Quantifying the Value of Building Reuse  
A Life Cycle Assessment of Rehabilitation and New Construction

Prepared for:  
The National Trust for Historic Preservation

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This report has been prepared by Quantis, a team of world-leading experts in the field of environmental life cycle assessment. Quantis works with companies, governments and other decision-makers to identify and implement the right actions for minimizing the environmental footprint of products and services. Founded in 2009, the firm maintains its global headquarters in Lausanne, Switzerland with branches in Boston, Montréal, and Paris. Quantis provides the highest level of proficiency in delivering state-of-the-art analysis and solutions for organizations striving to be leaders in the global sustainability effort.

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## Project Summary

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Project Team and Acknowledgements

The project team consisted of a diverse group of experts from both the building industry and life cycle assessment arena. Green Building Services provided the energy use research and recommendations for energy modeling and assisted in identifying buildings on which to base the assessments. GBS also lead the team as the overall project managers in the first portion of project. Skanska identified buildings on which to base the LCA and quantified input data for the LCA model, including material quantities and demolition activities. Cascadia Green Building Council prepared numerous narratives regarding the background information for the study and served as project manager in the last phases of the work. In addition, the Cascadia Green Building Council crafted the aesthetic components and layout for the larger report. Quantis performed the LCA components of the project. All team members conducted research that informed project assumptions; offered expert judgment as needed; and contributed to the writing of reports.

The Project Team would like to express their appreciation to all those who contributed their expertise to this study. Many thanks for helping to enhance the practicality and integrity of this work.
**Executive Summary**

Life cycle assessment (LCA) is increasingly being employed by the construction industry to evaluate the environmental performance of buildings, building materials, and construction practices. The National Trust for Historic Preservation (NTHP), a non-profit organization focused on promoting continued use of aged structures, has engaged in efforts to better understand the conditions under which rehabilitating and energy retrofitting a building is environmentally preferable to demolition and new construction. This study aims to explore that question through the application of LCA. The results of this study are intended for public disclosure by the NTHP.

This study assesses the life cycle of rehabilitated and newly constructed buildings from the extraction and processing of all raw materials through the end-of-life of all building components. For purposes of this study, ‘New Construction’ (or ‘NC’) includes complete demolition of the existing structure and erection of a new building. ‘Rehabilitation and Retrofit’ (or ‘RR’) describes the (selected) demolition, renovation, and energy retrofitting of an existing building.

This analysis examines 6 building typologies that are frequently demolished and replaced by new construction in the United States. These typologies are as follows:

- Commercial Office
- Single-Family Residence
- Multifamily Residence
- Elementary School
- Urban Village (Mixed Use)
- Warehouse

The warehouse scenario in this study is evaluated as both a conversion to multifamily residential space and a conversion to commercial office space, rather than as an existing warehouse undergoing renovation for continued service as a warehouse.

Additionally, each of these buildings is evaluated in four U.S. climate zones, as defined by the U.S. Energy Information Administration (EIA): Pacific, Mountain, East North Central, and South Atlantic. In each zone, a representative city is selected to assist in identifying buildings and making assumptions. These are Portland, Phoenix, Chicago, and Atlanta, respectively.
The functional unit for this study is providing one square foot (1 ft²) of usable interior space for a period of 75 years. The use of the space, and therefore the function, differs between building types. A home provides residential space; an office building, commercial space; a school offers educational space, and so on. It is therefore not possible to compare buildings of different use types within the present analysis as each building type can be considered to have a distinct functional unit providing space for the use appropriate to that building type. Occupant density, i.e., the number of occupants per square foot between NC and RR for a given building, is assumed to be equivalent. Operating energy use is calculated based on this assumption.

Three sensitivity and scenario analyses are conducted to assess the influence of key parameters on the study results. The analysis of electricity grid mix evaluates results under various combinations of energy technologies, including the national average mix (the Base Case analysis uses regional grid mixes) and two that consist of increasing proportions of renewable energy technologies—one at a conservative rate of change and the other a more optimistic pace and achieving 100% renewables by 2050. An analysis of building energy performance is also conducted in which the energy performance of each building is improved by approximately 30% through the addition of relevant energy efficiency measures (EEMs). In addition, for the Commercial Office scenario, the RR building is evaluated without the EEMs implemented to bring it to an average level of energy performance. The intent is to represent an existing building that, owing to historic construction techniques that offer inherent efficiency strengths, performs at code level without any energy upgrades.

This analysis brings to light several observations related to the balance between materials and energy. These themes remain constant across climate zones, building typologies, and environmental indicators. It is found that where the energy performance of NC and RR buildings can be considered equivalent, the material differences between NC and RR primarily determine the relative environmental profiles of the buildings. In general, because NC requires more materials than RR during construction/rehabilitation, it is responsible for a larger magnitude of impact. Additionally, this need for fewer materials implies that RR offers near-term environmental savings, a particularly important benefit in the context of Climate change pressures. Repurposing projects may not offer these savings due to the amount and types of materials needed, which can be similar to those needed NC.

The environmental benefit of improving a building’s energy performance is a function of the building’s expected lifetime; the materials required for the improvements; and the actual energy use reduction
attained. It is possible that impacts caused by material-related requirements can outweigh the savings in impacts gained by the achieved energy reduction. This observation is a function of the EEMs implemented (i.e., materials used), as well as the actual energy savings achieved. This can vary by environmental indicator, as some are more influenced by materials-related activities than building energy use. In order to make a well-informed decision regarding rehabilitation, multiple environmental indicators should be assessed to identify any trade-offs in type of impact. Additionally, the anticipated building age can determine whether NC or RR is environmentally preferable as a higher-performing building can overcome the additional materials-related impact associated with energy improvement measures over time. Sufficient savings, however, are often not accumulated until several decades into the building’s life span.

Since building energy use—both end use profiles and energy use intensity (EUI)—play key roles in determining environmental impact, and because these differ by climate zone, geography can be an important factor in determining the total environmental impacts of a given building. However, the relative results between NC and RR are unaffected by location. This conclusion is valid only if the energy demand, end use profile, and materials are the same across climate regions for NC or RR. For instance, if NC uses natural gas for space and water heating in the Portland and Atlanta scenarios, and RR uses natural gas for these in the Portland scenario but electricity in the Atlanta scenario, the relative results between NC and RR could vary. These parameters are held constant across regions in this study. Further analysis is required to draw conclusions regarding these assumptions.

The LCA conducted identifies some key parameters and trade-offs to consider when deciding whether to demolish an existing building and erect a new structure on a site or rehabilitate and retrofit an existing structure. Results of any LCA are a function of many factors, including the model assumptions, data employed, and choices in study boundary and functional unit. This context should be considered when interpreting and applying the information presented in this report.
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Abbreviations and Acronyms

CH₄  Methane
CO₂  Carbon Dioxide
DALY Disabled Adjusted Life Years
EEMs Energy Efficiency Measures
EOL End of Life
EUI Energy Use Intensity
GWP Global Warming Potential
ISO International Organization for Standardization
kg Kilogram = 1,000 grams (g) = 2.2 pounds (lbs)
kWh kiloWatt-hour = 3,600,000 joules (j)
LCA Life Cycle Assessment
LCI Life Cycle Inventory
LCIA Life Cycle Impact Assessment
MJ Megajoule = 1,000,000 joules
NC New Construction
PDF*m²*year Potentially Disappeared Fraction per Square Meter of land per Year
RR Rehabilitation & Retrofit
I. Introduction

Increased awareness of the importance of the environmental consequences associated with construction products and services has sparked the innovation of methods to better understand and proactively manage such potential impacts. A leading tool for achieving this—and the only tool that can make a full evaluation of 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 2006a; ISO 2006b).

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 life cycle, inform decision-making and support marketing and communication efforts. It is important to note, however, that the impacts described by LCA are estimates of potential impacts rather than direct measurements of real impacts.

LCA is increasingly being employed by the construction industry to evaluate the environmental performance of buildings, building materials, and construction practices. The National Trust for Historic Preservation (NTHP), a non-profit organization focused on promoting continued use of aged structures, has engaged in efforts to better understand the conditions under which rehabilitating and retrofitting a building is environmentally preferable to demolishing the building and constructing a new one.\(^1\) To begin collecting this foundational knowledge, the NTHP has contracted with Quantis, through a primary contract with Green Building Services, to compare the environmental impacts of newly constructing versus rehabilitating a building.

The study is conducted in three phases. The first phase consists of a screening-level LCA characterizing the relative environmental profiles of demolishing and constructing anew versus rehabilitating and retrofitting a building. This phase analyzes an elementary school located in the U.S. Pacific climate zone, i.e. constituting the Portland scenario. The second phase applies lessons learned from the first phase to develop a consistent, credible and transparent methodology for conducting an LCA around several building typologies, each to be represented in four U.S. cities situated in different climate zones, as defined by the U.S. Energy Information Administration (EIA)—the Pacific (the Portland scenario), Mountain (Phoenix), East North Central (Chicago), and South...
Atlantic (Atlanta). This scenario development exercise details the conditions under which each building type is typically rehabilitated and reused versus built new, including material variations, energy profiles, and other key parameters. This report presents the third phase of the endeavor—the full LCA—which assesses the spectrum of identified scenarios, drawing conclusions about the environmental trade-offs of building reuse versus new construction. The LCA approach in this second iteration is an extension of, and improvement upon, the pilot LCA. Specifically, the following has been accomplished to upgrade the quality of the results:

- Refinement of assumptions around building products (service) lifetimes;
- Modification of allocation methodology to better reflect economic realities;
- Enhancement of product and assembly modeling through expert estimation of materials composition; and
- Addition of numerous sensitivity tests and scenario analyses.

These improvements were the result of extensive literature research and input from building industry and LCA experts. A peer review has been commissioned to validate the reliability of the results; comments and responses are provided in the Appendices.

For purposes of this study, ‘new construction’ includes complete demolition of the existing structure and erection of a new building. ‘Rehabilitation and retrofit’ describes the (selected) demolition, renovation and retrofitting of an existing building. Throughout this document, the abbreviation ‘NC’ refers to the former, while ‘RR’ refers to the latter.

II. Goal and Scope of the Study

This chapter describes the goal and scope of the study, along with the methodological framework of the LCA.

A. Objectives and intended application

This investigation aims to identify conditions under which rehabilitation and retrofit of a building is environmentally preferable to demolition and new construction. Specifically, the objectives of the study are as follows:

1) To compute and compare the life cycle environmental impacts of buildings undergoing rehabilitation to those generated by the demolition of an existing building and new construction;
2) 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
3) To assess the influence of building typology, geography, energy performance, electricity grid mix, and lifespan on environmental impacts throughout a building’s life cycle. This study offers comparative statements regarding the environmental influence of building-stock management, as exemplified by the many scenarios and conditions considered here. This study does not include any definitive comparisons of the environmental performance of specific products, materials, building designs, building practices, or related decisions beyond the central question of building restoration. More focused studies are needed in order to assess the relative environmental impact of these factors.

Assessment of an entire building is an extremely complex task and relies on numerous data sources and assumptions. While the results presented by this study are considered reliable, they should only be used only within the context of the boundaries and limitations discussed in this document.

According to ISO standards, a critical review of an LCA is mandatory if its results are to be communicated publicly. The intent of the third-party review is to enhance quality and credibility, thereby improving public acceptability of the study. This report has undergone a critical review by an expert in the field of LCA. (See APPENDIX H: Critical Review.)

B. Description of the Buildings Studied

In order to identify those building types to be used in the study, research is first performed to characterize the existing building stock in the United States. Potential building typologies were then vetted based on several criteria, including the most prevalent building types (by total square footage); building types that are frequently torn down and replaced by new construction, and availability and access to data from building owners and project teams. Six building types are selected for analysis to best represent each of these target criteria:

- Commercial Office
- Single-Family Residence
- Multifamily Residence
- Elementary School
- Urban Village (mixed use)
- Warehouse Conversion (to Commercial Office and Multifamily Residence)

Based on common practices in the real estate market, the warehouse scenario in this study is evaluated as (1) a conversion to a multifamily residential building, and (2) a conversion to commercial office space, rather than as an existing warehouse undergoing renovation for continued service as a warehouse.
Every attempt was made to select NC and RR case study buildings that are comparable in terms of functionality and construction. In other words, the buildings must be constructed with common practices and materials for their period of construction and offer equivalent services. This was done by identifying buildings of similar sizes (i.e., based on height and square footage), operating hours, and programmatic elements. However, because actual buildings are used rather than hypothetical buildings, the two case studies undergoing comparison are not completely equivalent. Thus, the case study buildings are ‘normalized’ in order to more accurately compare the NC and RR scenarios. The normalization methodology involves removing any program elements that represent a significant difference in scope between the two buildings (e.g., due to the existence of a parking garage).

Case study buildings are not normalized based on their size. Instead, life cycle impacts for the buildings are calculated based on the current building design and an appropriate ‘intensity’ calculated by dividing impacts over the total building area to arrive at an ‘impact per square foot’ metric. This methodology minimizes error that may be introduced by changing the design of an existing building to more closely match another project. For instance, removing floors from one building would change the envelope and glazing ratios for the project and induce errors in the reported results. A similar condition could occur with the downsizing or upsizing of a project that drives a change in mechanical systems or other components (e.g., cooling towers, vertical transportation). It is anticipated that leaving the buildings as designed results in a more accurate comparison between the two.

The buildings selected in this study are believed to represent structures that are common across the United States and especially within the climate zone in which they in reality exist and for the period in which they are constructed. However, it is recognized that different design features are as or more common in different climate zones. The results of this study should be applied in consideration of the buildings’ designs.

1. Commercial Office

Commercial Offices represent the most prevalent non-residential building type in the United States, with over 12 billion square feet of existing floor space.\(^2\) Nationally, these buildings average 14,800 ft\(^2\) in size, although the vast majority are under 25,000 ft\(^2\).

A warehouse conversion to commercial office space is included in this analysis in order to evaluate the life cycle impacts of this reuse method relative to new construction. Approximately 14% of the
square footage of U.S. building stock is warehouse buildings. The conversion of warehouse buildings to office (or residential) uses most often occurs in urban and suburban locations, mainly with buildings of older vintage and potentially functionally obsolete. Frequently, the areas surrounding the warehouse building undergo changes in land use, and new development adjacent to warehouse districts influence their reuse.

The process of converting an older building, such as a warehouse, to an office or residential-type building typically involves updating the building entries and mechanical, electrical and plumbing systems, as well as potentially updating the structure and fenestration. As a result, the building is remodeled to include features and equipment that are expected in these new uses, such as elevators, central heating/cooling equipment, general and decorative interior lighting, appliances, and extensive electrical outlets. The buildings’ energy uses also shift to mimic the appropriate occupancy schedules. As part of this study, it is assumed that the energy uses in a converted warehouse would align with other office buildings.

The buildings selected for the analysis are shown in the table on the following page. In order to normalize the functions of the three buildings, the 818 Stewart parking structure is removed from the assessment. This is achieved by eliminating the four floors dedicated solely to parking and adjusting the total material and system quantities that make up the building envelope, structure, and mechanical, electrical, and plumbing systems to reflect a smaller overall square footage. The existing small parking area related to the 14th & Everett building is also eliminated.
### Commercial Office Building

<table>
<thead>
<tr>
<th>NEW CONSTRUCTION</th>
<th>REHABILITATION and RETROFIT</th>
<th>WAREHOUSE REHABILITATION and RETROFIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building name</td>
<td>818 Stewart</td>
<td>Joseph Vance Building</td>
</tr>
<tr>
<td>Location</td>
<td>Seattle, WA</td>
<td>Seattle, WA</td>
</tr>
<tr>
<td>Year built</td>
<td>2008</td>
<td>1929</td>
</tr>
<tr>
<td>Year renovated</td>
<td>N/A</td>
<td>2007</td>
</tr>
<tr>
<td>Building height</td>
<td>14-story</td>
<td>14-story</td>
</tr>
</tbody>
</table>

**Space Summary**

<table>
<thead>
<tr>
<th></th>
<th>265,845</th>
<th>128,007</th>
<th>188,097</th>
</tr>
</thead>
<tbody>
<tr>
<td>Square footage</td>
<td>Ground floor retail, commercial office, parking structure, multi-tenant</td>
<td>Ground floor retail, commercial office, multi-tenant</td>
<td>Commercial Office, single tenant</td>
</tr>
<tr>
<td>Building program elements</td>
<td>N/A</td>
<td>Interior finishes updated, repairs to mechanical system, operable windows refurbished</td>
<td>Full exterior envelope upgrade and major interior renovation, added elevators</td>
</tr>
<tr>
<td>Renovation description</td>
<td>Removed parking structure</td>
<td>N/A</td>
<td>Removed small parking area</td>
</tr>
<tr>
<td>Normalization</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Core & Shell**

<table>
<thead>
<tr>
<th></th>
<th>Concrete and Steel</th>
<th>Steel</th>
<th>Concrete and steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure type</td>
<td>Curtinwall, rigid and batt insulation, built-up roofing</td>
<td>Double hung operable windows, single glazing, masonry wall system</td>
<td>Concrete and masonry assembly, rigid and batt insulation, high performance windows, rooftop garden</td>
</tr>
<tr>
<td>Envelope</td>
<td>Glass, metal panel, precast concrete</td>
<td>Terra cotta</td>
<td>Concrete and masonry with elastomeric coating</td>
</tr>
<tr>
<td>% Glazing (window : wall)</td>
<td>38%</td>
<td>25%</td>
<td>27%</td>
</tr>
<tr>
<td>HVAC System</td>
<td>Split direct expansion heating and A/C, every other floor</td>
<td>Steam and natural ventilation</td>
<td>Electric, underfloor air distribution, variable refrigerant flow heating and cooling system at perimeter</td>
</tr>
</tbody>
</table>

**Interior**

<table>
<thead>
<tr>
<th></th>
<th>Open office</th>
<th>Closed office</th>
<th>Open office</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Carpet, vinyl flooring, metal framing, casework</td>
<td>Carpet, plaster/GWB, metal, masonry, casework, terrazzo lobbies/corridor</td>
<td>Access flooring, concrete panel, flexible glass interior wall system</td>
</tr>
</tbody>
</table>
2. **Single-family Residence**

Detached, single-family housing represents the majority of building stock in the United States, constituting over 210 billion square feet.⁴ Over half of these units are located within urban or town limits as opposed to suburban or rural areas. Almost 50% of the nation’s single-family residential building stock is 1-story, with 2-story units making up over a quarter of the remaining units.

Only 13.5% of the existing building stock was built prior to 1940. However, buildings from this era were selected for analysis because they belong to a market of commonly demolished homes that would otherwise have significant community and historical value.

Two homes in Portland, OR are analyzed in this study. No normalization is necessary in these scenarios, since the two buildings are similar in size and programmatic elements.
<table>
<thead>
<tr>
<th>Building name</th>
<th>SW 34th Street</th>
<th>2373 NW Pettygrove</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Portland, OR</td>
<td>Portland, OR</td>
</tr>
<tr>
<td>Year built</td>
<td>2011 targeted</td>
<td>1896</td>
</tr>
<tr>
<td>Year renovated</td>
<td>N/A</td>
<td>2009</td>
</tr>
<tr>
<td>Building height</td>
<td>2-story</td>
<td>2-story</td>
</tr>
</tbody>
</table>

### Space Summary

<table>
<thead>
<tr>
<th>NEW CONSTRUCTION</th>
<th>REHABILITATION and RETROFIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Square footage</td>
<td>2,360</td>
</tr>
<tr>
<td>Building program elements</td>
<td>3 bedroom, 2.5 bathrooms, below-grade partial basement</td>
</tr>
<tr>
<td>Renovation description</td>
<td>N/A</td>
</tr>
<tr>
<td>Normalization</td>
<td>N/A</td>
</tr>
</tbody>
</table>

### Core & Shell

<table>
<thead>
<tr>
<th>NEW CONSTRUCTION</th>
<th>REHABILITATION and RETROFIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure type</td>
<td>Dimensional lumber, prefab truss system</td>
</tr>
<tr>
<td>Envelope</td>
<td>2x6 wood framing, batt insulation, wood windows, cedar shingle roofing</td>
</tr>
<tr>
<td>Cladding</td>
<td>Cedar shingle</td>
</tr>
<tr>
<td>% Glazing (window: wall)</td>
<td>18%</td>
</tr>
<tr>
<td>HVAC system</td>
<td>Gas furnace, air conditioning unit</td>
</tr>
</tbody>
</table>

### Interior

<table>
<thead>
<tr>
<th>NEW CONSTRUCTION</th>
<th>REHABILITATION and RETROFIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Custom</td>
</tr>
<tr>
<td>Scope</td>
<td>Granite countertops, wood paneling, carpet, ceramic and wood flooring</td>
</tr>
</tbody>
</table>
3. **Multifamily Residence**

After detached, single-family homes, multifamily buildings with 5 or more units represent the second largest category of residential buildings in the United States. This subset of buildings accounts for roughly 15% of all residential structures, the majority of which are rental rather than occupant-owned housing units. The following criteria were used to select a NC Multifamily case study: (1) Mid-rise building; (2) characterized as ‘4-over-1’ construction type (ground floor concrete structure with up to four stories of wood framing above); (3) with ground-floor retail.

The conversion of a multifamily residence to a warehouse is a popular adaptive reuse approach; it is included here in order to evaluate the life cycle impacts from this type of use relative to new multifamily construction. As described in Section II.B.1, the construction activities associated with warehouse (e.g., updates to mechanical, electrical and plumbing systems) incorporate elements that would typically be included in a new multifamily building, e.g., such as elevators. Energy schedules are also modified to reflect the appropriate occupancy schedule. As part of this study, it is assumed that the energy uses in a converted warehouse would align with a multifamily building as listed in the RECS data. This assumption is based on the fact that the extensive renovation activities required for repurposing would likely trigger code-compliant upgrades to the building’s envelope and mechanical systems. Additional discussion of this topic can be found in the Main Report, *The Greenest Building: Quantifying the Environmental Benefits of Building Reuse.*

Both Block 49 and the Avenue Lofts buildings were adjusted in order to normalize the comparison between the case studies. For purposes of this analysis, the garage and associated systems were removed from Block 49. 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 Residence

<table>
<thead>
<tr>
<th>Building name</th>
<th>NEW CONSTRUCTION</th>
<th>REHABILITATION and RETROFIT</th>
<th>WAREHOUSE REHABILITATION and RETROFIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Block 49</td>
<td>New Holland Apartments</td>
<td>The Avenue Lofts</td>
</tr>
<tr>
<td>Block</td>
<td>Portland, OR</td>
<td>Danville, IL</td>
<td>Portland, OR</td>
</tr>
<tr>
<td>Year built</td>
<td>Anticipated 2012</td>
<td>1906 with a 1927 addition</td>
<td>1923</td>
</tr>
<tr>
<td>Year renovated</td>
<td>N/A</td>
<td>2006</td>
<td>2004</td>
</tr>
<tr>
<td>Building height</td>
<td>6-story</td>
<td>5-story</td>
<td>7-stories</td>
</tr>
</tbody>
</table>

### Space Summary

<table>
<thead>
<tr>
<th>Space Summary</th>
<th>NEW CONSTRUCTION</th>
<th>REHABILITATION and RETROFIT</th>
<th>WAREHOUSE REHABILITATION and RETROFIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Square footage</td>
<td>167,180 residential, 19,640 retail excludes parking</td>
<td>73,875 including basement</td>
<td>215,000-sf excluding basement</td>
</tr>
<tr>
<td>Building program elements</td>
<td>209-unit rental, ground floor commercial, 2,000-sf community space, underground parking</td>
<td>47-unit, rental, 1-, 2- and 3-bedroom units</td>
<td>153-unit loft-style condos</td>
</tr>
<tr>
<td>Renovation description</td>
<td>N/A</td>
<td>Ground source heat pump, replacement windows, masonry rehabilitation, lead paint and asbestos removal</td>
<td>Complete exterior refurbishment, high performance windows, full interior renovation, new vertical transportation, open atrium</td>
</tr>
<tr>
<td>Normalization</td>
<td>Removed parking and raised slab on grade to ground floor, assumed full build-out of retail space</td>
<td>N/A</td>
<td>Removed underground parking</td>
</tr>
</tbody>
</table>

### Core & Shell

<table>
<thead>
<tr>
<th>Core &amp; Shell</th>
<th>NEW CONSTRUCTION</th>
<th>REHABILITATION and RETROFIT</th>
<th>WAREHOUSE REHABILITATION and RETROFIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure type</td>
<td>Concrete, CMU, dimensional lumber</td>
<td>Concrete</td>
<td>Concrete</td>
</tr>
<tr>
<td>Envelope</td>
<td>Storefront, vinyl windows, 2x6 framing, batt insulation, membrane roofing</td>
<td>Operable windows, masonry and metal stud wall system, batt insulation, 3-tab asphalt roofing</td>
<td>Masonry wall system with elastomeric coating, operable windows, rigid and batt insulation, SBS roofing</td>
</tr>
<tr>
<td>Cladding</td>
<td>Brick veneer and metal panel</td>
<td>Brick</td>
<td>Brick</td>
</tr>
<tr>
<td>% Glazing (window : wall)</td>
<td>30%</td>
<td>20%</td>
<td>28%</td>
</tr>
<tr>
<td>HVAC system</td>
<td>Air to air heat pump per unit</td>
<td>Ground source heating and cooling, natural ventilation</td>
<td>Fan coils, electric heating coils and DX refrigerant lines</td>
</tr>
</tbody>
</table>

### Interior

<table>
<thead>
<tr>
<th>Interior</th>
<th>NEW CONSTRUCTION</th>
<th>REHABILITATION and RETROFIT</th>
<th>WAREHOUSE REHABILITATION and RETROFIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scope</td>
<td>Gypsum wallboard, carpet and resilient flooring, plastic laminate countertops</td>
<td>Gypsum wallboard, wood framing, clay tile/plaster, carpet and vinyl flooring</td>
<td>Wood floors and trim, ceramic tile, metal framing drywall, exposed ceilings</td>
</tr>
</tbody>
</table>
4. **Elementary School**

Educational facilities represent the fourth largest type of non-residential commercial building stock in the United States. Due to several market factors, including state-required acreage standards and a lack of tax incentives for rehabilitation, smaller community-centered schools are now being replaced by ‘mega-schools’ on the outskirts of town. For this reason, this analysis compares a pre-1940s urban elementary school building to a newly construction elementary school.

Elementary Schools are selected such that no additional steps were necessary to normalize the basic programmatic elements of the two buildings. The buildings used for the analysis are described in the table on the following page.
<table>
<thead>
<tr>
<th>Building Name</th>
<th>Sue Buel Elementary</th>
<th>Central Elementary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>McMinnville, OR</td>
<td>Albemarle, NC</td>
</tr>
<tr>
<td>Year Built</td>
<td>2008</td>
<td>1924</td>
</tr>
<tr>
<td>Year Renovated</td>
<td>N/A</td>
<td>2008</td>
</tr>
<tr>
<td>Building Height</td>
<td>2-stories</td>
<td>3-stories</td>
</tr>
</tbody>
</table>

### Space Summary

<table>
<thead>
<tr>
<th></th>
<th>Sue Buel Elementary</th>
<th>Central Elementary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Square footage</td>
<td>80,837</td>
<td>60,121 existing</td>
</tr>
<tr>
<td>Building Program Elements</td>
<td>Classrooms, gymnasium, cafeteria and kitchen, auditorium, commons, music room</td>
<td>Classrooms, gymnasium, cafeteria, media center</td>
</tr>
<tr>
<td>Renovation Description</td>
<td>N/A</td>
<td>New kitchen, new classrooms, refurbishment of existing rooms, energy upgrades</td>
</tr>
<tr>
<td>Normalization</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

### Core & Shell

<table>
<thead>
<tr>
<th></th>
<th>Sue Buel Elementary</th>
<th>Central Elementary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure Type</td>
<td>Slab on grade, concrete tilt-up construction</td>
<td>Concrete and steel</td>
</tr>
<tr>
<td>Envelope</td>
<td>Storefront, tilt-up walls, rigid and batt insulation, membrane roofing</td>
<td>Masonry wall system, rigid and batt insulation, upgraded windows, SBS roofing</td>
</tr>
<tr>
<td>Cladding</td>
<td>CMU veneer, metal wall panels</td>
<td>Masonry</td>
</tr>
<tr>
<td>% Glazing (window : wall)</td>
<td>24%</td>
<td>22%</td>
</tr>
<tr>
<td>HVAC System</td>
<td>Four pipe chilled/heated water system to distributed fan boxes using heat recovery boxes</td>
<td>Four pipe system, gas boiler and chiller</td>
</tr>
</tbody>
</table>

### Interior

<table>
<thead>
<tr>
<th></th>
<th>Sue Buel Elementary</th>
<th>Central Elementary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scope</td>
<td>Plastic laminate countertops, cabinetry, acoustical ceiling tile, carpet, ceramic and linoleum flooring, built-in cabinetry</td>
<td>VCT floor, ACT, metal framing, drywall</td>
</tr>
</tbody>
</table>
5. **Urban Village (mixed use)**

The Urban Village scenario represents the other end of the spectrum when evaluating the existing stock of non-residential buildings. Mercantile buildings represent the second most prevalent commercial building type in the United States, after offices. For this reason, a traditional mercantile building located within an urban village was selected for analysis. Additional criteria included mixed-use ground floor retail or office space with 1 or 2 stories of offices or residential units above, party wall construction, and a preference for pre-1940s vintage buildings. This classic ‘Main Street’ building type is common in historic neighborhoods and the older, downtown core areas of small-to-medium-sized American cities.

The following page presents the buildings selected for the comparison. The normalization process involves removing foundations and other structural elements of the Assurety NW building (i.e., NC scenario) associated with a future pedestrian bridge designed to connect to an adjacent building.
Urban Village Mixed Use

<table>
<thead>
<tr>
<th>Building name</th>
<th>NEW CONSTRUCTION</th>
<th>REHABILITATION and RETROFIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Assurety Northwest Building</td>
<td>Whitmore Building</td>
</tr>
<tr>
<td>Year built</td>
<td>2009</td>
<td>1880</td>
</tr>
<tr>
<td>Year renovated</td>
<td>N/A</td>
<td>2010</td>
</tr>
<tr>
<td>Building height</td>
<td>2-story</td>
<td>2-story</td>
</tr>
</tbody>
</table>

**Space Summary**

<table>
<thead>
<tr>
<th>Square footage</th>
<th>22,975</th>
<th>21,785 including basement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building program elements</td>
<td>Mixed-use commercial office and retail</td>
<td>Mixed-use commercial office, restaurant and residential</td>
</tr>
<tr>
<td>Renovation description</td>
<td>N/A</td>
<td>Extensive energy upgrades including installation of ground source heat pump, insulation, and new and refurbished windows, architectural restoration</td>
</tr>
<tr>
<td>Normalization</td>
<td>Removed foundations and other support structure for a future pedestrian bridge designed to connect to an adjacent building</td>
<td>Removed appliances and commercial kitchen equipment.</td>
</tr>
</tbody>
</table>

**Core & Shell**

<table>
<thead>
<tr>
<th>Structure type</th>
<th>Steel structure on concrete spread footings with slab on grade and slab on metal deck</th>
<th>Slab on grade, masonry wall system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Envelope</td>
<td>Punched window and storefront systems, perimeter insulation</td>
<td>Double hung wood windows, single glazing, masonry wall system</td>
</tr>
<tr>
<td>Cladding</td>
<td>Storefront, brick</td>
<td>Storefront, brick</td>
</tr>
<tr>
<td>% Glazing (window : wall)</td>
<td>34%</td>
<td>34%</td>
</tr>
<tr>
<td>HVAC system</td>
<td>Rooftop units for air supply with electric reheat in VAVs</td>
<td>Ground source heating and cooling</td>
</tr>
</tbody>
</table>

**Interior**

| Scope | Typical open office build out some perimeter offices | Gypsum wallboard, plaster finish, carpet and Wood flooring, wood frame, drywall |

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C. Building Function and Functional Unit

LCA relies on a ‘functional unit’ as a reference point for evaluating the components within a single system and/or among multiple systems. In order to ensure a common basis for evaluation, it is critical that this parameter is clearly defined and measurable. The functional unit for this study is the provision of 1 square foot of usable interior space for a period of 75 years. Occupant density (i.e., the number of persons per square foot) is assumed to be the same between NC and RR for a given building typology.

The use of space, and therefore its function, differs between building types. A home provides residential space; an office building offers commercial space; a school offers educational space; and so on. It is therefore not possible to compare buildings of different use types within the present analysis, as each building type has a distinct functional unit providing space for the use appropriate to that building type.

While it is ideal to assess real examples of comparable construction projects, this is not feasible in the present project; the goals of this study demand an evaluation of activities that could be chosen for a given building, of which one could occur in reality. In other words, a building may either be demolished and newly constructed or rehabilitated and retrofitted, but not both at the same time. Evaluating two alternate paths for one existing building site requires estimating the inputs for at least one scenario. In contrast, using empirical data for both scenarios requires evaluating two different building sites. Both approaches draw questions regarding the comparability of the data; the former concerns data accuracy, while the latter concerns the relative function and comparability of the buildings.

The buildings evaluated in this study are based on actual construction projects in the United States, which have been modified in some cases to best reflect an equivalent function. While the precise functionality of the buildings could vary to some extent, the general functionality within a building category (e.g., office building) is considered to be equivalent on a basis of equal area provided for an equal time period. Criteria for building selection are established to ensure that equivalence of functionality is maximized. For the case study buildings, the area (square feet of usable floor space) is not modified to avoid introducing additional complexities and error; changing the design of the building would require revisions to the ratios of skin to floor area, glazing percentages, floor-to-roof area, and foundation designs, among other parameters. Further details, including building selection, are described above, in Section II.B.
D. System Boundaries

System boundaries identify the life cycle stages, processes, and flows considered in the LCA and include all activities necessary to provide the specified function relevant to attaining the above-mentioned study objectives. The following presents a description of the system and the temporal and geographical boundaries of this study.

1. General system description

This study assesses the life cycle of rehabilitated and newly constructed buildings from the extraction and processing of all raw materials through the end-of-life of all building components. Figure 1 depicts the boundaries of this study. Figure 2 provides the specific activities considered within each life cycle stage.

This boundary raises a question regarding the inclusion of materials from the existing building that remain on-site for use in the rehabilitated building (i.e., ‘remaining materials’). This analysis excludes the production and management of these materials, because the choice to rehabilitate produces no difference in either the occurrence or details of the production or management of these materials; they have already been produced, and they will be disposed of by transport routes and material handling practices that will not differ substantially—other than in their timing—whether they are disposed during demolition (if new construction is elected) or during final demolition of the renovated building (if rehabilitation is elected). This exclusion requires assuming that (1) these materials are durable enough to not require replacement during a building’s lifetime, and (2) that material handling processes will not change significantly during a building’s lifetime. These are assumed here to be reasonable conclusions, as depicted in Figure 2.

The decision to exclude this material is also based on the inability to obtain information characterizing (1) the types and quantities of remaining materials (contractor plans for the rehabilitation do not typically catalogue this); and (2) the original impact of producing these materials decades or even a century ago, when many industrial systems were radically different.

Within each of these stages, the LCA considers all identifiable ‘upstream’ inputs, in order to provide a comprehensive, practical view of the product system. For example, with regard to the environmental impact of transportation, truck emissions are considered in addition to the impact of additional processes and inputs needed to produce the fuel, among other items. In this way, the production chains of all inputs are traced back to the original extraction of raw materials.
Figure 1. Life cycle stages considered in this study. The Existing Building Life Cycle (grey boxes) is excluded in both the NC and RR scenarios, although it is shown here for context.

*Includes only energy use (e.g., electricity, heating)
**Excluded in this study
Table 1. Activities within the scope of the buildings’ life cycles. The grey text indicates a stage that is not included in the analysis.

<table>
<thead>
<tr>
<th>Activity</th>
<th>LIFE CYCLE STAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre-occupancy</td>
</tr>
<tr>
<td></td>
<td>Occupancy</td>
</tr>
<tr>
<td></td>
<td>Post-occupancy</td>
</tr>
<tr>
<td>Extraction of raw materials</td>
<td>Production of original materials</td>
</tr>
<tr>
<td>Refinement of raw materials</td>
<td>Production of replacement materials</td>
</tr>
<tr>
<td>Manufacture of products</td>
<td></td>
</tr>
<tr>
<td>Transportation occurring upstream of the product supplier</td>
<td></td>
</tr>
<tr>
<td>Transportation of products from supplier to building site</td>
<td>Transportation of materials</td>
</tr>
<tr>
<td>Operation of heavy machinery</td>
<td>Demolition/Selected demolition</td>
</tr>
<tr>
<td>Use of electricity by construction-related activities</td>
<td>New construction/Rehabilitation &amp; retrofit</td>
</tr>
<tr>
<td>Transportation of construction workers to and from building site</td>
<td>Maintenance</td>
</tr>
<tr>
<td>Space and water heating</td>
<td>Heating, cooling &amp; plug loads</td>
</tr>
<tr>
<td>Electricity use</td>
<td></td>
</tr>
<tr>
<td>Water use</td>
<td></td>
</tr>
<tr>
<td>Operation of heavy machinery</td>
<td></td>
</tr>
<tr>
<td>Use of electricity by demolition-related activities</td>
<td></td>
</tr>
<tr>
<td>Transportation of construction workers to and from building site</td>
<td></td>
</tr>
<tr>
<td>Transportation of materials from the building site to end-of-life</td>
<td></td>
</tr>
<tr>
<td>Landfill, recycling, and incineration/waste-to-energy processes</td>
<td>End-of-life of materials</td>
</tr>
</tbody>
</table>
Figure 2. Material flows for the NC and RR scenarios. Materials sourced from the existing building (grey boxes) are excluded from the analysis but are shown here for context.
In the present project, all building materials and construction processes are included in cases where the necessary information is readily available or a reasonable estimate can be made. A strict cut-off threshold is not applied, and any data for which reasonable estimates can be made and/or LCA data of reasonable quality can be obtained are included. Data collection for the NC and RR buildings has been conducted so as not to bias one system to be more inclusive than the other.

The following are excluded from consideration:

- Water consumption during building use;
- Building furnishings (i.e., any items not “nailed down”, including appliances and furniture);
- Direct occupation of land by the building;
- Emissions (off-gassing) from building materials and associated human health effects;
- Final demolition of the buildings (activities only, such as equipment operation); and
- The impact of individuals using the building (e.g., transport to and from the building).

Each of these items is assumed to be equal between the NC and RR scenarios, per square foot of floor space, except for materials emissions. The occurrence and magnitude of off-gassing are complex assessments, dependent on numerous factors, including the types and ages of materials in a given building. Further, emissions may be primary (i.e., released directly from a product’s composition); secondary (i.e., generated through a reaction occurring within a product); between multiple products (e.g., flooring material and associated adhesive); or within the indoor environment. This warrants an in-depth analysis of the building components and is beyond the scope of this study. Further discussion of the implications of excluding off-gassing is provided in Section VI.

2. **Temporal and geographical boundaries**

This LCA reflects the building industry and associated processes (e.g., transportation modes, distances, electricity grids mixes) in the United States (from 2010 to 2011, the term of this study). Regional variations are included to the extent possible, such as for grid mixes, and are noted in this report accordingly. (See APPENDIX B: Assumptions.)

Some processes within the system boundaries might take place in a wide variety of climate regions and points beyond the lifetime of a building. The processes associated with supply chains (e.g., building material production) can take place in the United States or abroad, and materials used in a building could have been produced—and their associated impacts induced—many months before placement in the structure. Similarly, certain processes may generate emissions over a longer period
of time than the reference year. This applies to landfilling, which causes emissions (i.e., biogas and leachate) over a period of time; this may be a matter of several decades or many centuries, depending on the design and operation parameters of the burial cells and how emissions are modeled in the environment.

E. Allocation Methodology

A common methodological decision point in LCA occurs when the system being studied is directly connected to a past or future system. For instance, in the building industry, a reused material is a product that endures two lifespans: one as a virgin product in the original building, and another as a reused product in a second building or other application. Similarly, at the end of a building’s life, materials can be incinerated, and the energy can be recovered as heat or electricity. In either case, the building’s life cycle cannot be considered in isolation.

When systems are linked in this manner, the boundaries of the system of interest must be widened to include the adjoining system, or the impacts of the linking items must be distributed or allocated across the systems. While the ISO 14040 series recommends as a first resort expanding the system boundaries to include all of the linked systems, such a task often requires more resources than what is available for a project. A secondary ISO recommendation is to allocate the resource’s impacts across the adjoining systems it enters over its entire lifetime—past, present, and future. This approach was selected for this study.

When performing allocation, for which impacts are systems responsible? For instance, should a system be credited for recycling its material, while another system is credited for using recycled content? Alternatively, should the credit be split, and if so, what should the ratio be? These questions must be answered in an objective, consistent and transparent manner in order to maintain the credibility of the study.

One approach to this challenge is to consider the economics of material markets, i.e., whether there is a demand for, or an excess of, recycled materials. However, such specific information is not uniformly available for the wide variety of materials contained in the buildings examined here. Further, it is unclear whether these precise, present-day economic figures would be applicable at the time the materials are actually disposed, which is assumed to extend decades into the future. Thus, a broad assumption is made here: recycled material markets are generally limited by supply rather than demand. That is, increased supply results in increased use of recycled material, whereas increased demand does not necessarily increase the amount of material recycled (the same is
assumed for other end-of-life uses, such as energy recovery). Therefore, the impact and benefit of recycling are given to the system providing the recycled material to reflect that the presumed limiting factor in achieving more recycling is the availability of recycled materials (i.e., a supply-limited market). This assumption results in the allocation of 100% of the impact and benefit of a material’s end-of-life (EOL) management to the system preceding the EOL management. This is often referred to as the *avoided burden approach*. TABLE 2 summarizes the inclusion and impact allocation of materials within this study.

**TABLE 2.** Scope and allocation of materials applied in this study.

<table>
<thead>
<tr>
<th>Material production</th>
<th>Material transport to building site</th>
<th>Material end-of-life transport</th>
<th>Material end-of-life processing impacts</th>
<th>Material end-of-life benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Materials in the existing building that are used in the rehabilitated building</td>
<td></td>
<td></td>
<td>Excluded from scope</td>
<td></td>
</tr>
<tr>
<td>Virgin materials that are used in the new or rehabilitated building</td>
<td></td>
<td></td>
<td>Allocated entirely to new or rehabilitated building</td>
<td></td>
</tr>
<tr>
<td>Materials containing recycled content that are used in the new or rehabilitated building</td>
<td>Benefit of recycling assigned entirely to prior life; Recycled content assigned same impact as virgin material</td>
<td></td>
<td>Allocated entirely to new or rehabilitated building</td>
<td></td>
</tr>
</tbody>
</table>
This method is distinctively conservative, favoring to a maximal extent the NC scenarios. In other words, the NC scenarios generally contain a large amount of material, and therefore send more material to beneficial end-of-life fates. Any allocation that assigns less than the entire benefit of recycling to the material donating system would disadvantage the NC scenarios. This is the case because the building assemblies include minimal recycled content compared to the amount assumed to be recycled or sent to energy recovery.

The quality of LCA results depends on the quality of data used in an evaluation. Every effort has been made to ensure that this investigation implements the most credible and representative information available.

F. Data collection

The data collection process, including choices in study assumptions, has been conducted iteratively between Quantis, Skanska, Green Building Services, and Cascadia Green Building Council. This team includes experts from building design, construction practices, energy performance and modeling, building industry, and life cycle assessment landscapes.

All life cycle inventory data is drawn from the ecoinvent database v2.2. While life cycle inventory (LCI) information for many building materials is provided in this source, information describing assemblies is less readily available. In order to maintain consistency in data sources, and thus avoid additional uncertainty, assemblies are modeled as a combination of their material components. Material compositions for all products are provided as expert estimates by Skanska.

The study team, which includes experts from the construction and energy-modeling industries, performed quantification of reference flows. These items are described below.

- **Material take-off lists** describe real construction projects, with modifications as needed to meet the objectives of this study. Material mass is calculated by Skanska using material dimensions, density, and, in the case of products with multiple components, expert judgment as to the relative proportions of materials in a given product. Materials are grouped according to the Construction Specifications Institute (CSI) Master Format 2004. Details are specific to building typology and scenario (i.e., NC and RR) and are located in APPENDIX A: Materials and Energy Inputs.

- **Equipment use, electricity consumption, and worker-hours** required during Demolition/Selected demolition and Construction/Rehabilitation and retrofit are estimated.
by experts at Skanska and based on real construction projects. (See APPENDIX A: Materials and Energy Inputs.)

- **Energy use** during the buildings’ operations is based on statistics for average building EUI by typology and region. (See Section 0 for additional details.)

Assessment of an entire building is an extremely complex task and relies on numerous data sources and assumptions. Every effort has been made to establish the best available information and consider key influential factors, such as geography, temporal relevance, scientific credibility, and internal study consistency. While the results presented by this study are reliable, they should only be used within the context of the boundaries and limitations discussed in this document. In cases where important information is unknown, uncertain or highly variable, sensitivity analyses are performed to evaluate the potential significance of the data gap; details can be found in Section II.H.

### G. Assumptions

Several assumptions are made throughout this body of work. This section describes those that are central to the study, while building-specific assumptions are provided in the descriptions of the typologies in Section II.B. (See APPENDIX B: Assumptions for further details.)

Prior research conducted by Quantis, particularly regarding residential construction practices in Oregon, serves as an initial basis for assumptions in this work. Assumptions were reviewed by the project team and tailored to the commercial construction sector where appropriate, and to geography, where data is available.

#### 1. Building lifetime

The longevity of a building is dependent on several factors, including economic and physical considerations, and at the time of construction, the lifespan of a structure is almost never known. Nevertheless, estimates of the average building lifetime are available; Pacific Northwest National Laboratory which approximates the median lifetime of commercial buildings to be between 70 and 75 years. The 2010 update to the Buildings Energy Data Book identifies the median building age average for all building types as 56.5 years. This study assumes that all buildings survive for 75 years, after which they are demolished and materials are transported to their end-of-life fates. Sensitivity analyses are conducted to better understand the effect of this parameter on the choice between NC and RR.
2. Waste factors

Waste factors describe the additional quantity of each material brought to the construction site that will not be used in a building (e.g., due to damage during transport or installation) but that cannot be saved for use in a future project. These materials are assumed to go to their end-of-life immediately following Construction/Rehabilitation and Retrofit or Maintenance activities.

The waste factors are set to 15%, 5%, or 0% for all materials. Zero percent is used for those materials in which there is no reason to expect a certain percent is wasted (e.g., elevators). Five percent is used for those materials for which it can reasonably be expected that most additional materials will be reused at another building site (e.g., roofing shingles). Fifteen percent is used for those materials that are not expected to be reused (e.g., lumber). These assumptions are based on the expert judgment of staff at the Oregon Home Builders Association. The assumption made for each material has been reviewed by the current project team.

3. Material replacement rates

Each product included in this analysis is assumed to be replaced over time according to the average service life of the item. Where data is available, these numbers are specific to typology (residential or commercial); otherwise, the available information for commercial is used for all buildings. Some replacement rates are set to zero (0) to indicate that the material is not replaced, as in the case of concrete foundations.

The assumed service lives are primarily derived from a limited set of publicly available literature, and the expertise of team members is drawn upon where no value has been located. (See APPENDIX B: Assumptions.) Replacement is implemented in the model as an annual average rate of replacement and is specific to each material and each material’s application. For example, lumber used in flooring has a different rate than lumber used in walls, which is specified with a different rate than gypsum plasterboard used in walls.

Material replacement is distributed over the life of a building. For instance, carpeting is assumed to be replaced every 12 years. Using a lifetime of 75 years, the building will need 6 replacements (i.e., at ages 12, 24, 26, 48, 60, and 72) and is assumed to receive 8.5%, or 1/12, of new carpeting each year. Calculating the replacements in this manner leads to some absurdity when considering a building, which in reality would not have 8% of carpet replaced each year for 75 years. However, the carpeting is not necessarily replaced every 12 years, either, and taking the average approach allows for an illustration of the overall trend over time. This avoids focus on large fluctuations in impacts at discreet points in the building’s lifespan.
4. **Materials transportation**

Materials transportation is characterized by a material’s weight and the distance it travels. For all transportation, it is assumed that shipments are limited by weight rather than volume, and that the impact can be accurately quantified based on the product of distance and weight (i.e., metric ton-kilometers).

All materials are assumed to be trucked 497 mi (800 km) from a site of production to a building site. A distance of 45 mi (72 km) is assumed for all materials to be trucked at their end-of-life to their eventual disposal or processing location (e.g., recycling, incineration). While this distance may in fact be much shorter than the actual distances traveled, as building products are fabricated globally, the use of longer distances in this analysis would have unfairly favored the building reuse scenario. Thus, because fewer new materials are used in renovation processes compared to building construction processes, it is a more conservative approach to use the shorter distances.

All transportation occurring upstream of the manufacturing facility is included in materials production, as provided by ecoinvent. This can include the transportation of raw materials from extraction sites to processing and/or manufacturing locations and/or transportation to regional storage. The specific legs of transportation involved in individual processes have not been determined.

For all building models, transportation weight is adjusted according to modifications in the material lists. The assumed transportation distances remain constant for all scenarios.

5. **Demolition and selected demolition activities**

The quantification of equipment operation, truck loads and transport distances for waste disposal, as well as worker-hours required for demolition or selective demolition for NC or RR, respectively, is based on real project data and professional judgment. These values are provided by Skanska. Worker-hours are used to compute impacts of commuting.

6. **Construction and rehabilitation and retrofit activities**

The quantification of equipment operations associated with construction, rehabilitation and retrofitting for NC or RR is based on real project data in combination with professional judgment. These values are provided by Skanska.
7. Building energy performance

The pilot LCA undertaken in Part I of this study, as well as previous LCA research concerning whole buildings, indicates that energy use during the operating phase of a building is a major component of its total environmental impact over its lifespan. The project team carefully considered the approach to establishing Base Case energy use specific to building type and geography.

The Base Case analyses are intended to represent typical buildings in each typology, operating at an average level of energy efficiency, as described in Green Building Services’ Energy Methodology. The Base Case assumes that buildings in both the NC and RR scenarios have the same operating energy performance, implying that the rehabilitated building is retrofitted to include EEMs, such that it is operating on par with new construction. While it is often assumed that a new, energy efficient building will typically outperform a retrofitted existing building, national data on building energy performance indicates that many structures from the early 20th century perform as well as, or better than, modern-day buildings. For example, data from the EIA demonstrates that commercial buildings constructed before 1920 use less energy, per square foot, than buildings from any other decade of construction. 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. Further details are provided in Green Building Services’ Energy Methodology.

The methodology used to determine operating energy varies by building typology. For single-family and multifamily residences, the Energy Information Administration’s 2003 Residential Energy Consumption Survey (RECS) forms the basis of the operating energy analysis and is further described in Green Building Services’ Energy Methodology. National survey data is used as the foundation for this study in order 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 (i.e., high rise office, elementary school, and urban village mixed use), energy use data is derived from a variety of sources. These include the Energy Information Administration’s 2003 Commercial Building Energy Consumption Survey; a 2011 white paper prepared by the New Buildings Institute; a study prepared by Cadmus; and findings from the Oregon Department of Energy. A more complete description is available in Green Building Services’ Energy Methodology.
Warehouse buildings converted to multifamily residences are assumed to operate the same as new or retrofitted multifamily buildings. 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 the extensive renovation activities required for repurposing would likely trigger code-compliant upgrades to the building’s envelope and mechanical systems. In reality, it is difficult to generalize the energy performance of warehouse conversions. Original design characteristics, such as large, single-pane windows and uninsulated walls, floors or roofs, may make energy retrofitting financially or technically challenging. Further research is needed to evaluate the actual energy usage of warehouse conversions.

The following describes the general approach to developing energy consumption rates for all typologies:

- **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 in each city. Determine annual energy used for space heating and cooling, lighting, fan/pump energy, hot water, and other categories.
- **Step 3**: Develop an extensive list of EEMs that could be applied to various building types to improve energy performance. Appropriate EEMs are selected and applied to case study buildings to achieve Base Case level of performance.¹⁷
- **Step 4**: Select EEMs that provide approximately 30% energy savings over the Base Case by estimating energy reductions for each measure and applying them to both the RR and NC scenarios.
- **Step 5**: Document the results including key assumptions, and quantify materials inputs associated with EEMs (e.g., additional insulation) for inclusion in the LCA model.

More information on these steps is provided in Green Building Services’ Energy Methodology.

Space and water heating are modeled using natural gas combustion, while all other uses are modeled with the regional electricity grid mix.¹⁸ The EUIs and end use profiles used for the models in this study are shown in TABLES 3 through 7. (See APPENDIX D: Energy Performance Scenario Analysis, which includes a list of the EEMs that have been applied to each case-study building.)

The recommended EEMs are derived from energy-code prescriptive requirements, energy performance guides, and professional experience. It is assumed that a set of EEMs selected from a list of 20 to 25 EEMs that are appropriately designed, installed and maintained can deliver the
energy efficiency improvements assumed in this study. This approach then allows for the quantification of the materials inputs for all of the identified EEMs and for their inclusion in the LCA model.

Table 3. Energy Use Intensity (EUI) and end use profiles assumed for the Commercial Office and Warehouse-to-Commercial Office.

<table>
<thead>
<tr>
<th>End use profile</th>
<th>City</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Portland</td>
</tr>
<tr>
<td>Energy Use Intensity (EUI), kBtu/ft²/year</td>
<td>70</td>
</tr>
<tr>
<td>Space cooling</td>
<td>3%</td>
</tr>
<tr>
<td>Space heating</td>
<td>28%</td>
</tr>
<tr>
<td>Domestic hot water</td>
<td>2%</td>
</tr>
<tr>
<td>Vent fans</td>
<td>17%</td>
</tr>
<tr>
<td>Pumps &amp; Auxiliary</td>
<td>0%</td>
</tr>
<tr>
<td>Exterior lighting</td>
<td>7%</td>
</tr>
<tr>
<td>Miscellaneous equipment</td>
<td>23%</td>
</tr>
<tr>
<td>Interior lighting</td>
<td>22%</td>
</tr>
</tbody>
</table>

Table 4. Energy Use Intensity and end use profiles assumed for the Multifamily Residence and Warehouse-to-Multifamily Residence.

<table>
<thead>
<tr>
<th>End use profile</th>
<th>City</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Portland</td>
</tr>
<tr>
<td>Energy Use Intensity (EUI), kBtu/ft²/year</td>
<td>63</td>
</tr>
<tr>
<td>Space cooling</td>
<td>6%</td>
</tr>
<tr>
<td>Space heating</td>
<td>44%</td>
</tr>
<tr>
<td>Domestic hot water</td>
<td>22%</td>
</tr>
<tr>
<td>Refrigerators</td>
<td>5%</td>
</tr>
<tr>
<td>Lighting &amp; appliances</td>
<td>22%</td>
</tr>
</tbody>
</table>
TABLE 5. Energy Use Intensity and end use profiles assumed for the Single-Family Residence.

<table>
<thead>
<tr>
<th>City</th>
<th>Portland</th>
<th>Phoenix</th>
<th>Chicago</th>
<th>Atlanta</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Use Intensity (EUI), kBtu/ft²/year</td>
<td>46</td>
<td>37</td>
<td>47</td>
<td>39</td>
</tr>
<tr>
<td>Space cooling</td>
<td>7%</td>
<td>32%</td>
<td>4%</td>
<td>15%</td>
</tr>
<tr>
<td>Space heating</td>
<td>50%</td>
<td>14%</td>
<td>53%</td>
<td>33%</td>
</tr>
<tr>
<td>Domestic hot water</td>
<td>22%</td>
<td>27%</td>
<td>21%</td>
<td>26%</td>
</tr>
<tr>
<td>Refrigerators</td>
<td>4%</td>
<td>5%</td>
<td>4%</td>
<td>5%</td>
</tr>
<tr>
<td>Lighting &amp; appliances</td>
<td>17%</td>
<td>22%</td>
<td>17%</td>
<td>21%</td>
</tr>
</tbody>
</table>

TABLE 6. Energy Use Intensity and end use profiles assumed for the Elementary School.

<table>
<thead>
<tr>
<th>City</th>
<th>Portland</th>
<th>Phoenix</th>
<th>Chicago</th>
<th>Atlanta</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Use Intensity (EUI), kBtu/ft²/year</td>
<td>60</td>
<td>61</td>
<td>80</td>
<td>65</td>
</tr>
<tr>
<td>Space cooling</td>
<td>5%</td>
<td>41%</td>
<td>4%</td>
<td>25%</td>
</tr>
<tr>
<td>Space heating</td>
<td>45%</td>
<td>8%</td>
<td>60%</td>
<td>29%</td>
</tr>
<tr>
<td>Domestic hot water</td>
<td>10%</td>
<td>10%</td>
<td>8%</td>
<td>9%</td>
</tr>
<tr>
<td>Vent fans</td>
<td>10%</td>
<td>11%</td>
<td>6%</td>
<td>9%</td>
</tr>
<tr>
<td>Pumps &amp; Auxiliary</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Exterior lighting</td>
<td>2%</td>
<td>2%</td>
<td>1%</td>
<td>2%</td>
</tr>
<tr>
<td>Miscellaneous equipment</td>
<td>12%</td>
<td>11%</td>
<td>9%</td>
<td>11%</td>
</tr>
<tr>
<td>Interior lighting</td>
<td>17%</td>
<td>16%</td>
<td>13%</td>
<td>15%</td>
</tr>
</tbody>
</table>
TABLE 7. Energy Use Intensity and end use profiles assumed for the Urban Village.

<table>
<thead>
<tr>
<th>End use profile</th>
<th>Portland</th>
<th>Phoenix</th>
<th>Chicago</th>
<th>Atlanta</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy Use Intensity (EUI), kBtu/ft²/year</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Space cooling</td>
<td>5%</td>
<td>24%</td>
<td>3%</td>
<td>13%</td>
</tr>
<tr>
<td>Space heating</td>
<td>24%</td>
<td>6%</td>
<td>45%</td>
<td>21%</td>
</tr>
<tr>
<td>Domestic hot water</td>
<td>3%</td>
<td>3%</td>
<td>2%</td>
<td>3%</td>
</tr>
<tr>
<td>Vent fans</td>
<td>14%</td>
<td>15%</td>
<td>10%</td>
<td>13%</td>
</tr>
<tr>
<td>Pumps &amp; Auxiliary</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Exterior lighting</td>
<td>4%</td>
<td>4%</td>
<td>3%</td>
<td>4%</td>
</tr>
<tr>
<td>Miscellaneous equip</td>
<td>23%</td>
<td>22%</td>
<td>17%</td>
<td>21%</td>
</tr>
<tr>
<td>Interior lighting</td>
<td>27%</td>
<td>26%</td>
<td>20%</td>
<td>25%</td>
</tr>
</tbody>
</table>

Base Case energy consumption rates are determined here using industry-average data rather than actual or modeled performance. This approach focuses less on a comparison of two specific buildings and their unique energy use profiles; it emphasizes producing results that can be applied more generally across the building stock. The CBECS and RECS energy data used here is empirical, while energy modeling results are theoretical and predictive. While actual buildings are used for the renovation and new construction cases to derive materials quantities, their actual energy performance is not used; doing so would too narrowly define energy performance for that building type and would fail to rule out potential performance anomalies for that building type. Therefore, energy use profiles for each building type are assumed to be standard representations of those buildings within that typology category. It is also acknowledged that actual building energy use may depend significantly on a number of factors, such as occupant behavior, maintenance practices, and plug loads. These factors are assumed to be the same for both the NC and RR buildings and are therefore excluded from this study.

8. **Electricity grids**

Electricity grids are constructed in the model according to the EPA’s regional estimates of electricity grid mix (eGRID2010 v1.0) for 2007, the most current version available. Specifically, ecoinvent LCI data describing the various energy-production technologies (e.g., electricity from coal, hydropower) is combined based on the percent of generation shown by eGRID for each of these technologies.
Notably, while eGRID also provides emissions data for electricity generation facilities throughout the United States, the publication provides only the direct emissions from these facilities and not the full cradle-to-outlet emissions of electricity generation that is warranted by the LCA. Thus, only the grid mixes reported by eGRID are used for the model as eGRID is the most comprehensive database of such information for the United States.

It should be noted that the eGRID data describes electricity generation, not grid mix at the outlet in a building. However, it is impossible to know the exact mix that reaches consumers due to the economic and temporal dynamics of North American electricity markets; the electricity generation mix is considered an adequate proxy. \textsuperscript{19} TABLE 8 provides the figures used to create the electricity grid mixes for the regions examined this study. \textsuperscript{20}

It is assumed that the proportions of energy technologies (e.g., coal, wind) comprising each grid do not change over time. However, over a 75-year period, it is likely that energy technologies and their ratio in the grid will vary; in fact, the EIA publishes an annual report predicting such trends over the next 25 years. \textsuperscript{21} A sensitivity analysis is conducted to explore how changing conditions may affect the conclusions of this study. Section II.H.1 describes the approach to the analysis.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|}
\hline
\textbf{Energy source} & \textbf{Chicago (RFC\textsuperscript{2})} & \textbf{Portland & Phoenix (WECC\textsuperscript{2})} & \textbf{Atlanta (SERC\textsuperscript{2,3})} \\
\hline
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 \\
\hline
\end{tabular}
\caption{U.S. regional grid mixes used for the regions examined in this study and based on the EPA's eGRID2010 v1.0 \textsuperscript{22}}
\end{table}

\textsuperscript{1} Columns may not sum to 100% due to rounding errors.

\textsuperscript{2} Acronym used for the region in the eGRID model.

\textsuperscript{3} The WECC eGrid region includes both the EIA's Pacific (the Portland scenario) and Mountain (Phoenix) regions.
9.  End-of-life management of materials

Each material that travels to the building site during Construction, Rehabilitation and Retrofit, or Maintenance activities for use in the structure, including waste, is distributed across a combination of recycling, landfill, and/or incineration facilities, with partial energy recovery. It is particularly difficult to find data on the fates of building materials; while information regarding the composition of loads delivered to EOL management facilities is readily available, data describing the division of the original load between facility types is scarce. The data used here is based on materials management in Oregon, and may not accurately describe the fate of materials in other regions.23 (See APPENDIX B: Assumptions, which provides a detailed list of these figures.)

It is assumed that a substantial portion of materials are recycled and/or incinerated with energy recovery rather than landfilled or incinerated without energy capture. Because the avoided burden approach is used here (see Section II.E), many materials are supplying buildings with a benefit (in the form of negative impacts), thereby lowering the total impact of the system. Regions where recycling and/or incineration with energy recovery are less frequent will demonstrate a greater total impact than what is calculated here.

10.  Temporal changes

Many aspects of building construction, maintenance and energy efficiency can be expected to change in important ways over time. In addition, the external conditions affecting buildings change over time, such as the production technologies used to provide building energy and power various industrial processes occurring in fabricating materials. The approach taken here assumes that these aspects have remained static, due in part to very high uncertainty regarding the manner, pace and extent to which they will change, as well as modeling complications associated with buildings under dynamic conditions. It should be recognized that this is a very important source of uncertainty regarding the outcomes of the present project. Sensitivity analyses are conducted in an attempt to better understand how discrete modifications to certain parameters could affect the results of this work.

H.  Scenario and Sensitivity Analyses

In order to understand the influence of key assumptions and parameters on the results, two sensitivity analyses are conducted: evaluations of electricity grid mix and building lifetime. Further, building energy performance is explored through scenario analysis in order to better understand the environmental implications of retrofitting.
1. **Electricity grids**

The energy consumed during building operation is the greatest contributor to the building life cycle impacts, of a building is often energy consumption during its operation, particularly when the predominant source of energy is fossil fuels, as is the case today in the United States. Thus, it is important to assess potential configurations of the grid mix over time and space in order to understand the influence of this variable on the LCA results.

This study assesses the spatial aspects of the grid by representing each building in four geographic regions of the United States and using an appropriate, regional electricity grid mix, as indicated by the eGRID statistics concerning the sources of electricity production around the country. In addition, a sensitivity analysis using the national average grid mix demonstrates the importance of the approach in selecting a geographic resolution of grid mix.

Temporal variation refers to the differences in impact due to a changing grid mix over time, over the lifetime of a building. It is reasonable to assume that over the course of 75 years, the energy sources used to generate electricity will vary. At one extreme, the grid could be comprised of 100% fossil fuels, which is not far from the current average national grid mix composition of approximately 91% fossil fuels. Alternatively—perhaps the more popular prediction—a ‘cleaner’ grid consisting of more renewable sources could take the stage. An evaluation of these scenarios illustrates the influence the grid mix has on the life cycle environmental impacts of the buildings under evaluation.

Assuming the proportional contribution of fossil fuels will only decrease, it is reasonable to estimate that the current state of electricity generation is indeed the ‘worst case.’ As such, only grids with greater percentages of renewable energy sources are considered—specifically, grids that conservatively move toward ‘cleaner’ technologies and take more progressive steps. While it is difficult to estimate future grid mixes, the EIA provides an annual assessment and prediction of the national average grid mix for the coming 25 years. Additionally, the WWF offers a global plan for achieving a 100% renewable grid mix by 2050. These insights are used to evaluate the LCA results under a conservatively and a progressively transitioning grid mix, respectively. Further details on these calculations, as well as the grid mixes, are provided in Appendix C: Energy Technologies.

2. **Energy performance adjustments (and associated changes to materials)**

The influence of energy efficiency is explored through a two-pronged approach. First, energy performance of the Base Case analyses is improved approximately 30% by adding to the buildings a combination of EEMs to the buildings. These packages are quantified from a materials basis, with
appropriate scaling for building floor space as applicable, and included in the take-off list for each building (i.e., RR and NC). Additionally, the Base Case electricity and heating (natural gas) demands are reduced by 30%.

Results are then computed for this ‘Advanced’ scenario.

Additionally, an evaluation is conducted to assess the life cycle impacts of an existing building that has undergone renovation but has not included EEMs to bring it up to an average level of energy performance. Operating energy of this ‘Pre-EEM’ case is assumed to be equivalent to the Base Case. This scenario is included because it is possible for older buildings to exhibit inherent efficiency strengths and perform on par with new construction. This is only conducted for the Commercial Office. Further details are provided in Appendix D, including the implemented EUIs and EEMs.

3. Building lifetime

The magnitude of the LCA results is highly dependent on the assumed building life span. Over time, a greater quantity of materials is needed to maintain a structure, and additional utilities (e.g., energy and water—which is excluded here) are used. However, the choice of building lifetime is a challenge as buildings survive from a few decades to a century or longer, depending on a number of factors, including economics, physics (i.e., structural stability), and even personal choice. There is also the question of whether a rehabilitated building can last as long as a new building. While research around building life span is limited, a study by the Athena Institute finds that the decision to demolish is due to “area redevelopment” as frequently as the “building’s physical condition”.

Further, when the issue is indeed the physical state of the building, the most common (54/70 respondents) reason for the unfit condition is “lack of maintenance”. These observations indicate that many existing buildings can indeed be fit for a second service life, particularly if they have been well maintained.

A sensitivity analysis is conducted to understand if and how the choice of lifetime affects the relative results of the study. In other words, does a building’s longevity influence the decision to rehabilitate or construct new?

The Base Case scenario assumes a 75-year lifetime. To assess the potential range of this parameter, lifetimes of 5, 10, 15, 25, 50, and 100 years are evaluated. Annualized results are plotted to assess whether the choice in lifetime affects the rate that impacts are generated.

In addition to the Base Case results, these lifetimes, plus lifetimes of 1 and 2 years, are evaluated in combination with the energy performance scenario analysis. The intent of this exercise is to identify
whether cross-over (i.e., a switch in terms of which building has the greater total impacts) exists between the various scenarios. This probes deeper into the question of how building lifetime affects the decision to rejuvenate an existing structure or start from scratch. Such a cross-over point is essentially the ‘year of carbon equivalency,’ where net total NC and RR impacts are equivalent.

III. LCA Modeling Methodology

A. Computation

The life cycle assessment is conducted using a customized calculation system created in MS Excel. This model is constructed to represent the total environmental impacts of all activities included in the scope of this study, as defined in Section II.D. This is done by linking material, energy, and process reference flows for a given building with preexisting or modified data that represent the impacts of producing, using, or disposing of materials, as well as the production and use of energy.

It should be recognized that this model uses a steady-state or probabilistic approach, implying that the quantity of annual impacts is assumed to be the same for each year of building occupancy (i.e., use). While this is not realistic, it is impossible to estimate the actual quantity of impacts occurring annually due to random rates of material replacement and varying energy consumption.

Supporting LCA work is conducted in the SimaPro 7.2 commercial LCA software.

B. Life cycle impact assessment

Impact assessment classifies and combines the flows of materials, energy, and emissions into and out of each product system by the type of impact their use or release has on the environment. The method employed here is the peer-reviewed and internationally-recognized LCIA method IMPACT 2002+ v2.29 The exception to this is the Climate change indicator, which is calculated based on the IPCC 2007 100-year GWP weighting with biogenic carbon dioxide excluded.30 This method utilizes the most current science regarding global warming and offers the greatest consistency with data that might be presented elsewhere. The exclusion of biogenic carbon dioxide avoids potentially misleading results, which can arise when considering only a portion of a building’s life cycle, e.g., the production of materials or EOL management. For indicators relating to human health, this study only considers the those impacts resulting from the release of substances into the outdoor environment and the exposure to humans in that environment; direct exposure through indoor air or dust is excluded. An indoor exposure assessment is beyond the current capabilities of life-cycle science due to a lack of information on the...
chemicals released by building materials and the lack of an established method for incorporating indoor environmental exposures into a life cycle impact assessment. However, recent developments are moving toward making this feasible.\textsuperscript{31}

All midpoints and endpoints within the IMPACT2002+ framework are calculated and provided in the Base Case results. Further analyses focus on the endpoints plus Climate change for efficiency, although all conclusions are based on the full results. Descriptions of the impact categories reported in this document are located in APPENDIX F: Impact assessment indicators. No weighting of indicators is performed.

Due to the vast quantity of results generated throughout this study and in attempt to lessen the complexity of digesting all of this information at once, some sections of the main body of this report are limited to showing results for only Climate change. In cases where other indicators may point to a different conclusion than Climate change, results for these impact categories are also shown. All results are available in APPENDIX E.

Where results are limited to Climate change, in no way does it imply that other environmental impact categories evaluated are of lesser concern or that results of Climate change alone represent an overarching conclusion about total environmental impact. Each key conclusion is confirmed by considering all indicators.

IV. Results

A. Base Case evaluation

This section provides the Base Case results of the study. The following diagram explanations apply to all typologies and are presented here to avoid repeating them in each section.

For the Base Case analysis diagrams showing all indicators (e.g., Figure 3):

- For a given impact category, comparisons can be made across all (eight) bars and within each climate zone. The first provides a sense of environmental performance for all climate regions, while the second offers a comparison of NC and RR in a given zone. Color coding indicates the endpoint group to which the midpoints contribute. For instance, Human Toxicity is included in the calculation of the Human health endpoint, so these are both shown in green; the brighter variation indicates the endpoint. Climate change contributes to all three endpoints, but it is reported as a stand-alone midpoint indicator for informational purposes. While Aquatic eutrophication as well as Aquatic and Terrestrial acidification and
nutrification are aspects that cause damage at the Ecosystem quality endpoint, these midpoint indicators are not included in the Ecosystem quality endpoint in the present assessment due to the lack of an appropriate conversion factor at the time of publication of v2 of the IMPACT 2002+ methodology (Humbert et al. 2009).

- The electricity in the Chicago scenario is predominately produced from coal (64.8%), with a notable amount (26.6%) sourced from nuclear power plants. The Atlanta scenario is similar, with nearly 60% of electricity sourced from coal power and one-quarter from nuclear energy. The Portland and Phoenix scenarios, on the other hand, source only 30% of electricity from coal, one-third from natural gas, and just under another one-third from hydropower. ecoinvent data demonstrates that, on a per megajoule (MJ) basis, electricity production from coal is the most environmentally burdensome of these technologies in the majority of categories evaluated. (See APPENDIX C: Energy Technologies.) Natural gas and nuclear energy tend to be the next most impactful, and hydropower is generally least burdensome across the indicators assessed. Some exceptions exist, but these benchmarks help to explain the results of all building analyses across climate zones.

- For the Base Case analysis diagrams showing the contribution of life cycle stages (e.g., FIGURE 4): For all scenarios evaluated, on a per megajoule (MJ) basis, natural gas heating (i.e., space and water heating) contributes less than electricity use to total energy-related impacts. This is due to the relatively higher impact of electricity use as compared to natural gas use (for heating purposes). (See APPENDIX C: Energy Technologies.)

- The variation across climate zones is attributable to differences related to building energy use across regions as only these characteristics of the buildings change between climate regions. In particular, these variations are a result of the EUI, end use profile, and electricity grid mix specified for each region evaluated. For instance, buildings located in a zone that has a relatively high EUI, uses a large quantity of electricity, and is supplied by an electricity grid that utilizes a large portion of coal-fired power plants will likely be more impactful than buildings that have a lower EUI, use less electricity, and/or sources its electricity from a grid using a large portion of hydropower.

- All scenarios demonstrate negative (<0) impacts for management of materials at their end-of-life. This is a result of the approach used to model the benefits associated with recycling and waste-to-energy incineration. For both cases, a “credit” is given to this system for offsetting the conventional production of products (i.e., a virgin material) and energy (i.e., through the electricity grid). This “credit” is equal and opposite in sign to the production of virgin material and electricity, respectively. Impacts associated with the recycling process, waste-to-energy process, incineration without energy capture, and landfilling are included.
(as impacts, >0) in this section of the bars, but the total is sometimes outweighed by the “credits.” This results in an overall negative impact for materials EOL management.

For the materials contribution analysis by MasterFormat Divisions (e.g., FIGURE 5):

- The values plotted are calculated by subtracting the RR materials-related impacts from the NC materials-related impacts and dividing them by the absolute value of the net total impacts. Thus, a negative value indicates that NC is environmentally advantageous, while a positive value illustrates an environmental advantage for RR. Materials-related impacts refer to impacts due to production (original and replacement materials); transport to building sites and end-of-life destinations; and EOL management (i.e., landfill, recycling, incineration).

- Since the energy performance of a given building typology is assumed to be equal for NC and RR on a square-foot basis, differences observed between the NC and RR Base Case results are due to differences in material-related impacts, which are caused by differences in the types and quantities of materials used for each scenario. These disparities (i.e., NC impact minus RR impact) are plotted with materials grouped by CSI MasterFormat Divisions. All assumptions and inputs associated with materials production, transport, and EOL management are the same across climate regions, so the results presented are applicable to any location evaluated here. Note the different scales on the y-axes between the three plots.

1. Commercial Office

Figure 3 provides Base Case results for the Commercial Office across all climate zones and indicators assessed. In comparing the NC and RR results for each zone, the RR scenario is less impactful in every indicator evaluated. The difference between impacts for the two scenarios ranges from 4.5% to 48% of those computed for the NC scenario, with an average difference of 18%, based on data presented in Figure 3.

a) Life cycle stages

To better understand the sources of impacts, FIGURE 4 shows results by life cycle stage for the endpoints and Climate change. It is clear that, in each zone, building operating energy is a main contributor to impact. For Climate change and Resources, material-related impacts (i.e., production, transport, and end-of-life of original and replacement materials) comprise approximately 12-21% of net total impacts in the NC scenarios and 9-16% for RR scenarios, depending on the region. These same activities contribute to the net total Ecosystem quality impacts—about 39-55% for NC scenarios and 34-53% for RR scenarios, again depending on geography. Falling between these
ranges, Human health is comprised by material-related impacts 23-31% for NC and 19-27% for RR. This observation indicates that Climate change, Human health and Resources are more influenced by energy-related impacts than is Ecosystem quality, which is influenced nearly 50/50 by energy use and materials.

In regions where building energy use (i.e., the combination of EUI, electricity grid, and end use profile is relatively more burdensome, materials play a smaller, yet important, role in total life cycle impact. For instance, consider Climate change. Energy-related impacts are more dominant for the Chicago scenario than any other region on account of the relatively high EUI, high use of electricity and an electricity grid that is predominantly powered by coal and natural gas—generally the most burdensome electricity-generating technologies—in total more than any other region. In comparison, the Portland scenario demonstrates the lowest EUI, a moderate use of electricity, and the least burdensome grid mix in the majority of indicators. (See TABLE 3 and FIGURE 36 for supporting information.)

b) Geographic trends

Across climate zones, building energy use contributes to 34-84% of net total impacts for the NC scenarios and 46-91% for the RR scenarios, depending on impact category. For Climate change, Human health, and Resources, energy-related impacts contribute on the upper ends of these spectrums, while no more than 65% of the net total Ecosystem quality impacts source from operating energy use. This trend is demonstrative of the sources of these impacts; the former are provided to a greater extent by building energy use, while the latter is influenced nearly equally by energy-related and material-related impacts.

As previously shown in TABLE 3, the EUI is greatest for a Commercial Office in the Chicago scenario followed by the Atlanta, Phoenix and Portland scenarios; on a square foot basis, an office in the Chicago scenario uses more than 130% as much energy as the same building in the Portland scenario. This is primarily due to the increased expenditure of energy on space heating as compared to other regions, a direct result of climate patterns across the country.

Only slight variation exists between regional end use profiles, as shown in TABLE 3, except in the cases of space heating and space cooling. These end-use disparities are important because of the differences in energy source (i.e., natural gas used for heating and electricity used for other activities). In fact, nearly half of the energy used by the Chicago scenario is in the form of natural gas combustion (for heating), whereas the natural gas used in the Portland and Atlanta scenarios
FIGURE 3. Base Case results for the Commercial Office across all climate regions with color coding to indicate midpoints that contribute to each endpoint.
Figure 4. Base Case results shown by life cycle stage as a percentage of Portland NC impact for the Commercial Office across all climate regions.
comprise no more than 30% of the total energy use. The Phoenix scenario consumes a negligible amount of gas. These usage patterns result in a dampening of differences in energy-related impacts across climate regions. While the Chicago scenario demonstrates the highest EUI, it uses the greatest quantity of natural gas (which is less impacting than electricity per MJ consumed, lowering its overall environmental impact. (See APPENDIX C: Energy Technologies.) The opposite is true for the Phoenix scenario.

Within each indicator, the trends observed across climate regions are due to the balance between EUI, end use profile, and electricity grid mix. The Chicago scenario generally shows the highest magnitude of impact due to the large extent of coal and nuclear power and high EUI. Similarly, the Portland scenario tends to offer the least impacts due to its relatively low EUI and somewhat improved electricity grid, as compared to the Chicago scenario. Commercial Office buildings in the Atlanta and Phoenix scenarios tend to mimic the magnitude of impacts in the Chicago and Portland scenarios, respectively, primarily on account of similar grid mixes. An exception exists in the case of Human health in the Phoenix scenario where the total impact is the highest of all cities. In comparison to the Portland scenario Human health impact, the difference is attributable to the greater extent of electricity use. In contrast, the larger impact as compared to the Chicago and Atlanta scenarios is due to a difference in electricity grid mix; electricity generated in the Phoenix (and Portland) scenario primarily sources from natural gas combustion—as opposed to coal combustion—which is nearly twice as impactful in the area of Human health than coal-generated electricity and more than 95% more impactful than nuclear (See FIGURE 36).

An exception to these observations occurs in the category of Mineral extraction where, in each city evaluated, the results (NC or RR) across locations have approximately the same magnitude, and RR results are approximately half (53%) of the NC results. This can be explained by the definition of Mineral extraction, which is computed as the difference in the amount of energy required to extract minerals now and in the future, the difference being due to the need to mine at a greater depth from the surface as a result of depleted near-surface resources (Goedkooop and Spriensma 2000). This energy difference is termed surplus energy. Indeed, the consistent magnitudes of NC or RR across climate zones indicate that this impact category is more dependent on the materials used than the energy consumed by building operation, which varies with geography.

c) Materials contributions
Across all MasterFormat Divisions, the impact categories tend to follow similar trends, with the exception of Land occupation in a few Divisions (e.g., 09700 Wall finishes). This is due to a few key
materials that have a relatively large impact in this indicator, namely wood and soya (soy) oil production, the latter being an ingredient in the paint used to model the various wall coatings. While several groups contribute to differences in results, Divisions 03100 Concrete foundation, 03300 Cast-in-place concrete, 08800 Glazing, 15000 Mechanical and 16000 Electrical are most responsible for disparities between NC and RR.

The appearances of Divisions 03100 and 03300 are due to the fact that RR does not require any item (e.g., concrete foundations, decking) in this category whereas NC uses a notable amount of concrete and associated reinforcing steel. The same is true for Division 08800 as NC uses a vast amount of glazing for an exterior curtain wall, while RR does not require any.

Disparities within Divisions 15000 Mechanical and 16000 Electrical are attributable to differences in materials quantities, specifically ducting, plumbing and electrical components. The gaps between NC and RR is attributable to RR employing the mechanical and electrical systems already in the existing building and not demanding that new products be fabricated, as is necessary for the NC building.

These observations indicate that differences between NC and RR are a result of several key factors. First, the RR building reuses systems and assemblies, thereby avoiding impacts related to materials production, transport, and EOL management. This can occur when no replacement is needed, such as in the case of building foundations, or when relatively little replacement is required, as in the case of mechanical and electrical systems. Additionally, as seen in the case of the glass curtain wall, differences in materials types—perhaps a result of differences in aesthetics—can be important contributors to overall disparities. Comparison of building products, however, is beyond the scope of this work.
Figure 5. Contribution of materials (production, transport, and end-of-life) by MasterFormat category to the total difference between NC and RR impact for the Base Case Commercial Office in all climate regions evaluated. A negative value indicates that NC is more impacting, while a positive value indicates RR is more impacting.
2. **Warehouse to Commercial Office**

In this analysis, the NC Commercial Office is compared to rehabilitating and retrofitting a warehouse in order to repurpose it as a commercial office space. **Figure 3** provides Base Case results for this Commercial Office across all climate zones and indicators assessed. The difference between the NC and RR impacts span from -14% and 25% of those computed for the NC scenario, with an average difference of 5.8%, based on figures presented in **Figure 6**. (A negative difference indicates that the RR scenario is more impacting.) The repurposed warehouse is less burdensome in every indicator evaluated, except for Aquatic eutrophication, Land occupation and Mineral extraction. The first and last show no appreciable (<1%) difference between the two scenarios, while Land occupation is as much as 14% higher for RR. Additionally, Human toxicity results for RR range from 1.0-2.4% less than that of NC, depending on geography.

Unlike the Commercial Office results in **Section IV.A.1**, the repurposed warehouse shows some trade-offs in environmental impacts in comparison to a new office building. This is likely attributable to the nature of a conversion project in which additional materials are needed as compared to rehabilitating without repurposing. Further exploration is offered in the following sections.

a) **Life cycle stages**

**Figure 7** displays results by life cycle stage for the endpoints and Climate change. In each zone, it is evident that operating energy use is a main contributor to impact, although materials play an important role, particularly in the case of Ecosystem quality. For Climate change and Resources, material-related impacts comprise approximately 12-21% of net total impacts in both the NC and RR scenarios, depending on the geography. Similarly, Human health consists from 23-33% of materials-related impacts in both NC and RR. These same activities contribute to the net total Ecosystem quality impacts about 39-55% for NC scenarios and 42-61% for RR scenarios, again depending on geography. This observation indicates that Ecosystem quality is about equally influenced by materials and energy, while operating energy is more important to Human health and especially Climate change and Resources impacts.

In regions where building energy use (i.e., the combination of EUI, electricity grid, and end use profile) is relatively more burdensome, materials play a smaller, yet still important, role in the total life cycle impact. Moving from the Portland to Phoenix to Atlanta and finally to Chicago scenario, materials comprise an increasingly smaller portion of total impact as energy-related impacts rise. The only exception to this pattern is in the case of Human health and is due to differences in end-use and electricity grid energy technologies, as explained in **Section IV.A.1** for the Commercial Office.
Figure 6. Base Case results for the Warehouse-to-Commercial Office across all climate regions with color coding to indicate midpoints that contribute to each endpoint.
Figure 7. Base Case results shown by life cycle stage as a percentage of Portland NC impact for the Warehouse-to-Commercial Office across all climate regions.
A relatively small (percent) difference is seen between the NC and RR scenarios for this analysis, and in some cases no difference is seen or RR demonstrates somewhat greater impact. In fact, when comparing the results of the Commercial Office analysis to those of this analysis, it is evident that this analysis simply expands the material-related sections of the bar chart. This is attributable to the nature of a repurposing project in that RR requires similar quantities of some materials as NC. Nevertheless, because overall the RR scenario still requires fewer building products than NC, some environmental savings are offered by a warehouse conversion over erecting a new structure.

b) Geographic trends

Across climate zones, operating energy use contributes from 34-84% of net total impacts for the NC scenarios and from 37-87% for RR scenarios, depending on impact category. Total Climate change, Human health and Resources impacts tend to be more dominated by energy use (a minimum of 73% for NC and 78% for RR), while Ecosystem quality is comprised to a lesser—yet still substantial—extent of energy-related impacts (a maximum of 53% for NC and 56% for RR). This observation underlines the sensitivity of total life cycle impacts to operating energy consumption, especially for climate zones where the combination of EUI, end use profile, and electricity grid mix cause relatively high energy-related impacts (e.g., the Chicago scenario).

Within each indicator, the patterns observed across cities are due to the balance between EUI, end use profile, and electricity grid mix. (See Section IV.A.1.b for further explanation.) An office building in the Chicago scenario is computed to have the greatest net total impacts due to the large extent of coal power, high electricity use, and high EUI. Similarly, buildings in the Portland scenario tend to offer the least burden due to the region’s relatively low EUI and somewhat favorable electricity grid. Commercial Office buildings in the Atlanta and Phoenix scenarios tend to follow the impact of the Chicago and Portland scenarios, respectively. For the Portland and Phoenix scenarios, this is due to the similarities between EUI and electricity grid, which are essentially identical. In the case of the Chicago and Atlanta scenarios, these energy-related attributes are somewhat different. The Chicago scenario has a much higher EUI than the Atlanta scenario but utilizes a greater portion of natural gas, and the former’s electricity grid mix is only somewhat more environmentally burdensome than the latter’s. The balance of these three factors results in similar energy-related impacts for these two regions.

An exception to these patterns exists for Mineral extraction where, in each climate zone evaluated, the results (NC or RR) have approximately the same magnitude (<2% difference). This can be explained by the definition of Mineral extraction, which is computed based on the additional energy
required to extract minerals now and in the future, which are presumably less accessible due to limited near-surface resources (Goedkeep and Spriensma 2000). Indeed, the consistent magnitudes of NC or RR across climate zones indicate that this impact category is more dependent on the materials being used than the energy consumed during the building’s operation, which varies with geography. However, the endpoint Resources indeed varies with geography on account of the relatively low weight given to Mineral extraction in the calculation of the endpoint.

c) Materials contributions

As shown in Figure 8, the differences in environmental impacts fall across numerous MasterFormat Divisions, with the greatest disparities within 08800 Glazing and 10270 Access flooring; Also notable are 03100 Concrete foundation, 03300 Cast-in-place concrete, 06100 Rough carpentry, 07500 Membrane roofing, 15000 Mechanical and 16000 Electrical. These Divisions are similar to those in the Commercial Office analysis (Section IV.A.1.c), an unsurprising result given the fact that all buildings evaluated are intended to function as offices and therefore are constructed in a similar fashion and with similar materials.

Disparities between NC and RR impacts are due to differences in the quantities of materials used. For instance, all materials in Division 03300 are concrete, and where RR requires 54 kg of concrete per ft$^2$ of rentable area, NC requires 88kg/ft$^2$; this results in an environmental advantage for RR. Differences observed in the remaining Divisions are explained in a similar fashion.

Materials-related impacts also vary between NC and RR when the buildings require different types of products. Ecosystem quality, for example, shows differences in all of the key Divisions identified in the first paragraph of this section. The environmental preferability of each building is therefore dependent on the balance between these Divisions.

These observations indicate that while the quantities of materials are predominantly responsible for differences between NC and RR, the types of materials used can factor into the decision to rehabilitate or start new, particularly when a relatively large amount is used by only one of the buildings. Additional analysis is required to probe at specific materials.
Figure 8. Contribution of materials (production, transport, and end-of-life) by MasterFormat Division to the total difference between NC and RR impact for the Base Case Warehouse-to-Commercial Office in all climate regions evaluated. A negative value indicates that NC is more impacting, while a positive value indicates RR is more impacting.
3. **Warehouse-to-Multifamily Residence**

This evaluation compares the NC Multifamily Residence to rehabilitating and retrofitting a warehouse in order to repurpose it as multifamily residential space. Figure 9 provides Base Case results for these residences across all climate zones and indicators assessed. The difference between the scenarios ranges from -34% to 15% of the NC impact, where a negative value implies that the RR scenario is more impacting. However, this span is somewhat deceptive in that, except for Human toxicity, Photochemical oxidation and Mineral extraction, differences in impacts are within only approximately +/- 8% of NC burdens. The average difference is 1.0% of the NC burden.

Similar to the Warehouse-to-Commercial Office, the environmental profile of converting a warehouse to a multifamily residence is not clearly preferable to that of new construction. In fact, impacts associated with NC and RR are approximately equivalent in many of the indicators evaluated. A deeper dive into the results is offered here to further understand these results.

**a) Life cycle stages**

Figure 10 displays results by life cycle stage for the endpoints and Climate change relative to the Portland scenario. In each zone, it is evident that utility (energy) use is a main contributor to impact, although materials are somewhat more important for Ecosystem quality. For Climate change, and Resources, material-related impacts comprise approximately 18-24% of net total impacts for NC and 12-15% for RR, depending on the climate zone. These same activities contribute to the net total Ecosystem quality impacts about 48-62% for NC scenarios and 45-58% for RR scenarios, again depending on geography. The ranges for Human health fall between these two groups with 25-36% for NC and 26-37% for RR. This observation indicates that Ecosystem quality is more influenced by materials than are Climate change, Human health and Resources; in fact, Ecosystem quality is about equally influenced by materials-related and energy-related impacts. In regions where building energy use is relatively more burdensome (i.e., the Chicago and Atlanta scenarios), materials comprise a somewhat smaller proportion of total impact.

The environmental performance of the Warehouse-to-Multifamily Residence is on par with that of NC primarily because the materials-related impacts of RR are similar in magnitude to those of NC. This is due to the nature of a repurposing project in that it requires large quantities of materials in comparison to an RR project that does not change the intended service of the existing building. Also contributing to the disparities is the relatively large extent of activities (i.e., vehicle and equipment operation) associated with Selected demolition (for RR) as compared to Demolition (for NC). In fact, when comparing the results of the Multifamily Residence analysis to those of this analysis, it is
Figure 9. Base Case results for the Warehouse-to-Multifamily Residence across all climate regions with color coding to indicate midpoints that contribute to each endpoint.
Figure 10. Base Case results shown by life cycle stage as a percentage of Portland NC impact for the Warehouse-to-Multifamily Residence across all climate regions.
evident that this analysis simply expands the materials-related and Selected demolition sections of the bar chart. This extension is sufficient in Human health and Ecosystem quality—the indicators that are more influenced by materials—to surpass the total impacts of NC in all climate zones. While the net total impacts are still less for RR in Climate change and Resources, the RR scenario burdens are within 10% of those for NC.

b) Geographic trends

Building energy use contributes from 74-84% of net total Climate change and Resources impacts for both scenarios, from 56-72% of Human health net total impacts, and 32-48% of Ecosystem quality net total impacts, depending on the climate zone. RR burdens fall on the upper ends of the Climate change and Resources ranges but span about the same range for Human health and Ecosystem quality in comparison with NC. In other words, where materials-related impacts dominate the indicator (i.e., in Human health and Ecosystem quality), the difference between NC and RR is about negligible.

Within each indicator, the patterns observed across climate zones are due to the balance between EUI, end use profile, and electricity grid mix. (See the beginning of this section, IV.A Base Case evaluation, for further explanation.) For instance, the Portland and Phoenix scenarios are modeled using the same grid mix, yet the Phoenix scenario has slightly lower impact in Climate change and Resources but higher impact in Human health and Ecosystem quality. This is due to Phoenix’s lower EUI—which reduces impact—but greater portion of electricity use—which increases impacts, particularly in the case of Human health. (See APPENDIX C: Energy Technologies.) The magnitude of Climate change and Resources impacts associated with the electricity grid are not sufficient to overcome the zone’s lower EUI, although the values are raised to nearly the height of the Portland scenario.

An exception to the dependency on energy-related impacts is seen for Mineral extraction as the results (NC or RR) across climate zones have approximately the same magnitude, and RR results are approximately 112% of NC results. This can be explained by the definition of Mineral extraction, which is computed based on the difference in energy currently required to extract resources from the biosphere in relation to the amount of predicted required energy to extract minerals in the future (Goedkeep and Spriensma 2000). Indeed, the consistent magnitudes of NC or RR across climate zones indicate that this impact category is more dependent on the materials being used than the energy consumed during the building’s operation, which varies with city. However, the endpoint Resources indeed varies somewhat with geography on account of the relatively low weight given to
Mineral extraction in the calculation of the endpoint. This is more evidently reflected in both the exact values and signs (positive values) of the endpoint which are nearly identical to the results for Non-renewable energy.

c) Materials contributions

Important differences in material production impacts appear in numerous MasterFormat Divisions, although due to the dominance of Land occupation in several Divisions, it is difficult to see this in Figure 11. Land occupation impacts in this case are due to the use of wood. The case of Division 06100 is straightforward as the Warehouse uses no items in this category. On the other hand, looking at Division 09600, the buildings both use wood flooring, but the Warehouse includes nearly 30 times that used by NC on a per square foot basis (1.16 kg/ft² versus 0.0419 kg/ft², respectively).

Removing Land occupation (not shown), the Divisions showing the greatest disparities between NC and the Warehouse include 09600 Flooring and 15000 Mechanical. Divisions 06100 Rough Carpentry and 08400 Entrances & Storefronts are also notable, and several other Divisions demonstrate almost 100% difference.

Not unlike other buildings evaluated, differences seen between materials-related impacts for this analysis is attributable to the buildings using unequal quantities of materials. This is due to the RR scenario’s ability to reuse some of its existing components but is also attributable to aesthetic differences between the buildings. This is the case for Division 08400, among others, where NC requires a much larger quantity of doors and windows than does the Warehouse.

Perhaps more common for this scenario, disparities are due to differences in the types of materials chosen for a given application. This is indeed the reason for differences within Divisions 06100, 09600 and 15000. For example, Division 09600 is comprised of floor and wall products made from a host of different materials. While both NC and RR utilize the same type of materials for these items—carpet, ceramics, linoleum, and wood—they consume different quantities per square foot of building. The range of differences appearing on Figure 11 reflects the different impacts associated with these materials. For instance, RR uses a larger mass of wood flooring (1.16 kg/ft² versus 0.0419 kg/ft² for NC) which—as previously noted—has a particularly high Land occupation impact as compared to other products in this Division. The result is that wood flooring is an important contributor to the NC preferability in this indicator. Similarly, and in the opposite direction, NC utilizes more than six (6) times the mass of carpet that is required by RR (0.88 kg/ft² versus 0.14 kg/ft², respectively). Since carpeting has relatively high Aquatic acidification impacts (as compared
Figure 11. Contribution of materials (production, transport, and end-of-life) by MasterFormat Division to the total difference between NC and RR impact for the Base Case Warehouse-to-Multifamily Residence in all climate regions evaluated. A negative value indicates that NC is more impacting, while a positive value indicates RR is more impacting.
to other products in this Division), NC is particularly more burdensome in this materials category for this indicator.

This analysis brings to light an important point regarding repurposing projects: large quantities of materials required to convert buildings to a new use may eliminate any environmental advantage gained by saving the structure. Design limitations of a repurposing project can be a driver for this materials demand. Further, due to the array of products that may be used in a building, such as for flooring applications, an assessment of material quantities alone is insufficient; different materials have different impacts, an even small differences in material quantities can result in large differences in impacts. The environmental implications of building conversions would be most accurately addressed on a case-by-case basis due to the significance of material quantities and types.

4. Multifamily Residence

Figure 12 provides Base Case results for the Multifamily home across all climate zones and indicators assessed. In comparing the NC and RR results for each zone, the RR scenario is less impactful in every indicator evaluated. Burdens for the RR scenario are 7.7-66% less than those computed for the NC scenario, with an average difference of 20% across all indicators and climate regions evaluated.

a) Life cycle stages

Results by life cycle stage are shown in Figure 13 for the endpoints and Climate change. Similar to other buildings evaluated in this study, including the Warehouse-to-Multifamily Residence, utility (operating energy) use is a main contributor to impacts across all climate zones and all indicators. Material-related impacts comprise approximately 18-24% for NC and 11-15% for RR of net total impacts for Climate change and Resources. These same activities contribute about 48-62% for NC and 33-47% for RR of the net total Ecosystem quality impacts, depending on the climate zone. Similar to other buildings evaluated in this study, the ranges for Human health fall between these two groups at 25-36% for NC and 16-24% for RR. The greater portions observed for the latter two indicators demonstrates the relative importance of material-related impacts in generating these environmental burdens, particularly for Ecosystem quality where the importance of materials and operating energy are about equal.

In regions where energy use is relatively more burdensome, materials play a smaller, yet still important, role in total life cycle impacts. This is well demonstrated between the Portland and Chicago scenarios where operating energy in the latter plays a somewhat more dominating role due
to the generally more burdensome grid mix as compared to that in the Portland scenario. (End use profile and EUIs are nearly equivalent; See Table 4.)

**b) Geographic trends**

Evaluating the endpoints and Climate change across all climate zones, energy use contributes 33-79% of net total impacts for the NC scenarios and 47-87% of net total impacts for the RR scenarios, depending on the indicator. Energy-related impacts for Climate change, Human health and Resources span the upper ends of those ranges, while those contributing to Ecosystem quality fall on the lower ends. This observation indicates that the former three categories are to a larger extent provided by energy use, while the latter is nearly equally contributed to by materials and energy.

Not unlike results for other buildings, no one climate zone demonstrates the greatest energy-related impacts in all indicators. Differences in the magnitudes of results between NC or RR in different climate zones (e.g., RR in Atlanta versus RR in Chicago) are due to differences in the EUIs, energy sources, and electricity grid mixes. Where one region may have the lowest EUI, its more extensive use of electricity coupled with a more impactful grid mix balances the impacts saved from reduced energy use. This is indeed the case for the Atlanta scenario. Further, trade-offs exist between indicators when evaluating the environmental profiles of the various electricity grid mixes; no single grid is more or less impactful than all others in every indicator. The differences seen in the net total results are a reflection of the balance between these factors.

Also similar to other buildings evaluated here, Mineral extraction shows approximately the same absolute results across all climate zones, and RR impacts are consistently 63% of those for NC. Since only energy-related attributes of the buildings (i.e., EUI, end use profile, and electricity grid) change across climate zones, steady magnitudes across climate regions indicate that energy-related impacts contribute negligibly to total impacts.

**c) Materials contributions**

To understand how specific material types contribute to the Base Case results, the difference in material-related impacts are plotted in Figure 14. Important differences between NC and RR occur in a variety of Divisions, with some Divisions exhibiting differences in both directions (i.e., positive and negative). Environmental trade-offs in a Division signify a difference in material types between the buildings, either because the buildings use completely different products or because each scenario uses more of one and less of another. This is the case for Division 15000 Mechanical where a variety of ducting and plumbing products—modeled with different combinations of steel,
Figure 12. Base Case results for the Multifamily Residence across all climate regions with color coding to indicate midpoints that contribute to each endpoint.
FIGURE 13. Base Case results shown by life cycle stage as a percentage of Portland NC impact for the Multifamily Residence across all climate regions.
FIGURE 14. Contribution of materials (production, transport, and end-of-life) by MasterFormat category to the total difference between NC and RR impact for the Base Case Multifamily Residence in all climate regions evaluated. A negative value indicates that NC is more impacting, while a positive value indicates RR is more impacting.
chromium steel and copper—is used by the buildings in different quantities. On a mass basis, a copper product (as modeled in this project) is most burdensome in terms of Aquatic eutrophication, followed by chromium steel and finally steel. For Mineral extraction, chromium steel is most impacting, copper follows, and steel again is least burdensome. The resulting differences in this Division reflect the relative amounts of materials used by the buildings.

In most Divisions, RR is environmentally advantageous due to requiring fewer building products. For instance, while NC uses large quantities of steel and concrete in Divisions 03100 and 03300, respectively, RR requires a negligible amount of reinforcing steel and no concrete. Division 08500 Windows is the only category to show the opposite of this trend where NC is favorable to RR; material types are similar (predominantly glass with some aluminum and wood), and the mass of windows and associated materials required by RR is over twice that of NC. These observations emphasize the finding that material types can play important roles in determining overall impacts. Additional analysis is needed to compare specific materials and assemblies.

Single-family ResidenceFigure 15 provides Base Case results for the Single-family home across all climate zones and indicators assessed. In comparing the NC and RR results for each zone, the RR scenario is less impactful in every indicator evaluated. The difference in impacts between NC and RR are computed to be 6.5%-49% of those computed for the NC scenario, with an average difference of 20% across all indicators and climate regions evaluated.

d) Life cycle stages

Results by life cycle stage are shown in Figure 15 for the endpoints and Climate change. Similar to the Commercial Office, utility (energy) use is a main contributor to impacts across all climate regions and all indicators. Material-related impacts (i.e., production, transport, and end-of life of original and replacement materials) comprise approximately 27-31% for NC and 19-23% for RR of net total impacts for Climate change and Resources. These same activities contribute about 64-78% for NC and 52-68% for RR of the net total Ecosystem quality impacts, depending on the climate zone. The ranges for Human health are 32-48% for NC and 22-36% for RR, slightly higher than for Climate change and Resources, yet still less than for Ecosystem quality.

In regions where energy use is relatively more burdensome, materials play a smaller, yet still important, role in total life cycle impacts. This relationship between EUI, grid mix, and end use profile is well demonstrated between the Portland and Atlanta scenarios; while the Portland scenario has a larger EUI (46 kbtu/ft²/y compared to 39 kbtu/ft²/y; See Table 5), the substantially larger portion of electricity use coupled with the generally more burdensome grid mix of the South
Atlantic causes the Atlanta scenario energy-related impacts to exceed those of the Portland scenario.

\textit{e) Geographic trends}

Evaluating the endpoints and Climate change across all climate zones, energy use contributes 21-72\% of net total impacts for the NC scenarios and 32-80\% of net total impacts for the RR scenarios, depending on the indicator. The impacts for Climate change, Human health and Resources fall on the upper ends of those ranges, while those for Ecosystem quality vary on the lower end. This observation indicates that the former three categories are to a larger extent affected by energy use, while the latter is more so a result of the material-related impacts. Single-family Residences in the Portland scenario tend to have somewhat lower impact than the same residences in other climate regions, as demonstrated in 13 of the 17 indicators evaluated. This is attributable to a combination of relatively low electricity use and less burdensome technologies powering the electricity grid. These two factors are substantial enough to overcome the high EUI in this region as compared to the others. Only the Chicago scenario demonstrates a higher EUI, which is pronounced by a relatively burdensome electricity grid mix, despite a majority of the energy used being consumed as natural gas. The Portland scenario tends to be more impacting in indicators related to Human health as heating (with natural gas) as well as Pacific zone electricity grid mix tend to be particularly more burdensome than other electricity grids in these categories.

The exception to these trends occurs in the category of Mineral extraction where the results (NC or RR) across climate zones have approximately the same magnitude, and RR results are approximately 879\% of the NC results. Such stability across climate zones signify that this indicator is more dependent on the materials being used than the energy consumed during the building’s operation, which varies with geography. The Resources endpoint indeed varies across location due to the influence of the other midpoint (Non-renewable energy use) included in the endpoint calculation.
Figure 15. Base Case results for the Single-family Residence across all climate regions with color coding to indicate midpoints that contribute to each endpoint.
FIGURE 16. Base Case results shown by life cycle stage as a percentage of Portland NC impact for the Single-family Residence across all climate regions.
Materials contributions

Several MasterFormat Divisions are responsible for the disparities in results observed between NC and RR scenarios. Those with the greatest number of indicators showing the greatest differences include 03100 Concrete foundation, 03300 Cast-in-place concrete, 06100 Rough carpentry, 07200 Thermal protection, 09900 Paints & coatings, and 16000 Electrical.

Similar to other buildings evaluated in this study, differences in materials-related impacts are primarily due to differences in material quantities. In most cases, RR requires negligible amounts of materials as compared with NC. In Division 03100, for example, NC uses 3.10 kg/ft\(^2\) of steel (the only material within this category), whereas RR requires 0.127 kg/ft\(^2\). Along the same line of thought and in the opposite direction, Divisions 09900 shows an advantage for NC because it uses only 0.862 kg/ft\(^2\) of paint (again, the only material in this Division) versus 1.24 kg/ft\(^2\) by RR.

The large disparity in Mineral extraction observed in Division 15000, where very little to no other differences exist, indicates that differences in impacts are caused by varying material types used by the buildings. In this case, NC consumes a greater mass of all materials, except copper (used in the plumbing systems), and NC also requires in total a greater mass (kg/ft\(^2\)) of materials. However, because copper is particularly more burdensome than other materials in this Division in the category of Mineral extraction, the RR Mineral extraction impacts are greater than for NC. This observation underlines the potential importance of material types.
Figure 17. Contribution of materials (production, transport, and end-of-life) by MasterFormat category to the total difference between NC and RR impact for the Base Case Single-family Residence in all climate regions evaluated. A negative value indicates that NC is more impacting, while a positive value indicates RR is more impacting.
Elementary School

FIGURE 18 provides Base Case results for the Elementary School across all climate zones and indicators assessed. In comparing the NC and RR results for each region, the difference between impacts for the two scenarios ranges from -15% and 45% of those computed for the NC scenario, with an average difference of 10%, as shown in results presented in FIGURE 18. The negative percentage indicates that the RR scenario is more burdensome.

It is important to note that the case study used to model the RR scenario includes an addition of 37,624ft², which is approximately 38% of the total size of the completed RR building. These activities warrant not only a greater amount of materials but also additional activities during Selected demolition. However, these added impacts do not cause the environmental preferability of RR to be eliminated, except perhaps in the case of Land occupation. Further exploration is provided in the sections that follow.

a) Life cycle stages

To better understand the sources of impacts, results by life cycle stage are shown in FIGURE 19 for the endpoints and Climate change. In each zone, it is evident that energy use is a principle contributor to impact, particularly for Climate change and Resources. For these indicators, material-related impacts comprise approximately 16-24% of net total impacts in the NC scenarios and 9.8-15% for RR scenarios, depending on the geography. These same activities contribute to the net total Human health impacts about 22-36% for NC scenarios and 16-28% for RR scenarios, again depending on climate zone. Similar to other buildings evaluated in this study, materials contribute approximately half of the total Ecosystem quality impacts, between 43-62% for NC and 36-55% for RR. This observation indicates that the latter indicator is more influenced by materials than are Climate change, Human health and Resources.

In regions where building energy use (i.e., the combination of EUI, electricity grid, and end use profile) is relatively more burdensome, materials play a smaller, yet still important, role in the total life cycle impact. This is particularly the case for the Chicago and Atlanta scenarios.
Figure 18. Base Case results for the Elementary School across all climate regions with color coding to indicate midpoints that contribute to each endpoint.
Figure 19. Base Case results shown by life cycle stage as a percentage of Portland NC impact for the Elementary School across all climate regions.
b) **Geographic trends**

Building energy use contributes from 29-81% of net total impacts for the NC scenarios and from 33-86% for RR scenarios, depending on climate zone and impact category. Climate change and Resources tend to be comprised of materials-related impacts at the upper ends of these spectrums, while Ecosystem quality consists of materials-related impacts at the lower ends; Human health consists of materials-related impacts within the middle portion of these ranges. Similar to all other building types evaluated in this study, this illustrates that Human health and particularly Climate change and Resources are to a greater extent contributed by building energy use, while Ecosystem quality is about equally added by material-related and energy-related impacts.

Across climate zones, only energy-related attributes of the buildings change; thus, trends observed across climate regions are due to the balance between EUI, end use profile, and electricity grid mix. As previously shown in TABLE 6, the EUI for the Chicago scenario is over 120% of that for the Atlanta scenario. Further, the Chicago scenario is more burdensome in Climate change, Ecosystem quality and Resources, with only a 7% less impact in Human health. However, FIGURE 19 shows that the Atlanta scenario is somewhat more burdensome than the former in each of these four indicators. This unintuitive observation is due to the different end use profiles between the regions. While the Chicago scenario draws only 26 kBTU/ft²/y from electricity (the remaining 54 kBTU/ft²/y is energy from natural gas), the Atlanta scenario consumes 40 kBTU/ft²/y from electricity. This disparity is sufficient to cause the Atlanta scenario to be more burdensome than the Chicago scenario.

An exception to these observations occurs in the category of Mineral extraction where, in each climate zone evaluated, the NC or RR results across locations have approximately the same magnitude, and RR results are approximately 55% of the NC results. This can be explained by the definition of Mineral extraction, which is computed based on the difference between the amounts of energy required to withdraw resources from the biosphere currently and in the future when minerals are presumably less accessible (Goedkeeop and Spriensma 2000). Indeed, the consistent magnitudes of NC or RR across climate zones indicate that this impact category is more dependent on the materials being used than the energy consumed during building operation, which varies with geography.

c) **Materials contributions**

To better understand the disparities between NC and RR materials-related impacts, differences in materials production are plotted in FIGURE 20 by MasterFormat Divisions. Across all Divisions, the impact categories tend to follow similar trends, although Land occupation is particularly different in
several Divisions. These points are caused by using different quantities of wood and paint between NC and RR.

Aside from Divisions where Land occupation is particularly different between NC and RR, the greatest disparities between the buildings occur in Divisions 08400 Entrances & storefronts and 15000 Mechanical. A few other Divisions are also notable, including 07200 Thermal protection and 16000 Electrical.

In the cases of Divisions 08400 and 16000, the overall gap between NC and RR is primarily caused by the differences in material quantities. For instance, NC is environmentally advantageous in Division 16000 due to the slightly smaller weight of electrical systems required in the building: 1.2 kg/ft^2 for NC versus 1.3 kg/ft^2 for RR. It is important to note that the case study used to represent the RR scenario here includes an addition that comprises nearly 40% of the total building area. Thus, the nearly equivalent quantity of a standard system such as electrical equipment is perhaps expected.

Results for Divisions 07200 and 15000 are similar to those for the Multifamily and Single-Family Residences. This is because different material types are used by NC and RR in differing quantities, and therefore some indicators favor RR while others favor NC. The latter is in fact the case solely for Division 15000 and in only one impact category: Human toxicity. NC’s advantage is attributable to the RR scenario using PVC in some of its plumbing and control systems; NC uses in this Division no items with PVC.

For the Elementary School, differences in materials-related impacts are primarily due to quantity differences as opposed to differences in material types. This is arguably expected, as the case study used to simulate the RR building includes an extensive addition. It is logical that the methods used to build this addition (i.e., in terms of the materials used) are somewhat similar to the construction practices of the NC building.
Figure 20. Contribution of materials (production, transport, and end-of-life) by MasterFormat category to the total difference between NC and RR impact for the Base Case Elementary School in all climate regions evaluated. A negative value indicates that NC is more impacting, while a positive value indicates RR is more impacting.
6. Urban Village

Base Case results for the Urban Village across all climate zones and indicators assessed are provided in Figure 21. In comparing the NC and RR results for each zone, RR is environmentally preferable in all impact categories, except Land occupation. The difference between impacts for the two scenarios ranges from -34% and 73% of those computed for the NC scenario, with an average difference of 28%, based on results presented in Figure 21. The negative percentage indicates that the RR scenario is more burdensome.

a) Life cycle stages

To better understand the sources of impacts, results by life cycle stage are shown in Figure 22 for the endpoints and Climate change. In each zone, it is evident that energy use is a chief contributor to impact, particularly for Climate change and Resources. For these two indicators, material-related impacts comprise approximately 19-27% of net total impacts in the NC scenarios and 5.3-8.5% for RR scenarios, depending on the climate zone. These same activities contribute to the net total Ecosystem quality impacts about 51-66% for NC scenarios and 26-40% for RR scenarios, again depending on geography. Similar to other buildings evaluated in this study, the ranges for Human health fall within these spectrums with 32-41% for NC and 9.5-13% for RR. This observation indicates that the latter two indicators—particularly Ecosystem quality—are more influenced by materials than are Climate change and Resources.

In regions where building energy use is relatively more burdensome, materials play a smaller, yet still important, role in the total life cycle impact. This is clearly illustrated by reviewing the composition of the Ecosystem quality bars in Figure 22. Where the energy-related impacts are larger, materials-related impact comprise a smaller percentage (although the same magnitude) of the net total impacts.

b) Geographic trends

Building energy use contributes from 30-79% of net total impacts for the NC scenarios and from 54-93% for RR scenarios, depending on climate zone and impact category. Energy-related impacts for Climate change, Human health and Resources contribute on the upper ends of these spectrums (a minimum of 56% of impacts for NC and 83% of impacts for RR), whereas these activities’ contribution to Ecosystem quality sit on the lower ends (a maximum of 46% for NC and 70% for RR). These observations indicate that Climate change, Human health and Resources are to a greater extent a result of operating energy use. On the other hand, the relative composition of Ecosystem quality changes between the buildings. For NC, materials are somewhat more important, while for RR energy comprises a larger portion of net total impacts. Considering that only materials change
**Figure 21.** Base Case results for the Urban Village across all climate regions with color coding to indicate midpoints that contribute to each endpoint.
Figure 22. Base Case results shown by life cycle stage as a percentage of Portland NC impact for the Urban Village across all climate regions.
between the NC and RR buildings, this outcome reflects the larger quantities of and/or more impacting materials required by the NC building in comparison to RR. Further exploration is offered in the section that follows.

Within each indicator, the trends observed across climate regions are due to the balance between energy-related parameters: EUI, electricity grid mix, and end use profile. For instance, as shown earlier in Table 7, the EUI is greatest for an Urban Village in the Chicago scenario, followed by Atlanta, Phoenix, and finally the Portland scenario. Despite using the same electricity grid mix and nearly equal EUIs, the Phoenix scenario is slightly more impacting in all four indicators than the Portland scenario. This is attributable to the end use profiles of the two regions; the Phoenix scenario expends more of its energy as electricity (66 of 72 kbtu/ft$^2$/y), as compared to the Portland scenario which expends only 52 of 72 kbtu/ft$^2$/y from electricity. This slight difference, coupled with the slight difference in EUI, translates into a small environmental advantage for the Portland scenario.

A deviation from regional dependency on impacts associated with operating energy occurs in the category of Mineral extraction where, in each climate zone evaluated, the NC or RR results have approximately the same magnitude; RR results are approximately 28% of the NC results. The constant magnitude of NC or RR across climate zones indicates that this impact category is far more dependent on the materials used than on the energy consumed during building operation.

c) Materials contributions

The importance of MasterFormat Divisions to total differences in material production impacts are shown in Figure 23. Across all Divisions, the impact categories tend to follow similar trends, with the exception of Land occupation in a few Divisions (e.g., 06100 Rough carpentry, 09600 Flooring). This is due to differences in the quantities of various materials used by NC and RR that have a relatively large impact in this indicator, specifically wood and soya (soy) oil, the latter an ingredient in paint. In the case of Division 06100, for example, RR consumes over 200 kg/ft$^2$ of wood products (i.e., wood, glulam and plywood), whereas NC uses none, thus resulting in a negative point on Figure 23.

While several Divisions show some differences between NC and RR materials-related impacts, Division 08800 Glazing, 09600 Flooring, 15000 Mechanical and 16000 Electrical show the greatest disparities in the most indicators. Similar to other buildings studied in this work, disparities in these categories are on account of the differences in material quantities between NC and RR. For instance, in Division 08800, RR requires a relatively small mass of window replacements, whereas NC needs
Figure 23. Contribution of materials (production, transport, and end-of-life) by MasterFormat category to the total difference between NC and RR impact for the Base Case Urban Village in all climate regions evaluated. A negative value indicates that NC is more impacting, while a positive value indicates RR is more impacting.
glazing for the entire building; the same types of materials are used by the buildings. Overall, the particularly smaller amounts of materials required by RR provide it an environmental advantage in nearly all indicators across all Divisions. These observations assert that for the Urban Village differences in material production impacts are primarily due to differences in material quantities, as opposed to differences in material types.

B. Sensitivity analyses

1. Electricity grid mix

A sensitivity analysis is conducted around electricity grid mixes to illustrate the influence that grid mix composition has on the study results. This is performed for one building—the Commercial Office—as the overall observations will be similar for all building types. Figure 24 provides the results for Climate change, and Figure 26 shows results for Resources. Ecosystem quality and Human health are depicted in Figure 26 and Figure 27, respectively.

When considering trends across all climate zones and scenarios, all indicators—except Human health—demonstrate the same pattern within a given region. The Portland and Phoenix scenarios show (in Climate change, Resources and Ecosystem quality) an increase from the Regional mix to the Average national mix and a drop from the Regional mix to the Conservative mix with a further decline in impact from the Conservative mix to the Progressive mix. The Atlanta and Chicago scenarios illustrate environmental savings moving from the Regional mix to any of the three other scenarios for these three indicators. The Progressive mix provides savings across all climate regions and in all four indicators evaluated.

Differing patterns are demonstrated by the indicator of Human health across each location. Results for the Portland and Phoenix scenarios are approximately on par with those under the Average national grid, while the Atlanta and Chicago scenarios show greater burden when calculated using the Average national grid. Similarly, while the Conservative projection offers savings for the Portland and Phoenix scenarios, results for the Atlanta and Chicago scenarios are about equal under the Baseline and Conservative grid mixes. As previously noted, the Progressive mix offers savings from the Baseline conditions (i.e., Regional grid mixes) in all locations.

Human health’s different patterns within climate zones are due to the importance of coal and—particularly—natural gas in a given region’s grid mix. Electricity sourcing from natural gas combustion causes the greatest burden to Human health as compared to other technologies; the
next largest is coal-generated electricity, which demonstrates approximately half the impact of natural gas. All other technologies cause less than 5% the impact of natural gas in this category. In the Portland scenario, for example, proportions of coal and nuclear energies notably increase (18% and 9.8%, respectively) in the average national grid, along with smaller increases in oil and biomass, while the remaining technologies’ proportions in the grid decrease. In particular, the use of the natural gas technology decreases by more than 10%. Thus, impacts are approximately on par with the Regional grid mix to the Conservative grid mix as there is a nearly equivalent trade-off in impact between the (primarily) coal-generated electricity and natural gas-generated electricity.

a) Average national grid mix
The Average national grid mix offers environmental savings in climate zones where the regional grid mix is more impacting than the Average mix, and it is reasonable that some climate zones are less impactful than the Average national scenario, while others are more impactful. In fact, because (1) coal, natural gas, and nuclear power tend to be the most dominant energy sources for electricity generation in the U.S. and (2) these are the most burdensome energy technologies for the four indicators evaluated here, the shifts in proportions of these technologies used in a given grid mix are the chief reason for differences between the Regional (Base Case) and Average national scenarios. For instance, the Portland and Phoenix scenarios (both modeled with the WECC regional electricity grid in the Base Case assessment) use a large portion (24%) of hydropower. Since the average national grid mix consists of only 5.8% hydro, plus larger portions of coal and nuclear power, total impacts increase. The opposite effect is seen in the Chicago and Atlanta scenarios where the percentages of coal and nuclear decrease, although the increase in natural gas dampens the overall environmental savings. As previously explained, Human health impacts demonstrate an opposite trend for the Portland and Phoenix scenarios due to the relative importance of natural gas electricity in this indicator.

These observations indicate that the choice in the scale of grid mix—regional versus national average—can be important when the focus is on absolute results. However, because the same parameter is being altered in the same way for both NC and RR, the relative results of the analysis does not change.

b) Conservative projected grid mix
Applying the Conservative grid mix over time offers some environmental savings in every climate zone and indicator, except for Human health in the Atlanta and Chicago scenarios. The reductions are a bit greater in the Portland and Phoenix scenarios, spanning from 5-10% of net total impacts, whereas the Chicago and Atlanta scenarios vary from less than one (<1) to three (3) percent.
Impacts generally decrease to a relatively small extent under the Conservative grid mix on account of the EIA’s projected change in grid mix that takes into account both a shift toward renewable energy technologies as well as the need to meet increasing demand for energy. These factors change the proportions of energy technologies only moderately (See APPENDIX C: Energy Technologies.) The somewhat larger improvement for the Portland and Phoenix scenarios is attributable to the relatively high use of a less burdensome energy technology—hydropower—in its grid mix. Even the small percent increase in the proportion of this technology within the grid coupled with decreases in fossil fuel technologies results in impact reductions that exceed those of the other climate zones. TABLE 9 illustrates the change in grid mixes from the Regional mix to the Conservative projected mix.

TABLE 9. Change in the proportion of the Base Case Regional grid mixes and Conservative regional grid mixes for each energy technology.

<table>
<thead>
<tr>
<th>Energy source</th>
<th>Change in proportion of energy technology from Regional mix to Conservative mix (%)</th>
<th>Chicago (RFC)</th>
<th>Portland &amp; Phoenix (WECC)</th>
<th>Atlanta (SERC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>-1.70</td>
<td>-4.90</td>
<td>-2.50</td>
<td></td>
</tr>
<tr>
<td>Oil</td>
<td>-0.0320</td>
<td>-0.0810</td>
<td>-0.0620</td>
<td></td>
</tr>
<tr>
<td>Gas</td>
<td>0.360</td>
<td>-2.80</td>
<td>0.600</td>
<td></td>
</tr>
<tr>
<td>Nuclear</td>
<td>0.700</td>
<td>-1.15</td>
<td>0.200</td>
<td></td>
</tr>
<tr>
<td>Hydro</td>
<td>0.299</td>
<td>8.00</td>
<td>0.880</td>
<td></td>
</tr>
<tr>
<td>Biomass</td>
<td>0.380</td>
<td>0.400</td>
<td>0.920</td>
<td></td>
</tr>
<tr>
<td>Wind</td>
<td>0.0770</td>
<td>0.590</td>
<td>0.00267</td>
<td></td>
</tr>
<tr>
<td>Solar</td>
<td>0.00</td>
<td>0.0288</td>
<td>0.00</td>
<td></td>
</tr>
</tbody>
</table>

*A negative value indicates a reduction in technology use. For instance, the proportion of coal used in the Chicago grid mix is reduced by 1.70% from the Base Case to the Conservative scenario.

c) Progressive projected grid mix

The Progressive grid mix provides important reductions in impacts across all indicators and climate zones, from approximately 18-59% of the net total impact, depending on impact category and geography. This result is due to the aggressive shift in grid mix toward renewable energy technologies, which tend to be particularly less burdensome on the environment (See APPENDIX D). TABLE 10 describes these changes.
The Chicago and Atlanta scenarios have somewhat greater potential for reductions in electricity-related impacts due to the minimal use of renewable energy technologies in the regional grid mixes. Where the Portland and Phoenix scenarios’ (regional Base Case) grid mix consists of 26% renewable energies, the regional mixes of the Chicago and Atlanta scenarios include less than 5%. While some energy is still derived from fossil fuels and nuclear power in the Progressive mixes, in total it does not exceed 30% of the grid mix.

It is important to note that the WWF (2011) proposal assumes that there is a trend toward chiefly solar and wind power. It is perhaps unlikely that regions like the Portland and Phoenix scenarios would abandon renewable energy technologies currently being employed in favor of others, at least in the near future. Nevertheless, it is very difficult to predict how any grid mix might transform over the coming years as the production and provision of energy is directly tied to technological advancements, economics, politics, among other factors. The results shown here demonstrate the considerable potential environmental savings through improved electricity technologies across the U.S.

Table 10. Change in the proportion of the Base Case Regional grid mixes and Progressive regional grid mixes for each energy technology.

<table>
<thead>
<tr>
<th>Energy source</th>
<th>Chicago (RFC)</th>
<th>Portland &amp; Phoenix (WECC)</th>
<th>Atlanta (SERC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>-46.1</td>
<td>-22.6</td>
<td>-40.6</td>
</tr>
<tr>
<td>Oil</td>
<td>-0.387</td>
<td>-0.313</td>
<td>-0.597</td>
</tr>
<tr>
<td>Gas</td>
<td>-4.69</td>
<td>-23.4</td>
<td>-10.0</td>
</tr>
<tr>
<td>Nuclear</td>
<td>-18.9</td>
<td>-7.19</td>
<td>-17.4</td>
</tr>
<tr>
<td>Hydro</td>
<td>9.43</td>
<td>-7.10</td>
<td>8.61</td>
</tr>
<tr>
<td>Biomass</td>
<td>2.16</td>
<td>1.84</td>
<td>1.40</td>
</tr>
<tr>
<td>Wind</td>
<td>21.2</td>
<td>20.5</td>
<td>21.2</td>
</tr>
<tr>
<td>Solar</td>
<td>37.4</td>
<td>38.3</td>
<td>37.4</td>
</tr>
</tbody>
</table>

*A negative value indicates a reduction in technology use. For instance, the proportion of coal used in the Chicago grid mix is reduced by 46.1% from the Base Case to the Progressive scenario.*
Figure 24. Net total Climate change results for the Commercial Office using different electricity grid mixes.
Figure 25. Net total Resource results for the Commercial Office using different electricity grid mixes.
FIGURE 26. Net total Ecosystem quality results for the Commercial Office using different electricity grid mixes.
Figure 27. Net total Human health results for the Commercial Office using different electricity grid mixes.
2. Energy performance

The Base Case results assert that building energy use is an important player in the life cycle impacts of a structure, particularly when the energy sources to a large extent from fossil fuels. It is therefore important to understand how enhanced energy performance—including consideration of additional materials required to achieve this—can aid in reducing environmental burdens for both the NC and RR.

Similar to the electricity grid mix sensitivity analysis, this assessment includes computation of all three endpoints, plus Climate change. Shown here are the Portland and Chicago scenarios results as they consistently show in the Base Case results a trend toward an extreme; the Portland scenario tends to have the lowest energy-related impacts, while Chicago often has the highest. Evaluating these two zones will offer a sense for the range of potential impacts and patterns. Likewise, only Climate change and Ecosystem quality results are provided in order to assess indicators where energy or materials is the dominating contributor; Climate change typically is driven by energy-related impacts in this study, while Ecosystem quality predominantly sources from materials-related activities (i.e., production, transport, and EOL management of building products).

It should be noted that the Advanced scenario assumes that electricity use (i.e., plug loads) and natural gas use (i.e., water and space heating) are reduced by 30% (See Section II.H.2). In reality, reductions may be smaller or larger. Lesser energy improvement would raise the total height of the bars eventually to the extent of no appreciable savings between the Base Case and Advanced scenarios, whereas greater improvement would enhance the disparity. Further exploration is required to better understand the influence of particular EEMs and actual energy savings achieved.

a) Trends within NC and RR

Perhaps the most apparent and consistent trend is the environmental savings between the Base Case and Advanced scenarios for a given building (i.e., NC Base Case versus NC Advanced, RR Base Case versus RR Advanced); in almost all combinations of climate zone and environmental indicator, it is environmentally preferable to include EEMs. Two exceptions to this exist, one for the Single-family Residence and one for the Commercial Office.

First is the case of Ecosystem quality results for the Single family residences where neither the NC nor RR Advanced scenario shows an advantage to the associated Base Case analysis. In fact, the NC Advanced scenario is 7.8% more impacting than the NC Base Case results, and the RR Advanced scenario is 4.5% more impacting than its associated Base Case analysis. This observation is due to
the additional materials-related impacts incurred during the energy efficiency upgrade coupled with the large influence of these burdens on total Ecosystem quality impacts. Such a result is not seen for Climate change on account of its control by operating energy use.

The Commercial Office Base Case scenario similarly shows no environmental advantage over the RR Pre-EEM analysis. Since these two scenarios assume the same EUI, only the materials-related impacts change and, in fact, slightly increase (up to 2%, depending on climate zone and indicator) owing to the additional materials requirements for incorporating the energy efficiency measurements.

**b) Trends between NC and RR**

In comparing the NC scenarios to those for RR, two distinct patterns emerge for the indicators evaluated. Regarding Climate change, in the majority of instances impacts are greatest for NC Base Case followed by RR Base Case then NC Advanced and finally RR Advanced. An exception exists in the Portland scenario where NC Advanced for the Urban Village somewhat surpasses the total impact of RR Base Case. For Ecosystem quality, the NC Advanced scenario for all building types is as or more impacting than the RR Base Case analysis, except in the case of the warehouse conversions on account of the relatively small (absolute) difference between NC and RR.

The different trends observed within the two environmental indicators are indicative of the sources of these impacts. As explained in several places throughout this document, Ecosystem quality impacts are predominantly provided by materials-related activities (i.e., production, transport and EOL management of building products), while Climate change is more dependent on operating energy use. The balance between materials and energy determines the magnitude of results in each indicator.

While it is perhaps a common perception that a highly energy efficient new building offers environmental savings over a rehabilitated building, the results shown here indicate that it is not always accurate. While environmental benefits can be achieved in certain impact categories, other categories show an increase in impact on account of the additional materials required for energy upgrades. Outcomes are nevertheless dependent upon the specific energy improvement measures (and associated materials) evaluated in this study, and further effort is needed to understand the trade-offs between specific measures and resulting energy reductions. This analysis underscores the necessity of evaluating several indicators when making decisions regarding building reuse and new construction.
Figure 28. Total Climate change results for buildings located in Portland with various energy performance.

- Other life cycle stages: Demolition/Selected demolition and Construction/Rehabilitation & retrofit.
- Energy use-related impacts: Operating energy use.
- Materials-related impacts: Original material production, Replacement material production, Delivery of all materials to building site, Transport of all materials to end-of-life, and the End-of-life of all materials.
Figure 29. Total Ecosystem quality results for buildings located in Portland with various energy performances.
Figure 30. Total Climate change results for buildings located in Chicago with various energy performances.
Figure 31. Total Ecosystem quality results for buildings located in Chicago with various energy performances.

"Other stages": Demolition/Selected demolition and Constructions/Rehabilitation & retrofit.
"Energy use-related impacts": Operating energy use.
"Materials-related impacts": Original material production, Replacement material production, Delivery of all materials to building site, Transport of all materials to end-of-life, and the End-of-life of all materials.
3. **Building lifetime**

Annualized impacts are calculated here to address (1) whether the building lifetime selected influences the relative results between NC and RR and (2) how building lifetime plays a role under various energy performance scenarios. The initial analyses for all buildings assume the building lasts for 75 years before being demolished. This analysis evaluates all energy performance conditions (Pre-EEM, Base Case and Advanced) under building lifetimes of 1, 2, 5, 10, 15, 25, 50 and 100 years.

It should be noted that while impacts here are reported on an annual basis, they are not true annual impacts; this is the purpose for choosing the term *annualized*. Impacts are calculated as a total over the lifetime of the building and subsequently divided by this lifetime. The timing of impacts is not tracked by year for the building’s occupancy phase.

Due to the large number of scenarios that could be calculated here (i.e., 7 buildings X 4 climate zones x 4 indicators), only one combination of building and geography is shown for all indicators as an example. Tables summarizing all cross-over points for each typology and indicator for the Portland and Chicago scenarios are offered, and all results are provided in APPENDIX E: Results. The table includes two climate zones to gain a sense for how cross-over points may differ in regions where energy-related impacts are relatively low (Portland) or high (Chicago).

**a) Trends across typology, geography, and indicator**

Several patterns are consistent across building type, climate zone and environmental indicator. First, the slope of the trend lines between shorter-lived buildings (i.e., 1 through 25 years) tends to be somewhat sharper than trend lines between other points and becomes shallower as lifetime extends. These initial spikes are due to the high consumption of materials (i.e., original materials) in combination with impacts associated with construction activities (i.e., Demolition/Selected demolition and Construction/Rehabilitation & retrofit) at the beginning of a building’s life, which are spread out across an increasing number of years as the building becomes older, thus dampening the slope of the plotted lines. The sharper grade seen for the NC scenario is a result of requiring a greater quantity of materials during Construction in comparison to the amount of materials required by RR during Rehabilitation. (Of course, this trend is the opposite when RR demonstrates greater initial impacts, as seen for the Warehouse-to-Multifamily Residence in Climate change and Resources. Additional discussion of this is offered in the section that follows.) Eventually, the lines become approximately horizontal as the impact of these initial materials become negligible in comparison with the total (annualized) impacts from replacement materials and energy use over time.
A second similarity between the buildings is that the percent difference between NC Base Case and RR Base Case begins to shrink as the building lifetime extends. This is attributable to the dampening of impacts contributed by the original materials, as discussed in the previous paragraph. Thus, at some building lifetime, the impact of the original materials becomes negligible, and—under the assumption that operating energy performance is equal between the RR and NC buildings—the difference between the environmental performance of the buildings is due only to differences in materials replaced, which, theoretically, are similar between scenarios. (Every attempt has been made in this study to model the buildings using generally the same materials.) Thus, the lines will show no to very small difference in annualized impact, although difference in total impact may still be important. Nevertheless, if it is assumed that buildings tend to last less than a century, total impacts of NC and RR do not converge.

b) Base Case scenarios

For nearly every combination of building typology, geography and indicator, the Base Case RR scenario has a smaller environmental impact for all lifetimes analyzed as compared with the Base Case NC scenario. This is because the relatively large quantities of materials required for NC in combination with the relatively extensive activities (i.e., equipment use) during Demolition and Construction are not recovered within a 100-year time frame. Moreover, since the only parameter within the model that changes with lifetime is the number of times products are replaced (i.e., a product replaced every 10 years would be replaced twice in the 25-year building and seven (7) times in the 75-year building), the smooth slope of the lines and consistent outperformance of RR over NC demonstrate that no substantial anomalies in terms of replacement materials exist. In other words, the result that RR performs more preferably than NC with a 75-year lifetime is not due to a particularly burdensome building product used only in the NC office that is replaced before year 75. Similarly, the Base Case results are not due to a particularly burdensome building product used only in the RR office that is replaced after year 75. If one of these had been the case, the points would not plot as smoothly; a jump up in NC annualized impact after the replacement (and before year 75) or a jump up in RR annualized impact after the replacement (and between years 75 and 100), respectively, would occur. The observation that NC has less preferable environmental performance over its life cycle is not dependent on building lifetime.

An exception to this observation exists in the case of the warehouse conversions, particularly for the Warehouse-to-Multifamily Residence. For the Multifamily warehouse repurposing project, in both climate zones, it takes approximately five (5) years for the warehouse to recover Climate change and Resources impacts to the level of NC. This result is due to the relatively large impacts associated
with Selected demolition of the warehouse; in comparison to the Demolition stage of the NC building's life cycle, RR Selected Demolition is approximately twice as impacting. (See Figure 10.) Only Climate change and Resources exhibit this trend as the activities associated with these stages—operation of vehicles and construction equipment—predominantly affect these indicators; Ecosystem quality and Human health are more dominated by materials-related impacts. Thus, the Warehouse is initially more burdensome due to these added impacts, which become negligible over time as energy-related burdens dominate net total impacts.

c) **Base Case versus Advanced scenarios**

In comparing the RR Base Case to the RR Advanced and NC Advanced, the determinants of whether the Advanced scenario is environmentally advantageous are the lifetime of the building and the difference in materials quantities between the scenarios.

The RR Advanced building is always or will always become more favorable than RR Base Case, although the point at which this occurs varies by indicator and building typology. Except for the Commercial Office, Elementary School, Single-family Residence and Urban Village, RR Base Case is never environmentally preferable to RR Advanced. This is because the additional materials-related impacts of the EEMs needed by the Advanced scenario are insufficient to overcome the environmental savings provided by the reduction in operating energy use. When the impacts associated with EEMs are large enough to overcome the gap between NC and RR material differences, RR Base Case is initially favorable. However, as energy-related impacts dominate the net total impacts over time, RR Advanced eventually becomes favorable; this cross-over point can occur as quickly as a lifetime of two (2) years or only after three (3) decades, depending on typology and indicator. In particular, Climate change and Resources tend to recover somewhat more quickly than Human health and Ecosystem quality. This is due to the former two being more influenced by energy-related impacts than the latter two. That is, Climate change and Resources converge to a consistent annualized impact more rapidly as their materials-related contributions become negligible faster. No discernable deviation from these trends is seen across climate zones.

When comparing results of the NC Advanced scenario to those of the RR Base Case, the RR scenario tends to be preferable to the NC until the lifetime of the building exceeds at least one (1) decade, although two (2) to five (5) is perhaps more common. Exact points of cross-over are dependent on typology and to some extent indicator. Similar to the discussion of RR Base Case and RR Advanced, Climate change and Resources tend to recover faster due to the relatively small proportion of net total impacts that are attributable to materials-related burdens; Human health and especially
FIGURE 32. Annualized Climate change results for the Commercial Office located in Portland assuming various building lifetimes.
Figure 33. Annualized Resources results for the Commercial Office located in Portland assuming various building lifetimes.
Figure 34. Annualized Ecosystem quality results for the Commercial Office located in Portland assuming various building lifetimes.
Figure 35. Annualized Human health results for the Commercial Office located in Portland assuming various building lifetimes.
TABLE 11. Cross-over points of the Commercial Office under various lifetimes and energy performance scenarios for NC and RR in Portland and Chicago.

<table>
<thead>
<tr>
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<th>RR Base Case is more favorable than...</th>
<th>At a lifetime of...</th>
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<td>(never)</td>
</tr>
<tr>
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<td>NC Base Case</td>
<td>(always)</td>
</tr>
<tr>
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<td>RR Pre-EEM</td>
<td>(never)</td>
</tr>
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<td>NC Advanced</td>
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<td>RR Advanced</td>
<td>(never)</td>
</tr>
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<td>(never)</td>
<td>NC Base Case</td>
<td>(always)</td>
</tr>
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<td>(never)</td>
<td>NC Advanced</td>
<td>&lt; 54 years</td>
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<tr>
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<td>(never)</td>
<td>RR Pre-EEM</td>
<td>(never)</td>
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<td>(never)</td>
<td>RR Advanced</td>
<td>&lt; 7 years</td>
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<td>(never)</td>
<td>NC Base Case</td>
<td>(always)</td>
</tr>
<tr>
<td>RR Base Case</td>
<td>(never)</td>
<td>NC Advanced</td>
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<tr>
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<td>(never)</td>
<td>RR Pre-EEM</td>
<td>(never)</td>
</tr>
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<td>(never)</td>
<td>RR Advanced</td>
<td>(never)</td>
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**PORTLAND**

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<th>At a lifetime of...</th>
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<td>(never)</td>
<td>NC Base Case</td>
<td>(always)</td>
</tr>
<tr>
<td>RR Base Case</td>
<td>(never)</td>
<td>NC Advanced</td>
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<td>RR Pre-EEM</td>
<td>(never)</td>
</tr>
<tr>
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<td>(never)</td>
<td>RR Advanced</td>
<td>(never)</td>
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<td><strong>RESOURCES</strong></td>
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<td></td>
</tr>
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<td>(never)</td>
<td>NC Base Case</td>
<td>(always)</td>
</tr>
<tr>
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<td>NC Advanced</td>
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<td>RR Pre-EEM</td>
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<td>(never)</td>
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<td>NC Base Case</td>
<td>(always)</td>
</tr>
<tr>
<td>RR Base Case</td>
<td>(never)</td>
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<td>&lt; 54 years</td>
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<tr>
<td>RR Advanced</td>
<td>(never)</td>
<td>RR Pre-EEM</td>
<td>(never)</td>
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<tr>
<td>NC Advanced</td>
<td>(never)</td>
<td>RR Advanced</td>
<td>&lt; 7 years</td>
</tr>
<tr>
<td><strong>HUMAN HEALTH</strong></td>
<td></td>
<td></td>
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<tr>
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<td>(never)</td>
<td>NC Base Case</td>
<td>(always)</td>
</tr>
<tr>
<td>RR Base Case</td>
<td>(never)</td>
<td>NC Advanced</td>
<td>&lt; 25 years</td>
</tr>
<tr>
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<td>(never)</td>
<td>RR Pre-EEM</td>
<td>(never)</td>
</tr>
<tr>
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<td>RR Advanced</td>
<td>(never)</td>
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**TABLE 12.** Cross-over points of the Warehouse-to-Commercial Office under various lifetimes and energy performance scenarios for NC and RR in Portland and Chicago.

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<td>(never)</td>
<td>NC Base Case</td>
<td>(always)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>RR Advanced</td>
<td>(never)</td>
<td>NC Advanced</td>
<td>&lt; 19 years</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
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<td>(never)</td>
<td>RR Advanced</td>
<td>(never)</td>
<td></td>
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<td></td>
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<tr>
<td>Resources</td>
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<td>(never)</td>
<td>NC Base Case</td>
<td>(always)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>RR Advanced</td>
<td>(never)</td>
<td>NC Advanced</td>
<td>&lt; 15 years</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
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<td>(never)</td>
<td>RR Advanced</td>
<td>(never)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ecosystem quality</td>
<td>RR Base Case</td>
<td>(never)</td>
<td>NC Base Case</td>
<td>(always)</td>
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<td></td>
</tr>
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<td>&lt; 73 years</td>
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<td>(never)</td>
<td>RR Advanced</td>
<td>(never)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Human health</td>
<td>RR Base Case</td>
<td>(never)</td>
<td>NC Base Case</td>
<td>(always)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>RR Advanced</td>
<td>(never)</td>
<td>NC Advanced</td>
<td>&lt; 24 years</td>
<td></td>
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<td></td>
</tr>
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<td>NC Advanced</td>
<td>(never)</td>
<td>RR Advanced</td>
<td>(never)</td>
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<td></td>
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<table>
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<tr>
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<td>At a lifetime of...</td>
<td><strong>RR Base Case</strong> is more favorable than...</td>
<td>At a lifetime of...</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>RR Base Case</td>
<td>(never)</td>
<td>NC Base Case</td>
<td>(always)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>RR Advanced</td>
<td>(never)</td>
<td>NC Advanced</td>
<td>&lt; 12 years</td>
<td></td>
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<td></td>
</tr>
<tr>
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<td>(never)</td>
<td>RR Advanced</td>
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<td>Resources</td>
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<td>NC Base Case</td>
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<td></td>
</tr>
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<td>NC Advanced</td>
<td>&lt; 10 years</td>
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<td>RR Advanced</td>
<td>(never)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ecosystem quality</td>
<td>RR Base Case</td>
<td>(never)</td>
<td>NC Base Case</td>
<td>(always)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>RR Advanced</td>
<td>(never)</td>
<td>NC Advanced</td>
<td>&lt; 33 years</td>
<td></td>
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<td>(never)</td>
<td>RR Advanced</td>
<td>(never)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Human health</td>
<td>RR Base Case</td>
<td>(never)</td>
<td>NC Base Case</td>
<td>(always)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>RR Advanced</td>
<td>(never)</td>
<td>NC Advanced</td>
<td>&lt; 25 years</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>NC Advanced</td>
<td>(never)</td>
<td>RR Advanced</td>
<td>(never)</td>
<td></td>
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</table>
TABLE 13. Cross-over points of the Warehouse-to-Multifamily Residence under various lifetimes and energy performance scenarios for NC and RR in Portland and Chicago.*

<table>
<thead>
<tr>
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<th><strong>PORTLAND</strong></th>
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<th><strong>CHICAGO</strong></th>
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<td><strong>NC Base Case is more</strong></td>
<td><strong>RR Base Case is more</strong></td>
<td><strong>NC Base Case is more</strong></td>
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<td></td>
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<tr>
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<td>&gt; 5 years</td>
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<tr>
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<td>(never)</td>
<td>RR Advanced</td>
<td>(never)</td>
</tr>
<tr>
<td>NC Advanced</td>
<td>(never)</td>
<td>NC Advanced</td>
<td>(never)</td>
</tr>
<tr>
<td><strong>Resources</strong></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>RR Base Case</td>
<td>&lt; 4 years</td>
<td>RR Base Case</td>
<td>&gt; 5 years</td>
</tr>
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<td>RR Advanced</td>
<td>(never)</td>
</tr>
<tr>
<td>NC Advanced</td>
<td>(never)</td>
<td>NC Advanced</td>
<td>(never)</td>
</tr>
<tr>
<td><strong>Ecosystem quality</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RR Base Case</td>
<td>(always)</td>
<td>RR Base Case</td>
<td>(never)</td>
</tr>
<tr>
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<td>&lt; 14 years</td>
<td>RR Advanced</td>
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<tr>
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<td>&lt; 3 years</td>
<td>NC Advanced</td>
<td>(never)</td>
</tr>
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<td><strong>Human health</strong></td>
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</tr>
<tr>
<td>RR Base Case</td>
<td>(always)</td>
<td>RR Base Case</td>
<td>(never)</td>
</tr>
<tr>
<td>RR Advanced</td>
<td>&lt; 16 years</td>
<td>RR Advanced</td>
<td>(never)</td>
</tr>
<tr>
<td>NC Advanced</td>
<td>(never)</td>
<td>NC Advanced</td>
<td>(never)</td>
</tr>
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</table>

*Note that a gap between the time of cross-over indicates that the two scenarios are about equal for that period of time. For instance, consider the comparisons of NC Base Case to RR Base Case for Climate change in Portland. The information here implies that for lifetimes of 2-5 years, the buildings performance approximately the same in terms of life cycle environmental impact.
TABLE 14. Cross-over points of the Multifamily Residence under various lifetimes and energy performance scenarios for NC and RR in Portland and Chicago.

<table>
<thead>
<tr>
<th>PORTLAND</th>
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<th>RR Base Case is more favorable than...</th>
<th>At a lifetime of...</th>
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<td>RR Base Case</td>
<td>(never)</td>
<td>NC Base Case</td>
<td>(always)</td>
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<tr>
<td></td>
<td>RR Advanced</td>
<td>(never)</td>
<td>NC Advanced</td>
<td>&lt; 20 years</td>
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<td>(never)</td>
<td>RR Advanced</td>
<td>(never)</td>
</tr>
<tr>
<td>Resources</td>
<td>RR Base Case</td>
<td>(never)</td>
<td>NC Base Case</td>
<td>(always)</td>
</tr>
<tr>
<td></td>
<td>RR Advanced</td>
<td>(never)</td>
<td>NC Advanced</td>
<td>&lt; 18 years</td>
</tr>
<tr>
<td></td>
<td>NC Advanced</td>
<td>(never)</td>
<td>RR Advanced</td>
<td>(never)</td>
</tr>
<tr>
<td>Ecosystem quality</td>
<td>RR Base Case</td>
<td>(never)</td>
<td>NC Base Case</td>
<td>(always)</td>
</tr>
<tr>
<td></td>
<td>RR Advanced</td>
<td>(never)</td>
<td>NC Advanced</td>
<td>(always)</td>
</tr>
<tr>
<td></td>
<td>NC Advanced</td>
<td>(never)</td>
<td>RR Advanced</td>
<td>(never)</td>
</tr>
<tr>
<td>Human health</td>
<td>RR Base Case</td>
<td>(never)</td>
<td>NC Base Case</td>
<td>(always)</td>
</tr>
<tr>
<td></td>
<td>RR Advanced</td>
<td>(never)</td>
<td>NC Advanced</td>
<td>&lt; 46 years</td>
</tr>
<tr>
<td></td>
<td>NC Advanced</td>
<td>(never)</td>
<td>RR Advanced</td>
<td>(never)</td>
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</table>

<table>
<thead>
<tr>
<th>CHICAGO</th>
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<th>At a lifetime of...</th>
<th>RR Base Case is more favorable than...</th>
<th>At a lifetime of...</th>
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<td>NC Base Case</td>
<td>(always)</td>
</tr>
<tr>
<td></td>
<td>RR Advanced</td>
<td>(never)</td>
<td>NC Advanced</td>
<td>&lt; 16 years</td>
</tr>
<tr>
<td></td>
<td>NC Advanced</td>
<td>(never)</td>
<td>RR Advanced</td>
<td>(never)</td>
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<tr>
<td>Resources</td>
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<td>(never)</td>
<td>NC Base Case</td>
<td>(always)</td>
</tr>
<tr>
<td></td>
<td>RR Advanced</td>
<td>(never)</td>
<td>NC Advanced</td>
<td>&lt; 15 years</td>
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<tr>
<td></td>
<td>NC Advanced</td>
<td>(never)</td>
<td>RR Advanced</td>
<td>(never)</td>
</tr>
<tr>
<td>Ecosystem quality</td>
<td>RR Base Case</td>
<td>(never)</td>
<td>NC Base Case</td>
<td>(always)</td>
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<tr>
<td></td>
<td>RR Advanced</td>
<td>(never)</td>
<td>NC Advanced</td>
<td>(always)</td>
</tr>
<tr>
<td></td>
<td>NC Advanced</td>
<td>(never)</td>
<td>RR Advanced</td>
<td>(never)</td>
</tr>
<tr>
<td>Human health</td>
<td>RR Base Case</td>
<td>(never)</td>
<td>NC Base Case</td>
<td>(always)</td>
</tr>
<tr>
<td></td>
<td>RR Advanced</td>
<td>(never)</td>
<td>NC Advanced</td>
<td>&lt; 70 years</td>
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<td>RR Advanced</td>
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TABLE 15. Cross-over points of the Single-family Residence under various lifetimes and energy performance scenarios for NC and RR in Portland and Chicago.

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<th>Chicago</th>
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<td>**RR Base Case is more</td>
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<td>favorable than...</td>
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<td>At a lifetime of...</td>
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<td>NC Base Case</td>
</tr>
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<td>RR Advanced</td>
<td>(never)</td>
<td>NC Advanced</td>
</tr>
<tr>
<td>NC Advanced</td>
<td>&lt; 5 years</td>
<td>RR Advanced</td>
</tr>
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<tr>
<td>NC Advanced</td>
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<td>RR Advanced</td>
</tr>
<tr>
<td>Ecosystem quality</td>
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<td>NC Base Case</td>
</tr>
<tr>
<td>RR Advanced</td>
<td>(never)</td>
<td>NC Advanced</td>
</tr>
<tr>
<td>NC Advanced</td>
<td>&gt; 6 years</td>
<td>RR Advanced</td>
</tr>
<tr>
<td>Human health</td>
<td>RR Base Case</td>
<td>NC Base Case</td>
</tr>
<tr>
<td>RR Advanced</td>
<td>(never)</td>
<td>NC Advanced</td>
</tr>
<tr>
<td>NC Advanced</td>
<td>&gt; 19 years</td>
<td>RR Advanced</td>
</tr>
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</table>

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TABLE 16. Cross-over points of the Elementary School under various lifetimes and energy performance scenarios for NC and RR in Portland and Chicago.

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<th>CHICAGO</th>
</tr>
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<td>RR Base Case is more favorable than...</td>
<td></td>
</tr>
<tr>
<td></td>
<td>At a lifetime of...</td>
<td></td>
<td>At a lifetime of...</td>
</tr>
<tr>
<td>Climate change</td>
<td>RR Base Case (never)</td>
<td></td>
<td>RR Base Case (always)</td>
</tr>
<tr>
<td></td>
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<td></td>
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<tr>
<td>Resources</td>
<td>RR Base Case (never)</td>
<td></td>
<td>NC Base Case (always)</td>
</tr>
<tr>
<td></td>
<td>RR Advanced (never)</td>
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<td>NC Advanced &lt; 3 years</td>
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<tr>
<td></td>
<td>RR Advanced (never)</td>
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<td>NC Advanced &lt; 3 years</td>
<td></td>
<td>RR Advanced &lt; 3 years</td>
</tr>
<tr>
<td>Human health</td>
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<td>NC Base Case (always)</td>
</tr>
<tr>
<td></td>
<td>RR Advanced (never)</td>
<td></td>
<td>NC Advanced &lt; 23 years</td>
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<td></td>
<td>NC Advanced &lt; 2 years</td>
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<td>RR Advanced &lt; 2 years</td>
</tr>
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TABLE 17. Cross-over points of the Urban Village under various lifetimes and energy performance scenarios for NC and RR in Portland and Chicago.

<table>
<thead>
<tr>
<th>PORTLAND</th>
<th></th>
<th>PORTLAND</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>NC Base Case</strong> is more favorable than...</td>
<td><strong>RR Base Case</strong> is more favorable than...</td>
<td>At a lifetime of...</td>
</tr>
<tr>
<td>Climate change</td>
<td></td>
<td></td>
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<tr>
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<td>(never)</td>
<td>NC Base Case</td>
</tr>
<tr>
<td>RR Advanced</td>
<td>(never)</td>
<td>NC Advanced</td>
</tr>
<tr>
<td>NC Advanced</td>
<td>(never)</td>
<td>RR Advanced</td>
</tr>
<tr>
<td>Resources</td>
<td></td>
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<tr>
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<td>(never)</td>
<td>NC Base Case</td>
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<tr>
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<td>(never)</td>
<td>NC Advanced</td>
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<tr>
<td>NC Advanced</td>
<td>(never)</td>
<td>RR Advanced</td>
</tr>
<tr>
<td>Ecosystem quality</td>
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<td>(never)</td>
<td>NC Base Case</td>
</tr>
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<td>NC Advanced</td>
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<tr>
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</tr>
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<td>Human health</td>
<td></td>
<td></td>
</tr>
<tr>
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<td>(never)</td>
<td>NC Base Case</td>
</tr>
<tr>
<td>RR Advanced</td>
<td>(never)</td>
<td>NC Advanced</td>
</tr>
<tr>
<td>NC Advanced</td>
<td>&lt; 3 years</td>
<td>RR Advanced</td>
</tr>
</tbody>
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<table>
<thead>
<tr>
<th>CHICAGO</th>
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</thead>
<tbody>
<tr>
<td><strong>NC Base Case</strong> is more favorable than...</td>
<td><strong>RR Base Case</strong> is more favorable than...</td>
<td>At a lifetime of...</td>
</tr>
<tr>
<td>Climate change</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RR Base Case</td>
<td>(never)</td>
<td>NC Base Case</td>
</tr>
<tr>
<td>RR Advanced</td>
<td>(never)</td>
<td>NC Advanced</td>
</tr>
<tr>
<td>NC Advanced</td>
<td>(never)</td>
<td>RR Advanced</td>
</tr>
<tr>
<td>Resources</td>
<td></td>
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<tr>
<td>RR Base Case</td>
<td>(never)</td>
<td>NC Base Case</td>
</tr>
<tr>
<td>RR Advanced</td>
<td>(never)</td>
<td>NC Advanced</td>
</tr>
<tr>
<td>NC Advanced</td>
<td>(never)</td>
<td>RR Advanced</td>
</tr>
<tr>
<td>Ecosystem quality</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RR Base Case</td>
<td>(never)</td>
<td>NC Base Case</td>
</tr>
<tr>
<td>RR Advanced</td>
<td>(never)</td>
<td>NC Advanced</td>
</tr>
<tr>
<td>NC Advanced</td>
<td>&lt; 16 years</td>
<td>RR Advanced</td>
</tr>
<tr>
<td>Human health</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RR Base Case</td>
<td>(never)</td>
<td>NC Base Case</td>
</tr>
<tr>
<td>RR Advanced</td>
<td>(never)</td>
<td>NC Advanced</td>
</tr>
<tr>
<td>NC Advanced</td>
<td>&lt; 3 years</td>
<td>RR Advanced</td>
</tr>
</tbody>
</table>
Ecosystem quality recovers more slowly, if at all. Additionally, the Chicago scenario sees somewhat faster recovery than the Portland scenario due to a more impacting electricity grid mix. The Warehouse-to-Multifamily Residence is the only exception to these observations as the RR Base Case never outperforms the NC Advanced scenario.

These results indicate that the environmental advantage of achieving a highly energy efficient rehabilitated or new building (i.e., in comparison to achieving a rehabilitated building with average energy performance) is dependent on the expected lifetime of the structure and its location. It can be between a few years to over 50 years to recover impacts incurred from the EEMs needed for a building to perform at an advanced level of energy efficiency. The exact year of indifference depends on the quantities of additional materials needed to achieve the performance level desired, as well as the importance of energy-related impacts in comparison to materials-related impacts for a given indicator. Also illustrated by these results is the importance of considering multiple indicators as trade-offs in environmental performance may exist.

**d) Commercial Office Base Case versus Pre-EEM scenario**

Results for the Pre-EEM analysis quite closely follow those of the RR Base Case scenario. The nearly negligible (<1.6%) difference seen between the two evaluations reflects the materials differences between the scenarios. The Pre-EEM scenario is intended to represent an existing building that is already operating at an average level of energy efficiency and is modeled as the Base Case scenario without the EEMs (See Section II.H.2). The small resulting disparity in net total impacts is due to the small quantities of materials needed for the EEMs and their relatively low impacts as compared to the other materials required by the building.

These results imply that existing buildings needing no EEMs to achieve an average level of energy performance are generally as environmentally favorable as the RR Base Case in comparison to the NC Base Case. It is possible that the Pre-EEM scenario could also be preferable to the RR Base Case if the required EEMs (for the Base Case) are extensive.

**V. Discussion and Implications**

This section provides a digestion of all results compiled in this study. Important observations for specific climate regions or typologies are pointed out where there are implications for overall conclusions, but
details regarding each building type are provided in Section IV.

A. Trends across building typologies

While LCA results for buildings of different typologies cannot be compared directly as the buildings have very different functions (i.e., an office does not provide the same service as a home), the patterns observed across the typologies can be considered. This assessment shows three themes in particular that transcend building typology, climate zone, and environmental indicator: RR is more likely to be environmentally preferable to NC, there exists a balance between impacts related to materials and energy, and building lifetime is an important factor when deciding between RR a more energy efficient new building. Some disparities exist within a given building due to differences in materials (types and quantities), as well as the parameters around energy use. Thus, while there remains an important balance between materials and energy, the details of this balance—including materials contributions and energy end use profiles—are specific to typology, climate zone, and environmental indicator.

For all climate regions and typologies evaluated, Base Case results show that it is more often than not environmentally advantageous to rehabilitate and retrofit a building than to demolish the existing building and construct a new one. The range of savings is quite wide, from less than 10% to more than 70% of the NC impact. While the lower end of that range may seem negligible at the level of a single building, scaling up these savings to a population of buildings that are slated for rehabilitation (instead of demolition and new construction) could provide substantial environmental benefits. Further, primarily due to a need for fewer materials, rehabilitation and retrofit can offer near-term environmental savings, which even a new building that achieves a higher level of energy efficiency may not recover for decades. These near-term environmental savings offered by rehabilitating and retrofitting an existing building are particularly important when considering the current concern over Climate change.

B. Balance between materials and energy

One of the most important observations from this study are that (1) the greatest contributors to environmental burdens are materials and building energy use and (2) there exists a balance between the relative importance of these contributors. Regarding the latter, energy generally plays a stronger role than materials in overall Climate change, Human health and Resources impacts, while Ecosystem is about equally influenced by the two. This observation indicates that environmental trade-offs in impacts exist when considering how to operate and maintain a building.
The decision to rehabilitate and renovate an existing building or to construct a new, more energy efficient building is a prime example. Even though upgrades in the latter result in lower energy consumption over the life of the building, they increase material-related impacts. For a given building lifetime, this addition of materials—and thus material-related impacts—can outweigh the savings from reduced energy use in some impact categories, like Ecosystem quality, even though the magnitudes of others, such as Climate change, decline. Over time, the new building may recover some of these impacts, but it can take as long as several decades before it is environmentally preferable to RR.

The balance between materials and energy and its ability to cause trade-offs in impacts demonstrate the criticality of examining multiple indicators when assessing the environmental performance of the decision to rehabilitate, as well as the decision to include energy performance upgrades.

C. Influence of building lifetime

No matter the length of a building’s lifetime, if new and rehabilitated buildings have the same energy performance, the trend between NC and RR generally remains the same: material-related impacts during Construction are not recovered by NC even after a century, and RR remains environmentally favorable. This outcome is emphasized as the quantity of Original materials required for NC (in comparison to the quantity of Original materials needed for RR) increases. Where the NC building is more energy efficient, it is possible for the new building to outperform the rehabilitated building, although it can take decades for this to occur.

The message here is that building lifetime plays a role in the balance between materials and energy. As building lifetime extends, material-related impacts to improve energy efficiency are paid off through the reduction in energy use. However, it can be more environmentally preferable to rehabilitate a building without substantial energy improvements (as compared to constructing a new building that demonstrates advanced energy efficiency) if that building is intended to live for a relatively short duration. The definition of “short” and “long” in terms of building lifetime is not only specific to typology but also to indicator. Impact categories that are predominantly contributed to by building energy consumption (e.g., Climate change, Resources) show a shorter time to payback than do categories with greater contributions from material-related impacts (e.g., Ecosystem quality, Human health). This observation reinforces the importance of assessing more than just Climate change when considering under what conditions it is preferable to rehabilitate and retrofit an existing building as compared to new construction.
VI. Study application, certainty and limitations

This body of work is conducted for the NTHP, and the information provided here can be used in the following exercises:

- Comparison of the life cycle environmental profiles of buildings undergoing rehabilitation and retrofit to those generated by demolition of the existing building followed by new construction;
- Identification of key parameters and hotspots of the system, including life cycle stages and material categories;
- Comprehension of the influence of the assumptions and variables selected in the model, namely building typology, climate zone, energy performance, electricity grid mix, and building lifetime; and
- Public communication of the outcomes of this work at the discretion of the NTHP.

In applying the results, it is important to make a consideration of the level of certainty in the conclusions being drawn. To interpret certainty in a study with so many underlying points of data requires a sophisticated treatment or understanding of the interaction of these data within the model to produce the results and how uncertainty in each data point might contribute to the total uncertainty. Though still a developing area, there exist methods to apply a quantitative estimate of uncertainty to both the absolute and comparative results of a life cycle assessment. In doing so, one must consider independently the uncertainty existing in the estimate of how much of various materials, energy or processes occur in the system, the uncertainty in the flows to and from the environment caused by each, and the uncertainty in the characterization of the impact due to those environmental flows. Even the best methods currently available largely omit this last aspect, impact characterization, from their consideration of uncertainty. It is, however, generally recognized that the characterization factors for such categories as Climate change and energy use are of reasonably high certainty (tens of percents), whereas the uncertainty may range into the orders of magnitude for some categories such as ecological toxicity.

From such an assessment of uncertainty, one can obtain an estimate of the uncertainty in each absolute or comparative conclusion drawn from the LCA. It is important to note that it is often the comparative results that are of most interest in LCA and that these results tend to have a higher level of certainty than the absolute results. The reason is that many comparisons alter only some of the material and energy flows in the system, and for those that remain unchanged, we are certain that there is no
difference between the systems, even as we are uncertain of what the magnitude of that portion of the system is. Further, within those parts of systems that are different among scenarios, some further reduction of uncertainty may occur because different materials may be linked within their supply chains to the same underlying activities or environmental flow, e.g., use of electricity or lead emissions. Because of these nuances in the interaction of uncertainties within the model, it is difficult to make a reasonably definitive statement of uncertainty without doing a detailed quantitative treatment. However, this has not been accomplished within the present scope.

The reader is thus left to make her own interpretations of the certainty of results. The authors have offered their own qualitative evaluations of certainty and believe that the conclusions presented here are generally supported by the findings of the study. They have also made efforts to highlight places where some potential exceptions exist. The following interpretation is offered as an example in considering the results for the Multifamily Residence in Figure 30:

The difference among the scenarios shown here is slightly less than 10%. For the impact category of Climate change, this is in a range where it would be justifiable to eye such a difference with some suspicion. However, a closer examination of this result shows that for both systems, the energy use component is identical and is contributing more than 75% of the total impact. There is no uncertainty in that 75% of the result. When considering the difference in material-related impact, which is the major source of the difference in results, the difference between these scenarios is more than 50%, a range that would make many experts feel much more comfortable in relying on the results. When viewing the remainder of Figure 30 from this perspective, one may obtain some further confidence in the significance of the results than they might have had at first pass, noting that many of the differences in the total impact are indeed in a range of 10 to 20% or less.

In applying the same logic to Figure 29, one sees that generally the contribution of energy is smaller and the contribution of materials and other stages is higher. Therefore, even though the total differences in this figure are the same, or perhaps slightly more extreme, than in Figure 30, the certainty may be less because the differences in the stages that are different are more pronounced. In such cases, a difference of only 10% in the total result may be cause by, for example, a difference of only 20% in the material-related impact. Further, the ability to estimate damage to Ecosystem quality is much less certain than for Climate change. One should therefore take much more suspicion in the results from Figure 29 than from those in Figure 30.

Finally, one should consider certainty in the context of the conclusions that are being drawn from the whole body of the work rather than, or in addition to, the certainty of individual findings. The broad conclusions of this work are that there are important environmental savings to be gained by restoring existing buildings. When looking across all the results in Figures 29, 30 and the surrounding figures, one sees a variety of case studies and a variety of impact categories and while we might suspect that many of the individual findings shown could be within the margin of error, the repetition of the trend across many examples builds confidence that the broad conclusion holds well. Further, the existence of small margins, and even contrary findings in some cases,
illustrate a point that these are complicated systems and that one must indeed pay attention to the details when implementing actions based on the outcomes of the study.

Regarding limitations, it is important to understand how this study is conducted so that its results and conclusions are applied appropriately. The following should be considered along with the context described in earlier sections of this report when interpreting the information presented in this work.

**Several parameters are assumed to remain constant across the cities evaluated** which may or may not be accurate. This applies to materials service lifetime, materials transport distances (to building site and to EOL) and EOL management (i.e., the portion of each product going to recycling, incineration, and landfill). Roofing in Chicago may require more frequent replacement than in Atlanta due to more frequent harsher weather events. Portland may recycle a greater portion of spent construction materials than does Atlanta. Materials may need to travel greater distances to arrive at the various locations, and some materials may even be imported. Additional effort is required to understand such dynamics of materials markets.

**The study assumes that many aspects of the building’s life cycle and associated activities remain unchanged over the life span of the building.** This includes the technologies used to generate energy, processes employed to fabricate and transport materials, as well as the ways in which materials are handled at end-of-life. Potential changes in electricity generation are partially addressed by the sensitivity analysis around grid mix, although it is possible that individual technologies, such as coal-fired power plants, could operate very differently in the future. Due to very high uncertainty in how these aspects may change over time and at what rate those changes might occur, the analysis here takes a steady-state approach.

**The majority of LCI data implemented describes European operations**, implying that the study here may not be 100% representative of U.S. practices (and thus impacts). However, a database of equivalent quality, transparency, and robustness is not yet available for the U.S. or other climate regions (beyond Europe) from which the U.S. building industry may source its materials. Further rationale is offered in Section II.F.

**An important consideration excluded from this study is indoor air quality**, specifically emissions of building materials. As described in Section II.D.1., the complexity of this topic requires resources and
expertise beyond the realm of this work. However, it is possible to offer some reflection on indoor air quality due to materials off-gassing in the context of comparing NC to RR. Where it can be assumed that (1) NC and RR use the same types of materials and (2) the potential risk presented by materials emissions is diminished as products age, it is perhaps reasonable to conclude that NC offers the greater impact to human health as it requires a larger quantity of new materials. Of course, if the majority of impact is due to particular materials that may be about equally required in NC and RR—such as furnishings, which are not considered in this study and are assumed to be equal per square foot of floor space—no discernable difference between the buildings may exist. Because real buildings are used in the model, it is possible in this study that RR requires a material important to indoor air quality that NC does not require. This would result in a greater burden on human health in the rehabilitated building. However, as the intent is to compare equivalent buildings, it is less feasible that RR would cause a greater impact, unless off-gassing increases with material age. Further research is needed to better understand the trade-offs in indoor air quality between the two scenarios.

LCIA results are relative expressions and do not predict impacts on category endpoints, the exceeding of thresholds, safety margins or risks. Unlike environmental risk assessment conducted in a regulatory context, which uses a conservative approach, LCA seeks to provide the best possible estimate (Udo de Haes et al., 2002). In other words, the LCIA seeks to represent the most probable case; the models (i.e., of transport, fates of environmental contaminants, and toxic effects on biological receptors) do not attempt to maximize exposure and environmental damage, which is the worst-case scenario approach.

This study does not support or provide definitive comparisons of the environmental performance of specific products or materials or of building designs, practices or related decisions beyond the central inquiry of NC versus RR. Furthermore, conclusions regarding new construction version rehabilitation and retrofit are only valid if the case studies used to model these buildings are deemed to be typical of new construction and rehabilitation and retrofit, particularly with regard to materials inputs as these are the primary cause of differences between NC and RR. While the buildings selected for this study are intended to represent common designs in the U.S. for each typology, they are not representative of all possible schematics typical for a given U.S. climate zone. However, if it can be assumed that NC and RR will demonstrate differences in material quantity requirements regardless of design (and assuming NC and RR remain comparable), the general conclusions of the study may hold true for buildings exhibiting design features different from those evaluated in this study. Further investigation is warranted to
evaluate particular building designs across climate zones. **Results may not be applicable to buildings that use quantities and/or types of materials that differ greatly from those applied to the case studies in this analysis.**

**VII. Conclusions**

Throughout the many evaluations conducted here—between different typologies, cities (climate zones), and key variables (e.g., energy performance and building lifetime)—several consistent themes emerge. In particular, these themes center on the balance between energy performance and materials. The conclusions made here are applicable to all buildings studied, although details vary between typologies.

*Overall environmental profiles of NC and RR*

- Where the energy performance of NC and RR buildings can be considered equivalent, the material differences between NC and RR primarily determine the relative environmental profiles of the buildings. In general, because NC requires more materials than RR during construction, it yields a larger magnitude of impact.

- When a RR project includes extensive renovation and/or additions to the space, the potential for environmental savings can be greatly decreased or even eliminated due to the additional quantities of materials required for the project.

- Where energy performance of NC and RR buildings is different, both energy and material-related impacts must be considered to understand the environmental trade-offs between the buildings.

*Geography*

- Geography can be an important factor in determining the total environmental impacts of a given building, but the relative results between NC and RR do not change by location. This conclusion is valid only if the energy demand, end use profiles, and materials do not change or do not change in different ways between NC and RR.

- In order to make a well-informed decision regarding the decision to rehabilitate, multiple environmental indicators should be assessed to identify any trade-offs in type of impact.

*Electricity grid mix*

- The electricity grid mix can be an important factor in determining the total environmental impacts of a given building, but the relative results between NC and RR do not change.
The conclusion is valid only if the grid mixes (i.e. energy technologies) employed for NC and RR are the same.

*Energy performance*

- The environmental benefit of improving a building’s energy performance is a function of the building’s expected lifetime; the materials required for the improvements; and the actual energy-use reduction attained.

- When considering energy-performance improvements, it is possible that impacts caused by material-related requirements can outweigh the savings in impacts gained by the achieved energy reduction. This is a function of the EEMs implemented (i.e., materials used) as well as the actual energy savings achieved and may be most important for Human health and Ecosystem quality. However, over time these impacts can be recovered through the reduced demand for energy.

*Building life cycle & lifetime*

- If the NC and RR buildings have the same service life and the same energy performance, the choice in building lifetime does not change the relative results of the study.

- Impacts associated with ongoing materials and energy consumption become increasingly important to total life cycle impact over time. Yet, within a typical building lifetime (<100 years), there will always be a difference between NC and RR impacts.

- RR offers immediate environmental savings due to the need for a relatively smaller quantity of materials initially required for the renovation and, to a lesser extent, shorter duration of construction activities. This is particularly important in the context of Climate change.

The LCA conducted identifies some key parameters and trade-offs to consider when deciding whether to demolish an existing building and erect a new structure on-site or to rehabilitate and retrofit the existing structure. The results of any LCA are a function of many factors, including the model assumptions, data employed, and choices in study boundary and functional unit. The context of this study should be considered when interpreting and applying the information presented in this report.
VIII. References


National Renewable Energy Laboratory, “U.S. Lifecycle Inventory Database” (http://www.nrel.gov/lci [July 2010].)


Swiss Center for Life Cycle Inventories. 2010. ecoinvent database v2.2 (http://www.ecoinvent.org/home [2010].)


IX. Appendices

APPENDIX A: Materials and Energy Inputs

Please refer to associated Excel file.

APPENDIX B: Assumptions

Please refer to associated Excel file.

Appendix C: Energy Technologies

This section provides further context for the electricity grid sensitivity analysis conducted in this study, as well as a comparison of the types of energy—electricity and natural gas combustion—used by the buildings in this study.

Electricity grid sensitivity analysis

The economic and temporal dynamics of electricity markets in North America are complex, as described by Weber (2010), and the exact grid mix generating the electrons reaching a consumer is never known. It is therefore important to assess the influence of grid mix assumptions on the results of this study. This is conducted through a sensitivity test using the average national U.S. grid mix, as defined by the Energy Information Administration (EIA 2010), in place of the regional mixes for all climate zones. The mix is presented in TABLE 17.

TABLE 18. U.S. 2008 average national grid mix used in this study and based on the EPA’s eGRID2010 v1.0 (EPA 2008).

<table>
<thead>
<tr>
<th>Energy technology</th>
<th>Contribution to 2008 U.S. average national grid mix (%)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>48.9</td>
</tr>
<tr>
<td>Oil</td>
<td>1.59</td>
</tr>
<tr>
<td>Gas</td>
<td>21.9</td>
</tr>
<tr>
<td>Nuclear</td>
<td>19.6</td>
</tr>
<tr>
<td>Hydro</td>
<td>5.84</td>
</tr>
<tr>
<td>Biomass</td>
<td>1.32</td>
</tr>
<tr>
<td>Wind</td>
<td>0.836</td>
</tr>
<tr>
<td>Solar</td>
<td>0.0148</td>
</tr>
</tbody>
</table>

*Columns may not sum to 100% due to rounding errors.
Conservative grid mix

Regional grid mixes that contain a conservatively increasing quantity of renewables are assembled based on EIA predictions for national grid change from 2010 through 2035 (EIA 2010). Figure 34 shows a summary of these trends. To arrive at changes in the regional grids, growth rates for each electricity source found in the national grid are applied to the regional grid mix electricity sources. Beyond 2035, the grid mixes remain constant at the 2035 profiles.

In the national EIA data, renewables are lumped into one category and must be unpacked for each region. The contribution of each renewable (i.e., hydropower, biomass, wind, and solar) to this renewables category is assumed to maintain its 2007 eGRID ratio.

Table 19 displays the 75-year grid mixes for the conservative scenario. This is the average mix of the grid over the course of 75 years, which is calculated from the annual grid mix estimated using the EIA projections.

Figure 36. Summarized predictions for annual average U.S. grid mix from 2008-2035 reported by the Energy Information Administration (EIA 2010), excluding electricity imports.
TABLE 19. Seventy-five year conservative U.S. regional grid mixes based on the EPA’s eGRID2010 v1.0 (EPA 2008) and EIA’s grid mix projections through 2035.

<table>
<thead>
<tr>
<th>Energy technology</th>
<th>Chicago (RFC)</th>
<th>Portland &amp; Phoenix (WECC)</th>
<th>Atlanta (SERC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>63.1</td>
<td>26.0</td>
<td>54.6</td>
</tr>
<tr>
<td>Oil</td>
<td>0.512</td>
<td>0.348</td>
<td>0.778</td>
</tr>
<tr>
<td>Gas</td>
<td>6.95</td>
<td>29.3</td>
<td>14.7</td>
</tr>
<tr>
<td>Nuclear</td>
<td>27.3</td>
<td>8.70</td>
<td>24.7</td>
</tr>
<tr>
<td>Hydro</td>
<td>0.846</td>
<td>31.6</td>
<td>2.57</td>
</tr>
<tr>
<td>Biomass</td>
<td>1.08</td>
<td>1.61</td>
<td>2.68</td>
</tr>
<tr>
<td>Wind</td>
<td>0.217</td>
<td>2.36</td>
<td>0.0079</td>
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<tr>
<td>Solar</td>
<td>0.00</td>
<td>0.114</td>
<td>0.00</td>
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</tbody>
</table>

*Columns may not sum to 100% due to rounding errors.

Progressive mix

Grid mixes comprised of a progressively-increasing quantity of renewables are constructed based on a recent WWF report and an accompanying Ecofys report that offers an approach to eliminating the use of fossil fuels across the globe by 2050 (WWF 2011). In this scenario, total electricity consumption decreases 15% worldwide by 2050 as well. Beyond 2050, it is assumed that the electricity grid mixes remain constant at the 2050 proportions.

The WWF’s plan places great emphasis on solar and wind electricity and marginalizes the other sources. For regions currently using a large quantity of other renewables—such as the Pacific zone, which uses a large proportion of hydropower—it is assumed that there is also a shift between the types of renewables being used. While this shift may seem inappropriate for the region, it is impossible to predict how the mixes will change. For this reason, and for the purpose of consistency, the WWF emphasis on solar and wind is applied without consideration of these current regional mix specificities.
TABLE 20. Seventy-five year progressive U.S. regional grid mixes based on the EPA’s eGRID2010 v1.0 (EPA 2008) and the WWF’s proposal to achieve 100% renewables by 2050.

<table>
<thead>
<tr>
<th>Energy technology</th>
<th>Chicago (RFC)</th>
<th>Portland &amp; Phoenix (WECC)</th>
<th>Atlanta (SERC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>18.7</td>
<td>8.33</td>
<td>16.5</td>
</tr>
<tr>
<td>Oil</td>
<td>0.157</td>
<td>0.116</td>
<td>0.243</td>
</tr>
<tr>
<td>Gas</td>
<td>1.90</td>
<td>8.67</td>
<td>4.08</td>
</tr>
<tr>
<td>Nuclear</td>
<td>7.69</td>
<td>2.66</td>
<td>7.08</td>
</tr>
<tr>
<td>Hydro</td>
<td>9.98</td>
<td>16.5</td>
<td>10.3</td>
</tr>
<tr>
<td>Biomass</td>
<td>2.86</td>
<td>3.05</td>
<td>3.16</td>
</tr>
<tr>
<td>Wind</td>
<td>21.3</td>
<td>22.3</td>
<td>21.2</td>
</tr>
<tr>
<td>Solar</td>
<td>37.4</td>
<td>38.4</td>
<td>37.4</td>
</tr>
</tbody>
</table>

*Columns may not sum to 100% due to rounding errors.

**Impacts of energy technologies**

It is necessary to consider the relative impacts of the various technologies in order to fully understand the possibility of increased impact using a grid mix comprised of a greater proportion of renewable energy technologies. Figure 37 presents the impacts of several technologies relative to coal technology impacts. While the intent here is not to conduct a robust LCA around energy technologies, this analysis begins to demonstrate that trade-offs indeed exist between the technologies.
Impacts of electricity versus natural gas

The energy used by buildings is typically in the form of electricity and/or natural gas. In this study, the buildings use a combination; natural gas is assumed to be used for space and water heating, while electricity powers all other demands (i.e., plug loads). Interpreting some results of this study requires an understanding of the relative impacts of electricity and natural gas as they are used by a building during its operation. Figure 36 depicts the environmental impacts of heating space or water (with natural gas) and of using electricity. Similar to Figure, the purpose of displaying this information is to gain a sense for the relative impacts of each form of energy, not to conduct a rigorous analysis. Under this caveat, it is apparent that on the basis of 1 MJ of heat consumed, electricity is more impactful in every impact category, barring Ozone depletion. Further, the RFC zone (Chicago) is most impactful in the majority of indicators, generally followed by the SERC (Atlanta) and finally the WECC (the Portland and Phoenix scenarios).
FIGURE 38. Impacts of electricity use and natural gas use (combustion for heating) as a percent of the most impactful. Calculations are performed on the basis of 1 MJ of energy consumed.
APPENDIX D: Energy performance scenario analysis

This section provides additional information regarding the energy improvement measures incorporated in each building for the NC and RR scenarios.

Once the Base Case energy performance for each building type is established, a set of EEMs is devised to represent a building for each building type that would perform to the Base Case scenarios and one that would exceed this by approximately 30%. These recommended EEMs are derived from energy code prescriptive requirements, energy performance guides and professional experience. It is understood that many factors influence building performance including the design approach, microclimates, building orientation, massing, installation, operations practices and occupant behavior. These factors are assumed to be the same for both the NC and RR buildings and are therefore been excluded from this study. Thus, it is assumed that a set of EEMs selected from a list of 20-25 EEMs, appropriately designed, installed and maintained could deliver the energy efficiency improvements assumed in this study. This approach then allows the quantification of the materials inputs for all of the identified EEMs and inclusion of them in the LCA model.

Commercial Office

The following information applies to the Commercial Office and Warehouse-to-Commercial Office scenarios.

<table>
<thead>
<tr>
<th>Region</th>
<th>Pre-EEM</th>
<th>Base Case</th>
<th>Advanced</th>
</tr>
</thead>
<tbody>
<tr>
<td>Portland</td>
<td>70</td>
<td>70</td>
<td>53</td>
</tr>
<tr>
<td>Phoenix</td>
<td>71</td>
<td>71</td>
<td>50</td>
</tr>
<tr>
<td>Atlanta</td>
<td>76</td>
<td>76</td>
<td>57</td>
</tr>
<tr>
<td>Chicago</td>
<td>93</td>
<td>93</td>
<td>74</td>
</tr>
</tbody>
</table>

TABLE 22. EEMs applied for each scenario of the Commercial Office energy performance analysis.

<table>
<thead>
<tr>
<th>Energy Efficiency Measure (EEM)</th>
<th>Pre-EEM</th>
<th>Base Case analysis</th>
<th>Advanced</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lighting/Daylighting</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Building Lighting Power Density 0.8 watt/sf</td>
<td>RR</td>
<td>NC</td>
<td></td>
</tr>
<tr>
<td>Night Sweep/Occupancy Sensors</td>
<td>RR</td>
<td>NC, WH*</td>
<td></td>
</tr>
<tr>
<td>Building Lighting Power Density 0.85 watt/sf</td>
<td></td>
<td>WH</td>
<td></td>
</tr>
<tr>
<td>Office Lighting Power Density 0.8 watt/sf</td>
<td></td>
<td>WH</td>
<td></td>
</tr>
<tr>
<td>Daylight Dimming Controls</td>
<td></td>
<td>WH</td>
<td></td>
</tr>
<tr>
<td>HVAC</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Demand Control Ventilation (DCV)</td>
<td></td>
<td>RR, NC</td>
<td></td>
</tr>
<tr>
<td>Variable Frequency Drive (VFD) HVAC Motors</td>
<td>NC, WH</td>
<td>RR</td>
<td></td>
</tr>
<tr>
<td>Chilled Beams</td>
<td></td>
<td>RR, NC</td>
<td></td>
</tr>
<tr>
<td>Boiler 90%+ Minimum Efficiency</td>
<td>NC, WH</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Economizer Control</td>
<td>NC</td>
<td>RR</td>
<td></td>
</tr>
<tr>
<td>Heat Recovery of Exhaust Flow</td>
<td></td>
<td>RR, NC, WH</td>
<td></td>
</tr>
<tr>
<td>Envelope</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R-20 Roof Insulation</td>
<td>RR, NC, WH</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R-13 Wall Insulation</td>
<td>RR, NC, WH</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R-19 Wall Insulation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Infiltration Reduction- Caulking</td>
<td></td>
<td>RR</td>
<td></td>
</tr>
<tr>
<td>Infiltration 0.20 air change/hour</td>
<td>RR, NC</td>
<td>WH</td>
<td></td>
</tr>
<tr>
<td>Glazing</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>U-0.32 or better</td>
<td>RR, NC, WH</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low-e Coated</td>
<td>RR, NC, WH</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water Heating</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gas heat with 90% efficiency</td>
<td>RR, NC</td>
<td>RR</td>
<td></td>
</tr>
<tr>
<td>Gas heat with 93% efficiency</td>
<td></td>
<td>WH</td>
<td></td>
</tr>
<tr>
<td>Solar Thermal Hot Water</td>
<td></td>
<td>WH</td>
<td></td>
</tr>
<tr>
<td>Hot Water Pipe Insulation</td>
<td></td>
<td>NC</td>
<td></td>
</tr>
</tbody>
</table>

*Warehouse conversion
**Multifamily Residence**

The following information refers to the Multifamily Residence and Warehouse-to-Multifamily Residence.

**TABLE 23.** Multifamily Residence and Warehouse-to-Multifamily Residence EUI assumed for each energy performance scenario across climate zones.

<table>
<thead>
<tr>
<th>Region</th>
<th>Base Case</th>
<th>Advanced</th>
</tr>
</thead>
<tbody>
<tr>
<td>Portland</td>
<td>63</td>
<td>41</td>
</tr>
<tr>
<td>Phoenix</td>
<td>50</td>
<td>29</td>
</tr>
<tr>
<td>Atlanta</td>
<td>53</td>
<td>32</td>
</tr>
<tr>
<td>Chicago</td>
<td>64</td>
<td>42</td>
</tr>
</tbody>
</table>
TABLE 24. EEMs applied for the Multifamily and Warehouse-to-Multifamily Residence energy performance analyses.

<table>
<thead>
<tr>
<th>Energy Efficiency Measure (EEM)</th>
<th>Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Base Case analysis</td>
</tr>
<tr>
<td><strong>Lighting/Daylighting</strong></td>
<td></td>
</tr>
<tr>
<td>50% of Fixtures Compact Fluorescent</td>
<td>NC, WH*</td>
</tr>
<tr>
<td>Corridors Lighting Power Density 0.5 watt/sf</td>
<td>WH</td>
</tr>
<tr>
<td>Occupancy Sensors in Corridors</td>
<td>WH</td>
</tr>
<tr>
<td><strong>HVAC</strong></td>
<td></td>
</tr>
<tr>
<td>Gas Boiler/Furnace 80% AFUE</td>
<td>RR</td>
</tr>
<tr>
<td>Gas Boiler/Furnace 90% AFUE</td>
<td>WH</td>
</tr>
<tr>
<td>Gas Boiler/Furnace 95% AFUE</td>
<td>RR, NC</td>
</tr>
<tr>
<td>Water Source Heat Pump 4.5 COP</td>
<td>RR, NC</td>
</tr>
<tr>
<td>Variable Frequency Drive (VFD) HVAC Motors</td>
<td>WH</td>
</tr>
<tr>
<td>Variable Refrigerant Flow Units 3.2 to 4.5 COP</td>
<td>WH</td>
</tr>
<tr>
<td>Energy Recovery Ventilator (ERV)</td>
<td>RR, NC, WH</td>
</tr>
<tr>
<td><strong>Envelope</strong></td>
<td></td>
</tr>
<tr>
<td>R-13 Wall Insulation</td>
<td>RR, NC, WH</td>
</tr>
<tr>
<td>R-19 Wall Insulation</td>
<td>RR</td>
</tr>
<tr>
<td>R-20 Roof Insulation</td>
<td>WH</td>
</tr>
<tr>
<td>Infiltration 0.35 air change/hour</td>
<td>NC</td>
</tr>
<tr>
<td><strong>Glazing</strong></td>
<td></td>
</tr>
<tr>
<td>Wood/Vinyl Windows U-0.54</td>
<td>RR</td>
</tr>
<tr>
<td>Energy Star Windows U-0.32 or better</td>
<td>RR, NC, WH</td>
</tr>
<tr>
<td>Low-e Coated</td>
<td>WH</td>
</tr>
<tr>
<td><strong>Water Heating</strong></td>
<td></td>
</tr>
<tr>
<td>Gas heat with 80% efficiency</td>
<td>NC</td>
</tr>
<tr>
<td>Solar Thermal Hot Water</td>
<td>WH</td>
</tr>
</tbody>
</table>

*Warehouse conversion
Single-family Residence

The following information describes the energy performance attributes of the Single-family Residence.

Table 25. Single-family home EUI assumed for each energy performance scenario across climate zones.

<table>
<thead>
<tr>
<th>Region</th>
<th>Base Case</th>
<th>Advanced</th>
</tr>
</thead>
<tbody>
<tr>
<td>Portland</td>
<td>46</td>
<td>39</td>
</tr>
<tr>
<td>Phoenix</td>
<td>36</td>
<td>29</td>
</tr>
<tr>
<td>Atlanta</td>
<td>39</td>
<td>32</td>
</tr>
<tr>
<td>Chicago</td>
<td>47</td>
<td>40</td>
</tr>
</tbody>
</table>
### TABLE 26. EEMs applied for the Single-family Residence energy performance analysis.

<table>
<thead>
<tr>
<th>Energy Efficiency Measure (EEM)</th>
<th>Scenario</th>
<th>Base Case analysis</th>
<th>Advanced</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Lighting/Daylighting</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interior Lighting Power Density &lt; 1 watt/sf</td>
<td></td>
<td>NC</td>
<td></td>
</tr>
<tr>
<td>Lighting Controls</td>
<td></td>
<td>NC</td>
<td></td>
</tr>
<tr>
<td>Efficient Exterior Lighting (CFL/LED)</td>
<td></td>
<td>NC</td>
<td></td>
</tr>
<tr>
<td>Skylights</td>
<td></td>
<td>NC</td>
<td></td>
</tr>
<tr>
<td><strong>HVAC</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Programmable Thermostats</td>
<td></td>
<td>NC</td>
<td></td>
</tr>
<tr>
<td>Gas Heating Minimum Efficiency 92%</td>
<td></td>
<td>RR, NC</td>
<td></td>
</tr>
<tr>
<td>Cooling Efficiency SEER 14+</td>
<td></td>
<td>RR, NC</td>
<td></td>
</tr>
<tr>
<td>Energy Recovery Ventilator</td>
<td></td>
<td>NC</td>
<td></td>
</tr>
<tr>
<td>Seal/Insulate Ductwork</td>
<td></td>
<td>RR, NC</td>
<td></td>
</tr>
<tr>
<td>Direct/Indirect Evaporative Cooling</td>
<td></td>
<td>NC</td>
<td></td>
</tr>
<tr>
<td>Ground Source Heat Pump</td>
<td></td>
<td>NC</td>
<td></td>
</tr>
<tr>
<td>Hydronic Radiant Heating</td>
<td></td>
<td>NC</td>
<td></td>
</tr>
<tr>
<td><strong>Envelope</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R-30 Roof/Attic Insulation</td>
<td></td>
<td>RR, NC</td>
<td></td>
</tr>
<tr>
<td>R-13 Wall Insulation</td>
<td></td>
<td>RR, NC</td>
<td></td>
</tr>
<tr>
<td>R-19 Wall Insulation (includes wall furring)</td>
<td></td>
<td>NC</td>
<td>RR</td>
</tr>
<tr>
<td>Infiltration Reduction- Sealing</td>
<td></td>
<td>RR, NC</td>
<td></td>
</tr>
<tr>
<td>Insulated Door and Window Frames</td>
<td></td>
<td>NC</td>
<td>RR</td>
</tr>
<tr>
<td><strong>Glazing</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>U-0.32 or Better</td>
<td></td>
<td>RR, NC</td>
<td></td>
</tr>
<tr>
<td>Low-e Solar Film (SE and SW regions only)</td>
<td></td>
<td>NC</td>
<td>RR</td>
</tr>
<tr>
<td><strong>Water Heating</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gas heat with 90%+ efficiency</td>
<td></td>
<td>RR, NC</td>
<td></td>
</tr>
<tr>
<td>Instantaneous Hot Water</td>
<td></td>
<td>NC</td>
<td></td>
</tr>
<tr>
<td>Hot Water Pipe Insulation</td>
<td></td>
<td>NC</td>
<td></td>
</tr>
<tr>
<td>Hot Water Recirculation System</td>
<td></td>
<td>RR, NC</td>
<td></td>
</tr>
<tr>
<td>Solar Thermal System</td>
<td></td>
<td>NC</td>
<td></td>
</tr>
</tbody>
</table>
Elementary School

The following information describes the energy performance attributes of the Elementary School.

<table>
<thead>
<tr>
<th>Region</th>
<th>Base Case</th>
<th>Advanced</th>
</tr>
</thead>
<tbody>
<tr>
<td>Portland</td>
<td>60</td>
<td>49</td>
</tr>
<tr>
<td>Phoenix</td>
<td>61</td>
<td>45</td>
</tr>
<tr>
<td>Atlanta</td>
<td>65</td>
<td>51</td>
</tr>
<tr>
<td>Chicago</td>
<td>80</td>
<td>67</td>
</tr>
</tbody>
</table>

TABLE 27. Elementary School EUI assumed for each energy performance scenario across climate zones.
TABLE 28. EEMs applied for each scenario of the Elementary School energy performance analysis.

<table>
<thead>
<tr>
<th>Energy Efficiency Measure (EEM)</th>
<th>Base Case analysis</th>
<th>Advanced</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Lighting/Daylighting</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Night Sweep/Occupancy Sensors</td>
<td>RR, NC</td>
<td></td>
</tr>
<tr>
<td>Daylight Dimming Controls in Classrooms</td>
<td></td>
<td>RR</td>
</tr>
<tr>
<td>Classroom Lighting Power Density 1.4 watt/sf</td>
<td>NC</td>
<td></td>
</tr>
<tr>
<td>Office Lighting Power Density 1.1 watt/sf</td>
<td>NC</td>
<td></td>
</tr>
<tr>
<td><strong>HVAC</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Variable Frequency Drive (VFD) HVAC Motors</td>
<td>NC</td>
<td></td>
</tr>
<tr>
<td>Demand Control Ventilation (DCV) in Classrooms and Assembly Spaces</td>
<td></td>
<td>RR</td>
</tr>
<tr>
<td>Chilled Beams in Classrooms</td>
<td>RR, NC</td>
<td></td>
</tr>
<tr>
<td>Boiler 90%+ Minimum Efficiency</td>
<td>NC</td>
<td>RR</td>
</tr>
<tr>
<td>Infiltration 0.7 air change/hour</td>
<td>NC</td>
<td>RR</td>
</tr>
<tr>
<td>Energy Recovery Ventilator (ERV)</td>
<td></td>
<td>RR</td>
</tr>
<tr>
<td>Variable Flow Kitchen Exhaust/MUA System</td>
<td>RR, NC</td>
<td></td>
</tr>
<tr>
<td><strong>Envelope</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R-13 Wall Insulation</td>
<td>RR, NC</td>
<td></td>
</tr>
<tr>
<td>R-20 Roof Insulation</td>
<td>NC</td>
<td></td>
</tr>
<tr>
<td>Infiltration 0.35 air change/hour</td>
<td></td>
<td>RR</td>
</tr>
<tr>
<td><strong>Glazing</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy Star U-0.32 or better</td>
<td>RR, NC</td>
<td></td>
</tr>
<tr>
<td>Low-e Coated</td>
<td>RR, NC</td>
<td></td>
</tr>
<tr>
<td><strong>Water Heating</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gas heat with 93% efficiency</td>
<td>RR, NC</td>
<td></td>
</tr>
<tr>
<td>Solar Thermal Hot Water</td>
<td></td>
<td>RR, NC</td>
</tr>
</tbody>
</table>
Urban Village

The following information describes the energy performance attributes of the Urban Village.

TABLE 29. Urban Village EUI assumed for each energy performance scenario across climate zones.

<table>
<thead>
<tr>
<th>Region</th>
<th>Base Case</th>
<th>Advanced</th>
</tr>
</thead>
<tbody>
<tr>
<td>Portland</td>
<td>71</td>
<td>53</td>
</tr>
<tr>
<td>Phoenix</td>
<td>72</td>
<td>52</td>
</tr>
<tr>
<td>Atlanta</td>
<td>76</td>
<td>57</td>
</tr>
<tr>
<td>Chicago</td>
<td>94</td>
<td>75</td>
</tr>
</tbody>
</table>
TABLE 30. EEMs applied for each scenario of the Urban Village energy performance analysis.

<table>
<thead>
<tr>
<th>Energy Efficiency Measure (EEM)</th>
<th>Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Base Case analysis</td>
</tr>
<tr>
<td><strong>Lighting/Daylighting</strong></td>
<td></td>
</tr>
<tr>
<td>Occupancy Sensors</td>
<td>RR, NC</td>
</tr>
<tr>
<td>Daylight Dimming Controls</td>
<td>NC</td>
</tr>
<tr>
<td>Retail Lighting Power Density 1.4 watt/sf</td>
<td>NC</td>
</tr>
<tr>
<td>Office Lighting Power Density 1.1 watt/sf</td>
<td>NC</td>
</tr>
<tr>
<td><strong>HVAC</strong></td>
<td></td>
</tr>
<tr>
<td>Variable Frequency Drive HVAC Motors</td>
<td>RR, NC</td>
</tr>
<tr>
<td>Gas Boiler/Furnace 90% AFUE</td>
<td>RR</td>
</tr>
<tr>
<td>Chilled Beams in Offices</td>
<td>RR, NC</td>
</tr>
<tr>
<td>Variable Refrigerant Flow Units 3.2 to 4.5 COP</td>
<td>RR, NC</td>
</tr>
<tr>
<td>Energy Recovery Ventilator (ERV)</td>
<td>RR</td>
</tr>
<tr>
<td>Infiltration 0.7 air change/hour</td>
<td>NC</td>
</tr>
<tr>
<td><strong>Envelope</strong></td>
<td></td>
</tr>
<tr>
<td>R-13 Wall Insulation</td>
<td>NC</td>
</tr>
<tr>
<td>R-20 Roof Insulation</td>
<td>NC</td>
</tr>
<tr>
<td>Infiltration 0.35 air change/hour</td>
<td>RR</td>
</tr>
<tr>
<td><strong>Glazing</strong></td>
<td></td>
</tr>
<tr>
<td>Energy Star Windows U-0.32 or better</td>
<td>NC</td>
</tr>
<tr>
<td>Low-e Coated</td>
<td>NC</td>
</tr>
<tr>
<td><strong>Water Heating</strong></td>
<td></td>
</tr>
<tr>
<td>Solar Thermal Hot Water</td>
<td>RR, NC</td>
</tr>
</tbody>
</table>

APPENDIX E: Results

Please see associated Excel file.
APPENDIX F: Impact assessment indicators

This study calculates midpoint and endpoint indicators, classes of metrics that differ by their intended purpose. Midpoints aim at characterizing processes caused by fluxes of substances to and from the natural environment, while the objective of an endpoint is to better illustrate the overall effects of these processes in the context of societal value—human health, ecosystems, and resources.

Midpoint indicators are the physical, chemical, and biological processes that can be triggered by the consumption or emission of a particular substance. For example, ozone depletion caused by the release of, among other compounds, chlorofluorocarbons (CFC's) is one midpoint indicator in the IMPACT 2002+ system. This type of result is generally calculated from the inventory of flows into and out of the environment, such as consumption of crude oil or emissions of methane (CH₄).

Endpoint indicators attempt to quantify damage to human health or the environment, generally as a result of the midpoints. For instance, the Human health endpoint indicator in IMPACT 2002+ attempts to estimate the years of useful life lost due to all the human health impairments that can be quantified with the methodology. Similarly, the Ecosystem quality indicator reports on the amount of species loss that might occur. These calculations are performed using scientifically-derived algorithms that require relevant midpoints as data inputs.

It should be noted that while “midpoint” and “endpoint” are common terms throughout the science of LCA, the specific indicators and the algorithms used to calculate the indicators can vary—sometimes significantly—between impact assessment methods.

An intent of this report is not to teach the impact assessment methodology applied, but it is important that those who use the results of this study understand the indicators. Brief descriptions of the indicators are provided here with a focus on the endpoints and Climate change.

Aquatic Acidification
The reduction of pH in natural water bodies through the release of acidifying substances to air, land, or water.
Carcinogens/Carcinogenic Toxicity

Chemicals which are believed to contribute to the incidence of human cancers through release into the environment and subsequent human exposure; contributes to the IMPACT 2002+ Human Toxicity midpoint.

Climate change

Climate change is calculated based on the Intergovernmental Panel on Climate change’s 100-year weightings of the global warming potential of various substances (IPCC, 2007). Substances known to contribute to global warming are weighted based on an identified global warming potential expressed in kilograms of carbon dioxide equivalents (kgCO2e). Because the uptake and emission of CO2 from biological sources (termed biogenic CO2) can lead to misinterpretations of results, it is not unusual to omit biogenic CO2 from consideration when evaluating global warming potentials. Here, the recommendation of the PAS 2050 (BSI, 2008) product carbon footprinting guidance is followed; the uptake and emission of CO2 from biological systems is tracked separately from the other CO2 and not reported. The emissions of other greenhouse gasses from biological matter are corrected by subtracting the equivalent value for CO2 based on the carbon content of the gas. Additionally, the global warming potential (GWP) of all carbon-containing GHG’s is corrected to account for their degradation into CO2 over time. This is calculated using mass ratios of carbon and results in a slightly higher GWP for each of these substances as conventional (uncorrected) computations assume a GWP of zero (0) after degradation.

Ecosystem quality (endpoint)

The health of an ecosystem can be impaired by the release of substances that cause acidification, eutrophication, toxicity to wildlife, and land occupation, in addition to various other mechanisms. An evaluation of the overall impact of a system on ecosystem health is made by the Ecosystem quality endpoint IMPACT 2002+ methodology (Jolliet et al., 2003), in which substances are weighted based on their ability to cause each of a variety of damages to wildlife species. These impacts are measured in units of potentially disappearing fractions (PDFs), which relate to the likelihood of species loss. The calculation of Ecosystem quality ideally includes Aquatic acidification, Aquatic ecotoxicity, Aquatic eutrophication, Land occupation, Terrestrial acidification & nutrification, and Terrestrial ecotoxicity. It should be noted that this study employs IMPACT 2002+ v2 which does not include the midpoints Aquatic acidification or Aquatic eutrophication in the calculation of the endpoint due to a lack of a published, quantitative link between these midpoints and species disappearance.
Ecotoxicity
Harm to wildlife, including all types of flora and fauna, through toxic effects of environmental pollution.

Eutrophication
The process of nutrient enrichment (particularly of phosphorous and nitrogen) of a water body, which leads to algal growth, oxygen depletion, and potentially death of the water body.

Human health (endpoint)
Damage to Human health is caused by the release of substances that affect human beings through acute toxicity, cancer-based toxicity, respiratory effects, increases in UV radiation, and other processes. An evaluation of the overall impact of a system on human health is made following the human health endpoint in the IMPACT 2002+ methodology (Jolliet et al., 2003), in which substances are weighted based on their abilities to cause each of a variety of damages to human health. These impacts are measured in units of disability-adjusted life years (DALYs), which combine estimations of morbidity and mortality from a number of causes. The calculation of Human health includes the midpoints Human toxicity, Ozone depletion, Photochemical oxidation, and Respiratory effects.

Ionizing Radiation
Air- and waterborne radionuclides released into the environment in the nuclear fuel cycle, in phosphate rock extraction, in coal power plants, and in oil and gas extraction (Goedkoop and Spriensma 2000).

Land occupation
The impact of long-term occupation of land on ecosystems.

Mineral extraction
Decrease in mineral concentration due to extractions, translated into surplus energy (Goedkoop and Spriensma 2000).

Non-Carcinogenic toxicity
Chemicals whose release to the environment is believed to contribute to the incidence of human morbidity or mortality through chronic health effects other than cancer; contributes to the IMPACT 2002+ Human Toxicity midpoint.

Non-Renewable energy use
The consumption of fossil and nuclear resources excluding sources of renewable energy at all stages of the life cycle and in all upstream processes.

Photochemical oxidation
The creation of oxidizing compounds in the troposphere from environmental pollution (usually the release of nitrogen oxides and volatile organic compounds), also commonly called smog.
Ozone depletion
The decrease in ozone (O₃) in the stratosphere, where it serves to block UV rays from penetrating the atmosphere.

Resources (endpoint)
Resource depletion is caused when nonrenewable resources are consumed or when renewable resources are used at a rate greater than they can be renewed. Materials are weighted based on their abundance and difficulty to obtain. An evaluation of the overall impact of a system on resource depletion is made by the resources end-point in the IMPACT 2002+ methodology (Jolliet et al., 2003), which combines nonrenewable energy use with an estimate of the increased amount of energy that will be required to obtain an additional incremental amount of that substance from the earth based on the Ecoindicator 99 method. These impacts are measured in megajoules (MJ). The calculation of Resources includes the midpoints Non-renewable energy and Mineral extraction.

Respiratory effects
Results of releasing chemicals to the environment that cause acute harm to human respiratory systems and that may contribute to morbidity or mortality through these pathways.

Terrestrial acidification & nutrification
Change in nutrient level and acidity in soil caused by depositions of inorganic substances such as sulphates, nitrates and phosphates (Goedkoop and Spriensma 2000).

APPENDIX G: Glossary

Allocation/Allocation methodology: Partitioning the input or output flows of a process or product system between the product system under study and one or more other product systems (ISO 2006b)

Cradle-to-grave: LCA model which includes the whole product life cycle, i.e. all steps from raw material extraction to waste disposal (ISO 2006b)

Cut-off criteria: Specification of the amount of material or energy flow or the level of environmental significance associated with unit processes or product system to be excluded from a study (ISO 2006b)

End-of-life: In a typical cradle-to-gate assessment, the final stage of the life cycle in which materials are either sent to a final disposal option, such as landfill or incineration, or are recycled or otherwise managed for inclusion in another system. End-of-life typically includes any transport and processing of materials occurring after the end of the use phase of the life cycle.

Endpoint indicator: Attribute or aspect of natural environment, human health, or resources, identifying an environmental issue giving cause for concern (ISO 2006a)

Functional unit: Quantified performance of a product system for use as a reference unit (ISO 2006b)
**ISO 14040-series**: The series of published International Organization for Standardization (ISO) standards for conducting Life Cycle Assessment

**Life cycle**: Consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal (ISO 2006b)

**Life cycle assessment (LCA)**: Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle (ISO 2006b)

**Life cycle inventory analysis (LCI)**: Phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle (ISO 2006b)

**Life cycle impact assessment (LCIA)**: Phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product (ISO 2006b)

**Midpoint indicator**: Represents environmental issues of concern to which various flows or actions tabulated as LCI results contribute, involving common or similar processes (e.g. acidification, ionizing radiation) (Jolliet et al. 2003)

**Process**: Set of interrelated or interacting activities that transforms inputs into outputs (ISO 2006b)

**Reference flow**: Measure of the outputs from processes in a given product system required to fulfill the function expressed by the functional unit (ISO 2006b)

**Unit process**: Smallest element considered in the life cycle inventory analysis for which input and output data are quantified (ISO 2006b)

**Upstream emissions**: Indirect emissions from purchased or acquired goods and services, up to the point of receipt (IPCC 2007)
APPENDIX H: Critical review

This section provides the feedback offered by the critical review (in italics) conducted by Pascal Lesage, PhD at CIRAIG, a leading LCA research group housed at the University of Montréal’s École Polytechnique de Montréal. Also provided are responses to these comments. Dr. Lesage’s feedback is not intended to be a full ISO-compliant review. Note that a change was made to the Warehouse to Multi-family scenario after this review was conducted. The modification was described to Dr. Lesage in a memo to which he offered a response as an addendum to the initial review. Both the memo and response are provided in the second portion of this Appendix.

Appendix H.1: Principle review and responses

1 Introduction

REVIEWER COMMENT:

*NTHP has sponsored a study aimed at quantifying the potential environmental impacts of building rehabilitation and reuse (RR) versus demolishing and newly constructing (NC). The study was conducted in three phases: (I) screening-level LCA focusing on relative potential environmental impacts of NC versus RR for a K-12 school located in the U.S. Pacific climate zone; (II) development of methodology for conducting an LCA around several building types in four climate zones of the U.S.; and (III) a full LCA comparing NC and RR for each of the building types and climate zones. In November 2010, I conducted a first review on the Phase I report. The purpose of the report at hand is to provide comments on Phase III of the study (non-public version 1.0 distributed for feedback from NTHP and reviewers). This is not to be considered a formal critical review as per ISO 14044. No statement is provided on the plausibility of the actual values used in the LCA, especially for material requirements for different scenarios: this type of review extends beyond my field of competence. However, the report states clearly that these values were already reviewed by the building experts that are part of the team. The present review focused on LCA methodology and interpretation of the results. Finally, since it is not the aim of the study authors to produce a report that fully complies with the ISO 14044 requirements for third party reports used in comparative assertions, a list of elements that would missing for such compliance was not compiled. Note however that if the NTHP decides to go ahead with the diffusion of the study results, it would be important for missing elements to be integrated in the report and for a formal critical review to be carried out. The missing elements can be determined by comparing the present report with Sections 5.1-5.3 of ISO 14044.*

AUTHOR RESPONSE:

No comment from authors.

2 Functional unit

REVIEWER COMMENT:

*The functional equivalence between the studied buildings is one of the sensitive issues in this study, and the authors can be commended both for their normalization procedure that attempts to remove programmatic differences and for their discussion of the issue in Section 2.3 [Section II.C in final report].*
However, the functional unit used, “provide a square foot of usable interior space for a period of 75 years”, makes an implicit assumption that one square foot of NC building provides the same function as one square foot of RR building. It is unclear whether this implicit assumption is correct, e.g. whether a square foot of NC elementary school and a square foot of RR elementary school are indeed equivalent. If one looks at the schools that were chosen in the study, the NC offers 151 square feet per student while the RR offers 283 square feet per student (87% more). Without a discussion on trends in “service per square foot” for RR and NC, one is unable to know whether such a difference is due to the specific choice of building or due to a larger trend in RR vs. NC. Since this “intensity of service” issue is not addressed in the study, it is also not possible to know whether this observed difference drives some of the results that were obtained.

A functional unit based on the service rendered by the buildings (e.g. provide space for educational services for 1 student for one year for the elementary school) may have been more appropriate, and would necessarily have yielded very different results. This said, given that the project team included building sector experts that necessarily agreed with the choice of functional unit, it is possible that the building sector do in fact compare buildings on a “per square foot” basis regardless of how much service is offered per unit surface area. In this case, the functional unit could be just fine; however, since the objective of LCA is to evaluate the actual function provided by products (and not the products themselves), it would be a good addition to the report to at least discuss this issue.

AUTHOR RESPONSE:

The intent of this study is to select buildings that are as comparable programmatically and operationally similar as possible. However, since real buildings are used to represent the structures evaluated here, some differences inevitably exist between the NC and RR case studies. Thus, a normalization process is undertaken to achieve a realistic yet apples-to-apples comparison. This included removing dissimilar programmatic elements, assuming similar operating schedules, and other exercises, as discussed in this report. After undergoing this normalization process, it is assumed that the structures selected for a given typology exhibit the same occupancy rates. Additional explanation has been included in the text to clarify and bolster the assumptions of this study.

REVIEWER COMMENT:

The initial comment questioned specifically the validity of the assumption that the structures selected for a given typology exhibit the same occupancy rates, and used the elementary school as an example where the observed "service per square foot" was drastically different between RR and NC. The response and the changes in the report simply restate that this is an assumption, but do not explore or discuss its validity in the field (are there known differences in "service per square foot" between old and new construction) nor its incidence (if such a systematic difference is indeed possible, then how would this affect the conclusions presented in the study? Unless it is evident to all in the building sector that there are no trends in "service per square foot", this issue should be clearly discussed when introducing the functional unit and again in the interpretation (limitations) of the study. Also, the new version of the report no longer contains the number of students in elementary schools, hence hiding the difference in occupancy per square foot from the reader.
AUTHOR RESPONSE:
Indeed occupancy is an important consideration when identifying an appropriate functional unit for a building as it directly influences the amount of energy, among other resources, used by the structure. Basing the analysis on actual occupant density would certainly produce different results, but this approach is considered to be an inappropriate choice due to the variability of occupant density over space and time. To be clear, “occupant density” in this study refers to the actual number of people using the building on a given day. It does not refer to the code-prescribed allowances for the number of persons per square foot.

The consideration of occupant density was raised after conducting the pilot analysis in discussions around functional unit (See Appendix I). It was determined by the team’s building industry experts that computing results on the basis of a square foot of space is an appropriate and more useful way of analyzing the buildings than on the basis of occupant density. The reasoning behind this was three-fold. First, area (i.e., per square foot) is a common metric in the building industry and would be most comprehensible and useful to readers. Further, this metric allows for the projection of results across the building stock in a straightforward manner. Finally, and perhaps most importantly, area is a temporally and geographically consistent measurement; occupant density, on the other hand, changes with time and location due to a variety of economic and social factors. For instance, an urban school may be more crowded than if the building is located in a rural district, but the structure itself remain constant and offers the same service. Because social and economic factors are beyond the scope of this study, occupant density is not a variable in this analysis and is assumed the same between NC and RR buildings. Further, by making this assumption, it is implied that the occupant density applied is within the legal (code) requirements for occupancy rates of each building (NC and RR).

The values that were provided in the initial report describe the current number of people on average occupying the schools on a daily basis; they are not the occupancy rates prescribed by code for the buildings. Thus, this information was removed to avoid confusion.

3 System definition and inventory modeling
3.1 Distinction between types of differentiators

REVIEWER COMMENT:
As was mentioned in the initial review of the screening LCA, it is important to carefully distinguish between (1) differences that are a result of choosing one type of option over the other and (2) differences
that are incidental to the case studies. The normalization procedure that the authors have used eliminates some of the incidental differences. However, there is no discussion in the report on whether e.g. glazing ratios and the nature of building materials for the compared scenarios are strictly specific to the buildings retained for the study or whether they are generalizable to all of RR or NC. Since general conclusions are drawn from the specific evaluations, an evaluation (or at least an educated discussion) of what is actually generalizable is required for appropriate interpretation of the results.

AUTHOR RESPONSE:
While the analysis of materials (i.e., sections entitled Materials contributions) is intended to dive into the differences seen between NC and RR, some discussion when presenting the case study buildings is warranted. Information has been added in the background information to expand on this topic for each building.

REVIEWER COMMENT:
The analysis of materials is included helps in seeing the differences between NC and RR, but does not necessarily help in understanding if these differences are incidental to the buildings chosen or generalizable (e.g. are there trends in glazing ratios that are known to be generalizable and observed in the case studies). While it is understood that if this information on all materials were available in quantitative form, it would have been possible to bypass the use of case studies, a discussions based on the collective experience of the team members would have been useful. Note that if Section 2.2 [Section II.B in final report] (description of the buildings) is what is meant by "background information", then I was unable to find a direct discussion of the point I brought up.

AUTHOR RESPONSE:
The buildings selected in this study are believed to represent structures that are common across the United States and especially within the climate zone in which they in reality exist and for the period in which they are constructed. However, it is recognized that different design features are as or more common in different climate zones. The results of this study should be applied in consideration of the buildings’ designs. This explanation is now provided in Section II.B, and the limitation is noted in Section VI.

3.2 Allocation methodology

REVIEWER COMMENT:
The choice of what is sometimes called “end-of-life recycling” approach for dealing with recycled materials is clearly justified in the report, and the assumptions that this approach relies on (notably that the recycled material markets are generally limited by supply) are presented. Although the choice of allocation methodology is not contested, the following would make the study stronger:
• It would be useful to have a list of markets where the authors feel this assumption may not be representative, and to later discuss if the allocation method chosen for these building materials drives some of the observed results;

• A column in Table B5 indicating what is displaced when each material is recycled would increase report transparency, especially given that some building materials will be “downcycled”, e.g. concrete can be reused as aggregates but not as concrete.

• ISO 14044 states that “Whenever several alternative allocation procedures seem applicable, a sensitivity analysis shall be conducted to illustrate the consequences of the departure from the selected approach”. This was not done in this study.

Note also that:

• While it is true that system expansion is a process that can lead to “widening of systems can occur indefinitely if not curtailed in some way”, this is normally not considered a problem since each successive expansion is associated with an ever-diminishing amount of products and one can stop the process once the study results have become stable (usually very quickly).

• The use of economic data and models to help inform what happens when an additional amount of material is recycled can provide help make more reliable assumptions, but one cannot say that it allows one to “precisely assign an amount of impact or benefit to the systems donating or receiving a material”.

AUTHOR RESPONSE:

A sensitivity test on the end-of-life allocation methodology was not elected to be done due to an expectation that the currently selected method (avoided burden) is a conservative approach in this case, favoring as much as is possible the New Construction scenarios. The reason for this assumption is that the New Construction scenarios generally contain a large amount of material, therefore sending more material to beneficial end-of-life fates. The avoided burden approach therefore assigns a maximal benefit to the New Construction scenarios based on this distinction and any allocation assigning less than the entire benefit of recycling to the material donating system would further disadvantage the New Construction scenarios. The building assemblies include relatively minimal recycled content in comparison to the amount assumed to be recycled or sent to energy recovery.

REVIEWER COMMENT:

The response explains well why the method was chosen and why no sensitivity analysis was carried out. Since the study does not aim at being completely compliant with the ISO 14044 standard, eschewing the sensitivity analysis is fine. I was happy to see a column had been added to what is now Table B5.

3.3 Material input modeling

REVIEWER COMMENT:

The report itself provides almost no information on how the materials take-off lists were quantified, and Appendix A provides a detailed list but is not accompanied with text that would help navigate the numbers. At the very least, explanation needs to be included on the process for developing baseline RR scenarios that are different from what actually took place. One only learns in Section 2.7.2 [Section II.G]
that the RR scenarios included an energy package (“Thus, the energy performance package added by the project team (for the baseline analysis) is simply removed.”).

AUTHOR RESPONSE:
Tables in Appendices A and B have been expanded to include additional resolution regarding how building products are modeled during production and end-of-life.

REVIEWER COMMENT:
The added resolution will help readers understand the model.

3.4 Energy use

REVIEWER COMMENT:
The rational for using the EIA’s average EUI data rather than building-specific or modeled energy performance is well explained in the study. However, it is not clear (to me) why one can assume that a NC building and a RR building have an equal probability to be associated with energy consumptions equal to the average EUI. The assumption is backed in the report with the following statement: “According to the New Building’s Institute’s Energy Performance of LEED for New Construction Buildings report, modeled baseline EUIs for buildings seeking LEED certification are approximately equal to CBECs data on average building energy use (NBI 2008). Therefore, for the purposes of this study it is assumed that the new construction building meeting a regional code baseline is, on average, predicted to perform as well as a similar existing building in the same locale.” It is unclear to me how this addresses the question of potential differences in energy efficiency in NC and RR buildings.

AUTHOR RESPONSE:
Additional explanation and supporting information has been included in Section 0 regarding the assumption that NC and RR buildings can exhibit the same operating energy performance.

REVIEWER COMMENT:
The additional explanation is clear and sufficient.

3.5 Exclusion of off-gassing

REVIEWER COMMENT:
It is true that data on off-gassing of building materials are hard to find and that their inclusion in LCA is not commonplace, and so their exclusion seems justified. However, since the amounts of new building materials will be different between NC and RR, it would be helpful, if possible, to discuss this issue qualitatively, noting directionally whether NC or RR would typically be associated with more off-gassing impacts.
AUTHOR RESPONSE:
Additional discussion has been added in Section VI to explore the implications of excluding (or including) materials off-gassing.

REVIEWER COMMENT:
The additional discussion is clear and relevant.

4 LCIA
REVIEWER COMMENT:
The authors can be commended for their extremely detailed walkthrough of results in Section 4.1 [Section IV in final report]. The report would however be stronger if there was some mention of the significance of the differences observed between scenarios or, in other words, what level of difference is required in order for one to be able to state that they are significant, per impact category. For example, terrestrial ecotoxicity impacts are known to be extremely uncertain, and that differences of approximately two to three orders of magnitude are required to be able to state with any confidence that scenarios are significantly different. The differences found in this report are much lower than that.

A justification for using a European LCIA method in the context of a U.S. focused study would be welcome.

Note also that the report states that the Mineral extraction impact category “is computed based on the quantity of resources extracted from the biosphere in relation to what is considered to be available and the amount of energy required to extract the remaining minerals”. In fact, the indicator (originally taken from the models developed for the EcoIndicator 99 methodology) does not consider what is available, only long-term trends of lowering resource quality.

AUTHOR RESPONSE:
While we would agree that the uncertainty in some impact categories, such as Terrestrial ecotoxicity, can range into the level of one or more orders of magnitude, we strongly disagree that this necessitates a difference of such a magnitude in average results to be able to state that scenarios are significantly different. When considering the confidence in a comparison, it is our certainty about what is different between scenarios that is of concern rather than our certainty regarding the characterization of the scenarios as a whole. In many cases, systems under comparison are characterized by much of the same data and assumptions. Uncertainty in these data and assumptions can therefore be correlated and in effect cancel out. This allows us to be able to often have higher confidence in comparative results than we do in absolute results. For example, consider the simple case of a child’s rubber ball. LCA may only

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allow us to estimate the damage producing this ball did to survival of species due to toxic releases within only a factor of 100 of the true impact. Does this imply that if we compare that ball to one that is identical other than being 50 times larger that we should have some doubt that the larger ball caused more harm to species in its production? The reason that makes no sense is that the balls are made of the same material and regardless of what the impact of producing that material is, we know that more material equals more impact. Similarly, in the present case, we are comparing buildings of a similar material composition and supplied with similar energy sources. It is therefore quite feasible that a difference of much less than our level of confidence in the absolute results might be sufficient to be believable. With significant effort, it would be feasible to make a more systematic and quantitative estimate of whether the differences between the results shown for the scenarios here deserve our confidence. However, such a comparison has not been able to have been made under the scope of the present project. Lacking that, we have opted not to give the audience specific guidance on interpreting certainty based on a proportion of difference to absolute results because we feel it is unreliable and misleading to make such judgments based on a “rule-of-thumb.”

Justification for selecting a European database has been added to II.F Data collection.

The definition of Mineral extraction has been corrected throughout the report.

REVIEWER COMMENT:

I completely agree with the authors that, in simple cases where the difference between explored scenarios are strictly due to differences in amounts of materials rather than differences in the nature of these materials, the uncertainty associated with different characterization models is irrelevant. However, in cases (such as this one) where the differences between scenarios are not strictly due to a change in amount of materials, then the issue cannot be offhandedly ignored. Indeed, while it is true that the scenarios use the same materials, the proportion between the amounts of materials for the different options do change, and the issue that was brought up in the review report remains entirely relevant.

To use their child rubber ball example, let’s suppose that a second material (say a steel core for weight) was added to the rubber ball. Suppose further that the emission profile associated with rubber production and steel production are completely different. Finally, suppose ball A has 50 times less rubber but 10 times more steel. In this case, the interpretation of the results would definitely need to account for the uncertainty associated with the characterization factors since the emission profile, while being made up of the same elementary flows, would be very different.

Also, the authors state that they have “opted not to give the audience specific guidance on interpreting certainty based on a proportion of difference to absolute results because we feel it is unreliable and misleading to make such judgments based on a “rule-of-thumb.” While laudable to refrain from giving false or unwarranted guidance on how to interpret the results, the complete lack of guidance will
probably, in many cases, result in an inappropriate interpretation of the results, with very small differences regarded as meaningful.

No further comment (except that the author response should refer to the LCIA method, not the LCI data source).

No further comment.

AUTHOR RESPONSE:
Indeed, we agree very much with the understanding of uncertainty in these systems that you have presented here. The example of the ball was of course an over-simplification to make the distinction between the uncertainty in the underlying data, such as characterization factors, and the uncertainty in the project findings, which may be highly or minimally influenced by each of those underlying uncertainties. The crucial issue is to what extent the study’s results are determined by factors of high uncertainty, and it would indeed be helpful to see a thorough treatment of that question in the present context. We agree with the reviewer that the reader would benefit from some guidance in thinking about uncertainty in these results as they consider their level of confidence in the study findings. We have therefore added a discussion of this along with an example narrative interpretation to Section VI of the report. The focus in this added section is on informing the reader of important considerations to make regarding uncertainty, while avoiding oversimplifying the consideration of uncertainty by attempting to simply claim the results are sufficiently certain because above some threshold.

Thank you to the reviewer for catching the error in the comment. The response should have read as follows: Justification for selecting a European impact assessment method has been added to III.B Life cycle impact assessment.

5 Scenarios
REVIEWER COMMENT:
The report contains some very useful and well-executed sensitivity analyses. Notably, for building lifetime, the screening LCA review had mentioned that, because of the wording of the functional unit, longer building lifetimes translated in greater impacts per functional unit. The annualized impact graphics shown in Section 4.2.3 [Section V.C in final report] are very useful (and quite elegant) to show the advantages of greater building lifetime and are a great improvement over the sensitivity analysis graphs in the screening LCA that showed impacts summed over the entire lifetime. However, the interpretation of the sensitivity analysis makes the implicit assumption that, although the lifetime can be varied, it will always be equal between the NC and RR buildings. This assumption, which would not hold
if it could instead be assumed that e.g. RR buildings can be associated with longer lifetimes, should be stated.

Also, given the importance of energy use and the uncertainty associated with choosing an appropriate EUI, the report can be commended for including a sensitivity analysis looking specifically at energy use scenarios. However, it is not clear why the baseline and the “As-built” scenarios are not equal since the report states that for “As-built building scenarios, baselines are also drawn from CBECS averages”. If the baseline EUIs are averages taken from CBECS, why are they different for baseline and “as-built” scenarios? If the CBECS averages are differentiated by e.g. insulation, then this should be stated clearly in the report, and it should be explained why differentiated numbers were not used for the RR and NC scenarios. If they are not differentiated, then it should be explained why the baseline and “as-built” scenarios are not identical.

Finally, regarding the electricity grid mix scenario, the design is interesting and the interpretation adequate. However, the comparison of potential impacts of technologies, shown Figure 36, shows differences between technologies that I had not observed before. The following two figures, taken directly from a comparative analysis in SimaPro (ecoinvent 2.0, IMPACT 2002+), show very different results.
AUTHOR RESPONSE:
Additional discussion on the lifetime of the NC building versus that of the RR building has been added to Section 4.2.3 [Section IV.B.3 in final report].

Clarification on the process of deriving appropriate EUIs has been included in Section 2.7.7 [Section 0 in final report].

An error in the data was identified and corrected.

REVIEWER COMMENT:
The text in section 2.7.3 [Section II.H.3 in final report] is useful, and the assumption should be restated in section 4.2.3 [Section IV.B.3 in final report].

The section is much clearer.

No further comment.

AUTHOR RESPONSE:
The assumption has been restated in section 4.2.3 [Section IV.B.3 in final report].

6 Interpretation

REVIEWER COMMENT:
In the limitations of the study, it should be clearly stated that all building material impacts are those of specific buildings, and hence any generalization of the results require one to assume that the chosen buildings are typical of all RR and NC. This is especially important given that building material impacts are what drive the differences between the compared scenarios. If one is unwilling to accept that the chosen buildings can be generalized, then the study cannot be said to allow the “comparison of the life cycle environmental profiles of buildings undergoing rehabilitation and retrofit to those generated by demolition of the existing building followed by new construction” beyond the chosen buildings. Some discussion of the materiality of observed differences in potential environmental impacts should also be included to allow the readers less familiar with LCA (and the IMPACT2002+ methodology) to evaluate the significance of the results.

AUTHOR RESPONSE:
Discussion has been added to the Limitations section [Section VI in final report] noting the need to consider building’s similarities to the structures used here when applying the results of this study.

Please refer to the previous response regarding uncertainty for explanation regarding the decision to not perform a sensitivity analysis on the results.
AUTHOR COMMENT:

Date: November 30, 2011
To: Pascal Lesage
CC: Patrice Frey, National Trust for Historic Preservation
From: Amanda Pike, Quantis

Regarding: Modifications to LCA study Quantifying the Value of Building Reuse since review

Since conducting the formal peer review of the LCA report Quantifying the Value of Building Reuse, two major modifications have been made to the study. These modifications were undertaken after further consideration of assumptions made by the project team and are intended to improve the quality of the study. The purpose of this memo is to communicate these changes to you and capture feedback you may have regarding these new assumptions. The modifications are described below.

The assumptions concerning operating energy use were reviewed in detail by an external party considered to have expert knowledge in building energy performance across the United States. During this assessment, it was identified that for the “Advanced” energy performance scenario analysis (where energy consumption was assumed to be reduced by 30%), energy demand had actually been reduced by less. While the building’s electricity demand had indeed been decreased by 30%, natural gas use dropped only by 9%. The project team had thought that this approach would be a more accurate depiction of the energy savings achieved through the energy efficiency measures (EEM’s) included in the scenarios. Feedback from the expert reviewing this approach indicated that increasing both values by 30% would actually be a more appropriate assumption. Thus, the reduction in natural gas use was modified to 30% for the scenario. Due to the dominance of impacts associated with electricity use as
compared to those associated with natural gas use, this change induced only a minor reduction in results, and overall conclusions were unaltered.

The second modification was done to correct an error in the materials list. Specifically, it was found that Division 16000 Electrical for the Warehouse to Multifamily Residence had been quantified in a manner inconsistent with the approach used to quantify these materials in the other Multifamily Residence buildings (e.g., NC and RR). This oversight was identified after digging into the LCA results in attempt to explain the differences seen between NC and the Warehouse. The Warehouse inputs have been recalculated such that the amounts of items in Division 16000 are equivalent to those found in the NC Multifamily Residence. The difference in impact (per square foot) between these two structures is now zero for Division 16000. Due to the importance of burdens associated with items in Division 16000, life cycle impacts for the Warehouse have decreased, and the Warehouse is now more competitive with NC in some indicators. However, the change is not sufficient to substantially modify the conclusions of the study. While the potential for environmental advantage is somewhat more optimistic for the Warehouse, it is still not possible to say that either the Warehouse or the NC Multifamily Residence is clearly preferable.

We look forward to your response.

REVIEWER RESPONSE:
I have read your memo dated November 30, 2011 regarding changes you have made to the report since I wrote my review report. From what you report, the changes are, on the level of interpretation, rather minor. I am glad the errors were caught before publication. I have no comments to make beyond those already in the report.

AUTHOR RESPONSE:
No further comment.
APPENDIX I: Summary of Pilot LCA

The team conducted a screening analysis in the process of developing the approach for this study. The intent of the pilot LCA was to identify the point(s) in a building’s life cycle where important differences in environmental performance exist and where resolution and data accuracy are most critical. Moreover, the exercise provided an opportunity to understand whether the scope initially identified was appropriate for each scenario that was to be explored in the full LCA.

The pilot study evaluated the cradle-to-grave life cycle environmental impacts of newly constructing versus rehabilitating a high school. The specific goals of this study were as follows:

I. To assess the relative environmental performance of a building that either undergoes rehabilitation and retrofitting or is demolished and newly constructed;
II. To identify the most important factors for and differences between the impacts of rehabilitation and new construction;
III. To identify potential conditions under which rehabilitation may be environmentally advantageous; and
IV. To inform a full LCA to be conducted on additional building types, geographic locations, energy performance, and other key parameters, as identified in this study.

The functional unit for this study is the operation of a high school under a typical public school calendar in Portland, Oregon for a lifetime of 70 years. After 70 years, it is completely demolished.

In this study, buildings are modeled based on real construction projects in the Pacific Northwest U.S. While the precise functionality of the buildings could vary to some extent, the general functionality is considered equivalent under the defined functional unit.

Primary data is employed for the quantities of building materials, the amount of utility (energy) consumption during building use, and the operation of diesel equipment (hours-equipment) as well as worker commuting (worker-days) associated with Demolition/Selected demolition, Construction, and Final demolition. All of this information sources from the global construction company Skanska. The remaining information is primarily drawn from the ecoinvent database v2.2 (SCLCI 2010). A variety of
other information is garnered from literature review, database searches, team expertise, vendor product data, and interviews with experts, among other sources.

*Four indicators* are calculated in this study: Climate change, Human health, Ecosystem quality, and Resource Depletion. The method employed here is the peer-reviewed and internationally recognized LCIA method IMPACT 2002+ (Jolliet et al. 2003, as updated in Humbert et al. 2009). The exception to this is the Climate change indicator, which is calculated based on the IPCC 2007 100-year GWP weighting with biogenic carbon dioxide excluded (IPCC 2007, BSI 2008).

Redmond High School is selected to represent the New Construction scenario, and Stadium High School is selected for Rehabilitation. In attempt to ensure that these buildings are functionally equivalent, the material inputs for Redmond High School are adjusted to quantities that are appropriate for the building had it been constructed with approximately the same square footage and site restrictions as Stadium High School. This is accomplished by reducing the size of program elements in order to achieve approximately the same total floorspace (square footage) as Stadium High School. Program element reductions are completed by Skanska in order to ensure realistic and possible modification. Note that energy performance is not reassessed under this new floor plate. Additionally, program elements of the two buildings are not exactly the same.

In order to understand the influence of key assumptions on the results, two sensitivity analyses are conducted—specifically, explorations of building lifetime and energy demand. To assess the potential lower and upper bounds of the former, a minimum lifetime of 50 years and a maximum lifetime of 100 years are evaluated. In terms of operating energy use, the influence of increased energy efficiency by the rehabilitated school is explored. Reductions of 30% and 60% in the annual electricity use are evaluated. No other parameter (e.g., bill of materials) is modified in this analysis.

The baseline analysis shows that New Construction is environmentally advantageous in the four indictors evaluated. This is due to the fact that Rehabilitation uses nearly twice as much energy (for electricity and heating combined) as New Construction.

The sensitivity analysis around the lifetime of a building affects the quantity of replacement materials and energy consumed over the course of its life cycle. An increase or decrease in the building’s lifetime
can have important effects on total impact, particularly when an indicator is dominated by energy use. Nevertheless, if the lifetimes and NC and RR are the same, the relative results are constant; NC is environmentally preferable.

Results of the energy performance scenario indicate that enhanced energy performance can provide major strides in reducing total environmental impact. The savings and relative impacts may vary based on the method chosen to reduce energy consumption, and trade-offs may exist between different practices.

The study illuminated a number of important considerations for the full LCA. First, the function of the buildings to be compared should be more closely considered. Only data describing buildings that provide equivalent services should be employed, as the intention is to use these buildings as generic proxies for the scenarios (RR and NC) under evaluation. Specifically, program elements and other site details (e.g., use of pavers) should be comparable and geographically appropriate.

Second, all energy consumption data should source from either a building energy model or empirical data for buildings that are compared. The latter is preferred for the purpose of accuracy, although data source can change between building types if the same model is used.

Third, when evaluating energy performance, modifications to the structure (i.e., material quantities and types) must be taken into account. In addition, only feasible solutions to achieving reductions in energy use should be considered for the purpose of maintaining the study’s value.

Fourth, the differences in a building’s life cycle due to geographic location should be identified, particularly parameters such as building lifetime, product/material replacement rates, and end of life management.

Finally, characteristics of several products should be better defined and more accurately modeled to ensure reliable results. These include windows, steel products, and photovoltaic cells.

During the screening-level exercise, several questions were recommended to be addressed in the full LCA. These centered on three themes—energy performance, building typology, and geography—and
encompass the following:

Energy performance

- What is required for a rehabilitated building to achieve the same energy efficiency as a newly constructed building? How does this affect the overall environmental profile of the rehabilitated building?
- If energy performance is equal between a newly constructed and rehabilitated building, what are the main drivers for environmental differences?

Building Type

- Are there trends in the environmental performance of a newly constructed versus rehabilitated building across building types?
- Does the type of original building affect the choice between new construction and demolition?

Geography

- How do parameters (e.g., recycling rates) vary geographically, and what is their influence on environmental performance of the buildings?

An intensive workshop was held with the project team to review the process of conducting this pilot LCA, consider the study’s implications, and devise the goal and scope of the full LCA.
ENDNOTES

1 Use of the term ‘retrofit’ throughout this report refers to energy retrofits.
3 Ibid.
6 While actual occupant density may be different between NC and RR case study buildings, it is assumed that NC and RR for a given typology could theoretical service the same number of people per square foot. In cases where plans for the case study NC buildings do not include the full build out, floor plates are estimated to be comparable to that of the existing building. Operating energy use for each typology is calculated based on an equivalent occupant density for NC and RR. See the Critical review in the Appendices for additional discussion.
8 Several factors should be considered when choosing sources of data to use in preparing a life cycle inventory or life cycle impact assessment (LCIA). Among these, representative geography is important but not deterministic. Therefore, while it would be preferable to choose a methodology tailored to the United States rather than Europe in the present case, the authors consider the importance of that distinction to be minor relative to the advantages of the LCIA method chosen; Swiss Center for Life Cycle Inventories, ecoinvent database v2.2 (2010).
9 The impact of assembling the components is excluded if not explicitly modeled by ecoinvent.
15 Ibid.
17 In many instances, it was determined that both the existing and new buildings are unlikely to achieve even the base case level of energy performance without the addition of select EEMs. Additional details are offered in the appendices.
18 While this study assumes that space heating and domestic hot water systems are powered by natural gas in each of the four regions, in reality 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. However, according to Pacific Northwest National Laboratory’s 2006 Energy End-Use Flow Maps, natural gas represents the most common fuel source for space heating and water heating in both residential and commercial building nationally. 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; U.S. Department of Energy, “Energy End-Use Flow Maps for the Buildings Sector” (2006).
20 Three categories listed in the eGRID data—Geothermal, Other fossil, and Unknown—are removed from the list due to a lack of information needed to model these technologies, and the remaining sources are scaled up to arrive at 100% electricity consumption. These categories comprise less than 1.0% of the total energy use for the RFC and SERC regions and less than 2.5% of the total used by the WECC region, and, therefore, it is expected that their exclusion does not cause an important disparity in impacts between the actual grid and the grid as modeled.

22 U.S. Environmental Protection Agency (2010).


25 Ibid.


27 According to consultants from the building industry, EEMs would enable buildings to achieve between 15% and 45% performance improvement. This study assumes a mid-range performance improvement of 30%.

28 These results are based on 227 public and private buildings in St. Paul, Minnesota. Approximately half are residential structures and half are commercial structures. Sixty-six percent have a wood structure, followed by 25% with concrete. See Athena Institute, “Minnesota Demolition Survey: Phase Two Report” (2004).

29 Several factors should be considered when choosing sources of data to use in preparing a life cycle inventory or life cycle impact assessment (LCIA). Representative geography is one such factor. In considering impact-assessment categories, other factors might include the comprehensiveness of the impacts considered; the framework for structuring the mechanisms of environmental impact; the comprehensiveness of the inventory flows for which characterization is offered; and the quality of the characterization factors. Of course, in the case of LCIA methods, one is primarily limited to those in existence, as the development of new methodologies is beyond the scope of a given evaluation and could raise concerns about a lack of review. In considering the geography of the United States, the U.S. EPA’s Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts is therefore the remaining option (see TRACI, http://www.epa.gov/nrmrl/std/sab/traci/ [2012]). Alternatively, a method from another geography may be adopted. Among the limitations of TRACI relative to several other prominent LCIA methods are: the lack of a midpoint-damage framework, which has achieved considerable international consensus (see, e.g., Jolliet et al. [2004]); and the lack of several categories of environmental impact available in other methods (including land occupation, radiation, differentiation of terrestrial and aquatic ecotoxicity, and depletion of non-renewable energy and resources). The significance of the location of a resource use or environmental emission can range from negligible (e.g., Climate Change, depletion of resources) to substantial (human respiratory impact or aquatic acidification). However, in many cases where geography is important, the range of sensitivities within countries and continents can be much greater than the sensitivities between countries and continents. For example, in both Europe and the United States, there are highly and sparsely populated regions that would account for high and low-intake fractions of local air pollutants, as well as regions that are highly or minimally sensitive to the effects of acid precipitation. Furthermore, many material supply chains are global, so while buildings may be located in the United States, environmental flows may be occurring elsewhere. Therefore, while it would be preferable to choose a methodology tailored to the United States rather than Europe in the present case, the authors have determined that the importance of that distinction is minor relative to the advantages of the LCIA method chosen; See Jolliet et al. (2003), as updated in Humbert et al. (2009).
