Balancing Trade-Offs Between Deep Energy Retrofits and Heritage Conservation

By

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Abstract

An 81% reduction in carbon emissions from existing and heritage buildings by 2030 is required to achieve climate change mitigation targets of preventing warming above 1.5°C. A methodology and decision framework is presented for deep energy retrofit analyses that balances trade-offs between conservation and sustainability of a building's components. An historic house in Ottawa, Canada was studied to demonstrate the use of the methodology. The energy retrofit analysis suggests 71% energy savings are achievable through modest envelope retrofits, upgrading HVAC, sensors, controls, and renewable energy. The simple cost payback period is analysed to estimate feasibility for homeowners to implement deep energy retrofits. The carbon emissions saved over 20 years of operation are estimated. This thesis reveals that heritage conservation and sustainability have intersecting values, demonstrating that conserving and upgrading heritage buildings in a respectful way can play a key role in achieving carbon reductions within the existing building stock.

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Nomenclature

ACH	Air-changes per hour
AMY	Actual meteorological year
ASHP	Air-source heat pump
ASHRAE	American Society of Heating, Refrigeration and Air-Conditioning Engineers
CAD\$	Canadian dollar
CV(RMSE)	Coefficient of variation of the root mean square error
DER	Deep energy retrofit
DHW	Domestic hot water
Eppy	Library in Python for editing EnergyPlus files
EUI	Energy use intensity
g CO ₂ eq	Grams of carbon dioxide equivalent
GHG	Greenhouse gas emissions
GoF	Goodness of fit
GWP	Global warming potential
HB	Historic/heritage building
HDD	Heating degree day
HRV	Heat recovery ventilator
HVAC	Heating ventilation and air-conditioning
ICOMOS	International Council on Monuments and Sites
IDF	Input description file for EnergyPlus
IEQ	Indoor environmental quality
LBNL	Lawrence Berkeley National Laboratory
Low-E	Low emissivity coating for window glazing
NECB	National Energy Code of Canada for Buildings
NMBE	Normalized mean bias error
PIR	Polyisocyanurate
PV	Photovoltaics
R ²	Coefficient of determination
RH	Relative humidity

R-value	Thermal resistance of an object
SHGC	Solar heat gain coefficient
TMY	Typical meteorological year
U-value	Thermal conductance of an object

1 Introduction

1.1 Heritage Conservation and its Role in Climate Change Mitigation

The development of new buildings to replace existing buildings is around 1.0-3.0% per year in developed countries (Ma, Cooper, Daly, & Ledo, 2012) because of the long lifespan of buildings. Existing and heritage buildings that are present today are estimated to comprise about 75% of the building stock in 2030 (Schulte, 2018). For these reasons, it is recommended by the IPCC Special Report on 1.5°C (Zhou, 2018) to put efforts into retrofitting the existing building stock of developed areas, “to avoid lock-in of inefficient carbon and energy-intensive buildings.” The IPCC Special Report on 1.5°C reveals that carbon emissions from the building sector need to reduce from about 8 Gt CO₂/year in 2010 to around 1.5 to 2.2 GtCO₂/year in 2030 (81% reduction) and 0.1 to 0.9 GtCO₂/year in 2050 (99% reduction).

Although it is evident that carbon reductions are required, the rate of energy retrofits to achieve this within existing buildings globally is at a low rate of 2.2% per year (Ma et al., 2012). The NECB (National Energy Code of Canada) outlines energy performance standards for new construction (CCBFC, NRC, 2015), while the Ontario provincial building energy code has identified that conservation of existing buildings and energy upgrades should be a focus for achieving energy and carbon reduction targets, recognizing that the upgrades should not be detrimental to the conservation of cultural values within heritage buildings (MMAH, 2016). The question then is, how can deep energy retrofits be undertaken in heritage buildings in a respectful way and what are the potential carbon savings? Though there may be some conflicts between heritage conservation and sustainability, there is a missed opportunity in retrofitting heritage

buildings to improve their overall sustainability, while conserving important cultural values.

While the current operational carbon emissions of existing buildings may be greater than new low-carbon buildings, there are other sustainability reasons to retrofit existing buildings. Reusing buildings contributes to the UN Sustainable Development Goals 11.6 by reducing environmental impact through reduction of construction materials and waste, and 11.C by making buildings more resilient through retrofits to reduce energy use and improve comfort (United Nations, 2019). Grytli, Kvaerness, Rokseth, & Ygre, (2014) compared the environmental impact of operational energy use and life cycle carbon for different conservation scenarios for an historic building. The study found that conserving the historic building and improving its energy efficiency has a lower environmental impact than replacement with a new building built to passive house standards. These findings were dependent on the lifespan of the historic building and demonstrate that there is a greater importance to reduce the energy use of the building as the lifespan increases (Grytli et al., 2014).

The existing building stock in the U.S. consists of over 90% built before the 1990s which are now requiring major retrofits (Diamond, 2001). These retrofits may be for seismic performance and to prevent safety risks due to natural deterioration, to improve thermal comfort and energy performance (Webb, 2017), to conserve heritage values through preservation and rehabilitation (Grimmer, 1995), and for adaptive reuse by current

and future generations (Bullen & Love, 2011). Historic buildings (HBs)¹ worldwide present a great opportunity to achieve large energy reductions as they comprise between 10% and 40% of the building stock and will continue to exist because of their cultural value (CIBSE, 2002; DOE, 2011; Economidou et al., 2011; Troi, 2011; Webb, 2017). A study was done for the EU, showing that there is potential for large-scale carbon savings of 180 Mt CO₂ emissions through a 75% reduction in carbon emissions by energy retrofitting HBs² (Troi, 2011). These carbon savings equate to about 2% of the carbon emissions from the global building sector in 2010 (Zhou, 2018). The carbon and energy cost savings are in addition to the benefits of increased indoor comfort and decreased energy costs, improving overall sustainability (Troi, 2011). In Canada, 48% of residential building energy use is from buildings constructed before 1977 (NRCan, 2016). If all these buildings implemented retrofits to achieve a 75% reduction in carbon emissions, then the carbon savings would be about 39.7 Mt CO₂ (NRCan, 2016; Senate, 2018). Although these carbon savings are only 0.5% of the global building emissions, every country needs to do their best to help achieve climate mitigation targets.

Currently, HBs are exempt from energy efficiency codes in many regions (EU-Parliament, 2010; CCBFC, NRC, 2015), but it is likely that energy reduction targets will also be required in HBs soon to meet climate change targets. There are similarities between implementing energy retrofits in existing buildings and in historic and traditional buildings (Webb, 2017). The main differences between energy retrofits in these buildings are

¹ An historic (or heritage) building in this thesis defines a building that is 40 years or older, has retained most of its original building fabric, and has cultural significance for a community.

² This study considered all buildings in the EU constructed before 1945 as historic.

encountered within the physical characteristics of the building (e.g. the construction materials are non-homogenous, HVAC systems are older and inefficient, etc.) and the constraint of conserving the cultural values within these HBs (Webb, 2017).

1.2 Deep Energy Retrofits and Building Performance Simulation

Deep energy retrofits are defined as “a major building renovation project in which site energy use intensity (including plug loads) has been reduced by at least 50% from the pre-renovation baseline with a corresponding improvement in indoor environmental quality and comfort” (IEA, 2017). This type of retrofit requires a detailed whole building analysis where the performance of building systems is considered together (IEA, 2017). If the typical retrofits of achieving between 10-20% energy savings from no-cost to low-cost options are followed for existing buildings, then the carbon reduction targets to mitigate climate change effects of warming above 1.5°C will not be achieved (Fifita et. al, 2018).

The difficulty in achieving deep energy retrofits in HBs is that a prescriptive compliance pathway is not a viable option to conserve the heritage values of the building. This pathway may not be viable since it prescribes low levels of air infiltration or specific R-values for envelope components, among other things, which may not be attainable for the type of construction of HBs (Pracchi, 2014). A performance compliance pathway allows deviations from prescribed energy requirements through energy analyses that demonstrate the desired building performs better than a prescribed building of the same massing and internal loads. This makes a performance compliance pathway a better option to conserve heritage buildings. However, creating a calibrated energy model is more

difficult for HBs because of their unique constructions (Adhikari et al., 2011) and lack of as-built documentation.

1.3 Organization of Research and Thesis Document

This document includes the literature review, background information on the case study, methodology, sensitivity analysis, thermography, calibration of energy model, use of decision framework, cost analysis, and carbon analysis. Finally, concluding remarks summarize the findings and provide suggestions for further research.

2 Literature Review

2.1 Case Studies

There are a few studies that demonstrate deep energy retrofits can save between 40-89% energy in historic buildings in cold climates (Bin & Parker, 2012; Jermyn & Richman, 2016), exploring combinations of envelope retrofits and HVAC upgrades to achieve great energy savings. See Table 1 for a summary of these deep energy retrofit case studies. Alev et al. (2014), Harrestrup and Svendsen (2015), Morelli et al. (2012) suggest insulating the walls to achieve high energy savings of 14% to 47%. This recommendation may be appropriate depending on the wall assembly and environmental conditions. Straube and Schumacher, (2007) advise specific methods to prevent deterioration risk as the wall assembly will experience a large change in temperature and moisture conditions. Adding insulation to an existing building can be invasive and costly, but the benefits of improved occupant health and reduced energy costs outweigh the cost of adding insulation by 1.9:1 (Chapman et al., 2009). Infiltration can contribute up to 50% of total heat loss in a building making air-tightening an important retrofit option (Sedovic & Gotthelf, 2005). Rehabilitating a building envelope to have an air-barrier and air-sealing leakage areas

should be able to achieve 4.4 ACH at 50 Pa as this is the average for residential buildings in Canada (Fennell & Haehnel, 2005). Additional case studies in North American cold climates are important, as less than 5% of publications originate in continents other than Europe and Asia (Bertolin & Loli, 2018). Blaszak & Richman, (2013) noted that energy retrofit strategies will have varying effects for different types, styles, and ages of houses, which varies from region to region.

Table 1: Findings from case studies about energy retrofits in historic buildings in cold climates

HB state	Retrofit	Energy Savings
High thermal conductivity of envelope	Additional interior insulation on exterior walls	14-47% (Alev et al., 2014; Harrestrup & Svendsen, 2015; Morelli et al., 2012)
High air leakage through cracks, openings, and envelope construction	Air-tightening	5-6% after improving thermal performance of envelope (Alev et al., 2014; Morelli et al., 2012)
Inefficient HVAC	Upgrade to new efficient systems that have low impact on heritage character	50-68% (Arumägi & Kalamees, 2014; Morelli et al., 2012)
Heating setpoint and window opening	Influence occupant behaviour to reduce window opening and lower heating setpoint	50% relative to a high energy user scenario (Ben & Steemers, 2014)
High thermal conductance and air leakage of windows	Replace with new lower thermal conductance windows	5% (Arumägi & Kalamees, 2014; Morelli et al., 2012)

2.2 Methodologies

Many papers (Adhikari et al., 2011; Alongi, Scoccia, Motta, & Mazzearella, 2015; Ascione, de Rossi, & Vanoli, 2011; Grytli et al., 2014; Loli & Bertolin, 2018; Ma et al., 2012; Young, 2012) outline methodologies for conservation and sustainability projects with a commonality being that a high level of understanding of the building is required prior to analyses. Ma et al., (2012) outline a methodology for cost optimal retrofits of existing buildings. This methodology describes many important things to consider in the methodology for a HB energy retrofit such as: an initial survey of the building and

definition of project objectives, energy audit and performance assessment, identification of retrofit options through several analysis methods (energy, economic, risk assessment, etc.), site implementation, and validation and verification of energy savings. Loli & Bertolin (2018) outline that the following should be included in a methodology balancing heritage conservation and sustainability: identifying the cultural values of a building and protecting them, determining level of intervention based on condition of structure, reducing costs without compromising occupant comfort, compatibility with existing materials, and life-cycle assessment to maximize reuse of materials and reduce carbon footprint of interventions.

Ascione, de Rossi, & Vanoli, (2011) consider energy savings and economic benefit in their methodology. This study collected data from heat flux sensors, calibrated to historical monthly data, and simulated individual retrofit options. Then the most viable retrofits were combined to predict the total savings. A cost analysis was conducted for all the retrofit options. A similar approach is used in this study, but a simple payback is calculated to consider cost.

Adhikari et al. (2011) proposes a procedure for modelling and simulating energy performance of HBs: documenting the building, calculating thermal transmittance of walls, climate and microclimate data, model calibration using measured indoor air temperature, and then simulation. Alongi et al. (2015) conducted a detailed performance analysis of an historic castle in Italy and described their modelling and simulation methodology using TRNSYS, but there was no calibration method explained. Roberti, Oberegger, and Gasparella (2015) start with a detailed initial model based on energy data of the building, a sensitivity analysis, calibration to indoor air temperatures, and validation of the

calibration. The importance of the calibration is to determine values for the most sensitive parameters in the model.

Grytli et al. (2014) outline a methodology and case study that assesses retrofits based on their environmental impacts and their impact on heritage values. Their approach focused on the heritage assessment from archival analysis, to surveying, condition assessment, values assessment, and life cycle assessment in addition to the energy assessment, which was not seen in many other papers that considered energy retrofits in HBs. For the heritage assessment, a numerical ranking was given based on how an intervention would impact the heritage values of the building. A single methodology that combines the strengths of the above methodologies, while being simple enough for a high adoption rate would be useful for achieving carbon reductions in historic buildings at scale.

2.3 Embodied Carbon

Demonstrating that great energy savings can be achieved and saying that “the greenest building is...one that is already built,” is not enough on its own as the driver of climate change is the increase in greenhouse gas emissions (Elefante, 2017). The avoided carbon equivalent emissions should also be demonstrated when analysing a retrofit to determine its benefit over a period. Schulte, (2018) urges that embodied carbon of existing structures should be recognized as well as the protection of unique characteristics of heritage buildings.

A study comparing the carbon emissions mitigated through a net positive renovation of an existing building vs a new conventional building constructed to code showed that the reuse of the existing building mitigated 70% of the embodied carbon of the new building (Ecological Building Network, 2015). The study demonstrates the importance of the time

value of carbon since 70% of emissions are mitigated from the very beginning of the building's reuse due to savings in the manufacturing of new materials. Another study showed that there is a potential for 55-83% CO₂ emissions savings when historic buildings are retrofitted using the Passive House Planning Package and renewables such as PVs are implemented (Moran, Blight, Natarajan, & Shea, 2014). A case study done by Ferriss (2019) on the carbon payback timeline of a new construction vs renovating the existing building, shows that the payback of the new construction performing 65% better than code is about 30 years. If this scenario takes place in 2020, then the new construction will not have contributed to greenhouse gas emissions reductions until 2050 when we are supposed to achieve a 99% reduction in carbon emissions from the existing building stock. There is a need for more studies on the avoided carbon of building reuse and retrofit to higher energy efficiency levels. For this reason, the research presented here also includes a life cycle carbon analysis of the energy retrofits.

2.4 Problem Definition

The issue for heritage and energy retrofit professionals is that there is no standard process for conducting a deep energy retrofit analysis for heritage buildings in order to respect the heritage values of these buildings while achieving great energy and carbon savings.

2.4.1 Motivation

The motivation of the research presented in this thesis is to help mitigate the climate change effects due to anthropogenic greenhouse gas emissions. Retrofitting existing buildings is a pathway to achieve great carbon emissions reductions. There is still a lot of push back from heritage conservationists about which retrofits may be done within heritage buildings. Toshiyuki Kono, president of ICOMOS (International Council on Monuments and Sites),

advises that, “it would be foolish to imagine the practice of heritage remaining static while the world goes through the rapid and far-reaching transitions discussed in the IPCC’s recent Special Report on Global Warming of 1.5°C,” (ICOMOS, 2019). Heritage professionals have the fundamental knowledge and values in stewardship, conservation and community to help drive climate action, but the majority are not facilitating this effort.

2.4.2 Research Objectives and Contributions of Research

This research is meant to provide a methodology and decision framework to help heritage and building professionals leverage heritage buildings to achieve great reductions in greenhouse gas emissions in historic single detached residential buildings. The methodology and decision framework can be used on other building archetypes. The approach is exemplified using a case-study heritage house.

This thesis aims to combine the many critical elements described in the literature review of methodologies to present one cohesive general methodology for conducting deep energy retrofits in historic buildings, while considering other important aspects (occupant comfort, cost, etc.). The general methodology is presented below in Figure 1. The application of the methodology is demonstrated for an historic wood framed house in Ottawa, Canada, where there are minimal studies considering heritage values and energy savings in a similar region and climate. The methodology delineates the creation of a calibrated energy model for an HB without invasive time-consuming testing and an appropriate level of documentation by leveraging the use of calibration to measured data. A decision framework (Figure 26) is presented to guide decision making for balancing the trade-offs between heritage conservation and energy savings objectives. While this study is conducted on a single-detached home, the goal is that this methodology and decision

3 Case Study – Historical Analysis and Documentation

A study was conducted on a residential home that is about 120 years old (built around 1898 to 1910) in the Glebe community (Keller-Herzog, 2018b), a mature neighbourhood³, in Ottawa to provide recommendations for reducing the energy use and carbon footprint of the house. The addition of the house was likely added around 1956 based on historic aerial images from GeoOttawa. The house has 330 m² of floor area and was recently recorded in its current state (floor plans, elevation drawing, condition report, photos, laser scanning, etc.) by a group of Carleton University students. A thorough condition assessment of the house was performed including indoor environmental quality (IEQ). This documentation was used to create accurate geometry of the case study house within energy modelling software. This model was created with as much detail as feasible to produce an accurate whole building simulation. The model was calibrated using utility bill data of the house and information obtained through an interview with the owner and survey of the site. The house is currently used as a bed and breakfast, a daycare for children, and home office. Since the house is old and contains many of the original materials, it is possible that this building may have heritage significance for its stakeholders. The following sections outline the historical analysis of heritage values of the site and the utility bill data analysis to understand the monthly energy use of the building.

³ Mature neighbourhood overlay shown in GeoOttawa (<http://maps.ottawa.ca/geoOttawa/>). Historic map in GeoOttawa from 1928 shows the house on the lot already existed at this time. The City of Ottawa heritage study (2019) indicates three main eras of development in the Glebe as Early Development (1791-1890), Suburban Development (1891-1945), and Post-war Development (1946-present). It is likely that the construction of the original house occurred during the Suburban Development phase.

3.1 Understanding Heritage Values of the House

There are not many designations in the Glebe neighbourhood so designating a significant house like this one may be important to conserve the architectural, associative, and environmental values of the 1950s to the 21st century. The Glebe Heritage Committee is also in the process of conducting historic research and submitting applications to designate the following areas in the Glebe: Clemow Avenue West, Monkland Avenue, Linden Terrace, and Central Park West (“Clemow Estate Phase II,” 2016). There are exterior similarities between the houses found on the streets that have cultural value for the Glebe community and 166 Glebe avenue, the case study house, suggesting that this house may also be significant to the community (Figure 2).

Figure 2: 166 Glebe Avenue, Ottawa. Angela's Bed and Breakfast. Located at the corner of Lyon street and Glebe avenue (Larissa Ide, June 2019).

James Harvey Hopper was the architect of several expressive houses on the streets that the Glebe community has deemed to have significant heritage value (Elliott, 2011). Two houses on Glebe Avenue, designed by William D. Hopper architect and builder (James Hopper's brother), exhibit a combination of Dutch Colonial Revival and Queen Anne Revival architectural styles (Figure 3). These styles are also well pronounced in Angela's house and have similar features including: masonry details, stone foundation walls, portico, a front balcony (previously existed on the case study house), large bay windows, and dormer windows (Elliott, 2011). It is possible that the case study house was also designed by William Hopper or at least influenced by his designs because of the similarities. The two houses designed by William Hopper were later connected to become a row house that served as a senior's home for many years. Today this row house has retained its exterior front façade, but the back and interior have undergone major changes to be more modern (Elliott, 2011). This loss of heritage features provides a reason to protect the case study house which still contains original interior and exterior features.

Figure 3: 174 and 176 Glebe Avenue, June 1974 (Elliott, 2011).

3.1.1 Current State and Future Intentions

The case study house is currently kept in great condition as a result of fixing water shedding features of the house, repairing damaged mortar, adding insulation to the exterior walls and attic, air sealing the house, and the addition of steel support beams where settlement was occurring. Angela is a proactive house owner which is why the house is in such great condition. Several interior character-defining elements have also been preserved. The few elements of the house that are in poor condition are the basement door to the exterior and the wood shingles on the roof of the back addition of the house (Figure 4 and Figure 5).

The energy interventions as well as upgrades to appliances and water fixtures were conducted based on analyses from energy audit reports and thermography reports to improve the building's performance from an EnerGuide rating of 33 in 2012 to 67 in 2017 out of 100 (Belisle, 2017; Ferland, 2012). While this is a significant improvement, the owner is interested in reducing her carbon footprint as much as possible, which will entail reducing the heating load and improving the efficiency of the heating system, comprised of a gas boiler and iron radiators. Angela is also interested in adding an air-source heat pump for air-conditioning as the summers are getting hotter due to climate change. The goal of the energy analysis is to identify combinations of interventions that will achieve a 50% energy reduction in the house's energy use and reduce the carbon footprint as much as possible.

Figure 4: Rear view of case study house. Deteriorated wood shingles on roof of back addition to house (Larissa Ide, June 2019).

Figure 5: Basement door to exterior. Deterioration due to moisture: paint peeling and biological growth (Larissa Ide, June 2019).

3.1.2 Proposed Heritage Statement and Character Defining Elements

Based on the historical analysis, the following heritage statement is proposed for 166 Glebe Avenue. Heritage significance is recognized in the house at 166 Glebe Avenue, constructed around 1898 to 1910, for its Dutch Colonial Revival and Queen Anne Revival architectural styles, its influence from prominent architects of the Glebe neighbourhood, James and William Hopper, the mature trees that surround the house which reflect the streetscape of Glebe avenue, its sustainability features, and the association with the current owner who is a community influencer through participation in several Glebe committees and programs. While this is not an extraordinary house, it is the modest nature, integration in the community, and example of the time it was built that make this house culturally significant. The character defining elements of the house were determined following guidelines in Parks Canada (2006) and Van Balen (2008). The Nara grid outlining key values of the place is provided in Table 2.

The Nara grid is one way to assess the significance of a place and was chosen because it captures intangible and tangible values of a place (Van Balen, 2008). A rating for each element in the grid is given to indicate the level of significance as low, medium, high or very high. Older original elements that are unique to the style or character of the house have higher significance, while newer elements that may contribute to the newer values of the house have a lower significance.

Table 2: Nara grid for case building. A rating of low, medium, high, or very high heritage significance has been assigned to each value.

	Artistic	Historic	Social	Scientific	Photos
Form and Design	The mansard roof, large bay windows, and portico all define the Dutch Colonial and Queen Anne Revival architectural styles of this house. High	The main house area wood framed structure and external cladding are the original structure from 1889 giving it historical value. High	The addition of the house reflects the styles of the main house and provide additional spaces for the permanent occupants and guest of the house facilitating its current use as office space, a daycare, and bed and breakfast. Medium	The portico and strategic placement of windows provide shading and protection from environmental elements as well as allow ample use of daylight to light the interior spaces. High	Front façade of house.
Materials and Substance	Stone lintels provide accents in the aesthetic of the brick masonry façade. High	Stone foundation, stone lintels, red brick, and wood framing are historic materials conserved on this site. High	The historic wood mouldings and cast-iron radiators provide additional cultural value on the interior of the house. High	The durability and repairability of the materials used in this house (brick and stone masonry, wooden framed windows, and wood structural elements) provide examples of quality historic materials. High	Fully pitched scotch bond masonry foundation.
Use and Function	The chimney and fireplace were historically used to heat the home, but now serve as decorative elements. Medium	The house has historically been used as a home and continues to be a home to the owner of the house. Medium	The use of the house as a daycare and bed and breakfast add social value to the building by bringing together a wide variety of demographics that pass through this house. Medium	Water shedding features were repaired to reduce moisture damage on the exterior of the building. Mortar was repointed where damage was incurred. Repairing these historic materials fulfill the important protective and sheltering functions of the building envelope. High	Interior view of brick chimney and fireplace.

	Artistic	Historic	Social	Scientific	Photos
Tradition, techniques, and workmanship	The fully pitched scotch bond masonry used in the foundation are a beautiful element of the aesthetic value of the building and demonstrate the high level of craftsmanship. High	Historic decorated radiators also demonstrate the amount of detail and workmanship that went into this house. Medium	The high quality of workmanship throughout the house increase the place's value to the community. The current energy conscious features such as the solar PVs add the social value of being an example of reducing one's impact on the planet. High	The exposed wood structural frame in the basement exhibit the techniques used in the construction of the building. The wood balloon framing of the house is a traditional technique for constructing houses of this age with quality timber. Medium	<p>Cast-iron radiators used to heat the house.</p>
Location and setting	The architectural style of the house reflects the styles of many houses in the Glebe community, contributing to a cohesive urban landscape. High	The house was designed or influenced by historic architects of the area James and William Hopper evidenced by its age and style. Low	The house is in a walkable community, situated close to Bank street, a main street that constitutes many local stores, increasing its social value. Because of its connection to Glebe Community leader, the location on Glebe Avenue is significant. Medium	Many mature deciduous trees strategically placed on the site provide necessary shading during the summer to reduce solar gains within the house. High	<p>Deciduous trees providing shade during the summer.</p>
Spirit and feeling	The similar aesthetic of the house to other houses in the neighbourhood contribute to the feeling of community that is tied with the current owner's commitment to a greater good. Medium	The good state of the conservation of the historic structure, materials, and elements portray the age and significance of the building. High	The place provides a sense of community, due to the welcoming porch steps and LGBTQ flag in front. Angela Keller-Herzog, the owner of the house, is a community leader in climate action. Medium	The use of advanced technologies on the site (solar PVs) help create the spirit of the place being respectful of its surrounding environment by reducing its energy use for the operation of the building. Low	<p>Back façade of house.</p>

3.2 Utility Bill Data Analysis

3.2.1 Heating Degree Day Analysis

As part of the historical analysis of the building, past utility bill data should be analysed and annual energy use (kWh/m^2) should be compared to similar aged buildings and newer buildings with the same construction type. Knowing the heritage values, condition, and comparative energy use intensity of the house will help determine a realistic energy reduction target. For comparison, space heating energy statistics were analysed because this was the most complete data and it consumes the most energy in residential buildings in Canada. The oldest most complete data in Canada for buildings constructed in 1990 shows that the space heating energy use is 206 kWh/m^2 for Ontario (NRCan, 2016). The average space heating for buildings constructed in 2011-2016 is 133 kWh/m^2 for Ontario.

The measured gas and electricity data from utility bills for 2015 to 2017 are shown in Figure 6. The average annual electricity use is 40 kWh/m^2 (24% of total) for lighting, appliances and a small portion for pumps used in the hydronic heating system⁴. The electricity use does not have much variation throughout the year because of its type of usage (mostly appliances and lighting). There is a slight increase in electricity use during the summer due to an increase in guests during that time. The average annual gas use is 128 kWh/m^2 (76% of total) for the gas boiler used for heating and a tankless gas heater for the domestic hot water (DHW). The gas use increases for the heating season and decreases for the cooling season when it is only used for DHW. A heating degree day analysis was

⁴ Note: The power generated by the existing PVs on site is not included in the baseline EUI of the house since PV calculations are done outside of the detailed energy model to be calibrated. There is no air conditioning or mechanical ventilation in this house.

conducted for the gas energy use since it is mostly used for heating (Figure 7). HDD is calculated using the following equation:

$$HDD = \sum(T_{bal} - T_{out}) \quad (\text{eq. 1})$$

Where T_{bal} is the balance temperature which is the outdoor temperature at which no heating is required; T_{out} is the average temperature for each day of the year; the HDD for each day can not be negative (zero if it calculates to be negative); and this is summed for the entire year. Only monthly utility bill data was available, so the calculation was done on a monthly basis (instead of hourly) and summed for the year. A regression was conducted to determine what portion of the gas energy use was not correlated to the required heating for the house, therefore indicating the energy use for the DHW. The coefficient of determination is 0.876; since this is an older home with a building envelope that allows more airflow, the performance of the house is more dependent on the outdoor temperature than a newer building that has a more air-tight envelope. This regression analysis also gave the baseload of 1.7 kWh/m² per month and about 20 kWh/m² per year which corresponds to the DHW use. This means that space heating is about 108 kWh/m² which is 47% and 19% better than Ontario's 1990 and 2011-2016 space heating energy use for residential buildings, so this house is already performing better than many houses.

Figure 6: Measured gas and electricity consumption for 2015-2017. May to August have higher occupancy due to guests in bed and breakfast, resulting in greater DHW consumption than the estimated baseload. Electricity use is greatest in July because of several personal fans during hottest month (no air-conditioning in the house).

Figure 7: Heating degree day analysis for the house with a base temperature of 15°C. Estimated baseload DHW energy use is 1.7 kWh/m²/month and 20.4 kWh/m²/year.

3.2.2 Current PV Power Generation

The site also has some solar photovoltaic panels on the roof of the house and detached garage that generate power to offset the electricity consumption. The energy generated by the PVs is supplied to the grid and is credited on the electricity energy bill. The PV generation for 2015-2017 (Figure 8) shows that there is significantly more PV generation during the summer than in the winter as expected because of the greater number of overcast days in the winter and the lower solar altitude of the sun in the winter. The annual total PV power generation for 2015, 2016 and 2017 are 11.6 kWh/m², 11.9 kWh/m², and 10.8 kWh/m². The data shows that the average PV power generation has been quite consistent from 2015-2017 at around 31% (11.4 kWh/m²) of the annual electricity consumption.

Figure 8: Current PV power generation intensity in kWh/m² for 2015-2017. The average electricity generation is about 2.7 kWh/m²/year.

4 Detailed Energy Model

4.1 Methodology

A detailed energy model was created using OpenStudio and EnergyPlus⁵ (*EnergyPlus*, 2018; *OpenStudio*, 2018). To achieve a deep energy retrofit, multiple retrofits need to be combined, and a simple model will not predict the interactions of multiple retrofits. First, a representation of the geometry of the building (see Figure 9) was created using floor plans (see Appendix A) and elevation drawings that were recorded in 2018. All sides of the final building model are shown in Appendix B.

Simplifications were made for the geometry as the geometric resolution does not significantly impact the simulation results for the purposes of this study. This improves reproducibility, reduces model complexity and simulation run time, while keeping the necessary data. The simplifications made were: modelling smaller dormer windows as in-plane windows, creating a flat roofed third floor/attic with an equivalent volume as the mansard roof attic (the existing roof has a small slope), and using an average floor area to have a consistent footprint for each floor (no small overlaps in floors). Shading by trees (deciduous and evergreen) was represented in the model to account for reduction in solar radiation, daylighting, wind and change in longwave radiation to environment. Thermal zones were separated by floor and by the different constructions of the house (main part of house separated from more recent addition), resulting in seven thermal zones in total.

⁵ Software was chosen because it has been tested and validated using the BESTest (DOE, 2020).

Separating the house into these thermal zones allows for adjustments in each individual thermal zone as necessary to match the behaviour of the existing house.

Figure 9: Geometry of model in SketchUp plug-in and view of back of house from the same perspective (Larissa Ide, June 2019). Purple/gray shading objects are used to represent trees and adjacent building.

The schedules, plug loads, occupancy, and HVAC were defined for the model based on information obtained from an interview with the house owner and survey of the house. The average permanent occupancy for the calibration year was four occupants. Additionally, there are 5-10 children and one adult present during the day for the daycare that is run in the house. The occupancy varies throughout the year because of the guests that come for the bed and breakfast service in the house. The summer occupancy and DHW use are higher than the rest of the year due to increased number of guests. Unique schedules for occupancy, equipment and DHW were created based on this information instead of using ASHRAE recommended occupancy schedules. Figure 10 shows occupancy during holidays/Saturdays/Sundays. The typical occupancy was assumed to be 3.6. The occupancy reduces for a few hours during the morning, assuming that occupants may need/want to leave for errands or other things. The figure below also shows the occupancy schedule for a weekday (Monday to Friday); it starts at the typical occupancy and increases

to 6 people to account for the daycare provider and children for the daycare. Then at 5 pm, the daycare service ends, and the occupancy returns to the regular level. Additional details about the internal gains inputs are provided in Appendix B.

Figure 10: Occupancy schedule for holidays (left). Assumed Jan 1-5 and Dec 25-31 were typical holidays. Occupancy for weekdays Jan 6-Dec 24 (right).

To ensure that model inputs were correct, and the model was behaving as expected, outputs were examined for specific inputs. For example, when shading objects were added and schedules were assigned to represent deciduous trees, the incident solar radiation on exterior building surfaces were compared before and after adding shading devices and during winter or summer months.

The temperature setpoint for heating was initially set at 21°C because of the setpoint on the thermostats. The radiant hydronic heating system was modelled using a baseboard radiant convective water system. A baseboard radiator was assigned to each conditioned space. The radiators were connected to the gas boiler with a water outlet temperature of 82°C indicated by the boiler. The initial air infiltration was modelled using the calculated flow coefficients based on air changes per hour measured in a blower door test in 2017 which indicated 11 ACH at 50 Pa. The method used to calculate the air infiltration for the house in the energy model was the AIM-2 model by Walker & Wilson, (1998) which is

appropriate for smaller, residential buildings. The flow coefficient was calculated using the equation in the AIM-2 model rearranged:

$$C = Q/\Delta P^n \quad (\text{eq. 2})$$

Where Q is the air infiltration flow rate (m^3/s), C is the flow coefficient, ΔP is the pressure difference between inside and outside (about 50 Pa for a blower door test), and n is the power law pressure-flow relationship assumed to be 0.67 (*EnergyPlus Version 8.9 Documentation Input Output Reference*, 2018). Air changes per hour were converted to flow coefficients using equation 1 and the following equation to convert ACH to m^3/s .

$$Q (\text{m}^3/\text{s}) = \text{ACH} * V_{\text{space}} / 3600 \text{s/h} \quad (\text{eq. 3})$$

V_{space} is the volume of the space in m^3 . The flow coefficients for each of the seven thermal zones were calculated for each iteration of total ACH for the house and weighted 20% basement, 20% ground floor, 20% level 1, and 40% level 2 based on the patterns observed in thermography. The equation below is how the air infiltration is calculated in EnergyPlus using the ZoneInfiltration:FlowCoefficient class:

$$\text{Infiltration} = (F_{\text{Schedule}}) \sqrt{(cC_s \Delta T^n)^2 + (cC_w (s * \text{WindSpeed})^{2n})^2} \quad (\text{eq. 4})$$

Where:

- F_{Schedule} , fractional schedule multiplier = 1
- c , flow coefficient, was calculated using eq. 2
- C_s , stack coefficient = 0.107 for three storey house with flue (ASHRAE 2017)

- ΔT , average temperature difference between the indoor zone air and outdoor air, calculated during simulation
- n , pressure exponent, was assumed to be a typical value of 0.67
- C_w , wind coefficient = 0.167 for three storey house with a basement and flue (ASHRAE 2017)
- s , shelter factor = 0.6 for an urban building on a larger lot (less than 0.61 shelter factor for typical urban building on larger lot because only sheltered on one side since it is a corner site)

4.2 Results and Analysis

The zone operative air temperature was checked to see if temperature setpoints were being met. It was found that the gas radiators in the model were not heating the space to the 21°C temperature setpoint. It seemed that the radiators were under sized at 75 W/m² max capacity each by the software potentially due to the high air infiltration modelled (Figure 11). The zone temperature during the summer peaks around 38°C because air flow networks were not used to model the natural ventilation used for cooling. The reason for this was because this level of complexity did not seem necessary for the purposes of estimating the energy use and occupants had indicated overheating during the summer with the use of natural ventilation alone. When the baseboard capacity was increased to 105

W/m^2 , the zone operative air temperature was able to stay closer to $21^{\circ}C$ than before (Figure 12) and the monthly energy use was closer to the measured 2017 utility data.

Figure 11: Zone operative air temperature with $75 W/m^2$ capacity baseboard heaters for each zone. The zone air temperature drops far below the temperature setpoint of $21^{\circ}C$ during the winter.

Figure 12: Zone operative air temperature with 105 W/m² capacity baseboard heaters for each zone. The zone air temperature drops below the temperature setpoint of 21 °C during the winter.

The air infiltration was checked as well. The total air infiltration for the house was determined to be about 14 ACH (air changes per hour) at 50 Pa (0.0078 m³/s/m² at 50 Pa or 1.54 cfm/ft² at 50 Pa) based on the calibrated model. The air infiltration from the simulation is output in ACH at ambient conditions rather than at a 50 Pa difference. A rough estimate of the ACH at ambient conditions would be to divide the ACH at 50 Pa by 20, which is about 0.70 ACH (0.00039 m³/s/m² or 0.83 cfm/ft²). The air infiltration was distributed by floor level of 20% for the basement header, 20% for the ground floor, 20% for the first floor, and 40% for the header of the second floor. The air infiltration fluctuates

with the windspeed and temperature difference between indoors and outdoors throughout the year.

Seen in Figure 13, the second floor air infiltration is an average of 0.31 ACH over the entire year. The other zones have an average air infiltration ranging from 0.09 ACH for the basement addition which has the smallest area above ground, to 0.16 ACH for the first floor space. Other things that were checked were the change in solar radiation when adding PV arrays as shading objects, blinds for windows, lighting schedules, equipment schedules, and people schedules. Checking outputs helped determine if inputs were correct or if they needed to be improved to better represent the reality of the house.

Figure 13: Zone air infiltration (ACH) for calibrated baseline model

5 Calibration of Energy Model

The model was calibrated to the measured utility bill data of recent years (2015-2017) shown in 3.2. The method of calibration was heuristic and evidence based. Important parameters to calibrate were selected through a sensitivity analysis. Thermography was conducted for qualitative understanding of the heat transfer in the building and potential areas of moisture issues. Other information obtained from the survey of the house also helped with calibration.

5.1 Sensitivity Analysis

5.1.1 Methodology

A one factor at a time sensitivity analysis was conducted on the initial energy model to identify the most sensitive parameters that may require additional measurements to improve accuracy of calibration and to inform most effective retrofit options. Uncertain parameters that were explored were the air infiltration, indoor air temperature setpoint, boiler efficiency, thermal resistance of insulation in the main house walls and addition walls, window thermal performance, stone foundation density, ground temperature, brick wall density, chimney thermal bridging, concrete floor slab density, and roof insulation thermal conductivity. Discrete values for parameters were input and simulated for each individual change. Properties of materials with different densities were obtained from ASHRAE (2017). Densities were examined for thermally massive materials because this characteristic has an impact on the material heat transfer. The sensitivity analysis process was automated by writing a python code (see GitHub link for samples of code:

<https://github.com/larissaide24/Deep-Energy-Retrofits-for-Heritage-Buildings>) to change the EnergyPlus IDF files using Eppy, simulate, and store results to then be plotted.

5.1.2 Results and Discussion

The air leakage, heating setpoint temperature, boiler efficiency, wall thermal resistance and window properties were the most sensitive parameters. Parameters that were found to be less sensitive in the model were the ground temperature, stone foundation properties, and others so reasonable baseline values were chosen for these parameters. Figure 14 shows a summary of the sensitivity analysis results (see Appendix C for the full sensitivity analysis results of all discrete values simulated). The reason the temperature setpoint was considered in the sensitivity analysis was because the thermostat is close to the entrance of the house. People come and go throughout the day so the house may be heating more than it needs to due to the cold breeze hitting the thermostat frequently. To represent this in a simplified way, the setpoint was adjusted as if it was heating to a higher setpoint.

Figure 14: Summary of sensitivity analysis results for change in annual gas energy use from initial baseline 117 kWh/m²/year (before calibration). Most sensitive parameters were determined to be air changes per hour of air leakage, heating setpoint, boiler efficiency, main house insulation, and improved windows.

5.2 Thermography

Thermography was used to qualitatively enhance understanding of thermal bridging, air infiltration, and other issues in the house.

5.2.1 Methodology

Qualitative thermography helps to visualize relative differences in temperature to identify potential areas of thermal bridging, air infiltration and moisture issues. The thermographic tool used was a point and shoot focus-free FLIR E4 Wifi Imaging IR Thermometer with: 80×60 pixels resolution, accuracy of $\pm 2^\circ\text{C}$ ($\pm 2\%$), thermal sensitivity of $<0.15^\circ\text{C}$ (<150 mK), and temperature range of -20°C to 250°C . Thermography was done in the evening around 7 pm in December to allow solar radiation to dissipate from the building envelope exterior surfaces to the environment. The greater temperature difference between interior and exterior during the evening also helps promote greater air infiltration, enhancing these patterns in the thermography. Digital photos were taken concurrently with thermographic photos (multi spectral dynamic imaging - MSX) to be able to identify objects in photos. The centre point measurements of photos are an accurate measurement of the surface temperature of objects based on the distance of measurements indicated in settings. The alignment distance used was 1.5 m. The distance of measurements was set to 2 m for interior photos and 10 m for exterior photos. The reflected temperature was 20°C

and emissivity was set to 0.9 because of the typical emissivity of building materials. The iron colour scale was used for infrared images and the temperature scale was not fixed.

5.2.2 Results and Discussion

The thermography revealed temperature difference patterns that suggest air infiltration occurs around the baseboards and addition back door on the ground floor (Figure 15 and Figure 16), around windows, and around the header of the second floor (Figure 17). The reason these patterns are more suggestive of air infiltration is because of their irregular shapes, whereas a moisture issue or thermal bridging would appear as a more uniform pattern. The thermography helped identify a large hole in the basement wall (Figure 18) that was previously undiscovered. Thermal bridging occurring through the chimney is evident because of the composition and the uniform higher temperature of the chimney from the exterior (Figure 17). The air infiltration from the blower door test was a good initial value for the energy model, but due to uncertainties and sensitivity of this parameter, it was adjusted for the calibration of the model. See Appendix H for the thermography photo key plans.

Figure 15: Thermography showing patterns suggesting air infiltration along baseboards of north wall of house at ground level and digital photo.

Figure 16: Patterns suggesting air infiltration along base of addition back door and digital photo.

Figure 17: Heat transfer around roof (third floor) and chimney potentially indicating air infiltration at the warmest spots and likely thermal bridging through the chimney.

Digital photo to accompany thermography. Taken during day to see building features.

Figure 18: Hole in basement wall near addition of house discovered with thermography (digital photo on right).

Some areas of thermal bridging or potential moisture issues were found within the addition walls (Figure 19 and Figure 20). These problem areas should be investigated further to

catch any moisture issues early on before mold starts to grow which could impact human health. To test for a moisture issue, a moisture probe can be inserted within these walls. Creating an exploratory opening to identify the materials within the wall could help identify if the pattern is from a thermal bridge. Spray foam was implemented as a recent intervention in the basement addition to reduce heat loss in this space. The issue found underneath the spray foam may be difficult to address with a minimal intervention since spray foam is difficult to remove. This demonstrates the necessity to thoroughly assess the existing condition of wall assemblies before adding additional insulation.

Figure 19: Wall connecting addition to main house on ground floor. Potential thermal bridging or moisture issue in wall (digital photo on right).

Figure 20: Potential moisture issue or thermal bridging in basement addition wall (digital photo on right).

The historic double pane windows are performing much better than one might have expected as seen in Figure 21 because of it being able to maintain a warmer temperature. There is only some pattern of likely air infiltration occurring along the edge of the window which is operable since the surface was not wet. This can be rehabilitated to be more airtight. The figure also demonstrates the use of curtains reducing the heat loss to the exterior environment because of its warmer temperature. Thermography was useful in identifying problem areas of the house, which should be carefully examined with further testing before implementing retrofits. Conducting thermography with a blower door test would be able to identify air infiltration areas with more certainty. Inserting moisture probes in areas that are speculated to have moisture and/or thermal bridging issues based on the thermography would determine the level of moisture in these areas. Exploratory openings would determine the composition of components and help determine moisture issues and/or thermal bridges definitively.

Figure 21: Historic double pane window performing quite well, only some air infiltration along opening edges of operable window. Curtains help to reduce heat loss to outdoors (digital photo on right).

5.3 Calibration of Energy Model

5.3.1 Methodology

An actual meteorological year (AMY) file (*Urbandale, 2017*) was used for calibration of the model to utility bill data over a full year following the ASHRAE Guideline 14 criteria for calibration to monthly data: NMBE (normalized mean bias error) between -5% and 5% and CV(RMSE) (Coefficient of variation of the root mean square error) < 15% (ASHRAE, 2014). The NMBE and CV(RMSE) were calculated using the following equations (eq. 5 and 6) from ASHRAE (2014) equations shown below:

$$NMBE = \frac{1}{\bar{m}} \frac{\sum_{i=1}^n (m_i - s_i)}{n} \times 100\% \quad (\text{eq. 5})$$

Where m_i = measured energy use, s_i = simulated energy use, $\bar{m}$ is the mean of the measured data, and n is the number of measured data points. This means that a negative NMBE indicates an overall overprediction of annual energy use and a positive NMBE indicates an underprediction.

$$CVRMSE = \frac{1}{\bar{m}} \sqrt{\frac{\sum_{i=1}^n (m_i - s_i)^2}{n}} \times 100\% \quad (\text{eq. 6})$$

Information obtained about the house was input into the initial model to improve estimates and acceptable discrete values of sensitive uncertain parameters were simulated to complete calibration (heuristic, evidence-based calibration as described by Coakley, Raftery, and Keane (2014)). The energy model was manipulated interactively using Eppy in Python to increase speed of execution and minimize manual edits. The energy use for appliances and lighting was estimated using the average measured electricity consumption from 2015-2017 and modified until calibrated. The energy use for DHW was estimated

based on the heating degree day (HDD) analysis for the study to determine the baseload (see Section 3.2.1).

The heat flux (Hukseflux thermal sensor HFP01-05, with $\pm 3\%$ uncertainty and LI-19 data logger) was measured for a north wall in the main part of the house and the recent addition of the house as they have different constructions. However, surface temperature measurements were not measured at the time, which led to inaccurate R-value calculations using ambient outdoor and indoor temperatures, especially with the amount of air flow occurring throughout the house. The effective R-value of the walls in the main house was estimated to be around $2.2 \text{ m}^2\text{-K/W}$ based on an initial value of $3.32 \text{ m}^2\text{-K/W}$ for a double-brick with $38 \times 140 \text{ mm}$ fibreglass batt insulation from Blaszak and Richman (2012) and then adjusting for calibration. For the addition of the house, $2.6 \text{ m}^2\text{-K/W}$ was the thermal resistance because of the recent insulation improvement. The schedules for occupancy, equipment use, and DHW use were refined based on detailed occupancy variation throughout the year.

Table 3 summarizes important modelled parameters and discrete values tested for calibration of uncertain parameters. The detailed calibration methodology applied to air infiltration as an example is explained here. Air changes per hour were converted to flow coefficients using equation 1 and equation 2 (see Section 4.1). Then the flow coefficients for a range of possible ACH values were input into the energy model to calibrate this unknown parameter (see code on GitHub). First, the initial baseline energy model was edited using Eppy, to contain the iteration of flow coefficients. Then the new IDF was saved with a new name, simulated using an AMY weather file, the new output table was analysed to calculate NMBE and CV(RMSE) using a custom function, and the results were stored in a dictionary. The dictionary was then displayed as a table to view which iteration had the lowest NMBE and CV(RMSE) (Figure 22). Based on Figure 22, 13.5 ACH at 50 Pa had the lowest CV(RMSE) and NMBE values so it was chosen to update the baseline model to continue further calibration of other parameters. After continuing heuristic calibration of other parameters, it was determined that the calibrated air infiltration was 14.0 ACH at 50 Pa.

Table 3: Model and calibration parameters

Component	Sources of Uncertainty	Parameter (Units)	Source for initial model value	Baseline model value (after calibration)	Discrete values tested for calibration or modelling choice
Windows	Not all windows are the same (size, frames, time of implementation), air infiltration around windows	SHGC and U-value (W/m ² -K)	LBNL WINDOW	0.708 SHGC 2.69 U-value (W/m ² -K)	Modelled clear double glazing, air gap, and wooden frames in LBNL WINDOW. Input complex window object in EnergyPlus.
Number of occupants and schedule	Variation in occupants due to bed and breakfast and daycare	Number of people	Log of occupants from owner of house	Between 4-9 throughout year	Average of 4 permanent occupants throughout year and variations of 4-9 during the day.
DHW	Variation in use due to guests	Peak flowrate (L/hr)	Estimate based on floor area and number of occupants	16.6 to 17.5 depending on floor area	Modelled using water-use equipment, hot water temperature 67°C. 11.2 to 17.5 starting at the estimated baseload and increasing by 2% at a time.
Electrical equipment and lighting	Scheduling of several different appliances, portion used for lighting and portion used for appliances.	Watts per zone floor area (W/m ²)	Average of measured electricity energy use	6.21 for equipment and 2.4 to 2.6 for lighting depending on the zone	Modelled using general electrical equipment object. More detailed modelling not required for monthly resolution.
Ground temperature	Ground temperature is not measured in weather file and can vary over year	Average temperature of ground at 6 m depth (°C)	Default in EnergyPlus (18°C)	5.0	5.0, 6.8
Roof construction	Amount and condition of insulation	Effective R-value (K-m ² /W)	OpenStudio component library	9.8	Recently insulated with blow-in cellulose. Low sensitivity parameter.
Basement wall insulation	Condition of insulation and R-value	R-value (K-m ² /W)	OpenStudio component library	1.9	1.5 to 5 (0.1 increments)
Basement floor	Concrete slab properties	R-value (K-m ² /W)	OpenStudio component library	0.3	Used 8-inch heavyweight concrete as approximation.

Component	Sources of Uncertainty	Parameter (Units)	Source for initial model value	Baseline model value (after calibration)	Discrete values tested for calibration or modelling choice
Basement addition walls	Amount and condition of insulation	Effective R-value (K-m ² /W)	OpenStudio component library	2.6	2 to 5 (0.1 increments)
Main house walls	Amount and condition of insulation	Effective R-value (K-m ² /W)	OpenStudio component library; Blaszak, 2013	2.2	Estimated from Blaszak and Richman (2012).
Addition of house walls	Amount and condition of insulation	Effective R-value (K-m ² /W)	OpenStudio component library; Blaszak, 2013	2.6	Estimated from previous house retrofit report. Additional insulation installed recently.
Thermal bridging	Location and magnitude	-	Thermography	Geometry and construction for thermal bridging along chimney	Created geometry for chimney and used brick construction with air gap.
Heating system on/off schedule	Whether HVAC system is heating for a setpoint of 21°C	Temperature setpoint (°C)	Keller-Herzog, 2018	23.0	21 to 25 (0.5 increments), 23.0 to 23.6 (0.1 increments)*
Air leakage	Accuracy of previously conducted blower door tests	Air-changes-per-hour at 50 Pa (h ⁻¹)	Blower door test	14	7-14.0 ACH (0.5 increments) at 50 Pa
HVAC System	Existing gas boiler efficiency	Efficiency of system (fraction)	Documentation of existing system in house	Gas boiler with 0.7 efficiency	0.6 to 0.8 (0.5 increments)**

Notes for Table 3:

* The thermostat temperature was a sensitive parameter. It is located close to the entrance of the house which has cold air flowing in frequently due to guests coming in and out of the house. The house is likely heating more than it needs to.

** The boiler was installed in 2013.

	11.2	11.399999999999999	11.599999999999998	11.799999999999997	11.999999999999996	12.5
CVRMSE	37.1877	36.7898	36.3557	35.9602	35.5423	34.5078
Monthly Elec	[1099.69, 992.8900000000001, 1097.54, 1045.31,...	[1100.16, 993.32, 1098.02, 1045.76, 1067.23, 1...	[1100.66, 993.7600000000001, 1098.51, 1046.17,...	[1101.13, 994.19, 1098.99, 1046.6100000000001,...	[1101.61, 994.6300000000001, 1099.48, 1047.06,...	[1102.83, 995.73, 1100.7, 1048.19, 1069.49, 10...
Monthly Gas	[5048.81, 4296.14, 4127.62, 1885.83, 1436.12, ...	[5069.66, 4315.92, 4150.01, 1894.6, 1441.4, 59...	[5097.04, 4336.42, 4173.12, 1903.46, 1446.65, ...	[5117.87, 4356.21, 4195.48, 1912.23, 1451.9, 5...	[5142.26, 4376.56, 4218.4699999999999, 1921.110...	[5202.81, 4427.21, 4275.66, 1943.25, 1470.4, 6...
NMBE	27.0578	26.7258	26.3745	26.0429	25.6976	24.8384

	13.0	13.5
CVRMSE	33.4803	32.4695
Monthly Elec	[1104.04, 996.84, 1101.93, 1049.27, 1070.54, 1...	[1105.25, 997.9200000000001, 1103.15, 1050.35,...
Monthly Gas	[5263.42, 4477.89, 4332.9, 1965.3899999999999,...	[5323.5, 4528.14, 4389.6900000000005, 1987.38,...
NMBE	23.9795	23.1273

Figure 22: Table displaying NMBE and CV(RMSE) values for different ACH values of air infiltration at 50 Pa.

5.3.2 Results and Discussion

The calibration achieved for the gas use had a NMBE of -2.1 % and CV(RMSE) of 14.9% (Figure 23). The calibration achieved for electricity had a NMBE of -3.6% and CV(RMSE) of 14.4% (Figure 24). The annual gas and electricity consumption of this baseline model were 121 kWh/m² (includes 24.4 kWh/m² for DHW heating) and 39 kWh/m².

After calibration, the model should be validated with a separate year of measured utility bill data (if possible) to ensure that the model still meets calibration guidelines and to check for overfitting. Validation with another year of utility bill data was not possible for this case study because the previous and following years involved additional changes to the building. The washing machine was replaced with a super high efficiency one, a new

door was ordered, and a few new windows were installed in 2018 (Keller-Herzog, 2018a). In 2014, 2015, and 2016, a pump was replaced, the hot water heater was replaced with a tankless hot water heater, and a condensing dryer was purchased to replace the low efficiency dryer (Keller-Herzog, 2018a). Other parameters that can be used to evaluate the quality of calibration are Goodness of Fit (GoF, lower number is better) and the coefficient of determination (R^2 , closer to 1 is best) as explained by Ruiz & Bandera (2017). These values were calculated to be 10.67 and 0.35 for the final calibration. If time permitted, the calibration would be improved with further measurements such as precise heat flux measurements with surface temperature measurements indoors and outdoors, submetering the different hydronic heating loops, submetering electrical lighting, and recording occupancy in detail throughout the day to improve these other important indicators.

Figure 23: Measured gas and calibration results for gas energy use. NMBE = -2.1% and CV(RMSE) = 14.9%.

Figure 24: Measured electricity and calibration results for electricity energy use. NMBE = -3.6% and CV(RMSE) = 14.4%.

5.4 Conclusion

The one factor at a time sensitivity analysis was useful to inform the calibration of the energy model based on most sensitive parameters. Thermography was useful to have a holistic understanding of the behaviour of the house and identify problem areas of potential thermal bridging, air infiltration, and moisture issues. The calibration was conducted heuristically based on evidence known about the house to achieve -2.1% and 14.9% NMBE and CV(RMSE) for gas energy use and -3.6% and 14.4% for NMBE and CV(RMSE) for electricity energy use. For future calibrations, it is recommended to collect data about the house such as precise heat flux measurements coupled with surface temperature measurements of the walls indoor and outdoors and correct environmental conditions

(greater than 10°C temperature difference between indoors and outdoors), submetering the different hydronic heating loops, submetering electrical lighting, and recording occupancy in detail throughout the day. It is also recommended to use multiple indicators (NMBE, CV(RMSE), GoF, R^2) to achieve a higher accuracy in the calibration and representation of energy use profile in reality.

6 Balancing Between Heritage Conservation and Energy Reductions

6.1 Decision framework for Balancing Heritage Conservation and Sustainability

Once the model is fully calibrated and validated, viable retrofit options should be selected based on sensitive parameters and other risk factors in terms of conserving heritage values. For example, if the lighting power is sensitive and can be changed without impacting the heritage character, a lighting retrofit that maximizes daylight should be selected for the analysis. This may also favour inherent energy efficient features in an HB and help conserve the heritage characteristics. A library of retrofit options, created by the author, is presented in Figure 25 to help identify the parameters for analysis. Important risk analyses to consider include heritage impact, hygrothermal analysis to assess change in moisture behaviour (e.g. when adding insulation), cost analyses, and occupant health/comfort.

Figure 25: Library of retrofit options by retrofit type

The balance between heritage and environmental sustainability can be achieved by comparing the energy savings and risk to heritage values, while also considering other aspects of sustainability (e.g. occupant comfort). The following metrics and criteria may be used in the analysis of balancing heritage and sustainability.

Environmental Sustainability Metrics and Criteria

- Overall wellness of occupants (IEQ, CO₂, daylight)
- GHG emissions including embodied carbon of new materials vs existing materials
- Reduction in total EUI (energy use intensity) by 50% or more to achieve a deep energy retrofit
- Climate change resilience – indoor air temperature in free floating conditions, change in energy use and renewable energy

Heritage Metrics and Criteria

- Minimal intervention (refer to Parks Canada, (2010))
- Respectful of heritage values
- Reversibility (i.e. can not solely use spray foam on entire wall, but may be able to do this on new materials which do not have heritage values)
- Adaptability to current and future needs
- Proven technology

Knowing the sustainability and heritage criteria above, the balancing of these two broad objectives becomes clearer, but which has a higher priority in the comparison between the two? Does heritage have higher priority over environmental sustainability, or the other way around? Prioritization will depend on the significance of the element impacted by each retrofit option. That is why the heritage impact assessment is crucial in utilizing the decision framework to balance heritage and energy reductions. The potential heritage impact assessment should be carried out following Section 5 of ICOMOS (2011) (see

Appendix I). To summarize this evaluation method, a more significant element of a place and a greater severity or scale of impact results in a greater overall potential impact.

Many retrofit options will have low heritage impact and implementing more changes to more HBs would help to mitigate the severity of climate change and conserve the heritage values in a new manner. This does not mean drastically changing the existing building to construct a net zero energy/carbon building. With many major changes, there is a risk of jeopardizing the authenticity and integrity of the heritage values of the building. It is still best to utilize the existing materials of the building and prioritize minimal intervention. Minimal intervention can be executed in different ways. It may mean repairing the existing historic windows so that they are airtight and adding a storm window because this is the minimal intervention required to improve the thermal performance of the windows.

To utilize the decision framework, first we look at reducing the current operational energy use intensity by a total of 50%. Any measure that contributes to EUI reduction individually should be considered. A measure is determined to be viable based on reduction in EUI, occupant comfort, and respecting heritage values using the guidance provided by the decision framework shown in Figure 26. Then it can be evaluated based on climate change resilience and other project objectives not included in this study.

Decision Framework for Selecting Viable Energy Retrofit Measures—Evaluate Individual Measures

Figure 26: Decision framework for balancing energy reductions and heritage conservation, while also considering occupant comfort. If not proven technology, perform in-depth research to understand the risk before considering the technology.

6.2 Retrofit Options

First retrofit measures for the building envelope were considered because this would impact the peak load for the HVAC system. Adding insulation was considered for the interior of the exterior walls because of the character defining exterior brick cladding. To determine appropriate levels of insulation, the existing wall assembly was examined and only a thickness of insulation that would fit in the existing stud cavity or on the interior of the studs before new gypsum board was considered (see Figure 27 for wall details). It was important to ensure no increase or minimal increase in wall assembly thickness. PIR (polyisocyanurate) rigid insulation board was considered as the insulation material for its high thermal resistance of 0.022 W/m-K and potential to easily remove this retrofit (whereas with spray foam, it is much more difficult to remove if necessary). Wall rehabilitation scenario 1 results in a 2.5 mm increase and 0.8 m²-K/W improvement in thermal resistance, scenario 2 results in a 15.5 mm increase and 1.9 m²-K/W improvement, and scenario 3 results in a 40.5 mm increase and 2.9 m²-K/W improvement. Since there is already some insulation on the basement walls but not on the floor, insulation for the basement floor was considered (see Appendix D for table of insulation retrofit scenarios). The roof was recently insulated with blow-in cellulose, so this was not explored as an option.

Window retrofits were considered to reduce infiltration and improve thermal resistance, such as adding an interior storm window to effectively make the assembly a triple-pane clear glass window or a new triple glazed window with low-E coating and argon gas. If it is possible to modify the existing window to have low-E coating and argon gas filling, this would be a good option to conserve the authenticity of this value of the house

(Historic England, 2016; Parks Canada, 2010). Air sealing the leakage pathways in the house was also explored as an option.

On the mechanical side, an air-source heat pump was analysed as an option because the house does not have mechanical ventilation for cooling during the summer, and the owner noted that guests are feeling uncomfortable as temperatures increase each summer. This would not have a negative impact on the character of the house if the historic radiators are conserved. The air-source heat pump is assumed to provide supplemental heating to the house to reduce gas energy use of the boiler above outdoor temperatures of -5°C (NRCan, 2004). Daylight sensors and controls were modelled to turn off electrical lighting when daylight lux at the working plane is greater than 500 lux. This level of illuminance from daylight provides ample lighting to complete regular tasks and will save energy from unnecessary electrical lighting. Additional PV panels were explored as a retrofit option to increase the on-site electricity generation from renewable sources (see Sections 7 and 8, and Appendix E). Appliance upgrades of connecting sensors and controls to the plugs of appliances was also considered as a low heritage impact measure. Timers and timer plug strips or load-sensors and plug strips may be used to turn appliances off after specific times or below a specific load threshold which indicates the appliance is not in use. Older appliances may also be replaced with new efficient ones at the end of their lives. These appliance upgrades can save between 19%-40% based on Mercier & Moorefield (2011). See Table 4 for a summary of the retrofits explored, heritage significance of the element impacted by retrofit, and the potential overall heritage impact.

Existing Wall Detail: 2.2 m²-K/W

Rehabilitation 1 Detail: 3.0 m²-K/W

Rehabilitation 2 Detail: 4.1 m²-K/W

Rehabilitation 3 Detail: 5.1 m²-K/W

Figure 27: Wall details of existing wall in main part of house and three rehabilitation scenarios. Similar rehabilitation scenarios for addition of house except stud space is 152 mm and the second scenario includes 12 mm extra of PIR on the interior side of the stud space.

Table 4: Summary of retrofits explored, values simulated for analysis, and heritage impact assessment

Energy retrofit	Current state	Values for analysis	Significance of element impacted	Scale of change	Potential overall impact on heritage values
Additional insulation for exterior walls	2.2-2.6 m ² -K/W	3.0, 4.1, 5.1 m ² -K/W	Low to high. The internal plaster is not deemed a significant element. If the insulation is incorrectly applied without consideration for hygrothermal impact, then the high significance exterior façade will be negatively impacted.	Major	Slight/Moderate to Large/Very Large
Reduce air infiltration	14 ACH at 50 Pa (0.00781 m ³ /s/m ² at 50 Pa, 1.54 cfm/ft ² at 50 Pa)	By 30% to 80% (9.8 to 2.8 ACH at 50 Pa)	Low. Air sealing should have a minimal impact on aesthetic and may be beneficial to aesthetic in the case of repointing and closing large gaps in the envelope. The suggested level of air infiltration does not pose indoor air quality issues, especially with the implementation of mechanical ventilation from the air-source heat pump.	Moderate	Slight
Window retrofits	Historic wooden frame, double pane, U-value = 2.67 SHGC = 0.7	triple pane rehab, triple pane + low-E coating rehab, new triple pane low-E coating with argon gas	High. The historic large bay windows are character defining of the house and should be conserved through rehabilitation (fixing weights in frames and improving airtightness).	Moderate to Major	Large/Very Large
Air-source heat pump as supplementary heating supply	2013 gas boiler, efficiency = 0.7	-	Low. Adding the air-source heat pump units in the house should have minimal aesthetic impact and it will greatly improve occupant comfort by providing controlled heating and cooling. The historic radiators will not be removed to implement the air-source heat pump.	Minor	Neutral/Slight

Daylight sensors and controls	None	> 500 lux turn lights off	Negligible. The lighting and light fixtures are not character defining of this house. Making use of the daylight will maintain this inherently sustainable feature of the house.	Negligible	Neutral
Additional PV power generation	11.4 kWh/m ²	Additional 26 kWh/m ²	High. The PV panels will be added to the top of the mansard roof which is not visible from the ground. This is easily reversible if required.	Minor	Moderate/Slight
Appliance upgrade	No sensors and controls for plugs. Some appliances upgraded 2014 to 2018.	27.5% appliance energy savings due to upgrades	Negligible. Sensors and controls would be added to appliance plugs and some appliances may be replaced with new more efficient appliances.	Minor	Neutral/Slight

Note: The window rehabilitation involves adding interior storm windows.

6.3 Building Science Considerations

Since there are changes to the thermal resistance and vapour permeability of the wall assembly, the risk of moisture accumulation needs to be considered. If moisture accumulates within the walls, then the thermal resistance will be decreased and there will be a potential for mould growth if the moisture is present for a prolonged period (Straube & Schumacher, 2007). Additionally, if moisture accumulation occurs within the brick layer past the critical saturation point, then there will be freeze thaw damage during the winter. To consider the moisture accumulation, vapour diffusion through the wall, RH (relative humidity) at each interface between materials, and the rate of condensation need to be calculated. One way to minimize the vapour diffusion from the interior to the exterior in a cold climate and prevent moisture accumulation is to add a vapour barrier to the inner side of the insulation layer.

Vapour diffusion calculations were done using the simple Glaser Method, which uses psychometrics and are an estimate of whether there will be moisture accumulation due to vapour diffusion based on assumptions (Appendix F). The aluminum foil on the PIR insulation acts as a vapour barrier and provides a vapour resistance of $0.35 \text{ Pa}\cdot\text{s}\cdot\text{m}^2/\text{ng}$. The outdoor conditions of -20°C and 75% RH were chosen for Ottawa as a worse case where the temperature is lower than average, and RH is higher than average. Indoor conditions are assumed to be 21°C and 35% RH, and the insulation has a thermal resistance of 3.7 RSI. With these conditions there is no condensation plane within the wall assembly (RH does not exceed 80%-100%), indicating no concern for moisture issues. The relative humidity within the wall assembly reaches a maximum of 72% in the brick layer under these conditions. The vapour barrier solves the issue of moisture accumulation in the

insulation. For this reason, if insulation is added, it is also recommended to add a vapour barrier on the interior side of the insulation layer to minimize vapour diffusion through the wall from the interior.

6.4 Ranking of Options and Recommended Package

A parametric analysis aided in the ranking of retrofit options. The results of the parametric analysis are shown in Figure 28 which are relative to the calibrated model. The modelled air-source heat pump produces the highest individual annual energy savings of about 29% of the total baseline energy use. The additional PV panels offset electricity energy use by 17%. Reducing air infiltration by 80% resulting in 2.8 ACH at 50 Pa ($0.00156 \text{ m}^3/\text{s}/\text{m}^2$ at 50 Pa or $0.31 \text{ cfm}/\text{ft}^2$ at 50 Pa) achieves the next highest energy savings of about 13%. A thermal resistance of $5.1 \text{ m}^2\text{-K}/\text{W}$ in the main house exterior walls achieves 12% energy savings. Reducing air infiltration by 70% and insulation to achieve $4.1 \text{ m}^2\text{-K}/\text{W}$ walls also achieve significant energy savings of 11% and 9%. New triple pane low-E argon windows and rehabilitated triple plane low-E windows both achieve 4% energy savings. Insulating the basement floor to a high level of 6.0 RSI only achieves 2% energy savings, so it was not considered for the retrofit packages because of its invasiveness and low energy savings. Daylight controls save about 1% energy through the reduction of electrical lighting use and has no impact on the heritage character of the building, so it was considered for the retrofit packages. Increasing insulation in the addition of the house achieved only 1% energy savings due to the smaller surface area and higher starting level of insulation. It was recently insulated in 2017, so it is also not practical to retrofit the walls of the addition of the house again (time, money, disturbance to occupants). Specific envelope improvements were selected based on the sensitivity of a retrofit on the energy savings; for example, if

the walls are to be insulated, it can be insulated to 4.1 m²-K/W instead of 5.1 m²-K/W because of the small change in savings (3%).

Figure 28: Results of parametric analysis of retrofit options. Thermal resistances are indicated for the level of insulation, not the effective thermal resistance of the entire wall assembly. This baseline considers the current PV generation of 11.4 kWh/m²/year. The window rehabilitation involves adding interior storm windows.

The retrofits that are viable from a sustainability and heritage perspective were combined and simulated to demonstrate the potential energy savings. Two different packages were simulated to compare the energy savings of highest feasible savings to a package which balances heritage conservation with energy reduction targets. A third option would be the minimal intervention approach of air sealing large cracks in the envelope without any other upgrades, which is assumed to achieve a 40% reduction in air-leakage. This minimal

intervention option would only achieve about 6% energy savings, which is not adequate for achieving deep energy savings. The best energy savings package (air-source heat pump, 80% reduction in air leakage to 2.8 ACH at 50 Pa, 5.1 m²-K/W exterior walls, new triple pane low-E argon windows, daylighting controls, additional 26 kWh/m² PV power generation, and 27.5% appliance improvement) achieved 74% energy savings and a 24% increase in number of hours that the temperature setpoints are met.

The package that balanced heritage conservation and energy reductions implemented an air-source heat pump, reduced air infiltration by 70% to 4.2 ACH at 50 Pa (0.00234 m³/s/m² at 50 Pa or 0.46 cfm/ft² at 50 Pa), insulated to have 4.1 m²-K/W exterior walls, used the existing windows with interior storm windows to achieve triple pane low-E windows, daylight controls, and 27.5% appliance improvement. A 70% reduction in air leakage is likely more feasible in this house based on the construction and should not require the removal of the character defining chimney. The lower level of insulation still achieves a considerable amount of savings and increases the wall thickness by 15.5 mm, which results in a total of 1.62 m² of lost floor area (ground floor, level 1 and level 2) compared to 4.32 m² of lost floor area for the higher level of insulation, which increases the wall thickness by 40.5 mm. The new window frames compared to rehabilitated windows do not have a difference in energy savings and achieve a lower than 10% energy savings, so it does not make sense to risk impacting the heritage character with new window assemblies. For this reason, interior storm windows that follow the aesthetic but are distinct from the existing windows are a good option to improve the window assemblies. This second package achieved 71% energy savings (Figure 29) and a 30% increase in number of hours that the temperature setpoints are met. The incremental savings of each option

demonstrates that it is crucial to simulate combinations of retrofits to get an accurate estimate of total savings and impact of each retrofit when packaged with others.

Figure 29: Incremental annual energy savings of package of retrofits that balances heritage conservation and energy reduction target relative to calibrated baseline. The window rehabilitation involves adding interior storm windows.

6.5 Discussion

The incremental energy savings of the recommended retrofits shown in Figure 29 demonstrate that upgrading the HVAC system and reducing air infiltration into the house are the most important retrofit measures to implement. Reducing the air infiltration to 4.2 ACH at 50 Pa (70% reduction) was recommended because any lower is unlikely to be feasible in the house due to the air leakage pathways in the existing construction. Obtaining this level of airtightness would require the addition of an air-vapour barrier within the envelope. The hole in the basement, the chimney, and other problem areas should be sealed to achieve this level of airtightness. When air sealing the chimney, the fireplace should be conserved as a decorative character-defining element. Since the benefit of adding insulation is greater than the capital cost shown in literature, it should be implemented

along with the addition of an air-vapour barrier to prevent moisture issues in the envelope. These recommended envelope retrofits will need to be done with care to conserve the historic mouldings around windows and doorways.

Greater energy savings from the air-source heat pump compared to other retrofits were expected since replacing older HVAC equipment was found to have the greatest energy savings in literature (see Table 1). The air-source heat pump increases electricity use by 14 kWh/m²/year when combined with envelope, lighting, and appliance retrofits, whereas when implemented alone, it increases electricity use by 47 kWh/m²/year. This demonstrates the importance of retrofitting the envelope before applying HVAC retrofits, so the systems can be reduced in size and operate efficiently. A ductless air-source heat pump should not be an invasive retrofit for the heritage values of the building, and it improves the comfort of occupants by providing cooling in the summer, making the building more sustainable long-term. The additional PV panels with all other retrofits results in the electricity use stays about the same at 27 kWh/m²/year.

The end use breakdown for the recommended retrofits is shown in Figure 30 (excluding renewables). The gas energy used for heating can be reduced to 3.3 kWh/m²/year. After retrofit, the most carbon intensive source of energy use is the DHW, heated using natural gas⁶, which can be reduced with an integrated air-source heat pump

⁶The carbon intensity depends on region; in Ontario, Canada, the annual marginal emission factor of electricity is about 0.134 kgCO₂/kWh (Sotes, 2019) and 0.525 kgCO₂/kWh for natural gas (*Intrinsic Corp.*, 2016).

system. Further reductions in electricity can be achieved using a smart thermostat, which was not modelled due to uncertainties in occupant behaviour.

The trade-offs between the heritage conservation and energy reduction objectives are minimal and ensure that society continues to thrive through the connection to a sense of place, as promoted in Sustainable Development Goal 11.4 (United Nations, 2019), and through minimal impact on the environment. The package that balances heritage and energy savings vs the package that maximizes energy savings achieves a greater level of comfort by 6% due to greater levels of comfort during the summer. If a retrofit option involves a greater intervention, then the energy savings must be great enough, and this option must not have a detrimental impact on the heritage values of the site. The change in hygrothermal behaviour can be considered in more detail through hygrothermal modelling to minimize potential moisture issues when the building envelope conditions are drastically changed.

Figure 30: End use breakdown for recommended retrofits combined. Pumps are not shown in the pie chart because their energy use is close to zero.

6.6 Conclusion

About 71% energy savings and 30% improvement in comfort can be achieved in an historic single-detached house in a cold climate through deep energy retrofits of the building envelope, the HVAC systems, lighting controls, and the addition of on-site renewable energy, while conserving the character defining elements of the house. A balance between energy savings, sustainability, occupant comfort, and heritage conservation was achieved using the methodology and decision framework presented. The recommended retrofits include reducing air infiltration by 70% to 4.2 ACH at 50 Pa, adding insulation and an air-vapour barrier to achieve 4.1 m²-K/W exterior walls, repairing and rehabilitating the windows to triple pane low-E windows, the addition of an air-source heat pump for supplemental heating, daylighting sensors and controls, appliance sensors and controls, and additional on-site solar PVs.

The results of this study may be representative for houses of similar construction and age in the Glebe neighbourhood; therefore, these retrofits may be applied to other houses for larger scale energy reductions within Ottawa and potentially other cold climate North American cities. The methodology in this study may be applied to retrofits for all types of existing buildings to provide more holistic sustainability retrofit recommendations. The results of this study suggest that the presented methodology and decision framework facilitate deep energy retrofits in historic residential homes in a cold climate, while conserving the heritage values of the historic house. In most cases, the energy retrofits

benefitted heritage conservation values and occupant comfort demonstrating how heritage conservation can play a key role in sustainable development.

7 Cost Analysis

A cost analysis was conducted to compare the operational costs of the baseline and retrofit scenarios and determine the simple payback for the capital costs (purchase and installation) of the retrofit package.

7.1 Methodology

The methodology for the cost analysis was to estimate capital costs for each retrofit measure, cost savings as a result of operational energy savings and a simple payback for the entire retrofit package to give the client/owner an idea of costs and payback. This cost analysis does not consider inflation, taxes, or maintenance costs. A reasonable payback period might be around 10-15 years. Since components will not need to be replaced within 25 years of installation this simplifies the analysis.

7.1.1 Capital Costs

Capital costs were determined from previous retrofits conducted on the house (considering inflation to 2020), local contractor websites, and economic studies. The carbon tax is assumed to be \$50/ton CO₂ presuming that the retrofits are implemented in 2022. The final capital cost considers the carbon tax cost of \$50/ton CO₂ by subtracting the tax for the associated carbon savings of 150 tonnes over 20 years (see Section 8 for details of carbon savings). Table 5 shows the capital costs for retrofits which includes material/equipment and labour/installation. The windows had the highest capital cost of all the building retrofits. For this reason, three different window options were considered to

see if capital cost could be reduced. The first option explored was a rehabilitation of the existing windows and adding a storm window with low-E coating. Since windows are now usually constructed as double pane units, this was considered as the storm window. The second option explored was the rehabilitation of the existing windows and adding only a low-E film to the interior side of the glazing. Purchasing costs were calculated by multiplying the cost per unit by the number of units.

Table 5: Capital costs of individual retrofits (costs are in CAD\$)

Retrofit	Cost per Unit	Number of Units	Purchase Cost	Labour Cost	Total Capital Cost	Source
Air-source heat-pump (mini split ductless)	\$ 2250/unit	4	\$ 9,000	\$ 4,000	\$ 13,000	("Home Stars Get a Quote," 2020; Kegel et. al, 2012)
Air tightening envelope (weather stripping and filling in large holes in envelope)	\$ 250/house	1	\$ 250		\$ 250	(Keller-Herzog, 2018a)
Adding 125 mm PIR (3.7 RSI) insulation to achieve 4.1 RSI wall assembly	\$ 0.254/m ² -mm	271.77 m ² exterior walls*125 mm insulation	\$ 8,635	\$ 3465	\$12,100	(Palmer, 2017; "PIR Boards," 2019)
Rehab/retrofit historic windows + low-E coating (option 1)	\$ 175 rehab/window \$ 826.50 retrofit/window	20 windows	\$ 20,730		\$ 20,730	(Irving, 2019; "Window Replacement Cost Estimator," 2019)
Only low-E film and rehab of windows (option 2)	\$ 175 rehab/window \$ 53.82/m ²	20 windows, 39.13 m ² window area	\$ 6,305		\$ 6,300	(Debusk, 2012; Irving, 2019)
Only repair/rehab windows (option 3)	\$ 175 rehab/window	20 windows	\$ 3,500		\$ 3,500	(Irving, 2019)
Daylight sensors and controls	\$394 for a school, assume 25% of the cost for a house	1	\$ 98.50		\$ 99	(Wireless Lighting Controls, 2016)
Appliance plug sensors and controls	\$ 0.00 because province installs smart metering		\$ 0.00		\$ 0.00	(Armcl et. al, 2013)
Additional PV panels	\$ 320.67/panel	20 panels	\$ 6413	\$ 7723	\$ 14,140	("Canadian Solar," 2020; "Cost of Solar Power In Canada," 2019)
Total with option 1 window retrofit with storm window					\$ 59,620	
Total with option 1, minus carbon tax (\$50/ton CO₂ saved)					\$ 52,320	
Total with option 2 window repair and rehabilitation with low-E coating					\$ 45,190	
Total with option 2, minus carbon tax (\$50/ton CO₂ saved)					\$ 37,890	
Total with option 3 window repair/rehabilitation					\$43,090	
Total with option 3, minus carbon tax (\$50/ton CO₂ saved)					\$ 35,790	

Note: The purchase cost includes the combined cost of materials/equipment and labour if no labour cost given.

7.1.2 Operational Costs

The amount of energy used during each hour of the day in winter and summer were summed to calculate the different time of use costs. Table 6 shows the total winter and summer on/off/mid peak hours and electricity costs for the different times of use in Ontario. The retrofit results in a \$384 cost increase and \$52 decrease (\$332 total increase) attributed to electrical heating and cooling supplied by the air-source heat-pump.

Table 7 gives the cost breakdown for Enbridge gas energy use in Ontario. The gas pricing was multiplied by the total volume (m^3) of gas used each month. The volume of gas was calculated from energy simulation output using a conversion of 10.33 kWh/m^3 (NRCan, 2015). Table 8 shows the monthly cost of gas energy use for the baseline and retrofit options. The cost savings from gas operation after retrofit are \$1057 annually.

Table 6: Total on/off/mid peak hours and electricity time of use costs for baseline and retrofit

Season	Time of Use	Price (\$/kWh)	Energy (kWh)		Operational Cost (\$)	
			Baseline	Retrofit	Baseline	Retrofit
Winter	off peak weekdays 1 - 7 hrs, 19 - 24 hrs	0.065	1731	3906	\$ 113	\$254
	on peak weekdays 7 - 11 hrs, 17 - 19 hrs	0.132	1590	2300	\$ 210	\$304
	mid peak weekdays 11 - 17 hrs	0.095	1391	1917	\$ 132	\$182
	off peak weekend 1-24 hrs	0.065	1958	3483	\$ 127	\$226
	Total	-	6670	11605	\$ 582	\$ 966
Summer	off peak weekdays 1 - 7 hrs, 19 - 24 hrs	0.077	1651	1776	\$ 127	\$137
	on peak weekdays 11 - 17 hrs	0.157	1358	1308	\$ 213	\$205
	mid peak weekdays 7 - 11 hrs, 17-19 hrs	0.113	1569	1395	\$ 177	\$158
	off peak weekend 1-24	0.065	2257	1733	\$ 147	\$113
	Total	-	5184	5389	\$ 664	\$ 612

Table 7: Gas price breakdown from utility bills

Cost breakdown	Prices (\$/m3)
Delivery to customer	\$ 0.13
Site restoration clearance	-\$ 0.01
Transportation to Enbridge	\$ 0.05
Gas supply charge	\$ 0.12
Total	\$ 0.29

Table 8: Monthly gas cost for baseline and retrofit

	Baseline			Retrofit		
Month	Energy used (kWh)	Energy used (m ³)	Cost (\$)	Energy used (kWh)	Energy used (m ³)	Cost (\$)
Jan	8083	782	\$ 224.2	1736	168	\$ 48.15
Feb	6656	644	\$ 184.6	1289	125	\$ 35.74
Mar	4689	454	\$ 130.1	835.0	80.8	\$ 23.16
Apr	2747	266	\$ 76.18	742.5	71.8	\$ 20.59
May	1574	152	\$ 43.66	762.1	73.7	\$ 21.13
Jun	732	732	\$ 209.9	439.5	42.5	\$ 12.19
Jul	692	67	\$ 19.19	454.1	43.9	\$ 12.59
Aug	721	70	\$ 20.00	454.1	43.9	\$ 12.59
Sep	1056	102	\$ 29.29	222.4	21.5	\$ 6.17
Oct	2893	280	\$ 80.22	764.9	74.0	\$ 21.21
Nov	4339	420	\$ 120.3	743.7	72.0	\$ 20.62
Dec	6376	617	\$ 176.8	844.3	81.7	\$ 23.42
Total	40,560	4,590	\$ 1,310	9,290	900	\$ 260

7.2 Results and Discussion

7.2.1 Operational Cost Savings

Table 9 shows a summary of the baseline and retrofit operational costs. Although electricity costs increase by \$332, the gas savings are \$1057, resulting in a total annual savings of \$724. New PVs on available site area (see Figure 31) were considered for the retrofit package to help offset costs and carbon emissions. Electricity generation from PVs was assumed to occur mostly during mid peak winter hours and summer on peak hours (11-17 hrs). Based on the average of 2015-2017 current PV generation, the generation split

between winter and summer was estimated to be about 32% during the winter and 68% during the summer (see Appendix E for full power generation data). About 3.25 times greater annual operational savings of \$2356 are achieved when additional PVs generating 8608 kWh/year are added.

Figure 31: Available areas for new PVs shown as light blue surfaces, which were selected based on least amount of shading and most direct sunlight.

Table 9: Summary of baseline and retrofit operational costs

Operational Energy Source	Baseline Costs	Retrofit Costs	Annual Savings	Retrofit with new PVs	Annual Savings
Electricity	\$ 1,250	\$ 1,580	-\$ 330	-\$ 50	\$ 1,300
Gas	\$ 1,310	\$ 260	\$ 1,060	\$ 260	\$ 1,060
Total	\$ 2,560	\$ 1840	\$ 720	\$ 200	\$ 2,360

7.2.2 Payback Period

A summary of the simple payback cost analysis is presented in Table 10 below. The simple payback for the retrofit package with the window rehabilitation⁷ is around 30 years, with the low-E film⁸ is around 33 years, and about 53 years for a full retrofit when the savings of renewables are not considered. With additional PVs, the capital cost increases but the simple payback period is shortened significantly to 15 years, 16 years, and 22 years for the three options. From a cost perspective, the retrofit package with option 3 of repairing the windows and adding PVs is the better option.

The estimated capital costs for this deep energy retrofit package of \$43,085 is within the estimated capital costs of \$40,420 +/- \$30,358 USD from Brennan Less & Jain Walker (2014). For cold climate deep energy retrofits, the same study found the cost of retrofits to be about \$815 USD/MMBtu energy savings. The recommended retrofit package costs about \$359/MMBtu (35,196 kWh = 120 MMBtu) energy savings, which is significantly cheaper than the study. This may be due to advancements in technology that lower purchasing costs from the time of the study to present. The lower costs are also likely because there were already some recent energy retrofits done on the house, so it was performing better than average.

⁷ The reduction in energy savings for just the rehabilitation of windows is about 4% and was accounted for in the payback calculation.

⁸ The reduction in energy savings for just the low-E coating is about 2% and was accounted for in the payback calculation.

Table 10: Summary of simple payback for complete retrofit package considering different window retrofit options and carbon tax of \$50/ton CO₂

	1. Retrofit windows + low-E film	2. Rehab existing windows + low-E film	3. Rehab existing windows	New PVs + option 1	New PVs + option 2	New PVs + option 3
Total capital cost	\$ 45,480	\$ 31,050	\$ 28,950	\$ 59,620	\$ 45,190	\$ 43,090
Total cost minus carbon tax	\$ 38,180	\$ 23,760	\$ 21,650	\$ 52,320	\$ 37,890	\$ 35,790
Simple payback period (years)	53	33	30	22	16	15

7.2.3 Considerations

Cost calculations do not consider taxes, inflation in future years, discount rates, or rate of return on investment. The calculations for PV generation were simplified due to time constraint and are only an estimate of the potential energy generation of new solar panels. Miscellaneous array and power conditioning losses were assumed to be 5%. The Maxpower CS6X-310 PV panels were considered because they are a good option for Canada with high inverter efficiency of 97% and durability against environmental deterioration (*PV Module Product Datasheet*, 2017). The payback period may be greater or less depending on real capital costs and power generation from PV arrays.

7.3 Conclusion

The recommended package of retrofits with the simple repair of the existing windows has a simple payback period of 15 years. This payback period was possible with the additional savings of new solar PV panels installed on available site area and considering the cost of carbon emissions (carbon tax). The recommended retrofit package is viable if the capital

costs of \$43,085 can be paid by the homeowner. Government incentives and policies can aid in the cost feasibility of homeowners implementing deep energy retrofits.

8 Carbon Analysis

Athena Impact Estimator for Buildings was used for the embodied carbon analysis to compare the embodied carbon of the retrofits to the carbon savings of reducing the energy use.

8.1 Methodology

The location of the building is input to consider the location's electricity grid and transportation of materials. The carbon intensities of power generation sources in Athena reflect the industry average efficiencies in North America and grid mix depends on location. The location is also used to determine transportation modes and distances, and technologies for product manufacturing. A regional market share analysis is conducted to determine the source location of products. Ecoinvent 3.4 electricity data is used to determine carbon intensity of electricity grids for Canadian provinces.

The building height is input for estimates of crane use if necessary. The building type selected was single family residential which impacts the maintenance of the building in the software. The annual operational energy use for different energy sources was input based on the baseline calibrated energy model and recommended retrofit model. The system boundary option of A to C includes raw material supply, transport, manufacturing, transport, construction-installation process, repainting of surfaces for maintenance (excludes all other kinds of maintenance), replacement, operational energy use, deconstruction demolition, transport, disposal (facility equipment energy use and landfill

site effects). A to D would also include the benefits and loads beyond the building life for example of steel recycling and carbon sequestration of wood products. The A to D boundary condition was chosen to consider the carbon sequestration of the existing wood structure of the building. The A to C boundary condition was chosen for calculating the embodied carbon of retrofit materials since the analysis period was only 20 years.

The bill of materials report generated by Athena's calculations shows the details of quantities of each material used for different components of the existing house (Figure 32). The program calculates amounts of nails and other building materials required for the size (dimensions of component are input by user) of specific components (e.g. walls). The LCA report only shows the total environmental impact for different metrics (global warming potential, fossil fuel consumption, etc.) for components of the house (walls, roofs, foundation, floors, beams, columns, and extra materials), not individual materials.

The bill of materials for the retrofit package is shown in Figure 33. It is assumed that a similar amount of piping and materials would be used for mechanical systems in a new house. Additionally, embodied carbon of building systems (e.g. HVAC, sanitary, sprinklers, elevators) was found to be quite low at around 2% of total embodied carbon of a building (Häkkinen, Kuittinen, Ruuska, & Jung, 2015). Due to the assumed similar systems and insignificance of building systems in the total embodied carbon, it was not considered in the carbon analysis. The embodied carbon of daylight and appliance sensors and controls was not considered due to limitations in data available in embodied carbon tools and research.

To calculate the embodied energy saved by conserving most of the existing building, the lifespan of the existing materials was assumed to be 180 years since it is about

131 years old (built in 1889) now and it is assumed to endure at least another 50 years. For the retrofit, a life span of 20 years and A to C lifecycle was used as the analysis period since this is an acceptable time until significant maintenance/repair/replacement is required. Other assumptions are shown in Table 11 below.

Table 11: Assumptions made for the existing building material inputs for Athena calculations

Component	Assumption
Roof insulation	406 mm thickness
Wood shingles on roof of addition of house	Type of wood assumed to be cedar siding
Plaster and lath	Used 5/8" thickness of gypsum fibre board to represent existing plaster and lath since it is not available in the software

Athena does not allow calculations without having a framing for the wall since it is designed for new construction calculations. However, for the retrofit, the wood studs and plywood in the wall framing will be conserved to reduce unnecessary waste so we would ignore the carbon from the framing in the total retrofit carbon. The carbon emissions and payback of the PV array was calculated separately from the envelope retrofit since it is not included in the Athena database.

Material	Unit	Total Quantity	Columns & Beams	Floors	Foundations	Roofs	Walls	Project Extra Materials	Mass Value	Mass Unit
#15 Organic Felt	m2	4,334.9306	0.0000	0.0000	0.0000	3,010.3334	1,324.5972	0.0000	3.1636	Tonnes
1/2" Glass Mat Gypsum Panel	m2	418.0898	0.0000	268.3560	0.0000	80.6837	69.0501	0.0000	4.1377	Tonnes
5/8" Gypsum Fibre Gypsum Board	m2	194.1058	0.0000	0.0000	0.0000	0.0000	194.1058	0.0000	2.7175	Tonnes
8" Normal Weight Concrete Block	Blocks	1,694.4219	0.0000	0.0000	0.0000	0.0000	1,694.4219	0.0000	30.0421	Tonnes
Ballast (aggregate stone)	kg	12,602.6575	0.0000	0.0000	0.0000	12,602.6575	0.0000	0.0000	12.6027	Tonnes
Blown Cellulose	m2 (25mm)	1,231.9826	0.0000	0.0000	0.0000	1,231.9826	0.0000	0.0000	0.7885	Tonnes
Cedar Wood Bevel Siding	m2	240.9541	0.0000	0.0000	0.0000	0.0000	240.9541	0.0000	1.0192	Tonnes
Cold Rolled Sheet	Tonnes	0.0744	0.0000	0.0000	0.0000	0.0000	0.0744	0.0000	0.0744	Tonnes
Concrete Benchmark CAN 25 MPa	m3	8.9629	0.0000	0.0000	8.9629	0.0000	0.0000	0.0000	20.8784	Tonnes
Double Glazed No Coating Air	m2	172.6875	0.0000	0.0000	0.0000	0.0000	172.6875	0.0000	2.7964	Tonnes
FG Batt R11-15	m2 (25mm)	912.7683	0.0000	0.0000	0.0000	0.0000	912.7683	0.0000	0.2857	Tonnes
Galvanized Sheet	Tonnes	0.1624	0.0000	0.0380	0.0000	0.1244	0.0000	0.0000	0.1624	Tonnes
Grout-Coarse	m3	4.5921	0.0000	0.0000	0.0000	0.0000	4.5921	0.0000	9.8088	Tonnes
Joint Compound	Tonnes	0.1937	0.0000	0.0000	0.0000	0.0000	0.1937	0.0000	0.1937	Tonnes
Large Dimension Softwood Lumber, kiln-dried	m3	6.4893	0.0000	6.4893	0.0000	0.0000	0.0000	0.0000	2.7458	Tonnes
Mortar	m3	11.5075	0.0000	0.0000	0.0000	0.0000	11.5075	0.0000	21.7262	Tonnes
Nails	Tonnes	0.1743	0.0000	0.0352	0.0000	0.0453	0.0938	0.0000	0.1743	Tonnes
Natural Stone	m2	135.5538	0.0000	0.0000	0.0000	0.0000	135.5538	0.0000	10.2218	Tonnes
Ontario (Standard) Brick	m2	251.1943	0.0000	0.0000	0.0000	0.0000	251.1943	0.0000	30.3945	Tonnes
Paper Tape	Tonnes	0.0022	0.0000	0.0000	0.0000	0.0000	0.0022	0.0000	0.0022	Tonnes

Material	Unit	Total Quantity	Columns & Beams	Floors	Foundations	Roofs	Walls	Project Extra Materials	Mass Value	Mass Unit
Rebar, Rod, Light Sections	Tonnes	0.2680	0.0000	0.0000	0.0000	0.0000	0.2680	0.0000	0.2680	Tonnes
Roofing Asphalt	kg	5,156.8617	0.0000	0.0000	0.0000	5,156.8617	0.0000	0.0000	5.1569	Tonnes
Screws Nuts & Bolts	Tonnes	0.0039	0.0000	0.0025	0.0000	0.0008	0.0006	0.0000	0.0039	Tonnes
Small Dimension Softwood Lumber, kiln-dried	m3	8.4587	0.0000	0.0000	0.0000	2.0492	6.4094	0.0000	3.5791	Tonnes
Softwood Plywood	m2 (9mm)	843.4765	0.0000	323.5707	0.0000	97.2845	422.6213	0.0000	3.8321	Tonnes
Unclad Wood Window Frame	kg	1,482.5816	0.0000	0.0000	0.0000	0.0000	1,482.5816	0.0000	1.4826	Tonnes
Water Based Latex Paint	L	177.3373	0.0000	0.0000	0.0000	0.0000	177.3373	0.0000	0.1330	Tonnes
Welded Wire Mesh / Ladder Wire	Tonnes	0.0772	0.0000	0.0000	0.0772	0.0000	0.0000	0.0000	0.0772	Tonnes

Figure 32: Bill of materials for existing house.

Material	Unit	Total Quantity	Columns & Beams	Floors	Foundations	Roofs	Walls	Project Extra Materials	Mass Value	Mass Unit
1/2" Glass Mat Gypsum Panel	m2	196.0134	0.0000	0.0000	0.0000	0.0000	196.0134	0.0000	1.9399	Tonnes
Double Glazed No Coating Air	m2	13.9565	0.0000	0.0000	0.0000	0.0000	13.9565	0.0000	0.2260	Tonnes
Nails	Tonnes	0.0390	0.0000	0.0000	0.0000	0.0000	0.0390	0.0000	0.0390	Tonnes
Polyiso Foam Board (unfaced)	m2 (25mm)	921.4752	0.0000	0.0000	0.0000	0.0000	921.4752	0.0000	0.6901	Tonnes
Screws Nuts & Bolts	Tonnes	0.0018	0.0000	0.0000	0.0000	0.0000	0.0018	0.0000	0.0018	Tonnes
Water Based Latex Paint	L	2.4584	0.0000	0.0000	0.0000	0.0000	2.4584	0.0000	0.0018	Tonnes

Figure 33: Bill of materials for retrofits.

8.2 Results and Discussion

8.2.1 Carbon Emissions Calculations using Athena

The annual operational global warming potential is 10,747 kg CO₂eq, calculated from Athena's carbon intensities based on the house location in Ottawa. The avoided emissions of conserving the historic building would be 15,900 kg CO₂eq for an assumed lifespan of 180 years (50 years of continued use in the future) and considering the carbon sequestration of wood components (Figure 34). About 400 kg CO₂eq would be wasted from the plaster and lath and old insulation that would not be conserved during the retrofit. The retrofit would create about 2130 kg CO₂eq of embodied carbon. The operational energy savings from the envelope, HVAC, lighting and appliance sensors and controls retrofit corresponds to about 135,870 kg CO₂eq carbon emissions saved over 20 years of operation or 6793 kg CO₂eq annually (Figure 35). The carbon emissions of the envelope retrofit would be paid back within the first year after the retrofit is completed (see calculations in Appendix G for details). The carbon emissions saved from the retrofit over about 2.3 years of operation is already equal to the carbon emissions of the existing structure.

Assembly Group	Unit	Total
Beams And Columns	kg CO2 eq	0.00E+00
Floors	kg CO2 eq	-7.22E+02
Foundation	kg CO2 eq	2.95E+03
Project Extra Materials	kg CO2 eq	0.00E+00
Roofs	kg CO2 eq	4.41E+03
Walls	kg CO2 eq	8.83E+03
Total	kg CO2 eq	1.55E+04

Figure 34: Avoided carbon emissions of conserving most existing building components for a 180-year lifespan (A to D).

Figure 35: Existing unretrofitted vs retrofitted embodied and operational carbon emissions

8.2.2 Solar PV Carbon Emissions

Based on Bush, Jacques, Scott, & Barrett, (2014) the embodied carbon intensity of solar PVs is about 100 g CO₂eq/kWh output⁹. For the estimated output of 8608 kWh/year, the embodied CO₂eq emissions are calculated to be about 860.8 kg CO₂eq. The 8608 kWh/year equates to 17,346 kg CO₂eq of carbon emissions saved over 20 years from solar PV power generation¹⁰. The operational savings per year equates to about 867 kg CO₂eq per year. Therefore, the embodied energy of the solar PV array is also paid back within the year. The total carbon savings, accounting for the savings from solar PV power generation, over 20 years is 150 tonnes CO₂eq (Figure 36).

For the type of existing construction, massing, and the relatively low embodied carbon retrofit, the embodied carbon becomes quite negligible over the lifespan of the building as it only comprises 1.9% over a 180-year period of operation (includes PV solar embodied energy). Embodied carbon calculations become more important when selecting more environmentally friendly materials for specific retrofits or construction. In this case, it makes sense to conserve most of the existing structure because of the savings of 15.5 tonnes CO₂eq from reduced construction materials in the present, saving the associated direct damages to the environment and conserving the historic value of the building.

⁹ Used Fig. 7 from Bush, Jacques, Scott, & Barrett, (2014) of carbon intensities (g CO₂eq) vs kWh/m² average annual irradiance. Based on the average annual solar irradiance of the PV surfaces of about 2095 kWh/m² (modelled using a TMY weather file), then the carbon intensity is estimated to be about 100 g CO₂eq/kWh output.

¹⁰ PV operational carbon savings were calculated comparing the difference in operational carbon emissions with and without PV solar panels in Athena (see Appendix G).

Figure 36: Existing unretrofitted vs retrofitted (including solar PV) embodied and operational carbon emissions. Total carbon savings from retrofit is 150 tonnes CO₂eq.

8.3 Other Considerations

The refrigerant in air-source heat pumps needs to be properly contained to avoid unwanted greenhouse gas emissions with a high GWP (global warming potential) of around 1370 to 2100 for commonly used refrigerants. Exploring the use of a lower GWP refrigerant, such as RHR-1 (mix of 75% R152a and 25% R32), can reduce the GWP to 279 and performs well in comparison to the other refrigerants (Kong, Zhang, & Nie, 2018). However, this mixture is combustible whereas the commonly used refrigerants are not. The safety and viability of alternative refrigerants needs to be researched for cold climates. Athena does not account for destruction of vegetation, eco-system alteration and land disturbance (Athena Institute, 2019). The protection of the environment and natural land are important benefits of reusing as much materials of the existing building as possible. The embodied energy calculations may not show whether a material should be conserved based on a quick

carbon payback, but the principles of conservation align well with environmental sustainability. If the element is in good condition, has heritage significance, and does not severely hinder the building performance, then it should be conserved. The embodied energy and carbon payback of a new house constructed to code was not compared to the existing building and retrofit scenarios, but this would be an interesting future analysis to complete.

8.4 Conclusion

In conclusion, the carbon payback of 2991 kg CO₂eq associated with the retrofit package (including additional solar PV) would occur within the first year of operation after the retrofit. The annual carbon emissions from the operation of the house was reduced from 10,747 kg CO₂eq to 3087 kg CO₂eq, which is a 71% decrease. This demonstrates that the deep energy retrofit is beneficial to save 150 tonnes CO₂eq over 20 years of operation compared to the existing building operation. Conserving most of the existing structure which comprises 15,500 kg CO₂eq of embodied energy is good heritage conservation and environmental sustainability practice.

9 Recommendations and Future Work

Recommendations to further validate the research done for this thesis would be to focus on the implementation, monitoring, and maintenance step of the methodology, which was not in the scope of this thesis. This could entail updating the model and comparing it to measured energy data and submetering after retrofits are implemented. The energy analysis and cost analysis demonstrate that a full retrofit of the historic windows is not economically feasible, nor does it achieve a high amount of energy savings (4%). The airtightness of rehabilitated heritage windows should be tested, since this is the main energy loss pathway compared to new window assemblies. As part of real-world validation, it would also be beneficial to demonstrate how a chimney can be well sealed to reduce heat loss and air leakage, while conserving this character defining element of a heritage house. Another element of the implementation phase that should be tested is how to best make use of historic radiators with new HVAC systems such as implementing a water heat pump system using historic decorated radiators. Conducting and integrating quantitative thermography into the process of creating a calibrated energy model is suggested as part of future work. Utilizing more non-invasive tools that do not require large amounts of data measured over long periods are good for reducing cost, the impact on the building, and improving the efficiency of the process of creating a calibrated energy model.

Informing the public about habits within their homes and offices that could reduce energy consumption to drive energy reductions is advised, since occupants are a significant variable in energy use predictions. The large-scale potential carbon reductions of changes

in occupant behaviour and how to influence occupants to change may be pursued to help achieve additional carbon savings.

Detailed energy modelling should be made more easily adoptable by many people through workshops, improving software to be more user friendly, and possibly a certification process. This way the most appropriate energy retrofits for a specific building can be selected based on environmental and economic factors. The creation of the energy model involved simplifications in the geometry due to the software limitations. Improving energy modelling software so that complex geometry can be modelled and understood by the software without issues would advance the modelling process.

Additional policies to aid homeowners in implementing deep energy retrofits including on-site renewable energy for their homes will facilitate climate action within the residential sector. It is also important that homeowners of older houses are made aware of the potential heritage significance of certain elements, which when conserved, have environmental and social benefits.

The metrics used for calibration in this thesis were NMBE and CV(RMSE) for monthly data as outlined by ASHRAE guideline 14. An improved standard of calibration for energy models should be explored to enhance the quality of simulation predictions. Using other metrics such as the coefficient of variation and goodness of fit to determine the adequacy of the calibration may be investigated.

The carbon analysis in this thesis only looked at the carbon payback of the retrofit and savings compared to the existing building. Future work could involve comparing life cycle carbon emissions of various types of new buildings (with varying levels of energy

consumption) compared to conserving an existing typology of heritage buildings such as the heritage house in this thesis.

The methodology of calibration used in this thesis was to conduct a one factor at a time sensitivity analysis on the initial energy model and use qualitative thermography and data from site surveys to inform the heuristic evidence-based calibration. The difficulty in applying Bayesian calibration to a complex heritage building model and how much it improves the energy predictions for the purpose of selecting measures to achieve a deep energy retrofit is a potential topic for further research. The methodology and decision framework presented in this thesis may be integrated into a software to facilitate the use of them for heritage conservation projects.

Finally, determining how to get better estimates from energy models, calculating uncertainty using a Monte Carlo analysis or other methods, and validating with real retrofits would improve the confidence in energy simulation results. Having this confidence will aid in appropriate decision-making by having accurate estimates of performance predictions.

10 Final Conclusions

Trade-offs between heritage conservation and sustainability are necessary, since the IPCC findings indicate that carbon intensive existing buildings should be retrofitted. The total carbon emissions from the building stock need to be reduced by 81% and 99% by 2030 and 2050 to keep global warming below 1.5°C. Heritage buildings embody cultural values that should be conserved for the social benefits. This presents a need to follow a methodology and decision framework for conducting deep energy retrofit analyses to achieve greater carbon reductions, while protecting significant values. While there are a handful of studies on energy retrofits and energy savings within heritage buildings, this thesis combines strategies from several methodologies to present a non-invasive methodology for creating a detailed calibrated energy model to simulate options in a systematic way. A decision framework is presented to help heritage and building professionals balance multiple objectives of energy and carbon reductions, occupant comfort, heritage values, and cost. The other contribution of this thesis was to provide a case study within a North American cold climate, where there have been limited studies done for energy retrofits of heritage buildings, which also considers occupant comfort and embodied carbon emissions.

The heritage house that was studied was built in 1889 in Ottawa, Canada. The heritage values are embedded within the Queen Anne Revival and Dutch Colonial architectural styles of the house. These values are identified by the historic red brick cladding, wooden double hung windows, large bay windows, stone foundation walls, and mansard roof. The house also has significant historical associations to James and William Hopper architects and current community leader and owner of the house, Angela Keller-

Herzog. On the interior, the character defining elements are the decorated iron radiators, wood moulding and fireplace.

The methodology consisted of: an historical analysis; documentation/technical measurements/energy audit (architectural drawings, laser scanning, thermography); detailed energy model; sensitivity analysis; calibration of energy model based on evidence; viable retrofit options selected based on heritage impact assessment and other risk analyses; individual options analysis; recommending an appropriate package; and implementation, monitoring, maintenance and documentation of retrofits. Following this methodology and decision framework, the character defining elements were conserved, and 71% energy savings are predicted with the recommended retrofit package. This was achieved through: retrofits to the building envelope (reducing air infiltration, additional insulation, adding a vapour barrier, and repairing and rehabilitating windows); upgrade of HVAC system with a supplementary air-source heat pump while still making use of the radiators; additional solar PVs on-site; daylight sensors and controllers to reduce electrical lighting; and appliance sensors and controls to reduce unnecessary appliance energy use.

The cost analysis demonstrated that the high cost and low energy benefit of new storm windows, results in a payback period of 54 years. A 15-year payback period is achieved for the entire retrofit package when windows are simply repaired and additional solar PV panels are installed. The additional energy, carbon and cost savings of the PV panels reduced the payback period by 16 years (when compared to the same package and window retrofit option). The recommended retrofit package has a capital cost of \$43,084.

The carbon payback of the retrofit occurs within the first year because of its low embodied carbon of 2991 kg CO₂eq. The retrofit package achieves a 71% reduction in

annual operational carbon emissions, saving 150 tonnes CO₂eq over 20 years of operation. Although the carbon payback may be quick for new retrofit elements, the payback period may be longer for a complete demolition and new construction, and other environmental impacts are not factored into the embodied carbon calculations. Considering the responsibility and values of heritage professionals and sustainability consultants, conserving the existing building has a positive social and overall sustainability impact.

This thesis presented a methodology and decision framework to balance the trade-offs between heritage conservation and sustainability for achieving deep energy and carbon savings within a heritage house in Ottawa. This approach can be applied to many residential or institutional/commercial heritage and existing buildings to realize a considerable amount of energy and associated carbon emissions reductions, to meet climate change mitigation objectives.

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Appendices

A: Floor Plans used to create model geometry

Only first floor is provided as it gives an idea of massing and spaces in building (other floors are similar).

B: Model Geometry and Model Details

Different views of the final model

(a) North-West façade

(b) South-East façade

(c) North-East façade

(d) South-West façade

Internal Gains:

People: Fraction radiant = 0.3. Fraction convective = 0.7.

Lighting was 2.56 W/m^2 or 2.40 W/m^2 (basement has a lower level of lighting) depending on the zone. Fraction radiant = 0.5. Fraction convective = 0.5.

Electrical equipment (appliances): 6.2 W/m^2 for all zones. Fraction latent = 0.1. Fraction radiant = 0.2. Fraction convective = 0.7.

Total sum of internal loads = 8.6 to 8.7 W/m^2

C: Full Sensitivity Analysis Results

D: Insulation Retrofit Scenarios

Existing – Main House Wall	Thickness (mm)
Brick	103
Air Cavity	25
Wood sheathing	25
Wood framing and batt	100
Lath and plaster	22.2
Total:	275.2
RSI based on model calibration	2.2
Measurements in Recap of combined point clouds - main house wall thickness	282
Measurements in Recap of combined point clouds - addition of house wall thickness	316

Rehabilitation 1	Thickness (mm)	Rehabilitation 2	Thickness (mm)	Rehabilitation 3	Thickness (mm)
Brick (old)	103	Brick (old)	103	Brick (old)	103
Air Cavity	25	Air Cavity	25	Air Cavity	25
Wood sheathing	25	Wood sheathing	25	Wood sheathing	25
Wood framing (old), PIR (50mm x2)	100	Wood framing (old), PIR (50mm x2)	100	Wood framing (old), PIR (50mm x2)	100
PIR	12	PIR	25	PIR	50
Gypsum board	12.7	Gypsum board	12.7	Gypsum board	12.7
Total:	277.7	Total:	290.7	Total:	315.7
Increase from existing (mm)	2.5	Increase from existing (mm)	15.5	Increase from existing (mm)	40.5
Total loss in area on ground floor, level 1 and level 2	21 cm²	Total loss in area on ground floor, level 1 and level 2	162 cm²	Total loss in area on ground floor, level 1 and level 2	4.17 m²
New RSI of wall considering thermal bridging of studs	3.5	New RSI of wall considering thermal bridging of studs	4.1	New RSI of wall considering thermal bridging of studs	5.2
RSI of insulation based on model inputs (other components are 0.36 RSI in model)	3.1	RSI of insulation based on model inputs (other components are 0.36 RSI in model)	3.7	RSI of insulation based on model inputs (other components are 0.36 RSI in model)	4.8

Existing - Addition Wall	Thickness (mm)	Thermal conductivity (W/m-K)	RSI = $\frac{\Delta X}{k}$
Brick	100	0.78	0.13
Air Cavity	25	--	0.17
Wood sheathing	13	0.07	0.19
Studs	152	0.15	1.01
Batt	152	0.05	3.0
Wood framing and batt, Req	152	0.05	2.4
Gypsum board	12.7	0.16	0.08
Total	303	Total RSI considering thermal bridging of studs	3.0
RSI of insulation based on model inputs (other components are 0.36 RSI in model)			2.6

Addition wall - Rehab 1	Thickness (mm)	Thermal conductivity (W/m-K)	RSI = $\frac{\Delta X}{k}$
Brick	100	0.78	0.13
Air Cavity	25	--	0.17
Wood sheathing	13	0.07	0.19
Studs (assuming 6 in (152 mm))	152	0.15	1.01
PIR	152	0.022	6.91
Wood framing and batt, Req	152	0.05	4.0
Gypsum board	12.7	0.16	0.08
Total	303	Total RSI considering thermal bridging of studs	4.6
RSI of insulation based on model inputs (other components are 0.36 RSI in model)			4.2

Addition wall - Rehab 2	Thickness (mm)	Thermal conductivity (W/m-K)	RSI = $\frac{\Delta X}{k}$
Brick	100	0.78	0.13
Air Cavity	25		0.17
Wood sheathing	13	0.07	0.19
Studs (assuming 6 in (152 mm))	152	0.15	1.0
PIR in stud space	152	0.022	6.9
PIR2	12	0.022	0.55
Wood framing and batt, Req	152	0.05	4.0
Gypsum board	12.7	0.16	0.08
Total	315	Total RSI considering thermal bridging of studs	5.1
RSI of insulation based on model inputs (other components are 0.36 RSI in model)			4.7

Basement Floor - Existing	Thickness (mm)	Thermal conductivity (W/m-K)	RSI = $\Delta X/k$
Concrete	101.6	1.31	0.077
Carpet			0.216
Total	101.6		0.29
Basement floor rehab 1			
Carpet	--	--	0.216
Wood floor	25.4	0.121	0.210
PIR insulation	50	0.022	2.27
Concrete	101.6	1.31	0.077
Total	177		2.8
Increase from existing	75		2.5
RSI of insulation based on model inputs			2.1
Basement floor rehab 2			
Carpet	--	--	0.216
Wood floor	25.4	0.121	0.210
PIR insulation	100	0.022	4.55
Concrete	101.6	1.31	0.077
Total	227		4.8
Increase from existing	125		4.5
RSI of insulation based on model inputs			4.1
Basement floor rehab 3			
Carpet	--	--	0.216
Wood floor	25.4	0.121	0.210
PIR insulation	150	0.022	6.82
Concrete	101.6	1.31	0.077
Total	277		7.1
Increase from existing	175		6.8
RSI of insulation based on model inputs			6.4

E: PV Power Generation Calculations

Site Information

	Addition shingles	Larger roof space	Smaller roof space	Overhang above back door
Available shingle area (m²)	8.5	13.5	16.1	3.74
Panel tilt (degrees)	83.2	66	12	5
Orientation	South	South	Northeast	South

Panel Information

Manufacturer	Canadian Solar
Model	Maxpower CS6X-310
Nominal panel power at STC (W)	310
Panel area (m ²)	1.92
Efficiency of panels	16%

Other Assumptions

Miscellaneous array and power conditioning losses (%)	5
Inverter efficiency (%)	97
PV absorption rate (%)	100
Temperature coefficient for module efficiency (%/°C)	0.40
Nominal operating cell temperature (°C)	45
Irradiance at STC (W/m ²)	1000
Reference temperature (°C)	25

Solar Resource Ottawa

	Daily solar radiation (kWh/m²-day)		Daily solar radiation - tilted (kWh/m²-day)				
Month	South orientation	NE roof surface	Addition shingles	Larger roof space	Smaller roof space	Overhang above back door	Clearness index (Duffie & Beckman, 1991)
Jan	0.225	0.0409	0.226	8.49	0.076	0.235	0.48
Feb	0.230	0.0751	0.230	8.66	0.140	0.240	0.54
Mar	0.267	0.1225	0.267	10.1	0.228	0.278	0.55
Apr	0.295	0.1854	0.295	11.1	0.346	0.307	0.51
May	0.337	0.2173	0.337	12.6	0.405	0.351	0.51
Jun	0.368	0.2272	0.369	13.8	0.423	0.384	0.51
Jul	0.370	0.2267	0.370	13.9	0.422	0.386	0.53
Aug	0.371	0.1870	0.372	14.0	0.348	0.387	0.51
Sep	0.347	0.1339	0.348	13.1	0.250	0.362	0.48
Oct	0.307	0.0746	0.307	11.5	0.139	0.320	0.44
Nov	0.276	0.0392	0.277	10.4	0.073	0.288	0.36
Dec	0.252	0.0305	0.252	9.49	0.057	0.263	0.41

	Addition shingles	Larger roof space	Smaller roof space	Overhang above back door	Total
Max panels at each location	4	7	8	1	20
Panel area (m²)	7.68	13.44	15.36	1.92	38.4

Energy Output

					Monthly energy output (kWh)			
Month	Mean monthly ambient temperature (°C)	Tc (°C)	Days per month	Avg monthly array efficiency (%)	Addition shingles	Larger roof space	Smaller roof space	Overhang above back door
Jan	-10.47	8.85	31	17.19%	8.5	560	5.8	2.2
Feb	-8.39	12.49	28	16.95%	7.7	509	9.4	2.0
Mar	-0.55	20.59	31	16.43%	9.6	634	16.5	2.5
Apr	6.42	26.52	30	16.05%	10.1	662	23.5	2.6
May	14.30	34.40	31	15.54%	11.5	757	27.6	3.0
Jun	19.30	39.41	30	15.22%	11.9	785	27.4	3.1
Jul	20.66	41.28	31	15.09%	12.3	807	28.0	3.2
Aug	20.17	40.28	31	15.16%	12.4	814	23.2	3.2
Sep	14.80	34.13	30	15.56%	11.5	756	16.5	3.0
Oct	8.47	26.75	31	16.03%	10.8	711	9.8	2.8
Nov	1.70	17.90	30	16.60%	9.7	642	5.2	2.5
Dec	-4.54	12.96	31	16.92%	9.4	617	4.2	2.4
Total output (kWh)					8608			
Total output (kWh/m²)					26			
Total retrofit energy use after considering PV generation (current and new)					44			
Total baseline including current PV					149			
Total % savings					71%			

F: Moisture Calculations

Winter Conditions

	Assumptions
T_i (C)	21
T_o (C)	-20
RH_i	0.35
RH_o	0.75

Materials	x (m)	k (W/mk)	mu (ng/Pa-s-m ²)
gypsum	0.0127	0.16	3760
PIR insulation enclosed in aluminum foil to act as a vapour barrier	0.125	0.022	2.9
wood sheathing	0.025	0.07	109
air	0.025	0.15	7000
brick	0.103	0.78	410

k = thermal conductivity

mu = permeance

R, thermal resistance = x/k

R_w , vapour resistance = 1/mu

p_w = vapour pressure

p_{sw} = saturated vapour pressure

q = heat flux

q_w = vapour flux

T_{dp} = dew point temperature

$p_{sw,i}$ (Pa)	2479
$p_{sw,o} = \exp(16.65 - 4030/(T(C)+235)) * 1000$ (Pa)	123.2
$p_{w,i}$ (Pa)	867.6
$p_{w,o} = p_{sw,o} * RH_o$ (Pa)	92.4
$q = (T_i - T_o) / R_{total}$ (W/m ²)	10.1
$q_w = (p_{wi} - p_{wo}) / R_{w, total}$ (ng/s-m ²)	2.14E+03

	R (m²-K/W)	Source	R_w (Pa-s-m²/ng)	Source
indoor film	0.100	assumed	-	
gypsum	0.079	(ASHRAE 2017)	0.000266	(ASHRAE 2017)
PIR insulation	3.20	(ASHRAE 2017)	0.350	(University of Alaska Fairbanks, 2017)
wood sheathing	0.36	(ASHRAE 2017)	0.00920	(University of Alaska Fairbanks, 2017)
air	0.17	(ASHRAE 2017)	0.000143	(ASHRAE 2017)
brick	0.132	(ASHRAE 2017)	0.00244	(ASHRAE 2017)
outdoor film	0.040	assumed	-	
Total	4.1		0.362	

Interfaces	P_w (Pa)	T_{dp} (C)	P_{sw} (Pa)	RH
gypsum	867.6	20.0	2329.6	37%
gypsum_PIR	867.0	19.2	2216.8	39%
PIR_woodsheathing	117.6	-13.0	222.4	53%
woodsheathing_air	97.9	-16.6	165.0	59%
air_brick	97.6	-18.3	143.1	68%
brick	92.4	-19.6	127.6	72%
outdoors	92.4	-20.0	123.2	75%

G: Carbon Calculations

Note: Athena was used to calculate the CO₂eq embodied carbon for stage A to C (excludes end of life) of the wood studs and plywood in the walls which was calculated to be 1340 kg CO₂eq. The total mass of the wood used in the house walls was calculated to be 3019 kg wood using dimensions input into Athena. This confirms an acceptable value for the carbon intensity of wood to be about 0.44 kg CO₂eq/kg of wood.

$$1340 \text{ kg CO}_2\text{eq} / 3019 \text{ kg wood} = 0.44 \text{ kg CO}_2\text{eq/kg of wood}$$

Embodied GWP saved by conserving existing building in its entirety (A to D), 180 years = 15,900 kg CO₂eq

Avoided embodied GWP by conserving existing elements (A to D), 180 years = 15,500 kg CO₂eq

Materials wasted from existing building = 15,900 - 15,500 = 400 kg CO₂eq

Avoided embodied GWP by conserving existing structure and elements (A to C), 180 years = 41,900 kg CO₂eq (Figure 37)

Embodied GWP for retrofit (A to C), includes wood studs and plywood, 20 years = 3470 kg CO₂eq (Figure 38)

Operational GWP after retrofit over 20 years = 79,070 kg CO₂eq

$$79,070 / 20 = 3954 \text{ kg CO}_2\text{eq annually}$$

Embodied GWP for retrofit (A to C) = 3470 kg CO₂eq – 1340 kg CO₂eq wood studs and plywood

$$= 2130 \text{ kg CO}_2\text{eq}$$

Operational GWP no retrofit over 20 years = 214,939 kg CO₂eq

$$214,939 / 20 = 10,747 \text{ kg CO}_2\text{eq annually}$$

Operational Carbon Savings = Operational GWP no retrofit – Operational GWP after retrofit

$$= 214,939 - 79,070$$

$$= 135,869 \text{ kg CO}_2\text{eq saved over 20 years}$$

$$= 135,869/20$$

$$= 6793 \text{ kg CO}_2\text{eq saved annually}$$

% Embodied Energy over 180-year lifespan of retrofitted building

$$= (\text{avoided EE emissions 20 years (A to C)} + \text{retrofit EE (A to C)}) / (\text{total EE} + \text{op. E 180 years}) * 100\%$$

$$= (30,400 + 2130) / (30,400 + 2130 + 79,070 + 214,939 * 7.5) * 100\%$$

$$= 1.9\%$$

PV carbon emissions saved from operation = Operational GWP without PVs – Operational GWP with PVs

$$= 79,070 - 65,657 \text{ kg CO}_2\text{eq}$$

$$= 13,413 \text{ kg CO}_2\text{eq saved over 20 years of operation}$$

Carbon Payback without Additional PV Generation

Year	Existing, unrenovated	Existing, renovated
0 (Present)	$y = 10747x + 0$ (no additional embodied carbon in present day)	$y = 3954x + 2130$
0	0	2130
1	10747	6084
2	21494	10038
3	32241	13992
4	42988	17946
5	53735	21900
6	64482	25854
7	75229	29808
8	85976	33762
9	96723	37716
10	107470	41670
11	118217	45624
12	128964	49578
13	139711	53532
14	150458	57486
15	161205	61440
16	171952	65394
17	182699	69348
18	193446	73302
19	204193	77256
20	214940	81210

Total savings over 20 years = 133,730 kg CO₂eq = 6,686.50 kg CO₂eq annually

Carbon Payback with Additional PV Generation

Year	Existing, unrenovated	Existing, renovated incl. PV
0 (Present)	$y = 10747x + 0$ (no additional embodied carbon in present day)	$y = (3954-867)x + 2130 + 860.8$
0	0	2991
1	10747	6078
2	21494	9165
3	32241	12252
4	42988	15339
5	53735	18426
6	64482	21513
7	75229	24600
8	85976	27687
9	96723	30774
10	107470	33861
11	118217	36948
12	128964	40035
13	139711	43122
14	150458	46209
15	161205	49296
16	171952	52383
17	182699	55470
18	193446	58557
19	204193	61644
20	214940	64731

Total savings over 20 years = 150,209 kg CO₂eq = 7,510 kg CO₂eq annually

Assembly Group	Unit	Total
Beams And Columns	kg CO2 eq	0.00E+00
Floors	kg CO2 eq	2.67E+03
Foundation	kg CO2 eq	2.91E+03
Project Extra Materials	kg CO2 eq	0.00E+00
Roofs	kg CO2 eq	5.49E+03
Walls	kg CO2 eq	3.08E+04
Total	kg CO2 eq	4.19E+04

Figure 37: Existing building embodied energy, 180 years, A to C

Assembly Group	Unit	Total
Beams And Columns	kg CO2 eq	0.00E+00
Floors	kg CO2 eq	0.00E+00
Foundation	kg CO2 eq	0.00E+00
Project Extra Materials	kg CO2 eq	0.00E+00
Roofs	kg CO2 eq	0.00E+00
Walls	kg CO2 eq	3.47E+03
Total	kg CO2 eq	3.47E+03

Figure 38: Embodied energy of envelope retrofits, 20 years, A to C

H: Photo Key Plans for Thermography

I: Potential Heritage Impact Assessment

Charts explaining the overall potential heritage impact. See Section 5 of ICOMOS (2011)

for the full explanation of this evaluation system.

VALUE OF HERITAGE ASSET	SCALE & SEVERITY OF CHANGE/IMPACT				
	No Change	Negligible change	Minor change	Moderate change	Major change
For WH properties Very High – attributes which convey OUV	SIGNIFICANCE OF EFFECT OR OVERALL IMPACT (EITHER ADVERSE OR BENEFICIAL)				
	Neutral	Slight	Moderate/ Large	Large/very Large	Very Large

For other heritage assets or attributes	SIGNIFICANCE OF IMPACT (EITHER ADVERSE OR BENEFICIAL)				
Very High	Neutral	Slight	Moderate/ Large	Large/very Large	Very Large
High	Neutral	Slight	Moderate/ Slight	Moderate/ Large	Large/Very Large
Medium	Neutral	Neutral/Slight	Slight	Moderate	Moderate/ Large
Low	Neutral	Neutral/Slight	Neutral/Slight	Slight	Slight/ Moderate
Negligible	Neutral	Neutral	Neutral/Slight	Neutral/Slight	Slight