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Life-cycle environmental assessment of energy-retrofit strategies on a campus scale

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ABSTRACT

The aim of this study is to determine the life-cycle environmental impacts associated with energy-retrofit strategies on an urban scale. A prototype campus model that includes deep retrofit clusters, moderate retrofit clusters, and baseline retrofit clusters is used as a case study. The retrofit strategies included major changes to the building envelope with additional insulation, replacement of exterior windows and doors, shading, primary mechanical system replacement, and lighting system replacement. The study aims to (1) compare the three levels of energy retrofit against the existing condition to determine potential reductions in environmental impact, (2) identify the life-cycle hotspots of the energy-retrofit strategies and possible mitigation methods, (3) calculate the payback time for each energy-retrofit level, and (4) demonstrate an example of how life-cycle assessment (LCA) could be used as a quantitative assessment method for energy retrofits done on a large scale. The life-cycle environmental impact is calculated for five categories. The results indicate that energy retrofits overall have a positive effect in terms of reducing life-cycle environmental impacts in all environmental categories except ozone-depletion potential. The deep energy retrofit has a much shorter payback time for its environmental-impact reduction than the other energy-retrofit levels.

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Life-cycle assessment; energy retrofit; environment impact; urban scale

Introduction

As outlined by the United Nations Environment Programme (UNEP), the path toward a temperature increase of less than 2°C requires reducing global energy and process-based carbon emissions by 60% by 2050 compared to a 2012 baseline (Otto, 2016). Overall, the building and construction industry is responsible for about 30% of global greenhouse gas emissions, 32% of global energy expenditures, and 40% of global waste (Nejat, Jomehzadeh, Taheri, Gohari, & Majid, 2015). Many studies indicate that sustainable, energy-efficient buildings are important factors in meeting the goal of a carbon-emissions reduction of 80% by 2050. With the energy consumption of buildings expected to increase and substantial construction activity projected for the next decade, emissions from the building sector could double by 2050 if no action is taken. Furthermore, energy demand is expected to rise 50% by 2050 due to population and economic growth (IEA 2018). At COP21, the building sector was identified as a key sector based on its environmental-impact mitigation potential. During COP 21, one single day was designated as the 'Buildings Day,' and COP 21 has supported the formation of the Global Alliance of Buildings and Construction, which focuses on carbon emissions reduction. The Alliance is composed of twenty countries. And, at the following COP 22, the sustainable, energy-efficient building movement took centre stage – more than 90 countries now include some mention of building-sector actions in their national climate-change and environmental-impact mitigation strategies (WGBC).

Most developed countries have a large stock of older buildings. For instance, in the European Union member states, existing buildings have an average age of about fifty-five years (D'agostino, Zangheri, & Castellazzi, 2017). These older buildings are less energy-efficient and close to the end of their lives, which means decisions need to be made and energy retrofit standards set. The European Commission conducted a study to determine the building retrofit rates in the European Union. The results were a 1.2% rate for Northwestern Europe, a 0.9% rate for Southern Europe, and a 0.5% rate for new member states (Eichhammer et al., 2011). The lack of awareness regarding the potential benefits from environmental-impact reductions might be contributing to the low overall retrofit rate. Hence, the rate might be raised by making the public and policymakers aware of

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such benefits. In order to support the promotion of existing-building retrofits as an acceptable, even popular solution to mitigating the environmental and climate-change impacts of the building industry globally, more empirical studies linking energy-retrofit strategies to environmental-impact reductions are needed. In developing countries, most nations have already realized the important environmental role of the building industry. These countries have passed regulations and set mandates accordingly to help realize the large environmental impact reductions made possible by energy-efficient new buildings. However, comprehensive guidelines for energy retrofitting existing buildings are lacking in most developing countries. Another issue is that the building lifespan in developing countries such as China is shorter, about 25–30 years on average, based on a 2010 study (Qian, 2010; Liu, Xu, Zhang, & Zhang, 2014). Therefore, these buildings will reach the end of their service life and require renovation and upgrades at a faster pace.

State of the art: linking energy-retrofit strategies to environment impact reductions using the life-cycle assessment method

The reduction of building operating energy consumption is generally believed to reduce environmental impact, since operating energy accounts for 80–90% of the life-cycle energy consumed in existing building stock, while embodied energy only accounts for a small portion (10–20%) of its life-cycle energy (Ramesh, Prakash, & Shukla, 2010). Operating energy is the energy used for lighting, heating, cooling, ventilation, equipment, and appliances. Embodied energy is the energy needed to construct and maintain a building during all processes of production, onsite construction, and final demolition and disposal (Chastas, Theodosiou, & Bikas, 2016). Research into the reduction of operating energy and its related greenhouse gas emissions has stimulated recent changes in the practices of the building industry (Chastas et al., 2016). However, as new buildings become increasingly energy efficient and older buildings are retrofitted to improve efficiency, embodied energy will account for a larger proportion of total life-cycle energy, more than 50% (Crowther, 1999; Crawford & Treloar, 2003; Pullen, Holloway, Randolph, & Troy, 2006). Meanwhile, concerns regarding embodied energy and related greenhouse gas emissions from buildings still need to be incorporated into design guidelines and building regulations (Hu, 2019). Using the life-cycle assessment (LCA) method to study energy-retrofit strategies could help designers, engineers, and contractors to reduce overall life-cycle energy consumption by using fewer energy-intensive yet high-performance materials, and optimizing design strategies.

Research connecting energy efficiency to environmental benefits has demonstrated that a building's energy and environmental performance depends on factors related to building material choices and construction methods as well as building systems and components. The literature presents a large number of studies that assess the environmental impact of renovation projects, with most of those studies focusing on individual buildings, including public (Ardente, Beccali, Cellura, & Mistretta, 2011), residential (Cuéllar-Franca & Azapagic, 2012; Rodrigues & Freire, 2017), and office buildings (Kofoworola & Gheewala, 2009; Kofoworola & Gheewala, 2008). The most frequently studied environmental categories to date are global warming potential (Scheuer, Keoleian, & Reppe, 2003; Beccali, Cellura, Fontana, Longo, & Mistretta, 2013), acidification potential (AP) (Crawford & Treloar, 2003; Ardente et al., 2011), and ozone depletion potential (ODP) (Ardent et al. 2011; Pombo, Allacker, Rivela, & Neila, 2016). This study includes a fourth and less studied environmental impact category, smog formation potential, since smog formation has become a major environmental problem in developing countries with fast-paced urbanization (Hasik et al., 2019).

Research has also found that the greatest environmental impact is associated with energy spent during operation and the energy embedded in building materials and components: the transportation and process energy used during construction and demolition of the dwellings comprised only approximately 1% of the total energy requirement during a building's lifetime (Atmaca & Atmaca, 2015;Hu, 2017).

While this body of literature includes comprehensive and thorough studies, some of which examine a large number of buildings, the majority of studies have been at the level of an individual building. Very few papers analyse the life-cycle environmental impact of a group of buildings on a larger scale. This may be due to the greater difficulty of evaluating a group of buildings or large scale urban block than a single building. First, they are complex and may be diverse in materials and function. Second, there is no one renovation that applies to all the different buildings: typically, a variety of retrofit strategies and techniques is applied to the different buildings.

LCA could be a useful tool for analysing the environment impact of multiple buildings on a large urban scale. LCA is a standard environmental assessment tool commonly used to evaluate individual buildings' environmental impacts through their entire life-span (Thormark, 2006; Goggins, Moran, Armstrong, &

Hajdukiewicz, 2016; Rauf & Crawford, 2015). Using LCA might also help designers, engineers, and policymakers to identify problematic areas (i.e. hot spots that occur during a building's life-span). It could also be used to study the impact of different building energy efficiency measures (Nicolae & George-Vlad, 2015; Passer, Ouellet-Plamondon, Kenneally, John, & Habert, 2016).

Over the past several decades, hundreds of LCA studies in the building industry have focused on new construction (Vilches, Garcia-Martinez, & Sanchez-Montanes, 2017). Most of these studies evaluated residential rather than commercial buildings (Chau, Leung, & Ng, 2015; Cabeza, Rincón, Vilariño, Pérez, & Castell, 2014; Ghose, McLaren, Dowdell, & Phipps, 2017) and very few assessed large-scale projects. Consequently, there are several research gaps. First, of the commercial building studies, the majority focused on office buildings (Azzouz, Borchers, Moreira, & Mavrogianni, 2017; Taborianski & Prado, 2012). Very few studies have been carried out on other building types, such as institutional buildings. Second, most studies developed their optimized energy-efficient retrofit solutions using energy simulation data rather than real energy consumption data. Third, the majority of these studies focused on the environmental impacts related only to operational energy performance (Stephan & Stephan, 2016; Stephan & Crawford, 2016) and building façade materials (Radhi & Sharples, 2013; Han, Wang, Yao, Liu, & Wang, 2015; Hong, Shen, Mao, Li, & Li, 2016). Few studies concentrated on the overall life-cycle impact of different energy-retrofit levels. The environmental impacts of buildings in other life-cycle phases, such as the product phase or end-of-life phase (demolition), have also been studied less often. Fourth, the different impacts of various energy-retrofit strategies have not been extensively analysed and compared. Finally, there is still a lack of research on the environmental impact reduction potential of energy retrofits of large-scale building blocks as well as retrofits that include multiple comprehensive efficiency measures for the building envelope and lighting and HVAC systems (Techato, Watts, & Chaiprapat, 2009; Ferreira, Pinheiro, & De Brito, 2015; Tokede, Love, & Ahiaga-Dagbui, 2018). To respond to these research gaps, this paper aims to study how comprehensive energy-retrofit strategies and techniques could contribute to environmental impact reductions, employing a complete life-cycle perspective.

A comprehensive literature review contributed by Alberto, Garcia-Martinez, and Sanchez-Montanes (2016) has found that most LCA have focused on energy retrofits, comparing the environmental impacts before and after renovation. A large number of studies have concentrated on the product and use phases, with building materials and components studied extensively; almost none of the LCA studies have focused on the environmental impact of a building system retrofit. Alberto et al. clarified and compared different definitions and terminology related to retrofitting used in Europe – such as refurbishment, renovation, repair, and restoration – and studied the LCA of single-family house, multi-family house, and non-residential building retrofits. They concluded that most studies in this field have assessed the environmental impact through the LCA method and have mainly focused on comparing performance before and after the energy retrofitting of individual buildings; the most frequently studied environmental category was carbon emissions (Pullen et al., 2006). Jones, Lannon, and Patterson (2013) studied three large-scale housing retrofit programmes in Wales, United Kingdom for their energy use and CO2 reduction benefits, and different retrofit levels were investigated as well: basic renovation and deep renovation with a CO2 emissions reduction of 10–30% and 60–80%, respectively (Jones et al., 2013). Itard and Klunder compared environmental impacts of renovated housing stock with new construction in the Netherlands using the LCA method, with results indicating that transforming existing housing stock was more environmentally efficient than demolition and rebuilding (Itard & Klunder, 2007).

Studies using the LCA method to investigate energy use at the urban scale have mainly focused on urban infrastructure (water, waste, and transportation) (Chang, Chu, & Lin, 2012; Uche, Martínez, Castellano, & Subiela, 2013), building blocks (Stephan & Crawford, 2014), and industry sectors (Azzouz et al., 2017). As mentioned above, although LCA has been used at an individual building level, the lack of integrated environmental impacts at a larger scale have been noted by researchers (Taborianski & Prado, 2012). The current barriers to linking environmental impact reduction benefits to energy-saving measurements at a larger urban scale include the complexity of the modelling domain (Keirstead, Jennings, & Sivakumar, 2012) and a lack of local data (Marcotullio & McGranahan, 2012) and readily accessible tools. Overall, most literature connecting energy retrofits to environmental benefits remains at an individual building level and only examines the global warming reduction potential while neglecting other environmental factors, such as the ODP and smog formation.

Method

Case-study description

The main campus consists of a 130,993 m^2 gross area (1,410,000 square feet) that has about 254 buildings on

1340 acres of land (UMD). The building types include classrooms, offices, laboratories, sport facilities, performance centres, farming facilities, and residential buildings. There are five categories of building type: Academic buildings (classrooms, laboratories), Administrative buildings (offices, conference spaces), Auxiliary Enterprise buildings (dormitories, cafeterias, student union buildings, stadiums, athletic facilities, housing), Library buildings, and Other Non-Academic buildings. Extracted from the existing building-stock inventory, the building-type percentages on campus are shown in Table 1. For the case study, a prototype building in each category was selected for the in-depth analysis described in the section of data collection and modelling (Figure 1).

As of 2018, 66% of the buildings on campus are more than 25 years old and were not built to comply with the current building energy-efficiency code; 32% of the buildings are 55 years or older and approaching the end of their serviceable lifespan[1] (Cosner, 2014; Hu, 2018). The energy consumption of the Academic building stock varies significantly – from 0.063 kWh/m^2/yr (20 kBTU/ft2) to 4.151 kWh/m^2/yr (1316 kBTU/ft2). The highest energy-use intensity was recorded in the engineering facility, which has large laboratories and large numbers of testing equipment. Of the spaces on campus supported by state funding, 17% were deemed to be in poor condition, 50% in fair condition, and 33% in good condition (Rauf & Crawford, 2015). Among those in poor condition, some of the buildings have not had a major renovation in more than 40 years.

Table 1. Building types on campus based on fall 2017 inventory (University of Maryland, 2011).

Building type	Percentage of gross area total (%)	Prototype building	Existing energy use (kWh/m^2)
Academic	44	School of Architecture	882
Administrative	2	LEE Building	361
Library	5	Main library	730
Auxiliary enterprise	43	Student dormitory	768
Other non-academic	6	Mixed-use office	560

Function units and project boundaries

The functional unit for this study was defined as '1 m^2 floor area of the retrofitted building that has achieved a 20% to 80% reduction in annual on-site energy consumption compared to its previous (existing) annual energy consumption' (CEN/TC 350). The 20% to 80% reduction represents three levels of building retrofit: deep retrofit, moderate retrofit, and baseline retrofit (refer to Section Energy-retrofit level definitions and Table 2 for a detailed explanation). This functional unit (i.e. square meter floor area/year) is also recommended by CEN TC 350 (Standard EN 15978:2011) (Vilches et al., 2017, p. 30), which provides a calculation method based on LCA to assess the environmental performance of a building. The project boundary was the whole building life-cycle, which is defined based on the same standard (Standard EN 15978:2011), as building service life. Building service life is different from building physical life. Service life refers to the usefulness of the building. A building's physical condition (such as its structure) could be very well preserved, even as the function of building is no longer needed. For instance, a historical manufacturing building is no longer needed since the industry has disappeared, and the building's function has become obsolete (Wilkinson, Remøy, & Langston, 2014), so the buildings will need to be modified to adapt to changes in environmental, functional, locational, and economic conditions (Hu, 2017). Instead of replacing the entire building, renovation is a better solution. To be more specific, the environmental impact of retrofits is derived from the following life stages as defined by the ISO 14040 and 14044 guidelines. In this study, the life-cycle stages included is A1–C4 (Table 2; Stephan & Crawford, 2016).

The building product and components included in this study are the building envelope, the primary building structure system, the interior walls and layout, the lighting system, and the HVAC system (see Table 4). The furnishing/finish and furniture are excluded. We assume there are no renovations to the primary building structure system and the interior walls and layout, and that the energy retrofit mainly entailed retrofitting the lighting system, building façade system, and HVAC system. The five environmental impact categories chosen for the assessment are global-warming potential (GWP), human-health particulate potential (HHP), smog potential (SP), ODP, and AP.

Energy-retrofit level definitions

The terms retrofit, renovation, and refurbishment have been used interchangeably in the scientific literature. Many energy-reduction measures are based on passive and active techniques. For instance, the installation of insulation in the building envelope can be considered a passive strategy and the installation of an efficient mechanical-system upgrade is an active measure (Pullen et al., 2006). Regardless of their being passive or active, these energy measures, which add new materials or elements

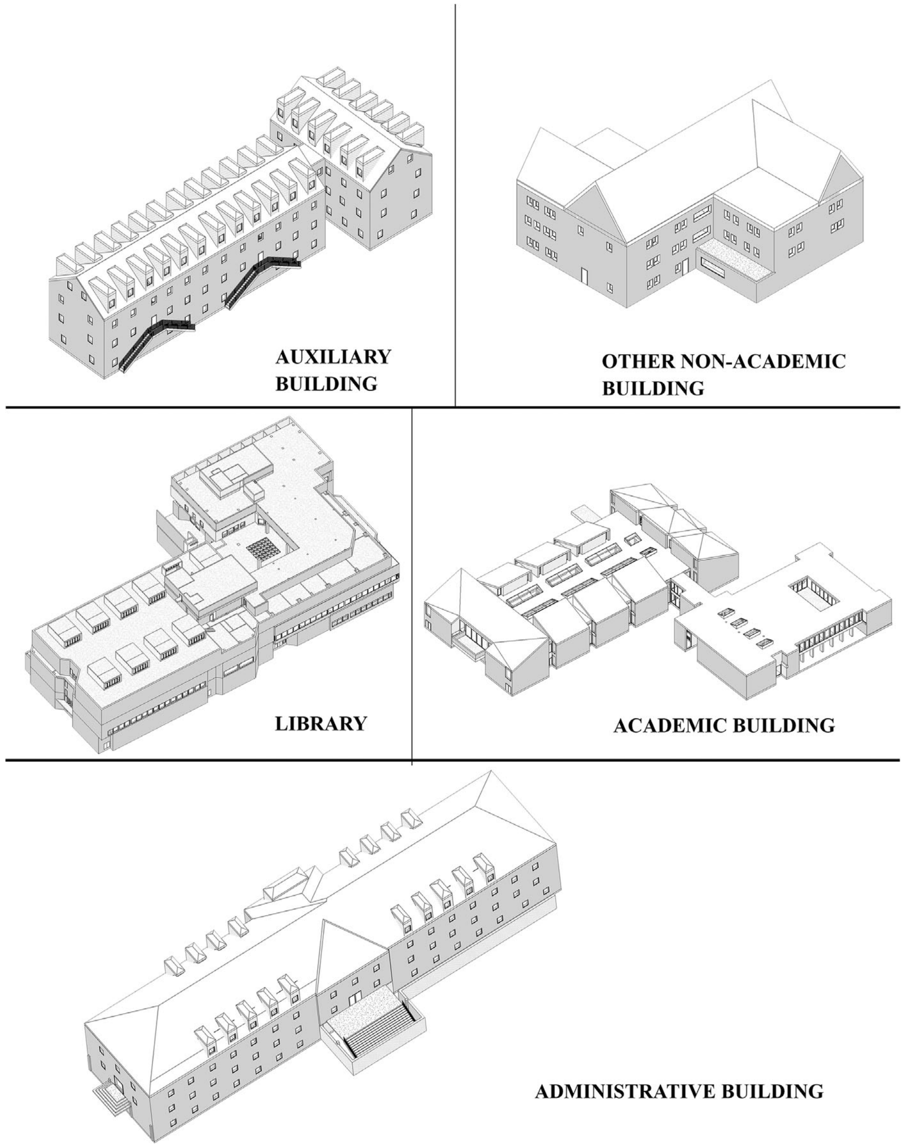

Figure 1. Prototype buildings (Autodesk Revit models).

Table 2. Building life-cycle stages.

Phase		
A – Production	A1	Prime materials extraction
	A2	Transportation to manufacture
	A3	Manufacturing
	A4	Products transportation
	A5	Installation and construction process
B – Use of Product	B1	Use
	B2	Maintenance
	B3	Repair
	B4	Replacement
	B5	Rehabilitation/retrofitting
	B6	Energy consumption
C – End of Life-cycle	C1	Deconstruction and demolition
	C2	Transportation
	C3	Reuse and recycling management
	C4	Final disposal

to the existing building, are defined as an energy retrofit in this study.

There is no consensus in the building industry as to the definitions of the levels of building energy retrofits. In this project, we relied on two government documents to define these levels, one published by the U.S. Department of Energy (DOE) and the other by the European Parliament's Committee on Industry, Research, and Energy. Since 2014, the DOE has published a serial titled *Advanced Energy Retrofit Guides (AERGs)* for existing office buildings, retail buildings, K-12 schools, grocery stores, and healthcare facilities. The different building types listed have different energy-saving goals and retrofit techniques. In the European Union, Recital 16 of the *Energy Efficiency Directive (EED)* defines 'deep renovations' as 'renovations which lead to a refurbishment

Table 3. Planned renovation project summary, Fall 2017–2030 (Azzouz et al., 2017; Ghose et al., 2017; Rauf & Crawford, 2015; Stephan & Crawford, 2016; Taborianski & Prado, 2012).

Renovation level	Gross area percentage of overall	Operational energy use reduction (compared to current use)	Embodied energy use increase (compared to existing building)
Deep retrofit	5%	60–90%	20%
Moderate Retrofit	10%	25–45% (US standard)	15%
Basic Renovation	85%	25%	10%
Total spaced needing renovation	278,648 m^2		

that reduces both the delivered and the final energy consumption of a building by a significant percentage compared with the pre-renovation levels, leading to a very high energy performance' (D'agostino et al., 2017). Based on the *EED* and *AERGs,* as well as UMD campus facility construction and renovation guidelines, the three levels of energy retrofit used in this study are defined below. Table 3 shows the target total building area for each level of energy retrofit. In all energy-retrofit levels, we included and calculated the additional embodied energy derived from the replacement of HVAC equipment, upgrades to the building envelope, and other related renovation strategies.

Baseline retrofit

The DOE estimates that a typical office building can cut energy use by up to 25% by basic renovation. In reality, in the EU and the United States, a minor or basic renovation could result in a reduction in energy use of between 0% and 30%, and around 85% of the buildings could achieve such a goal by implementing relatively basic renovation measures (Rauf & Crawford, 2015). Currently, on the University campus, the Leadership in Energy and Environmental Design (LEED) silver certification is the minimum standard for new construction and major renovation. After combining the minimal design requirements (LEED) and real project outcomes, the baseline retrofit in this study was defined as a 25% reduction in energy use that encompasses 85% of the total building area.

Moderate retrofit

In the United States, a moderate or standard retrofit typically involves a component-level replacement of existing HVAC equipment, which could lead to a 25–45% reduction in energy use compared to existing conditions (Liu et al., 2014). In the EU, moderate renovations result in an energy reduction of 30–60% (Goggins et al., 2016). About 10% of the buildings could achieve such a goal by implementing some moderate renovation techniques, including an HVAC system upgrade (Liu et al., 2011).

Deep retrofit

According to the DOE, a typical office building can cut energy use over 45% (against existing energy use) by pursuing deep retrofits (Liu et al., 2011). Deep retrofit projects combine many O&M and standard retrofit measures in an integrated whole-building design approach (Azzouz et al., 2017; Shnapp, Sitjà, & Laustsen, 2013). Since the deep energy retrofit could achieve much higher energy reduction goal, up to 60–90%, researchers and policy-maker predict only 5% of the existing building stock is projected to meet this goal (Artola, Rademaekers, Williams, & Yearwood, 2016; Shnapp et al., 2013). The performance of existing building stocks on campus is between 882 and 361 kWh/m^2. The numbers are

Table 4. Retrofit package/techniques explanation (Azzouz et al., 2017; Ghose et al., 2017; Rauf & Crawford, 2015; Stephan & Crawford, 2016; Taborianski & Prado, 2012).

	Retrofit techniques/building components	Retrofit levels		
		Baseline	Moderate	Deep
Lighting system	Retrofit interior fixtures to reduce lighting power density 11%.			X
	Install occupancy sensor.		X	X
	Integrate daylight harvesting.		X	X
	Retrofit exterior fixtures to reduce lighting power density and install lighting control.		X	X
HVAC System (Airside)	Widen the room's set temperature range.	X	X	X
	Lower the variable air volume (VAV) box minimum-flow setpoints; reset duct static pressure (upgrade to direct digital zone control).	X	X	X
	Add demand-controlled ventilation.	X	X	X
	Replace supply-fan motor and variable frequency drive (VFD).	X	X	X
Building Envelope	Add roof insulation			X
	Replace all exterior windows and doors with energy-efficient products.			X

based on the actual building performance data collected by University's facility management office. Therefore, with a maximum 90% energy use reduction, a deep retrofit could result in 88.2–36.1 kWh/m^2. With a 60% energy use reduction, a deep retrofit could result in 352.8–144.4 kWh/m^2. To compare a building with a deep retrofit to a newly constructed high-performance building, we used one of the most stringent building energy efficiency standards, Passive House, as the benchmark. The Passive House standard requires that the building's primary energy use not exceed 120 kWh/m^2. Therefore, a deep retrofit with a 60–90% energy use reduction could provide the potential for existing buildings to become Passive House-certified and surpass most existing high-performance building standards.

The *EED* and *AEGs* also outline the recommended retrofit techniques. Table 4 details the renovation techniques included in the three levels of retrofit: the lighting system, the building envelope, and the HVAC system (airside).

Data collection and modelling

In this study, five prototype buildings are modelled, measured, and assessed in order to populate the data to a campus-wide assessment. The energy-use data were obtained from the UMD facility management office database. The data represent the normalized five-year average of real-time energy use. A prototype building means a building represent a typical condition of the buildings with similar function and age. All prototype buildings are investigated in this study. Because the majority buildings on campus shared very similar construction types and built around same period, therefore one set of general data is used for each type for retrofit simulation. The detailed breakdown of building property data used for simulation are included in Appendix.

The prototype buildings' building-material and construction data were collected from original construction documents archived by the campus facility management office. The researcher also conducted some field measurements to confirm the existing conditions that are not reflected on original construction documents. Construction-document data and field-measurement data then are used to create a three-dimensional building information model (BIM) using a software called Autodesk Revit (Figure 1). BIM uses a process involving the generation and management of digital representations of physical and functional characteristics of buildings. It was developed to facilitate the life-cycle management of buildings (Chen, Lu, Peng, Rowlinson, & Huang, 2015). The BIM model can also support complex decision-making by providing opportunities to link numerous aspects and a large amount of information in a common data environment (Lu, Fung, Peng, Liang, & Rowlinson, 2014). The amount of building materials required for building renovations and the generation of waste materials from existing buildings are estimated and measured in BIM models. Then, the embedded material data is extracted as a bill of materials (BoM) and imported into the Athena Life-Cycle Inventory (LCI) database to generate a cradle-to-grave LCI profile for a full life-cycle environmental-impact assessment.

The U.S. EPA TRACI method was used for the LCA assessment and the Athena Impact Estimator for Buildings (IE4B) was chosen as the software used to conduct the assessment, since the Athena calculation is consistent with TRACI, and IE4B is the tool widely used in LCAs for buildings in North America (Hu, 2017). Both TRACI and Athena comply with the ISO 14040 and 14044 guidelines for LCA.

Building envelope: façade, roof, window, and door

The materials used on existing building façades are mainly composed of brick veneer with concrete and concrete masonry unit backup and no insulation or air space in between. Without insulation, the existing exterior building façades provide a limited insulation value (*R*-value) of about 10.78 W/m^2 K. The original roof was made of concrete slab with 25.4 mm insulation board and composition roofing materials over it. Its estimated *R*-value is about 28.3 W/m^2 K. The composition roofing has a warranty of 20 years, so we assume the roofing has been replaced sometime between the original construction and now. However, there were only limited records found indicating that the roofs had been replaced on some of the buildings. Therefore, we need to assume that the recorded roof replacements actually meet the current campus-wide standard, which is based on ASHRAE with an *R*-value of 30.

As for the exterior windows and doors, the conditions are more complicated. Based on the archived documents found in the facility office library, the original window and glass door units were composed of single-pane uninsulated glass with painted steel frames. Most windows are not operable, with the glazing having a *U*-value of around 7.3 W/m^2 K. Depending on the work done to individual buildings, some buildings have had a portion of the exterior windows and doors replaced with double-pane units with a higher performance value. Other buildings have not had anything done since their original construction. In order to estimate the maximum environmental benefit that could be derived from renovation, we assume the worst scenarios as the existing condition, that is, all existing buildings have their original windows and doors as described in the original construction documents. The windows and doors together account for around 40% of the total vertical surface area.

Mechanical system

In order to accurately model the upgraded HVAC system, we obtain the construction documents and specifications for two recently constructed buildings on campus. Those two buildings meet the LEED silver requirements. The data extracted from the material specification description of the HVAC equipment and products are then used to quantify the environmental impact of the most recent HVAC systems. Heat pumps and ventilation units are mainly composed of a variety of metals for structural supports, elastomers for tube or piles insulations, and refrigerants to store and transport heat. In this study, two types of heat pump are included based on new building conditions on campus. A 10 kW air–water heat pump and heat distribution unit is assumed to serve 150 m^2 of conditioned floor area. A 30 kW heat pump is used in larger areas and scaled from the 10 kW unit by a factor of 1.8 (Caduff, Huijbregts, Koehler, Althaus, & Hellweg, 2014). The raw material inputs are extracted based on a generic 10 and 30 kW units. The ventilating system has a ventilation rate of 10 l/s/ m^2 (20 cfm/min/ft^2). The components of the ventilating system are based on the building construction documents, and the environment-impact data are from the Athena database. Only major HVAC units are included. All mechanical ductwork is excluded. Natural ventilation of buildings has the potential to significantly reduce the cooling load. Previous research has indicated that the natural ventilation rate strongly depends on the location of the openings (windows and doors), their geometry (Schulze & Eicker, 2013), and a cross section of the building. However, natural ventilation as a viable renovation strategy has not been widely applied due to the limited information available on thermal comfort and indoor air quality without air conditioning (Schulze & Eicker, 2013). In this research, natural ventilation was not included in the potential retrofit strategies for two reasons. First, the majority of studies were conducted using a simulated model (Allocca, Chen, & Glicksman, 2003; Jomehzadeh et al., 2017), with limited data and research demonstrating the effectiveness using real projects. Second, altering the opening configuration and size in a normal energy retrofit project is most unlikely.

Lighting system

Based on the campus-wide guidelines, all existing lighting fixtures will be replaced with LED lights at a certain point, which could reduce the existing lighting power density by 75% (the ratio of the lumen output of LED light bulbs to that of incandescent light bulbs). The material data on LED lights are extracted from recent studies (Principi & Fioretti, 2014; Casamayor, Su, & Ren, 2018).

Inventory for construction materials

There are several life-cycle inventories (LCI) available for projects in North America. Ecoinvent includes some North American data (Cooper, Fava, Simonen, Boyd, & Baer, 2012). The National Renewable Energy Laboratory (NREL) U.S. LCI data are integrated into software such as Gabi and Simapro. The Athena Institute has been a major contributor to the United States' database since 2002. In 2010, the Athena team was engaged to update the 'LCI Data Submission Requirements' for the U.S. LCI database. They worked with the NREL on a process for automating the updating of key electricity generation profiles on a state, regional, and North American basis (Itard & Klunder, 2007; Martínez-Rocamora, Solís-Guzmán, & Marrero, 2016; Soust-Verdaguer, Llatas, & García-Martínez, 2017; Anand & Amor, 2017). In this project, the database integrated with Athena software is chosen since Athena addresses more than 95% of the shell construction building materials and systems (Itard & Klunder, 2007; Chang et al., 2012; Uche et al., 2013; Stephan & Crawford, 2014). Also, the process Athena uses to collect the materials inventory follows the ISO 14040 series of standards.

Building energy and environmental payback time

Research has shown that the life-cycle energy use of buildings depends on the operating (80–90%) and embodied (10–20%) energy of the buildings (Ramesh et al., 2010; Stephan, Crawford, & De Myttenaere, 2012; Chastas et al., 2016). The transportation and process energy used during construction and demolition of the dwellings comprises approximately 1% of the total energy requirement (Khasreen, Banfill, & Menzies, 2009). In this study, the energy used to construct or install the building components on site is included and calculated using Athena database. Demolition energy is also included and account for additional impact. Embodied energy is the energy embedded in the materials used for different retrofit levels and is included in the assessment.

For operational energy, the existing building energy-use intensity (Table 1) and energy-use reduction levels (Table 2) are used to calculated energy use at different retrofit levels. All major retrofitted mechanical and lighting components have about a 25-year lifespan before replacement (Balaras, Dascalaki, & Kontoyiannidis, 2004; Juan, Gao, & Wang, 2010). This study assumes that within the 25 years there is no functional degradation for the simplicity of assessment. For building façade components, all products are assumed to have a function life of up to 40 years. The cumulative environmental impact of buildings is calculated by adding the environmental impacts associated with operational energy use and embodied energy over the 40-year time span after the initial energy retrofit. The environmental impact results of the retrofitted campus are then compared to the campus in which none of the buildings are retrofitted. The environmental payback time is calculated using the adapted formula below (EPA 2008):

$$\text{Payback time} \quad (\text{years}) = \frac{\text{Total environmental impact of retrofit}}{\text{Net annual savings} \quad (\text{reduction in envirionmental impact per year})} \tag{1}$$

Results

All results are based on the total buildings on campus described in Table 1. The simulation and modelling are based on prototype buildings that are proportional to the built space on campus.

Environmental impact of retrofit comparisons (by environmental-impact category)

As illustrated in Figure 2, compared to existing conditions, the baseline retrofit reduces GWP by 16%, the moderate retrofit 36%, and the deep retrofit 65%. For AP, the baseline retrofit reduces the potential by 20%, the moderate retrofit 40%, and the deep retrofit 69%. For smog formation potential compared to existing conditions, the baseline retrofit reduces the potential 19%, the moderate retrofit 37%, and the deep retrofit 80%. For HHP potential, the baseline retrofit reduces potential 20% compared to the existing conditions, the moderate retrofit 39%, and the deep retrofit 68%.

However, for ozone-depletion potential, the results do not show a reduction. Instead, they show a slight increase for the different levels of retrofit. The baseline retrofit shows a 4% increase, the moderate retrofit 3%, and the deep retrofit 16%. When examining the building materials' and components' contribution to the ODP, it is clear that thermal insulation and moisture protection have contributed an unproportionally large amount. The total mass (weight) of insulation and moisture protection only accounts for 0.02% of all building materials; however, it contributes 44.19% to the overall ODP. Accordingly, it is reasonable to assume the increase may be linked to the insulation materials used in the retrofitted building envelope and upgraded HVAC systems.

Environmental impact hotspots (by life-cycle phase)

For three environmental impact categories (Figures 3–5) – AP, SP, and GWP – hotspots are identified in the product phase and the operational phase.

For SP, the operational phase (B6) is also the major contributor to the environmental impact: more than 50% in the existing condition, the baseline retrofit condition, and the moderate retrofit condition. For the deep retrofit scenario, the greatest impact on smog formation will come from the product phase (A1–A3) that is mostly related to the building-envelope retrofit – specifically, the insulation materials added in the roof. As for the SP impact mitigation, during the operational phase, the impact could be substantially reduced through increasing the building operational energy efficiency. As the building consumes less energy to operate, the SP can also be reduced. The energy use reduction is proportional to the impact reduction. In the product phase, the energy retrofit does not result in an impact reduction regardless of which level of retrofit. To the contrary, the deep retrofit has a slightly higher smog-formation potential.

For GWP overall, the product phase contributes over 69% of the overall GWP. The different retrofit strategies do not have any significant reduction impact during the product phase. Instead, the deep retrofit actually results in a slightly higher impact, around 12.5% compared to the existing condition. In the operational phase, the GWP could be reduced by employing different renovation techniques. The reduction potential is 20%, 40%, and 70%, respectively, for the three levels of retrofit.

For AP, the operational phase contributes the greatest environmental impact, around 80%, for the existing condition and the moderate retrofit. The second hotspot of acidification is the product phase, about 18%. None of the energy-retrofit strategies have any significant impact on acidification-potential reduction during the product phase.

Regarding the ODP (Figure 6), 99% of the impacts are contributed by the product stage. The product stage (A1 to A3) includes raw material extraction, manufacturing, and transportation. Based on the findings mentioned in Figure 6, the ODP at all levels of retrofit

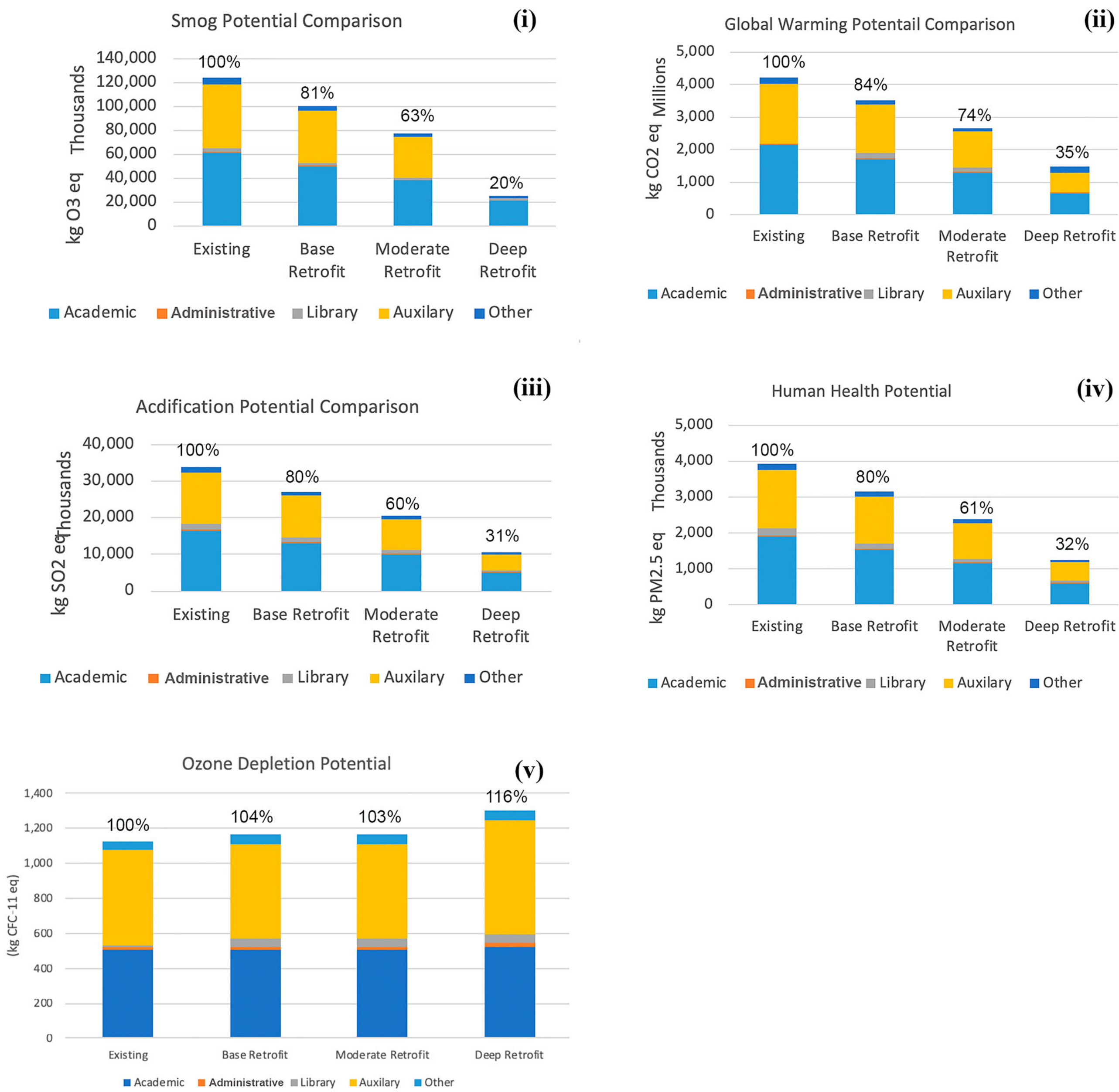

Figure 2. Environmental-impact potential reduction comparisons.

do not show a decrease. Instead, they indicate a varied increase across most life-cycle stages – particularly in the product stage and from a deep retrofit. This finding is aligned with the results from section 'Environmental impact of retrofit comparisons (by environmental-impact category)'. Therefore, it is reasonable to assume that a decrease in the environmental impact at the product stage could be the most effective approach to decrease the ODP. The major difference between a deep and moderate retrofit is the building envelope. In a deep retrofit approach, additional insulation is added, and all exterior windows and doors are replaced. Consequently, further studies examining different window and door systems will be helpful to define the mitigation strategies.

Last, the human-health particulate impact potential (Figure 7) shows environmental hotspots that are different from the other four impact categories. Two hotspots are identified: the use phase (B2 & B4) and the beyond-building-life phase (D). The use phase includes maintenance, repair, and replacement, which is mostly related to the building products and assemblies' quality and use condition. The different levels of retrofit could effectively reduce the impact by 19% (baseline retrofit), 24% (moderate retrofit), and 48% (deep retrofit), respectively, in both hotspots. The impact generated from the use

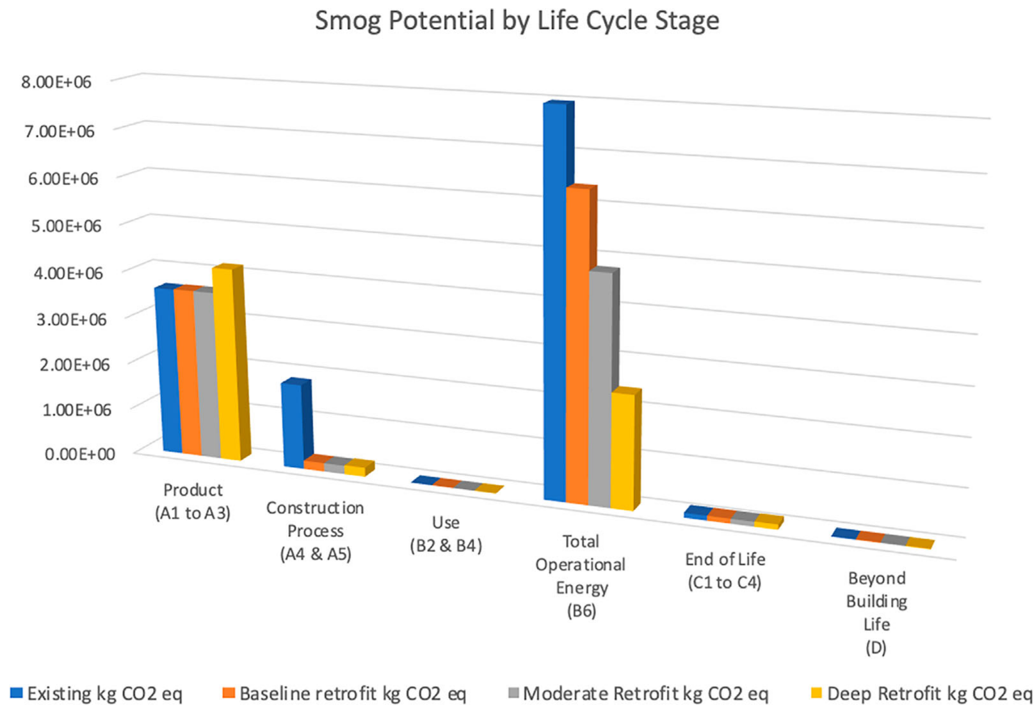

Figure 3. Smog formation potential reduction comparison of energy-retrofit strategies (SP, GWP, AP).

phase could be mitigated by the selection of higher-quality products with a longer use lifespan or products that require less maintenance and repair. The other potential mitigation strategy could be employing low-impact and sustainable maintenance techniques.

Environmental payback time

The net environmental benefits of energy-efficiency retrofits largely rely on the environmental impacts avoided due to the reduced energy use. This benefit is evaluated using Equation A mentioned above. Table 5 shows the payback time for each impact category for the three levels of energy retrofit. The deep retrofit has a much shorter payback time, 8–16 years, compared to the baseline retrofit and the moderate retrofit. When operation of the building is considered for all three retrofit levels, the payback time is over 100 years in the four impact categories for the baseline retrofit, less than or equal to 52 years in all categories for the moderate retrofit, and less than or equal to 16 years for the deep retrofit. Particularly in the smog-formation potential category, the upfront investment of a deep retrofit could be offset by the reduction of the impact in 8 years. The large difference between the payback time of a deep retrofit and a basic or moderate retrofit is related to the net annual environmental impact avoidance. The avoidant environmental impact is derived from operational energy saving through deep energy-retrofit techniques. According to equation A, although a deep retrofit would add some additional embodied energy and related impact, the avoided environmental impact during the operational phase still outweighs the added impact, which leads to a shorter payback time. For the baseline retrofit, there is essentially no cost-effective environmental impact reduction since the typical building lifespan is around 40–60 years. After 100 years, most buildings would be demolished or renovated with an additional environment impact that would need to be factored into the calculation. For the deep retrofit, the shortest payback time is 8 years for SP, and the longest payback time is 16 years for GWP. It is necessary to note here that the major difference between the moderate retrofit and the deep retrofit is the building envelope upgrades. For the deep retrofit, additional insulation is added in the roof and the building exterior walls.

In summary and as expected, the results for all impact categories except ozone-depletion potential indicate that a deep energy retrofit is advantageous over the baseline and moderate energy retrofits by virtue of its shorter environmental payback time. One can assume that the higher upfront cost is inversely proportional to the payback time, that is, the higher initial retrofit cost results in a faster payback. This could be very useful information for policymakers and decision-makers to consider.

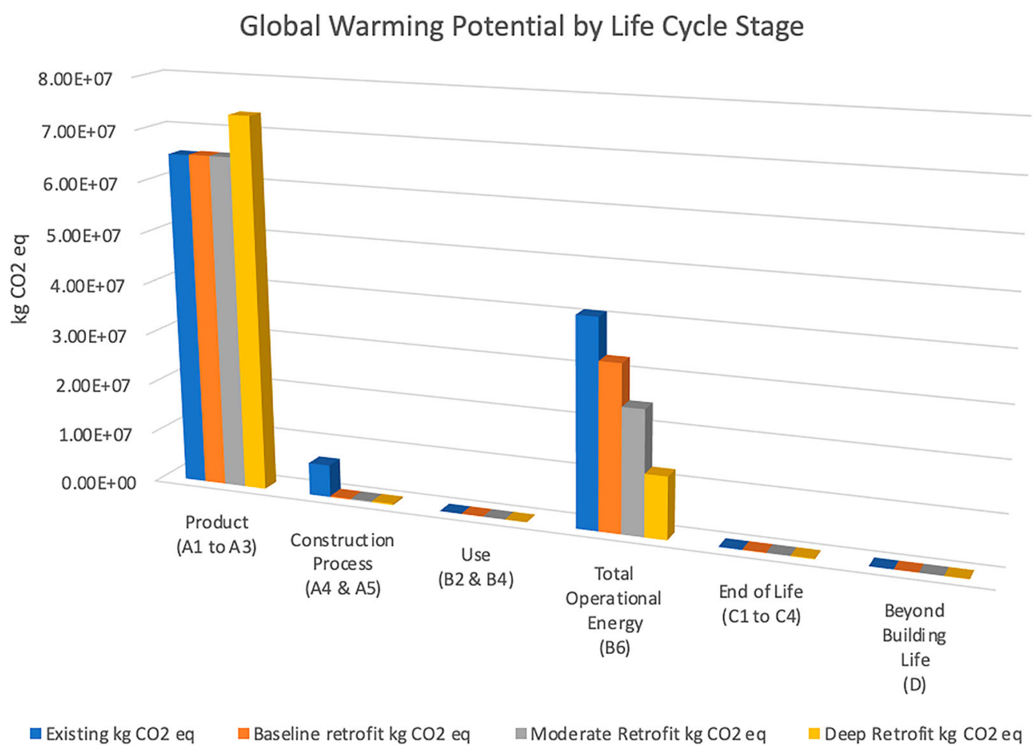

Figure 4. Global warming potential reduction comparison of energy-retrofit strategies.

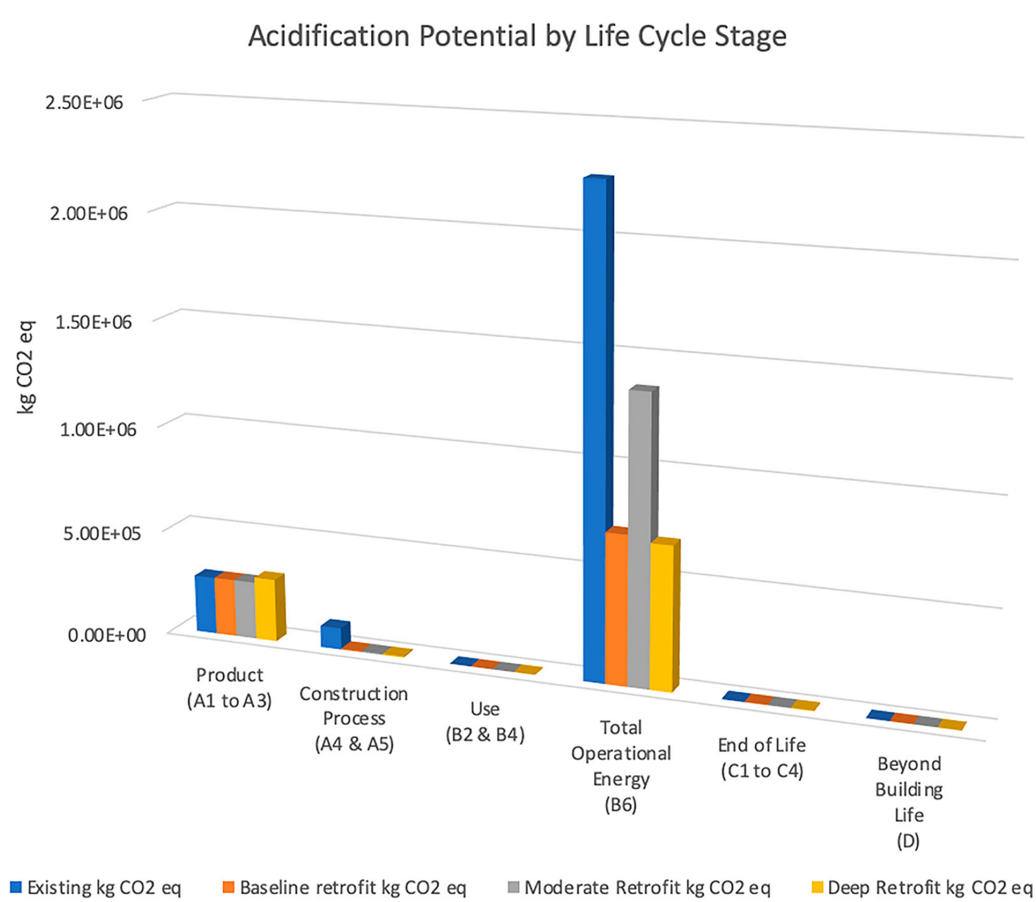

Figure 5. Acidification potential reduction comparison of energy-retrofit strategies.

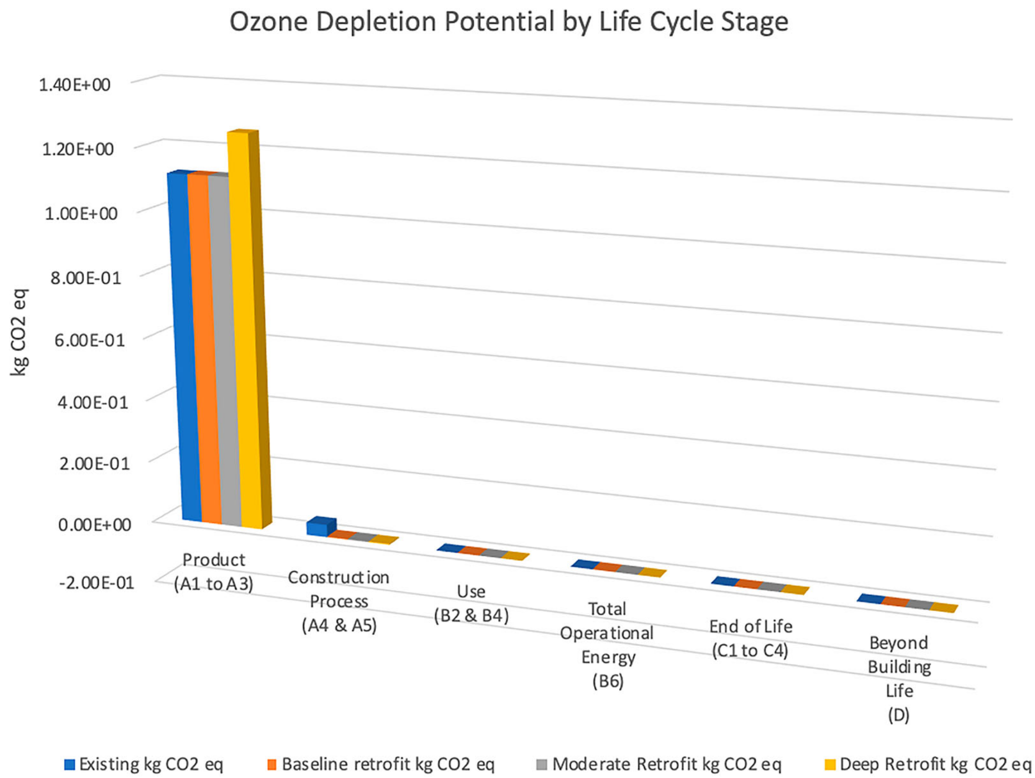

Figure 6. Ozone-depletion potential reduction comparison of energy retrofit.

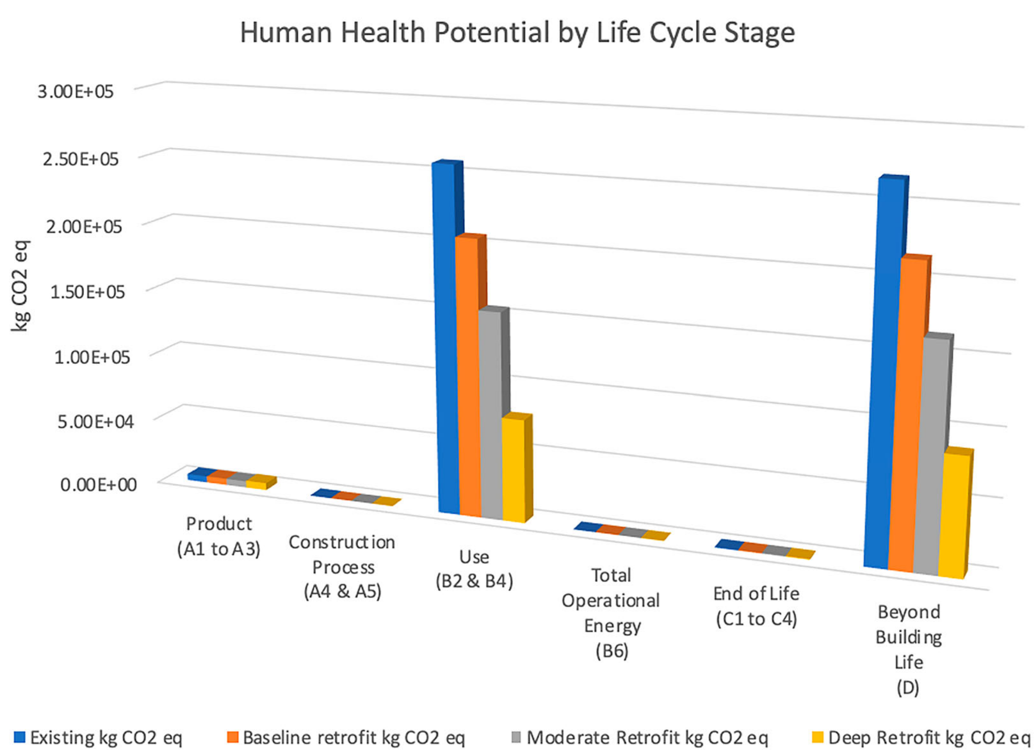

Figure 7. Human-health particulate potential reduction comparison of energy retrofit.

Table 5. Payback time for different levels of retrofit.

Environmental impact categories	Payback time (years)		
	Baseline retrofit	Moderate retrofit	Deep retrofit
Global Warming (GWP)	158	52	16
Smog (SG)	129	50	8
Acidification (ACID)	121	46	13
Human Health (HH)	123	47	14

Discussion

Environmental impact hotspots during life-cycle: contributors and mitigation strategies

Some trends emerge from this study: the product phase impact is more critical to GWP and ozone-depletion potential. The operational phase is influential regarding smog-formation potential and AP. For HHP potential, the use phase and beyond-building-service-life phase play equally important roles.

The first hotspot we want to focus on is the product phase. In general, the negative impact during the product phase and the use phase is not correlated with a building energy-efficiency increase. It is mainly associated with the building materials and products, especially the insulation materials used on the building envelope. Those materials include, among others, insulation materials, insulated exterior window and door units, and LED lighting. The modern energy-intensive materials might help reduce overall building operational energy consumption. However, the increase in building operational efficiency does not automatically lead to an environmental-impact reduction, particularly in the product phase. The deep retrofit even has a slightly higher impact in ozone-depletion potential, SP, and GWP. The impact could be mitigated through the use of low-impact and less-energy-intensive materials and products. Also, appropriate maintenance and operation could prolong the service life of building materials and products as well. In order to reduce the impact during the product phase, a potentially more effective way would be to revise the manufacturing process and techniques. For instance, Segovia, Blanchet, Amor, Barbuta, and Beauregard (2019) studied and compared the manufacturing of wood aluminium-lamented panels and aluminium honeycomb panels and found the wood aluminium-lamented panels to have a lower environment impact yet the same strength (Segovia et al., 2019).

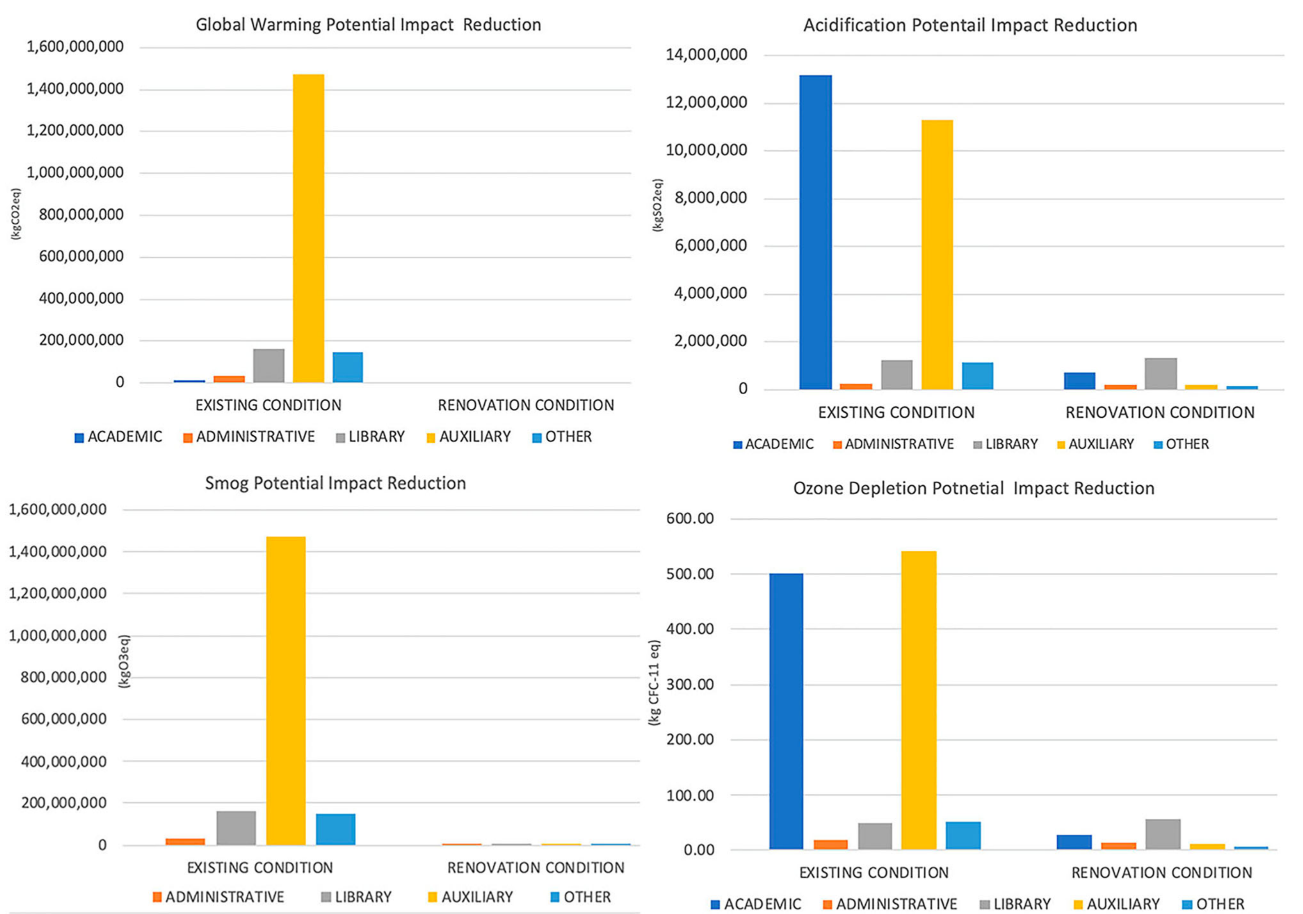

Figure 8. Comparison of environmental-impact reductions for existing and retrofit conditions.

On the other hand, extreme weather could accelerate the aging of building materials and products and consequently result in more frequent repair and replacement. Therefore, one can assume that climate change could indirectly worsen the environmental impact from buildings through their wear and tear.

When we look closely into the primary contributors (building materials) in each of the environmental-impact categories, some patterns are identified. AP is mainly associated with the use of concrete, which accounts for 60% of the impact. Brick masonry follows as the secondary contributor to AP, around 20%. The rest of the building materials and products together account for the remaining 20%. This breakdown is applicable to the majority of buildings on campus since there is a strong building tradition of using masonry construction in this region. Regarding ozone-depletion potential, the primary contributor is concrete as well. The secondary contributor is related to thermal and moisture protection, insulation, and moisture barriers. These two contributors together account for more than 95% of the ozone-depletion impact. Smog impact and GWP are mainly related to the use of concrete, masonry brick, and window frames and glazing.

The secondary hotspot in the environmental impact is the operational phase, which is associated with the energy spent during the building's operation. This result is expected since the operational phase accounts for the majority of time in the whole-building life-cycle (Stephan & Crawford, 2016). A building energy retrofit in this phase is more effective in reducing SP and GWP. For ozone-depletion potential, it appears that the impact overwhelmingly depends on the building material choices. Therefore, an energy-use reduction does not have any obvious benefit. In general, energy retrofits contribute to an environmental-impact reduction in all categories except ozone depletion, and the deep retrofit sees a much higher environmental-impact reduction in those categories, more than 50%. Continuous energy-efficiency improvements could help mitigate the environmental impact from the building industry during the operational phase.

Viability of retrofit strategies in offsetting environmental impacts on a campus level

The results for the retrofitted campus are based on the data presented in the previous sections and compared against the condition in which no retrofits happen on campus in the next 40 years. The results presented in Figure 8 indicate that the retrofit strategy is a viable solution to reduce the buildings' environmental impact in four environmental categories – GWP, smog-formation potential, AP, and ozone-depletion potential – and in most building types except the Library type. The retrofit is a particular effective strategy for Auxiliary buildings, where the reduction rate is 100%, 98%, 98%, and 98% for the four categories, respectively. The Academic building type also has 95% impact reductions in all categories. Academic buildings and Auxiliary buildings together account for 87% of the total building area on campus (Table 1). The higher reduction from Academic buildings and Auxiliary buildings offsets the lower impact reduction from other building types such as Library and Other Non-academic. Therefore, the energy retrofit could be considered to be an effective environmental-impact and climate-change mitigation strategy on an urban scale – in this case, for the entire campus.

The five different building typologies on campus have different energy profiles. The Academic buildings and Auxiliary buildings have a much higher percentage energy use due to heat loss and gain through the building envelope. Therefore, the deep retrofit concentrating on the building envelope sees a much higher impact reduction.

Due to the very long payback time for the baseline retrofit and the much shorter payback time for the deep retrofit, this assumption can be made: If the initial higher cost of the deep retrofit could be managed, then the deep retrofit could be considered a very viable option for an energy retrofit as well as an environmental-impact mitigation solution for a large-scale project. An additional life-cycle cost study could be conducted to verify this assumption.

Comparison of results with existing studies

In positioning this study in the context of existing literature that connects energy retrofit to environmental impact, a few studies were found. The environmental impact category GWP was chosen for consideration as it was the most frequently reported impact category (Ghose et al., 2017). Ghose et al. (2017) studied an office building in New Zealand; their findings of GWP payback periods vary from 12 years to 17 years for three different scenarios, and support the effectiveness of deep energy renovation over regular renovation to reduce GWP (Ghose et al., 2017). Dutil, Rousse, and Quesada (2011) conducted a review of a variety of building materials and renovation strategies, and found a minimal 10-year environmental payback period for typical building products, and the GWP reduction is highly dependent on the energy input (meaning how the energy consumed as a building is constructed) (Dutil et al., 2011). Other even shorter GWP payback periods were found in other studies. Ardente et al. (2011) studied six public buildings in the Czech Republic, and found the retrofit actions involve about a 50% energy saving, and the environmental impact due to renovation actions are fully repaid by the obtained benefits in a short period (Ardente et al., 2011). The longest payback time for individual building components is 31.9 years, for building insulation, while the shortest payback time is 0.1 year for Low-e windows (Ardente et al., 2011). The difference in the results could be induced by a variety of reasons: building types, location, and operational schedule, among others. There is not sufficient evidence to support explanations for the differences; therefore, further similar studies will be necessary and helpful. Despite the differences, it is useful to point out that certain findings are consistent with existing literature regarding individual buildings. For example, the product and operational stages are identified as two hot spots, and the use of insulation in the building envelope has shown significance in several environmental impact categories. Moreover, although the results of the environmental payback calculation in previous studies were different, ranging from 0.6 to 31 years (Stephan & Crawford, 2016), their conclusions support the results of this case study, which is that the deep energy retrofit could be a climate change mitigation strategy. Säynäjoki, Heinonen, and Junnila (2012) calculated the payback time of a large-scale residential project in Northern Europe to assess the overall life-cycle greenhouse gas emission. Their study suggests that the carbon payback time of constructing new residential areas is several decades long, even when using very energy-efficient buildings compared to utilizing current building stock (Säynäjoki et al., 2012). Therefore, constructing new energy-efficient buildings cannot be used as a means to achieve long-term climate change mitigation goals, as is often perceived (Säynäjoki et al., 2012). Besides the GWP reduction, there are other environmental impact reductions from an energy retrofit. For AP, the baseline retrofit reduces the potential by 20%, the moderate retrofit 40%, and the deep retrofit 69%. For smog formation potential, compared to existing conditions, the baseline retrofit reduces the potential 19%, the moderate retrofit 37%, and the deep retrofit 80%. For HHP potential, the baseline retrofit reduces potential 20% compared to existing conditions, the moderate retrofit 39%, and the deep retrofit 68%.

Despite the difference, while most of the existing literature has focused on individual commercial offices, public buildings, and residential buildings, this case study investigated campus-scale building blocks that included five different building types. The results of the study also further validate the conclusions that deep renovating an existing building seems to be a significantly better option than baseline renovation.

Limitations

The findings of this study are limited as the results are mainly derived from one case study. This study investigated one campus located in a moderate climate condition, and most building types on the campus have similar construction types and materials whereas diverse construction types and materials could alter the effectiveness of retrofitting strategies. Consequently, we cannot generalize the findings for other campuses, urban blocks, or building blocks that use different construction materials and methods and renovation strategies in varying locations and climate conditions. Further studies of diverse construction types, building function, location and climate condition could contribute to a better understanding of the environmental benefits of an energy retrofit. More cases are needed to verify the findings and generalize the conclusions. For example, the findings from this case study indicate that a retrofit is a particularly effective strategy for auxiliary buildings. Further sensitivity analysis will be useful to identify whether this particular building type could be used as a major indicator for the viability of retrofit strategies.

The second limitation is related to the environmental hot spots identified in this study. The first hot spot is associated with the building materials and products, especially the insulation materials used in the building envelope, which has a significant impact on global warming and the ODP. Studies and comparisons of different insulation materials can investigate the effects of insulation materials and hence find appropriate solutions. Another environmental impact hot spot identified was the operational stage, associated with the use of energy. There are a variety factors that can influence energy use that were not included as considerations in this study, such as user behaviour and site energy infrastructure. Other research projects found that the cumulative environmental impact (global warming, acidification, smog, etc.) is largely driven by the share of fossil fuels in the local and regional energy mix for the energy supply (Huijbregts et al., 2010; Stephan & Crawford, 2016). Conducting a sensitivity study will be helpful to understand, verify, and compare this case study to others.

The third limitation is the software used in the study. The accuracy of BIM models is dependent on the accuracy of the initially construction document and accurate documentation for each of the renovations that took place between initial building completion and the present day. To create a pre-existing (or as-built) BIM model from scratch, geometrical and topological information of buildings elements has to be gathered, modelled, and complemented by building property information manually (Volk, Stengel, & Schultmann, 2014). Many existing buildings on campus have insufficient pre-existing building property/attribute information; therefore, during the modelling process, it is necessary to make certain assumptions that could affect the accuracy of the model and subsequent LCA. Besides BIM, the project employed the Athena database to calculate the energy used to construct or install the building components onsite and the related environmental impact. In the future, calculating the impact using other, larger LCI databases and comparing the differences will help to produce more accurate results.

The fourth limitation is the exclusion of human factors, as occupant behaviour could have an impact on retrofit strategy selection and energy consumption. In future studies, the human factor could be included in the model to understand the level of impact of occupant behaviour.

Conclusion

The findings from this study provide insights for the ongoing discussion of the importance and validity of energy retrofitting as a climate-change mitigation strategy. In addition, this case study provides one more case that demonstrates how the LCA could be applied on a large scale. There were four main conclusions arising from this research:

(1) This research project compares three level of energy retrofit against existing condition. The analysis results show that energy retrofits could contribute more than a 50% reduction to the environmental impact in four categories – GWP, AP, SP, and HHP – on a campus scale. The assessment results do not show any noticeable impact reduction in ODP.
(2) ODP showed a slight uptick in impact in the three energy-retrofit scenarios. The potential cause might be related to the HVAC system upgrade. The increase in environmental impact needs further investigation.
(3) The study compares the environmental payback time for three levels of energy retrofit, and the results reveal that the deep energy retrofit has a significantly shorter payback time compared to the baseline retrofit and the moderate retrofit.
(4) The first common environmental hotspot for GWP, SP, AP, and ODP is the product phase, which includes building raw materials selection, extraction, and manufacturing. This impact could be mitigated through selecting more sustainable and low-impact materials or local materials that require less transportation. The second common hotspot is the operational phase, which could be mitigated by reducing operational energy consumption.

Overall, this study provides new evidence for the importance of understanding the link between energy retrofit and environmental reductions. The findings demonstrate the potential higher front cost of deep retrofit could be offset by shorter environmental payback time. The outcome reinforces the importance of considering appropriate retrofit strategies from life-cycle perspective.

Note

1. Serviceable lifespan is different from the building physical life span, physical life span is the building's physical condition, the serviceable life span is referring to the usefulness of building type and function.

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Appendix. Prototype building's thermal property for retrofit energy model

Energy model framework (auxiliary building)			
Envelope property	***U*-value**	**Ratio**	
Exterior wall	1.42 W/(m^2·K)		
Roof	1.88 W/(m^2·K)		
Floor	2.50 W/(m^2·K)		
Exterior window/door	7.3 W/(m^2·K)		
Wall-to-window ratio		40%	
Infiltration rate			1.97 L/s·m^2
Operation			
Temperature setpoint	Heating		20°C
	Cooling		25°C
Setback temperature	Heating		12°C
	Cooling		28°C
Operation hour	8 am–6 pm		
Density	Occupant density		4.0 m^2/person
	Equipment power density		9.7 W/m^2
	Lighting power density		15.1 W/m^2
Time steps			1 h
HVAC System	Heating efficiency		0.85
	Cooling efficiency		3
	Ventilation rate		0.3 L/s·m^2

Energy model framework (library building)			
Envelope property	***U*-value**	**Ratio**	
Exterior wall	1.42 W/(m^2·K)		
Roof	1.88 W/(m^2·K)		
Floor	2.50 W/(m^2·K)		
Exterior window/door	7.3 W/(m^2·K)		
Wall-to-window ratio		20%	
Infiltration rate			1.97 L/s·m^2
	Operation		
Temperature setpoint	Heating		20°C
	Cooling		25°C
Setback temperature	Heating		14°C
	Cooling		30°C
Operation hour	8 am–6 pm		
Density	Occupant density		8.0 m^2/person
	Equipment power density		9.7 W/m^2
	Lighting power density		12.0 W/m^2
Time steps			1 h
HVAC system	Heating efficiency		0.85
	Cooling efficiency		3
	Ventilation rate		0.3 L/s·m^2

Energy model framework (academic building)			
Envelope property	***U*-value**	**Ratio**	
Exterior wall	1.42 W/(m^2·K)		
Roof	1.88 W/(m^2·K)		
Floor	2.50 W/(m^2·K)		
Exterior window/door	7.3 W/(m^2·K)		
Wall-to-window ratio		30%	
Infiltration rate			1.97 L/s·m^2
	Operation		
Temperature setpoint	Heating		20°C
	Cooling		25°C
Setback temperature	Heating		12°C
	Cooling		28°C
Operation hour	8 am–6 pm		
Density	Occupant density		8.0 m^2/person
	Equipment power density		9.7 W/m^2
	Lighting power density		12.0 W/m^2
Time steps			1 h
HVAC system	Heating efficiency		0.80
	Cooling efficiency		3
	Ventilation rate		0.3 L/s·m^2

Energy model framework (Administrative building)			
Envelope property	*U*-value	Ratio	
Exterior wall	1.42 W/(m^2·K)		
Roof	1.88 W/(m^2·K)		
Floor	2.50 W/(m^2·K)		
Exterior window/door	7.3 W/(m^2·K)		
Wall-to-window ratio		30%	
Infiltration rate			1.97 L/s·m^2
	Operation		
Temperature setpoint	Heating		20°C
	Cooling		25°C
Setback temperature	Heating		12°C
	Cooling		28°C
Operation hour	8 am–6 pm		
Density	Occupant density		8.0 m^2/person
	Equipment power density		9.7 W/m^2
	Lighting power density		12.0 W/m^2
Time steps			1 h
HVAC system	Heating efficiency		0.80
	Cooling efficiency		3
	Ventilation rate		0.3 L/s·m^2