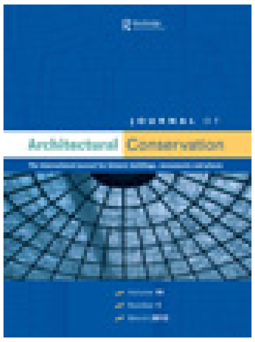

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Sustainable reuse of post-war architecture through life cycle assessment

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ABSTRACT
The mid-twentieth century was a period of architectural idealism and rapid technological innovation paired with unprecedented growth in construction and built square footage. As design movements became global and mechanical systems evolved to provide ready access to heating and cooling, buildings became less climate responsive and more energy intensive to operate. Architecture of this time also celebrated structural innovation and novel materials, which led to frequent integration of structure, envelope, and systems. These characteristics resulted in a building stock with typically poor energy efficiency and new material challenges for conservation. Rather than a justification to tear down these buildings and replace them, their vast numbers and significant contributions to global greenhouse gas emissions are reasons why mid-century buildings must be effectively repurposed to meet climate goals while respecting their history. With the imperative to limit global warming to less than 2 degrees Celsius, reusing and upgrading these buildings provides a critical near-term carbon reduction strategy. This paper presents two case studies involving the reuse of undergraduate residence halls of this era. The first illustrates the substantial total carbon savings from restoration and reuse. The second proposes an analysis-based methodology for designing retrofits that optimize carbon payback of targeted interventions.

KEYWORDS
Carbon; building reuse; life cycle assessment; climate action; circular economy

Introduction

We love to hate buildings constructed in the mid-twentieth century.[1] And yet, as these buildings reach the 50-year mark, the architectural heritage and design communities have begun to acknowledge their historical significance and grapple with the technical and social challenges of their conservation. In addition to their cultural value, these buildings have an enormous environmental value. To stay within the global emissions budget defined by the United Nations Intergovernmental Panel on Climate Change (IPCC), which would require a 65% reduction in emissions by the year 2030,[2] we cannot afford the operational carbon cost of allowing these buildings to continue to operate inefficiently, nor can we afford the embodied carbon cost to replace this

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significant percentage of the existing built environment with new construction. Globally, operation of all existing buildings accounts for approximately 28% of emissions, while embodied emissions from manufacturing of new building materials contributes roughly another 11%.[3] Reusing and upgrading these buildings drives down operational emissions while simultaneously avoiding emissions associated with new construction. Reuse of post-war architecture that both leverages environmental benefits and respects historic value is a powerful strategy to achieving a circular economy.

The mid-twentieth century was a period of architectural idealism and rapid technological innovation paired with unprecedented growth in construction. Architectural styles of this era are widely marked by formal clarity and a commitment to expression of materiality and structure. In embracing new technologies, buildings of this era frequently departed from passive design principles and energy conserving features – frequently present in older buildings as a necessity for human comfort – in favor of emerging mechanical heating, ventilatoin, and air conditioning (HVAC) systems. In the United States, buildings constructed in the 1960s, 1970s, and 1980s consume more energy per square foot than buildings of any other decade before or after.[4] This confluence of the popularity of new, fossil-fuel-dependent HVAC systems with the boom in construction during this period has resulted in a massive stock of buildings with poor energy efficiency and material, structural, and spatial challenges to reuse. Aside from a small number of iconic structures from this era, there are many existing buildings that exhibit the hallmark character-defining features of mid-century styles but are perceived by owners and the public as workhorse buildings. The design and construction industry is faced with the challenge of reusing and upgrading these buildings in a manner that respects their original design and materiality while maintaining or reestablishing their relevance through changing use requirements and the need for dramatic reductions in carbon emissions.

Challenges to decarbonizing post-war buildings

Buildings of the mid-twentieth century face several specific hurdles to successful reuse. The integration of building structure and enclosure is one such challenge. The advancement of concrete as a building material through the early twentieth century led to the dissolution of the idea of separate internal frame and exterior wall systems and the emergence of the monolithic frame.[5] Particularly in Brutalist design, concrete was not only used as a concealed structural material, but it was also celebrated and expressed as part of the building envelope. This application of concrete poses dual conservation and energy efficiency challenges. From a conservation standpoint, concrete exposed to the elements is highly vulnerable to water infiltration and temperature variation. Over time, this exposure will target any original material imperfections, ranging from reactive aggregate to under reinforcing to inadequate cover of ferrous element, causing progressive deterioration of the façade.

As relates to the building envelope, this integration of structure and façade creates significant limitations to the thermal performance of the building enclosure. Concrete structure directly exposed on the façade conducts heat from the conditioned interior to the exterior, creating a thermal bridge that can only be mediated by recladding or over-cladding, an approach that applies a new façade assembly over the plane of the original facade. Even when not exposed, concrete structural elements in plane with the exterior wall frequently interrupt existing or new interior insulation at columns and floor slabs; again, these thermal bridges can only be eliminated by recladding or overcladding outboard of the concrete structure. Cladding over or recladding original facades offers the opportunity to both protect exposed structural elements and provide a continuous thermal envelope; however, it challenges current heritage conservation practices and comes with its own upfront carbon costs that must be evaluated for value against potential improvements to performance.

There are also architectural challenges to upgrading HVAC systems in post-war buildings. While they were originally designed with active mechanical systems, these systems were typically not sized adequately for current requirements, and primary equipment is at the end of its life, if still in service. Many buildings of this era were designed with a structural economy that resulted in minimal floor-to-floor heights, making horizontal redistribution of systems particularly challenging. Additionally, distribution was often concealed within concrete structure, making it impossible to repair or reroute without destructive demolition. There are also risks to installing new materials and technologies without sufficient consideration for how they will perform within the existing building. For example, components such as chilled beams and radiant panels may see issues with condensation if environmental conditions are not controlled properly, and changing the flow of moisture across a building envelope may lead to condensation and deterioration of existing material to remain. Creative solutions and a thorough understanding of the existing building are required to understand which elements of the original systems may be kept in service through retrofit, where new systems are required, and how to design them appropriately.

Life cycle assessment approach for building reuse

Traditionally, environmental sustainability in building reuse has been evaluated based how well an existing building can perform relative to current standards. Energy performance, while important, only captures the impacts from one stage of a building's life cycle, ommitting the environmental footprint of the materials used and construction activities that occur over a building's life. Life cycle assessment (LCA) is a quantitative accounting methodology that predicts the environmental impacts of a material or assembly across the entire life cycle, from material extraction and manufacturing through use and end of life. When this analysis is applied to many or all of the materials that go into a building, this is referred to as whole-building life cycle assessment (WBLCA). As defined by ISO 14040, the international framework for life cycle assessment, the process of performing a LCA involves four phases:

1. Goal and scope definition: understand what the results of the assessment will be used for and thus which materials or assemblies are important to include and to what level of detail.
2. Inventory analysis: create an accounting of all the materials and activities that contribute to the scope defined in Step 1. This includes, but is not limited to, the bill of materials used in a building or portion of the building being evaluated.
3. Impact assessment: calculate environmental impacts by applying environmental impact factors to the inventory created in Step 2. This is most simply done using

tools that include building-specific data but can also be performed manually using open-source data sets.

4. Interpretation: analyze and understand the results to draw conclusions and respond to the goals defined in Step 1.

Life cycle assessment can be applied to existing buildings to measure and reduce the impact of renovation and to quantify the avoided impacts of renovation compared to new construction. In both cases, it is critical to create a meaningful scope boundary. Existing building fabric that will remain in place constitutes a ‘sunk cost’ and can be excluded from the analysis; those embodied carbon emissions were released in the past and are not impacted by reusing the building. The environmental impacts that do occur from renovation are related to the new material we add to buildings as well as the demolition and end-of-life treatment of material that we remove – these added and subtracted materials are, therefore, the materials that are critical to include in the inventory to measure the impact of renovation. This paper illustrates two ways in which LCA can be applied to building reuse: the first, to quantify the avoided impacts –in this case the carbon emissions that are saved – by reusing and upgrading an existing building instead of replacing it; and the second, to make decisions about the lowest-carbon approach for reusing a specific building.

It is important to note that LCA is not an exact science. While there are standards and product category rules in place, inconsistencies and uncertainties exist with LCA data, with tools, and in the methodology with which these are applied to individual projects. For example, some materials have only industry average data rather than product specific data, and different manufacturers may include different life cycle stages in their numbers. Data includes assumptions about what happens to a given material over its life cycle, from how often it must be refurbished or replaced to what happens at the end of its life. There are also questions about how to count biogenic carbon, emissions associated with the natural carbon cycle of materials like wood that sequester carbon as they grow and then release it at end of life.[6] LCA for existing buildings introduces its own set of challenges. Data can be more difficult to obtain for traditional building materials and techniques. Additionally, most LCA software tools are created with new construction in mind.[7] While these limitations lead to a margin of error in LCA results, the analysis is still highly valuable as a comparative assessment technique and is the only accepted methodology for calculating life cycle environmental impacts. LCA is the basis of many embodied carbon policies and is incorporated as a requirement into many green building rating systems, including LEED, BREEAM, and LBC.[8]

Case study: quantifying the carbon savings potential of whole building reuse

The first case study presented here is a residence hall at MIT designed by Josep Lluis Sert in 1974 (Figure 1). The 115,000 square foot, five-story building is located on the Charles River, a waterfront whose architecture was influenced by Sert’s academic leadership at Harvard’s Graduate School of Design and own design work of the mid-twentieth century. The residence hall comprises a minimal, cast-in-place structure clad in brick veneer with exposed concrete slab edges and cantilevers, and the fenestration displays

Figure 1. View of New House Residence Hall, c. 1975. Courtesy of Larry Spock.

Sert's signature multichromatic aluminum window frames, although in a stark black and white in this application. The building originally functioned as three distinct 'towers' housing nine independent social communities. Over its life, the building retained the same programmatic use; however, changing residential approaches, community sizes, and expectations of comfort and performance in conjunction with aging systems and envelope components had rendered the building in need of renovation and upgrade.

The student groups living in the building felt a strong affinity for the architecture of their home. However, there were tensions between the rigidity of the existing building and the evolving needs of the students living within it. The three towers of the building were connected only via a corridor at the ground floor, leaving communities physically isolated from one another. Additionally, as community sizes grew and shrank over time, the distribution of amenities became skewed with some communities physically disconnected from their assigned common spaces, which has led a lack of equity.

Physically, the building was facing systems at the end of their service life and deterioration and aging of exterior components. The original heating and cooling system consisted of a two-pipe hydronic system fed from a central plant, with a local chiller. The building was not mechanically ventilated, relying on operable aluminum, single-glazed windows for fresh air. The original envelope was brick veneer on metal studs, with a small amount of batt insulation in the stud cavity; roofs were entirely uninsulated. Additionally, all the building's MEP equipment was located on the first floor, which will become increasingly vulnerable to flooding through the coming decades.

After more than forty years with only minor renovations, the building needed a comprehensive renewal. The renovation project included new building systems to bring the building up to modern performance standards, upgrades to the building envelope to improve thermal comfort and reduce energy use, climate resilience improvements, and interior reconfigurations to support equity and flexibility in the future while maintaining the original design intent. Programmatically, the renovation physically connected the three towers to encourage strength of community and laid out residential groups via a series and 'anchors' and 'flex' spaces, which allow each community to maintain a

Figure 2. View of New House primary public corridor with original finishes, c. 1975. Courtesy of Larry Spock.

central heart while accommodating a changing population over time. A new circulation route was created through the building, consolidated amenities and taking advantage of the building's daylight and views (Figures 2 through 4).

The exterior restoration of the building involved repair and localized rebuilding of the brick masonry veneer, repair and recoating of exposed concrete, and replacement of the failing aluminum windows with double-glazed, thermally broken frames. The existing building design and condition presented challenges to envelope improvement, including the thermal bridge created by the concrete cantilevers and slabs extending to the outside face of the wall (Figure 5) and the unknown condition of the original felt paper air barrier. Thermal modeling was performed during the concept phase to establish the existing thermal resistance (R-Value) of the opaque wall and thermal bridge conditions and to explore the potential improvements in R-Value that could be achieved by filling the stud cavity or furring the wall out to create continuous insulation inboard of the existing wall at each floor level to achieve current prescribed levels of performance. Hygrothermal modeling in WUFI, a software that calculates moisture and heat flow through building materials over time, was then completed to evaluate several insulation materials, including mineral wool batt and open and closed cell spray foam to ensure that the proposed solution did not introduce a risk of condensation. Ultimately, due to factors of human health, long-term performance, and to maintain the moisture migration paths of the original wall construction, the stud cavities were filled with mineral wool and an air-sealed variable permeability vapor membrane was applied to allow moisture to continue to move through the wall similarly to the original condition. The roofs were insulated to code. More aggressive envelope improvements, including additional roof insulation and triple glazed windows, were evaluated through energy modeling, which showed negligible annual energy savings from additional upgrades. While recladding the building to enable installation of continuous insulation at the exterior would have eliminated the existing thermal bridges created by the building's structural system, this approach was rejected due to impact to historic appearance and cost; ultimately the carbon payback of this

Figure 3. View of New House primary public corridor prior to renovation, 2015.

scheme, while not evaluated during the project, may have been disadvantageous due to the high carbon footprint of additional enclosure materials.

The building HVAC system was upgraded from a two-pipe to a four-pipe hydronic system. Mechanical ventilation was introduced to the common spaces and corridors to improve indoor air quality, while ventilation to student rooms continues to be provided passively by the new operable windows to both minimize new ductwork and energy and due to spatial constraints. A wider temperature range was accepted in corridor spaces, reducing loads on the new systems. The majority of piping and duct distribution occurs at the ground floor where the height is more generous; upper floors have a clear height of only 7′–9″, so services needed to be kept to a minimum and were exposed to maximize available space. To address the threat of flooding from predicted future storm events, a small addition was constructed at the second-floor level to house critical equipment, including the new electrical substation. With these systems

Figure 4. View of New House primary public corridor after renovation, 2017.

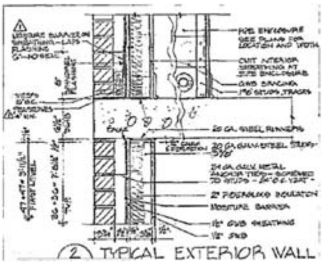


Figure 5. Typical detail of structural concrete slab extending to outer face of building envelope from original construction documents.

and envelope improvements, the building's annual energy use was reduced by approximately 55% below the pre-renovated condition.

To assess the total carbon impacts of the renovation, a whole building life cycle assessment was completed. LCA was used to first quantify the impacts of the new materials from the renovation, and then to compare the embodied environmental impacts of the renovation to a hypothetical comparable replacement building. The LCA was performed using Tally, a plugin for the Revit that uses a propriety construction industry-specific database created and maintained by Thinkstep. The analysis included manufacturing, maintenance and replacement, and end-of-life stages, and assumed a 60-year building life. All building structure, enclosure, and interior partition elements were modeled, but some finishes and mechanical systems were excluded from the scope. The total

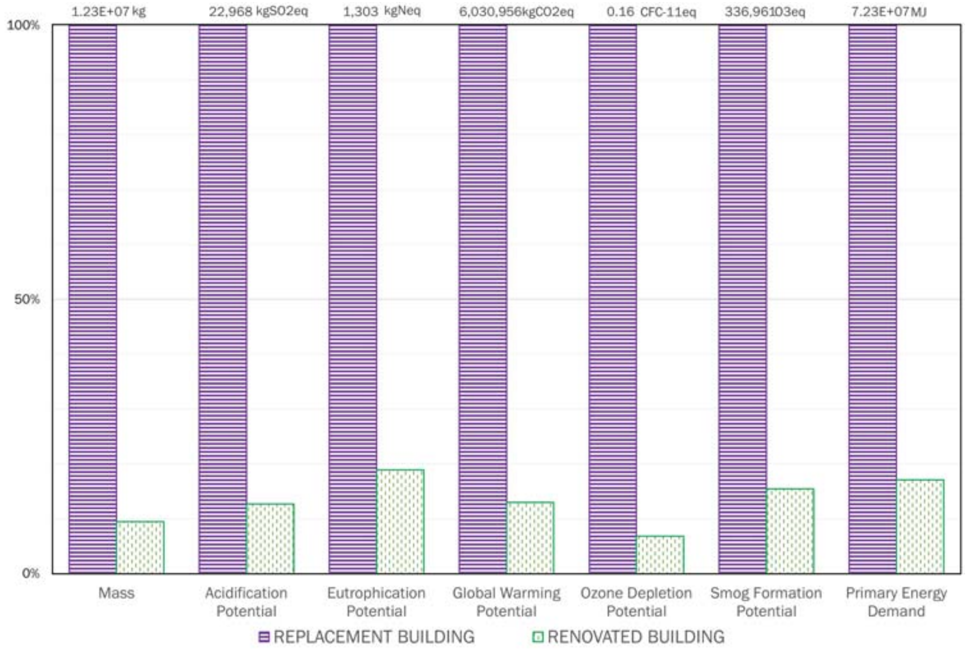


Figure 6. Chart illustrating environmental impacts of the New House renovation compared to an equivalent replacement building across six impact categories.

Global Warming Potential of the renovation was predicted to equal 782,000 $kgCO_2eq$. When compared to the hypothetical replacement building constructed of industry-average concrete and steel construction based on the Carbon Leadership Forum's benchmarking study,[9] the renovation showed a significant reduction in embodied impacts across all impact categories (Figure 6). The total savings in embodied carbon emissions, most of which occur by the time construction is completed, are the equivalent of emissions from thirteen million miles driven by a passenger vehicle; or, conversely, 133,000 seedlings would need to grow for a decade in an urban environment to sequester an equivalent quantity of emissions.[10]

Embodied impacts are only one contributor to emissions; to assess total carbon emissions, they must be paired with operational emissions to evaluate the cumulative impact over time (Figure 7). This chart illustrates three scenarios: the existing building unrenovated, the renovation as designed, and a replacement building of comparable square footage but using contemporary construction practices and performing with an additional 15% reduction in annual energy use. Based on the point at which the lines intersect, one can understand the 'carbon payback,' or point in time at which the environmental cost of embodied emissions is paid back by the savings in emissions achieved through improved operational efficiency. The act of renovating the building has a simple payback of only three years compared to making no intervention. New construction takes approximately thirty years to pay back compared to the renovation; that means that through the critical climate deadlines of 2030 and even 2050, reusing the existing building results in lower total emissions compared to ultra-high-performance new construction. Figure 8 illustrates the same three scenarios but accounts for locally established green energy targets, which require an 80% reduction in grid emissions by the year 2050.[11] Once the greening grid is factored in, operational emissions of the renovated and new buildings level off, resulting in lower total emissions from building reuse compared to replacement well beyond 2050.

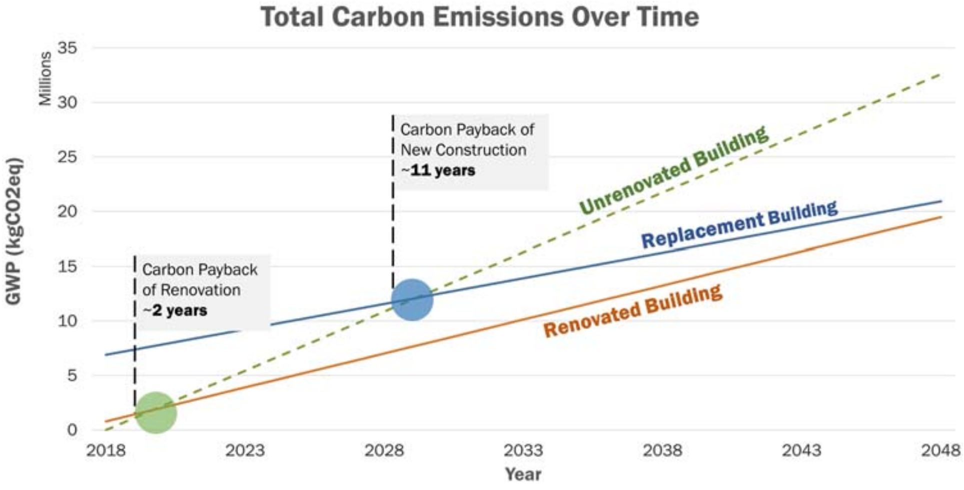


Figure 7. Graph representing the total carbon emissions over time of three scenarios: New House with no renovation, the renovated New House, and a hypothetical high-performance replacement building.

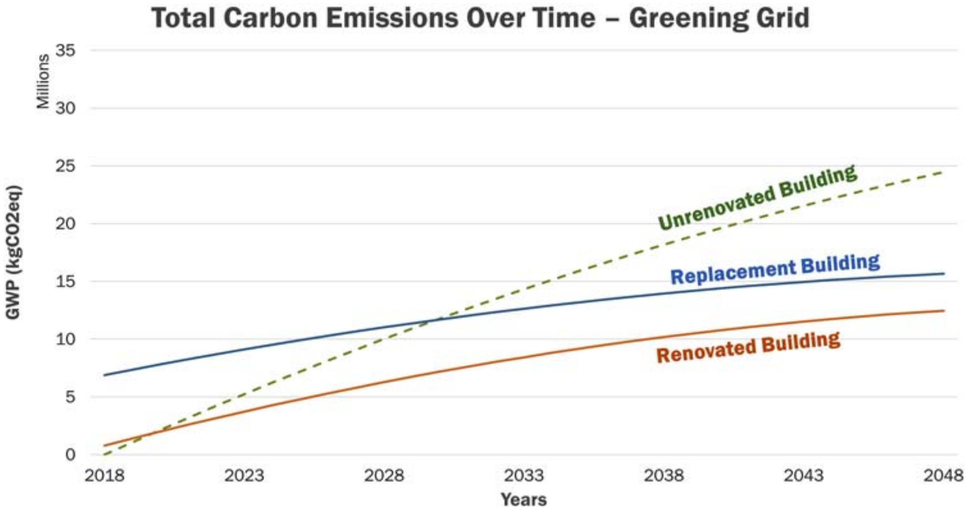


Figure 8. Graph indicating the same three scenarios as previously illustrated, but reflective of reduced grid emissions over time.

Case study: evaluating energy retrofit decisions for total carbon savings

Ham and MacGregor Halls are adjoining residence halls located on the northern edge of the Mount Holyoke College campus in South Hadley, Massachusetts. The buildings were designed by Hugh Stubbins and Associates in 1964 and 1966, respectively, and bear the designer's signature mid-century style. The buildings are five and six stories tall and are constructed of brick cladding on a cast-in-place concrete structure with steel windows. The south side of the buildings, facing the street, are austere and commanding, with sweeping planes of brick punctuated by punched openings providing light and air to student rooms, while the north side of each building employs a different modern interpretation of bay windows and balconies to take advantage of views of the Upper Pond (Figures 9 and 10).

Figure 9. Image from the southwest of Ham and MacGregor Halls, c. 1970. Courtesy of Mt. Holyoke College.

The residence halls have been used for their original program since construction and currently house approximately 280 undergraduate students. The dining halls and shared kitchen facilities on the lower floors of the two buildings have been rendered unnecessary with the construction of a new central dining facility, so the spaces remain largely underutilized as resident common space. While minor improvements and repairs to the systems and envelope have taken place over the buildings' lifetimes, there has not been a comprehensive major renovation since initial construction, and much of the building systems and fabric are original and in need of major upgrades or replacement.

The impetus for this study was the planned upgrade of the life safety systems within the two buildings, which was occuring within the context of a recent campus-wide pledge to achieve carbon neutrality by the year 2037. With the recognition that minor upgrades such as this occur more often over a building's life than a comprehensive renovation or replacement – and therefore afford both nearer-term and more frequent opportunities for decarbonization – this study evaluated the role incremental upgrades can play in contributing to fast-approaching carbon neutrality goals. Rather than looking only at energy efficiency or trying to design a deep energy retrofit that prioritized major upgrades to the envelope, this work aimed to define a 'smart' energy retrofit, one whose total carbon emissions including both embodied carbon footprint and operational carbon reductions were minimized in the critical near term. For a campus with many historic structures, this study provided a test case to both establish a process for evaluating energy retrofit projects and create a level of intuition about which approaches might be both historically appropriate and effective in achieving greatest carbon reductions.

Ham and MacGregor Halls demonstrate many of the typical barriers to high performance for buildings of this era. The concrete structure continues through the exterior envelope, creating major thermal bridges at balconies, bay windows, and staircases that weave in and out of the building. Single-paned steel windows are sources of air leakage and poor thermal performance; their poor condition further exacerbate problems of thermal comfort and functional operability. The walls and roofs are minimally insulated. Additionally, the original hot water heating system was designed to operate at over 200°F with minimal lengths of perimeter heat serving each student room, an unusually high and inefficient temperature; the system had no user controllability, leading to overheating in winter.

To assess potential improvements to energy efficiency, the existing conditions were thoroughly evaluated and used to create a calibrated baseline energy model. Blower door testing was performed in representative student rooms to quantify existing air leakage. Thermal imaging, a method that uses infrared radiation to map the surface temperature of an image, was used to validate the exterior detailing of original

Figure 10. Image from the north of Ham Hall, c. 1966. Courtesy of Mt. Holyoke College.

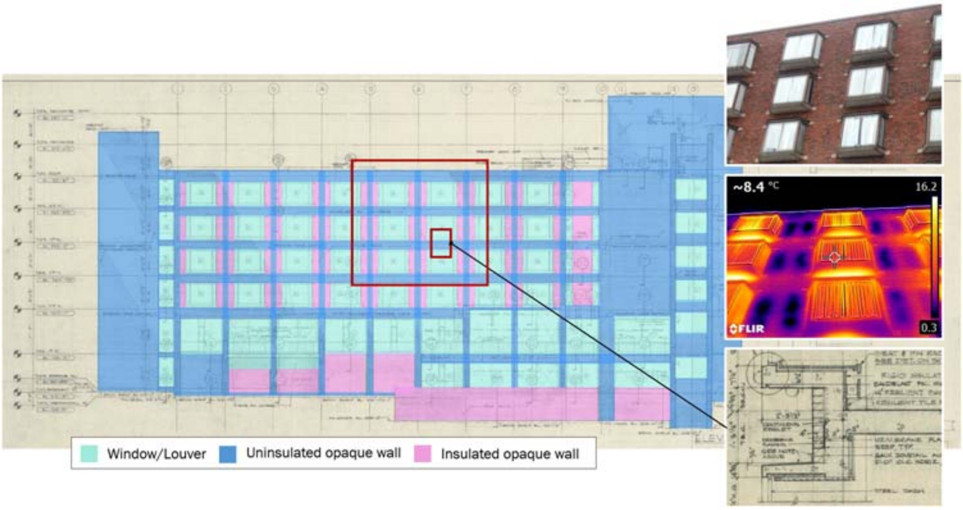


Figure 11. Axonometric rendering and thermal model results of existing bay windows of MacGregor Hall.

construction drawings and map out thermal resistance across the exterior (Figure 11). Thermal modeling in THERM, a two-dimensional conduction heat-transfer analysis software created by the Lawrence Berkeley National Laboratory, was used to calculate the effective thermal resistance at major thermal bridge locations. This data was input into the existing conditions energy model, which was then further calibrated using available energy use information.

A wide range of envelope and building systems retrofit measures were developed in response to the existing building design and conditions. With a goal of creating a meu of upgrades that could be assembled into a project of the appropriate scale while also exploring an expanded range of upgrades for future phases and as a reference for other buildings, the study looked at options ranging from the most minimal interventions to significant upgrades and component replacements in line with high-performance new construction standards. Proposed envelope options included both targeted upgrades based on existing conditions observations, such as selective overcladding at critical thermal bridges like the bay windows shown in Figures 12 and 13, or addition of interior insulation only at readily accessible locations that were originally uninsulated, as well as more typical comprehensive approaches such as insulation across the entire interior, complete overcladding, roof insulation, and window replacement. For each insulation option, a range of thicknesses and materials were evaluated. It should be noted that some options, like overcladding, would have a significant impact to the historic character of the buildings; their evaluation allowed for a comparative analysis against other options such as interior insulation that better preserve the original exterior design. Additionally, window restoration, while preferable from a conservation perspective, was not evaluated, as the existing windows were in poor condition with evidence of significant corrosion. From the building systems side, retrofit measures were defined at both the building and energy source levels. Within the building, options ranged from retrofitting existing hot water radiant systems to operate at a lower, more efficient temperature, to installing a

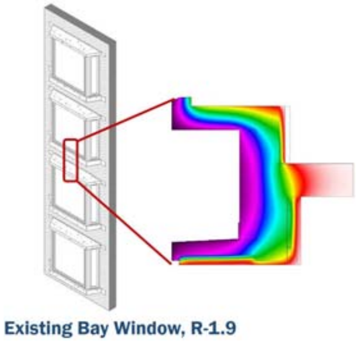


Figure 12. Axonometric rendering and thermal model results of proposed overclad retrofit of bay windows of MacGregor Hall.

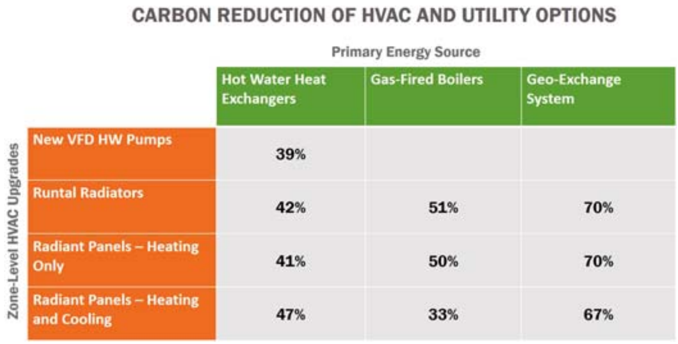
Figure 13. Map of thermal values of existing building envelope based on original construction drawings, visual observation, and thermal imaging.

variable refrigerant flow (VRF) system or new radiant ceiling panels that could provide both heating and cooling. Certain systems options would also necessitate the installation of a building-wide mechanical ventilation system to ensure proper functionality and mitigate condensation risks given the imperfect envelope. Primary energy source options included upgrades to hot water heat exchangers, new gas-fired boilers, and a geothermal system.

Analytical modeling was used to evaluate the relative energy and comfort impacts of the defined retrofit measures. First, thermal modeling was used to assess various insulation configurations for their potential to mitigate thermal weak points and establish the optimal R-value targets for different assemblies or details. Fifty individual measures were then evaluated using whole-building energy modeling to understand the relative impact of each intervention and quickly bound a range of possible energy and operational carbon reductions. The results of the analysis demonstrated that at the minimal end, replacing the existing windows – greatly reducing air infiltration and improving thermal performance – made the single greatest impact on energy use and thermal comfort, and it enabled minor modifications to the heating system that further reduced operational energy consumption for a total savings of just over 30% with no additional upgrades to the buildings. Improving the thermal resistance of the envelope by installing ultra-high-performance windows and applying the current code levels of insulation at the interior face of the exterior walls yielded only an additional 7% reduction at a large cost and level of disruption. Further upgrade to nearly-Passive-House levels of performance yielded only an additional 6% reduction in energy use. These findings illustrate that once you address the most vulnerable elements of the envelope, further intervention quickly reaches a point of diminishing returns; upgrading envelope components to meet or exceed current performance requirements and installing new HVAC systems does not necessarily yield substantially greater improvements to energy performance than strategic, selective interventions.

A second iteration of analytical modeling evaluated the interrelationships of retrofit measures and environmental impacts. Parametric energy modeling analyzed 240 combinations of the previously discussed retrofit measures to identify potential project approaches that optimized energy use, carbon emissions, and cost reduction. Life cycle assessment, conducted with Tally, evaluated the embodied carbon emissions of envelope options and quantified the potential to store carbon in the building through the use of natural materials, such as wood fiber insulation. One key finding, illustrated in Figure 14, is that net zero energy or operational emissions cannot be achieved solely through upgrades to the building envelope and HVAC systems. The only path to approaching net zero emissions is to address the primary energy source, in this case by installing a geo-exchange system, and to achieve net zero would require off-site renewable energy. This information was critical in understanding the relationship of the individual building project to the grid. While certain HVAC choices may yield incremental benefits with the current energy source, decisions needed to be driven by compatibility with the utility master plan to ensure optimized reductions over time.

The energy analyses indicate the savings in operational carbon emissions over time, they do not account for the upfront embodied emissions associated with the new materials needed to make implement efficiency upgrades. To look at the total carbon savings of the proposed retrofits over time, a simple payback model was used to evaluated environmental impacts. Life cycle assessment was used to define the embodied emissions, or the carbon 'cost' of each envelope upgrade option. These costs were then plotted against the 'savings' associated with improved operational efficiency. As illustrated in Figure 15, the carbon payback period varies greatly across the retrofit measures. The window replacement, which provided the greatest improvement to energy efficiency, are shown here to have a quick payback period. In contrast, many of the broad-stroke insulation options take more time to pay back due to their high embodied carbon and smaller benefits to energy consumption. Targeted applications of insulation (e.g. over-cladding the projecting concrete slabs of the bay windows) use a minimal amount of new material to address a major area of thermal loss, resulting in a good payback period; this measure has the added benefit of protecting the vulnerable exposed concrete on the north façade of the building. Of note are the opportunities for carbon positive measures, or those that store carbon. These measures are a win-win as they both store carbon in their production and reduction operational carbon use by improving efficiency.



CARBON REDUCTION OF HVAC AND UTILITY OPTIONS

Primary Energy Source

Zone-Level HVAC Upgrades	Hot Water Heat Exchangers	Gas-Fired Boilers	Geo-Exchange System
New VFD HW Pumps	39%		
Runtal Radiators	42%	51%	70%
Radiant Panels – Heating Only	41%	50%	70%
Radiant Panels – Heating and Cooling	47%	33%	67%

Figure 14. Potential reductions in annual operational carbon emissions resulting from combinations of primary energy source and building-level retrofit measures.

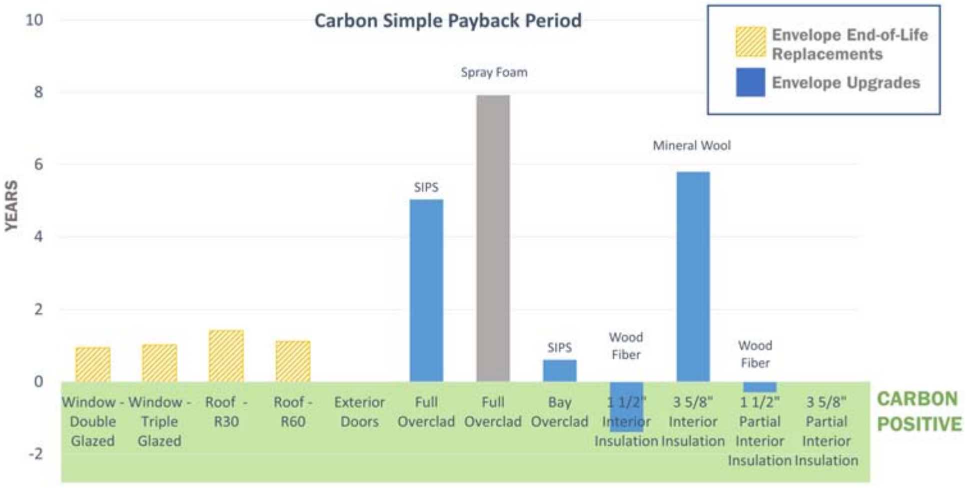


Figure 15. Graph of carbon payback period associated with envelope retrofit measures. Similar to a financial payback, this illustrates how quickly the environmental investment in terms of embodied carbon is offset by reductions in annual operational emissions.

Overall, the study of Ham and MacGregor Halls illustrates that Post-War buildings can dramatically reduce carbon emissions without requiring major renovation or like-new performance to do so. Stewardship of the existing building, including keeping the envelope airtight and the systems properly commissioned, contributes greatly to improved energy performance with minimal embodied carbon impacts. At the same time, radical envelope and HVAC upgrades would not bring operations within range of net zero, but they would have negative impacts to the buildings historic character and would increase environmental and financial costs. The study shows that quantitative analysis provides key decision-making information that allows for a retrofit approach that balances impact to historic fabric, embodied environmental impacts, and improvements to energy efficiency now and as energy sources evolve. Ultimately, minor upgrades and maintenance may lead to better near-term carbon savings while respecting historic materials and performance than a more invasive deep energy retrofit approach. Particularly in this case, where a major upgrade was not immediately feasible, the analyses showed how the available financial resources could be invested to reduce carbon emissions immediately while enabling significantly greater emissions in the future as the building is further renovated and the campus utilities are converted to greener energy.

Conclusions

The case studies presented here illustrate reuse and retrofit of Post-War buildings as a climate solution in the critical near term. They propose two methodologies for the application of LCA to retrofit projects to quantify total carbon reductions: the first to predict the avoided impacts of reuse versus replacement, and the second to critically evaluate retrofit approaches to reduce total carbon footprint. Both cases show that, even with the inherent challenges of the materiality and systems of buildings of this era, retrofit approaches can balance performance and carbon reductions with respect for original architectural intent and character. Furthermore, they begin to illustrate how use of low-carbon or carbon storing materials, many of which are natural and highly compatible with preservation, creates an opportunity to sink carbon into our existing buildings as we steward them to the next era of their lives.

The life cycle assessment of the New House Residence Hall illustrates the fact that reusing existing buildings provides a significant near-term reduction in carbon emissions compared to replacement construction. Strategic upgrades to the HVAC system that maintained operable windows and allowed an expanded comfort range in the corridor spaces, along with targeted upgrades to the building envelope that retained the character of the facades, resulted in a greatly reduced operational energy use, more efficient than code requirements for new construction. In combination with the substantial reduction in embodied upfront emission resulting from reusing the majority of the building structure and envelope, the project results in lower total carbon emissions through the year 2050 than high-performance new construction, particularly in the context of a greening grid.

While the first case study illustrates that reusing whole buildings of this period can result in significant total carbon savings, the second case study illustrates that a nuanced, targeted level of retrofit can result in a lower near-term carbon footprint than a deep energy retrofit that attempts to make a historic building perform like new net-zero construction. Both environmental and cultural needs are served by the same approach: a detailed understanding of the existing building performance and design and a life cycle-based evaluation method to implement targeted interventions that yield the greatest impacts.

Although buildings from the mid-twentieth century are perceived as a hurdle to a net zero built environment, it is not only possible to reuse them in an environmentally sustainable way, their reuse is in fact critical to meeting carbon neutrality targets. A life cycle approach enables the quantification of total carbon benefits of retrofit; in most cases, the upfront carbon savings of reuse lead to lower total carbon emissions than high performance new construction, particularly in the critical next decades. Furthermore, effective reuse of post-war buildings does not necessitate destruction of their character defining features. Analysis-driven, strategic retrofit approaches that capitalize on opportunities for improvement to performance, while respecting and working within the constraints of the existing building, make these structures a powerful climate action tool.

Notes

1. Alexandra Lange, *T Magazine*, June 5, 2015. https://www.nytimes.com/interactive/2015/06/05/t-magazine/architects-libeskind-zaha-hadid-selldorf-norman-foster.html (accessed 2021).
2. Architecture 2030. *Accelerating to Zero by 2040!* (October 2019). https://architecture2030.org/accelerating-to-zero-by-2040/ (accessed 2020).
3. Architecture 2030. *Accelerating to Zero by 2040!*
4. Energy Information Administration. *Table E2A. Major Fuel Consumption (Btu) Intensities by End Use for All Buildings, 2003* (December, 2008). U.S. Energy Information Administration Independent Statistics and Analysis: https://www.eia.gov/consumption/commercial/data/2003/pdf/e02a.pdf (accessed 2020).
5. Architecture 2030. *Accelerating to Zero by 2040!*; Reyner Banham. *A Concrete Atlantis* (Cambridge, MA: MIT Press, 1986); Aidan Duffy and others, *Understanding Carbon in*

the Historic Built Environment (Historic England, 2019); Energy Information Administration, *Table E2A*; 2020. *Greenhouse Gases Equivalencies Calculator – Calculations and References* (March, 2020). https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references; Alexandra Lange, *T Magazine*; Massachusetts Office of Energy and Environmental Affairs, *GHG Emissions and Mitigation Policies* (2021). https://www.mass.gov/info-details/ghg-emissions-and-mitigation-policies (accessed 2021); T. Reed Miller, Jeremy Gregory and Randolph Kirchain, *Critical Issues When Comparing Whole Building & Building Product Environmental Performance* (Cambridge: MIT Concrete Sustainability Hub, 2016); National Parks Service, U.S. Department of the Interior, *Technical Preservation Services* (n.d.). https://www.nps.gov/tps/sustainability/energy-efficiency.htm; Ryan Zizzo, Joanna Kyriazis and Helen Goodland. *Embodied Carbon of Buildings and Infrastructure – International Policy Review* (Forestry Innovation Investment, 2017).

6. Miller, Gregory and Kirchain, *Critical Issues When Comparing Whole Building & Building Product Environmental Performance.*
7. Aidan Duffy and others, *Understanding Carbon in the Historic Built Environment.*
8. Zizzo, Kyriazis and Goodland. *Embodied Carbon of Buildings and Infrastructure.*
9. CLF benchmarking.
10. EPA Greenhouse Gas Equivalencies Calculator.
11. Massachusetts Office of Energy and Environmental Affairs. *GHG Emissions and Mitigation Policies.*

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Lori Ferriss is a leader in sustainable stewardship for the built environment. Her professional practice as an architect, structural engineer and conservator combines broad policy development with deep technical insights to promote a culturally and environmentally sustainable world through design. She is a champion for preservation of our built heritage as a key measure towards meeting climate action goals through roles including Co-Chair of the Zero Net Carbon Collaboration for Existing and Historic Buildings, member of the ICOMOS International Scientific Committee on Energy, Sustainability, and Climate Change, Advisory Group member for the American Institute of Architects' Committee on the Environment.