The Greenest Building: Quantifying the Environmental Value of Building Reuse

A REPORT BY:

Preservation Green Lab
NATIONAL TRUST FOR HISTORIC PRESERVATION

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CASCADIA GREEN BUILDING COUNCIL

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ABOUT THE PROJECT PARTNERS

This research was made possible by a generous grant from the Summit Foundation to the National Trust for Historic Preservation. The project was coordinated by the Preservation Green Lab, a programmatic office of the National Trust.

PRESERVATION GREEN LAB

(www.preservationnation.org/issues/sustainability/green-lab/)
Launched in March of 2009, the Seattle-based Preservation Green Lab advances research that explores the value that older buildings bring to their communities, and pioneers policy solutions that make it easier to reuse and green older and historic buildings. The Green Lab seeks to minimize carbon impacts from the built environment through direct emissions reductions from older building retrofits and reuse, and to conserve character-rich and human-scale communities that attract people to more sustainable, urban living patterns.

CASCADIA GREEN BUILDING COUNCIL

(www.cascadiagbc.org)
Cascadia, the leading green building organization in the Pacific Northwest, is dedicated to making deep and lasting change within the building industry for positive environmental impact. A chapter of both the U.S. and Canada Green Building Councils, Cascadia is a cross-border education, research and advocacy organization that brings a bioregional approach to problem solving and market transformation. Cascadia is housed within the International Living Future Institute (ILFI), a U.S.-based NGO committed to catalyzing a global transformation toward true sustainability.

GREEN BUILDING SERVICES

(www.greenbuildingservices.com)
Green Building Services (GBS) is a recognized leader in the global green building movement. Since 2000, GBS has provided consulting services to major corporations, institutions, developers and design professionals domestically and abroad. From individual buildings, to portfolios of buildings, new construction or existing facilities, GBS expertise spans the entire life cycle of the built environment. GBS consultants provide innovative solutions that benefit the triple bottom line including facilitation, training, LEED project management, energy audits, energy modeling, daylight analysis and commissioning.

SKANSKA

(usa.skanska.com)
Skanska USA is one of the largest, most financially sound construction networks in the country serving a broad range of industries including healthcare, education, sports, data centers, government, aviation, transportation, and water/wastewater. Headquartered in New York with 35 offices across the country, Skanska USA employs approximately 7,000 employees who are committed to sustainable construction and an injury-free workplace.

QUANTIS

(www.quantis-intl.com)
Quantis is a leading life cycle assessment (LCA) consulting firm specialized in supporting companies to measure, understand and manage the environmental impacts of their products, services and operations. Quantis is a global company with offices in the United States, Canada, Switzerland and France and employs close to 70 people, amongst which several are internationally renowned experts in the LCA field.

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INDEX OF TERMS

BTU: BRITISH THERMAL UNIT

CO_2: CARBON DIOXIDE

DOQ: OREGON DEPARTMENT OF ENVIRONMENTAL QUALITY

EEM: ENERGY EFFICIENCY MEASURE

EOL: END-OF-LIFE

EIA: US ENERGY INFORMATION ADMINISTRATION

EPA: US ENVIRONMENTAL PROTECTION AGENCY

EUI: ENERGY USE INTENSITY

GHG: GREENHOUSE GAS EMISSIONS

ICE: INVENTORY OF CARBON EMISSIONS

ISC: INTERNATIONAL ORGANIZATION FOR STANDARDIZATION

LCA: LIFE CYCLE ASSESSMENT

MJ: MEGAJOULE

NC: NEW CONSTRUCTION

RECS: RESIDENTIAL ENERGY CONSUMPTION SURVEY

RR: REHABILITATION AND RETROFIT

WH: WAREHOUSE

EXECUTIVE SUMMARY

Until now, little has been known about the climate change reductions that might be offered by reusing and retrofitting existing buildings rather than demolishing and replacing them with new construction. This groundbreaking study concludes that building reuse almost always offers environmental savings over demolition and new construction. Moreover, it can take between 10 and 80 years for a new, energy-efficient building to overcome, through more efficient operations, the negative climate change impacts that were created during the construction process. However, care must be taken in the selection of construction materials in order to minimize environmental impacts; the benefits of reuse can be reduced or negated based on the type and quantity of materials selected for a reuse project.

This research provides the most comprehensive analysis to date of the potential environmental impact reductions associated with building reuse. Utilizing a Life Cycle Analysis (LCA) methodology, the study compares the relative environmental impacts of building reuse and renovation versus new construction over the course of a 75-year life span. LCA is an internationally recognized approach to evaluating the potential environmental and human health impacts associated with products and services throughout their respective life cycles.[1] This study examines indicators within four environmental impact categories, including climate change, human health, ecosystem quality, and resource depletion. It tests six different building typologies, including a single-family home, multifamily building, commercial office, urban village mixed-use building, elementary school, and warehouse conversion. The study evaluates these building types across four U.S. cities, each representing a different climate zone, i.e., Portland, Phoenix, Chicago, and Atlanta. A summary of life cycle environmental impacts of building reuse, expressed as a percentage of new construction impacts, is shown in the following figure (Summary of Results).

This research provides the most comprehensive analysis to date of the potential environmental impact reductions associated with building reuse.

KEY FINDINGS AND ANALYSIS

BUILDING REUSE ALMOST ALWAYS YIELDS FEWER ENVIRONMENTAL IMPACTS THAN NEW CONSTRUCTION WHEN COMPARING BUILDINGS OF SIMILAR SIZE AND FUNCTIONALITY.[2]

The range of environmental savings from building reuse varies widely, based on building type, location, and assumed level of energy efficiency. Savings from reuse are between 4 and 46 percent over new construction when comparing buildings with the same energy performance level. The warehouse-to-multifamily conversion – one of the six typologies selected for study – is an exception: it generates a 1 to 6 percent greater environmental impact relative to new construction in the ecosystem quality and human health impact categories, respectively.[3] This is due to a combination of factors, including the amount and types of materials used in this project.

ENVIRONMENTAL IMPACTS OF RENOVATION AS A PERCENTAGE OF NEW CONSTRUCTION

Legend

- New Construction (represents 100%)
- Rehabilitation + Retrofit in: Chicago, Atlanta, Phoenix, Portland

Impact Category	Case	City	Commercial Office	Warehouse to Office	Mixed-Use	Elementary School	Single-Family	Multifamily	Warehouse to Multifamily
Climate Change	Base Case	Chicago	-9%	-5%	-16%	-7%	-10%	-9%	-7%
		Atlanta	-10%	-5%	-17%	-7%	-11%	-10%	-7%
		Phoenix	-12%	-6%	-19%	-8%	-11%	-11%	-8%
		Portland	-13%	-7%	-21%	-10%	-12%	-11%	-8%
	Advanced Case	Chicago	-12%	-7%	-20%	-9%	-15%	-12%	-11%
		Atlanta	-13%	-7%	-20%	-9%	-16%	-13%	-12%
		Phoenix	-14%	-8%	-23%	-10%	-16%	-14%	-13%
		Portland	-16%	-9%	-25%	-12%	-17%	-14%	-13%
Resource Depletion	Base Case	Chicago	-8%	-4%	-15%	-7%	-10%	-9%	-6%
		Atlanta	-9%	-4%	-15%	-7%	-10%	-9%	-6%
		Phoenix	-10%	-5%	-18%	-8%	-11%	-11%	-7%
		Portland	-12%	-6%	-20%	-9%	-11%	-10%	-7%
	Advanced Case	Chicago	-11%	-5%	-18%	-9%	-15%	-12%	-9%
		Atlanta	-11%	-6%	-19%	-9%	-16%	-12%	-9%
		Phoenix	-13%	-7%	-22%	-10%	-17%	-14%	-10%
		Portland	-15%	-8%	-24%	-12%	-17%	-13%	-10%
Human Health	Base Case	Chicago	-15%	-7%	-33%	-9%	-21%	-17%	+6%
		Atlanta	-14%	-6%	-29%	-7%	-18%	-14%	+5%
		Phoenix	-12%	-5%	-26%	-6%	-14%	-12%	+4%
		Portland	-15%	-7%	-30%	-8%	-19%	-15%	+5%
	Advanced Case	Chicago	-15%	-9%	-38%	-11%	-26%	-20%	+5%
		Atlanta	-14%	-8%	-34%	-9%	-23%	-18%	+5%
		Phoenix	-12%	-7%	-31%	-7%	-19%	-15%	+4%
		Portland	-14%	-8%	-35%	-10%	-24%	-18%	+5%
Ecosystem Quality	Base Case	Chicago	-20%	-7%	-34%	-11%	-29%	-24%	+1%
		Atlanta	-20%	-7%	-34%	-10%	-28%	-23%	+1%
		Phoenix	-24%	-8%	-41%	-11%	-30%	-27%	+1%
		Portland	-27%	-9%	-44%	-13%	-33%	-30%	+1%
	Advanced Case	Chicago	-14%	-8%	-39%	-12%	-32%	-28%	-1%
		Atlanta	-14%	-8%	-38%	-11%	-31%	-27%	-1%
		Phoenix	-16%	-9%	-44%	-13%	-33%	-31%	-1%
		Portland	-17%	-10%	-46%	-14%	-35%	-33%	-1%

A full description of each impact category and the methods used to evaluate them is located in the *Technical Appendices*. Base Case = average energy performance; see Section 4 on methodology for determining energy use. Advanced Case = 30% more efficient than Base Case.

Reuse-based impact reductions may seem small when considering a single building. However, the absolute carbon-related impact reductions can be substantial when these results are scaled across the building stock of a city. For example, if the city of Portland were to retrofit and reuse the single-family homes and commercial office buildings that it is otherwise likely to demolish over the next 10 years, the potential impact reduction would total approximately 231,000 metric tons of CO_2 – approximately 15% of their county's total CO_2 reduction targets over the next decade.[4] When scaled up even further to capture the potential for carbon reductions in other parts of the country, particularly those with a higher rate of demolition, the potential for savings could be substantial. Given these potential savings, additional research and analysis are needed to help communities design and employ public-policy tools that will remove obstacles to building reuse.

REUSE OF BUILDINGS WITH AN AVERAGE LEVEL OF ENERGY PERFORMANCE CONSISTENTLY OFFERS IMMEDIATE CLIMATE-CHANGE IMPACT REDUCTIONS COMPARED TO MORE ENERGY-EFFICIENT NEW CONSTRUCTION.

It is often assumed that the CO_2-reduction benefits gained by a new, energy efficient building outweigh any negative climate change impacts associated with the construction of that building. This study finds that it takes 10 to 80 years for a new building that is 30 percent more efficient than an average-performing existing building to overcome, through efficient operations, the negative climate change impacts related to the construction process.[5] As indicated in the following table, an exception also exists here for the warehouse-to-multifamily building conversion. Upon analysis, this adaptive use scenario does not offer the carbon savings provided by other reuse scenarios.

This study finds that it takes 10 to 80 years for a new building that is 30 percent more efficient than an average-performing existing building to overcome, through efficient operations, the negative climate change impacts related to the construction process.[5]

Building reuse alone cannot fulfill the urgent task of reducing climate change emissions. The summary of results of this study, shown on the previous page, documents how reuse and retrofitting for energy efficiency, together, offer the most significant emissions reductions in the categories of climate change, human health, and resource impact. Certainly, the barriers to retrofits are numerous. However, a variety of organizations are presently working to address the obstacles to greening existing buildings. This study finds that reuse and retrofit are particularly impactful in areas in which coal is the dominant energy source and more extreme climate variations drive higher energy use.

MATERIALS MATTER: THE QUANTITY AND TYPE OF MATERIALS USED IN A BUILDING RENOVATION CAN REDUCE, *OR EVEN NEGATE,* THE BENEFITS OF REUSE.

In general, renovation projects that require many new materials – for example, an addition to an elementary school or the conversion of a warehouse to a residential or office use – offer less significant environmental benefits than scenarios in which the footprints or uses of the buildings remain unchanged. In the case of the warehouse-to-multifamily conversion scenario, the newly constructed building actually demonstrated fewer environmental impacts in the categories of ecosystem quality and human health.

Year Of Carbon Equivalency For Existing Building Reuse Versus New Construction

This study finds that it takes between 10 to 80 years for a new building that is 30 percent more efficient than an average-performing existing building to overcome, through efficient operations, the negative climate change impacts related to the construction process. This table illustrates the numbers of years required for new, energy efficient new buildings to overcome impacts.

Building Type	Chicago	Portland
Urban Village Mixed Use	42 years	80 years
Single-Family Residential	38 years	50 years
Commercial Office	25 years	42 years
Warehouse-to-Office Conversion	12 years	19 years
Multifamily Residential	16 years	20 years
Elementary School	10 years	16 years
Warehouse-to-Residential Conversion*	Never	Never

*The warehouse-to-multifamily conversion (which operates at an average level of efficiency) does not offer a climate change impact savings compared to new construction that is 30 percent more efficient. These results are driven by the amount and kind of materials used in this particular building conversion. As evidenced by the study's summary of results, as shown on page VII, the warehouse-to-residential conversion does offer a climate change advantage when energy performance for the new and existing building scenarios are assumed to be the same. This suggests that it may be especially important to retrofit warehouse buildings for improved energy performance, and that care should be taken to select materials that will maximize environmental savings.

Although warehouse conversions and school additions require more material inputs than other types of renovation projects, reusing these buildings is still more environmentally responsible – in terms of climate change and resource impacts – than building anew, particularly when these buildings are retrofitted to perform at advanced efficiency levels. Better tools are needed to aid designers in selecting materials with the least environmental impacts. Such resources would benefit new construction and renovation projects alike.

Warehouse conversions and school additions require large materials inputs, however reusing these buildings still has lower climate change and resource impacts.

STUDY OBJECTIVES AND APPROACH

Every year, approximately 1 billion square feet of buildings are demolished and replaced with new construction in the United States.[6] The Brookings Institution projects that some 82 billion square feet of existing space will be demolished and replaced between 2005 and 2030 – *roughly one-quarter of today's existing building stock.*[7] Yet, few studies to date have sought to examine the environmental impacts of razing old buildings and erecting new structures in their place. In particular, the climate change implications of demolition and new construction, as compared to building renovation and reuse, remain under-examined.

Although awareness about the need to reduce near-term climate change impacts is growing, a greater understanding of the potential environmental savings that can be offered by reusing existing buildings rather than developing new buildings is still needed. This study compares the environmental impacts of building demolition and new construction relative to building renovation and reuse. The study has three key objectives:

- To compute and compare the life-cycle environmental impacts of buildings undergoing rehabilitation to those generated by the demolition of existing buildings and their replacement with new construction;
- To determine which stage of a building's life (i.e. materials production, construction, occupancy) contributes most significantly to its environmental impacts, *when* those impacts occur, and what drives those impacts; and
- To assess the influence of building typology, geography, energy performance, electricity-grid mix, and life span on environmental impacts throughout a building's life cycle.

In examining these themes, the authors consider potential opportunities to reduce carbon emissions and other negative environmental impacts through building reuse and explore how differences in building type, climate, and energy-efficiency levels affect these opportunities.

This research is intended to serve as a resource for those who influence and shape the built environment, including policy makers, building owners, developers, architects, engineers, contractors, real estate professionals, and non-profit environmental, green building and preservation advocacy groups. To that end, the study identifies key environmental considerations and challenges related to new construction, retrofits and reuse. Findings from this study should be considered in light of the myriad realities that affect development decisions, such as building codes, zoning, financing, demographics, and design trends.

Each year, approximately 1 billion square feet of buildings are demolished and replaced with new construction.

CONCLUSIONS

For those concerned with climate change and other environmental impacts, reusing an existing building and upgrading it to maximum efficiency is almost always the best option regardless of building type and climate. Most climate scientists agree that action in the immediate timeframe is crucial to stave off the worst impacts of climate change. Reusing existing buildings can offer an important means of avoiding unnecessary carbon outlays and help communities achieve their carbon reduction goals in the near term.

Most climate scientists agree that action in the immediate timeframe is crucial to stave off the worst impacts of climate change. Reusing existing buildings can offer an important means of avoiding unnecessary carbon outlays and help communities achieve their carbon reduction goals in the near term.

This report sets the stage for further research that could augment and refine the findings presented here. Study results are functions of the specific buildings chosen for each scenario and the particular type and quantity of materials used in construction and rehabilitation. Great care was taken to select scenarios that would be representative of typical building reuse or conversion projects. However, environmental impacts will differ for building conversions that use different types and amounts of materials. Others are encouraged to repeat this research using additional building case studies; replicating this analysis will enhance our collective understanding of the range of impact differences that can be expected between new construction and building reuse projects.

This study introduces important questions about how different assumptions related to energy efficiency affect key findings. In particular, further research is needed to clarify how impacts are altered if a new or existing building can be brought to a net-zero level using various technologies, including renewable energy.

ABOUT THE PROJECT TEAM

This research was made possible by a generous grant from the Summit Foundation to the National Trust for Historic Preservation. The project was coordinated by the Preservation Green Lab, a programmatic office of the National Trust, which is dedicated to advancing research that explores the sustainability value of older and historic buildings and identifying policy solutions that help communities leverage their built assets. The project team includes Cascadia Green Building Council, Quantis LLC, Skanska, and Green Building Services.

ENDNOTES

1. Section 1 of this report explains Life Cycle Assessment (LCA) in greater detail.

2. Where energy performance for renovated and new buildings is assumed to be the same.

3. The warehouse-to-multifamily conversion required signi cantly more new materials than other reuse scenarios tested in this study. The table on page IX provides additional details.

4. Based on demolition rates between 2003-2011 provided by City of Portland Bureau of Planning and CO2 emission targets as outlined by the City of Portland and Multnomah County 2009 Climate Action Plan. Reduction in CO2 emissions assumes both the new and the existing buildings are considered to be of the same size and functionality.

5. In this study, energy-use gures for average-performing existing buildings, also known as the 'Base Case,' were established using national survey data and other recent research. More details are provided in Section 4 of the for the report. For purposes of this study, the term 'new, e cient buildings,' or the 'Advanced Case,' refers to new buildings that achieve 30 percent greater energy e ciency over Base Case energy performance.

6. National gures tracking demolition are out-of-date. However, a 1998 study by the U.S. Environmental Protection Agency (EPA) provides a sense of the annual scale of demolition nationwide; it estimates that approximately 925 million square feet of residential and nonresidential space were demolished in 1996. U.S. Environmental Protection Agency: O ce of Solid Waste, "Characterization of Building-Related Construction and Demolition Debris in the United States," EPA530-R-98-010. (Washington: U.S.Environmental Protection Agency, June 1998).

7. Arthur C. Nelson, "Toward a New Metropolis: The Opportunity to Rebuild America" (Washington: Brookings Institution, 2004).

1. INTRODUCTION

During the first decade of the 21st century, green building in the United States grew from a nascent movement into a mainstream phenomenon. Today, the nation's green building sector supports environmentally responsible and resource-efficient building design with the aim of reducing greenhouse gas emissions and other negative environmental impacts. During its short history, the sector has been particularly concerned with those impacts associated with the design and operation of buildings. This focus reflects an acute crisis within the U.S. construction industry; building operations account for approximately 41 percent of the nation's primary energy consumption, 72 percent of electricity consumption, 38 percent of carbon dioxide (CO_2) emissions, and 13 percent of potable water use.[1]

Though less understood, the extraction of natural resources for construction purposes and the production of building goods are also energy-intensive processes that release significant CO_2 emissions, among other negative impacts. While there is increasing discussion in various green building forums about the potential environmental benefit of reusing buildings, to date few studies have sought to quantify the differences between the environmental impacts of building reuse versus new construction. The handful of existing studies that explore this topic are of limited relevance to much of the U.S. building stock in several respects. First, dramatic changes in U.S. and global manufacturing, transportation, and building practices have rendered many older studies inapplicable in the modern context. Second, recent British and Canadian studies that otherwise offer relevant results lack U.S.-specific industry data for comparison. Third, many of these studies are inadequate in scope, addressing single buildings while overlooking potential differences across multiple building typologies.

To date few studies have sought to quantify the differences between the environmental impacts of building reuse versus new construction.

Thus, the existing body of research in this area provides relatively little instructive data and analysis on building reuse. Understanding the potential savings associated with reuse is of critical importance, since the demolition and replacement of buildings is a relatively common practice in the United States. While national figures tracking demolition are out-of-date, a 1998 study from the U.S. Environmental Protection Agency provides some sense of the annual scale of demolition in the United States. It estimates that approximately 925 million square feet of residential and nonresidential space were demolished in 1996.[2] The Brookings Institution estimates that significantly more square footage will be torn down in coming decades, projecting that upwards of 25 percent of our existing building stock – or 82 billion square feet – will be demolished and replaced between 2005 and 2030.[3]

The environmental impacts of this cycle of demolition and construction – and opportunities to gain carbon and other environmental savings through building reuse and retrofit – remain poorly understood. While some demolition and replacement will undoubtedly remain a necessity to meet contemporary needs, several questions persist: Are there significant opportunities to reduce carbon emissions by reusing buildings rather than constructing anew? Under what conditions is building reuse environmentally preferable to demolition and new construction? Do benefits differ by region and building type? Is it misguided to assume that the benefits of new "green" buildings will quickly overtake any negative environmental effects associated with new construction, due to their anticipated energy efficiency?

This study tackles these questions by comparing the relative environmental impacts of new construction to building reuse across different climate regions and building typologies. It is intended to serve as a resource for those who influence and shape the built environment, including policy makers, building owners, developers, architects, engineers, contractors, real estate professionals, and non-profit environmental, green building, and preservation advocacy groups. To that end, this report identifies key environmental considerations and challenges related to new construction, retrofits, and reuse. Findings from this study must be considered in light of myriad realities that affect development decisions, such as building codes, zoning, financing, demographics, and fashion.

This study is organized as follows:

- **Section 1** provides an introduction to the study and outlines key study questions;
- **Section 2** provides an overview of modern approaches to analyzing energy consumption by buildings;
- **Section 3** explains the life cycle assessment (LCA) approach to understanding the potential environmental impacts of buildings;
- **Section 4** describes the phases, scope, objectives, methodological framework, and data parameters for this study;
- **Section 5** features case studies of six different building typologies (single-family residential; multifamily residential; commercial office; urban village mixed use; elementary school; and warehouse); explains the normalization process applied in this study; and describes the application of energy efficiency measures (EEMs) to each building type;
- **Section 6** provides an overview of the results and key findings from the LCA study;
- **Section 7** analyzes the results and identifies further research needs; and
- **The Technical Appendices** describes the technical methods used in this study; it includes the full LCA results and assumptions, methodology for determining building energy usage, and bill of materials for each case study building used in the analysis.

LIFE CYCLE ASSESSMENT (LCA) AS A TOOL FOR UNDERSTANDING BUILDINGS AND ENVIRONMENTAL IMPACTS

Growing awareness of the environmental consequences associated with product creation and service delivery has sparked innovative methods for better understanding and proactively managing potential negative impacts. A leading tool for achieving this – and the only tool with the potential to fully evaluate all sources and types of impact – is life cycle assessment (LCA), a framework defined by the International Organization for Standardization (ISO) 14040-14044 standards (ISO 14040 2006; ISO 14044 2006).

This LCA study evaluates the numerous discrete actions related to materials manufacture, transport, construction, operation and the demolition and disposal of common building types. This analysis provides comparable data expressed in terms of environmental impact categories – such as climate change and human health impacts – with the aim of informing current understandings of the value of building reuse relative to new construction. The LCA framework enables an in-depth look at how key variables such as building life span and operating energy efficiency may affect the decision to reuse buildings versus build new.

THE INTERSECTION OF PRESERVATION AND ENVIRONMENTAL ADVOCACY

As the nation's premier advocacy organization for the conservation of older and historic buildings, the National Trust for Historic Preservation is particularly interested in understanding the environmental value that may be associated with building reuse. There are many compelling reasons to preserve a structure; it may tell a significant American story, serve as a tangible link to the past, or act as an economic engine within its community. However, aside from these cultural and economic values, environmental factors may also weigh in favor of building conservation. As communities around the country begin to take steps to reduce greenhouse gas emissions associated with buildings, it is increasingly important to understand the potential advantages and disadvantages of building reuse and retrofit.

Reuse and retrofit of existing buildings offers immediate opportunities to address climate change impacts.

2. UNDERSTANDING BUILDING ENERGY USE

Building development and operation involves significant energy consumption and has major environmental consequences. In order to effectively evaluate strategies for reducing energy use and minimizing environmental impacts, it is essential to understand the ways in which buildings use energy. Embodied energy, operating energy, and building transportation energy are three main categories of building-related energy consumption.

- *Embodied energy* is required to produce a building. It includes the up-front energy investment for extraction of natural resources, manufacturing, transportation, and installation of materials, referred to as *initial embodied energy. Recurring embodied energy* is needed over time to maintain, repair, or replace materials, components or systems during the life of a building.
- *Operating energy* is needed to operate a building and includes the energy required to heat, cool, and provide electrical services to a building over its life span.
- *Building transportation energy* is the energy utilized to transport occupants to and from a building.

Considerable focus is given in this study to the energy used in building operation and construction. For purposes of this analysis, however, transportation energy is assumed to be equal for both new construction and reuse scenarios and is not included in this evaluation. Section 7 discusses the importance of further research regarding building transportation energy, particularly as it relates to the benefits of added density to a site and reduced Vehicle Miles Traveled by occupants.

OPERATING ENERGY OF BUILDINGS

Operating energy is a prime factor in evaluating building-related energy impacts. As buildings continue to use more energy than ever before, accurate analyses of building operating energy and related impacts have become increasingly vital. In 2006, the operating energy of residential and commercial buildings in the United States constituted roughly 39 percent of total energy consumed nationwide, or about 39 quadrillion BTU – roughly the equivalent of 6.5 billion barrels of oil.[4]

The operating energy of buildings varies greatly. It is determined by building envelope and system performance, as well as building management and maintenance, occupant behavior and building life span. Thus, the ratio of buildings' annual operating energy to total embodied energy can diverge substantially – between 5:1 and 30:1.[5]

RESIDENTIAL BUILDINGS

Residential buildings, the most prevalent building type in the United States, are responsible for the largest portion of energy consumed by buildings nationwide. The parameters of energy use by residential buildings have changed substantially over the past three decades due to increases in house size and the number of occupants per home, as well as improved energy efficiency standards. While today's appliances and equipment use less energy on a per unit basis than in the past, efficiency improvements are often offset by greater quantities of electronics in homes and buildings.[6] Even so, space heating and cooling remain the dominant energy end uses in residential homes, as they have been historically. Figure 1 depicts typical energy end-use profiles for residential and commercial buildings in 2011.[7]

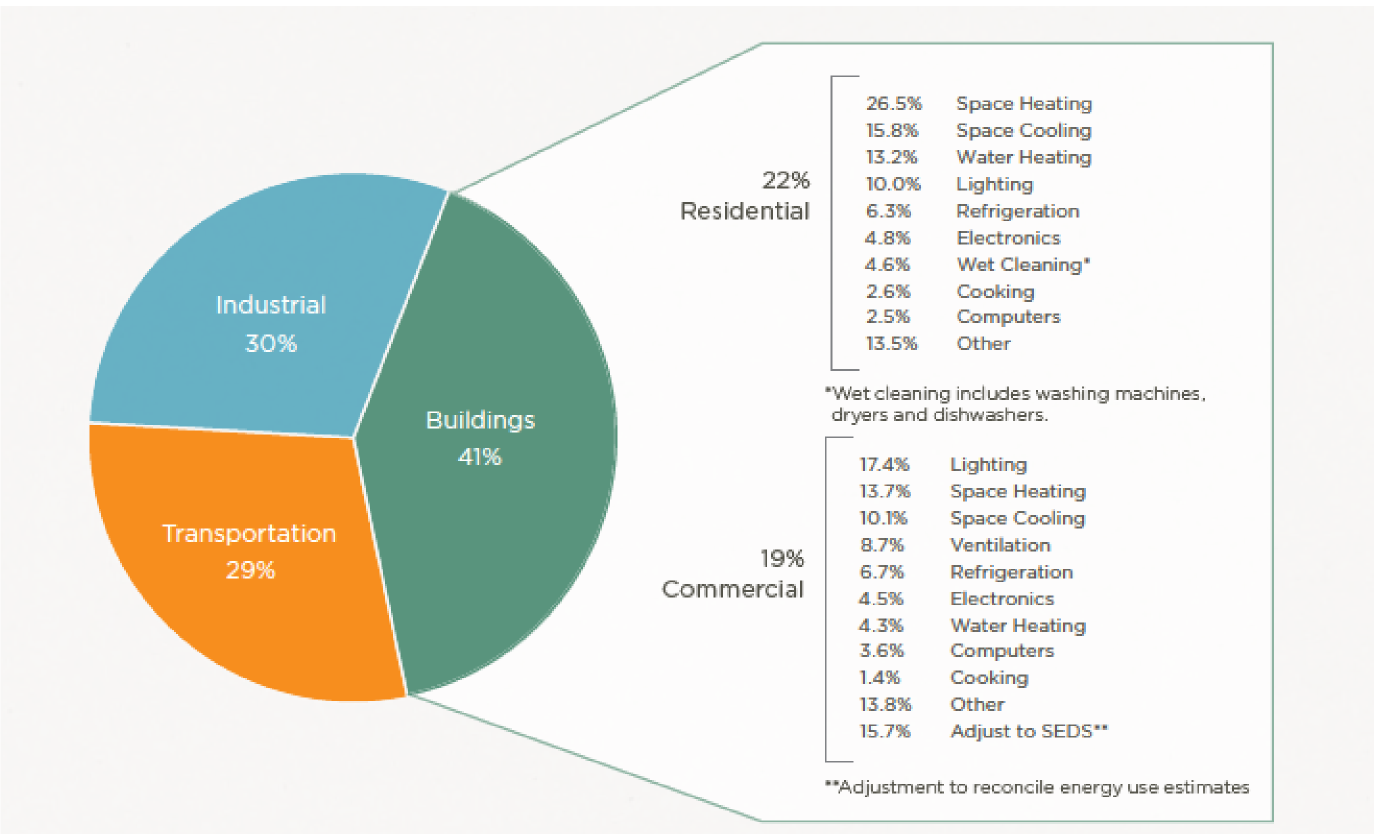
This study evaluates the life cycle impacts of two subsets of residential buildings: *Single-family* and *multifamily residential buildings*.

COMMERCIAL BUILDINGS

The energy-use profile for commercial buildings in the United States is radically different from that of residential buildings. Energy use by commercial buildings is dominated by electric lighting loads. On a square foot basis, food service buildings and healthcare facilities consume the greatest amounts of energy, as shown in Figure 2, due to the energy-intensive processes and equipment these buildings typically require. For all commercial building types, heating and cooling loads are heavily dependent on geographical location and regional climate characteristics.

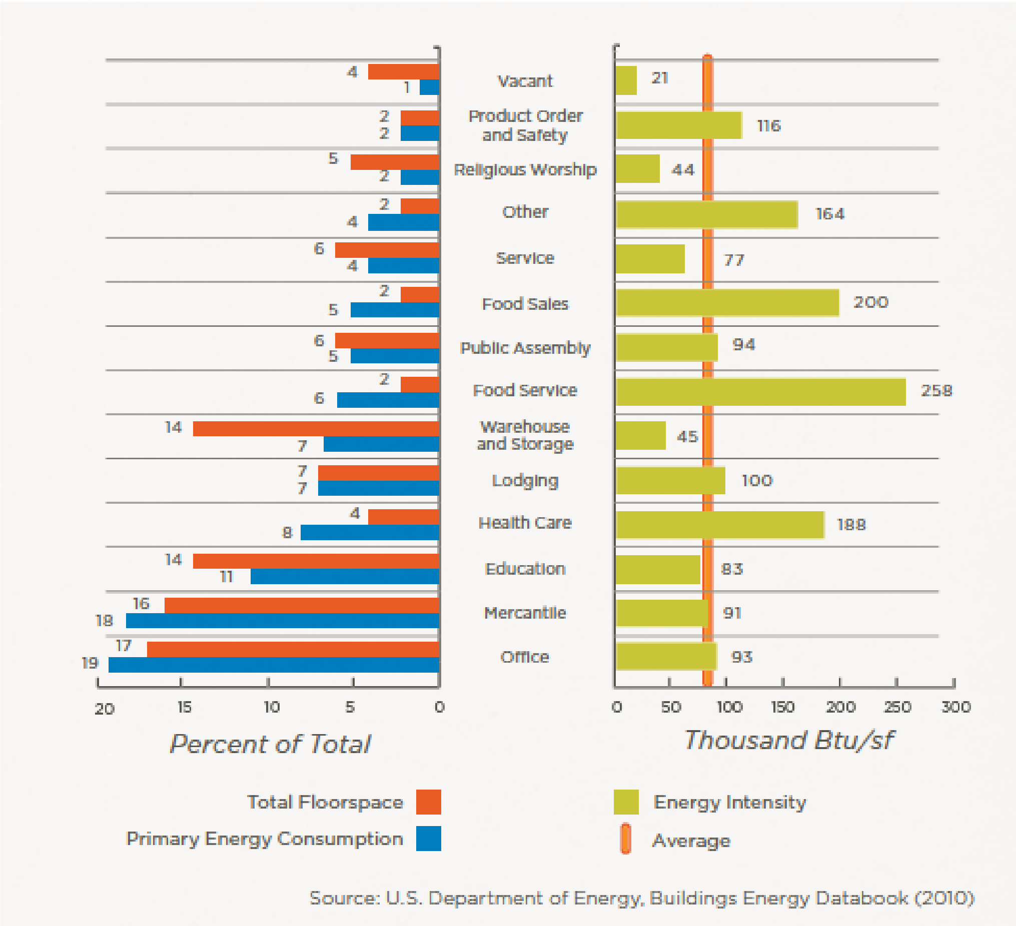
This study evaluates three types of commercial buildings that encompass a large portion of the nation's non-residential building stock: *offices, warehouse-to-office conversions, mercantile buildings (mixed-use village),* and *educational buildings*.

Figure 1: Energy Use by Sector



Source: U.S. Energy Information Administration and U.S. Department of Energy

Figure 2: Commercial Building Floorspace, Energy Consumption, and Energy Intensity, by Building Activity.



EVALUATING OPERATING ENERGY

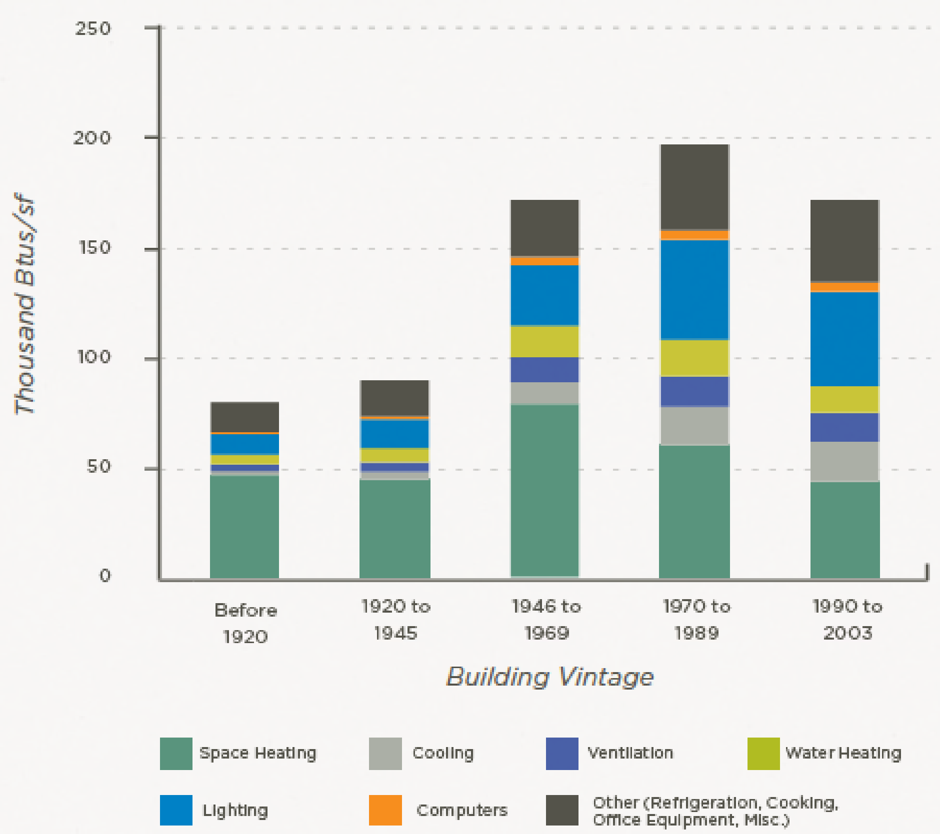
Building owners, developers, policy makers, and green-building experts often assume that it is preferable to build a new, energy-efficient building than to retrofit an older building to the same level of efficiency. Yet myriad examples exist of retrofits of older buildings that have achieved substantial energy savings. What is more, national data on building energy performance indicates that some existing buildings, particularly those from the early 20th-century, perform as well as, or better than, modern-day buildings. For example, data from the U.S. Energy Information Administration (EIA) demonstrates that commercial buildings constructed before 1920 use less energy, per square foot, than buildings from any other decade of construction, as shown in Figure 3. The comparative advantage of some older buildings may in fact be explained by the original building design, form, massing, and materials, as well as the window-to-wall ratio, limited installed equipment, or occupant density.

In addition, many often overlook the environmentally friendly characteristics of existing buildings when weighing new construction against retrofit or reuse options. These characteristics include passive design (older buildings designed before energy was cheap and abundant); passive survivability (the ability to operate without energy inputs for key functions, such as during a power failure); and adjacency to other buildings, which minimizes heat loss from exterior walls.

Unfortunately, attempts to measure the operating energy performance of U.S. building stock are currently complicated by limitations on data and variations between buildings. While some buildings are inherently energy efficient, or are operated and maintained to the highest performance standards, others lag far behind due to poor design or inadequate maintenance.

In some instances, systems are not optimized for performance or tenant behavior is unpredictable. There is a budding policy movement to incentivize or require building owners to track and record the energy use of their buildings, as well as a growing demand on the part of real estate investors and tenants for transparent and consistent data about building performance. Still, many existing buildings in the United States are not bench-marked against established baselines.

Figure 3: Commercial Building Energy Use by Vintage



Source: U.S. Energy Information Administration, Commercial Buildings Energy Consumption Survey (2003).

Despite gaps in data and research, several factors regarding operating energy performance are well-accepted. For example, regardless of a building's age, occupant behavior and building maintenance play huge roles in a building's operating energy performance, so much so that the energy consumption of any building type can easily be skewed based on these factors.

This study seeks to control the aforementioned variables by using normalized, industry-accepted data for energy use based on building type and location (explained further in this document and in the *Technical Appendices*). By doing so, a clearer picture can be provided to evaluate the role of both operating energy and embodied energy and how they factor into decision making regarding building reuse versus demolition and new construction.

EMBODIED ENERGY OF BUILDINGS

Embodied energy is the initial energy investment required to produce a material or product. It includes the energy needed for the extraction of natural resources, manufacturing, transportation, and installation. Thus, the embodied energy of a building reflects the total energy needed to produce all materials or assemblies, transport them to a building site, and assemble a building.

The 1970s and 1980s marked the beginning of efforts to quantify the environmental value of building reuse in the United States. These analyses focused on calculations of embodied energy in buildings. Among these was a report released by the Advisory Council on Historic Preservation during the peak of the energy crisis in 1979, which utilized embodied energy averages, on a per square foot basis, for over a dozen building types and allowed users to generate embodied energy estimates for nearly any building.[8] At the time, the case was often made that saving buildings was tantamount to saving energy. For example, Seattle's 80,000 square-foot Grand Central Arcade in the Pioneer Square Historic District was estimated to have 131 Billion BTUs embodied in the existing structure, and thus, it was argued that the same number of BTUs would be saved by conserving the building.

AVOIDED IMPACTS APPROACH

In recent times, many building and environmental scientists have been dismissive of the embodied energy approach to quantifying the benefits of building preservation; energy embedded in an existing building is often viewed as a 'sunk cost.' That is, it is often argued that there is no inherent current or future energy savings associated with preserving a building, because the energy expenditures needed to create a building occurred in the past, as did the environmental impacts associated with creating the building. In this view, the only value of building reuse is the avoidance of environmental impacts that results from not constructing a new building. This approach has given rise to the avoided impacts approach to understanding reuse, which measures the impacts that are avoided by not constructing new buildings.

> The "avoided impacts" approach measures environmental impacts avoided by choosing *not* to contruct new buildings.

The avoided impacts approach provides the foundation for the analysis undertaken in this report. The efficacy of this technique is borne out by a number of prior studies. A 2008 study by the U.K-based Empty Homes Agency, for instance, utilizes the avoided impacts approach to understand the environmental value of existing homes.[9] Using data from the University of Bath's Inventory of Carbon Emissions (ICE) database, the report compares the embodied CO_2 resulting from new home construction to that resulting from refurbishment of old properties. The six case studies featured in the study represent the most common housing types in England. CO_2 emissions from these homes were projected over a fifty-year period into the future. Key findings from the analysis reveal that the reuse of empty homes could yield an initial savings of 35 tons of CO_2 per property if the embodied energy related to new building materials and construction were eliminated.

The study finds that, when carbon emissions are looked at over time, it takes 35 to 50 years for a new, energy efficient home to recover through efficient operations all of the carbon that was expended during the initial construction process.

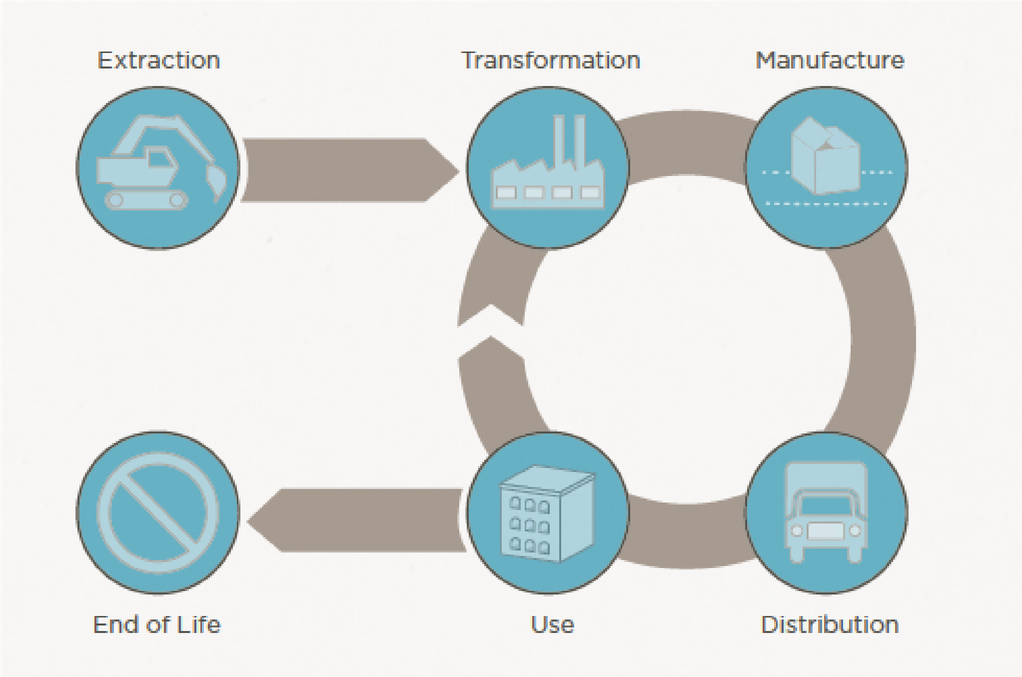
Studies of embodied and operating energy are necessary steps in evaluating the environmental impacts of a building. However, other relevant factors – such as impacts to health, habitat, and air pollution – must also be considered. Consequently, the life cycle assessment (LCA) framework is a valuable tool towards understanding the importance of building energy consumption and related environmental concerns.

3. LIFE CYCLE ASSESSMENT (LCA) APPROACH

Life cycle assessment (LCA) is an internationally recognized approach to evaluating the potential environmental and human health impacts associated with products and services throughout their life cycles, beginning with raw material extraction and including transportation, production, use, and end-of-life treatment. Among other applications, LCA can identify opportunities to improve the environmental performance of products at various points in their respective life cycles; inform decision making; and support marketing and communication efforts. LCA is increasingly being employed by the construction industry to evaluate the environmental performance of buildings, building materials, and construction practices.[10]

A full description of the LCA methods used in this study is contained in the *Technical Appendices*.

Figure 4: Life Cycle Stages



Extraction of raw materials for production of both new and replacement materials.

Transformation and refinement of raw materials.

Manufacture of products and distribution to suppliers.

Transportation of products to building site.

Use of building including construction-related activities and operating energy of the building over its lifespan.

End of Life disposal of materials, including transportations, to landfill, recycling or incineration.

This study expands upon previous LCA investigations into building reuse and retrofit practices. However, the goals and scope of this analysis differ from those of past studies. Previous LCA studies set out to ascertain the relative impacts of existing residential buildings versus new construction for one building type in one climate region. While these valuable studies provide a strong foundation for further research, they cannot necessarily be widely applied across building types or different geographies or climate zones. The following summary of whole-building LCA research provides a partial overview of analyses that are most applicable to this study.

A. LCA STUDY OF EMBODIED EFFECTS FOR EXISTING HISTORIC BUILDINGS

In 2009, the Athena Sustainable Materials Institute used LCA to assess the environmental impacts of four commercial and mixed-use historic buildings in Canada.[11] The project team used the ATHENA® EcoCalculator for building assemblies, in order to compare the e ects of retaining buildings versus building new structures in the same location. Four options for each of the following case studies were modeled: *the renovated building*; the *best-renovated building* (which assumed the best energy performance that could be achieved by an existing building); the *typical new building*; and the *best new building* (which assumed the best energy performance that could be achieved by a new building).

For each of these case studies, the project team obtained architectural drawings and renovation histories. For the 'best-renovated' option, the team developed a series of projected measures to improve the energy performance of the older buildings. The 'typical new building' and 'best new building' models were also inputted into the ATHENA® EcoCalculator. The impacts associated with building retro t were then compared to the impacts associated with new construction. Primary energy use and global warming potential were estimated and analyzed.

The study found that the initial avoided impacts associated with the reuse of the existing buildings ranged from a savings of 185 to 1,562 tons of carbon dioxide and between 2.6 million to 43 million MJ of primary energy.[12]

B. LCA AND SYSTEMS THINKING FOR RESIDENTIAL BUILDINGS

A 2010 report by the Oregon Department of Environmental Quality (DEQ) examines the life cycle impacts of over twenty green building practices, from design to construction techniques and material selections.[13] The analysis, which assumes a building life span of 70 years, indicates that the majority of impacts occurred during building occupancy and that materials represented only 14 percent of life cycle greenhouse gas emissions. Also, of the material reduction and reuse practices evaluated, reductions in home size and multifamily living were found to achieve the largest greenhouse gas reductions.

The project team for this study drew on the DEQ's research as the basis for several of its initial assumptions. However, this report expands on the DEQ analysis by including both commercial and residential buildings in various climate zones.

C. THE BUCHANAN BUILDING, UNIVERSITY OF BRITISH COLUMBIA

In 2006, the University of British Columbia studied the environmental impacts that could be expected from the replacement of the Buchanan building, which is located on the University's campus. The LCA analysis used the Athena Institute's Environmental Impact Estimator life cycle analysis tool to model the impacts that would be avoided by retaining the Buchanan building rather than replacing it with a new building. The analysis assessed the structure, envelope, and operational usage of the nearly 200,000 square-foot building and included an assessment that included raw material extraction, manufacturing of construction materials, construction of the structure and envelope, and associated transportation e ects.[14]

Significantly, the project team concluded that reusing the Buchanan building would result in major environmental savings. It determined that, over an 80-year period, total carbon emissions for the new building were merely 5 percent lower. Furthermore, it would take approximately 38 years for a new, energy efficient building to recover the carbon that was expended during the construction process and begin to accumulate carbon savings. In other words, net carbon emissions savings for the replacement building would begin only after 38 years.

Previous research shows it can take decades for new, energy efficient buildings to overcome the carbon expended during the construction process.

4. STUDY APPROACH AND METHODOLOGY

This report builds on existing research by casting a wider net than, and expanding the boundaries of, previous studies. Here, actual case-study buildings are used for *both renovation and new-construction scenarios* to derive materials inputs required for the LCA. (However, it should be noted that actual case study buildings were not used to generate projected energy usage. This is described further in the Methodology for Determining Building Operating Energy section, below.) This study also quantifies the amount of time needed for a newly constructed building to recover impacts expended in the construction process through efficient building operations. It is anticipated that the comprehensiveness of this study will allow for a broad application of results and thus be useful to policy leaders and decision makers across U.S. sectors, particularly in the building industry.

PROJECT PHASES

This investigation was conducted in *three phases*:

PHASE I: BUILDING INDUSTRY MARKET CONTEXT

The initial phase of the study included a review of existing literature on building LCA, energy use, and U.S. building stock, along with interviews with thought-leaders in the field of preservation and reuse. This phase also included the development of the LCA methodology; a pilot LCA was set up to test the methodology, evaluate assumptions, and determine effective inputs and outputs for delivering results.

This pilot LCA study is included in the Technical Appendices.

PHASE II: SCENARIO DEVELOPMENT

Phase II of the project was informed by the pilot LCA and involved careful consideration of the building types to be used in the study. The following six building types were selected:

- Single-Family Residential
- Multifamily Residential
- Commercial Office
- Urban Village Mixed-Use
- Elementary School
- Warehouse

Buildings were selected from around the United States, for both the renovation and new construction scenarios. Material quantities were estimated based on available project data. The selected case studies were comparable in terms of program, size, and construction type.[15] Differences between buildings were normalized in order to improve the accuracy of comparisons. In addition, a methodology informed by national survey data and peer-reviewed engineering analysis was established for evaluating building energy use, including the selection of energy efficiency measures (EEMs) appropriate to each building.

A full explanation of the methodology employed for the normalization and energy analysis approaches is contained in the *Technical Appendices*.

PHASE III: LIFE CYCLE THINKING AND ANALYSIS

Phase III of the study involved an *in-depth analysis* of each of the building scenarios. Full LCAs were run on each reuse/renovation and demolition-and-new-construction scenario across *four cities, each representing a di erent climate region:* Portland, Phoenix, Chicago, and Atlanta.

'Sensitivity analyses' were conducted to test how speci c changes to inputs – such as energy use, variations in fuel mix by region, or building life span – a ect nal LCA results. Conclusions were then drawn to highlight key ndings from the study.

LCA SCOPE AND METHODOLOGY

This investigation aims to identify conditions under which the rehabilitation and retro t of a building are environmentally preferable to demolition and new construction. The objectives of this LCA *do not* include any de nitive comparison of speci c products or materials, or speci c design or construction practices. Rather, this study examines the aggregate impact of an entire building rather than undertaking a product-by-product comparison.

RESEARCH OBJECTIVES

- To compute and compare the life cycle environmental impacts of buildings undergoing rehabilitation to those generated by the demolition of existing buildings and new construction;
- To determine which stage of a building's life (i.e., materials production, construction, occupancy) contributes most signi cantly to its environmental impacts, *when* those impacts occur, and what drives those impacts; and
- To assess the in uence of building typology, geography, energy performance, electricity-grid mix, and life span on environmental impacts throughout a building's life cycle.

THE PROJECT TEAM

The project team for this study included experts in the elds of building design and construction, energy performance and modeling, and life cycle assessment. A leading, national building contractor handled data collection on material quantities for the various scenarios explored by the team.

A pro le of the project team is available at the beginning of this report.

PEER REVIEW

This report has undergone critical review by Pascal Lesage, PhD at CIRAIG, a leading LCA research group housed at the University of Montréal's École Polytechnique de Montréal. His comments are provided in the Technical Appendices. Note that Dr. Lesage's feedback is not intended to be a full ISO-compliant review; the cost of a fully compliant ISO review was deemed to be prohibitive. Additional peer review feedback was offered by several LCA, green building, and preservation industry leaders.

METHODOLOGY

The project team had anticipated that designing this study would present many challenges, given the complexities inherent in framing reuse and construction scenarios. A central challenge was the fact that a building may either be demolished and newly constructed or rehabilitated and retrofitted, but not both. Specifically, the use of modeled versus real buildings also raised many questions; in the case of the former, modeled buildings could be designed to be as representative as possible of an 'average' building type, thereby making study results as generalizable as possible. 'Real world' case studies, however, would offer greater certainty in terms of the quantification of materials used for construction and would offer a significant project cost savings.

Ultimately, the project team determined that comparing the reuse of an extant building to an actual, new construction project would offer more data reliability, and as the less expensive option, would offer an opportunity to test more building typologies. Thus, the methodology employed in this LCA uses empirical data for two comparable case study projects, across six building typologies. Great care was taken to ensure that the case study buildings selected represent common existing and new construction typologies and that the equivalence of functionality between the two projects was maximized.

The case study buildings were, at the time of selection, either fully constructed or under development in the United States. The material inputs, construction/demolition activities, and operating energy for these projects were quantified over a 75-year life span.[16] While the precise functionality of the buildings in this study vary somewhat, the general functionality within a building category (e.g., office building) is assumed to be equivalent between the 'existing' and 'new' building models.

In some cases, a normalization process was used in the investigation in order to equalize the buildings in function. In these instances, theoretical calibrations were made to either the existing or new building so that it more closely matched the function of the other–for example, by excluding a parking garage if one building included parking and the other did not. Case study buildings were not normalized based on their size. Instead, life cycle impacts for these buildings were calculated based on their respective building designs and an appropriate 'intensity,' calculated by dividing impacts over the total aggregate floor area to arrive at an 'impact per square foot' metric. This approach allowed for the study of a wider range of projects and enabled comparison of two buildings of different sizes in a meaningful way.[17]

This study compares equivalent new and existing buildings on a square foot basis over a 75-year life span.

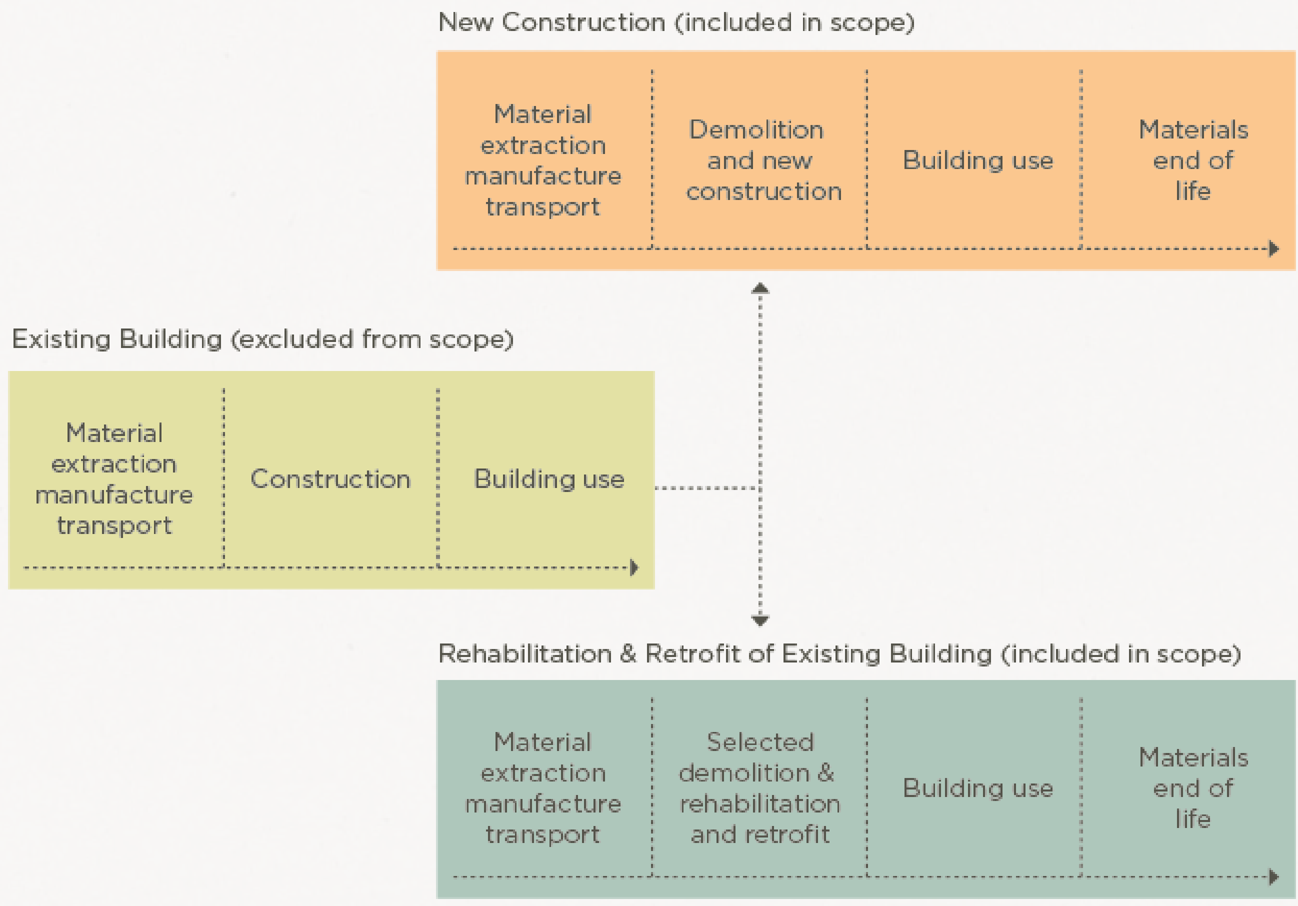
SCOPE OF THE ANALYSIS

The scope of analysis includes the following:

- Rehabilitated and newly constructed buildings are assessed from the extraction and processing of raw materials onward, through the end-of-life of all building components.
- The 'new construction' scenarios include the complete demolition of previously existing structures and the erection of new buildings.
- The 'rehabilitation-and-retrofit' scenarios include any demolition necessary for building improvements, renovation and retrofitting activities that existing buildings underwent during their respective rehabilitation phases.
- In both scenarios, energy use and the replacement of materials due to normal wear and tear are included throughout the assumed 75-year life span.

Figure 5 depicts the activities included within the boundaries of this study.

Figure 5: Boundaries of the LCA Study



In both the new construction ('NC') and the rehabilitation and retrofit ('RR') scenarios, only those activities occurring during demolition/ selected demolition and beyond are included. The impacts associated with use and maintenance of the existing building prior to the rehabilitation and retrofit phases are assumed to be the same for each scenario; therefore, they are excluded from this analysis.

In this study, 'NC' refers to the 'new construction' scenario. 'RR' refers to the rehabilitation and retrofit scenario. In both scenarios, the boundaries of the study include the following life cycle stages:

- Original materials production;[18]
- Replacement materials production needed over the life of the building;
- Material transportation to the building site;
- Demolition/selected demolition in reused building;
- Construction/rehabilitation and retrofit activities;
- Energy use during building occupancy; and
- Materials end-of-life.

Note that the boundaries of this study do not account for impacts related to materials that remain *in situ* in an existing building. This study seeks to understand the difference in impacts between reuse and new construction *in the current day*. The impacts associated with *in situ* materials occurred in the past and are not of interest in this study. Only the new materials and activities related to the reuse and renovation of an existing building and those related to demolition and new construction are considered here. This is consistent with the avoided impacts approach.

Some activities or materials are not within the scope of this study, as they are assumed to be identical in the NC and RR scenarios. The following items are *beyond the scope of this study:*

- Water consumption during building occupancy;
- Materials in the existing building that remain on-site during renovation;
- Building furnishings (i.e. any items not 'nailed down,' including appliances and furniture);
- Direct occupation of land by the building (i.e., the impact of a building on a specific site);
- Equipment operation associated with final demolition of the buildings, which is assumed to be the same for both buildings;
- The impact of individuals using the building (e.g., transport to and from the building); and
- Variations in material replacement rates between the RR and NC scenarios.[19]

In addition, impacts to human health related to material off-gassing and the resulting effects on indoor air quality are excluded from this study. Currently, the complexity of this topic requires resources and expertise beyond the capabilities of life cycle science, and further research is needed to determine how indoor air quality impacts compare between rehabilitated and newly constructed buildings.

LIFE CYCLE INVENTORY DATA SOURCES AND ASSUMPTIONS

The quality of data used in LCA evaluations determines the usefulness of LCA results. This study utilizes the most credible and representative information available to the project team. The following sections summarize the team's data collection process and key underlying assumptions of this investigation.

The *Technical Appendices* describes the life cycle inventory, data collection process, and applicable assumptions in greater detail.

DATA COLLECTION

All life cycle inventory data are drawn from the *ecoinvent* database v2.2 (SCLCI 2010). While life cycle inventory information for many building materials is provided in this source, information describing assemblies (i.e. building materials made up of multiple components) is less readily available. In order to maintain consistency and efficacy in data sources, the LCA models assemblies as a combination of their material components.[20]

Data was collected for each building to quantify materials and other inputs, including:

- Quantification of the materials used in each case study project;[21]
- Estimated equipment use, electricity consumption, and labor required for demolition/selected demolition and construction/rehabilitation activities; and
- Energy use during the buildings' operations, based on national survey data and multiple building energy performance studies.

KEY ASSUMPTIONS OF THE LCA

Several important assumptions have guided this investigation, including those concerning:

- Building life span;
- Material replacement rates;
- Materials transportation;
- Building energy performance; and
- End-of-Life (EOL) management of materials.

BUILDING LIFE SPAN

According to the Pacific Northwest National Lab, the median building lifetime in the United States is 75 years. This measure is used here as the baseline life span for each of the scenarios investigated. It is assumed that, after this period, a building is demolished and materials are transported to their EOL fates. In reality, some buildings have life spans that are much shorter or longer than 75 years. Therefore, the project team tested variations in lifetime in order to evaluate their impacts on environmental outcomes.

MATERIAL REPLACEMENT RATES

Each product included in the analysis is assumed to be replaced over time, according to the average service-life of the item. Replacement rate assumptions account for variations that may exist between building typology (e.g., residential versus commercial), geography, and material application. For example, the lumber used in flooring has a different replacement rate than that used in walls. Materials with long life spans, such as concrete foundations, are assumed to have a replacement rate of zero.

MATERIALS TRANSPORTATION

Materials transportation is in uenced by a material's weight and the distance it travels from a place of production to a building site.

In the absence of reliable data on the distance traveled by new building materials, this study uses the conservative estimate that materials are trucked 497 miles (800 kilometers) to a building site. It has further been assumed that demolished/replaced materials travel 45 miles (72 kilometers) to their respective disposal or processing (e.g., recycling, incineration) destinations.[22] In actuality, distances can vary widely, as some building materials are transported from the other side of the world. However, the project team intentionally assumed a distance of 497 miles for sourcing of new materials, as the use of longer distances in this analysis would have unfairly favored the building reuse scenario; fewer new materials are used in renovation processes as compared to building construction processes. Utilizing a relatively conservative transportation distance therefore allows for a more unbiased investigation into the impacts of new construction relative to building reuse.

BUILDING ENERGY PERFORMANCE

For both the NC and RR scenarios, operating energy performance is expressed as Energy Use Intensity (EUI) and assumed to be representative of a common building of its type in each of the four cities.[23] EUIs are calculated from a variety of different sources including national survey data provided by the U.S. Energy Information Administration (EIA) and recent research on building energy use.[24] Energy end use pro les provided by the EIA are used to designate a building's energy consumption by system (e.g., space heating, cooling, lighting). For all scenarios, space and water heating are assumed to be powered by natural gas. All other energy end uses are assumed to be powered by the regional electricity grid.[25]

Di erent areas of the country rely on di erent fuel sources to power electric grids, resulting in regional variation in the environmental impacts associated with energy use. This study accounts for diverse grid mixes by using regional grid mix data for the regions related to Portland, Phoenix, Chicago, and Atlanta, as determined by the U.S. Environmental Protection Agency (EPA).[26]

Table 1 lists the contribution of various energy sources to each region's grid mix.

Table 1. U.S. Regional Grid Mixes Used in This Study

CONTRIBUTION TO GRID MIX (%)			
Energy Source	**Chicago**	**Portland & Phoenix**	**Atlanta**
Coal	64.8	30.9	57.1
Oil	0.544	0.429	0.840
Natural gas	6.59	32.1	14.1
Nuclear	26.6	9.85	24.5
Hydro	0.547	23.6	1.69
Biomass	0.700	1.21	1.76
Wind	0.140	1.77	0.00512
Solar	0.00	0.0852	0.00

Source: eGRID2010 v.1.0

EOL MANAGEMENT OF MATERIALS

Every material that travels to a building site during construction, renovation or maintenance for use in a structure is eventually destined for a land ll, recycling facility, and/or incineration facility. Recycling provides partial energy recovery at the end of a material's life. For purposes of this study, EOL-materials management is assumed to be uniform across geographical regions, regardless of the availability of infrastructure for recycling or energy recovery.

SENSITIVITY ANALYSES

A *sensitivity analysis* evaluates the ways in which adjustments to discrete variables in uence

LCA results. In this study, sensitivity analyses were conducted in order to assess the in uence of three variables on LCA results:

- Building lifetime;
- Electricity grid mix; and
- Operating energy performance.

BUILDING LIFETIME

A building's assumed life span a ects the magnitude of its environmental impacts; over time, a greater quantity of materials is needed to maintain a structure, and additional energy is used to sustain building operations.

Here, the scenarios for both RR and NC assume a 75-year building lifetime. However, in order to assess the potential range of environmental impacts over time, the following life spans were also evaluated: *One year; two years; ve years; ten years; fteen years; twenty- ve years; fty years; and one-hundred years.*

ELECTRICITY GRIDS

The life cycle impacts of a building depend significantly on the amount of energy consumed by building operations. This is particularly evident where the dominant sources of energy are thermal energy and fossil fuel generated electricity, as in the United States.

Sensitivity analyses reveal the extent to which grid mix contributes to the environmental impacts of buildings.

The following section explains the methodology employed to determine building operating energy for each of the abovementioned conditions. Details regarding the energy analysis and methodology can be found in the *Technical Appendices*.

OPERATING ENERGY PERFORMANCE

This study explores the affect of increases in energy efficiency on building life cycle environmental impact. This is accomplished by using three distinct energy performance test conditions for each of the case study buildings, as follows:

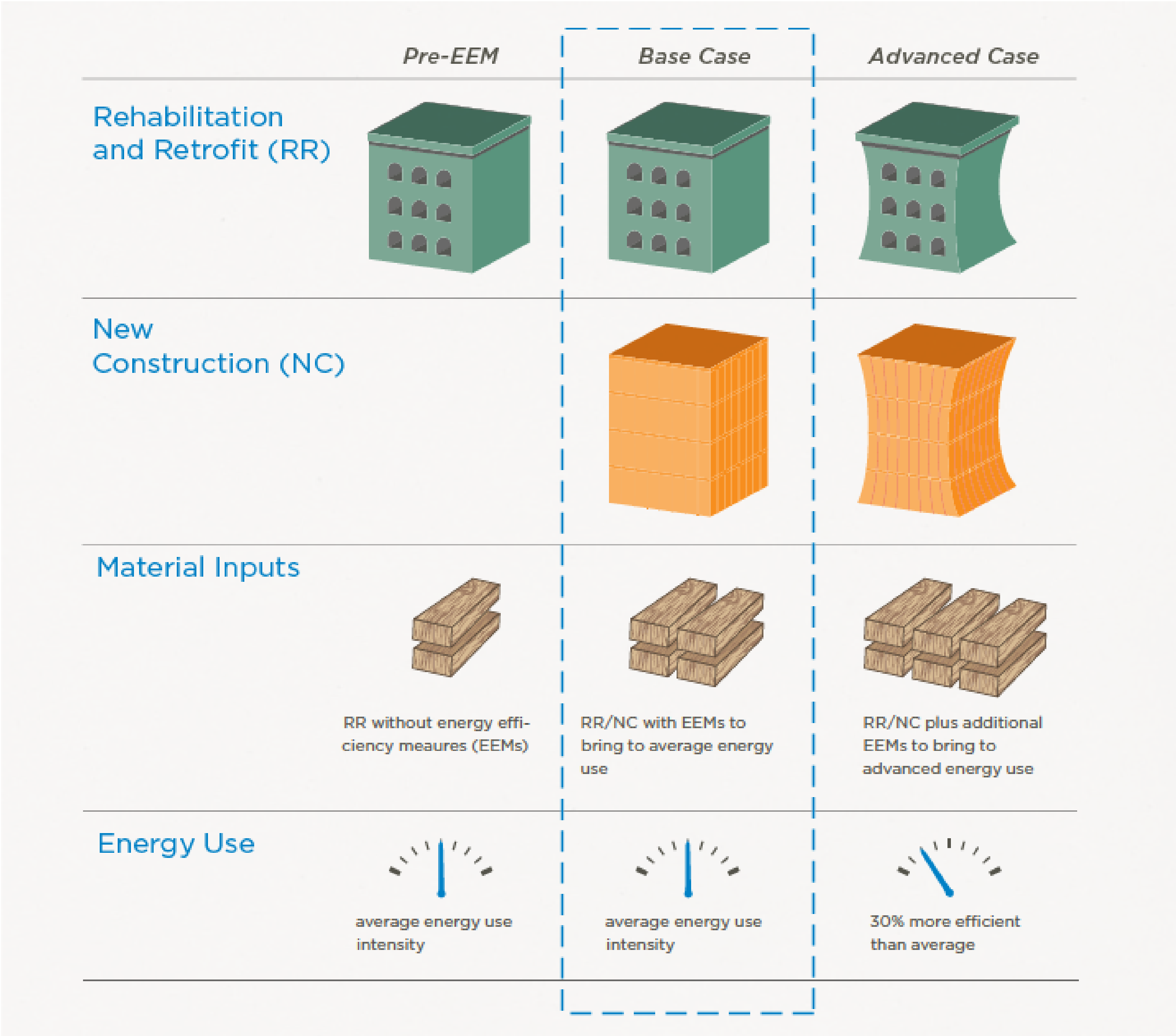
- **Base Case.** Represents a typical building, renovated or built to operate at an average level of energy efficiency.[27] The Base Case assumes that buildings in both the NC and RR scenarios have the same operating energy performance. This test condition assumes that a renovated building has been retrofitted to include EEMs, such that it is operating on par with new construction.

- **Advanced Case.** Represents an energy performance improvement over the Base Case. This test condition evaluates environmental impacts when buildings are operating at an advanced level of energy efficiency. For the Advanced Case, both buildings include EEMs that increase their operating energy performance by an estimated 30 percent.

- **'Pre-Energy Efficiency Measure' or 'Pre-EEM' Case.** Evaluates the life cycle impacts of an existing building that has been renovated to bring it to contemporary functional use (as is common for older buildings) but has not included energy efficiency measures to bring it up to an average level of energy performance. This test condition is key, because in many instances, older buildings have inherent efficiency strengths and perform on par with new construction.[28] The Pre-EEM Case is analyzed for the commercial office building only. The operating energy of the Pre-EEM Case is assumed to be equivalent to the Base Case test condition.

The following section describes the methodology employed to determine building operating energy for each of the above mentioned conditions. Details regarding the energy analysis and methodology are found in the *Technical Appendices.*

Figure 6: Study Test Conditions



METHODOLOGY FOR DETERMINING BUILDING OPERATING ENERGY

The pilot LCA, executed in Phase I of this study, indicates that *energy use during the operating phase of a building is a major driver of environmental impacts over its life span.* The project team sought to ensure that the most effective methods for establishing energy use were used in this study, specific to building type and geography.

While actual buildings were used for the RR and NC cases to derive materials quantities, their real energy consumption rates were not used, because doing so would have defined energy performance for each building type too narrowly. In turn, this would have made potential, building-specific performance anomalies difficult to detect, including those involving maintenance, management and occupant behavior. For this reason, EUIs and energy end use profiles for each building type are assumed to be standard representations of all buildings within a given typology group. However, it is acknowledged that levels of actual building energy use may vary significantly, depending on a number of factors that are excluded from this study.

Representative energy use data is used to produce results that can be applied more generally across the building stock.

The methodology employed in this study to determine operating energy varies by building typology.

For single-family and multifamily residential buildings, the Energy Information Administration's 2005 Residential Energy Consumption Survey (RECS) forms the basis of the operating energy analysis. The purpose of using national survey data as the foundation for this study is to produce empirical results that can reasonably be applied across the residential building stock. This approach is preferable to energy modeling results, which are based on theoretical projections.

For commercial buildings (office, elementary school, and urban village mixed-use), the methodology involved deriving energy use data from a variety of data sources, including national survey data and building energy performance studies.[29]

For all building typologies, great care was taken to ensure that EUIs accurately represent average performance in the four test cities of Portland, Phoenix, Chicago, and Atlanta, as there can be significant variation in the performance of a building type based on climate. More details on the methodology for establishing city specific EUIs is provided in the *Technical Appendices*.

In this study, warehouse buildings converted to multifamily residential buildings are assumed to operate the same as a new or retrofitted multifamily building. Warehouse buildings converted to commercial offices are likewise assumed to operate the same as new or retrofitted commercial offices. This assumption is based on the fact that extensive renovation activities within the building in order to change its use would likely trigger code-compliant upgrades to the building's envelope and mechanical systems. In reality, warehouse conversions are difficult to generalize in terms of energy performance. Further research is needed to evaluate the energy usage of warehouse conversions.

A multi-step approach was used to develop energy consumption rates for each performance condition:

- **Step 1 – Establish an energy use 'Base Case'** for each building typology using national survey data and other recent research.
- **Step 2 – Apportion total energy, by end use,** for each building typology and city. Determine the amount of energy used annually for space heating and cooling, lighting, fan/pump energy, hot water, and other categories.

- **Step 3 – Identify a list of appropriate EEMs,** by building type, and select EEMs such that case study buildings will be brought to the Base Case level of performance. While the actual energy performance of case study buildings was not known, the project team determined that, in many instances, both the new and renovated existing buildings would likely require the addition of EEMs in order to achieve a Base Case level of energy performance. An extensive list of EEMs, which could be applied to various building types to improve energy performance, was developed; these EEMs were derived from energy code prescriptive requirements, energy performance guides and professional experience. Professional judgment was then used to generate a specific set of EEMs appropriate to each case study building to bring buildings up to the Base Case energy usage.

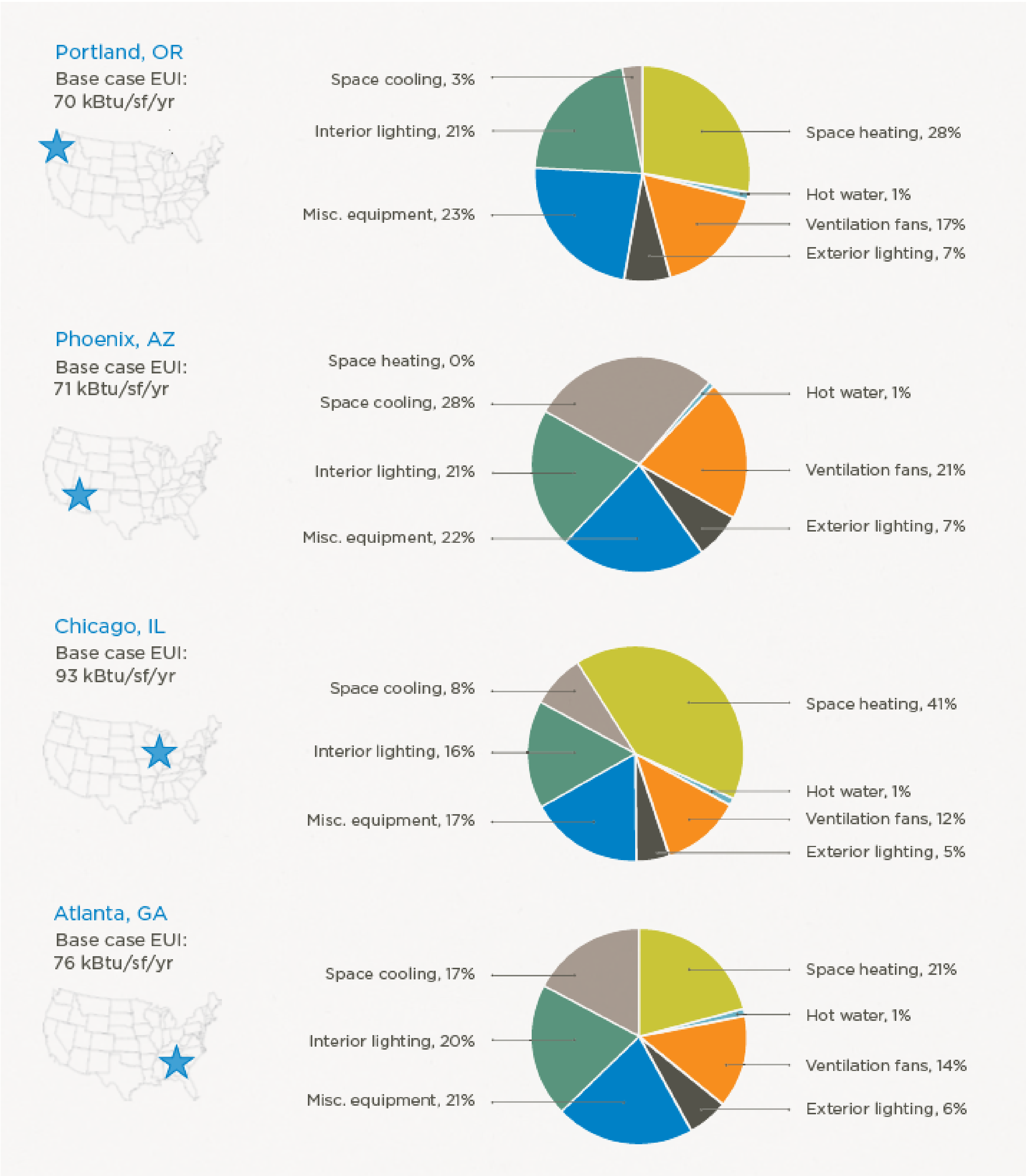
- **Step 4 – Select EEMs to bring each building type up to an Advanced Case level** of energy performance and calculate energy savings over Base Case. A "package" of EEMs was identified to achieve an Advanced Case level of performance, appropriate to each building type. EEMs to reduce electrical loads (cooling, lighting, plug loads, pumps, fans and equipment) and natural gas loads (heating and domestic hot water) were assumed to be achievable through integration of more efficient heating and cooling systems, high-efficiency lighting, equipment and appliances. The Advanced Case energy profiles were calculated for each building type by taking the Base Case EUI and reducing electrical and gas energy end uses by 30%, for an overall energy savings of 30% compared to the Base Case.

- **Step 5 – Document the results,** including key assumptions, and use them as inputs for the LCA sensitivity analysis. The material inputs for energy efficiency measures, e.g., additional insulation, were quantified and included in the LCA modeling.

Figure 7 shows EUIs and end uses for the Base Case for a single building type – the Commercial Office – in each city.

Many factors, beyond the EEMs described here, impact a building's energy efficiency. These include maintenance practices, occupant behavior, and plug loads (e.g., computers, equipment). These factors are assumed to be the same for both the NC and RR buildings and have therefore been excluded from this study.

Figure 7. Base Case EUIs and Energy Use Profiles for a Commercial Office Building in the Four Climate Regions Examined in this Study.



LCA IMPACT CATEGORIES

Life cycle impact assessment (LCIA) evaluates materials, energy, and emission flows by the type of impact their use or release has on the environment.[30] Various indicators are used as metrics to quantify these impacts. The following indicators are evaluated in this study:

- Climate Change
- Aquatic Acidification
- Aquatic Eutrophication
- Ecosystem Quality including:
  - Aquatic Ecotoxicity
  - Land Occupation
  - Terrestrial Acidification and Nutrification (Eutrophication)
  - Terrestrial Ecotoxicity
- Human Health,[31] including:
  - Human Toxicity
  - Ionising Radiation
  - Ozone Layer Depletion
  - Photochemical Oxidation
  - Respiratory Effects
- Resource Depletion, including:
  - Mineral Extraction
  - Non-Renewable Energy

A full description of each impact category and the methods used to evaluate them is located in the *Technical Appendices*.

In this study, reuse and retrofit of existing buildings are evaluated in terms of their potential for fewer negative environmental impacts compared to new construction.

5. CASE STUDY SCENARIOS

Preliminary research by the project team surveyed and characterized the nation's existing building stock. Building typologies were then vetted for further study, based on several criteria, including (1) the *most prevalent* building types in the United States, by total square footage; (2) the building types *most frequently torn down and replaced* with new construction; and (3) the *availability and access to data* from building owners and project teams.

Six building types were ultimately selected for analysis, based on their ability to represent each of these target criteria. These building types are:

- Single-Family Residential
- Multifamily Residential
- Commercial Office
- Urban Village Mixed-Use
- Elementary School
- Warehouse[32]

SINGLE-FAMILY RESIDENTIAL

The majority of U.S. building stock is detached, single-family housing; this typology accounts for 210 billion square feet nationwide.[33] Over half of all single-family residential units are located within urban or town limits rather than suburban or rural areas. Nearly 50 percent of single-family residences in the United States are single-story, with two-story units constituting over a quarter of the remainder of units.

Figure 8: Square Footage of Building Stock by Type

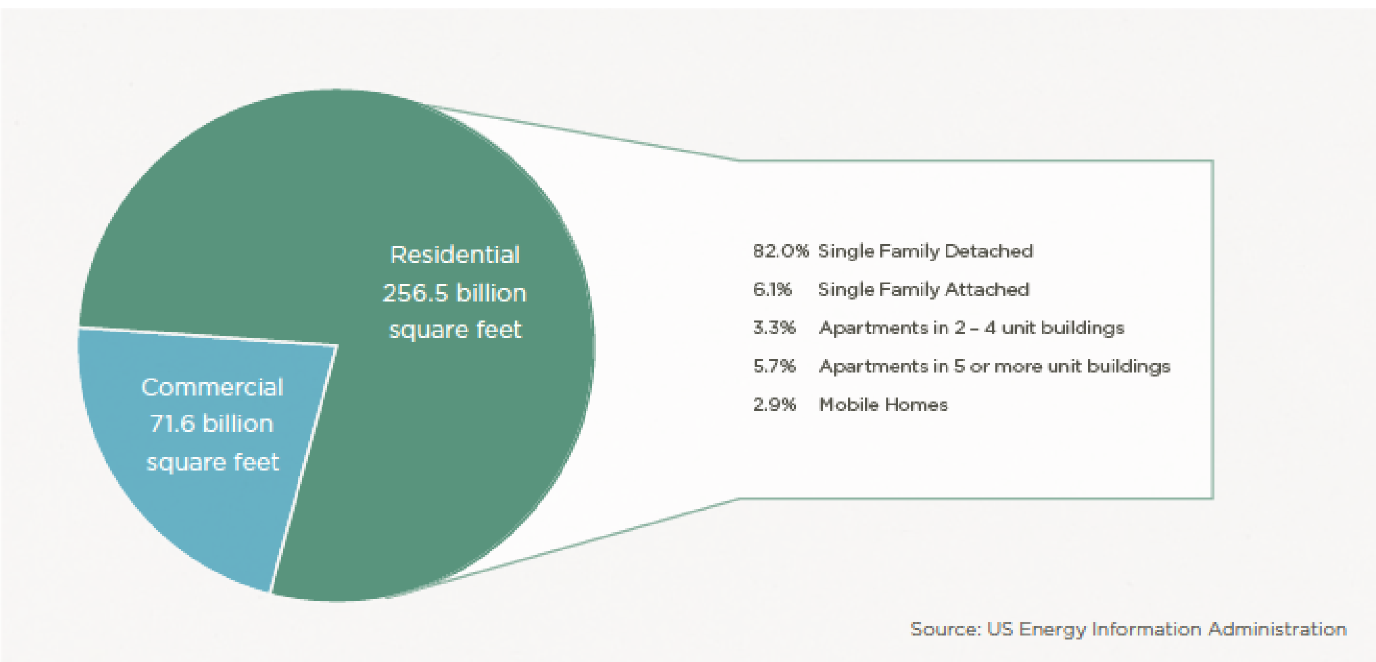
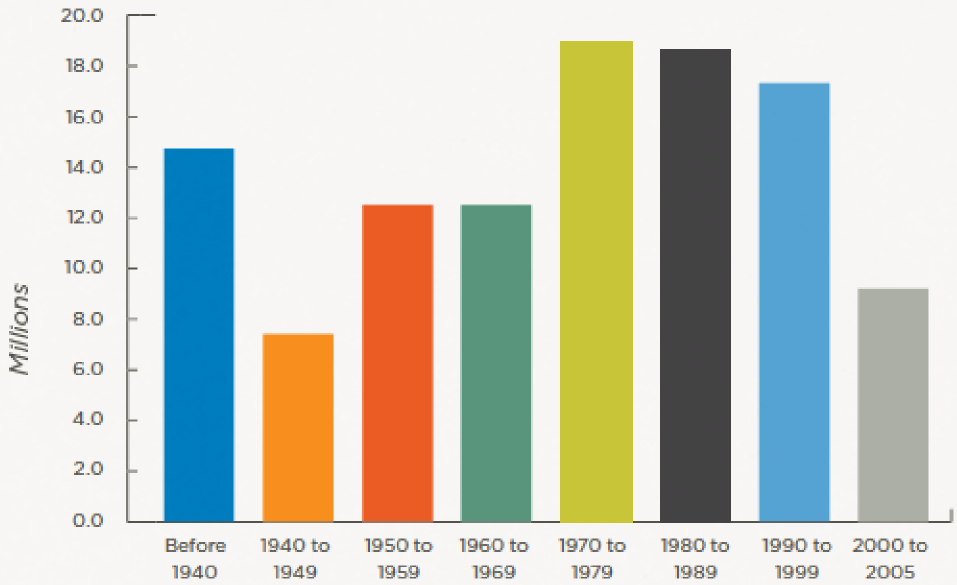


Figure 9: Number of U.S. Residential Units by Vintage



Source: US Energy Information Administration

Approximately thirteen percent of the existing building stock was built prior to 1940. A home of this era was selected for analysis because it represents a market of commonly demolished homes.

The following buildings were selected for comparison in this typology category:

- **NC scenario:** SW 34th Street Residence (Portland, OR)
- **RR scenario:** NW Pettygrove Street Residence (Portland, OR)

NORMALIZATION ANALYSIS

A *normalization analysis* was unnecessary in the single-family residential scenarios because the two buildings are similar in size and program elements.

Single-Family Residential

	New Construction	Rehabilitation and Retrofit
Building Name	SW 34th Street	2373 NW Pettygrove
Location	Portland, OR	Portland, OR
Year Built	2011 targeted	1896
Year Renovated	N/A	2009
Building Height	2-story	2-story
SPACE SUMMARY		
Square Footage	2,360	2,479
Building Program Elements	3 bedroom, 2.5 bathrooms, below-grade partial basement	3 bedroom, 2.5 bathrooms, below-grade finished basement
Renovation Description	N/A	Added master bath and basement bath, kitchen expansion
Normalized	N/A	N/A
CORE & SHELL		
Structure Type	Dimensional lumber, prefab truss system	Dimensional lumber
Envelope	2x6 wood framing, batt insulation, wood windows, cedar shingle roofing	2x4 wood framing, batt insulation, wood windows, asphalt roofing
Cladding	Cedar shingle	Cedar lap
% Glazing (window : walll)	18%	14%
HVAC System	Gas furnace, air conditioning unit	Gas furnace
INTERIOR		
Type	Custom	Custom
Scope	Granite countertops, wood paneling, carpet, ceramic and wood flooring	Granite countertops, wood paneling, carpet and wood flooring

ENERGY ANALYSIS

Table 2 summarizes the EUIs used in the analysis across each of the four climate regions.

Table 2. Single-Family Residential End-Use EUIs by City

END-USE	CLIMATE ZONE RELATIVE EUI (KBTU/SF/YR)			
	PORTLAND	PHOENIX	CHICAGO	ATLANTA
Space Cooling	3	12	2	6
Space Heating	23	5	25	13
DHW	10	10	10	10
Refrigerators	2	2	2	2
Lighting & Appliances	8	8	8	8
TOTAL	46	37	47	39

Notes:
1. EUIs in table above are from RECS Table US1 for climate zones 2 through 5.
2. Methodology devised from feedback from peer group and NBI research across different climate zones.

Table 3 outlines the EEMs included in each step of the energy analysis for the existing single-family home scenario.

Table 3. Single-Family Residential EEMs

SINGLE FAMILY RESIDENTIAL		
EEM	Additional EEMs to bring building to code	Additional EEMs to achieve 12% - 30% energy e ciency Improvement
LIGHTING/DAYLIGHTING		
Interior Lighting Power Density < 1 watt/sf	NC	
Lighting Controls	NC	
E cient Exterior Lighting (CFL/LED)	NC	
Skylights		NC
HVAC		
Programmable Thermostats	NC	
Gas Heating Minimum E ciency 92%	RR, NC	
Cooling E ciency SEER 14+	RR, NC	
Energy Recovery Ventilator		NC
Seal/Insulate Ductwork	RR, NC	
Direct/Indirect Evaporative Cooling		NC
Ground Source Heat Pump		NC
Hydronic Radiant Heating		NC
ENVELOPE		
R-30 Roof/Attic Insulation	RR, NC	
R-13 Wall Insulation	RR, NC	
R-19 Wall Insulation (includes wall furring)	NC	RR
In ltration Reduction- Sealing	RR, NC	
Insulated Door and Window Frames	NC	RR
GLAZING		
U-0.32 or Better	RR, NC	
Low-e Solar Film (SE and SW regions only)	NC	RR
WATER HEATING		
Gas heat with 90%+ e ciency	RR, NC	
Instantaneous Hot Water		NC
Hot Water Pipe Insulation	NC	
Hot Water Recirculation System		RR, NC
Solar Thermal System		NC

MULTIFAMILY RESIDENTIAL

Multifamily buildings – those with five or more units – represent the second largest category of residential buildings in the United States. This subset of buildings accounts for roughly 15 percent of all residential structures, the majority of which are rental housing units.

Because multifamily buildings can vary widely in terms of building size and type, a set of criteria was developed for selecting a representative NC multifamily case study building. These criteria included a mid-rise building with ground floor concrete construction and 4 to 5 stories of wood framing above. Additional criteria included ground floor retail space, a common characteristic of mid-rise multifamily buildings in urban areas. The project team also included in this study a warehouse that had been converted to a multifamily residential use, as this is a popular adaptive reuse of this building type.

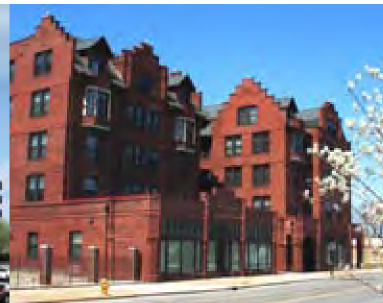
Based on these parameters, the following buildings were selected for comparison in this category:

- **NC scenario:** New Holland Apartments (Danville, IL)
- **RR scenario:** Block 49 (Portland, OR) and The Avenue Lofts (Portland, OR)
- **RR Warehouse scenario:** Avenue Lofts (Portland, OR)

NORMALIZATION ANALYSIS

Block 49 and the Avenue Lofts buildings were adjusted in order to normalize the comparison between the case studies. In Block 49, the garage and associated systems were removed from the analysis. The lower garage level was raised to the surface to represent slab-on-grade construction similar to New Holland. Underground parking was also removed from the Avenue Lofts building for purposes of the comparison.

Multifamily Residential



	New Construction	Rehabilitation and Retrofit	Warehouse Rehabilitation and Retrofit
Building Name	Block 49	New Holland Apartments	The Avenue Lofts
Location	Portland, OR	Danville, IL	Portland, OR
Year Built	Anticipated 2012	1906 with a 1927 addition	1923
Year Renovated	N/A	2006	2004
Building Height	6-story	5-story	7-story
SPACE SUMMARY			
Square Footage	167,180 residential, 19,640 retail excludes parking	73,875 including basement	215,000-sf excluding basement
Building Program Elements	209-unit rental, ground floor commercial, 2,000-sf community space, underground parking	47-unit, rental, 1- , 2- and 3-bedroom units	153-unit loft-style condos
Renovation Description	N/A	Ground source heat pump, replacement windows, masonry rehabilitation, lead paint and asbestos removal	Complete exterior refurbishment, high performance windows, full interior renovation, new vertical transportation, open atrium
Normalized	Removed parking & raised slab on grade to ground floor, assumed full build-out of retail space	N/A	Removed underground parking
CORE & SHELL			
Structure Type	Concrete, CMU, dimensional lumber	Concrete	Concrete
Envelope	Storefront, vinyl windows, 2x6 framing, batt insulation, membrane roofing	Operable windows, masonry and metal stud wall system, batt insulation, 3-tab asphalt roofing	Masonry wall system with elastomeric coating, operable windows, rigid and batt insulation, SBS roofing
Cladding	Brick veneer & metal panel	Brick	Brick
% Glazing (window : walll)	30%	20%	28%
HVAC System	Air to air heat pump per unit	Ground source heating and cooling, natural ventilation	Fan coils, electric heating coils and DX refrigerant lines
INTERIOR			
Scope	Gypsum wallboard, carpet and resilient flooring, plastic laminate countertops	Gypsum wallboard, wood framing, clay tile/plaster, carpet and vinyl flooring	Wood floors and trim, ceramic tile, metal framing drywall, exposed ceilings

ENERGY ANALYSIS

Table 4. summaries the EUIs used in the analysis across each of the profiled climate regions.

Table 4. Multifamily Residential End-Use EUIs by City

END-USE	CLIMATE ZONE RELATIVE EUI (KBTU/SF/YR)			
	PORTLAND	PHOENIX	CHICAGO	ATLANTA
Space Cooling	4	13	2	7
Space Heating	28	6	31	15
DHW	14	14	14	14
Refrigerators	3	3	3	3
Lighting & Appliances	14	14	14	14
TOTAL	63	50	64	53

Notes:
1. Space Heating & Cooling EUIs in table above are from RECS Table US1 for climate zones 1 through 5.
2. Methodology devised from feedback from peer group and NBI research across different climate zones.
3. EUI assumes 80% Apartment and 20% Core ratio.

Table 5 outlines EEMs for the Block 49, New Holland and Avenue Lofts buildings.

Table 5. Multifamily Residential EEM

MULTI-FAMILY RESIDENTIAL		
EEM	Additional EEMs to bring building to code	Additional EEMs to achieve 12% - 30% energy efficiency Improvement
LIGHTING/DAYLIGHTING		
50% of Fixtures Compact Fluorescent	NC, WH	
Corridors Lighting Power Density 0.5 watt/sf	WH	
Occupancy Sensors in Corridors		WH
HVAC		
Gas Boiler/Furnace 80% AFUE	RR	
Gas Boiler/Furnace 90% AFUE		WH
Gas Boiler/Furnace 95% AFUE		RR, NC
Water Source Heat Pump 4.5 COP		RR, NC
Variable Frequency Drive (VFD) HVAC Motors	WH	
Variable Refrigerant Flow Units 3.2 to 4.5 COP		WH
Energy Recovery Ventilator (ERV)		RR, NC, WH
ENVELOPE		
R-13 Wall Insulation	RR, NC, WH	
R-19 Wall Insulation		RR
R-20 Roof Insulation	WH	
Infiltration 0.35 air change/hour	NC	RR, WH
GLAZING		
Wood/Vinyl Windows U-0.54	RR	
Energy Star Windows U-0.32 or better		RR, NC, WH
Low-e Coated		WH
WATER HEATING		
Gas heat with 80% efficiency	NC	
Solar Thermal Hot Water		WH

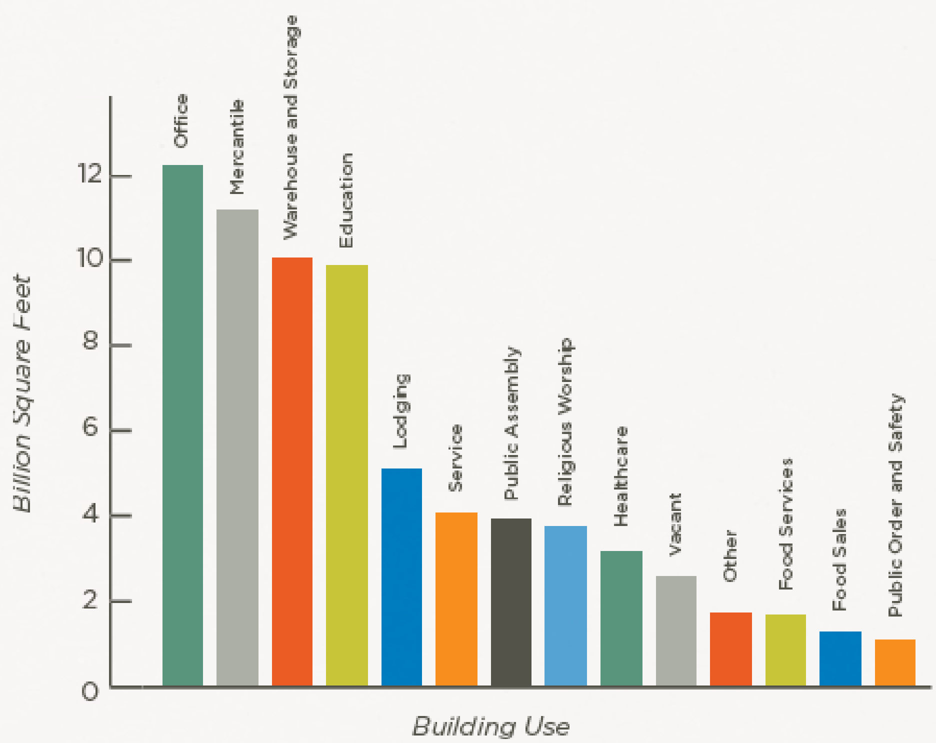
COMMERCIAL BUILDINGS

Commercial offices represent the largest portion of non-residential buildings in the United States, with over 12 billion square feet of existing floor space.[34] Nationally, these buildings average 14,800 square feet in size; the vast majority of these buildings possess under 25,000 square feet.

This study examines three building types in this category:

- Urban Village Mixed-Use
- Commercial Office Building
- Elementary School

Figure 10: Commercial Building Stock in the U.S.



Source: U.S. Energy Information Administration

URBAN VILLAGE MIXED-USE

Mercantile buildings represent the second-largest quantity of commercial building stock in the United States. Buildings were selected for study under the ‘urban village mixed-use’ subcategory if they met the following criteria: (1) A traditional mercantile building, with (2) mix-used ground oor retail, or an o ce with one or two stories of o ces or residential above; (3) party wall construction, and (4) a preference for pre-1940’s vintage buildings.

Urban Village Mixed-Use refers to the classic ‘Main Street’ buildings that are common in historic neighborhoods and older, downtown core areas of small and medium-sized cities around the country. The following buildings were selected for the comparison:

- **NC scenario:** Assurety Northwest Building (Portland, OR)
- **RR scenario:** Whitmore Building (Woodbine, IA)

NORMALIZATION ANALYSIS

The normalization analysis for buildings in this subcategory involved removing foundations and other structural elements of the Assurety Northwest Building associated with a future pedestrian bridge. In addition, appliances and commercial kitchen equipment were excluded.

Urban Village Mixed-Use

	New Construction	Rehabilitation and Retrofit
Building Name	Assurety Northwest Building	Whitmore Building
Location	Portland, Oregon	Woodbine, Iowa
Year Built	2009	1880
Year Renovated	N/A	2010
Building Height	2-story	2-story
SPACE SUMMARY		
Square Footage	22,975	21,785 including basement
Building Program Elements	Mixed-use commercial office and retail	Mixed-use commercial office, restaurant and residential
Renovation Description	N/A	Extensive energy upgrades including installation of ground source heat pump, insulation, and new and refurbished windows, architectural restoration
Normalized	Removed foundations and other support structure for a future pedestrian bridge designed to connect to an adjacent building	Removed appliances and commercial kitchen equipment.
CORE & SHELL		
Structure Type	Steel structure on concrete spread footings with slab on grade and slab on metal deck	Slab on grade, masonry wall system
Envelope	Punched window and storefront systems, perimeter insulation	Double hung wood windows, single glazing, masonry wall system
Cladding	Storefront, brick	Storefront, brick
% Glazing (window : walll)	34%	34%
HVAC System	Rooftop units for air supply with electric reheat in VAVs	Ground source heating and cooling
INTERIOR		
Scope	Typical open office build out some perimeter offices	Gypsum wallboard, plaster finish, carpet and Wood flooring, wood frame, drywall

ENERGY ANALYSIS

Table 6 summaries the EUIs used in the analysis across each of the four climate regions.

Table 6. Urban Village Mixed-Use End-Use EUIs by City

END-USE	CLIMATE ZONE RELATIVE EUI (KBTU/SF/YR)			
	PORTLAND	PHOENIX	CHICAGO	ATLANTA
Space Cooling	3	17	3	10
Space Heating	17	4	42	16
DHW	2	2	2	2
Vent Fans	10	11	9	10
Pumps & Aux	0	0	0	0
Extr. Lighting	3	3	3	3
Misc. Equipment	16	16	16	16
Int. Lighting	19	19	19	19
SUBTOTAL	71	72	94	76
ADJUSTMENT FACTOR %	1	1.02	1.33	1.08

Notes:
1. EUI of 71 kBTU/sf was determined from an average weighted calculation of retail & office space EUIs chosen from CBECS EUI tables.
2. Methodology devised from feedback from peer group and NBI research across different climate zones.
3. EUI's adjusted by climate zone in alignment with Table 6 in NBI Sensitivity Analysis Study (page 47) dated July 2011
4. Climate zone adjustment factors above will be used consistently across all other commercial buildings in this study.

Table 7 outlines the EEMs for the Whitmore and Assurety Northwest Buildings.

Table 7. Urban Village Mixed-Use EEM

URBAN VILLAGE		
EEM	Additional EEMs to bring building to code	Additional EEMs to achieve 12% - 30% energy efficiency Improvement
LIGHTING/DAYLIGHTING		
50% of Fixtures Compact Fluorescent		
Occupancy Sensors	RR, NC	
Daylight Dimming Controls	NC	RR
Retail Lighting Power Density 1.4 watt/sf	NC	
Office Lighting Power Density 1.1 watt/sf	NC	
HVAC		
Variable Frequency Drive HVAC Motors	RR, NC	
Gas Boiler/Furnace 90% AFUE		RR
Chilled Beams in Offices		RR, NC
Variable Refrigerant Flow Units 3.2 to 4.5 COP		RR, NC
Energy Recovery Ventilator (ERV)		RR
Infiltration 0.7 air change/hour	NC	
ENVELOPE		
R-13 Wall Insulation	NC	
R-20 Roof Insulation	NC	
Infiltration 0.35 air change/hour		RR
GLAZING		
Energy Star Windows U-0.32 or better	NC	RR
Low-e Coated	NC	RR
WATER HEATING		
Gas heat with 80% efficiency		
Solar Thermal Hot Water		RR, NC

COMMERCIAL OFFICE BUILDING

While the Urban Village Mixed-Use scenario allows for an analysis of life cycle impacts related to smaller commercial buildings, the Commercial O ce building category re ects a type of non-residential building stock that is commonly larger scale.

The commercial o ce buildings selected for this study belong to three di erent subtypes:

- **NC scenario:** 818 Stewart Ave (Seattle, WA)
- **RR scenario:** Joseph Vance Building (Seattle, WA)
- **RR warehouse scenario:** 14th & Everett Building (Portland, OR)

NORMALIZATION ANALYSIS

In order to normalize the functions of the three buildings in this category, the 818 Stewart parking structure was removed from the analysis. This was achieved by eliminating the four oors dedicated solely to parking and adjusting the total material and system quantities that make up the building envelope and structure and mechanical, electrical and plumbing systems to re ect a smaller, overall square footage. The existing, small parking area belonging to the 14th & Everett building was also eliminated.

Commercial Office

			
	New Construction	**Rehabilitation and Retrofit**	**Warehouse Rehabilitation and Retrofit**
Building Name	818 Stewart	Joseph Vance Building	14th & Everett
Location	Seattle, WA	Seattle, WA	Portland, OR
Year Built	2008	1929	1927
Year Renovated	N/A	2007	2011
Building Height	14-story	14-story	5-story
SPACE SUMMARY			
Square Footage	265,845	128,007	188,097
Building Program Elements	Ground floor retail, multi-tenant commercial office	Ground floor retail, multi-tenant commercial office	Single tenant commercial office
Renovation Description	N/A	Interior finishes updated, repairs to mechanical system, operable windows refurbished	Full exterior envelope upgrade and major interior renovation, added elevators
Normalized	Removed parking structure	N/A	Removed small parking area
CORE & SHELL			
Structure Type	Concrete and Steel	Steel	Concrete and steel
Envelope	Curtainwall, rigid and batt insulation, built-up roofing	Double hung operable windows, single glazing, masonry wall system	Concrete/masonry assembly, rigid and batt insulation, high performance windows
Cladding	Glass, metal panel, precast concrete	Terra cotta	Concrete and masonry with elastomeric coating
% Glazing (window : walll)	38%	25%	27%
HVAC System	Split direct expansion heating and A/C, every other floor	Steam and natural ventilation	Electric, underfloor air distribution, variable refrigerant flow heating and cooling system at perimeter
INTERIOR			
Type	Open office	Closed office	Open office
Scope	Carpet, vinyl flooring, metal framing, casework	Carpet, plaster/GWB, metal, masonry, casework, terrazzo lobbies/corridor	Access flooring, flexible glass interior wall system

ENERGY ANALYSIS

Table 8 summaries the EUIs used in the analysis across each of the four cities.

Table 8. Commercial Office End-Use EUIs by City

END-USE	CLIMATE ZONE RELATIVE EUI (KBTU/SF/YR)			
	PORTLAND	PHOENIX	CHICAGO	ATLANTA
Space Cooling	2	20	7	13
Space Heating	19	0	38	16
DHW	1	1	1	1
Vent Fans	12	14	11	10
Pumps & Aux	0	0	0	0
Extr. Lighting	5	5	5	5
Misc. Equipment	16	16	16	16
Int. Lighting	15	15	15	15
SUBTOTAL	70	71	93	76
ADJUSTMENT FACTOR %	1	1.02	1.33	1.08

Notes:

1. EUI of 70 kBTU/sf chosen for base case (Portland) based on Cadmus Study entitled "Northwest Commercial Building Stock Assessment" dated December 2009.

2. Methodology devised from feedback from peer group and NBI research across different climate zones.

3. EUI's adjusted by climate zone in alignment with Table 6 in NBI Sensitivity Analysis Study (page 47) dated July 2011

4. Climate zone adjustment factors above will be used consistently across all other commercial buildings in this study.

Table 9 outlines the EEMs for the Joseph Vance, 818 Stewart, and 14th & Everett Buildings.

Table 9. Commercial Office Building EEM

COMMERCIAL OFFICE		
EEM	Additional EEMs to bring building to code	Additional EEMs to achieve 12% - 30% energy efficiency Improvement
LIGHTING/DAYLIGHTING		
Building Lighting Power Density 0.8 watt/sf	NC	
Night Sweep/Occupancy Sensors	NC, WH	
Building Lighting Power Density 0.85 watt/sf	WH	
Office Lighting Power Density 0.8 watt/sf	WH	
Daylight Dimming Controls	WH	
HVAC		
Demand Control Ventilation (DCV)		RR, NC
Variable Frequency Drive (VFD) HVAC Motors	NC, WH	RR
Chilled Beams		RR, NC
Boiler 90%+ Minimum Efficiency	NC, WH	
Economizer Control	NC	RR
Heat Recovery of Exhaust Flow		RR, NC, WH
ENVELOPE		
R-20 Roof Insulation	RR, NC, WH	
R-13 Wall Insulation	RR, NC, WH	
R-19 Wall Insulation		RR
Infiltration Reduction- Caulking	RR	
Infiltration 0.20 air change/hour	RR, NC	WH
GLAZING		
U-0.32 or better	RR, NC, WH	
Low-e Coated	RR, NC, WH	
WATER HEATING		
Gas heat with 90% efficiency	RR, NC	RR
Gas heat with 93% efficiency	WH	
Solar Thermal Hot Water		WH
Hot Water Pipe Insulation	NC	

ELEMENTARY SCHOOLS

Educational facilities represent the fourth-largest quantity of non-residential commercial building stock in the United States.[35] Due to a number of market factors, including state-required acreage standards and a lack of tax incentives for rehabilitation, small community-centered schools are now being replaced by 'mega-schools' on the outskirts of towns. For this reason, a pre-1940s, urban elementary school building is compared here with a new elementary school.

The following educational buildings were selected for this analysis:

- **NC scenario:** Sue Buell Elementary School (McMinnville, OR)
- **RR scenario:** Central Elementary School (Albemarle, NC)

NORMALIZATION ANALYSIS

No additional analyses were needed to normalize the basic programmatic elements of the buildings selected.

Elementary School

	New Construction	Rehabilitation and Retrofit
Building Name	Sue Buel Elementary	Central Elementary
Location	McMinnville, OR	Albemarle, NC
Year Built	2008	1924
Year Renovated	N/A	2008
Building Height	2-story	3-story
SPACE SUMMARY		
Square Footage	80,837	60,121 existing, 37,626 (new addition)
Building Program Elements	Classrooms, gymnasium, cafeteria and kitchen, auditorium, commons, music room	Classrooms, gymnasium, cafeteria, media center
Renovation Description	N/A	New kitchen, new classrooms, refurbishment of existing rooms, energy upgrades
Normalized	N/A	N/A
CORE & SHELL		
Structure Type	Slab on grade, concrete tilt-up construction	Concrete and steel
Envelope	Storefront, tilt-up walls, rigid and batt insulation, membrane roofing	Masonry wall system, rigid and batt insulation, upgraded windows, SBS roofing
Cladding	CMU veneer, metal wall panels	Masonry
% Glazing (window : walll)	24%	22%
HVAC System	Four pipe chilled/heated water system to distributed fan boxes using heat recovery boxes	Four pipe system, gas boiler and chiller
INTERIOR		
Scope	Plastic laminate countertops, cabinetry, acoustical ceiling tile, carpet, ceramic and linoleum flooring, built-in cabinetry	VCT floor, ACT, metal framing, drywall

ENERGY ANALYSIS

Table 10 summarizes the EUIs used in the analysis across each of the four cities.

Table 10. Elementary School End-Use EUIs by City

END-USE	CLIMATE ZONE RELATIVE EUI (KBTU/SF/YR)			
	PORTLAND	PHOENIX	CHICAGO	ATLANTA
Space Cooling	3	25	2	16
Space Heating	27	5	48	19
DHW	6	6	6	6
Vent Fans	6	7	5	6
Pumps & Aux	0	0	0	0
Extr. Lighting	1	1	1	1
Misc. Equipment	7	7	7	7
Int. Lighting	10	10	10	10
SUBTOTAL	60	61	80	65
ADJUSTMENT FACTOR %	1	1.02	1.33	1.08

Notes:
1. EUI of 60 kBTU/sf chosen for base case (Portland) based on table within Oregon DOE SEED EUIs for Elementary School.
2. Methodology devised from feedback from peer group and NBI on their research across different climate zones.
3. EUI's adjusted by climate zone in alignment with Table 6 in NBI Sensitivity Analysis Study (page 47) dated July 2011
4. Climate zone adjustment factors above will be used consistently across all other commercial buildings in this study.
5. Space Cooling & Heating figures derived from relative performance using CBECS data (http://buildingsdatabook.eren.doe.gov/CBECS.aspx). All other end-uses were kept consistent.

Table 11 outlines the EEMs for the Sue Buel and Central Elementary School buildings.

Table 11. Elementary School EEM

ELEMENTARY SCHOOL		
EEM	Additional EEMs to bring building to code	Additional EEMs to achieve 12% – 30% energy e ciency Improvement
LIGHTING/DAYLIGHTING		
Night Sweep/Occupancy Sensors	RR, NC	
Daylight Dimming Controls in Classrooms		RR
Classroom Lighting Power Density 1.4 watt/sf	NC	
O ce Lighting Power Density 1.1 watt/sf	NC	
HVAC		
Variable Frequency Drive (VFD) HVAC Motors	NC	
HVAC Chiller E ciency 4.5 to 6.4 COP		
Demand Control Ventilation (DCV) in Classrooms and Assembly Spaces		RR
Chilled Beams in Classrooms		RR, NC
Boiler 90%+ Minimum E ciency	NC	RR
In ltration 0.7 air change/hour	NC	
Energy Recovery Ventilator (ERV)		RR
Variable Flow Kitchen Exhaust/MUA System		RR, NC
ENVELOPE		
R-13 Wall Insulation	RR, NC	
R-20 Roof Insulation	NC	
In ltration 0.35 air change/hour		RR
GLAZING		
Energy Star U-0.32 or better	RR, NC	
Low-e Coated	RR, NC	
WATER HEATING		
Gas heat with 93% e ciency	RR, NC	
Solar Thermal Hot Water		RR, NC

6. RESULTS AND KEY FINDINGS

The results of this LCA reflect the relative environmental value of building reuse and renovation as compared to demolition and new construction. This section summarizes these results and highlights the following key findings for the scenarios analyzed in this study:

- **Building reuse almost always yields fewer environmental impacts than new construction when comparing buildings of similar size and functionality.**
- **Reuse of buildings with an average level of energy performance consistently offers immediate climate change impact reductions compared to more energy efficient new construction.**
- **Materials matter: The quantity and type of materials used in a building renovation can reduce, or even negate, the benefits of reuse.**

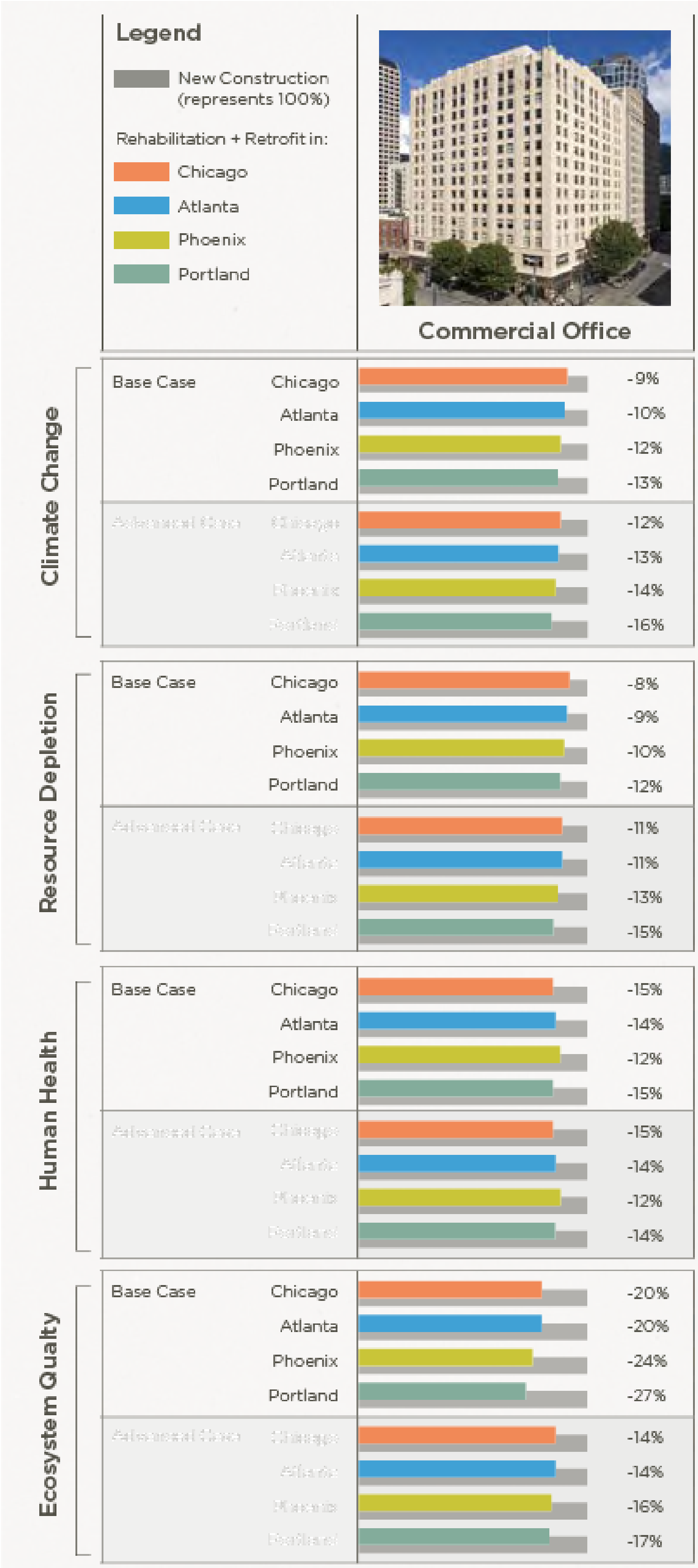
A complete description of the results generated in this study is contained in the *Technical Appendices.*

I. BUILDING REUSE ALMOST ALWAYS YIELDS FEWER ENVIRONMENTAL IMPACTS THAN NEW CONSTRUCTION WHEN COMPARING BUILDINGS OF SIMILAR SIZE AND FUNCTIONALITY.

The results of this analysis indicate that the renovation and reuse of existing buildings of comparable functionality and size, and equivalent energy efficiency levels, consistently yield fewer environmental impacts than demolition and new construction over a 75-year period. These findings apply to both the Base Case and Advanced Case test conditions, irrespective of building typology, local climate, and projected variations in grid mix.[36]

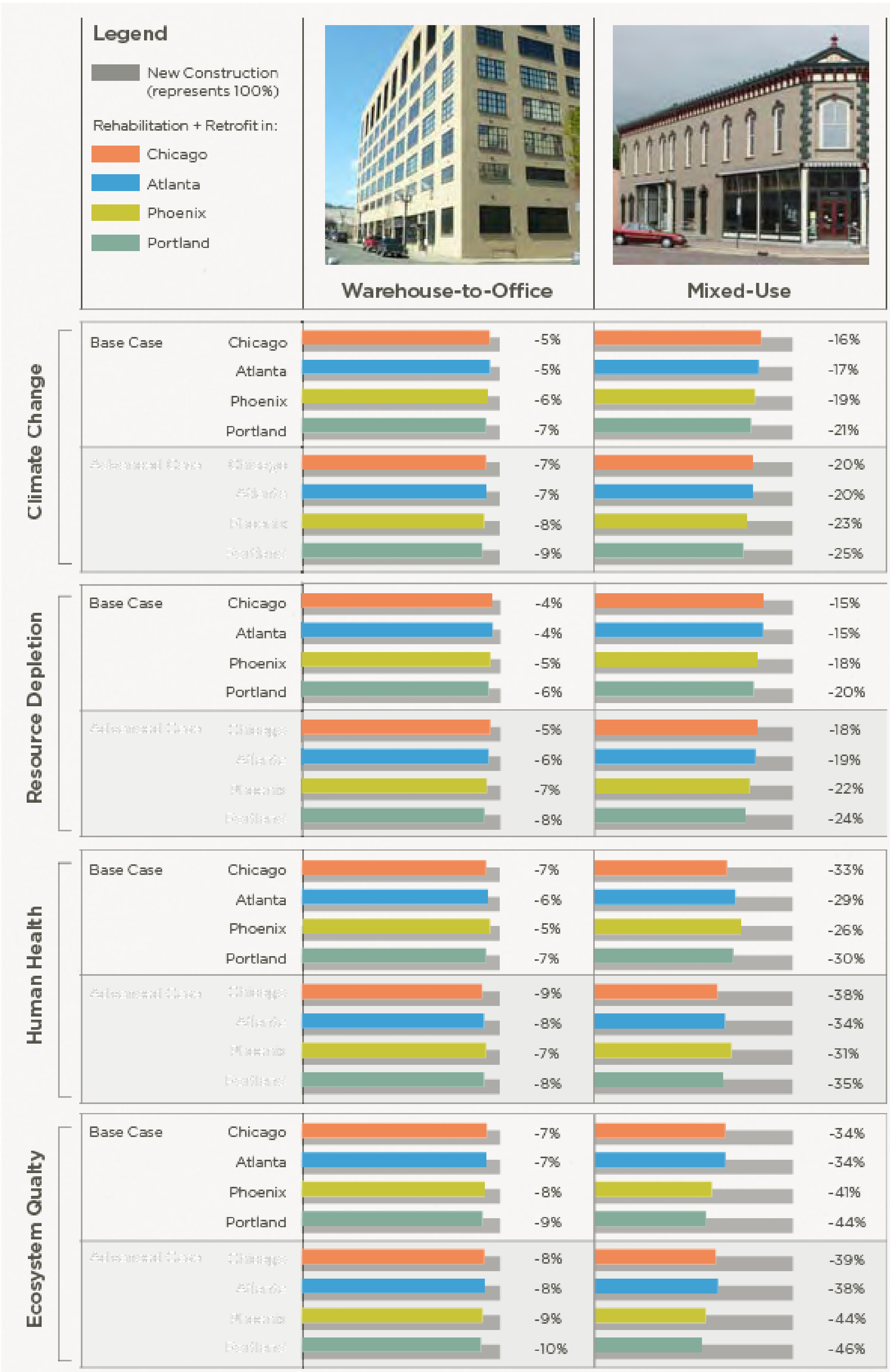
This finding is not unexpected, as operating performance is assumed to be equivalent for the reuse and new construction scenarios, and new construction typically uses more materials than renovation. However, the results of the Base Case analysis depict a notable range of differences in environmental impacts between the NC and RR scenarios for each of the locations studied. These differences are represented in Figures 11 – 14. The *range of savings* from building reuse varies widely, based on building type, region/climate, and impact category (i.e., Climate Change, Human Health, Resource Depletion, and Ecosystem Quality), from between 4 and 44-percent less than the environmental impacts associated with new construction. The warehouse-to-multifamily conversion scenario is an exception to this finding; the savings for this scenario range from *between 8-percent fewer impacts to 6-percent* ***greater*** *impacts* as compared to new construction.

Figure 11: Commercial Office Summary of Results - Impacts of Renovation Expressed as a Percentage of New Construction



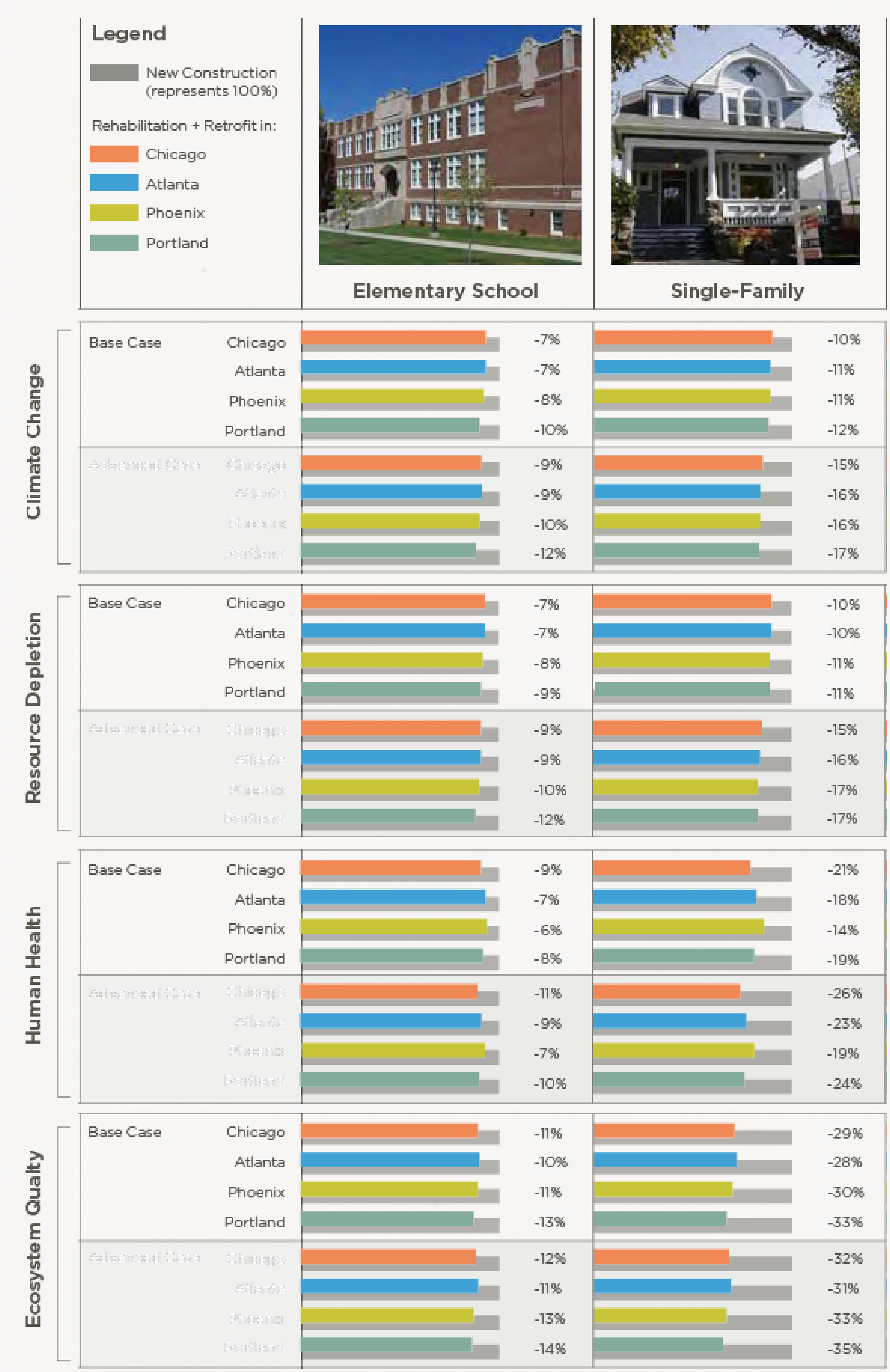
Figures 11 – 14 indicate that the renovation and reuse of existing buildings of comparable functionality and size almost always yield fewer environmental impacts than demolition and new construction over a 75-year period, when comparing buildings with equivalent energy efficiency levels. However, the range of savings varies greatly. In this study, the Base Case assumes an average level of energy efficiency for existing and new buildings, while the Advanced Case assumes a 30-percent improvement in energy performance over the Base Case.

Figure 12: Warehouse-to-Office and Mixed-Use Summary of Results - Impacts of Renovation Expressed as a Percentage of New Construction



Each building type represented in the analysis is considered to have a distinct functional unit providing one square foot of floor space for the use appropriate to that building type. For this reason, results cannot be compared across building types.

Figure 13: Elementary School and Single-Family Summary of Results - Impacts of Renovation Expressed as a Percentage of New Construction



Each building type represented in the analysis is considered to have a distinct functional unit providing one square foot of floor space for the use appropriate to that building type. For this reason, results cannot be compared across building types.

Figure 14: Multifamily and Warehouse-to-Multifamily Summary of Results - Impacts of Renovation Expressed as a Percentage of New Construction

Each building type represented in the analysis is considered to have a distinct functional unit providing one square foot of floor space for the use appropriate to that building type. For this reason, results cannot be compared across building types.

EFFECTS OF ENERGY PERFORMANCE

When comparing the Advanced Case test conditions, where both the RR and NC building scenarios are performing at 30-percent efficiency over the Base Case, rehabilitation and retrofit still outperform new construction, yielding fewer impacts over a 75-year lifespan (see Figures 11 – 14). This is true for all impact categories and building types, except the warehouse-to-multifamily conversion case study; the difference in environmental impacts for the Advanced Case test condition ranges from 46-percent fewer impacts to 5-percent *greater* impacts as compared to new construction.

This study provides significant findings in the Climate Change impact category. In the Base Case test condition, building reuse can lower carbon-related impacts for all building typologies, as shown in Figures 11 – 14. For instance, over the course of a building's 75-year life span, this adds up to 13 percent savings for commercial buildings and 12 percent savings for single-family dwellings in Portland as compared to demolition and new construction. In contrast, the warehouse-to-office and warehouse-to-residential conversion scenarios yield climate change savings of 7 and 8 percent in Portland, respectively, over new construction. This suggests that building types that require minimal material inputs during the renovation process will realize the greatest savings.

These same findings on climate change hold true for the Advanced Case test conditions. The range of climate change savings observed for the Advanced Case reuse scenario, as compared to the Advanced Case new construction scenario, is between 7 and 25 percent. While these savings may seem modest or negligible at the building scale, the potential for savings across a larger population of buildings is substantial.

IMPACT DRIVERS FOR NEW CONSTRUCTION AND REUSE

The relative environmental profiles of the buildings is primarily determined by *differences in types and quantities of materials*, where energy performance is deemed equivalent for the RR and NC scenarios. New construction typically requires a large quantity of material inputs, which generates a greater magnitude of immediate impacts. This is true across climate zones and almost all of the building types analyzed in this study, as shown in Figures 15 – 21.

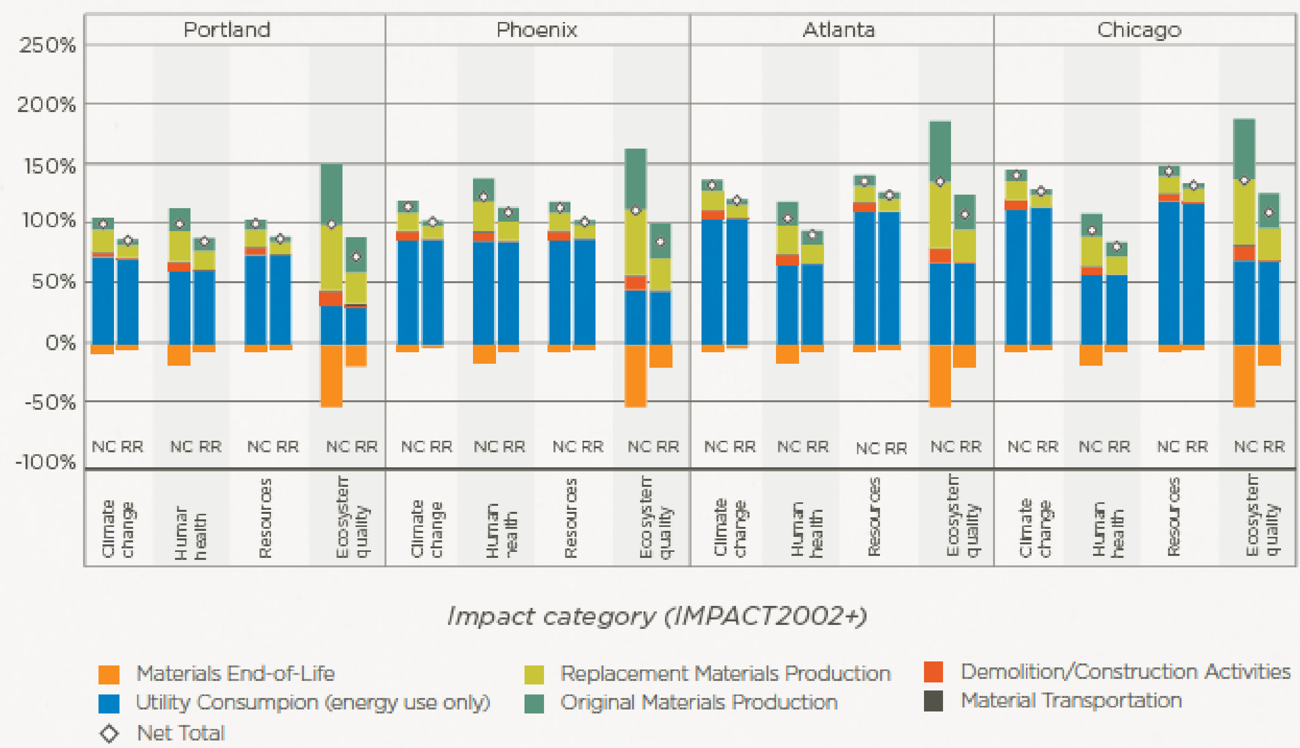
Various life cycle stages contribute to the overall environmental impact of a building (see Figures 15 – 21).[37] However, for the Climate Change, Resource, and Human Health impact categories, operating energy (i.e., as determined by end-use profiles and EUIs) is typically the dominant driver of building environmental impacts. In the Ecosystem Quality impact category, materials drive a notably larger share of overall life cycle impacts, suggesting that the potential for damage to wildlife species is more dependent on materials manufacturing processes than other elements of building life cycles.

An exception to this is the warehouse-to-multifamily scenario, as depicted in Figure 21. This scenario involved extensive renovation and repurposing of the existing building, and therefore a large quantity of material inputs, rendering reuse *less* environmentally preferable than demolition and new construction in two impact categories, human health and ecosystem quality. Material selections likely played a significant role in these results, since more materials were used in the newly constructed building.

EFFECTS OF CLIMATE

The results of this analysis indicate that the *total environmental impact* of a building depends on climate region, as indicated by Figures 15 - 21. This is due to variations in EUI; the ways that buildings use energy (i.e., end-use distribution); and regional electricity grid mixes.[38] For example, a commercial building in Portland has less environmental impact than the same commercial building in Chicago, because Chicago's climate is more extreme; its grid mix is predominately coal-based; and a building in Chicago has a distinctly different energy end-use distribution. While variations in climate may alter the degree to which building reuse is environmentally preferable to new construction, *geographical differences do not influence the finding that reuse is almost always preferable to new construction.*

Figure 15: Impacts by Lifecycle Stage - Commercial Office



Figures 15 - 21 show environmental impacts, by lifecycle stage, as a percentage of impacts for new construction in Portland, Oregon, on a square-foot basis. The diamonds on each bar represent total impacts for each building and take into account the savings offered by recycling materials at the end of their respective lifecycles.

The graphs show that in the Climate Change, Resources, and Human Health impact categories, building operating energy is typically the dominant driver of environmental impacts. In the Ecosystem Quality impact category, materials drive a noticeably larger share of overall lifecycle impacts. Figures 15 - 21 also demonstrate that a building's total environmental impact varies by climate region, though differences in geography do not influence the finding that reuse is almost always preferable to new construction.

Figure 16: Impacts by Lifecycle Stage - Warehouse-to-Commercial Office

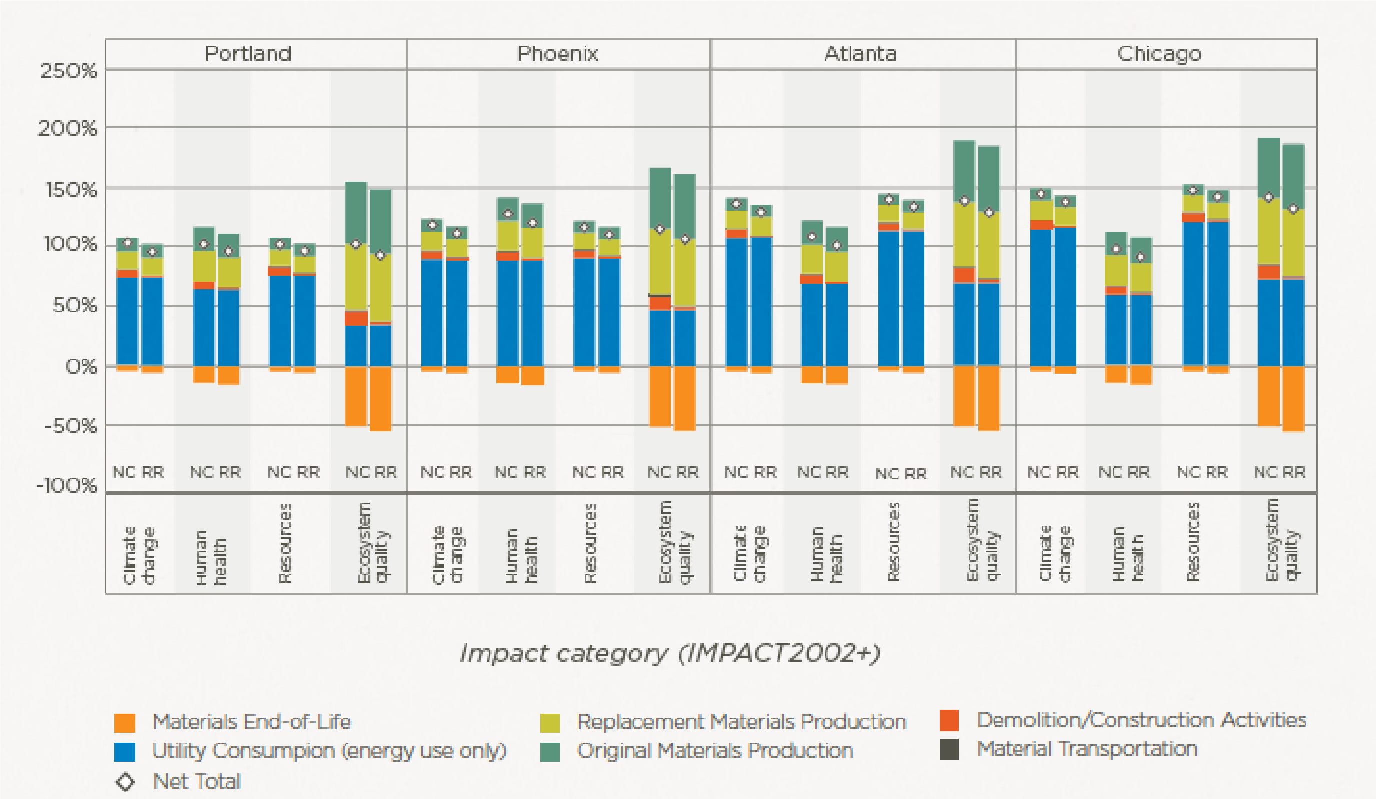


Figure 17: Impacts by Lifecycle Stage - Urban Village Mixed-Use

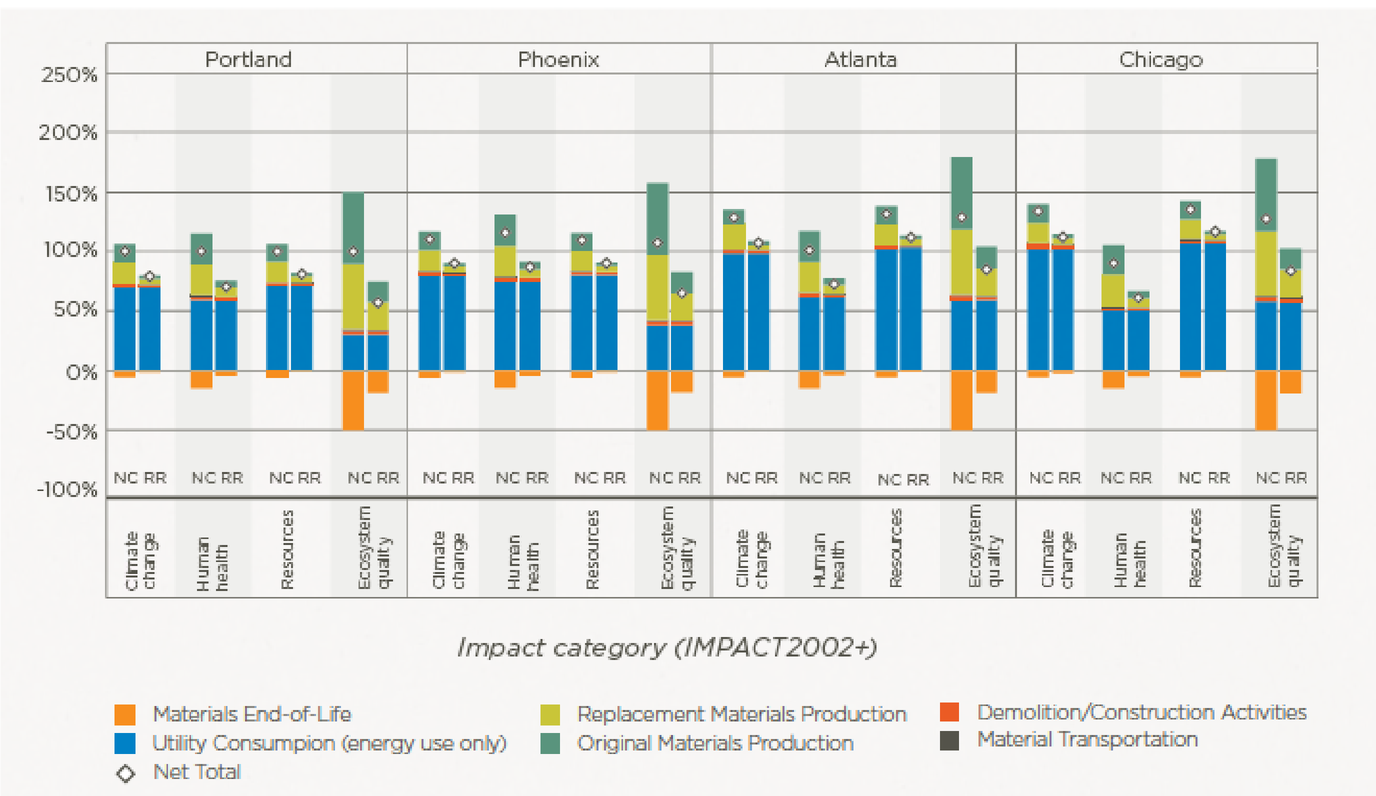


Figure 18: Impacts by Lifecycle Stage - Elementary School

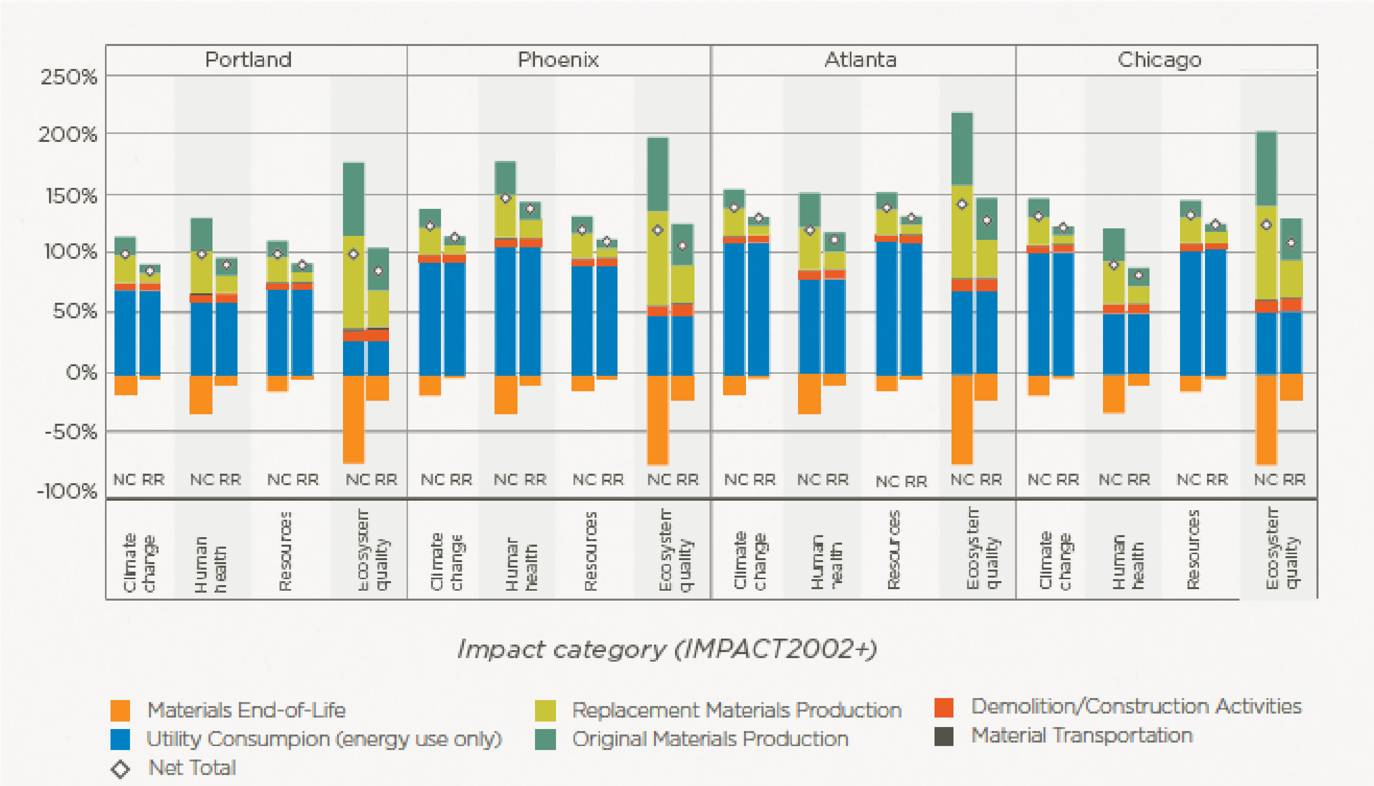


Figure 19: Impacts by Lifecycle Stage - Single-Family Residential

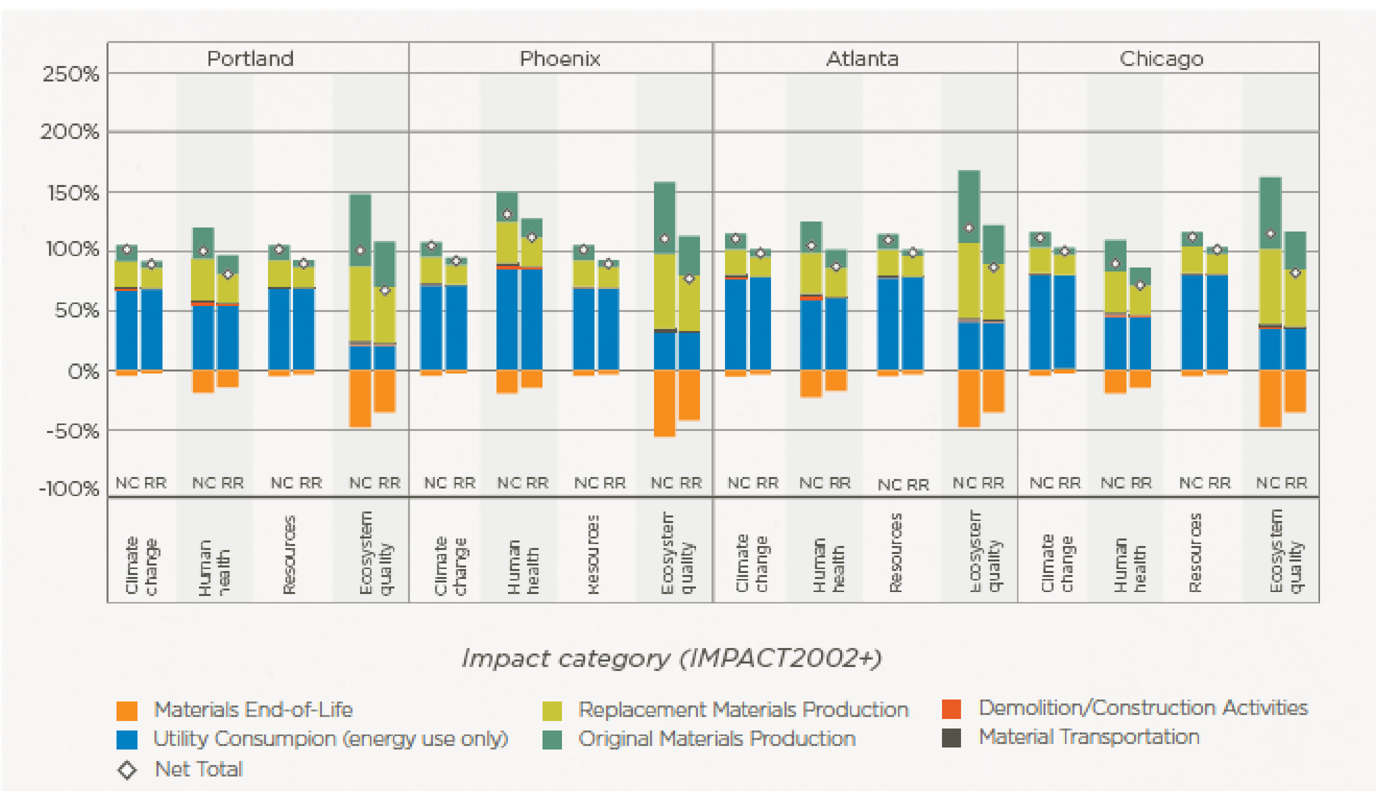


Figure 20: Impacts by Lifecycle Stage - Multifamily Residential

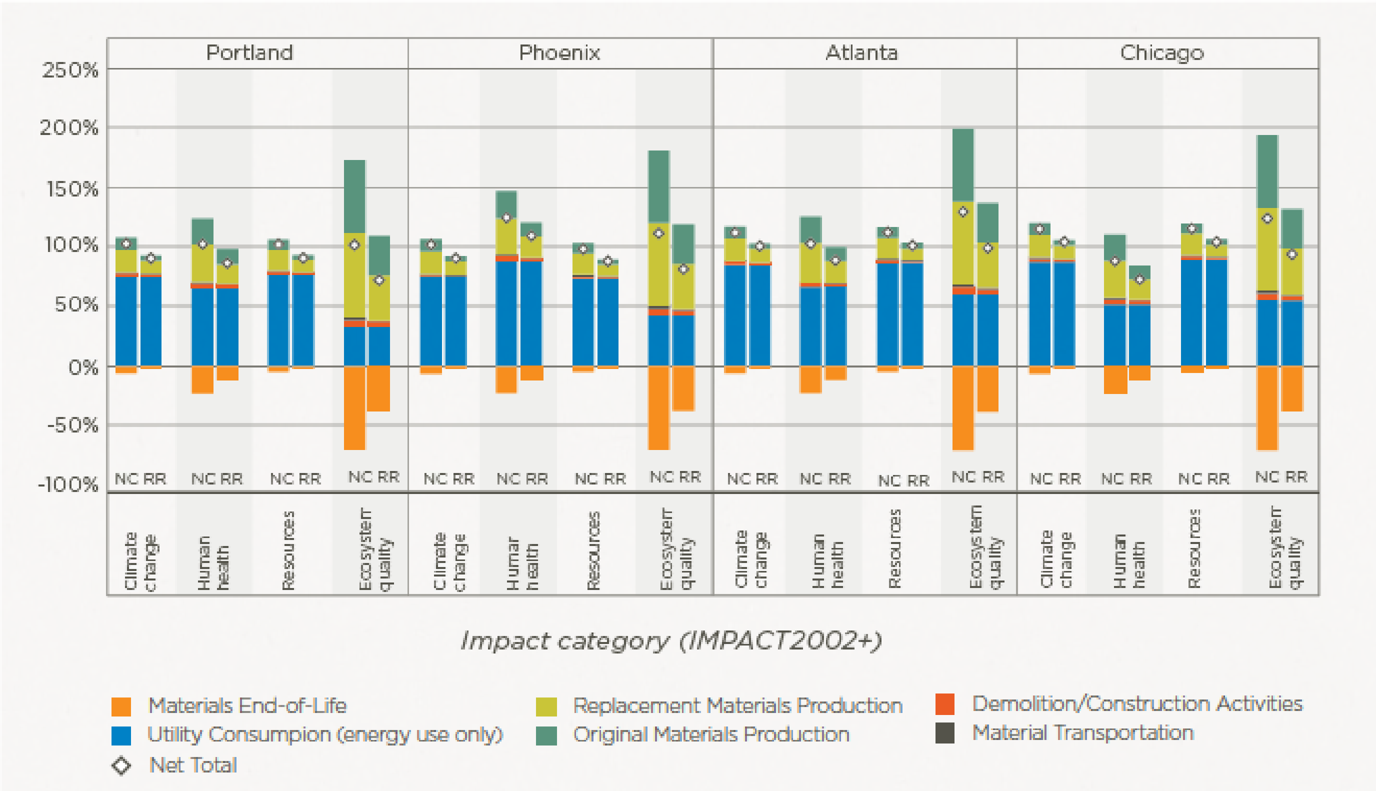
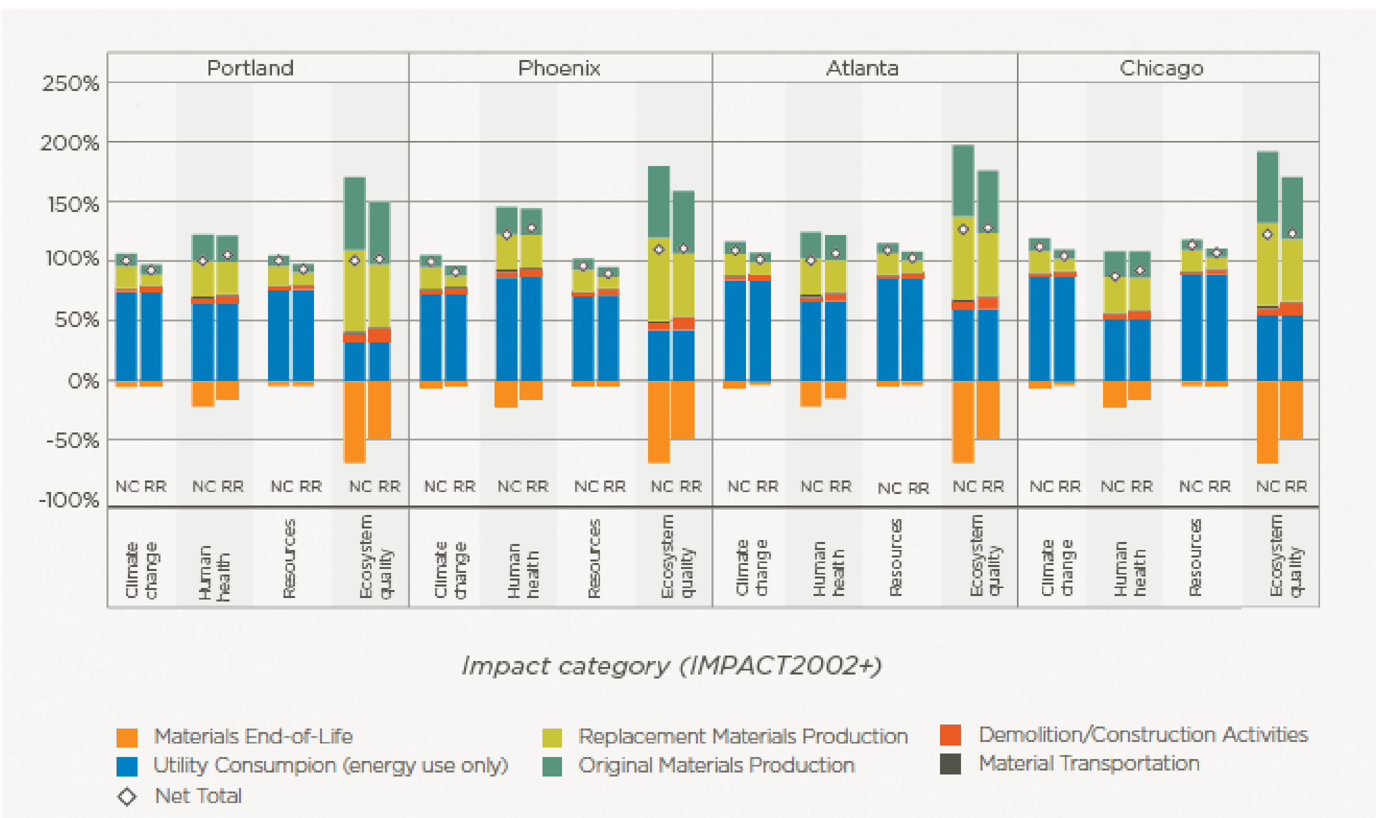


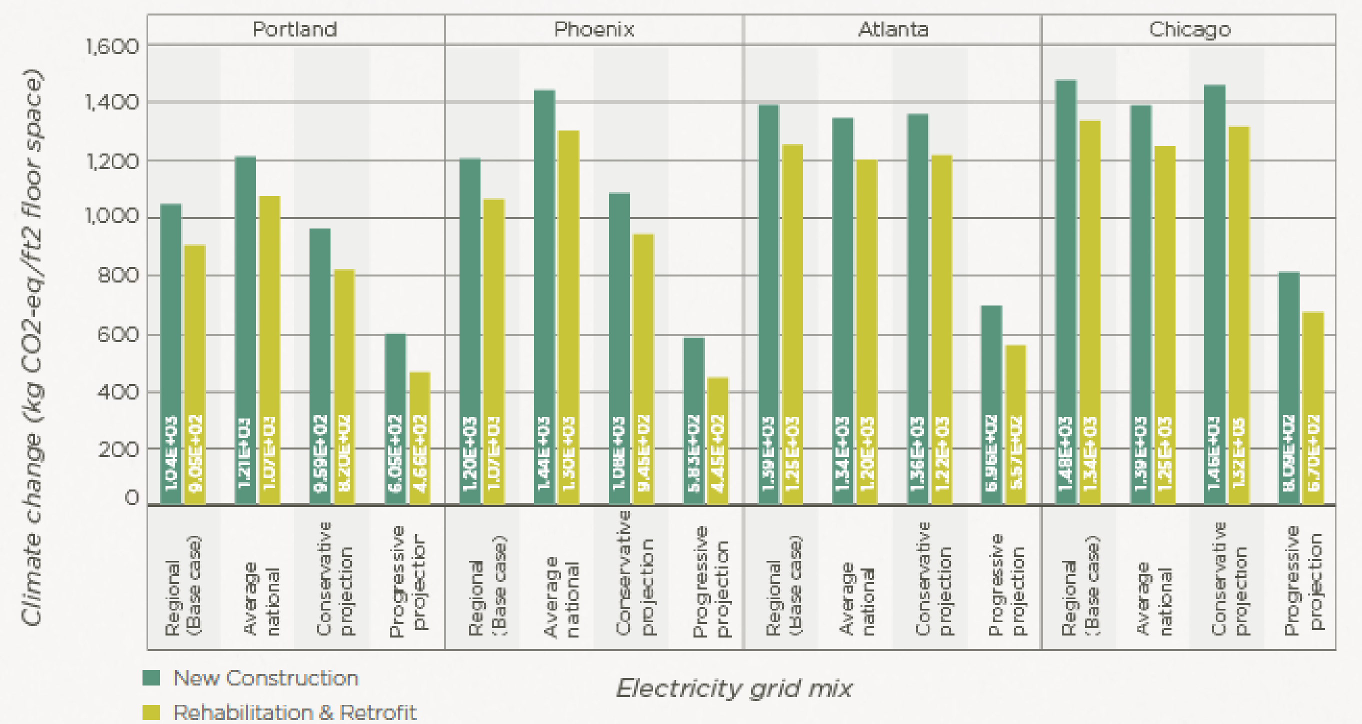
Figure 21: Impacts by Lifecycle Stage - Warehouse-to-Multifamily



EFFECTS OF GRID MIX

For each city in this study, the Base Case analysis relies on a regional grid mix, based on the U.S. EPA's eGRID2010. A sensitivity analysis was performed to evaluate how variations in grid mix may affect the results of the study. The grid-mix sensitivity analysis reveals that, while projections towards a 'cleaner' grid—one that includes more renewable sources—will impact the total quantity of carbon-related impacts, the relationship between the relative value of reuse versus new construction remains constant (see Figure 22).

Figure 22. Climate Change Impacts For Commercial Office, Based on Various Grid Mix Projections.



The energy sources used to generate electricity in each region will likely vary over the course of 75 years. A sensitivity analysis was run to analyze how climate change impacts for one building type, commercial office, may change as the grid mix shifts toward 'cleaner' technologies (i.e., more renewable sources). The ***conservative*** *projection is based on EIA's prediction of the national average grid mix over the next 25 years. The* ***progressive*** *projection assumes that a 100-percent renewable grid mix is achieved by 2050. Regardless of projected variations in grid mix, the results of this study indicate that the relative difference between reuse and the construction of new commercial buildings does not change.*

II. REUSE OF BUILDINGS WITH AN AVERAGE LEVEL OF ENERGY PERFORMANCE CONSISTENTLY OFFERS IMMEDIATE CLIMATE CHANGE IMPACT REDUCTIONS COMPARED TO MORE ENERGY EFFICIENT NEW CONSTRUCTION.

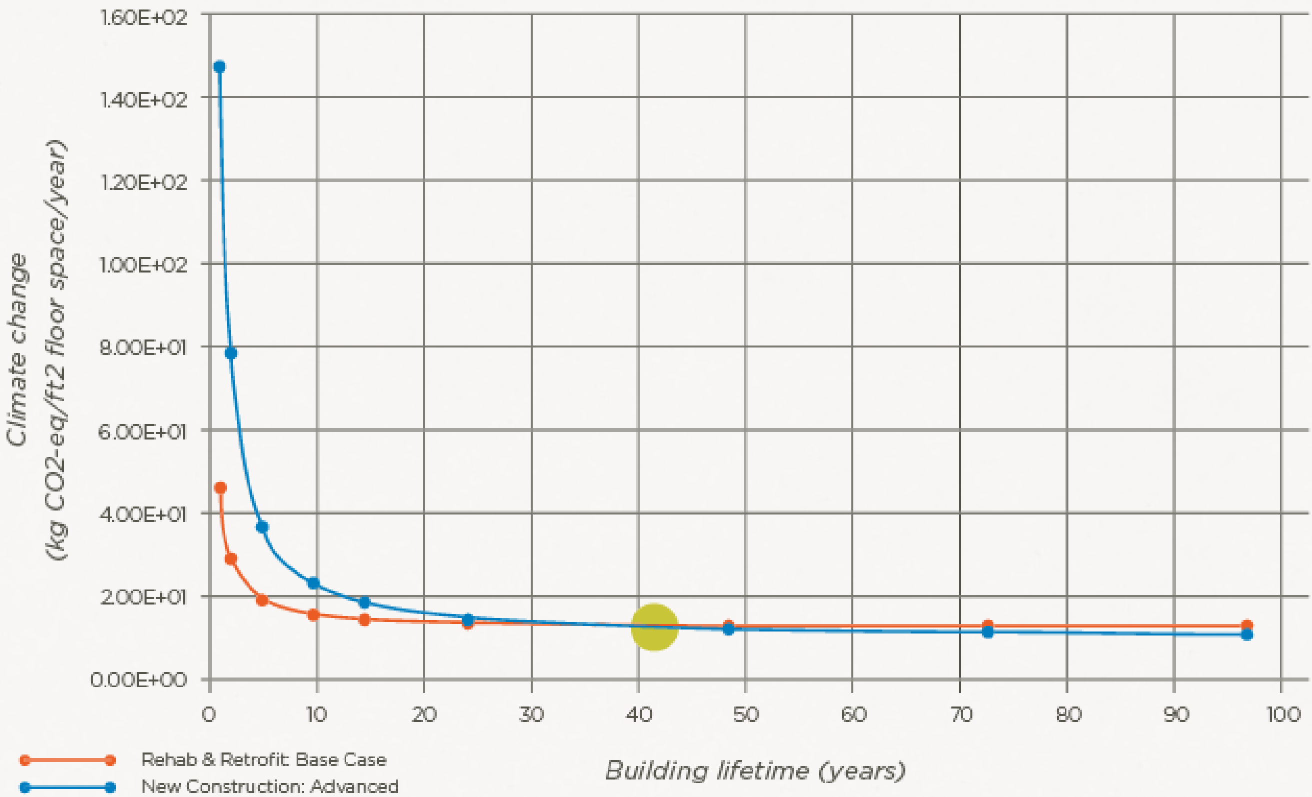
It is often assumed that new construction will operate more efficiently than an existing building. Indeed, in many instances, this holds true. However, this study finds that, when a renovated building that meets a Base Case level of energy performance is compared to a new building operating at a more advanced level of efficiency, the RR scenario offers immediate environmental savings for the majority of building types tested. *This finding is particularly relevant to our understanding of climate change impacts*. In particular, renovated buildings with fewer material inputs have the potential to realize the greatest short-term carbon savings.

Both the NC and RR scenarios require an initial outlay of materials; the NC scenario requires materials to construct an energy efficient building, and the RR scenario uses materials to make renovations that ensure contemporary functionality and a Base Case level of energy performance. The use and maintenance of these buildings over their (assumed) 75-year lifespans require energy for operation and replacement materials to maintain the buildings as some of their elements wear out over time.

In this analysis, the project team plotted the environmental impacts resulting from NC and RR materials usage and operating energy over time. Figures 23 - 26 chart climate change impacts for NC Advanced Case and RR Base Case commercial buildings in each of the four cities studied, with building life spans ranging from 1 to 100 years. The higher climate change impacts associated with new construction are most clearly visible in a building's early years, as seen in Figures 23 -26. As building lifetime increases, however, and the NC building operates more efficiently than the existing building, the gap in climate change impacts between NC and RR scenarios narrows.

Ultimately, a 'year of carbon equivalency' emerges – the point in a building's lifetime at which the environmental impacts associated with new construction equal those associated with renovation. For the commercial building in Portland, for example, the 'year of carbon equivalency' occurs at year 42; it takes approximately 42 years for the efficient, new commercial building in Portland to overcome the climate change impacts that were expended during the construction process.

Figure 23: Climate Change Impacts by Building Lifetime for Commercial Office in Portland



Figures 23 - 26 chart climate change impacts for both NC and RR scenarios as a function of building lifespan. The results are determined by dividing cumulative environmental impact by building lifespan, plotted for years 1 through 100. For the commercial office building used in this study, building reuse always yields more immediate carbon savings than demolition and new construction. The 'year of carbon equivalency' is highlighted in green, showing the point at which new construction and reuse yield the same climate change impacts.

Figure 24: Climate Change Impacts by Building Lifetime for Commercial Office in Phoenix

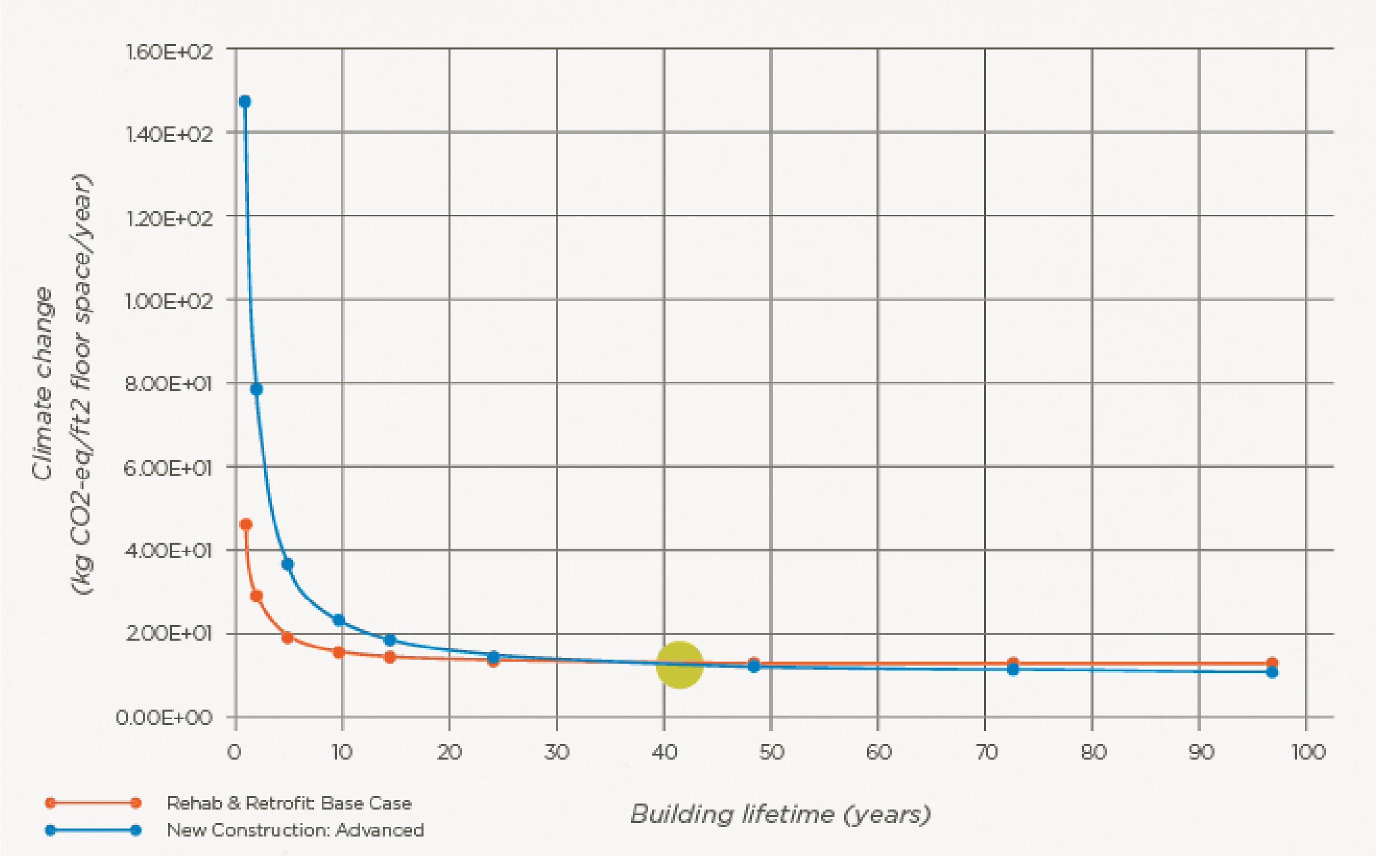


Figure 25: Climate Change Impacts by Building Lifetime for Commercial Office in Atlanta

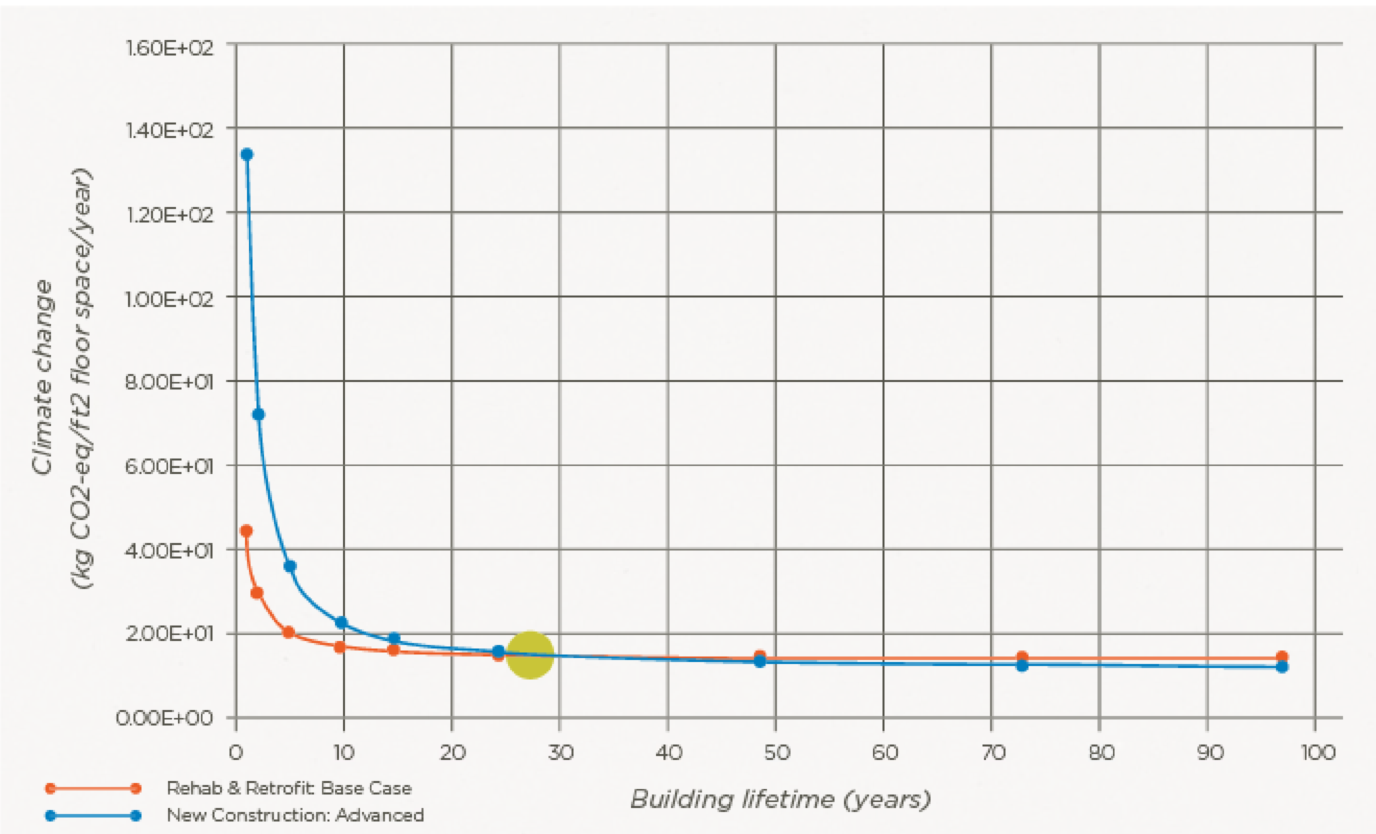
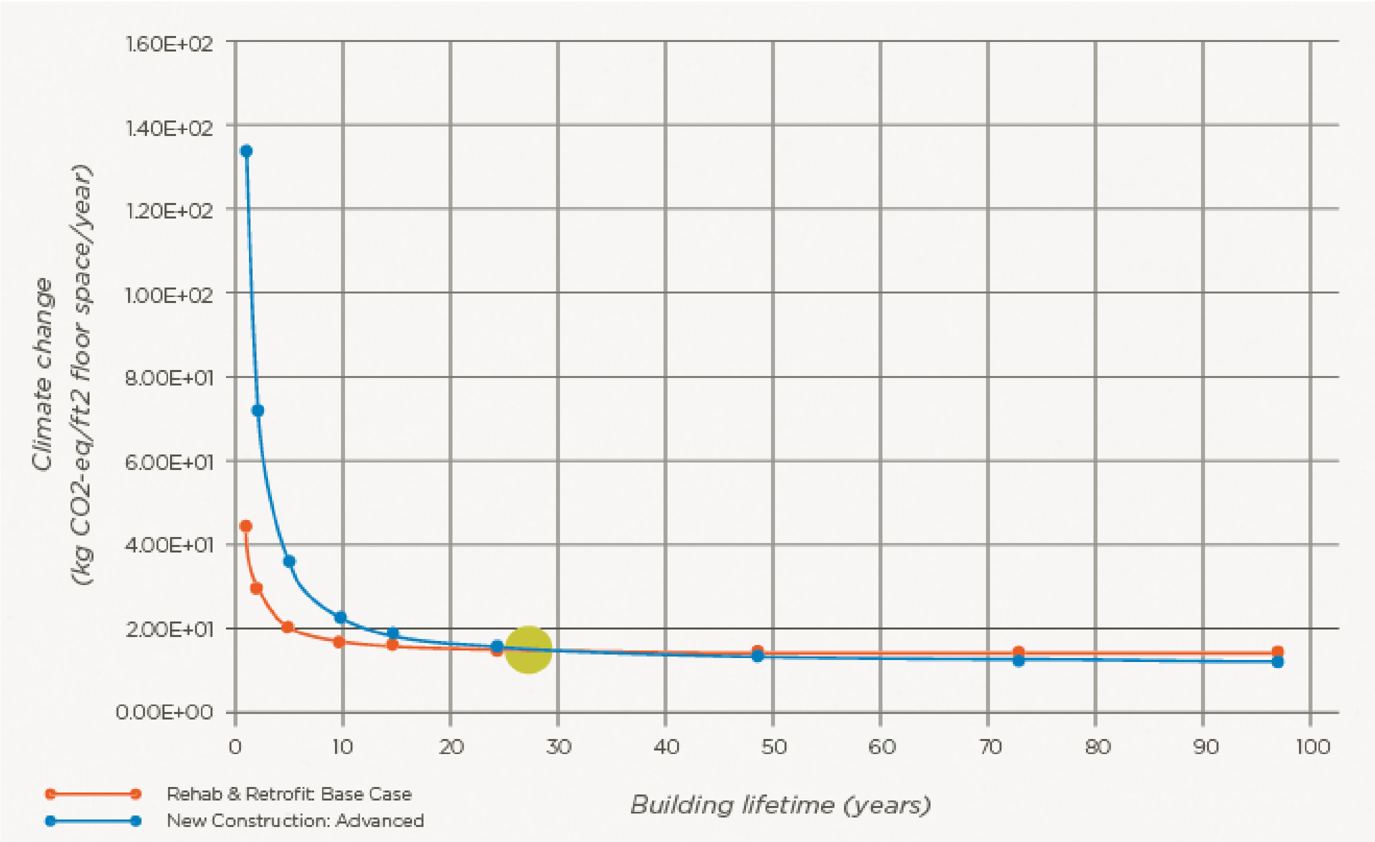


Figure 26: Climate Change Impacts by Building Lifetime for Commercial Office in Chicago



YEAR OF CARBON EQUIVALENCY' ANALYSIS

It is clear that renovation has the potential to provide near- and long-term carbon savings as compared to the construction of new, energy efficient buildings. This is especially relevant as new buildings in the United States continue to move toward higher levels of energy efficiency.

Table 12 indicates the building lifetimes at which a Base Case renovated building has lower cumulative climate change-related impacts as compared to new, high-performance construction. Among the cities analyzed, Chicago and Portland represent the most extreme climatic variations on life cycle impacts. Thus, for cities in other climate regions of the United States, the 'year of carbon equivalency' can be expected to fall within the parameters of these two cities. The 'year of carbon equivalency' ranges from 10 years for an elementary school in Chicago to 80 years for a single-family home in Portland. In other words, it can take between 10 and 80 years for a new, energy efficient building to overcome, through efficient operations, the climate-change impacts incurred during the construction process. The 'year of carbon equivalency' is highly influenced by building type, climate region, and the energy performance level of a given building.[39]

There is an important exception to these results. In this study, a new, efficient multi-family residential building outperforms a warehouse-to-residential conversion that has been renovated to achieve a Base Case level of energy efficiency. In this case study, material inputs for the warehouse-to-residential conversion are so significant that they erode some of the environmental advantage associated with building reuse.

Table 12. Number of Years Required for New Buildings to Overcome Climate Change Impacts from Construction Process

According to this study, it takes 10 to 80 years for a new building that is 30 percent more efficient than an average-performing existing building to overcome, through efficient operations, the negative climate change impacts related to construction. This table illustrates the number of years required for different energy efficient, new buildings to overcome impacts.

Building Type	Chicago	Portland
Urban Village Mixed Use	42 years	80 years
Single-Family Residential	38 years	50 years
Commercial Office	25 years	42 years
Warehouse-to-Office Conversion	12 years	19 years
Multifamily Residential	16 years	20 years
Elementary School	10 years	16 years
Warehouse-to-Residential Conversion*	Never	Never

*The warehouse-to-multifamily conversion (which operates at an average level of efficiency) does not offer a climate change impact savings compared to new construction that is 30 percent more efficient. These results are driven by the amount and type of materials used in this particular building conversion. The warehouse-to-residential conversion does offer a climate change advantage when the energy performance levels of new and existing building are assumed to be equal (see Figure 14). Thus, it may be particularly important to retrofit warehouse buildings for improved energy performance while renovating them. Furthermore, care should be taken to select materials that maximize environmental savings.

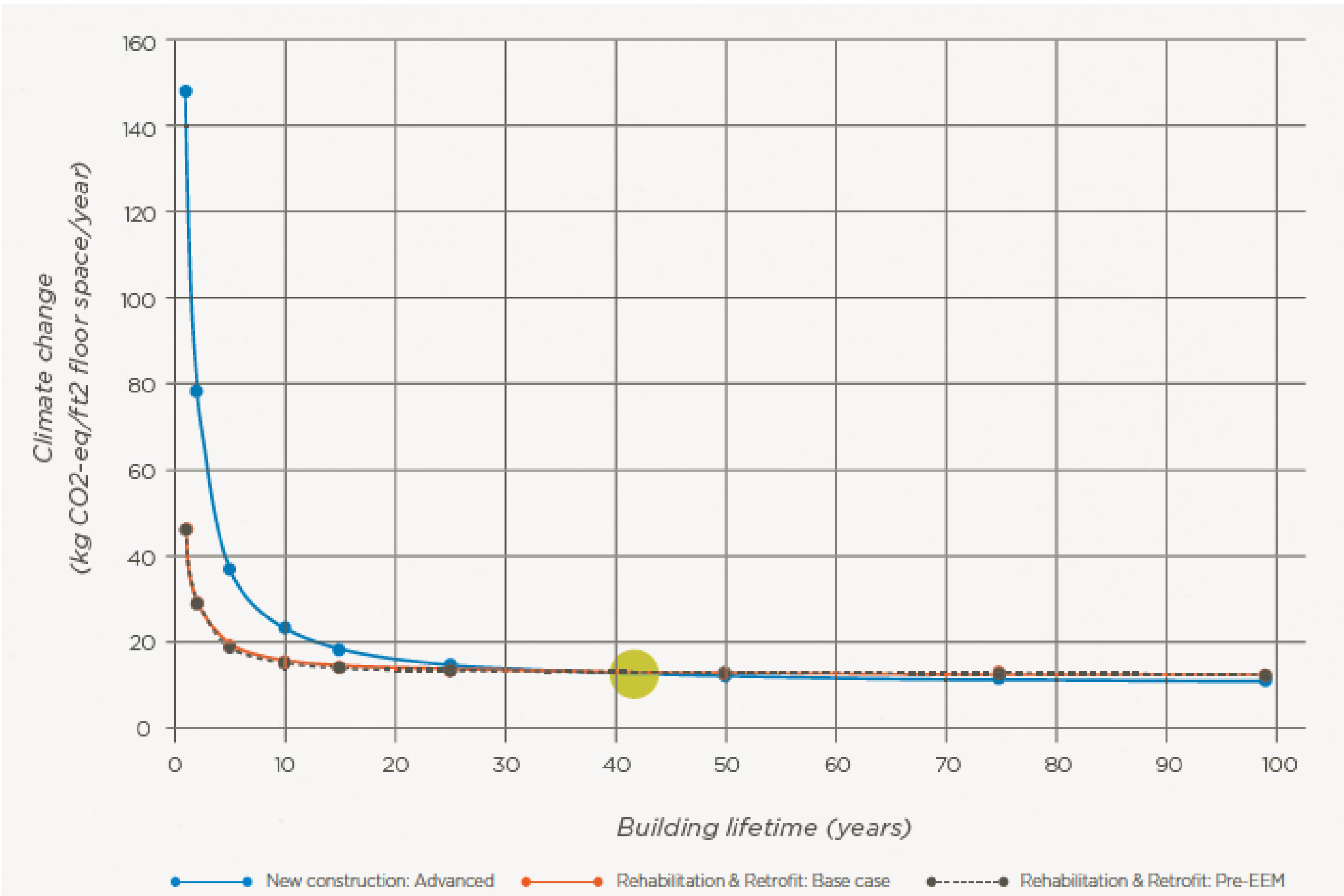
PRE-EEM SENSITIVITY ANALYSIS

In addition to the Base Case and Advanced Case test conditions, a third test condition was created in this study – the Pre-EEM analysis. This analysis evaluates the life cycle impacts of an existing building that has been renovated to bring it to contemporary functionality but has *not* included EEMs to bring the building up to an average level of energy performance. Here, the Pre-EEM Case was analyzed for the *commercial office building only*, and the operating energy of the Pre-EEM Case was assumed to be equivalent to the Base Case test condition. This test condition was created because, in many instances, older buildings have inherent efficiency strengths and perform on par with new construction.[40]

This test condition was designed to inform the team's understanding about the extent to which an existing building that is already performing at a Base Case level of energy efficiency might offer environmental benefits without requiring energy efficiency improvements to achieve such performance.

From a life cycle analysis perspective, there is little variation in the 'year of carbon equivalency' between a Pre-EEM and Base Case RR building (see the year-of-carbon equivalency analysis in Figure 27).

Figure 27. Climate Change Impacts for Pre-EEM and Base Case Reuse Versus Advanced Case New Construction for Commercial Office Buildings in Portland



The Pre-EEM test condition, shown as the dotted black line, yields roughly the same climate change impacts as applying efficiency measures to improve upon its energy performance.

III. MATERIALS MATTER: THE QUANTITY AND TYPE OF MATERIALS USED IN A BUILDING RENOVATION CAN REDUCE, OR EVEN NEGATE, THE BENEFITS OF REUSE.

This study reveals that the quantity and types of materials used in a reuse scenario can reduce or even eliminate the environmental advantage associated with reuse. For example, the converted warehouses and school addition require larger material inputs relative to other reuse scenarios, and as can be seen in Figures 11-14, the benefits of reuse tend to be less than those seen in other buildings typologies. In fact, in the instance of the warehouse-to-residential conversion scenario, reuse is *less* environmentally preferable than demolition and new construction in two impact categories, Human Health and Ecosystem Quality. In the case of Ecosystem Quality, the warehouse-to-residential conversion has a 1-percent higher impact than new construction in all climate areas, and the margin of benefit for new construction in the Human Health impact category ranges from 4 to 6 percent, depending on climate. These differences are relatively small, and findings will likely differ for other warehouse conversion scenarios based on variations in material inputs. It should be noted that the results for this scenario, as well as all other scenarios, are a function of the specific types and quantities of materials that were selected for this project. Buildings that use other varieties and amounts of materials will yield different findings.

The 'year of carbon equivalency' varies significantly between different building types. In general, the existing building projects that require more materials—the school addition and the warehouse conversions—do not offer as significant environmental benefits as scenarios in which the footprints or uses are unchanged. In the case of the warehouse-to-residential conversion scenario, material inputs are substantial enough for the RR scenario that the Base Case warehouse-to-residential conversion does not realize a near-term environmental benefit over an Advanced Case new building (however, as seen in Figure 14, the warehouse-to-residential conversion does offer a climate change advantage when energy performance between the new and existing building is assumed to be the same).

IMPACTS OF ENERGY PERFORMANCE UPGRADES

An analysis of energy performance upgrades demonstrates the potential impacts associated with materials usage, as shown in Figures 28 - 31. Upgrades result in lower energy consumption over the lifetime of a building, and therefore yield a significant reduction in environmental impacts in those categories that are dominated by operating energy: Climate Change, Resource Depletion, and Human Health impacts. In the area of Ecosystem Quality, however, materials contribute more substantially to total environmental impacts.

Figure 28: Climate Change Impacts for Commercial Office

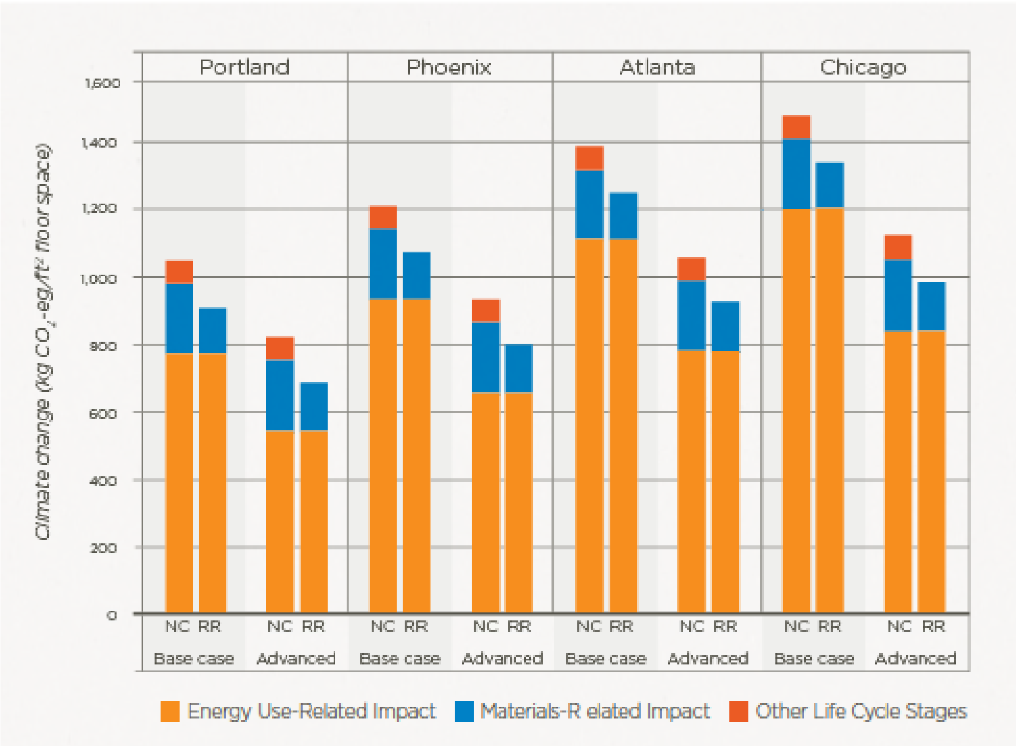
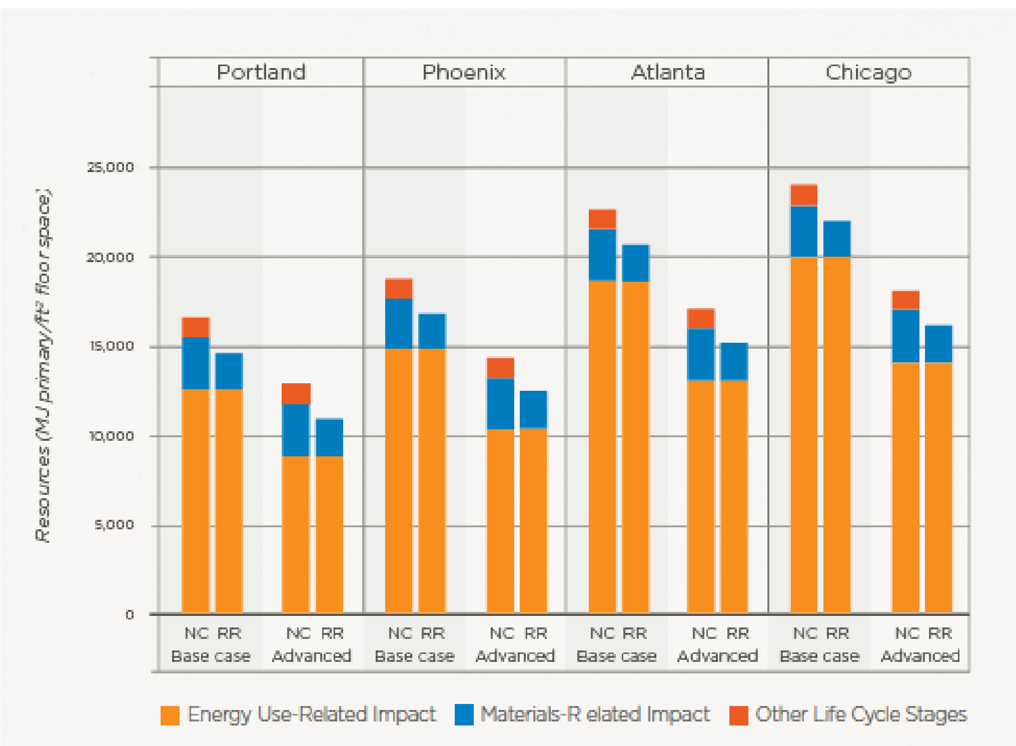


Figure 29: Resources Impacts for Commercial Office



Figures 28 - 31 show results for both the Base Case and Advanced Case test conditions for the Commercial Office Building category. As energy performance improves, both the new building and existing building result in fewer climate change, resource depletion, and human health impacts. However, in some instances, impacts to ecosystem quality are greater for the Advanced Case test conditions, due to the effects of material choices related to EEMs for selected buildings.

Figure 30: Human Health Impacts for Commercial Office

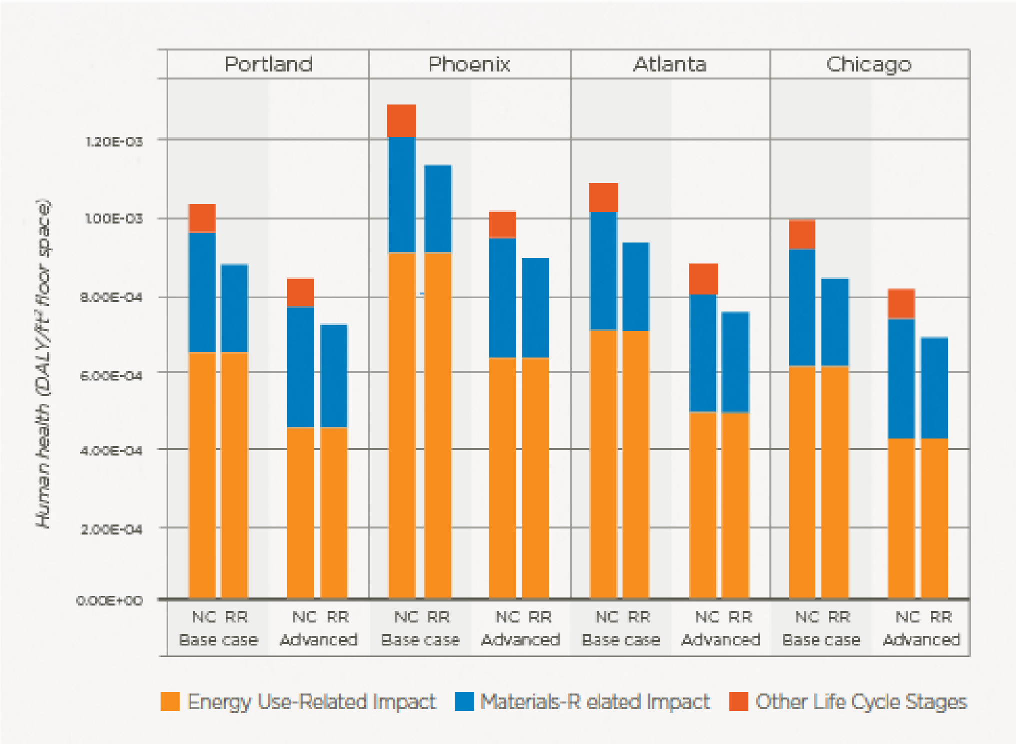
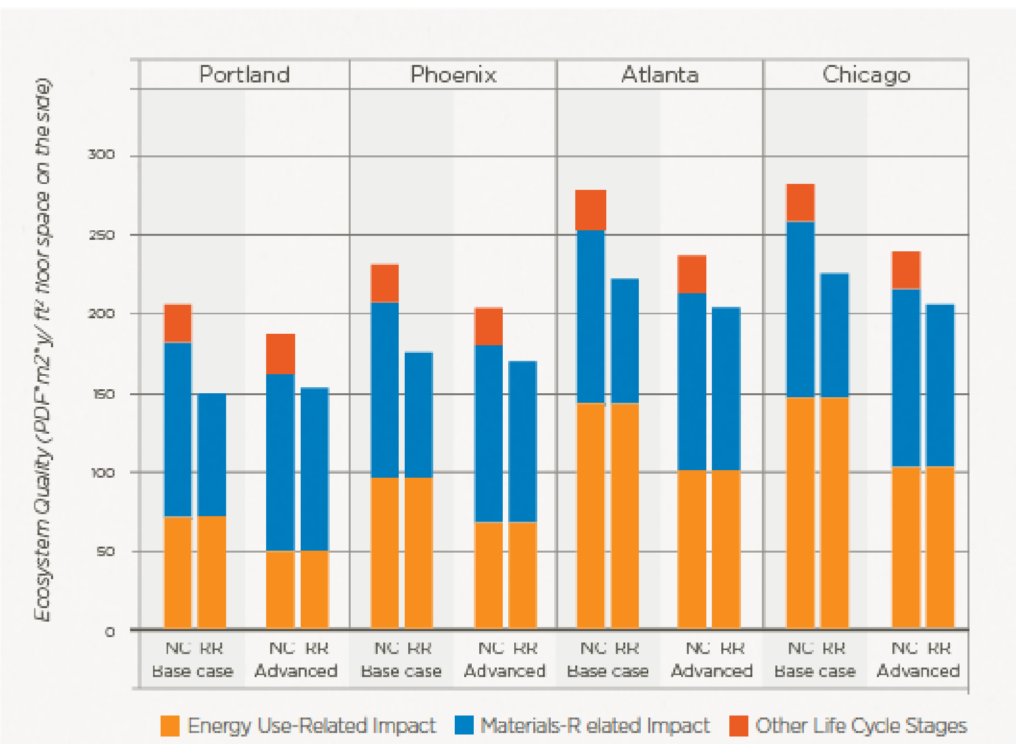


Figure 31: Ecosystem Quality Impacts for Commercial Office



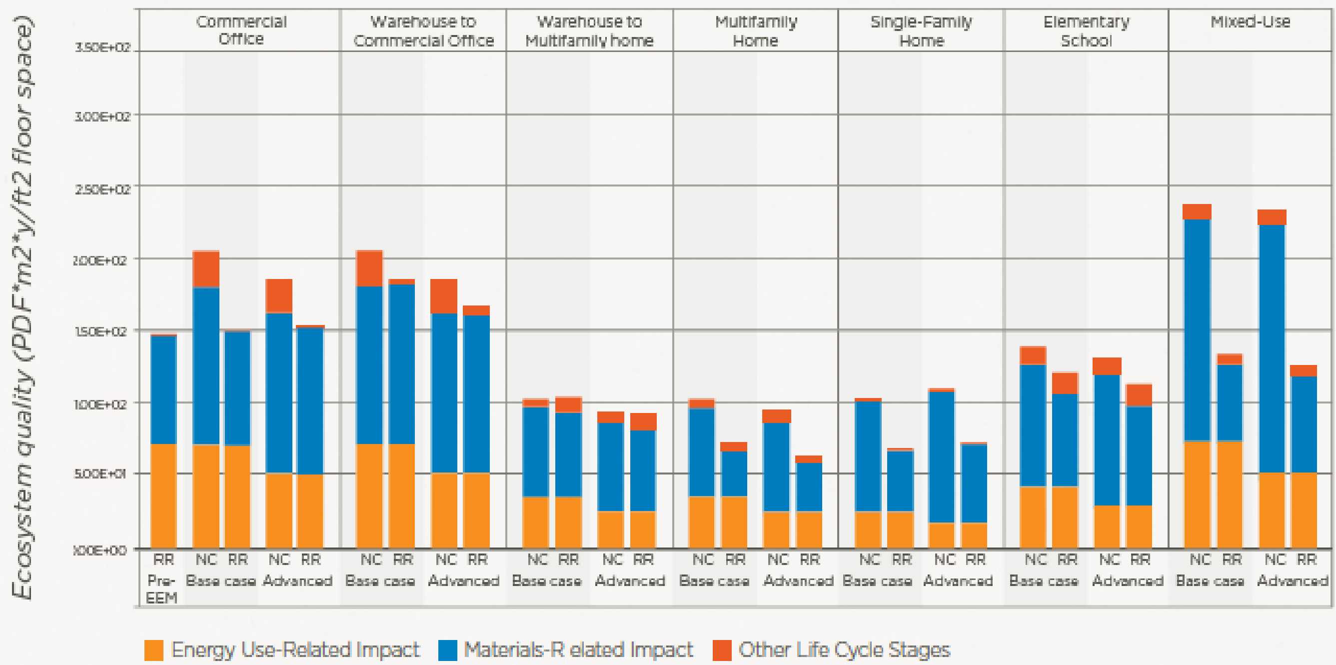
In the case of Ecosystem Quality, the use of additional materials to achieve efficiency upgrades can offset the value of the operating efficiency. The result is a reduced or eliminated benefit to Ecosystem Quality. For example, this is true for single-family new construction and building reuse scenarios in some climates, as shown in Figures 32 – 35.

Further, the Pre-EEM condition tested on the commercial building yields similar findings in the Ecosystem Quality impact category. The Pre-EEM condition – which assumes a Base Case level of energy efficiency but does not require materials inputs to achieve this level of energy performance – is *always* environmentally preferable to an Advanced Case, newly constructed building, and sometimes more advantageous than an Advanced Case existing building. From the perspective of impacts to ecosystem quality, *not* applying EEMs is the environmentally preferred option, due to the impacts that result from the material components of the EEMs. Further research is needed to evaluate whether this Pre-EEM trend is consistent across building typologies.

Efforts to reduce climate change impacts through reduced energy consumption can actually increase negative environmental impacts, depending on the modes of material sourcing and production involved. Thus, multiple indicators should be examined when assessing the environmental benefit at issue in a decision to upgrade building energy performance. However, modern science does not yet offer tools that enable easy decision making on this point.

The full results of this study, including a detailed explanation of all findings, can be found in the *Technical Appendices*.

Figure 32: Ecosystem Quality Impacts for Portland



Figures 32 - 35 show that in the Ecosystem Quality category, material selection plays an important role in overall environmental impacts. In the case of the Commercial Office and Single-Family Home typologies, energy efficient new construction demonstrated greater lifecycle impacts over existing buildings operating at a Base Case level of performance. Further, the Pre-EEM results for commercial office building in cities with lower EUIs and cleaner grid mixes (i.e., Portland and Phoenix) indicate that few, if any, reductions in ecosystem quality impact are achieved by including EEMs selected to ensure an Base Case level of performance.

Figure 33: Ecosystem Quality Impacts for Phoenix

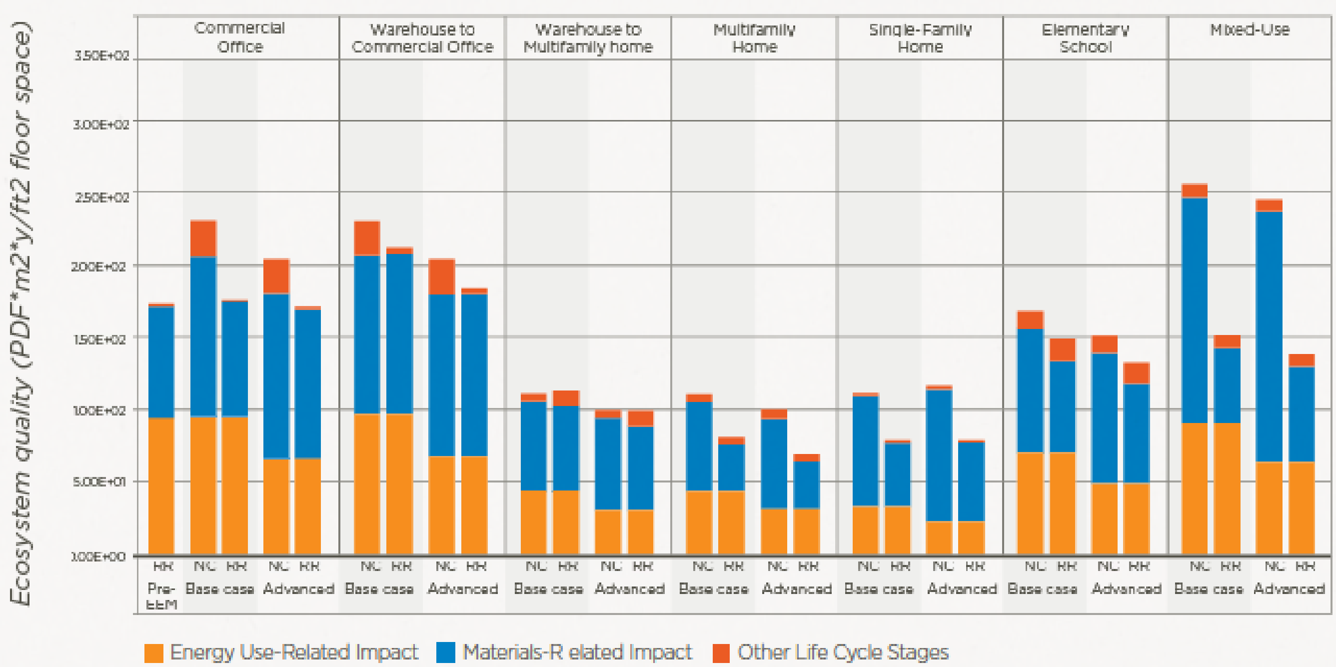


Figure 34: Ecosystem Quality Impacts for Atlanta

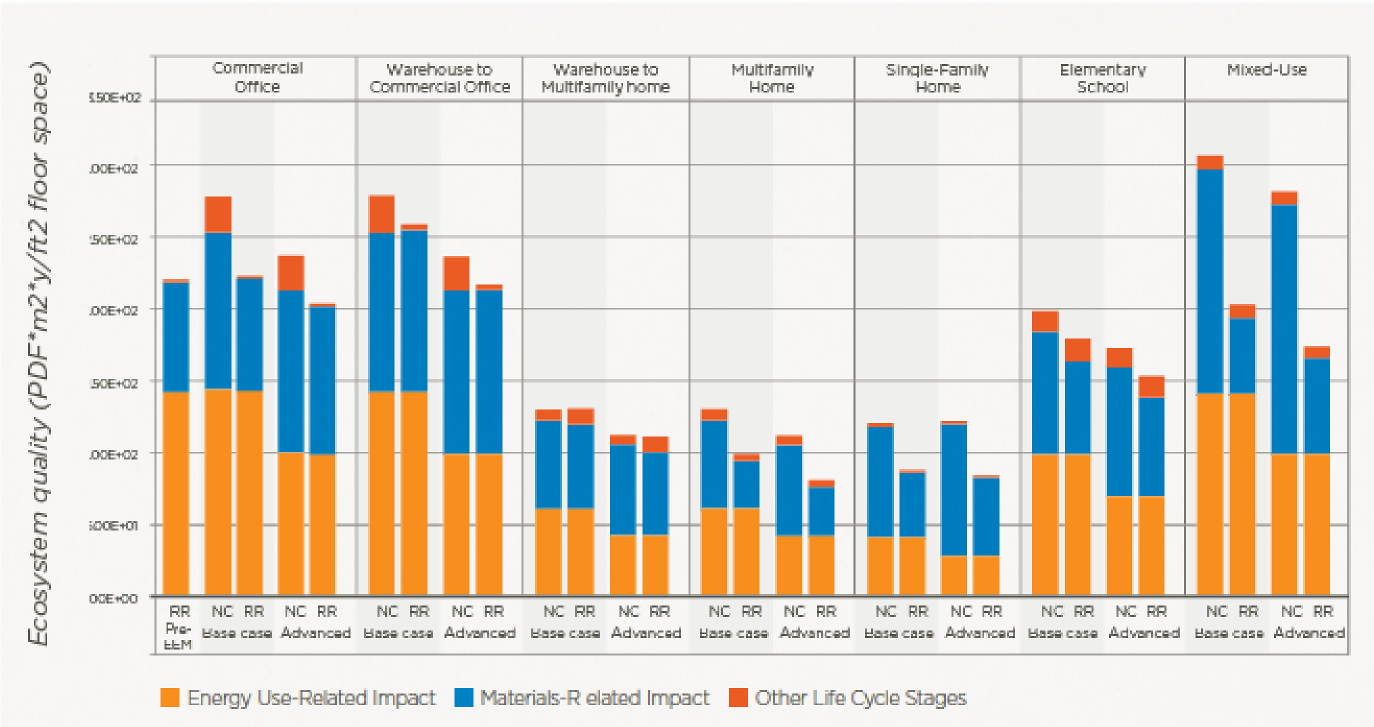
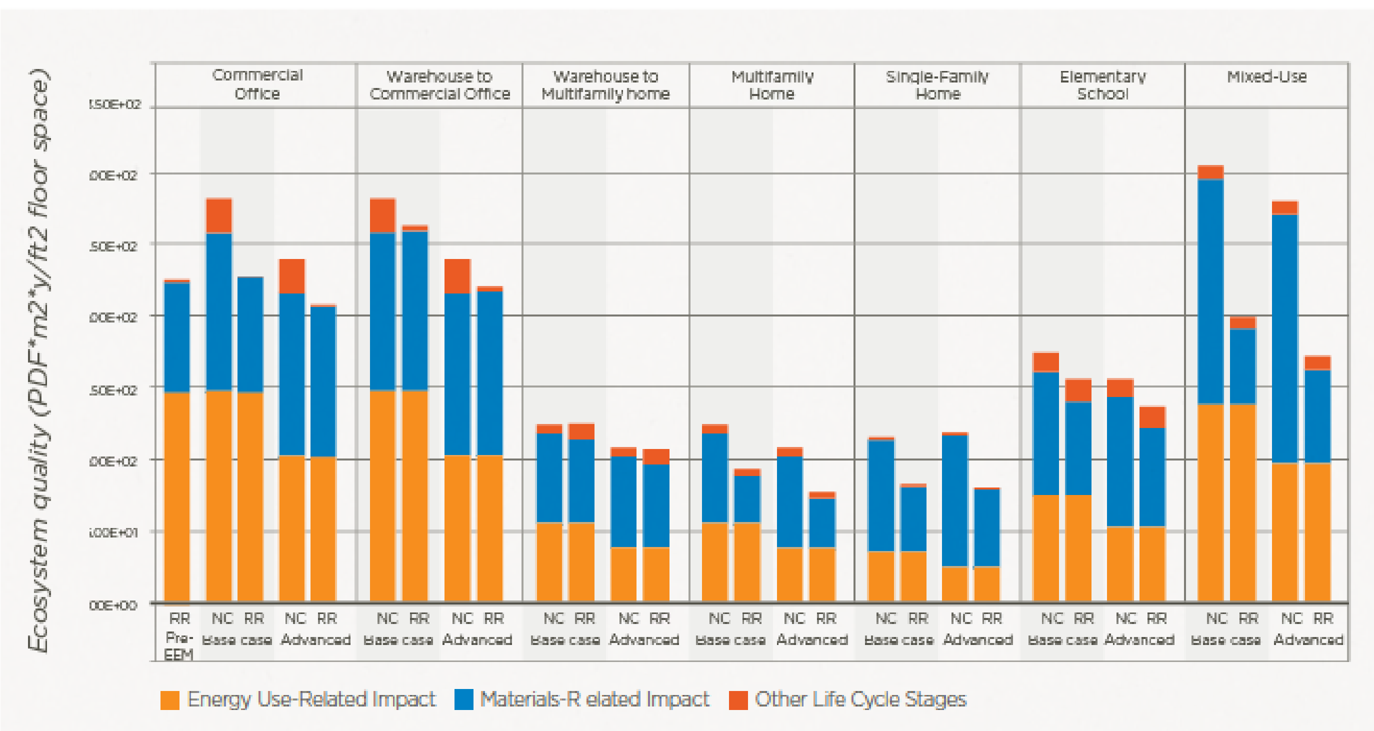


Figure 35: Ecosystem Quality Impacts for Chicago



7. ANALYSIS AND CONCLUSIONS

ANALYSIS OF FINDINGS

This study reveals that the reuse and retrofit of buildings of equivalent size and functionality can, in most cases, meaningfully reduce the negative environmental impacts associated with building development. Significantly, even if it is assumed that a new building will operate at 30-percent greater efficiency than an existing building, it can take between 10 and 80 years for a new, energy efficient building to overcome the climate change impacts that were created during construction. An exception to this is the multifamily-to-warehouse conversion; in this scenario, the average-performing reuse option does not offer a climate-change advantage as compared to a new, energy efficient building.

Notably, this study finds that the benefits of building reuse can be reduced or even eliminated depending on the type and quantity of materials selected for a reuse project. Therefore, care must be taken to select construction materials that minimize environmental impacts.

This section discusses the findings of this study and explores barriers to reuse, retrofit, and effective materials selection. It also offers recommendations for future research and analysis.

REUSE MATTERS

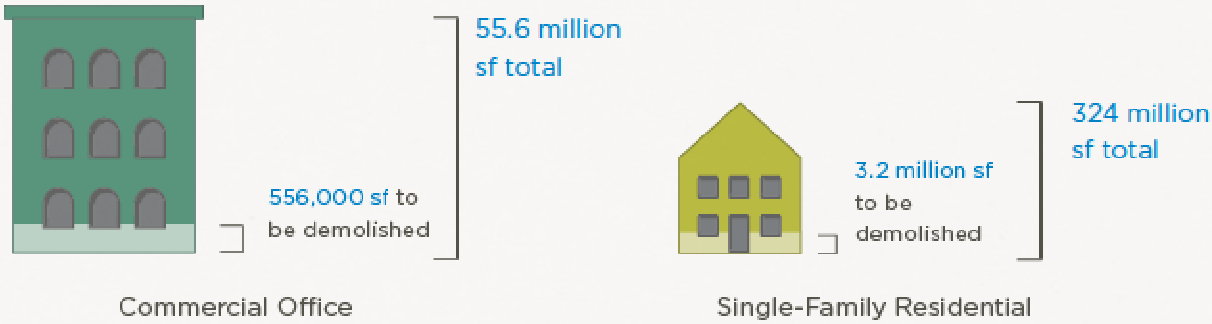
The demolition of buildings to make way for new construction is common in the United States. While some replacement of the existing building stock is undoubtedly necessary, the results of this study suggest that building reuse offers a significant opportunity to avoid environmental impacts. In all of the scenarios examined in this study, there is an immediate carbon savings associated with reuse and renovation as compared to new construction, when comparing buildings of equivalent size, functionality and energy performance. In all but one scenario, there is also an immediate carbon savings associated with reuse and renovation as compared to more energy efficient, new buildings.

Most climate scientists agree that immediate-term action is crucial to staving off the worst impacts of climate change. This study finds that building reuse can avoid unnecessary carbon outlays and help communities achieve their near-term carbon-reduction goals. An example from Portland, Oregon, illustrates this. Retrofitting, rather than demolishing and replacing, just 1% of the city of Portland's office buildings and single family homes over the next 10 ten years would help to meet 15% of their county's total CO_2 reduction targets over the next decade (Portland and Multnomah County share emissions reductions targets). When scaled up even further to capture the potential for carbon reductions in other parts of the country, particularly those with a higher rate of demolition, the potential for savings could be substantial.[41]

Most climate scientists agree that immediate-term action is crucial to staving off the worst impacts of climate change. This study finds that building reuse can avoid unnecessary carbon outlays and help communities achieve their near-term carbon-reduction goals.

Portland, Oregon

1% of the building stock in Portland (within Multnomah County) is expected to be demolished over the next 10 years.



15% of the county's total CO_2 reduction targets, over the coming decade, could be met simply by retrofitting and reusing existing buildings rather than demolishing and building new, efficient ones.

BARRIERS TO REUSE

There are many barriers to actualizing the environmental benefits of building reuse. In urban areas, there is a financial incentive to maximize the use potential of sites, which often involves adding floor space to achieve economies of scale and height for views, as well as higher rents. Thus, developers often perceive little economic justification for retaining existing buildings and instead look for developable land rather than buildings to retrofit. Moreover, the environmental costs associated with building construction and demolition are external to developer pro formas and excluded from value-chain analyses; this creates an incentive to demolish buildings in favor of new construction.

In addition, rehabilitation work is typically regarded as far riskier than new construction, because the process can be less predictable, and many developers fear being surprised by unforeseen challenges once rehabilitation is underway. This perception of risk and fear of the unknown can motivate decisions to demolish buildings even in instances where rehabilitation may be less costly and more profitable than new construction. Developers need new sets of tools and skills, as well as financial and technical resources, to help them incorporate existing buildings into their portfolios.

Regulations are also often obstacles to sustainability, inadvertently undermining efforts to reuse existing buildings. Building policies and codes in the United States have historically favored the needs and goals of new construction. Today, existing buildings and older communities must conform to regulatory environments that do not encourage adapting buildings for new uses or retrofitting them for energy efficiency. For example, building energy and zoning codes are particularly challenging for existing buildings; the up-zoning of height and floor area limits in urban areas threatens existing attractive, viable, lower-rise buildings that occupy smaller lots. In the absence of flexible land use regulations and incentives for reuse, older buildings are commonly torn down to make way for larger structures. Energy codes can also sometimes deter building reuse, as they are typically not well-adapted to the unique limitations and opportunities presented by individual buildings. Thus, when added to seismic and ADA requirements, these factors can be the 'tipping point' in decisions favoring demolition.

The findings of this study should be viewed in the context of two realities. First, the continued use of certain older buildings may be impractical for a number of reasons.. An existing building may not suit a new proposed use that makes sense in the context of its neighborhood, or geographical impracticalities may render reuse unrealistic, e.g. as in the case of many vacant buildings in depopulating cities. Secondly, changing demographics and the evolution of vibrant, successful urban spaces will continue to necessitate new construction. Even so, a paradigm shift is needed to account for the relative environmental benefits of reuse and to ensure that reuse be seriously considered in decisions regarding demolition and new construction.

A more comprehensive analysis of the policy barriers to reuse is needed in light of these realities, as are efforts to identify and design policies and development standards that successfully promote reuse.

RETROFITS MATTER

Building reuse alone is insufficient to meet our responsibilities to reduce climate change related impacts. This study demonstrates that retrofitting existing buildings with appropriate energy upgrades offers the most substantial emissions reductions over time. The results of this study also reveal that, while building reuse and retrofit are important for all regions, they are particularly impactful in areas in which coal is the dominant energy source and more extreme climate variations drive higher energy use. Thus, retrofitting an existing building in Chicago or Atlanta for energy efficiency will provide more substantial reductions in carbon-related impacts than a comparable renovation in Portland, due to differences in energy grid mix and climate. Given the high distribution of both residential and commercial building square footage in the Midwest and South Atlantic United States, the potential benefits from retrofits are tremendous.

As with reuse, the barriers to building retrofits are numerous. While many commercial building owners have achieved upwards of 20 to 60 percent energy savings in existing buildings, a lack of transparency in the retrofit market regarding measurable outcomes makes it difficult to convince owners of the positive payback and benefits associated with retrofits.[42] Financial drivers present another challenge for energy efficiency retrofitting; the financing obtained by owners for renovations is often spent in ways that fail to promote environmental efficiency. Motivated by a desire to attract and retain tenants, landlords commonly favor cosmetic retrofits over energy-related renovations. In many instances, building owners delay or avoid making efficiency investments, because it is their tenants—those paying the utility bills—who reap the financial benefits. In turn, tenants are often hesitant to invest in energy upgrades on properties they do not own. This 'split incentive' largely results from the prevailing dynamics of the real estate market. In response to these realities, emerging efforts, such as 'green lease' programs and utility-funded programs that finance retrofits in return for owning the energy savings, contribute to a wider acceptance of efficiency upgrades.

There are also significant obstacles to home energy retrofits. Owners of multifamily buildings confront many of the same challenges faced by commercial building owners, including 'split incentives' and a lack of transparency about the advantages and payback associated with retrofits. Meanwhile, many single-family homeowners are uncertain about how best to tackle energy efficiency improvements and lack the financial resources to make substantial improvements. Data from the U.S. Energy Information Agency suggests that older, single-family homes, particularly those built before 1950, perform more poorly than those homes of more recent vintage. Yet, there is an insufficient number of retrofit programs that target this sector of the building stock.

Numerous efforts by national organizations, federal agencies, energy utilities, and leadership cities are underway across the country to address barriers to retrofits. This study underscores the importance of this work, and suggests that it may be especially important to target retrofit efforts to those areas of the country with fossil-fuel-heavy grid mixes and harsher climate conditions.

MATERIAL CHOICES MATTER

This project does not evaluate individual materials, and recommendations as to which building materials offer the least environmental impact are not included here. It is clear, however, that material choices significantly affect the overall impact of a building during its lifecycle. Generally, where building renovation requires a substantial input of materials and materials have not been carefully selected, the environmental benefits of reuse can be eroded or substantially eliminated. In each of the materials-intensive reuse scenarios tested in this study, including the elementary school with a new addition and the warehouse-conversion scenarios, the benefits of reuse tended to be less significant or even reduced altogether. This suggests that great care is needed during the design process to minimize unnecessary additions to a building footprint through strategic space planning and the selection of appropriate materials that result in fewer environmental impacts. Better tools are clearly needed to inform design and materials selection processes.

LESSONS FROM WAREHOUSE-TO-MULTIFAMILY RESIDENTIAL SCENARIO

Beyond the quantity of materials used, the types of materials used in building construction and renovation are also important. This is evident in all scenarios, but special attention is given to the warehouse-to- multifamily residential conversion, the only case study in which building reuse did not offer an environmental savings in all impact categories over new construction. Even when energy performance was assumed to be the same, this reuse scenario was slightly more impactful than new construction in terms of Human Health and Ecosystem Quality impacts. It is noteworthy that the warehouse conversion does offer environmental savings, in terms of climate change and resource impacts, *when energy performance is assumed to be the same.*

The warehouse-to-multifamily scenario was examined in greater detail in order to explore which materials drove differences in results.[43] The project team determined that extensive replacement of glazing systems, choices of flooring materials, and differences in mechanical systems greatly affected the environmental impact profile of this scenario and made new construction the more desirable option. The negative impacts associated with the glazing system replacement are noteworthy, because it is typically assumed that window replacement offers significant environmental benefits over the retention of less energy efficient windows. Different material selections in these categories may have 'tipped' the scenario in favor of reuse in all impact categories. Further analysis is needed to better understand the trade-offs between material types.

While every effort was made to select case studies that are as representative of a particular building typology as possible, this study's results are functions of the specific buildings chosen for each scenario and the particular type and quantity of materials used in construction and rehabilitation. Impacts will differ for other building conversions that use different types and amounts of materials. Others are encouraged to repeat this research for additional building case studies; duplicating this analysis will enhance our collective understanding of the range of impact differences that can be expected between new construction and building reuse projects.

IMPACTS OF ENERGY EFFICIENCY MEASURES

This study demonstrates that the application of EEMs that require material inputs may reduce operating energy and climate-change related impacts over time, but may also induce greater environmental impacts in areas such as Human Health and Ecosystem Quality. Such impacts should be carefully balanced. The use of strategies that require few or no material inputs (e.g. operational adjustments to thermostat settings or greater occupant engagement to reduce energy use) are particularly promising given its potential to reduce environmental effects across all impact categories. Such approaches should be explored through further research and analysis.

Identifying and valuing building material options present several challenges, including a lack of transparency about the environmental impacts associated with different material choices. Various efforts are underway to benchmark or 'certify' the environmental performance of materials, however, few efforts are based on comprehensive assessments of life cycle impact.

While LCA serves as an important tool for evaluating material choices, it remains impractical for widespread use in the design process, as it is time consuming and costly. Furthermore, although LCA is the 'gold standard' for environmental impact analysis, even this method is challenged by limitations with data. A more affordable LCA-based tool, backed by better data and integrated into design processes, will allow designers to make informed decisions based on the impact profiles of various materials and systems and could provide substantial opportunities to minimize impacts associated with construction.

CONCLUSIONS AND FURTHER RESEARCH

The analysis of building scenarios in this study suggests that reusing an existing building and upgrading it to be as efficient as possible is almost always the best choice regardless of building type and climate. However, careful material selection and efficient design strategies for reuse are critical and can play a major role in minimizing the impacts associated with building renovation and retrofit projects.

These findings have critical implications for policy and practice, which are beyond the scope of this report but deserve exploration. Specifically, a better understanding of the drivers of demolition in the real estate market is needed, as is a closer examination of policy opportunities that address barriers to reuse and enable communities to better leverage existing built assets. This research also reinforces the need to address widespread obstacles to greening existing buildings and to develop tools that better enable designers to make more environmentally sensitive materials choices.

This report underscores a number of other issues requiring additional research. Further research will help to inform our understanding of the complex issues surrounding this study and should seek to achieve the following:

- **Improve upon life cycle inventory data.** In many ways, the science of LCA is still in its infancy. Currently, the majority of life cycle inventory data used in this study is sourced from a European database (ecoinvent) and is representative of European operations, which may not be entirely representative of U.S. practices (and thus impacts). However, the ecoinvent database is widely used in the United States, since a database of equivalent quality, transparency and robustness is not yet available. A serious, coordinated effort is needed to develop data that better reflects U.S. processes.

This study excludes impacts to human health due to material o -gassing and the resulting e ects on indoor air quality, which is a limitation that should be addressed by future analyses. Currently, the complexity of this topic requires resources and expertise beyond the capabilities of the project team, although e orts are underway within the LCA community to integrate this aspect of impact to human health. Better tools and further research are needed to compare the indoor air quality impacts associated with rehabilitated versus newly constructed buildings.

- **Further evaluate the durability of materials.** This LCA required the project team to apply certain assumptions about the durability of materials used in both the NC and RR scenarios, in order to determine the interval at which various building elements would be replaced over a 75- year life cycle. While durability data for some materials is fairly robust, it is substantially lacking in many areas, particularly with regard to relatively untested, newer materials. Better data and further analysis are needed to test the sensitivity of this study's ndings to di erent durability assumptions.

- **Explore the impacts of changing construction practices.** This study's comparison of reuse and new construction scenarios is based on current construction practices. Yet, there is a signi cant movement toward more sustainable construction practices in the United States, and study results may change markedly as a result of transformations in this dynamic eld. For example, the use of light-weight steel framing; improved focus on structural e ciency; and other factors could alter ndings.

- **Better understanding of building energy consumption.** Understanding how buildings use energy is an important part of reducing their environmental impacts in a meaningful way. However, actual data on building energy use is limited, and modeled predictions of energy use have proven to be, at times, inaccurate. The results of this study show that, in most cases, operating energy drives a large portion of a building's environmental impacts over the course of its lifespan. Much time and e ort was taken to determine the appropriate energy consumption data for the buildings analyzed in this study to ensure that they accurately represent 'typical' buildings. However, a more nuanced understanding of building energy consumption is needed, for both newly constructed and existing buildings, with more up-to-date and larger sample sizes than those currently available through the U.S. Energy Information Administration. Emerging state and city policies requiring owners to benchmark and disclose the energy usage of their buildings will contribute to a growing body of data on whole-building energy use. However, better research is also needed on the end-use breakdowns of energy use within di erent types of spaces within buildings, across building types, and in di erent climate zones.

- **Explore net zero energy scenarios.** As America's buildings reach higher levels of energy efficiency with the end goal of net-zero operating energy, further research is needed to identify the potential for environmental trade-offs between operating efficiencies and increased material inputs, such as the addition of renewable energy systems, across different climate regions. A deeper analysis is also need to evaluate potential environmental impacts associated with the latest materials and technologies used by net zero energy buildings to assess this trade-off in a meaningful way.

- **Include location efficiency considerations.** This study compares the impacts associated with renovation and reuse with the impacts associated with the demolition and construction of buildings of equal size. In reality, many existing buildings are replaced with new, larger structures that can potentially accommodate more residents or users. Thus, further research is needed to understand the relationship between density and environmental impacts as it relates to building reuse versus new construction. Additional density may be environmentally advantageous if buildings are located in areas that are walkable and transit accessible, thereby reducing the Vehicle Miles Traveled (VMTs) by occupants.

  Such an analysis should look at more than the carbon savings associated with reduced VMTs from additional occupants in a new building. Such studies should also consider the significant role that older buildings play in creating more character-rich and human-scale communities that attract people to more sustainable, urban living patterns.

- **A deeper dive into understanding material impacts.** Variations in the environmental impacts associated with new construction versus building rehabilitation are based on their material differences. However, this study does not provide definitive comparisons of the environmental performance of specific products or materials or specific building designs or practices. Further research is needed to evaluate the case study buildings used in this report to determine whether their materials are accurately representative of new and existing buildings, and to determine how variations in material inputs may affect outcomes. Furthermore, the use of salvaged materials in new and existing buildings is likely to shift results; this also warrants further analysis.

Older buildings foster a wider variety and intensity of uses and activities, and often provide more affordable spaces for economic incubation, than new buildings. Decisions to reuse and retrofit existing buildings are made for many reasons, including the economic, social, and cultural value these structures provide to their communities. This study demonstrates that building reuse and retrofit, coupled with responsible materials choices, offer tremendous promise for minimizing environmental impacts associated with the built environment. Future research and analysis in this important area will no doubt enrich industry practices and public policy in the years ahead.

ENDNOTES

1. U.S. Energy Information Administration, Green Building Facts (Department of Energy, 2009).

2. U.S. Environmental Protection Agency, Characterization of Building-Related Construction and Demolition Debris in the United States, available at http://www.epa.gov/osw/hazard/generation/sqg/c&d-rpt.pdf (1998.)

3. Arthur C. Nelson, "Toward a New Metropolis: The Opportunity to Rebuild America" (Washington: Brookings Institution, 2004).

4. U.S. Department of Energy, Building Energy Data Book (2010).

5. Mike Jackson, *Embodied Energy and Historic Preservation: A Needed Reassessment.* APT Bulletin: Journal of Preservation Technology. 36:4 (2005). Available at http://www.ironwarrior.org/ARE/Materials_Methods/EmbodHP.pdf

6. "Homes have more energy-e cient appliances, but the e ciency gains are partly o set by more consumer electronics," available at http://205.254.135.24/pressroom/releases/press355.cfm.

7. Energy end-use pro les apportion a building's annual energy use by various end uses, including for space heating and cooling, lighting, fan/pump energy, hot water, and other miscellaneous categories.

8. Advisory Council on Historic Preservation, "Assessing the Energy Conservation Bene ts of Historic Preservation: Methods and Examples" (1979).

9. Empty Homes Agency, "New Tricks with Old Bricks: How Reusing Old Buildings Can Cut Carbon Energy Emissions" (2008).

10. The impacts described by LCA are estimates of *potential* impacts, not measurements of real impacts.

11. Athena Sustainable Materials Institute, "A Life Cycle Assessment Study of Embodied E ects for Existing Historic Buildings" (2009).

12. The ATHENA EcoCalculator is a web-based life cycle assessment tool for building assemblies.

13. Oregon Department of Environmental Quality, "Prioritizing Green Building and Waste Prevention Practices with Life Cycle Assessment: Systems Thinking for Residential Buildings" (2010).

14. Busby, Perkins + Will, "Life Cycle Assessment, Buchanan Building-D," University of British Columbia (2006).

15. Here, the team reviewed each case study building, by region, for di erences in materials and determined that there was no signi cant impact on material usage or application by region that would require adjusting the methodology.

16. U.S. Department of Energy (2010); The Paci c Northwest National Laboratory estimates that the median lifespan of a commercial building is between 70 and 75 years. The 2010 update to the Buildings Energy Data Book identi es the median building age average for all building types as 56.5 years. However, the more conservative 75-year estimate is used as the basis for this study, with sensitivity analyses performed for longer and shorter life spans.

17. New buildings and old buildings typically have di erent con gurations. Thus, comparing them on a square-foot basis, rather than a whole-building basis, allows for a more meaningful comparison.

18. Original materials production includes raw materials extraction, processing, and transport for all materials associated with the NC scenario and those materials associated with rehabilitation and retro t in the RR scenario. In the RR scenario, on-site materials have been excluded.

19. The durability of materials often found in older existing buildings, such as masonry, were not evaluated as part of this study. We recommend additional LCA investigation into the e ects of durability on the environmental performance of buildings.

20. The impact of assembling the components is not explicitly modeled in Ecoinvent.

21. In one instance, the NC scenario was based on a building that had not yet been constructed, but for which architectural drawings were available and materials clearly quantified.

22. This study's conservative assumptions about materials-sourcing distances are based on USGBC's LEED standards, which provide credits for sourcing materials within a 500-mile radius.

23. Energy use intensity (EUI) is a unit of measurement that describes a building's energy use. EUI is calculated by dividing the total energy consumed in one year (measured in kBtu) by the total floorspace of a building, in square feet.

24. See U.S. Energy Information Administration, Residential Energy Consumption Survey (RECS) (Department of Energy, 2005); U.S. Energy Information Administration, *Commercial Buildings Energy Consumption Survey (CBECS)* (Department of Energy, 2003); New Buildings Institute, "Sensitivity Analysis: Comparing the Impact of Design, Operation, and Tenant Behavior on Building Energy Performance" (July 2011); Cadmus Group, Inc., "Northwest Commercial Building Stock Assessment" (2009); Oregon Department of Energy, State Energy Efficiency Design (SEED) Program, "User Guide for PGE Energy Use Index" (2006).

25. This study assumes that space heating and domestic hot water systems are powered by natural gas in each of the four cities. In reality, however, other fuel sources are often used. Heating, oil, propane, and electric resistance or electric heat pumps may be widely used in various building types across the country. According to the Pacific Northwest National Laboratory, natural gas represents the most common fuel source for space and water heating in the United States, in both residential and commercial sectors. The use of other fuels for heating and hot water would likely result in different outcomes due to the environmental impacts related to different fuel sources. Further research is needed to fully evaluate variations in fuels used by different building types. *See* D.B. Belzer, "Energy End-Use Flow Maps for the Buildings Sector" (Richland: Pacific Northwest National Laboratory, 2006).

26. Grid mix assumptions are based on 2007 data from the U.S. Environmental Protection Agency, sourced from the Emissions & Generation Integrated Database (eGRID v1.0). *See* U.S. Environmental Protection Agency (2008) eGrid. File eGRID2007V1_1_year05_aggregation.xls, Version 1.1. Accessed 24 March 2011. http://www.epa.gov/cleanenergy/energy-resources/egrid/index.html.

27. Further details are available in Section 5 and the Operating Energy Analysis Appendices.

28. CBECS data on commercial buildings indicates that prewar buildings use less energy than buildings built between 1900 and 2003. Pre-EEM Case energy use is therefore assumed to operate at the same level as a new building. In other words, both are assumed to operate at the Base Case energy performance.

29. EUIs for commercial buildings were derived from various sources. *See* U.S. Energy Information Administration (2003); New Buildings Institute (July 2011); Cadmus Group, Inc., (2009); Oregon Department of Energy (2006).

30. The method employed here is the peer-reviewed and internationally recognized LCIA method IMPACT 2002+ v.207. ***See*** Jolliet O, Margni M, Charles R, Humbert S, Payet J, Rebitzer G, Rosenbaum R (2003) Impact 2002+: A New Life Cycle Impact Assessment Methodology. International Journal of Life Cycle Assessment 8(6):324-330.

31. This study only considers the health impacts caused by the release of substances into the outdoor environment and human exposure to that environment. Direct exposure through indoor air or dust is excluded; life cycle science is currently unable to assess the human health impacts resulting from exposure to poor indoor air quality.

32. Here, the warehouse scenario is evaluated as both a conversion to multifamily residential and commercial office space rather than as a warehouse undergoing renovation pursuant to its existing use. This approach is based on common practices in the real estate market.

33. U.S. Energy Information Administration (2005).

34. U.S. Energy Information Administration (2003).

35. Ibid.

36. A statistical uncertainty analysis has not been conducted in the study. Yet, the authors are confident that the results support the overall conclusion that there is indeed a difference between the environmental profiles of the NC and RR scenarios. See Quantis Technical Report.

37. See Section III of the Quantis Technical Report for details on the use of the internationally recognized impact assessment method, IMPACT 2002+ v2.07.

38. For instance, electricity in the East North Central region (i.e., Chicago) is predominantly coal-based. This form of energy generation creates a greater environmental burden than sources such as hydropower, which make up a significant amount of the grid mix in the Pacific and Mountain regions (i.e., Portland and Phoenix, respectively). See Section 5 for relevant average EUIs and end-use distribution figures for buildings.

39. Year-of-carbon-equivalency variations based on building type are contingent on building uses, material compositions, and energy uses. However, current trends show that more efficient, new construction buildings will recover more quickly in regions with dirtier fuel mixes.

40. CBECS data on commercial buildings indicates that prewar buildings use less energy than buildings built between 1990 and 2003.

41. Based on demolition rates between 2003-2011 provided by City of Portland Bureau of Planning and Sustainability and CO2 emission targets as outlined by the City of Portland and Multnomah County 2009 Climate Action Plan. Accessed December 2011: http://www.portlandonline.com/bps/index.cfm?a=268612&c=49989. Reduction in CO2 emissions assumes both the new and the existing buildings are considered to be of the same size and functionality.

42. Victor Olgyay and Cheryln Seruto, "Whole-Building Retrofits: A Gateway to Climate Stabilization," *AHSRAE Transactions,* vol. 116(2) (2010); Eric Bloom and Clint Wheelock, "Retrofit Industry Needs Assessment Study, Public White Paper" (Rocky Mountain Institute, 2010).

43. The *Materials Contribution* Tab of the Quantis Results viewer provides details on the role that various materials play in driving impacts in all scenarios.