/wp-content/uploads/2020/05/R1-COOLING-LOAD-CALCUALTIONS.pdf.
Elsevier. 2022. Scopus. www.scopus.com/home.
Google Scholar. 2022. Google Scholar. https://scholar.google.com.
Hensley, Jo Ellen, and Antonio Aguilar. 2011a. Preservation Brief 3: Improving the Energy Efficiency in Historic Buildings. Washington DC. http://www.nps.gov/history/hps/tps/briefs/brief03.htm.
Huddleston, Scott. 2022. Long-Neglected 1906 Kelso House in Monte Vista Has Beautiful New Exterior — More Work Is Needed. San Antonio Express News, 2022. https://www.expressnews.com/news/local/article/1906-Kelso-House-in-Monte-Vista-restoration-work-17017952.php.
Institute for Veterinary Public Health. 2011. World Maps of Köppen-Geiger Climate Classification. 2011.
Kottek, Markus, Jürgen Grieser, Christoph Beck, Bruno Rudolf, and Franz Rubel. 2006. World Map of the Köppen-Geiger Climate Classification Updated. Meteorologische Zeitschrift 15 (3): 259–63. https://doi.org/10.1127/0941-2948/2006/0130.
Lidelöw, Sofia, Tomas Örn, Andrea Luciani, and Agatino Rizzo. 2019. Energy-Efficiency Measures for Heritage Buildings: A Literature Review. Sustainable Cities and Society: Elsevier Ltd. https://doi.org/10.1016/j.scs.2018.09.029.
Martinez-Molina, Antonio, and Miltiadis Alamaniotis. 2020. Enhancing Historic Building Performance with the Use of Fuzzy Inference System to Control the Electric Cooling System. Sustainability (Switzerland) 12 (14). https://doi.org/10.3390/su12145848.
Martinez-Molina, Antonio, and William Dupont. 2020. In Situ Assessment of Superficial Moisture Content in Façades of a UNESCO World Heritage Church Using Electrical Resistance Measuring (ERM). The Impact of the HVAC System Energy Retrofit of Historic Buildings View Project. https://www.researchgate.net/publication/351638824.
Myers, John H. 1982. Preservation Brief 9: The Repair of Historic Wooden Windows. Washington DC.
National Archives Catalog. 1998. Texas SP Monte Vista Residential Historic District. 1998. https://catalog.archives.gov/id/40971251.
Pachano, José Eduardo, and Carlos Fernández Bandera. 2021. Multi-Step Building Energy Model Calibration Process Based on Measured Data. Energy and Buildings 252 (December). https://doi.org/10.1016/j.enbuild.2021.111380.
ResearchGate. 2022. ResearchGate. 2022. https://www.researchgate.net/.
The United States Department of Energy. 2022. Recommended Home Insulation R–Values. 2022. https://www.energystar.gov/campaign/seal_insulate/identify_problems_you_want_fix/diy_checks_inspections/insulation_r_values.
Tiberio, Alberto Jiménez, and Pablo Branchi. 2013. A Study of Air Leakage in Residential Buildings. In Conference and Exhibition - 2013 International Conference on New Concepts in Smart Cities: Fostering Public and Private Alliances, SmartMILE 2013. https://doi.org/10.1109/SmartMILE.2013.6708180.
US Department of Commerce. 2022. National Weather Service. https://www.weather.gov/wrh/Climate?wfo=ewx.
U.S. Department of the Interior National Park Service. 1995. The Secretary of the Interior's Standards for the Treatment of Historic Properties with Guidelines for Preserving, Rehabilitating, Restoring & Reconstructing Historic Buildings. Washington DC.
U.S. Department of the Interior, and National Park Service. 1997. The Secretary of the Interior's Standards for Rehabilitation & Illustrated Guidelines on Sustainability for Rehabilitating Historic Buildings. Washington, D.C.
Web of Science. 2022. Web of Science. https://webofknowledge.com.
Webb, Amanda L. 2017. Energy Retrofits in Hisc and Traditional Buildings: A Review of Problems and Methods. Renewable and Sustainable Energy Reviews 77: 748–59. https://doi.org/10.1016/j.rser.2017.01.145.