Land Quality Division

A Life Cycle Approach to Prioritizing Methods of Preventing Waste from the Residential Construction Sector in the State of Oregon

DEQ
State of Oregon
Department of
Environmental
Quality

Phase 2 Report, Version 1.4 - Executive Summary

Prepared for DEQ by Quantis, Earth Advantage, and Oregon Home Builders Association

September 29, 2010
10-LQ-022

Project Team and Acknowledgements

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Overview and Project Goals

The purpose of this project was to evaluate the environmental benefits of potential actions aimed at reducing material use and preventing waste during the design, construction, maintenance, and demolition of residential buildings within the state of Oregon. Within this report, the phrase waste prevention practices1 is used to describe practices that reduce material use or reuse materials—and subsequently reduce waste generation.

Although the environmental benefits of the practices evaluated appear on the surface to be waste-related, much of the environmental benefit from many of these practices are gained not through the avoidance of needing to manage waste, but rather through avoided manufacturing and production of materials and/or the potential that some such practices may also reduce energy used by the

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home. It is therefore essential to consider benefits that may occur over the entire life cycle of residential homes and of the materials they contain.

The ultimate goal of this project is to support decisions by the Oregon Department of Environmental Quality and others in their efforts to form programs, policies, and actions to prevent waste generation from the residential building sector in a way that maximizes overall environmental benefits.

Boundaries and Assumptions

This assessment considers production and manufacture of all materials comprising the structure of the home, transportation of these materials to and from the site of the home, construction, maintenance of the structure, use of the home (including heating and cooling energy, electricity use, and water use/heating), demolition, and management of all waste materials. The lifespan of the homes modeled in this project was 70 years. Given the highly variable nature of a home's lifespan, there was a sensitivity test conducted for this variable.

Generally, those items that would typically be included with a home when it is sold or rented are included (e.g. refrigerator, furnace, water heater). Not considered within the lifecycle are home furnishings, cleaning supplies, other materials or services purchased by the occupants, or the yard, fences, and driveways. Additionally, this study does not consider any impacts associated with the direct occupation of land area by the home, impacts associated with daily transportation of the residents, or any indirect effects through development patterns.

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Methodology

Overview of Approach

The project is divided into two phases: The purpose of Phase 1 was to efficiently screen a list of candidate waste prevention practices to determine which ones to consider in more detail in Phase

2, which is the basis of this report. Phase 1 results can be found on DEQ's website.[2] Practices chosen for Phase 2 evaluation were those that showed the greatest potential to prevent waste and provide overall environmental benefit, as well as those with complex issues not able to be fully explored in the first phase.

The objectives of Phase 2 (this report) are to evaluate the impacts generated during the life cycle of (1) a typical home in Oregon under different construction scenarios and (2) the entire home population of Oregon. The latter includes all homes presently standing and those built until the end of 2030. In addition, a variety of improvements are made to the underlying data and methodology employed in the second phase.

Waste Prevention Practices

The construction practices assessed in this report are listed below. The original list (which included about 30 practices in Phase 1) was generated by DEQ staff through a literature search and in consultation with numerous residential building professionals in Oregon. The list was revised at the initiation of both phases to include additional practices anticipated to provide important insight regarding the project goals.

Table 1: Construction practices evaluated in this study.

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<tr><th>Home Size</th><th>Multi-Family Housing</th><th>Wall Framing</th></tr>
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[2] http://www.deq.state.or.us/lq/sw/wasteprevention/greenbuilding.htm

LCA Modeling Methodology

The evaluation of the building practices is accomplished using a combination of three models, as follows:

1. A CAD (computer aided design) model of the building structure created by the Oregon Home Builders Association to represent a standard Oregon home;
2. REM/Rate, commercially available software capable of estimating home energy use; and
3. A customized LCA-based calculation system created for this project in MS Excel. Supporting LCA work is conducted in the SimaPro commercial LCA software.

The building material lists provided by the OHBA model and the energy use provided by REM/Rate are used to characterize the building practice scenarios within the LCA modeling framework.

It should be recognized that this model uses a steady-state approach, implying that the quantity of annual impacts is assumed to be the same for each year of occupancy.

The Individual Home Models

The *Medium Standard Home* is a theoretical residence whose characteristics are selected to represent a relatively standard new construction home of average size in Oregon which meets the minimal 2008 Oregon Energy Efficiency Specialty Code requirements. This standard residence is the baseline against which all waste prevention practices are evaluated.

The *Average Home*s are a series of home models developed by averaging the properties of homes across the state, specifically home size and building practices. Therefore, this model does not emulate a real home but an average of home properties in Oregon. *Average Home*s have been created in the four size categories defined, and for the three sizes of multi-family structures. In addition, different *Average Home* models are employed for new-construction (i.e., post-2010) and pre-existing (pre-2010) homes to reflect an expected difference in energy efficiency among these homes.

Modeling the Population of Homes

Using the results of the *Average Home* models and the population numbers for the state, the total impact of the housing sector in Oregon is computed to identify the magnitude impact or benefits that might result from waste prevention actions or policies when applied at the level of the entire state. When estimating statewide impacts, consideration is made of the proportion of homes in various size categories, single- and multi-family buildings (including multi-family buildings of various sizes), heating and cooling type, geographic zone, as well as distinguishing the energy efficiency of pre-existing and new construction homes. For this population of homes, impacts are assessed through the year 2210, at which point the great majority of homes existing as of 2030 are anticipated to have been demolished.

Results

Principle results from this study are highlighted, as follows:

- For *Climate Change Impact*, the use of the home contributes about 86% of the total impact due to energy use (space and water heating, electricity consumption); materials production contributes 14%; followed by the construction, maintenance, and demolition phases which contribute a combined 2%; transportation of materials comprises less than 1%. Oregon's current waste management practices (recycling and energy recovery) for construction materials reduce the *Climate Change* impacts by about 4%.
- Energy use during the home's lifetime is the dominant contributor to most environmental impacts;
- Production of original and replacement materials are important contributors for several impact categories;
- Materials transport, construction, maintenance and demolition activities, and material end-of-life handling are relatively minor contributors in most impact categories;
- Only a small amount, approximately 6%, of the *Waste Generation* is predicted to occur during construction, with approximately 50% occurring during 70 years of use and maintenance and the remaining 44% occurring at the time of demolition;
- The combined practices of the waste prevention home show the greatest benefit in waste prevention, followed by material reuse, multi-family housing, small homes, green certification, and durable materials;
- Across all categories, the environmental impact of the *Extra-small Home (1149 sqft)* are reduced between 20% and 40% that of the *Medium Standard Home (2262 sqft)*, suggesting that home size is among the most important determinants of environmental impact;
- Depending on their design, multifamily homes are shown to be capable of providing benefit (10-15% reduction in impact) in comparison to equally sized single family homes;
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- Carpeting, asphalt shingles, fiberglass insulation, drywall, wood, and appliances are identified as the chief contributors to environmental impacts in the *Medium Standard Home*;
- Metal components, some plastics, and fiberglass insulation are materials with high potential for benefit from reuse per kilogram of material. When considering indirect land use impacts, reusing wood can have substantial benefits.
- When material reuse is "high" (2/3 of the home is comprised of reused material that is reused at its end of life), most environmental impacts are substantially reduced, especially waste generation; and
- Negligible correlation exists between waste prevention and overall environmental impact of the alternative wall assemblies evaluated.

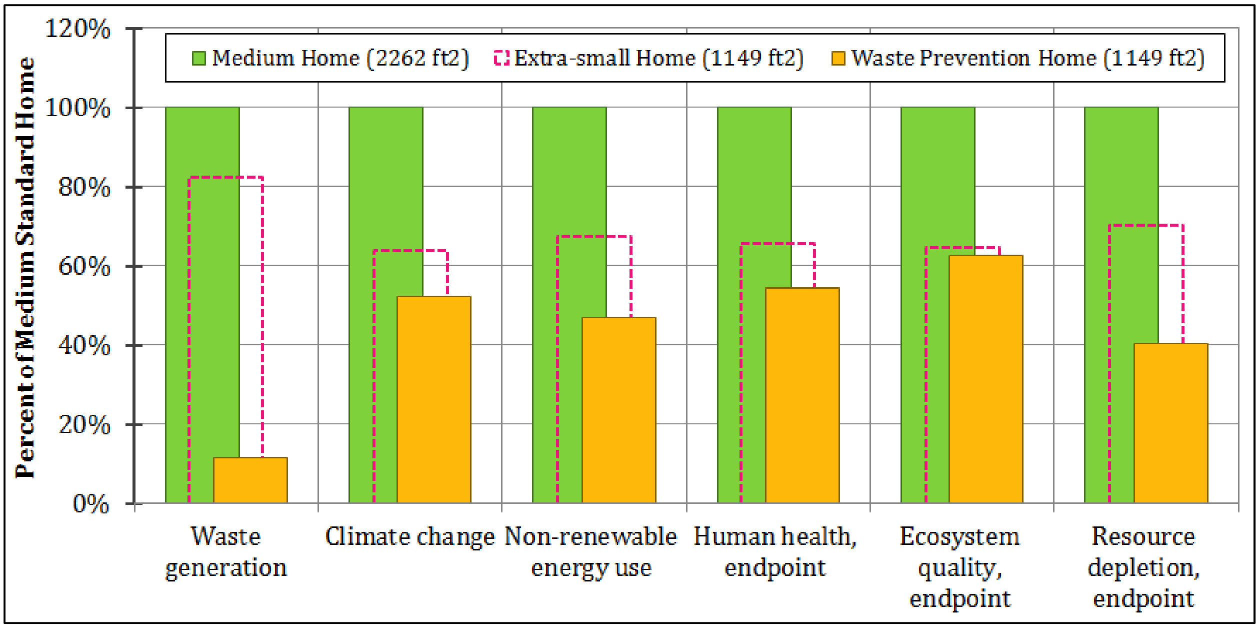

Figure 1: Summary of environmental benefits resulting from a home combining multiple waste prevention practices in comparison to a standard medium sized home and standard extra-small home

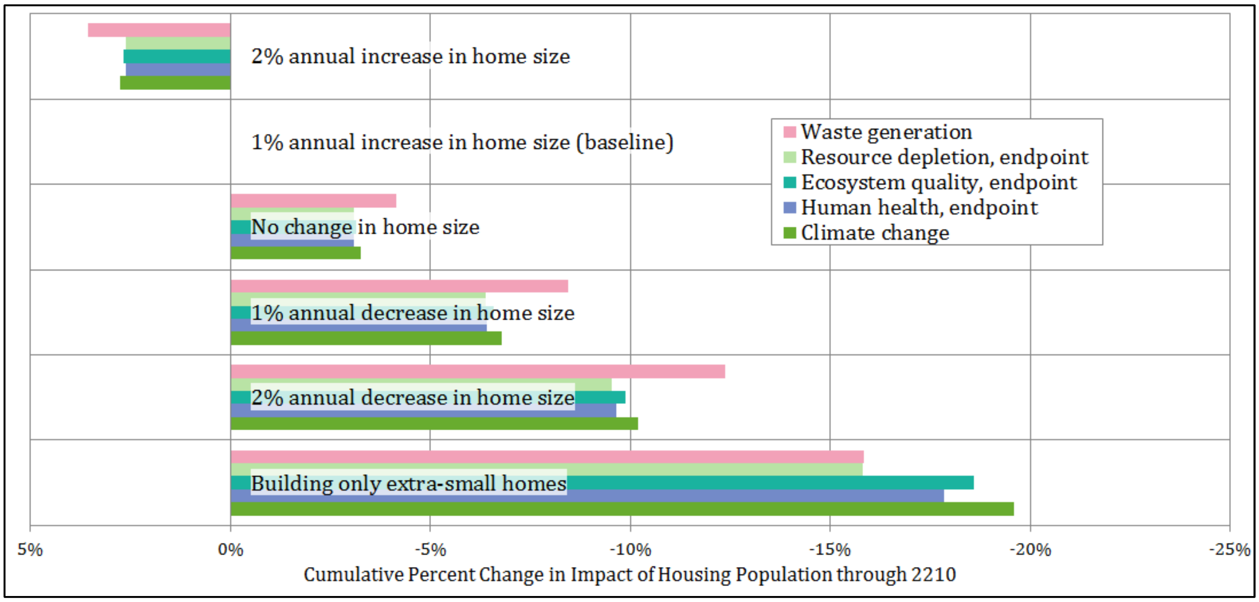

Figure 2: Summary of environmental benefits achieved over the entire home population life cycle by a given reduction in new home construction size for population of homes existing in 2010 or built before 2030

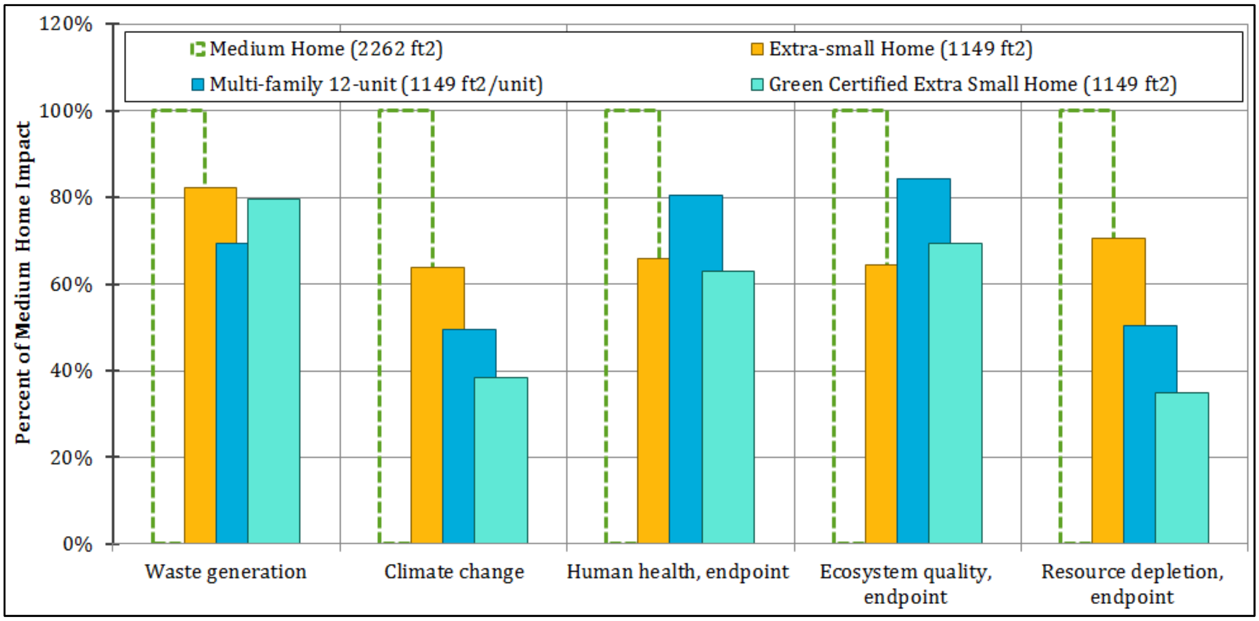

Figure 3: Summary of additional environmental benefit or impact of multi-family homes and homes with green certification in comparison to a home of similar size (extra-small) and a medium sized home

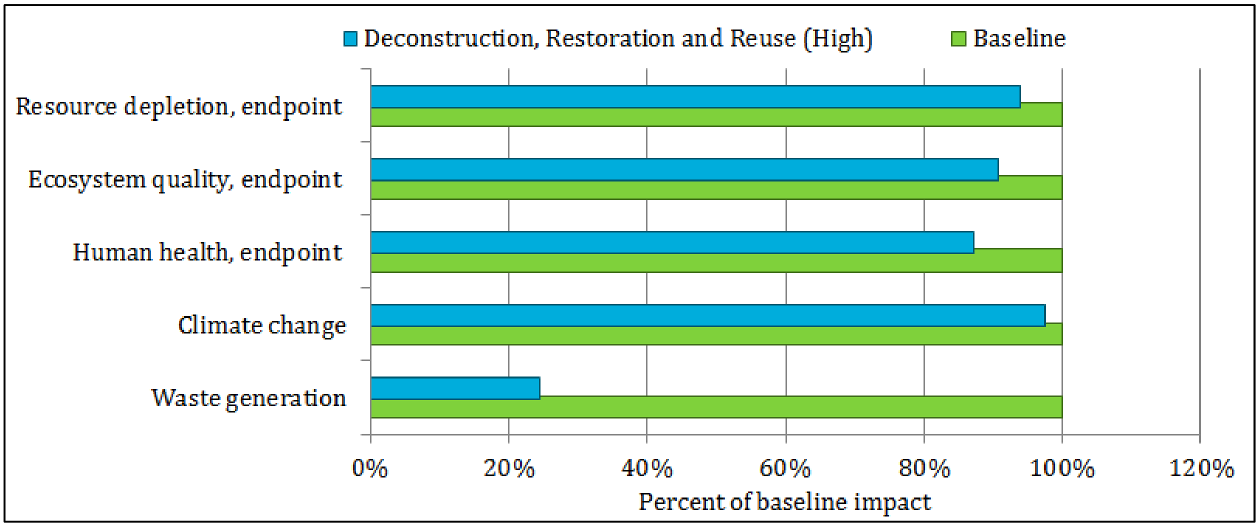

Figure 4: Summary of environmental benefits over their entire lifecycle achieved by salvaging and reusing 67% of materials in all Oregon homes existing in 2010 or built prior to 2030 through a program of deconstruction, restoration and material reuse

Implications, Conclusions and Recommendations

These results have important implications for policy-making in Oregon, particularly the following:

- Waste prevention practices that noticeably affect a home's energy use show the most potential to reduce other environmental impacts;
- Many of the waste prevention practices, especially those regarding home design, may have a long delay between their implementation and the realization of the reduction in material entering the waste stream although the benefits associated with reduced material production and reduction in operational energy use may be seen more immediately;
- Reducing home size is among the best tier of options for reducing waste generation in the Oregon housing sector, while simultaneously achieving a large environmental benefit across many categories of impact. Increased density and fewer home possessions were not explicitly included in the scope of this study and could further contribute to the benefit of small homes;
- Policies that reverse the trend in increasing house size would be extremely beneficial for both waste prevention and a broad range of environmental impacts and even modest decreases in home size are likely to produce important environmental outcomes;
- Families who choose or require more living space may mitigate a larger home's impact by adding green building practices. The relationship between home size and environmental impacts suggests that larger homes be held to a more stringent building standard;
- Reduction in home size is a significant leverage point for impact reduction and may be a more effective measure than achieving minimum levels of "green certification;
- If "larger" homes are still desired, one could consider designing an Accessory Dwelling Unit (ADU) directly into the new home. Providing flexibility and adaptability for different family configurations over time can provide more density of people within the home, thereby reducing the overall impacts of the home on a per person basis. Additionally, ADUs can be income generating rentals which may be an attractive option to homebuyers in today's market
- Depending on building design and materials, there could be an environmental benefit to promoting multi-family housing relative to single family homes;
- Reusing certain materials and selecting environmentally preferable materials can improve environmental performance, however, both require thorough analysis of individual materials and components;
- When selecting or substituting materials, each stage of a material's life cycle must be assessed to understand the relative environmental benefit;
- Wall framing practices should be selected based on overall environmental profile rather than being solely based on their ability to reduce material use or reuse materials due to their strong influence to operational energy use;
- A combination of numerous waste prevention practices show a potential for both a high level of reduction in waste generation as well as in a broad range of environmental impacts;

The implications above can be used to guide the Oregon DEQ and interested parties in better understanding environmental impacts associated with a wide variety of waste prevention practices applicable to residential buildings. The use of LCA provides a comprehensive view of the environmental implications of more than 30 building-related practices, in addition to several benchmarking activities.

The results indicate that the most beneficial action for overall improvement in environmental performance of the housing stock, while preventing waste, is to reverse the past trend toward increasing the size of homes. Similarly, multi-family housing presents a substantial level of environmental benefit.

To achieve maximum waste prevention and environmental benefits, a wide variety of practices that prevent waste generation, as exemplified by the Waste Prevention Home examined here, could be promoted and adopted.

Beyond preventing the use of materials, it is possible to address the environmental impact of those materials that are used by selecting materials for environmental performance and by reusing materials. While material substitution may be logistically simple in many cases, material selection is a very complicated manner. Better data and a thorough analysis are needed in each case to determine material preference. The LCA framework contained in the International Standards Organization (ISO) standards, and employed here, provide a roadmap for handling material selection. Selecting on the basis of product attributes alone, such as durability does not guarantee a high overall environmental performance.

Those building materials effecting energy use require an analysis that considers the entire life cycle of the home. The case of wall framing, examined in detail here, is shown to be an issue for which waste prevention is not a good guide for selecting the best environmentally performing options.

Material reuse, though clearly having the potential for environmental benefits, presents logistical challenges and presents some risks for added environmental impact. If promoted, it should be done aggressively to ensure that good information on this topic is produced and circulated and that infrastructure exists to allow efficient collection and transport of materials.

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Submitted by

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Submitted to

State of Oregon
Department of Environmental Quality
Jordan Palmeri
Project Officer

30 September 2010

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Explanation of Project Phases

This report discusses the results of the second of two project phases. This second phase of work considerably extends the work presented at the conclusion of the first phase by improving underlying data and assumptions, adding numerous scenarios, and including calculations of total statewide impact. Some relevant content from Phase 1 is retained here to provide relatively complete information in this report and to eliminate the need for the reader to refer also to the Phase 1 project report. Project information is maintained on the Oregon DEQ's website at:

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Principle results from this study are highlighted, as follows:

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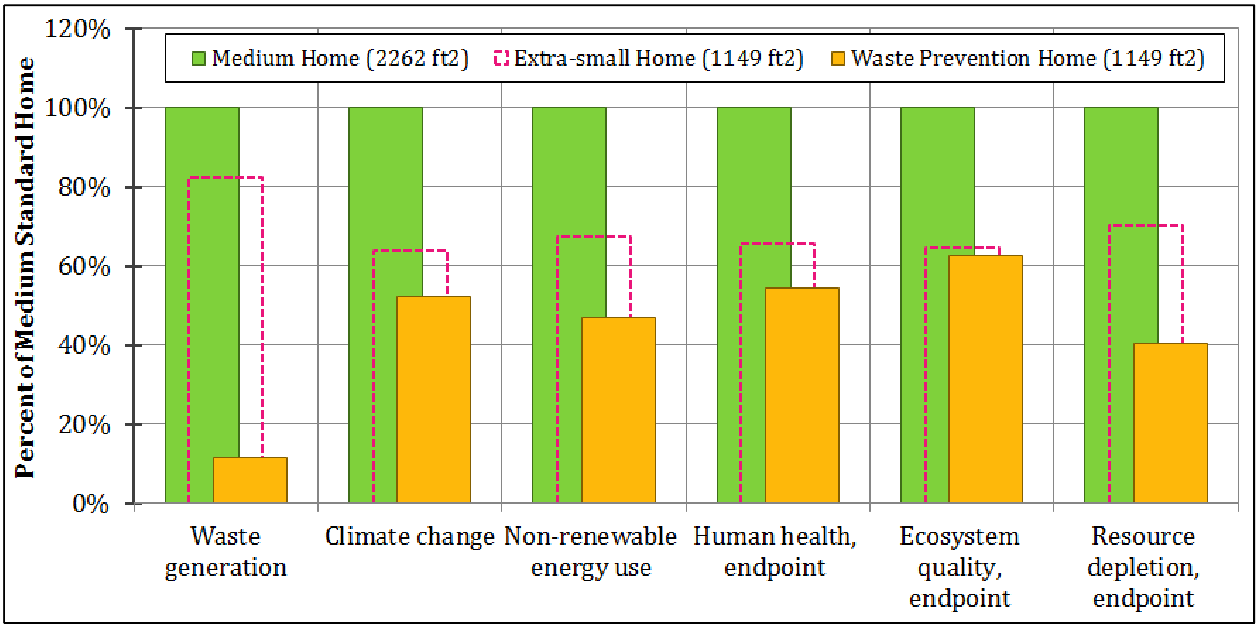
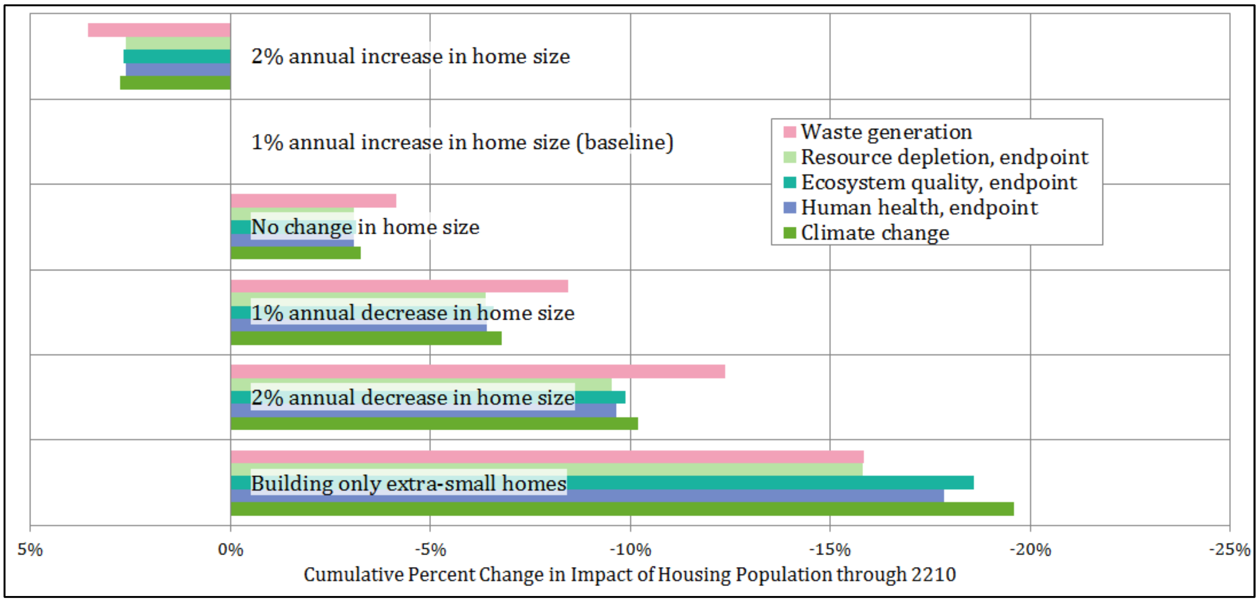


Figure 1: Summary of environmental benefits resulting from a home combining multiple waste prevention practices in comparison to a standard medium sized home and standard extra-small home



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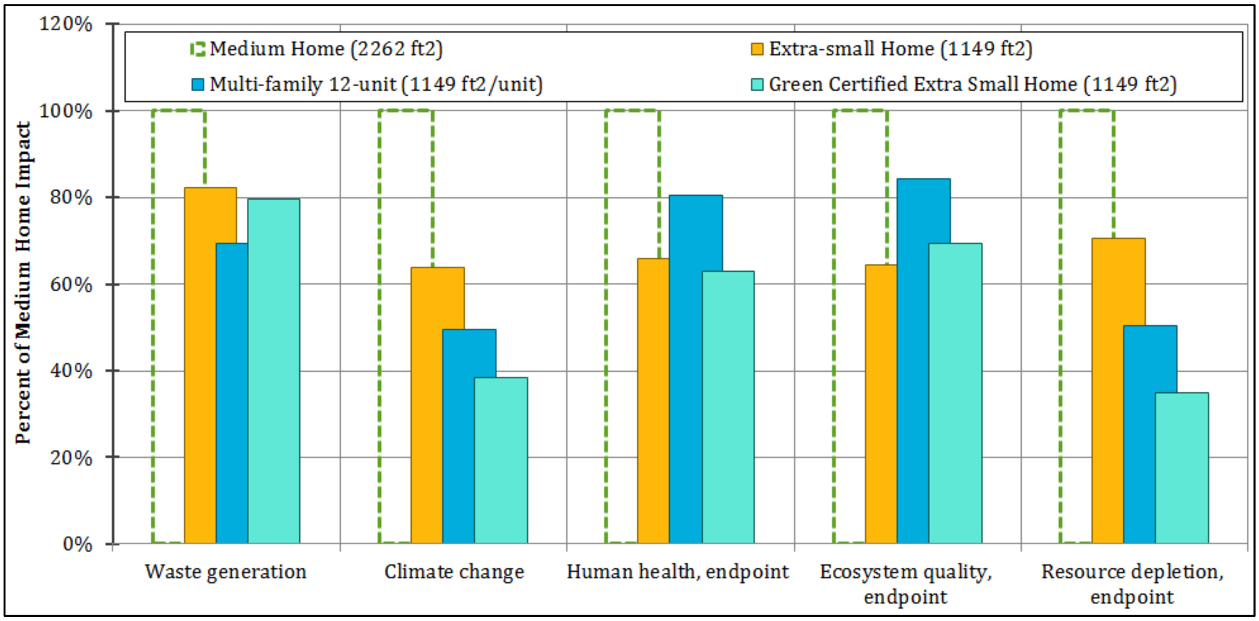

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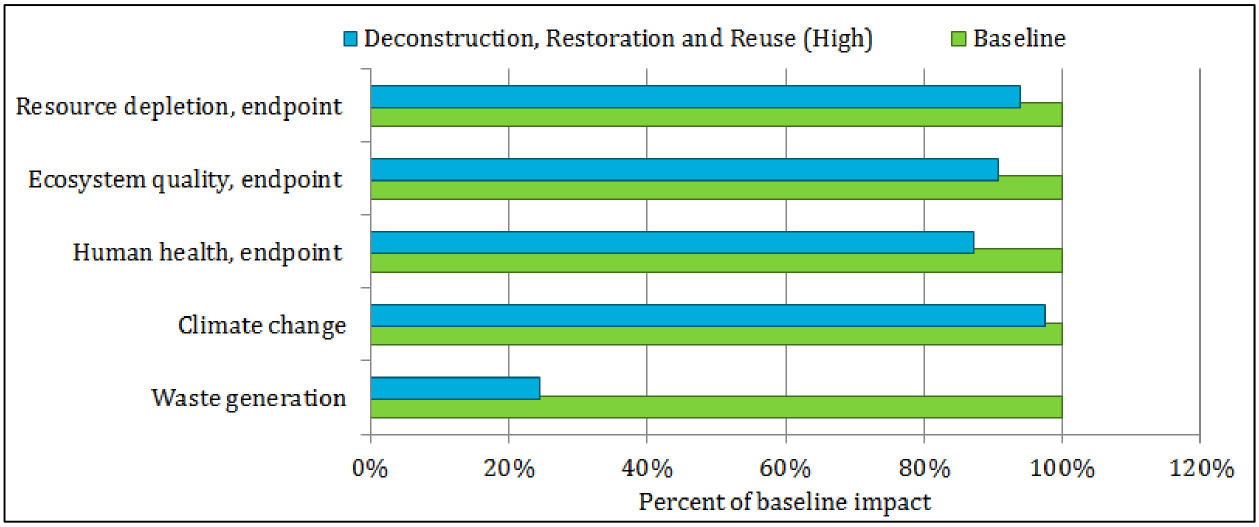

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Implications, Conclusions and Recommendations

These results have important implications for policy-making in Oregon, particularly the following:

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- Reusing certain materials and selecting environmentally preferable materials can improve environmental performance, however, both require thorough analysis of individual materials and components;
- When selecting or substituting materials, each stage of a material's life cycle must be assessed to understand the relative environmental benefit;
- Wall framing practices should be selected based on overall environmental profile rather than being solely based on their ability to reduce material use or reuse materials due to their strong influence to operational energy use;
- A combination of numerous waste prevention practices show a potential for both a high level of reduction in waste generation as well as in a broad range of environmental impacts;

The implications above can be used to guide the Oregon DEQ and interested parties in better understanding environmental impacts associated with a wide variety of waste prevention practices applicable to residential buildings. The use of LCA provides a comprehensive view of the environmental implications of more than 30 building-related practices, in addition to several benchmarking activities.

The results indicate that the most beneficial action for overall improvement in environmental performance of the housing stock, while preventing waste, is to reverse the past trend toward increasing the size of homes. Similarly, multi-family housing presents a substantial level of environmental benefit.

To achieve maximum waste prevention and environmental benefits, a wide variety of practices that prevent waste generation, as exemplified by the Waste Prevention Home examined here, could be promoted and adopted.

Beyond preventing the use of materials, it is possible to address the environmental impact of those materials that are used by selecting materials for environmental performance and by reusing materials. While material substitution may be logistically simple in many cases, material selection is a very complicated manner. Better data and a thorough analysis are needed in each case to determine material preference. The LCA framework contained in the International Standards Organization (ISO) standards, and employed here, provide a roadmap for handling material selection. Selecting on the basis of product attributes alone, such as durability does not guarantee a high overall environmental performance.

Those building materials effecting energy use require an analysis that considers the entire life cycle of the home. The case of wall framing, examined in detail here, is shown to be an issue for which waste prevention is not a good guide for selecting the best environmentally performing options.

Material reuse, though clearly having the potential for environmental benefits, presents logistical challenges and presents some risks for added environmental impact. If promoted, it should be done aggressively to ensure that good information on this topic is produced and circulated and that infrastructure exists to allow efficient collection and transport of materials.

I. Introduction

Project Background and Context

The State of Oregon has a long history of progressive environmental legislation including: a first-in-the-nation state land use plan to prevent sprawl and preserve resource and farm lands; a bottle bill; efforts to address global warming; and unprecedented waste management and waste prevention activities, such as a first-in-the-nation product stewardship requirement for paint manufacturers. With respect to waste management, existing statutes (e.g., ORS 459.015) place waste prevention as the first priority above all other solid waste management methods, followed by reuse (ODEQ 2006).

Oregon DEQ defines waste generation as the sum of materials recovered (recycled, composted, and, in some cases, burned for energy) and materials disposed of (via landfill and waste combustion units). It is a total of all materials discarded and a crude measure of materials consumption. Growth in the quantity of waste generation has been of increasing concern to the state. Published data from that department indicates that between 1993 and 2005, there has been a 70% increase in solid waste generation in Oregon. On a per capita basis, waste generation increased 43% during this same time period (ODEQ, 2007).

Solid Waste in Oregon

The contribution of the construction and demolition sector to total waste generation within the state of Oregon varies significantly as the construction sector grows and shrinks. A 2002 waste composition study for the state found that all construction and demolition debris together comprised 22% of the total waste generation in the state (ODEQ 2002).) National estimates by the US EPA (2003) have placed the percentage of all construction and demolition waste that is attributable to residential buildings at approximately half. It can therefore be estimated that the waste influence of the residential construction sector in Oregon is at least 10% of the total waste generated within the state.

Analysis by DEQ indicates that, while some of this increase is a result of better measurement and shifts in how materials are discarded (away from “non-counted” methods, such as home burning, and towards “counted” methods, such as recycling and centralized composting), an estimated 50-80% of the increase is likely attributable to real increases in waste-generating activities and materials use. That is, Oregon residents and businesses, in total, in recent years have been consuming and discarding far more materials than in the early 1990s. While one result is that landfills are filling up faster than anticipated, a greater environmental concern is the impact associated with production (and, in some cases, use) of these increasing quantities of materials.

Furthermore, DEQ has found building construction, remodeling, and demolition activity to be a major contributor to materials use and waste generation. In a 2007 study, DEQ found that not only are construction, renovation, and demolition debris a significant solid waste source but that they will remain so for some time into the future.

> Because most building-related waste results from renovation and demolition activities (as opposed to construction), the majority of building materials consumed don't end up as wastes until years or decades after construction. Today's building wastes are largely materials that were purchased and installed years or decades ago. (ODEQ, 2007)

Guidelines

Oregon DEQ recognizes that a successful waste prevention program must take an approach that considers the entire life cycle of materials and practices. Both upstream (resource extraction and production of goods) and downstream (end-of-life/waste management) impacts need to be addressed, as do impacts occurring in the use of a product or system. This perspective is necessary for DEQ to achieve the three objectives from its Waste Prevention Strategy (ODEQ, 2007):

Environment – Strategically reduce GHG emissions, waste generation, and environmental impacts.

Sustainability – Demonstrate that preventing waste can have a positive economic, social, and environmental impact, and that prevention is a relevant component of a sustainable society by addressing the broader impacts of materials, product use, and design.

Waste Generation – Take strategic actions that prevent waste generation and contribute to achieving Oregon's waste prevention (generation) goals established in state law.

Oregon DEQ defines waste prevention as those activities that prevent the generation of solid waste in an environmentally beneficial manner. Waste prevention includes using fewer materials and the reuse of materials. Recycling, composting, and energy recovery do not prevent the generation of solid waste and are therefore not considered waste prevention activities.

While this project does not seek to specifically identify the benefits of recycling practices or the use of materials with recycled content, it does consider current recycling practices as part of the modeling exercise. The current recycling rates for various construction materials in Oregon can be viewed in Appendix 9.

The project is guided by three main tenets:

1) Given the wide range of possible actions, resource limitations necessitate that well-informed policy decisions are made and that *the most effective measures are chosen* and *those of negative effect or even negligible effectiveness are avoided*.
2) Decisions that promote solid waste prevention have impacts that range far beyond the generation of waste to include *Climate Change*, energy use, resource use, human health, and ecological health. Therefore, ensuring that all actions achieve a net environmental improvement requires a decision framework that accounts for *impacts of the building sector within all categories of environmental impact*. There will also be tradeoffs among phases of a home's life; actions that may lead to benefits in materials production or construction that could have adverse impacts during the occupancy of the home and vice versa. Therefore, it is necessary to have a decision framework that properly accounts for the full impacts of residential buildings *over their entire life cycles*.

3) It is acknowledged that in many cases, actions will not lead to clear benefits at every point of a home's life or within every environmental impact category. There will therefore be tradeoffs that must be considered. While there may not be clear scientific guidance that can be provided to definitively justify such tradeoff, the scientific approach of LCA will *allow the nature of these tradeoffs to be made clear and transparent*.

II. Project Goals and Approach

The goal of this project is as follows:

> *To support decisions by the Oregon Department of Environmental Quality and others in their efforts to form programs, policies, and actions to prevent waste generation from the residential building sector in a way that maximizes overall environmental benefits.*

This goal is attained through the following more specific objectives of the project:

- Identify and characterize building practices that are likely to prevent waste from the residential building sector;
- Efficiently screen these methods to determine those which are most likely to provide the greatest environmental benefit across a range of impact categories and from a life cycle perspective;
- Identify and answer key questions regarding the best performing practices to provide further insights into these results;
- Provide relevant recommendations for enacting waste prevention measures for the residential building sector in Oregon that will provide the best overall benefit for the environment.

The intended audience of the report is the Oregon DEQ, which is the commissioner of the work. Recognizing that the Oregon DEQ may publicize the findings, the intended audience therefore also includes any and all interested parties to which the DEQ might publicize the information. The building community, policy makers and citizens are among potential audience groups.

The project includes a comparative evaluation of building systems and various waste prevention actions that might be undertaken by the Oregon DEQ or others. It is intended that this comparison be suitable for use in an open and informed public dialogue about the environmental impact of waste in the residential construction sector in Oregon.

The goals do not include any definitive comparisons of the environmental performance of specific products or materials. Where such comparison are obtainable or highlighted within the results shown here, the intention is to provide the best available information on such topics and especially to provide examples of the potential for material selection to be used as a means of environmental benefit in the building sector. However, it is not intended to make any definitive claims that a material or product is necessarily environmentally preferable to another. To do so requires more detailed work on the products in question than can be achieved within the broader aims of this project.

Key Questions Explored in Phase 2

Based on the Phase 1 results, the Oregon DEQ formulated a series of key questions to be explored in Phase 2 of the project, listed in the following table. A specific work plan was developed to target an ability to provide insights on these questions.

Table 2: Key questions to be explored in Phase 2 of the project

Small Homes
• How do impacts vary across a broader range of home sizes (e.g., 4 size classifications)? What is the level of benefits in all impact categories?
• How does this variation compare to the variation based on energy efficiency between a home that is meeting the minimum Oregon code and one that is significantly above code, such as doubling the insulation from that in the code home?
• What are the potential statewide benefits of promoting smaller homes? What is the expected trajectory of home growth by size and how do alterations in this trajectory affect the total statewide environmental impacts from this sector?
Multi-family Housing
• How do multi-family residences compare with single-family residences of similar sizes? How does this vary across size categories?
• What are the potential statewide benefits of promoting multi-family homes? What is the expected trajectory of growth in multi-family homes and how do alterations in this trajectory affect the total statewide environmental impacts from this sector?
Waste Prevention Home (multiple waste prevention practices)
• What level of waste prevention and other environmental benefit can be obtained by incorporating as many of the waste prevention practices as possible within a single home? For example: small house, durable materials, advanced wall framing practice, moisture management, proper installation, reduced remodeling, and dematerialization and use of salvaged materials.
• How do the benefits of this home compare with the individual waste prevention practices on their own, with other waste prevention practices that have not been included and against energy efficiency benchmarks, such as a home with doubled insulation or a passive solar home? What are the potential benefits if such practices were applied to all residences in the state?
Material Durability and Material Selection
• For each category of materials in the *Average Home*, what are the total amounts of waste generation, *Climate Change* impact, human health impacts and *Ecosystem* impacts?
• For the leading categories identified above: o What range of options exist to select materials with improved durability? o What sets of life cycle impact data are available for these materials and how do the results compare? Where information exists to compare impacts of production, how do the production impacts compare among the materials with varying durability for

each category?
    - Based on the differences in production impact, what is the range of "break-even" points for added durability that must be achieved for each material to realize a net environmental benefit?
    - Are there alternative end-of-life handling options that would substantially improve their environmental performance?

- How important is sourcing location and transportation in selecting materials? How does this importance vary among types of materials? Can any rules-of-thumb be offered?
- What is the approximate amount of benefit that could be obtained by increasing use of more durable materials on a state-wide scale?
- What issues and considerations are likely to arise when trying to select materials with best environmental performance over the life cycle of the home? How do considerations differ for energy-related and non-energy-related components?

Material Salvage and Reuse

- For various classes of material, at what distance of added transport does the benefit of reusing the material no longer exist?
- How do the environmental benefits of reusing wood compare to converting the wood to energy for each of several environmental impact categories? What variables are of primary importance in making this comparison? For *Climate Change*, how might consideration of indirect land use impacts or the timing of emissions and storage of carbon affect the comparison?
- Which material classes provide the most and least benefit to salvage from each house?
- Are there any areas where salvaged materials appear to or could reasonably be assumed to increase environmental impacts in any categories?
- How do the benefits change with alternative rates of recovery and incorporation of reused materials?
- What are the benefits of these practices when extrapolated to the existing and future housing stock?
- How are the benefits of these practices affected when we expand the boundary of the study to allow the inclusion of multiple lifetimes for materials and the ultimate inclusion of their end of life fate?
- How does the allocation of benefits between producer and user of salvaged material affect the results?

Wall Framing

- How do the wall framing practices assessed in Phase 1 compare to double studded walls and, staggered stud framing?

Approach Overview

The project takes a tiered approach of first cataloguing and characterizing the available options (Phase 1) then screening these options based on a simplified single-home LCA model to eliminate those that are unlikely to pose a high environmental benefit relative to the others (Phase 1) and finally conducting a more thorough analysis, including both single-home and population-based LCA models to compare the remaining options (Phase 2).

This LCA follows the international standards in the field of LCA, which are contained in the International Organization for Standardization (ISO) 14040 and 14044 documents. It should be noted that the intention of the present study is to compare among the building practices that are considered and to compare large-scale actions or policies by the state of Oregon, rather than to achieve highly accurate and reliable comparisons among specific materials or building products. To take a specific example, in the building practice "Use of Durable Materials," several types of building materials are exchanged for others to examine the influence on the impact over the homes lifecycle. The purpose of such a comparison if to provide information on the potential trade-offs of focusing on durable materials rather than other possible actions or policies; the aim is not to draw any conclusions regarding the specific materials under consideration. An expert external review panel has reviewed the project report and findings and provided their judgment on the adequacy of the methods used to fulfill the goals of the project. Their input is included as an appendix

The study is based on the best available information. Consideration of key influential factors, such as geographic relevance, temporal relevance, scientific credibility, and internal study consistency, is made paramount to this exercise. Nevertheless, assessment of an entire residential home, much less an entire state's population of homes, is an extremely complex task and relies on a myriad of data sources and assumptions. While the results presented by this study are considered reliable, they should be used only within the context of the boundaries and limitations discussed in this document.

Waste Prevention Practices

The waste prevention practices assessed in the study are listed below. The original list of practices was generated by DEQ staff through a literature search and in consultation with numerous residential building professionals in Oregon. The list was revised at the initiation of both Phase 1 and Phase 2 to include additional practices for which it was anticipated that important insights might be gained. While the list may not be exhaustive in covering every residential waste prevention practice possible, it does cover a substantial number of practices in the design, construction, remodel, and demolition of residential homes.

The practices considered in Phase 2 include the following:

Home Size:
- Extra-small Home (1149 sqft)
- Small Home (1633 sqft)
- Medium Home (2262 sqft; basis for comparisons with other homes)
- Large Home (3424 sqft)

Multi-family housing:
- 4-unit Multi-family Home (2262 sqft / unit)
- 8-unit Multi-family Home (1149 sqft / unit)
- 12-unit Multi-family Home (1149 sqft / unit)

Wall Framing Options (2262 sqft):

- Intermediate Framing
- Advanced Floor Framing
- Advanced Framing (with drywall clips)
- Double Wall
- Insulating Concrete Forms (ICFs)
- Staggered Stud
- Strawbale Home
- Structural Insulated Panels (SIPs)

Material Reuse Scenarios (2262 sqft):

- Deconstruction, Restoration and Reuse, Moderate
- Deconstruction, Restoration and Reuse, High

Multiple Waste Prevention Practices:

- Waste Prevention Extra Small Home (1149 sqft)

Material Selection:

- Durable Roofing, Flooring and Siding (2262 sqft)

Benchmarks[3]:

- Green Certified Extra Small Home (1149 sqft)
- Green Certified Extra Small Home with Passive Solar (1149 sqft)
- High Performance Shell Medium Home (2262 sqft)
- Optimized End-of-Life, Reuse Excluded (2262 sqft)

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[3] In addition to the above critical questions identified, the project team determined it would be of interest to compare the impact of the "*Standard Homes*" of various sizes with other homes that have perceived environmental attributes such as energy efficiency to demonstrate the actual trade-offs of these properties. This study assesses a number of scenarios or *benchmarks* with differences beyond size, including a waste prevention home, a high performance shell home, and a Green Certified home. The intention behind modeling each of these homes is to examine the collective benefits realized by combining a number of different practices. The Waste Prevention home presents the benefits of combining a number of the waste prevention practices modeled in Phase 1 while the High Performance Shell home studies the benefits associated with a variety of practices designed to improve the shell of the home (by reducing convection, conduction and radiation heat loss and/or gain). The Green Certified home was designed to represent the optimal package of green building practices, including principles of waste reduction (incorporating an appropriate selection of waste prevention practices), energy efficient design (including a high performance shell), as well as some sun tempered design features. The team also examined a passive solar designed home but those results are not included in the comparison. For more information regarding passive solar design, see the "*Green Certified Home with Passive Solar*" text box. Each of the benchmark home models is described below, and a full list of materials for the homes is shown in Appendix 5.

In addition, a series of *Average Home* scenarios have been conducted to represent the full population of homes within the state and are explained further below. Table 2 provides an explanation of each scenario modeled in Phase 2. The following practices have been modeled in Phase 1, but are not specifically addressed in this second phase. Some are included as aspects of the Waste Prevention Home. The Phase 1 report can be consulted for more detail on these practices.

- Adaptability: Utility Chase
- Off-site Pre-fabricated Components
- Proper Installation
- Reduced Packaging
- Reusable Packaging
- Detailed Framing Cut List
- Flashing and Rainscreening
- Deconstruction
- Design for Disassembly
- Design Using Salvaged Materials
- Restoration
- Dematerialization & Design for Simplicity

Functional Units: Home and Housing Population

The present study considers two scales of functional units: a standard single-family detached home and all homes (single and multi-family) in the state of Oregon.

For the assessments performed at the level of an individual single-family home, the functional unit is the provision of 70 years of single-family housing. The 2000 U.S. Census indicates that the average household in Oregon contains about 2.5 occupants, and the baseline scenario considered here is intended to this *Average Home*. However, the number of occupants is not used as a direct determinant of any of the results, and, therefore, the results will be equally applicable to the accommodation of more or less people within the same structure.4

For the assessments performed at the level of the statewide population, the functional unit is the provision of housing to the inhabitants of the State of Oregon for a period of 20 years. The current population of Oregon (2008 estimate from the U.S. Census Bureau) is 3,790,060 persons, living in

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[4] A possible exception to the lack of influence of occupant number is the non-HVAC energy. Although the number of occupants is not used as an input to REM/Rate in determining this value, it can reasonably be expected that more or less occupants would use a greater or lesser amount of electricity for powering non-heating/cooling related devices and appliances.

approximately 1,628,826 housing units. An assumed net growth in housing units of 1% per year is achieved by balancing a 3% rate of new construction and a rate of loss of existing homes of 2%[5] per year. These rates have been used to determine the net increase in total housing units needed to fulfill this functional unit, which is estimated to be 1,113,000 units constructed between 2010 and 2030 (resulting in a total of approximately 2,200,000 units in 2030). The homes in the state already existing at the start of 2010 have also been considered as part of the system required to meet this functional unit. Because decisions about housing characteristics are likely to last for the life of the home, the scope of the study also considers the impacts of the entire life cycle of homes existing prior to 2030. These boundaries are described further in the Boundaries and Stages of the Life Cycle section.

This assessment considers the production and manufacture of all materials comprising the structure of the home (including the original and replacement materials), the transportation of these materials to and from the site of the home, the construction of the home, maintenance of the structure, the use of the home (including heating and cooling energy, electricity use, and water use/heating), its demolition, and the management of all waste materials. Not considered within the lifecycle are the home furnishings, cleaning of the home, other materials or services purchased by the occupants[6], maintenance of the yard and fences, and pavement of driveways.

The selection of 70 years as an average life is a highly uncertain number. While establishing the average life of past and existing homes is difficult, predicting the lifespans of homes built today is even more difficult. The selection of 70 years has been validated by a scan of the American Housing Survey data, which suggests that the average annual rate of loss of homes in the Portland area ranges from 0.5% to 2%, depending on the decade of their construction (indicating an average life of 50 to 200 years). Two percent has been chosen to provide the closest relationship to the results reflecting single homes. Among the other residential home LCAs listed in the annotate bibliography,

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[5] To reflect the situation that homes have a low likelihood of being demolished very soon after construction and that other than this trend, there is little relationship of home age and likelihood of demolition, it has been assumed that no new-construction homes are demolished in their first 20 years of life and then all homes have an annual 2% chance of being demolished. This 20-year grace period, followed by a 2% annual chance of demolition provide an average lifetime in a similar range to the 70-year life assumed for the single home comparisons, although among the population some will last much less and some much more than 70 years. Assumptions regarding rates of new construction and demolition have been made based on the combined input of a variety of sources, including the Oregon Office of Economic Analysis (http://www.oregon.gov/DAS/OEA/economic.shtml#Leading_Economic_Indicators) and the US Census Bureau (www.census.gov)

[6] The Oregon DEQ has commissioned a separate project examining the carbon footprint of citizen consumption habits and a brief discussion to place those results in the context of the present results is provided within the results section.

none includes a more valid citation for their selection of home lifetime. As the LCA is intended to represent present and future homes, what data that might be found on already demolished homes would be questionable in its applicability and so the home lifetime is necessarily uncertain value.

Overview of Phase I Scenario Results

Figure 5 shows the total *Climate Change* impact for the 25 practices that are assessed in the first phase of the project. The values are based on the implementation of each practice in a single residence over a 70-year lifespan.

Due to the dominance of the use phase of the home's life cycle, it is difficult for those practices that do not impact the home's operational energy use to have a very large effect in comparison to those that do impact the use phase7. Even a reduction of 50% in the other phases, which is difficult to achieve, is roughly equivalent to only a 5% reduction in the home's energy use.

The best performing scenario reduces the total *Climate Change* impact for the home by approximately 20%, with several others achieving a reduction greater than 10%. Most of the practices (16 of 25) result in a decrease of less than 3%, one of which is a net increase in the *Climate Change* impact.

As discussed above, it is often those practices with large benefits in the use phase of the home that show the greatest improvement in the *Climate Change* impact. However, as shown by Design for Disassembly and Deconstruction, it is possible to achieve a substantial level of improvement in environmental impact without a benefit in the use phase, but the overall benefits of such practices remain substantially lower than the best performing tier of practices.

As with the *Climate Change* impact, there is a wide variation in the waste prevention benefits of each practice. For purposes of comparison, the total amount of waste generated over the lifetime of the *Standard Home* is estimated by the present study to be approximately 120,000 kg. The best performing practice results in a waste prevention benefit of over 50% of the total material mass generated. Those dealing with the reuse or salvaging of a large percentage of materials are shown to have the most substantial impact on waste prevention. There are a handful of practices with only

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[7] Note that a number of initiatives have been proposed to drastically reduce use-phase energy. Architecture 2030, for example sets the goal of "net-zero" energy use by the year 2030. If progress in this direction is made, the evolution of building standards toward extremely low energy use will make other factors, such as material production, relatively more important over time.

a very small benefit in preventing waste, while four (ICFs, SIPs, Strawbales[8], and Single-story Homes) are each shown to have a net negative influence on waste generation over the life of the

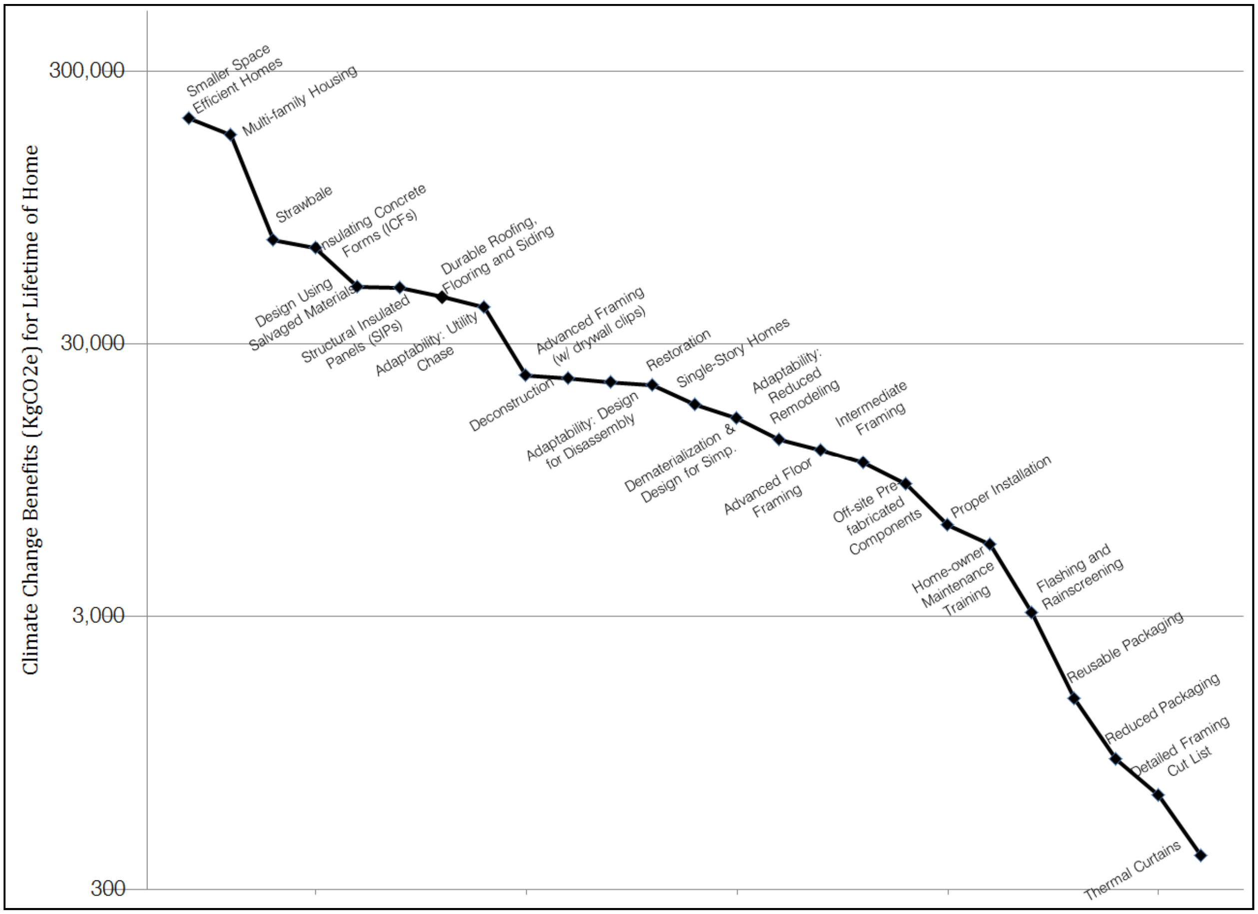

Figure 5: *Climate Change* benefits provided per home by the candidate practices (note the logarithmic scale)

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[8] For the *Strawbale Home*, it has been assumed, in both the first and second phases of the project, that 80% of straw material is disposed of and only 20% is put to beneficial use. It is therefore considered that this material is already in the waste stream before it is used by the home and therefore only 20% of the straw material used in the home is counted as waste generated by the home. Even so, the *Waste Generation* results for the *Strawbale Home* show this scenario to be a net waste generator over its lifetime.

home. Among the features of the Phase 1 report were a series of "report cards" for individual practices that provide additional detail on each practice.

Phase II Scenario Definitions

To address the above topics a variety of home scenarios have been established and evaluated. Some of these scenarios have been retained or updated from the first stage of the project work, while others have been added to specifically address key issues identified for Phase 2. Those home scenarios that are evaluated and discussed in the second phase are described in the following table.[9]

Table 3: Explanation of the home scenarios

Medium Home (Standard)[1]
The *Medium Standard Home* developed for this project is a typical two-level wood-frame house, 2262 square feet in living area, designed by the Oregon Home Builders Association to represent a home close to the average market size for new homes and including a suite of building practices that are as close as possible to the 2008 Oregon residential building code and typical current practices within the building industry. Most other scenarios are framed as deviations from the *Medium Home*. For example, the *Staggered-stud Home* is identical to the *Medium Home* with the exception of its wall framing using the staggered-stud pattern.
Small Home (Standard)
To represent the potential benefits of smaller home size, the *Medium Home* of 2262 square feet has been redesigned to a size of 1633 square feet, with an attempt to retain as much form and functionality as possible (same number of rooms, able to house same number of residents, etc.). Like the *Medium Home*, the *Small Home* is also a two-story structure.
Extra-small Home (Standard)
To further represent the potential benefits of smaller home size, a 1149 square foot *Extra-small Home* has been designed. Unlike the other three home sizes, the *Extra-small Home* is a single-story structure, which is far more typical in this size class. This change has implications for the relative amounts of materials in the home. For example, the *Extra-small Home* and *Medium Home* do not differ substantially in the area of their roof

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[9] Unless noted otherwise in the table, all wall assemblies have been designed to meet the current code of R-21

[1] As discussed later in this section, the term *Standard* is used to distinguish several of the scenarios from similar scenarios that have been made using *Average Home* properties for use in modeling the state-wide population and which are termed *Average Homes*. All building scenarios created for this project are in reference to either the *Medium Standard Home* or the *Standard Extra-Small Home*. The majority of the scenarios are made to be comparable to the *Medium Standard Home*, with the only exceptions being the *8-unit* and *12-unit Multi-family Homes*, the *Green Certified Home* and the *Waste Prevention Home*. Each of these exceptions has been developed to be comparable to the *Standard Extra-small Home* to better represent the typical implementation of these scenarios. Throughout the report, any reference is made to the "*Standard Home*," should be assumed to be in reference to the *Medium Standard Home*, unless the *Standard Extra-small Home* is explicitly mentioned.

surface and foundation. The *Extra-small Home* serves as a standard for comparison of several scenarios, including the 8-unit and 12-unit *Multi-family Homes and the Green Certified Home*. It is one of the practices incorporated in the *Waste Prevention Home* (smaller homes create less waste) and can variously be seen as either one of the elements of that home, to be viewed in comparison the *Medium Standard Home*, or a standard reference for comparison of the other elements of that home design.

Large Home (Standard)

To represent the potential impact of larger home size, the *Medium Standard Home* of 2262 square feet has been redesigned to a size of 3424 square feet, with an attempt to retain as much form as possible. Like the *Medium Home*, the *Large Home* is also a two-story structure.

4-unit Multi-family Home (Standard)

This scenario is represented as a set of four units in a row-house, each unit being similar in structure to the *Medium Standard Home* (they are 2262 square feet). The environmental impacts, in order to represent the function of housing one family, are represented as one-fourth of the impact incurred over the lifetime of the whole structure (that is, no distinction is made for differences between “middle units” and “end units”).

8-unit Multi-family Home (Standard)

This scenario is represented as an 8-unit structure arranged in a structure 2-units wide, 2-units deep and 2-units tall. Each unit is 1149 square feet and identical in as many ways as possible to the *Extra-small Home*.

12-unit Multi-family (Standard)

This scenario is represented as an 12-unit structure arranged in a structure 2-units wide, 2-units deep and 3-units tall. Each unit is 1149 square feet and identical in as many ways as possible to the *Extra-small Home*.

Intermediate Framing

While the *Standard Home* was designed to represent a traditional framing approach, some builders already incorporate framing practices that reduce framing members not strictly required for structural purposes. Much of this additional wood framing serves to support interior gypsum board, sometimes called “nailers”. Intermediate framing eliminates many nailers in exterior corners and re-orients others to provide proper support for gypsum board. This eliminates uninsulated areas of exterior walls and reduces the amount of lumber used.

Advanced Floor Framing

This practice uses the wall framing methods from Intermediate Framing, but adds an advanced floor framing system using I-joists and engineered wood. The insulation value for the floor was set to R-30

Advanced Framing

Advanced framing has the potential to reduce the environmental impacts of heating and cooling a home. More spacing between studs allows more insulation and fewer opportunities for thermal bridging. There are many variations in what is considered "advanced framing." In the present case, it has been represented as including:

- 24 inches on center studs;
- aligning roof trusses with wall studs to allow for the use of single top plate and the efficient transfer of loads;
- two stud corners;
- use of dry-wall clips;
- window openings that have one side on the stud spacing module;
- use of king, header support and cripple within window and door framing only as needed; and
- eliminating headers in closets and doors that aren’t in load bearing walls;

Dry wall clips are small pieces of hardware that function as structural backing / fastening for drywall. Drywall clips and stops can save wood and reduce labor. They are implemented here on top of the advanced framing option. It is assumed that partition wall intersections have one stud and eight drywall clips.

Double Wall

A double wall construction offers another option for improving the energy efficiency of wall construction by reducing thermal bridging and increasing depth for insulation in the wall. In this case a 2x4 structural wall is constructed with a second 2x4 wall inside. The distance between the walls is determined by the desired insulation value. In this case, the entire wall is modeled as 10 inches thick. The nominal insulation value in the cavity is R-40.

Staggered Stud (8-inch Staggered Stud Wall)

The 8-inch *Staggered Stud* wall provides another point of comparison based on alternative framing methods seeking to improve the energy efficiency of wall construction by reducing thermal bridging and increasing space for insulation in the wall. In this case, the wall thickness is established by 2x8 top and bottom plates. Two-by-four studs are placed 12-inches on-center, but are staggered. Every other stud aligns with the interior wall plane while the alternating studs align with the exterior. This allows nailing support for interior and exterior surfaces every 24 inches. The 7.25 inch wall cavity is filled with loose fiberglass or cellulose insulation at a density sufficient to prevent settling. The nominal insulating value in the wall cavity is R-30.

Structural Insulated Panels (SIPs Home)

Structural insulated panels (SIPs) are large, pre-fabricated wall panels containing insulation sandwiched between oriented strand board. These panels may reduce on-site construction waste, while leading to greater energy efficiency. The thicknesses of plywood and insulation varies, leading to a range of options that may balance material savings and energy savings. In the present case, it has been assumed a total weight of 1.25 Kg per square foot of SIP and that the insulation represents 15% of this weight. In this scenario, all exterior walls and ceiling have been replaced by SIPs. Although this allows for additional insulated attic space that might be used for ducting or other purposes, no changes in ducting were made in this scenario. Wall panels are specified at 6.5 inches overall thickness for an insulating value of R-23. Roof panels are 12.25 inches for R-46. Using roof panels increases the conditioned volume by 5,555 cu. ft. and the ceiling surface by 294 square feet. Air leakage is reduced to 5.0 air changes per hour (ACH) @50 Pascals.

Insulated Concrete Forms (ICFs Home)

Insulating concrete forms (ICFs) are hollow block that are stacked to create walls. Cavities in the foam insulation blocks are filled with concrete. They offer longer durability than standard wood framing, offering the potential for waste savings over the life of a home. In addition, they offer higher energy efficiency. In the present case, it has been assumed that the ICFs weigh 35 Kg per square foot of wall and that only 0.4% of this weight is the insulation, with the remainder being the concrete. In this scenario, all exterior walls have been replaced with ICFs. For the purposes of this assessment, the ICF is assumed to have 2.5 inches of foam insulation on each side for an assembly insulating value of R-24. As with SIPS, ICF does not have thermal bridges so this insulation is continuous across the entire wall surface. The ceiling and floor construction has not been changed from the base case. Air leakage has been set at 5.0 ACH@50 Pa using the same rationale as was used with SIPs.

Strawbale Home

In this scenario, strawbale construction replaces the wood-frame walls with bales of straw (such as from wheat, oats, etc.). It is assumed that 5.6 Kg of straw are needed per square foot of wall. The walls are covered by a layer of stucco or plaster. A timber frame design has been used for the structure of the home, which is typical for strawbale home designs.

Deconstruction, Restoration and Reuse (Mid and High)

These scenarios assume that material is reused among homes. When built, a given percentage of material is assumed to have been taken from a pre-existing home and when the home reaches it's end-of-life, it is assumed that the home is deconstructed, rather than being demolished, and that a percentage of material is salvaged for reuse in other applications. It has been assumed that additional electricity and worker time is needed to disassemble the home.

The baseline end-of-life routes of materials have been modified as listed in Appendix 9. The selection of these rates has been made based on assumptions regarding which materials are likely to be able to be reused and broad assumptions regarding the rates at which material reuse occurs. In making such determinations, input was considered from a deconstruction specialist.[2] Appendix 3 lists the assumptions regarding how much salvaged material of each material type can feasibly be taken from and incorporated into another home under

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[2] Brad Guy, Portland, Oregon.

the moderate and high versions of this scenario. For moderate, the general assumption is that materials that are eligible to be reused are reused at a rate of 33%, while 67% is assumed for the high version. The salvaged materials are assumed to be sourced from an average of 75 km away and to be shipped by a smaller truck than has been assumed for delivery of non-salvaged materials.[4]

Waste Prevention Home

The waste prevention home is modeled to demonstrate the benefits associated with the simultaneous implementation of as many environmentally advantageous waste prevention practices as possible. That is, the home incorporates a number of waste prevention practices examined in Phase 1 that show significant waste prevention benefits and that could be combined in one home. Practices inherently or potentially conflicting with other practices are not included; these are identified based on recommendations from industry experts. Overall, the goal is to evaluate the most realistic combination of practices that maximize waste prevention. The included practices are as follows:

- Advanced Floor Framing
- Advanced Framing (w/ drywall clips)
- Detailed Framing Cut List
- Design for Disassembly
- Utility Chase/Soffit
- Flashing and Rain Screening
- Durable roofing, siding and flooring
- Design using Salvaged Materials
- Proper Installation
- Smaller Homes (Waste Prevention home is 1149 ft2)
- Reusable Packaging
- Reduced Packaging
- Dematerializing and Design for Simplicity

High Performance Shell Home

To provide an ability to compare the potential benefits of a combination of practices aimed specifically at improving the shell of a home, the *High Performance Shell Home* is a home modeled with particularly high insulation and shell tightness. This model is partially based on the Oregon High Performance Home™ (HPH)[5] standard, which provides prescriptive path of building practices designed to achieve approximately 30% energy savings over a home built to the 2008 Oregon code. However, the HPH requires additional renewable energy features which were not included in the home modeled, as this study's focus is to evaluate different home construction methods and techniques, rather than the added benefits of onsite renewable power generation. Specifically, the *High Performance Shell Home* requires higher levels of ceiling, wall and underfloor insulation and less heat loss through windows than the *Medium Standard Home*, and also includes higher shell tightness. Further, duct placement is within conditioned space for additional energy savings. The elements of the building required to reach this threshold include: R-49 attics, wall heat loss of U-0.050 (which is equivalent to R-24), R-38 floor and windows at U-0.32.

Green Certified Home (with and without passive solar)

To provide an ability to compare the potential benefits of waste prevention practices with those that might be achieved by homes achieving an environmental certification, a scenario has been designed combining

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[4] The ReBuilding Center: www.rebuildingcenter.org/

[5] See *www.oregon.gov/ENERGY/CONS/BUS/docs/HPH_handout.pdf* for more detail on the Oregon High Performance Shell Home Program.

a variety of building practices to meet both Earth Advantage and LEED for Homes "certified" standards[[6][7]. The Green Certified home was designed to include principles of waste reduction (incorporating an appropriate selection of waste prevention practices), energy efficient design (including a slightly higher performance shell than the High Performance Shell Home), as well as some sun tempered design features. With the exception of these green building practices, other aspects of the home have been designed to be in keeping with the layout and functionality of the Extra-small *Standard Home*. Site-dependent measures, such as storm water retention, erosion control and landscaping, although a part of these certification programs, were excluded because they affect aspects of a home that are outside the scope of the project. The nominal insulating value in the wall cavity is R-30. Parallel path calculations determined the overall heat loss rate of the Green Certified Home wall assembly to be U-0.041 or R-25 for the entire assembly, including framing. The nominal insulating value in the wall cavity of the Green Certified home with passive solar is R-30. Parallel path calculations determined the overall heat loss rate of this assembly to be U-0.041 or R-25 for the entire assembly, including framing.

Durable Flooring, Roofing and Siding

To explore the potential impacts of benefits of substituting materials of greater durability, the materials list for the *Medium Standard Home* has been modified to include a steel roof (in place of 20-year asphalt shingle), fiber cement siding (in place of wood siding), wood flooring (in place of carpeting), and ceramic tile (in place of linoleum). Replacement rates for the original and replacement materials are listed in Appendix 4.

Optimized End of Life, excluding reuse (*Climate Change* optimized)

To provide a point of comparison between waste prevention options and waste treatment options, a scenario has been prepared where the best-performing waste treatment route for each material has been selected and all material of each type is assumed to be sent to its best-performing route. Because not all environmental impact types will agree with regard to which disposal route is best, it is impossible to establish a globally optimized set of disposal routes. The *Climate Change* indicator has therefore been used to establish the "optimal disposal" routes and it is therefore most useful to consider this benchmark as a comparison for *Climate Change* results. The fates of materials under this scenario are shown in Appendix 9. In short, all materials other than wood-derived products are sent to recycling, while wood-containing products are used to recover energy. It is anticipated that most other environmental indicators would favor a similar set of treatment options.

Average Homes

In addition to the "standard" home listed above for each size class and multi-family building size, a series of "average" scenarios have also been created. Whereas the *Standard* scenarios are intended to represent examples of homes that might actually exist, these *Average* scenarios are allowed to take on combinations of properties that better represent the population of homes, but are unlikely or impossible representations of a single home. For example, they may have fractions of various heating types, be assumed to be partly located in

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[6] In 2009, 689 homes were certified to Earth Advantage standards and approximately 16% of new homes built in Oregon that year met at least one of these two home certification standards.

[7] Under each of the green building standards the homes received sufficient "points" to be awarded certification, however, due to the exclusion of any non-design issues, nor any considerations that would be inconsistent with the scope of the *Standard Home* models (such as site issues), the homes, as modeled, do not meet the minimum point requirements in all of the areas examined by the certification standards simply because these issues were not evaluated. In reality, these additional points could be easily achieved without conflicting with the design of the home. The design can therefore be considered *capable* of achieving certification, but under these programs design alone is not sufficient to achieve certification.

various geographic zones, etc. These *Average* scenarios are used to more accurately reflect the properties of the population as a whole in ways that cannot be done within the context of the more realistic *Standard Homes*.

"Green Home" Certification Programs

The Earth Advantage and LEED programs are based on their own individual points systems. Green features are assigned points. When the feature is incorporated into the home and verified, those points are awarded. These third-party certification programs provide basic definitions of what green building means. Because the modeled Green Certified Home meets the minimum requirements of the two programs, it can safely be said that each the home meets minimum green building standards. This analysis is not intending to compare programs as every program allows points toward certification to be achieved in a variety of different areas (energy efficiency, water efficiency, site issues, indoor air quality etc.). Rather, the aim is to provide some supporting documentation regarding how to gauge the collective benefits of green features included in the overall design of this home. That is, it is intended that the certification information adds to the rigor of the home design rather than the home design appearing to be arbitrary.

The rating or score sheets for the evaluation of the 'Green Certified Home' modeled by the project team are included in Appendix 15 .This documents specific assumptions about the home model. As the focus was on the design, material selection and construction methods, major assumptions made were to only include building features that are integral to the design of the home as being eligible for 'points' under the two certification schemes. Obviously, due to the differences between the certification requirements the homes scored differently under each of the two rating systems. It is also of note that the home scored moderately under both methodologies, however, if other green building issues were considered such as site selection, landscaping, home-owner education, etc., this home has the potential to achieve higher ratings in each green building standard. The comparison here is limited to a subset of potential issues considered in green building standards as the scope of this study is limited to focus on waste prevention, design, material selection and construction methods, not site related issues.

It is important to note that the LCA analysis does not measure the impacts of certain features particularly well. For example, the toxicity of materials due to direct occupant exposure (and benefits associated with lower toxicity materials) has not been quantified for the features selected in the Green Certified Home. Additionally, certain things were not accounted for in the LCA model. For example, countertops with 25% or more recycled content (or made of reclaimed materials) have not been considered, due to the complications of modeling these materials, as well as the relatively small mass of these items relative to other materials used in the home. Finally, it should be noted that this home model incorporates many features also included in the Waste Prevention Home such as durable flooring (wood floors) and metal roofing, as well as similar construction techniques (such as advanced framing) that provide energy efficiency benefits.

III. Methodology

Overview of Project Approach

The project is divided into two stages in order to manage its complexity and to most efficiently achieve the goals of the study. The aim of the first phase is to inform the selection of a subset of construction practices to be evaluated in greater detail, while the second phase performs a robust analysis of the selected practices. This report provides the final results and includes outcomes from the first phase where warranted.

Phase 1

The purpose of Phase 1 is to efficiently screen the list of waste prevention practices to determine those with greatest potential to prevent waste and provide overall environmental benefit. Emphasis is placed on eliminating practices from further consideration while minimizing the risk of arriving at false negatives. It should be noted that exclusion of practices from Phase 2 does not necessarily indicate that they are not worthwhile practices to pursue or that substantial benefits might not be obtained from them. The impacts of the housing sector are quite large, and even an improvement of a few percent is substantial when considering all housing in the state.

In Phase 1, the potential waste prevention and environmental impacts from building activities are evaluated through a life cycle assessment (LCA). Using LCA in the screening process is of crucial importance because it avoids erroneous conclusions which might otherwise be reached using intuition, qualitative assumptions, or some other non-LCA based screening process. Nevertheless, these LCA-based calculations are conducted at a screening level only and are thus very limited in their application.

Phase 2

Following completion of Phase 1, a list of key areas for further focus is developed and priority questions are identified. These are listed in the above section “Key Questions Explored in Phase 2”. The scope of Phase 2 is established from these items. In addition, a variety of improvements are made to the underlying data employed in the calculations, most notably in nearly all of the life cycle inventory (LCI) data that are used to support the models.

The objectives of Phase 2 are to evaluate the impacts generated during the life cycle of (1) a typical home in Oregon under different construction scenarios and (2) the entire home population of Oregon. The latter includes all homes presently standing and those built until the end of 2030. Further description of this boundary is provided in the discussion of the home population model located in the following section.

LCA Modeling Methodology

The life cycle assessment model provides information at two scales: the level of an individual home and at the level of the population of all homes in the state of Oregon. Further, two categories of individual home assessments are conducted. The first is the assessment of a *Standard Home*, a home that is typical to the state of Oregon. The *Average Home* is the second model and uses a combination of the materials common to homes in the state. Further details describing these models are provided in the subsections below.

The evaluation of the building practices is accomplished using a combination of three models, as follows:

- A CAD (computer aided design) model of the building structure created by the Oregon Home Builders Association to represent a standard Oregon home and inform decisions on the implications of building practices on material use;
- REM/Rate, commercially available software capable of estimating home energy use based on a wide variety of inputs regarding the home's structure, equipment, geography, and numerous other factors[10]; and
- A customized LCA-based calculation system created for this project in MS Excel. This LCA model includes a component that considers the total population of homes within the state. Supporting LCA work is conducted in the SimaPro commercial LCA software.

A detailed description of each of the three modeling stages in the assessment is provided in Appendices 3, 4, and 5, along with a wide variety of the underlying assumptions and sources of information.

The outputs of the OHBA model are used to parameterize REM/Rate, which is then implemented to assess the home's annual energy usage. The energy consumption is estimated to include heating/cooling energy, water heating, lighting, appliance energy, and all other uses of electricity11. It is assumed that the *Standard Home* has a natural gas furnace with forced air heating and no air conditioning.

REM/Rate provides estimates of the average annual energy use of the home and, very importantly, is able to account for differences in the energy use based on many of the practices evaluated here. As prior LCA results on housing (e.g., Scheuer and Keoleian (2002), Peuportier (2001), Mithrarante and Vale (2002) and others; see the attached bibliography) indicate that the majority of environmental impacts occur from the use of energy during occupation, a more accurate system for determining differences in energy use is critical for the present study. Further details on the selection and operation of REM/Rate are included in Appendix 4 and from the Web site of the software developer.12 While REM/Rate is not without its faults, it is the experience of Earth Advantage (a national leader in home energy rating) that other available options have as many or

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[10] For all home scenarios, either direct estimates are made of energy use based on REM/Rate, or the energy use is assumed to be the same as the *Medium Standard Home* in cases where the changes to the home do not affect any inputs to the energy modeling software.

[11] The REM/Rate model is employed to estimate this electricity usage for each scenario and bases its estimation by matching home characteristics to a large body of data collected from existing homes. The apparent differences in these homes might just as likely be coincidental as causal, meaning that it could be a characteristic of the inhabitant's behavior that might not necessarily change by changing the home characteristic in question. This should be kept in mind when viewing these results.

[12] Architectural Energy Corporation, www.archenergy.com

more uncertainties. Recent benchmarking by Earth Advantage suggests that REM/Rate is sufficiently accurate for new construction.

The building material lists provided by the OHBA model and the energy use provided by REM/Rate are used to characterize the building practice scenarios within the LCA modeling framework. The LCA model is constructed to represent the total environmental impacts of producing all materials used in building and maintaining the home, transporting these materials to and from the home's location, the energy use of the home's occupants, the maintenance of the structure, its demolition, and the end-of-life processing of the materials. This is done by linking material, energy, and process inventories for the home with preexisting or modified data that represent the impacts of producing, using, or disposing of materials and energy.

It should be recognized that this model uses a steady-state approach, implying that the quantity of annual impacts is assumed to be the same for each year of occupancy. 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.

The modeling in this study is conducted to maximize applicability within the state of Oregon, and it should be noted that the assumptions made may limit the value of applying the results to other geographies. The housing design is based on current practices and codes within Oregon, and the energy modeling is based on typical Oregon climate. In addition, many sources of data are selected with an intention that they would be highly representative of Oregon, including, for example, the rates of waste disposal routes for various materials, the waste-to-energy processing of wood, wood product production, energy costs, home maintenance rates, and others. While some conclusions may be broadly applicable, others may be less applicable beyond Oregon conditions.

The Individual Home Models

The Medium Standard Home

The *Medium Standard Home* is a theoretical residence whose characteristics are selected to represent a relatively standard new construction home of average size in Oregon and meeting the minimal Oregon building code requirements. This home has a conditioned floor area of 2,262 square feet (210 square meters), which is slightly smaller, but near the average size of a newly constructed single-family home in the United States.13

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[13] The U.S. Census reports that in 2008, the U.S. average for new home construction was 2,534 square feet (www.census.gov). The 2,262 square feet counts only living space and does not include the area of the home's attached garage.

Characteristics of the *Standard Home* are selected based on the need to balance a number of important criteria, the most prominent of which are (1) a desire to represent the most common characteristics and practices presently employed in new-construction homes within the state and (2) a need to be able to use the standard as a backdrop for evaluating the waste prevention practices identified. The resulting *Standard Home* scenario is intended to represent a typical--but not optimal--new construction home in Oregon. There are many possible formats for such a typical baseline home, and while it is acknowledged that alternative baseline layouts could modify the results of the present study, it is assumed that the conclusions of this study are not sensitive to layout variations within the range of typical homes.

The standard residence is the baseline against which all waste prevention practices are evaluated. Thus, all environmental benefits or impacts of any given waste prevention practice are relative to the environmental performance of the *Standard Home*.

Figure 6 shows a view of the exterior of the *Standard Home*, while Figure 7 shows the layout in the interior.

Table 4 lists several key characteristics of the *Standard Home*.

Additional materials are added to the home's material inventory to better represent a typical new construction home at the time of its first occupation (and that would typically be transferred to the new owner during subsequent sales). This includes finish carpentry, electrical and plumbing fixtures, flooring, paint, and major appliances. With the exception of attached structures (including a garage and porch), no external structures or aspects of the home's yard are considered. To determine the influence of size on a home's environmental profile, a comparison is performed between "standard" homes of various sizes. The evaluation includes an extra small (1,149 ft2), small (1,633 ft2), medium (2,262 ft2), and large (3,424 ft2) residences. Appropriate bills of materials (BOM's) and energy models are developed to assess each home. For the comparisons of building practices, the medium home, as described earlier, is employed unless otherwise noted.

Figure 6: Exterior view of the *Standard Home* modeled in this study

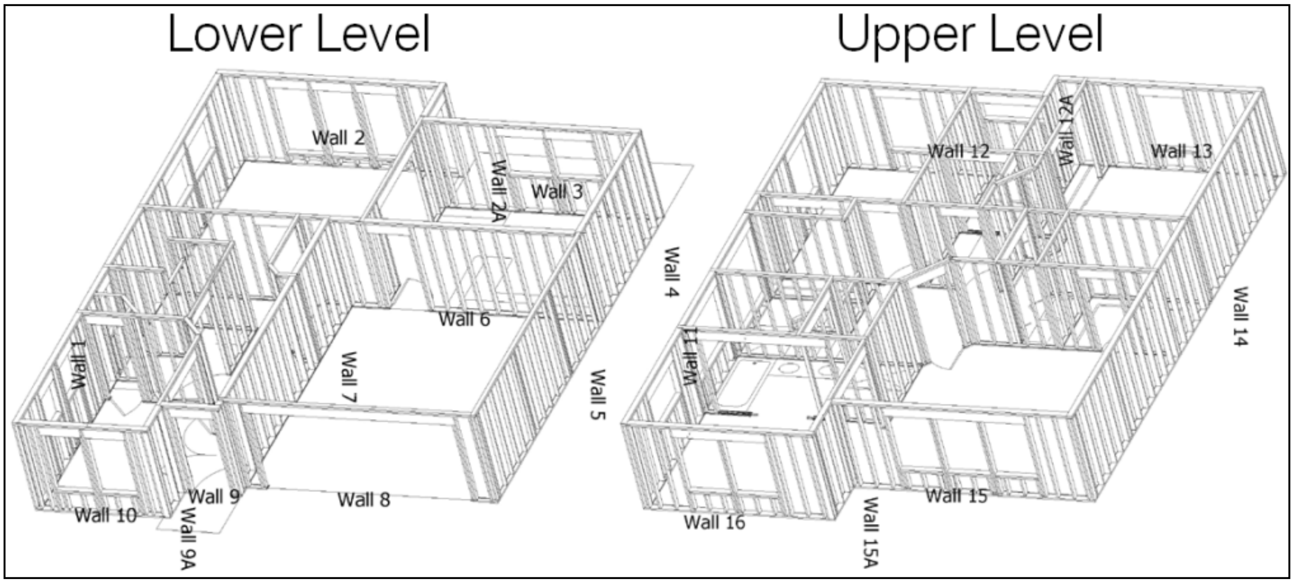

Figure 7: Interior view of the *Standard Home* modeled in this study

Table 4: Characteristics of the *Standard Home* modeled in this study

Characteristic	Description
Location	Portland, Oregon USA
Interior Size	2,262 square feet
Exterior Dimensions	33 ft x 35 ft
Stories	2
Garage	Yes, attached
Foundation	Vented crawl space
Conditioned Building Volume:	20358 ft^3
Bedrooms	3
Bathrooms	2
Framed Floor Insulation	R30 fiberglass
Walls Insulation	R21 fiberglass, framing factor 26%
Ceiling Insulation	R38 fiberglass
Windows	Double-glazed, low-e, vinyl frame, U-0.35; 374 ft^2 of windows, minimal solar gain orientation
Doors	2¼-in solid wood, R2.8
Heating	90% efficient gas furnace
Water Heating	58% efficient gas storage tank
Building Standards	Oregon building code minimum
Air Conditioning	None
Flooring	2,000 ft^2 carpet, 200 ft^{2}linoleum
Roofing	Asphalt shingles
Roof Truss	Standard truss
Duct Leakage	RESNET/HERS default, all leakage outside of thermal envelope
Building Air Leakage	6.5 ACH@50 Pascals
Siding	2124 ft^{2}of wood siding
Lifespan of House	70 years
Walls	92-5/8-in studs; 8’1” height; single sole/double top plates, headers on all
Floor Framing Style	Post and beam
Floors	4” x 8” beams[14],, 32” on-center,[15] plywood subfloors

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[15] Although other alternatives are available, the 4”x8” beams at 32” O.C. has been chosen because it still achieves a high level of the market share in Oregon. An estimate of the Oregon Home Builders Association is that as many as half of the non-I-beam floors built today use this floor framing. Although a R-30 bat insulation must be slightly compressed to fit within a 4” x 8” beam size, installing this insulation with slight compression is common and allowed within the building code.

Characteristic	Description
Wall Interiors	Drywall
Appliances Modeled for Material Production Impacts in Phase I	Furnace, Refrigerator, Stove, Dishwasher, Water Heater
Plumbing	PEX

The Average Homes

The *Average Home*s are a series of home model developed by averaging the properties of homes across the state, specifically home size and building practices, such that the resulting bill of materials and energy models are combinations of all commonly employed materials and energy sources in Oregon. For instance, assuming that 50% of homes in Oregon use carpeting and 50% use wood, half the square footage of the *Average Home* is assumed to be covered in carpet, while the remaining half is covered in wood. Therefore, this model does not emulate a real home but an average of home properties in Oregon. Table 5 shows the home components where an average is employed; all other aspects of the home are considered to be approximately the same as the *Standard Home*s.

*Average Home*s have been created in the four size categories defined, and for the three sizes of multi-family structures. In addition, different *Average Home* models are employed for new-construction (i.e., post-2010) and pre-existing (pre-2010) homes to reflect an expected difference in energy efficiency among these homes.

Modeling the Population of Homes

The total impact of the housing sector in Oregon is computed to highlight the potential impact of housing trends that might be affected by waste prevention policies when applied at the level of the entire state. These impacts are calculated by scaling up the impacts generated by the average residences in Oregon.

This is accomplished by first classifying the existing housing stock with regard to the size distribution of single-family homes (four size classes considered), home type[16] (single or multi-

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[16] While a broad range of home characteristics have been considered here, the home population within the State of Oregon is very diverse and there are a subset of homes that are clearly poorly represented within the home characteristics that have been defined. For example, census data indicates that as much as 10% of structures are mobile homes, vans and boats, all of which are fundamentally different than the wood-frame housing used to represent the home population. In addition, very large multi-family buildings are poorly represented by the larger size wood frame multi-family building represented here. Despite the poor match of these homes within the set of options considered, their number has not been removed from the population of

family ; three building sizes considered), heating and cooling type, and geographic zone. These classifications are based primarily on data gathered from the US Census Bureau's data on the state of Oregon and on information collected by the American Housing Survey on the Portland metropolitan area. This forms the starting point for the estimation of growth in housing numbers and changes in characteristics.

Modeling of materials and energy consumption is performed to identify the life cycle attributes of home of each of the 7 sizes (4 single-family and 3 multi-family) for each of two geographic zones and two fuel types, three heating systems, and with or without air conditioning (84 options), which are further divided to distinguish between pre-existing homes (i.e., homes built before 2010) and those constructed within the "period of action" (i.e., 2010 or later) to yield 168 options in total. Pre-existing homes are assumed, on average, to have a 20% less thermal energy efficiency.[17,18] There are therefore 84 types of homes that determine the properties of the *Average Home*. Energy consumption is the only difference between the characteristics of the new construction and pre-existing homes (although the portion of their life cycle considered within the scope also differs, see below under Boundaries for Calculations Regarding State-wide Home Population). All other characteristics, such as materials and other aspects of use during occupancy are assumed to be equal.

The pre-existing and new-construction *Average Home* properties in 2010 are determined based on a weighting of the above 84 options within each category. The weight is based on prominence in the population of total homes based on home census data. The stock of homes is assumed to grow and change during the 20-year period of action based on the best available information that can be obtained to estimate likely rates of growth and in what sizes and types of homes growth will occur.

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homes. That is, it has been chosen to accept that they are poorly represented, rather than to exclude them from the scope of the project.

[17] Because of confounding factors, such as a significant change in home size with time, and because pre-existing homes may or may not have been modified or updated in a variety of ways that affect their energy efficiency, it is very difficult to answer the question of how much more energy efficient, on average, a home built today is versus a home existing today of a similar type (size, etc.) but built at some time in the past. Various opinions among the project team indicate that improvements in the building code since 1975 have caused at least a 20% improvement in energy efficiency of new homes over the past 35 years.

[18] As described earlier, the study scope considers only the portion of the life cycle of the state's homes occurring after 2010 for homes built prior to 2030. This is the home population over which it is assumed that decisions or actions based on the current analysis might reasonably be based and during which policy-decisions made in the near future are likely to have influence. The construction of new homes that are considered within the study scope therefore ceases in 2030. It is assumed that beyond that point, the home technologies considered here may be significantly outdated and better information will be needed to guide action.

The standard set of assumptions is that the average square footage of newly constructed homes will grow by 1% per year over the coming 20 years. Other characteristics of the population, such as sources of heating fuel and division among single and multi-family homes are assumed to not change during the "period of action."

This growth rate is applied to determine a number of homes added to the population each year during the period of action. The rates and direction of change in housing type and characteristics are highly uncertain. For example, while past trends and some future predictions have shown a strong and steady move toward larger and larger homes, a recent report by the Northwest Power and Conservation Council suggests at least a possibility that home size may decline in the coming 20 years due to a significant growth in the retirement-age portion of the population.[19]

The best available data is used to estimate the rate of loss of homes from both the pre-existing housing stock and from new construction taking place during and beyond the period of action. This information, combined with the number of homes added is used to determine the number of existing homes each year until a point in the future at which the great majority of homes will have been demolished and the environmental influence of housing decisions made during or prior to the period of action will have become negligible. In cases where the total impact of the home population is shown, it is based on a 200-year timeframe (i.e., through 2210)

The estimates of numbers of homes of each type for each year are combined with the estimates of the impacts of each home type during the time-frame prior to its occupation (pre-occupancy), during its occupation, and afterward (post-occupancy) to estimate the total impacts arising from the residential housing stock each year and over the total period considered. The impacts occurring in year A are calculated as follows.

The impacts occurring in year A =

(Per annum occupancy impacts of pre-2010 homes * number of pre-existing homes in year A)
\+ (Per annum occupancy impacts for 2010-2030 homes * number of homes built prior to year A)
\+ (Pre-occupancy impacts for homes built in year A * number of homes built in year A)
\+ (Post-occupancy impacts for pre-2010 homes*number of pre-existing homes lost in year A)
\+ (Post-occupancy impacts for 2010-2030 homes * number of homes lost in year A from each year)

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[19] Northwest Power and Conservation Council's 6th Northwest Power Plan.

Table 5: Characteristics considered in developing the *Average Home* profiles

Characteristic	Division among single-family and multi-family	Division among single-family home sizes[20]	Division among multi-family building sizes	Geography	Air conditioning	Heating fuel type	Flooring and cladding materials
Beginning distribution	76.9% single-family 23.1% multi-family	27.8% Extra-small (<1400 sqft) 25.1% Small (1400 – 1950 sqft) 34.7 % Medium (1950 - 2850 sqft) 12.4% Large (>2850 sqft)	31.1% 2-5 Unit (1950 – 2850 sqft units) 18.6% 6-10 Unit (<1400 sqft units) 50.2% >10 Units (<1400 sqft untis)	87% Valley 13% Central	80% No air conditioning 20% with air conditioning	50% Natural gas furnace 10% Electric heat pumps 40% Electric zonal heat	50% Carpeting and linoleum tile 50% Wood and ceramic tile 50% Wood siding 50% Cement fiber shingle
Assumed change during "period of action"	None	Change based on 1% annual growth in in average size	No change	No change	No change	No change	No change

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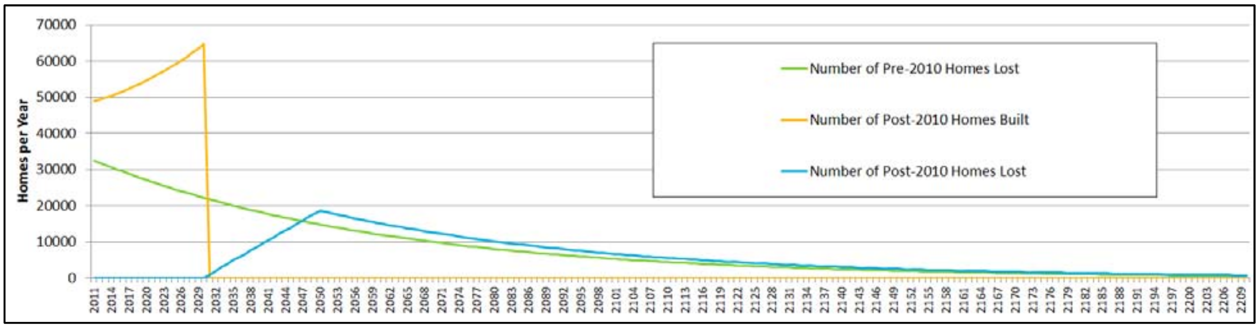
[20] Adapted from information in the American Housing Survey (http://www.census.gov/hhes/www/housing/ahs/ahs.html)

Based on this method, the total impacts of residential homes within the study scope are calculated by summing the results for each year. The calculation is terminated in year 2210 (200 years from the start of this project), at which point the annual impacts represent only 5% of the highest annual impact generated by the housing stock under question (they have declined 95% from their peak).

Additional scenarios are conducted to examine the importance of certain assumptions or to evaluate the outcomes of possible future trends. For example, more of the future housing stock is shifted from larger homes to smaller homes to illustrate the potential benefits of actions that could encourage such a shift. Such analyses, along with assessments of the various single-home models are the primary basis for the conclusions of the study.

As described above, the population of housing units is modeled based on the current number of housing units in Oregon and assumed rates of new home construction and demolition of existing housing units. The numbers of units constructed and demolished each year under the baseline assumptions are shown in Figure 8.[21] Note that following a 20-year period following construction in which demolition is considered to not occur, homes then have a 2% probability of being demolished each year. This explains the gradual increase and then decline in the number of homes from this population lost per year.

Figure 8: Projected number of homes constructed and demolished each year



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[21] As described earlier, the study scope considers only the portion of the life cycle of the state's homes occurring after 2010 for homes built prior to 2030. This is the home population over which it is assumed that decisions or actions based on the current analysis might reasonably be based and during which policy-decisions made in the near future are likely to have influence. The construction of new homes that are considered within the study scope therefore ceases in 2030. It is assumed that beyond that point, the home technologies considered here may be significantly outdated and better information will be needed to guide action.

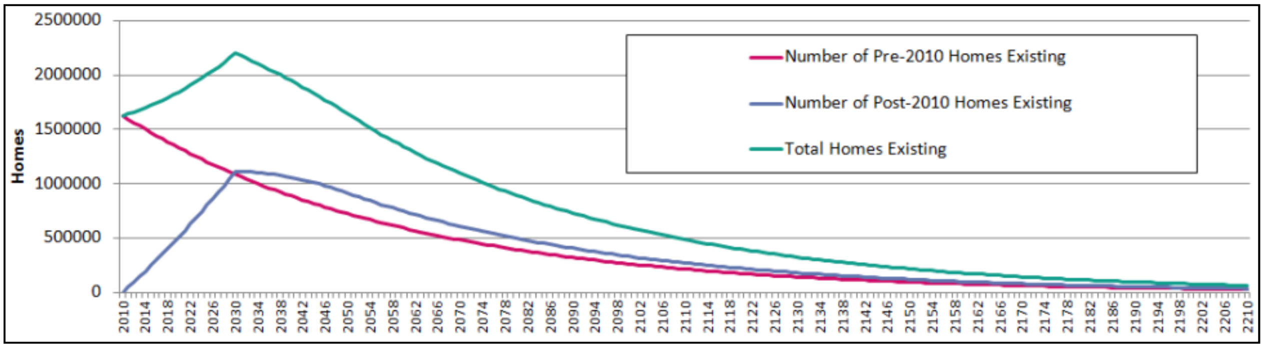

Figure 9: Projected Number of Pre-2010 and Post-2010 homes existing each year

The total number of homes within the study scope existing each year is shown in Figure 9, including both pre-2010 homes and post-2010 homes.

Note that under the baseline scenario (Figure 9), post-2010 homes comprise approximately 50% of all homes by 2030. This ratio is highly sensitive to assumptions about future rates of home construction and demolition.

These populations are divided among types of homes based on their size, number of residences per building, geography, and heating and cooling equipment. The number of homes in each category is used to determine the total impact of the population, assuming unchanged patterns of development (for example, assuming the trend for slightly larger *Average Home* size on an annual basis).

Study Boundaries

The life cycle of the home is divided into the stages depicted in Figure 10 . Materials production is divided into two components, one representing the original materials and one representing the replacement materials. The material end-of-life stage includes materials disposed of at the beginning of the home's life, as well as during maintenance and at demolition.

The boundaries of the study are intended to include all impacts within the production chain of the materials, energy, and processes that comprise the home's life cycle. For example, in calculating the carbon dioxide (CO_2) emissions from the combustion of natural gas, not only are the direct emissions from the furnace considered but those emissions occurring in the production of the gas are also included. Similarly, impacts caused by the lumber used in the home is a sum of impacts generated by all process in lumber production[22], including forestry activities and production of the materials and fuels used in forestry.

Aspect	Pre-occupancy	Occupancy	Post-occupancy
Extraction of original raw materials	1. Production of Original Materials	2. Production of Replacement Materials	
Refining raw materials			
Manufacture of products			
Production of packaging			
Transportation occurring upstream of the material supplier			
Transportation of materials from production site to site of the home	3. Transportation		
Operation of heavy machinery	4. Construction	5. Maintenance	9. Demolition
Use of electricity by construction-related activities			
Transportation of construction workers to and from the home site			
Natural gas used for heating		6. Heating and Cooling	
Electricity used for heating			
Electricity used for cooling			
All home electricity use other than for heating and cooling		7. Electricity Use	
Production/ delivery of municipal water		8. Water Use, Heating, Treatment	
Fuel for heating water			
Treatment of waste water			
Transport of materials from the site	10. End-of-Life		
Landfilling of materials			
Recycling of materials			
Incineration and/or energy recovery			
Reuse of materials			

Figure 10: Aspects represented in each stage of the home's life cycle

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[22] The information used to represent the production of most wood products is represented based on data from the Consortium for Research on Renewable Industrial Materials (CORRIM, www.corrim.org). This information is assembled based on the growth of wood in the Pacific Northwest and Southeast United States. Where there is an ability to select among these geographies, the Pacific Northwest data produced is chosen. No specific forestry practices or certification procedures are indicated to be the focus of the CORRIM project. It is therefore assumed that the data represent the typical wood and wood product production in those regions. It is not known how the results might vary under alternative forestry conditions, such as the use of forestry products certified to be raised with certain practices or forestry products from other geographies where growth conditions could be substantially different.

To efficiently carry out this complex scope of work and provide ability to assess the specific issues under consideration, simplifications are made where the certainty of the outcomes is not greatly sacrificed. However, a strict cutoff threshold is not applied, and any materials for which reasonable estimates can be made on the amount of material used and supporting LCA data of reasonable quality could be obtained.

Other aspects of home habitation, including for example the personal possessions of the occupants, are not considered within the life cycle of the home. However, the line between a component of the home and a possession of the inhabitants is not always distinct. In the present study, those items that would typically be included with a home when it is sold or rented are included; any other furnishings or other property of the homeowners are excluded. Therefore, major appliances (e.g., refrigerator, furnace) and lighting fixtures are included, while chairs, wall hangings, and minor appliances (e.g., toasters, televisions) are excluded. The text box in the Results: Home Size section discusses this issue further.

It should be highlighted that the analysis done here does not consider potential health effects on the inhabitants of a given home. Data regarding, for example, the gasses released within a home from building materials and resulting exposure on inhabitants is not well enough established to include application within the present project.

Uptake of carbon dioxide by biota in addition to the release of this carbon dioxide over time23 (e.g., during wood product incineration) are excluded from the study. Were this information to be included, it is anticipated that no change in the results would occur over the full life cycle, due to the inclusion of uptake and release that are of equal magnitude and opposite direction. The timing of carbon uptake and release is a potentially important issue that should be noted. In some cases, carbon is being stored for decades or even centuries in homes and landfills before its eventual re-emission. However, the present project does not differentiate in the magnitude of an emission or impact based on when the emission or impact occurs.

This study does not consider any impacts associated with the direct occupation of land area by the home (such as on fragmenting or limiting wildlife habitat), impacts associated with daily transportation of the residents, or any indirect effects through development patterns (such as additional traffic congestion and utility infrastructure).

Figure 11 depicts the scope of activities that are included within the boundary of the calculations made regarding the entire population of homes within the state. For the analysis of the provision of housing for the state of Oregon as a whole, all activities are included that occur after 2010 and relate to structures constructed prior to 2031, as depicted in Figure 1. Housing constructed after

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[23] Note that the release of methane from biological matter is accounted for, as this is a more potent greenhouse gas. The weighting factor for methane is adjusted to reflect the original uptake of CO_2

2030 is not considered because it is assumed that policy-related or other decisions made at the present time will likely be modified based on changing conditions, technologies and decision-making ability within the coming two decades. These 20 years are assumed to be a "period of action" over which the present-day decision makers have significant influence. Although new homes constructed after 2030 are not considered, the impacts occurring after 2030 of homes constructed prior to 2031 are considered because the decisions that influence the form of these homes will continue to have consequences over the life of the homes. In actuality, the total quantity of impacts from all homes in Oregon after 2030 will be greater than reported in this document.

Data Sources

Life cycle data used for this project are primarily drawn from the ecoinvent database (v2.01; ecoinvent, 2007), although the datasets are modified, using SimaPro software, so that all processes utilize the US electrical grid mix in place of all other regional electricity sources throughout all background processes. For example, when electricity is used to produce steel that is used in the home, or to produce steel that is in the supply chain of another commodity used in the home, the assumption is made that this electricity is always being supplied by the US electrical grid. In addition, the U.S. LCI database (NREL, 2008) and the BEES database (NIST, 2008) are implemented where ecoinvent provides no data or data that is less suitable. For example, wood production data sources from the U.S. LCI database because it is believed to be of particularly high quality and best represents U.S. wood production. Data sources are detailed in Appendix 10.

A variety of other information is garnered from literature review, database searches, team expertise, vendor product data, and interviews with experts, among other sources. This data includes information on material sizes and densities, costs, residential building characteristics, construction practices, material replacement rates and causes, material waste amounts and processing, transportation logistics, and aspects specific to many of the scenarios examined, among other information. An annotated bibliography (Appendix 19) is assembled to catalogue available sources of information to support the project.

Where data is either unavailable or incomplete, professional judgments or estimates are made by team members who have expertise in the residential building sector. To maintain transparency and credibility within this study,

Table 6 lists these instances.

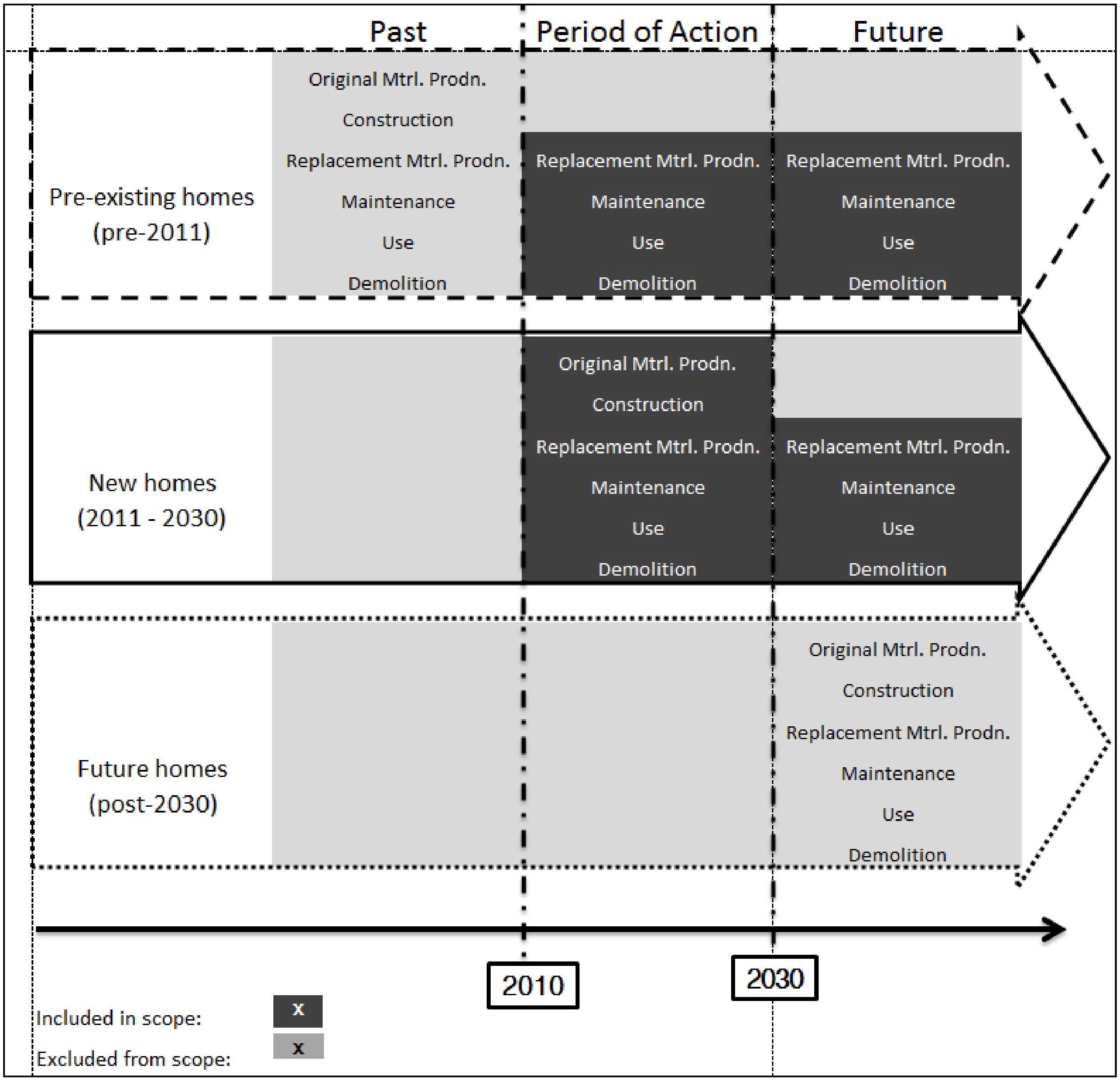

Figure 11: Boundaries of the assessment of pre-existing and new construction homes within the Oregon home population

Table 6: Key areas in which subjective decisions are made in performing the LCA.

Topic area	Basis for Decision or Judgment
Selection of waste prevention practices	The experience of Oregon DEQ's staff in investigating potential options for reducing waste from the residential construction sector.
Design of *Standard Home*	Expertise of Oregon Home Builders Association regarding current building codes, practices and trends in Oregon, complemented by expertise of Earth Advantage and ODEQ in these area.
Design specification of implementing practices	Expertise of OHBA and EAI in common green building practices applied in Oregon. Expertise of OHBA in home design.
Choice of where to exchange detail for efficiency in screening-level Phase 1 LCA	Expertise of Quantis in assessing complex systems with an LCA approach.
Assumptions for activities of workers and Assumptions for activities of workers and machinery during construction, maintenance and demolition	Rough approximations confirmed by the experience of OHBA Rough approximations confirmed by the experience of OHBA in residential home building.
Transportation distances of materials to the building site	Approximation made by the Oregon DEQ based on experience in examining various transportation networks.

Data Quality and Uncertainty

The quality of the results provided from any analysis is dependent on the quality of the information used to produce them. In the present case, a wide variety of data has been drawn from a range of sources and combined to produce the present analysis. Much of this data has been taken out of its original context and applied here in what may be a slightly different context and purpose than that for which it is intended. When seeking and choosing among data, one must consider factors such as the expected accuracy of the data in measuring what it has been intended to measure (i.e., within its original context), the geographic relevance of the data's context to the present case, the temporal relevance, the technological relevance (whether it is describing a similar system), and the consistency of data origin and properties with the other available data.

The project goal regarding data quality has been to assemble the best available combined body of data for the project among that available at the start of the project. Data can generally be divided into that data which describes the amount of flows of materials and energy within the housing systems modeled, and that data which describes the environmental impacts of these flows. In assembling information about the flows, highest priority has been given achieving geographic, temporal and technological relevance, while ensuring a very high level of consistency in those aspects that will differ among scenarios—and therefore are likely to be strong determinants of conclusions. In obtaining data to represent the environmental impact of material and energy flows, the strongest emphasis has been placed on creating a dataset that is internally consistent (drawn from similar data sources, created with similar methods, and applying the same data where similar processes are involved), with updates made where feasible to reflect the temporal, geographic and technological contexts of the project.

The project has produced primary data regarding the material and energy flows used in the lifecycle of various scenarios of residential homes. Because of the expected sensitivity of the desired results to changes in materials and energy use among various scenarios, the amount of material used among housing types and building practices and the implications of these housing forms on energy use are crucial elements for which to have not only high quality information, but information that is very consistent in its origin and properties across scenarios. Therefore, the primary data production under the project has focused on creating CAD models of various home types and of making energy use estimates based on these models.

Some specific assumptions made in the project are listed in the below section. Appendix 15 provides a more detailed assessment of the quality of various data sources, as well as identifying those that are anticipated to be important areas of uncertainty. Because of its breadth and attempt to predict conditions of an inherently unknown future state, the present project is subject to high levels of uncertainty. While methods exists to treat uncertainty in quantitative—or at least semi-quantitative—terms in LCA, the present project scope of work has not allowed for this to be done systematically. Because many of the most important uncertainties are of those regarding specific assumptions and conditions, sensitivity tests have been applied in several cases to illustrate the magnitude of such uncertainties.

Study Assumptions

Numerous assumptions are made throughout this study. Presented in this section are topics universal to the LCA, while assumptions specific to components of the LCA are described in appropriate sections, such as the already-presented sections on the standard and *Average Home*s.

Home Lifetime

It is assumed that each *Standard Home* lasts 70 years. At this point, it is demolished, and the materials are transported to their end-of-life fates, as described later. For the consideration of population-level impacts, removal of homes is modeled as an exponential decay of 2% per year, resulting in an average life in a similar range to the *Standard Home*, but with a distribution extending out to several hundred years for a small minority of structures.

Changing Conditions

The life cycle assessment model created here represents conditions taking place over many decades. It is nearly certain that many aspects of home construction, maintenance and energy efficiency will chain in important ways during this period. In addition, the external conditions in which the home exists will change, such as the production technologies used to provide energy to the home and to power various industrial processes occurring in providing material to the home. Within the approach taken here, these changing aspects have been assumed to remain static, partly due to very high uncertainty regarding in what manner, to what extent and with what pace they will change, and partly due to added modeling complications in representing homes or populations of homes in more dynamically changing situations. It should be recognized that this is a very important source of uncertainty regarding the outcomes of the present project.

Material and Processes

A bill of materials (BOM) for each home is established based on a detailed CAD (computer-aided design) model of the *Standard Home* created by OHBA. Additional materials are added to this list to represent some of the finishing elements, such as appliances and lighting fixtures. The full BOM for all scenarios is included in Appendix 9. The total amount of each material being used by a home each year is determined based on an estimate of the amount used in the home, a waste factor and a replacement schedule, which is determined based on a typical annual replacement rate. These replacement rates are determined primarily by interpretation of data from the American Home Survey and are crossed referenced with other data sources that can be found to assess their validity. The waste factor defines an additional amount of material that is brought to the construction site and discarded due to factory defects or damage and waste incurred via transport or on site; further details are provided in the next section. Movement of materials from the home to end-of-life is tracked throughout the life of the home, including construction and maintenance wastes (such as replaced materials), as well as at the time of demolition.

Material packaging is assumed to total 1,200 pounds for the life of the home. This is consistent with the estimates of studies of waste content from residential construction sites (Laquatra and Pierce, 2002). For simplicity, the packaging weight is evenly divided among corrugated cardboard, flexible plastic packaging (LDPE), and rigid plastic packaging (polystyrene).

Waste Factors

The waste factors are set to 15%, 5%, or 0% for all materials in the *Standard Home*. Zero percent is used for those materials in which there is no reason to expect a certain percent is wasted (e.g., furnaces). 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). For the reuse of salvaged materials, a waste factor is applied identical to that used for the equivalent amount of non-salvaged material. These waste factors have been based on the expert judgment of staff at the Oregon Home Builders Association.

For the scenarios of Detailed Cut List and Prefabricated Components, these estimates are revised downward for some materials, due to the waste reduction outcomes associated with this practice (see Appendix 7 for specifics).

Replacement Schedules and Rates

Each material in the home is assumed to be replaced over time based on a replacement rate (which can be equal to zero, indicating no replacement, for certain components such as foundation concrete and steel roofing). The information supporting replacement rates is primarily drawn and interpreted from the American Housing Survey.24 Replacement is implemented as an annual average rate of replacement and is specific to each material and to each material's application. For example, lumber used in walls is specified with a different rate than gypsum plasterboard used in walls, which has a different rate than lumber used in flooring.

The rate of replacement is divided into five primary causes, which reflect various reasons a homeowner might replace components and which might be impacted by the waste prevention scenarios under consideration. These include:

- replacement due to deterioration (i.e., the item wears out);
- replacement due to water damage from outside;
- replacement due to water damage from inside;
- replacement due to improper installation; and
- replacement due to owner's preference (i.e., remodeling for no other reason).

The total replacement rate is the sum of these individual rates.

Replacement of a material is distributed over the life of the home. For example, if the home will receive three replacement asphalt shingle roofs over its lifetime (e.g., at 20, 40, and 60 years), it is assumed to receive 4.29% (3/70) of a new roof each year. Calculating the replacements in this manner leads to some absurdities when considering a single home (none of which would actually have 4.29% of a roof replaced each year for 70 years) but offers a substantial benefit by avoiding the large gradations that occur in assuming an all-or-none replacement. For example, if assuming a new roof every 20 years, after extending the life to 24 years (at which point 2 replacements over the 70-year home lifetime would suffice rather than 3), a further lengthening of roof life would not be evident until it is lengthened to 35 years (at which point only one replacement occurs) in the all-or-none approach. Differences of any size can be reflected in the continuous approach. This difference is important in assessing some of the waste prevention scenarios which modify these replacement rates. Further, it is reasonable over a population of homes to assume a gradual replacement rate because the actual timing of replacement varies and homes are being continuously built and therefore at a variety of ages at any given time.

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[24] U.S. Census Bureau (www.census.gov/hhes/www/housing/ahs/ahs.html)

Data to support the quantification of each of these replacement causes is chiefly assembled from the American Housing Survey data for the Portland metropolitan area. In interpreting the data, many assumptions are made. The replacement rates that are used and the supporting rationale are given in Appendix 8.

Transportation of Building Materials

Material 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 most accurately quantified based on the product of distance and weight (e.g., metric ton-kilometers).

Material mass is calculated based on manufacturer's specified shipping weights or calculations using material dimensions and density. Most materials are assumed to travel 1,500 km (932 miles) from the site of production to the building site. Exceptions to this include cement, gravel, sand and lumber, each of which are assumed to be transported only 300 km (186 miles) from production to the site of the home. It is assumed a distance of 72 km (45 miles) is traveled at end-of-life to move the materials to their eventual disposal or processing location. While the 1,500 km (933 miles) and 300 km (186 miles) values are assumptions[25], the 72 km (45 miles) is a figure provided by Oregon DEQ staff and represents the average distance materials are hauled to disposal sites in the state. It is assumed that the same transportation takes place for other end-of-life fates (i.e., recycling).

All transportation occurring upstream of the manufacturing facility is included in materials production and is not calculated discretely in this study. These values are described in the ecoinvent database.

For all home and home population models, transportation weight is modified according to modifications in the BOM. No scenarios change the assumed transportation distances.

Heating Energy Source

Electricity is an important factor in the overall impact of the home throughout its life cycle, primarily due to it consumption by the home's inhabitants such as lighting, appliances and plug loads. For electricity production, the average U.S. grid dataset is employed (see the text box below: Discussion of GWP and eGrid / Ecoinvent). For individual homes (all the *Standard Home*s and individual home model scenarios), natural gas is the assumed heating fuel although some electricity is also calculated for the operation of fans associated with the heating system. In representing the

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[25] The 1500 and 300 km figures have been determined by the project team based on their experience in the building industry and other industries. The actual distances traveled by materials is likely to vary substantially and so these are chosen to be representative distances in the absence of an ability to identify a true average distance for the materials in question over the time period covered.

Average Home (and thus the population of homes), both natural gas and electrical heating (including a division among electric heat pumps and zonal electric heating) are included; this distribution is shown in Table 2. For electricity production, the average U.S. grid dataset is employed.

Water Use, Heating and Treatment

The use of municipal water services by the home has been included in the lifecycle. Modeling of water supply and treatment is represented based on municipal water treatment systems that are represented in the Ecoinvent database, which is primarily from European sources. To the extent that treatment technologies and efficiencies differ between Europe and Oregon, some error will be introduced through the use of this data. Heating is assumed to occur through a natural gas heater and gas usage is predicted by the same energy use model used for heating and cooling energy use predictions.

Construction, Maintenance, and Demolition

Quantification of construction, maintenance, and demolition activities are based on professional judgment of the Oregon HBA, which has experience at building sites. These figures are not verified by field-collected data. The assumed quantities for each activity are listed in Table 6.

Table 7. Assumptions for the Construction, Maintenance, and Demolition phases of the home's life cycle.

Stage	Process	Amount
Construction	Diesel Equipment Operation	100 equipment hours
	Electricity	2,000 kilowatt hours
	Worker Commuting	300 worker days at 50 km (31 miles) per worker-day
Maintenance	Diesel Equipment Operation	140 equipment hours (2 per year)
	Electricity	2,800 kilowatt hours (40 per year)
	Worker Commuting	420 worker days (6 per year) at 50 km (31 miles) per worker day
Demolition	Diesel Equipment Operation	12 equipment hours
	Electricity	1,000 kilowatt hours
	Worker Commuting	4 worker days at 50 km (31 miles) per worker day

Discussion of GWP and eGrid / Ecoinvent

The data for the US grid that has been applied is from the Ecoinvent database and indicates a "carbon intensity" of 0.86kg CO_2equivalents per kWh. It is important to note that this figure considers the life cycle emissions of the energy production, including factors such as the emissions associated with electricity lost during transmission, as well as emissions associated with the extraction and transportation of fossil fuels. Although reliable resources exist that more specifically identify the production within a given region, using such a dataset can lead to a false sense of greater precision because of the interconnectedness of the electrical system and exchange of energy that occurs between systems. In effect, electricity consumed in the sub-region in which Oregon lies (NWPP) could source from neighboring regions. NWPP is the Pacific sub-region defined by the U.S. EPA in its eGRID database that tracks emissions from electricity generation. NWPP is a sub-region of the Western Electrical Coordinating Council (WECC) region defined by the North American Electric Reliability Corporation (NERC).

End-of-Life Fate

The end-of-life (EOL) for each material used in the home (including waste) is distributed across reuse, recycling, landfill, and/or incineration facilities (with partial energy recovery). For materials that enter the general municipal waste disposal stream (meaning they are neither reused, recycled, or specifically diverted for energy recovery), it is assumed that 93% are sent to landfills, 6% are incinerated with energy recovery, and 1% are incinerated without energy recovery. Additionally, the end-of-life fates of materials by material class are shown in Appendix 9.

While it is assumed that reuse does not occur in the *Standard Home* scenario, there are other scenarios that have been explored where re-use of materials (in another home for the same purpose) does occur. Within those scenarios, material reuse is based on estimates provided by experts in the field of building deconstruction. Those scenarios are intended to represent the maximum possible salvage rates to be achieved by those practices. The materials that are not reused are assigned to fates of recycling, landfilling, or incineration based on information provided by the Oregon DEQ to this project (see Appendix 9) and based upon the State Material Recovery Survey and Waste Composition Study for 2005. Where reuse occurs, the amount of reused material is first subtracted from the pool of materials and then the rates of material heading to the other three fates are applied. (for example, if 80% of a material would usually head to landfill and 50% is reused, 40% (80% of the remaining 50%) would be sent to landfill in that instance.

Allocation of Reused Materials

All materials used in the home are assigned a fate at the time they leave the site of the home: reuse, recycling, incineration, or landfilling. Figure 9 presents the approach used for assigning impacts or benefits to the treatment of materials at the various end-of-life routes. For the amount of material sent to each end-of-life route, the associated impacts with end-of-life include the collection and transportation process, the services applied in treating the waste, and an accounting for any co-products that are produced in the waste treatment. Recycling, reusing, landfilling with methane recovery, and incineration with energy recovery result in the production of useful co-products. In these cases, the system boundary is extended to include the products that would otherwise need to

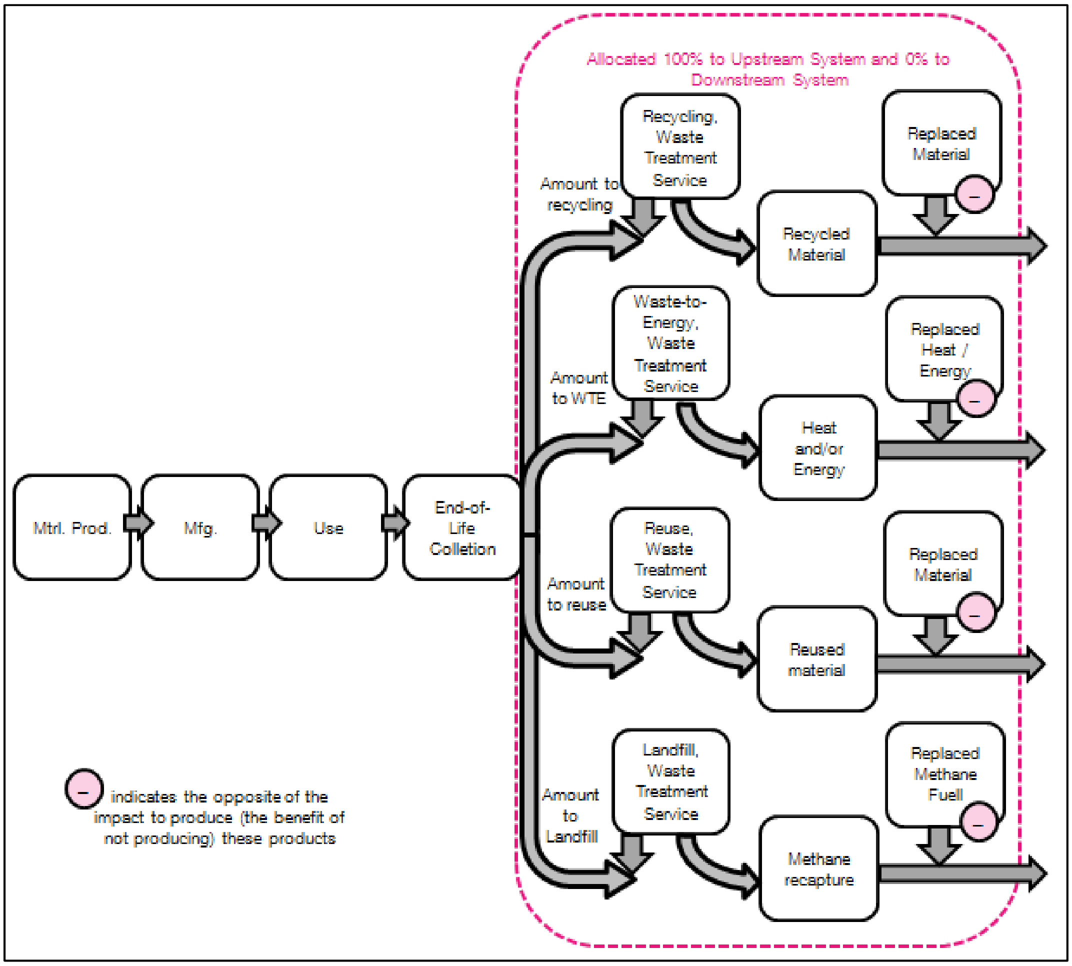

Figure 12: Representation of end-of-life treatment options

be produced to meet the equivalent function. A benefit is applied to them that is equal and opposite to the impact of producing these replaced materials. In these cases, the end-of-life impacts or benefits are allocated entirely to the upstream system (the home in question), leaving no remaining and no benefit to be considered for the downstream system (whatever the next use may be).

It is assumed reused material is reused in the same application. For example, if a door is reused, it is assumed to replace a door of equivalent composition and is not prorated to reflect a reduced durability. Wherever reuse occurs, the benefit given to the home donating materials is therefore equal to half the impact of producing the material.

The impact or benefit of recycling is determined as half the impact of producing a virgin equivalent of the recycled material, less half the impacts of recycling the material. For example, when polystyrene packaging is recycled, there is a credit for half the impact of producing virgin polystyrene less half the impact of the electricity used in processing the recycled polystyrene. For materials that are recycled in a way that does not result in production of an equivalent material, the production of a closer equivalent of the final product is used to calculate the credit. For example, when concrete is recycled, the credit given is equal to the impact of producing gravel rather than concrete because it is assumed that the concrete is crushed and used for aggregate, a use for which gravel would likely be used were the crushed concrete not available.

Incineration is assumed to occur with partial energy recovery. It is assumed that 50% of the heat content of the materials that is recovered is recaptured as electrical energy and 50% of the recovered heat content is captured as heat energy. A credit is then applied for the production of that electricity or heat by conventional means, less the impacts of the incineration itself (e.g., emissions from the incinerator). Factors of the heat content of material (see Appendix 9), amount of incineration with energy recovery in Oregon and efficiency of heat recovery from incineration have all been considered.

Landfilling is assigned impacts based on available data regarding the disposal of material of various types in municipal waste landfills. This data is primarily from the ecoinvent database. While coverage is available for a variety of the main materials that are used, there are some materials for which a close match does not exist. In this case, data for landfilling has been chosen based on as similar of materials as possible. With regard to *Climate Change*, landfills play a role in sequestering (at least temporarily) carbon and keeping it from the atmosphere. Because the timing of any emissions in weighing their importance is not considered here, this delayed release is not accounted for as a benefit for *Climate Change*. Furthermore, ignoring the uptake of biogenic carbon and the emission of carbon dioxide requires the assumption that all carbon entering a landfill from biologically-derived sources will eventually be emitted to the atmosphere. Methane emissions from landfills are assumed to be 50% captured or flared rather than being emitted from landfills, with 28% being captured for use as a fuel (we've assumed it displaces other methane fuel) and the remainder (22%) being flared.

Cost

Each material or process occurring during the life cycle of a home is assigned a cost. No efforts are been made to adjust for future inflation or to correct future prices with a discounting rate. It is therefore assumed that all costs over the 70-year life of a home occur in 2009 dollars and at a consistent price.

Cost data are taken from a wide variety of sources and assumptions. The assumed costs and references are listed in Appendix Table 12. In cases where no reference could be found, an approximation is made based on similar materials.

Impact Assessment Methodology and Calculation

The project uses a combination of the IMPACT 2002+ and the U.S. EPA's Tool for the Reduction and Assessment of Chemical Impacts (TRACI) methodology to calculate the environmental profile of each home. In particular, the endpoint indicators from the IMPACT 2002+ methodology are chosen to complement TRACI, which uses only midpoint indicators. This combination of methodology provides some advantages in offering methods designed for different geographies, with other methodological differences and with indicators at both the midpoint and endpoint level. No weighting is applied.

The exception to these methods 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). This method has been chosen to provide the most current science and to provide the greatest consistency with data that might be presented elsewhere. The exclusion of biogenic carbon dioxide is done to avoid potentially misleading results that can arise when considering only a portion of the home's life cycle, such as just the production of materials or just the management of end-of-life.

Note that for the impact categories relating to human health, only the health impacts occurring from the release of substances into the wider environment and the exposure to humans from the environment (*not* the direct exposure to those inhabiting the home through indoor air or dust) are considered in this LCA. An exposure assessment is beyond the current capabilities of life cycle science due to a lack of information on the release of chemicals from building materials and the lack of an established method for incorporating exposures within the indoor environment into a life cycle impact assessment. However, recent developments are moving toward making this feasible (Hellweg, 2009).

Midpoint and Endpoint Indicators

Midpoint and endpoint indicators are two types of results that can be generated from an LCA. The difference between them is level of calculation that is performed; endpoints are computed from midpoints which are computed from a life cycle inventory.

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 calculated directly from the inventory of flows into and out of the environment, such as consumption of water or emissions of methane (CH_4).

Endpoint indicators attempt to quantify damage to human health or the environment 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.

Based on the priorities of the Oregon DEQ, a prominent place is given throughout the report for the *Climate Change* impact. The focus on this indicator also provides opportunities for examining issues at a level of depth that is difficult to portray with ten or more indicators at once. These data are presented as kilograms of carbon dioxide equivalents (kgCO2e), which is a unit reflecting the estimated impact on global *Climate Change* of all greenhouse gasses emitted. Specifically, throughout the study the global warming potential time horizon of 100 years is used (see text box below). In no way is this focus intended to imply that the other environmental impact categories evaluated should be of lesser concern or that results of *Climate Change* alone represent an overarching conclusion about total environmental impact. Each key conclusion should be confirmed by checking other indicators.

An example calculation is presented in Appendix 15 to illustrate how the relative benefit of each scenario is tabulated. Descriptions of each of the impact metrics that are used here are provided below.

Climate Change

Global warming potential (GWP), or *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 (kgCO_2e). Because the uptake and emission of CO_2 from biological sources (termed *biogenic* CO_2) can lead to misinterpretations of results, it is not unusual to omit biogenic CO_2 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 CO_2 from biological systems is tracked separately from the other CO_2 and not reported. The emissions of other greenhouse gasses from biological matter are corrected by subtracting the equivalent value for CO_2 based on the carbon content of the gas. In some cases, a second *Climate Change* metric including consideration of the influence of forestry land use on *Climate Change* is presented. This is explained in further detail in the text box above.

Climate Change Impact Assessment

The International Panel on *Climate Change* (IPCC) has defined Global Warming Potentials (GWP) for the amount of warming caused over periods of 20, 100 and 500 years. For a project in which emissions are expected to occur over a period of up to 100's of years, it is quite easy to argue that the 500-year weightings will be more appropriate than the 20 or 100 year GWP weightings. However, there is now a substantial trend toward the use of the 100-year GWP scheme. Therefore, to maintain comparability with as broad a range of other information sources as possible, the 100-year weighting is employed.

Wood and Climate Change Impact

There are a variety of nuances to the treatment of wood and other bio-based products in LCA and this is especially true in assessing *Climate Change* impacts due to the uptake and release of carbon dioxide and other carbon-containing gasses from bio-products during their growth and end-of-life. This complexity leads to a requirement to make numerous methodological choices in how greenhouse gas uptake and emissions from bio-based products and production systems will be considered. Because such decisions can in some cases influence results, it is important to consider their implications and disclose to the extent practicable what alternative findings might be made under differing methodological choices. In the present case, there are two important issues worth considering in regard to the treatment of greenhouse gas emission in the wood life cycle. It might be important to explore how these choices effect the overall results of the home's carbon footprint, and also choices that might be made, such as the management of wood at end-of-life.

The first of these is the choice in the present study to not attribute climate impact to the uptake and release of CO_2 by biologic systems. Although these are accounted for in the life cycle inventory information used here, in the impact assessment, this uptake and release has been assigned a weighting of zero (methane emissions from biological systems or products are assigned a corrected global warming potential to account for the biogenic origin of their carbon). This choice does not affect the total life cycle impact of the home or of the wood containing products. Rather, shifts relative impact and benefit from one stage of the lifecycle to another. In particular, were biologic uptake and release of CO_2 to be weighted the same as fossil CO_2, there would be negative climate impact for the production of wood (corresponding to the CO_2 absorbed in its growth, and a large *Climate Change* impact at end-of-life corresponding to its release. Although the impact of wood at various stages would change, the net result would remain the same, leading to the same lifetime carbon footprint of each home and the same comparative impact between wood and alternative materials. In addition, the comparative result of various end-of-life fates of wood would remain the same, despite large changes in the *Climate Change* impact assigned to each (see Table 26 for example). Consideration of storage of carbon in landfills for many decades or centuries has not been considered here because the impact assessment applied makes no consideration or weighting based on when emissions occur.

Another important methodological choice is the exclusion of considerations of the indirect effects on land use that are caused by the demand for various bio-based products. The management of land can have a very large influence on the flux of carbon from the atmosphere to plants and soils. Where bio-product production shifts use of land from one use pattern to another, it may be possible to account for these differences and assign them to the product in question. For example, in their assessment of various end-of-life routes for wood, the US EPA has worked with the US Forest Service to model the marginal differences in carbon fluxes from paper-producing forests caused by changes in demand for paper (US EPA, 2006). In short, because the demand for paper currently causes trees to be harvested earlier than the optimal time for carbon management, reduced demand allows more carbon sequestration by the forests. In this work, the EPA has assigned a value of approximately 2 $KgCO_2e$ per Kg of wood to this effect, applying it as a credit given when wood production is avoided through reduced demand or product reuse. This value is substantially higher than the roughly 0.2 $KgCO_2e$ that is used here and reported by many sources of life cycle inventory data. Although data is lacking to thoroughly apply this consideration within the present project, to illustrate the potential importance of this topic on the results, in several cases throughout the report *Climate Change* impact results are mentioned or shown both with and without consideration of forestry land use impacts, applying the $2KgCO_2e/Kg$ figure as both an impact from wood production and as a benefit when wood is reused or production avoided. The application of the assumption from the EPA report mentioned above has been used in these cases and results in an increase of about 8% in the total *Climate Change* impact caused over the home's life cycle. However, implications on specific results may be more significant in cases where those results are heavily influenced by wood production data and some such cases are highlighted throughout the report. The intention of showing this alternate result in the present report is to indicate the general magnitude of the potential uncertainty associated with this topic. Further research is clearly needed to do more with such results than to add caution to other findings where appropriate (as well as to indicate where caution is less warranted).

Nonrenewable Primary Energy Use

Nonrenewable Primary Energy Use assesses the consumption of fossil and nuclear resources but excludes sources of renewable energy at all stages of the life cycle and in all upstream processes. This metric is expressed in megajoules (MJ), a common unit of measure for energy, and is computed in this study based on the IMPACT2002+ methodology (Jolliet et al., 2003).

Human Health

Human Health damage 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 causes. An evaluation of the overall impact of a system on human health is made following the human health end-point 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 variety of causes.

Ecosystem Quality

The health of an ecosystem can be impaired by the release of substances that cause acidification, eutrophication, toxicity to wildlife, 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* end-point 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.

Resource Depletion

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).

Carcinogens

Chemicals which contribute to the incidence of human cancers through release into the environment and subsequent human exposure are termed *Carcinogens*. The TRACI methodology (Bare, 2003) is employed in this study to assess these substances. This impact is measured in kilograms (kg) of benzene equivalents.

Non-carcinogens

Chemicals which contribute to the incidence of human morbidity or mortality through chronic health effects other than cancer are measured by the impact category *Non-carcinogens*. The TRACI methodology (Bare, 2003) is employed in this study to assess these substances. This impact is measured in kilograms (kg) of toluene equivalents.

Respiratory effects

Effects on the respiratory system can be a result 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. The TRACI methodology (Bare, 2003) is employed in this study to assess these substances. This impact is measured in kilograms (kg) of $PM_{2.5}$ equivalents[26].

Acidification

Acidification is the lowering of pH in natural water bodies through the release of acidifying substances to air, land, or water. The TRACI methodology (Bare, 2003) is employed in this study to evaluate this process. This impact is measured in moles of hydrogen ion (H^+) equivalents.

Ecotoxicity

Harm to wildlife, including all types of flora and fauna, through toxic effects of environmental pollution is generally referred to as *Ecotoxicity*. The TRACI methodology (Bare, 2003) is employed in this study to analyze this impact, which is measured in kilograms (kg) of 2,4-dichlorophenoxyacetic acid (2, 4-D) equivalents.

Eutrophication

Eutrophication is the process of nutrient enrichment (particularly of phosphorous and nitrogen) in a water body, which typically leads to excessive growth of microorganisms and depleted oxygen levels. The TRACI methodology (Bare, 2003) is employed in this study to analyze this process. These impacts are measured in kilograms (kg) of nitrogen (N) equivalents.

Ozone Depletion

Ozone Depletion refers to the decrease in ozone in the stratosphere, where it serves to block UV rays from penetrating the atmosphere. The TRACI methodology (Bare, 2003) is employed in this study to analyze this process. These impacts are measured in kilograms (kg) of chlorofluorcarbon-11 (CFC-11) equivalents.

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[26] $PM_{2.5}$ denotes particulate matter that is no larger than 2.5 micrometers (or microns) in diameter.

Photochemical Oxidation

The creation of oxidizing compounds in the troposphere from environmental pollution (usually the release of nitrogen oxides and volatile organic compounds) is known as *Photochemical Oxidation* or smog. The TRACI methodology (Bare, 2003) is employed in this study to analyze this process. These impacts are measured in kilograms (kg) of nitrogen oxides (NO_x) equivalents.

Uncertainty

Before considering the results of the study, it is important to convey the confidence level in the information presented. Uncertainty enters calculations made at each stage of the assessment. This includes the estimation of the amount of material or energy that is used, how this differs among scenarios, the impacts of producing these materials, their rates of replacement, the processes of constructing and demolishing the home, and the handling of materials at end of life. In addition, because the goal is for the results of the assessment to reflect broadly on a diverse set of housing structures in the state of Oregon, there is also uncertainty in assuming that the findings are indeed representative of all or most structures in the state. Even in the case of estimations made at the statewide level, it is necessary to group more than 1,000,000 Oregon residences into 84 archetypal categories or characteristics. While a formal uncertainty assessment is not done here, it is clear that the uncertainty of the overall estimation of the environmental impact of a home over a 70-year life is significant, and the total impact of a >1,000,000 population of homes even more so.

Fortunately, the uncertainties in comparison among the practices are likely to be much less than the uncertainty in the results as a whole. This is because many key areas of uncertainty are the same among the building practice scenarios because they are based on similar data or assumptions. For example, if the *Climate Change* impacts of the use of electricity are underestimated, using a higher value for this would increase the impact assigned to all the building scenarios in proportion to their use of electricity. The comparison among scenarios would therefore shift by a much lesser amount than the results for the scenarios in isolation. Because most areas of uncertainly are linked to some extent, the uncertainty in the conclusions is less than it would seem from simply considering the uncertainty in each parameter that is included. No formal uncertainty assessment is conducted here.

Finally, it should be noted that the study is constructed with the intention of addressing its aforementioned goals, which are to evaluate building practices and related policies or programs of action. Answering other, perhaps more detailed, questions might require a different scope and/or further refined study.

IV. Results Overview

Results: *Medium Standard Home*

Overview

Figure 13 shows an overview of the environmental impact of the *Medium Standard Home*, divided by the stages of the home's life cycle. The same information is provided in Table 8 in numeric form.

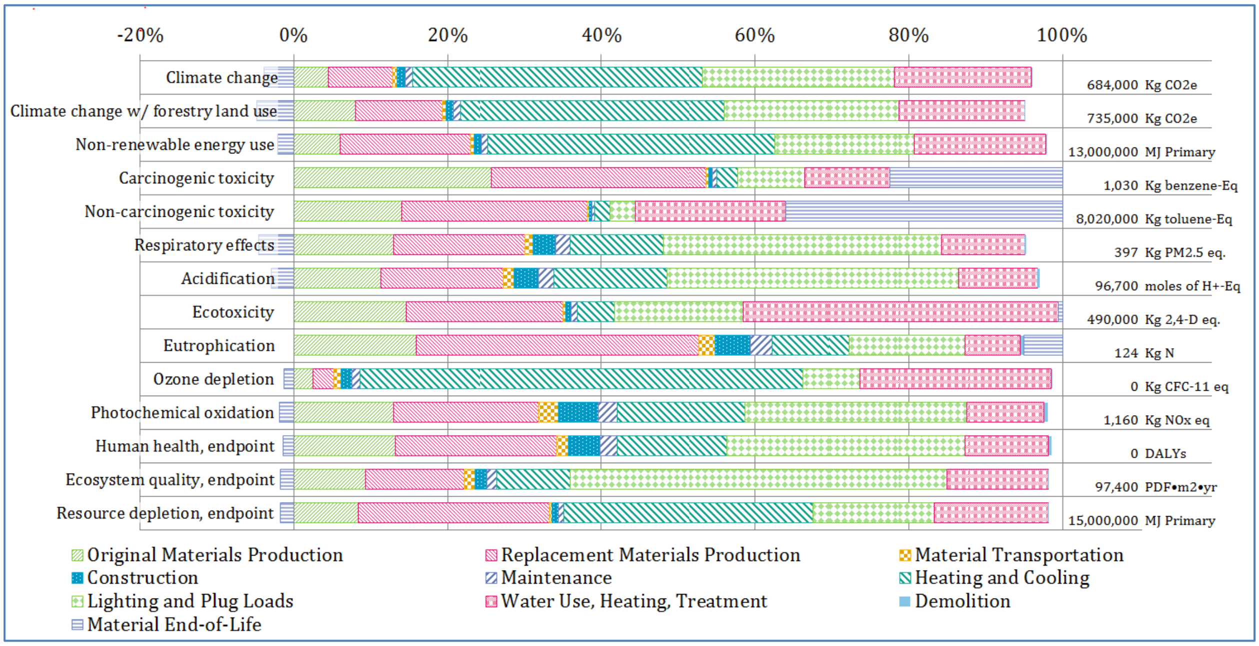

Figure 13: Contribution to environmental impacts by stage of the life cycle for the Medium Standard Home[27]

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[27] In Figure 13, the values in each category, the results are presented based on 100% of the impact in each category. This presentation is not intended to imply that the total environmental impact or relevance in each of these categories is equal. It is not appropriate to compare the magnitude of impact *across* environmental impact categories.

Table 8: Contribution to environmental impacts by stage of the life cycle for the *Medium Standard Home*

Environmental Impact Category	Original Materials Production	Replacement Materials Production	Material Transportation	Construction	Maintenance	Heating and Cooling	Lighting and Plug Loads	Water Use and Heating	Demolition	Material End-of-Life	Total
Climate Change (IPCC 2007 GWP100, Kg CO_2e)	33,000	62,500	3,760	8,430	6,940	280,000	185,000	133,000	640	-29,400	684,000
Climate Change (IPCC 2007 GWP100 with forestry land use, Kg CO_2e)	64,900	91,800	3,760	8,430	6,940	280,000	185,000	133,000	640	-39,400	735,000
Non-renewable energy use (IMPACT, MJ Primary)	808,000	2,300,000	62,300	128,000	107,000	5,060,000	2,450,000	2,320,000	9,580	-282,000	13,000,000
Carcinogenic toxicity (TRACI, Kg benzene-Eq)	264	286	3.3	5.5	6	28	89	113	0.26	230	1,030
Non-carcinogenic toxicity (TRACI, Kg toluene-Eq)	1,130,000	1,930,000	20,800	31,400	31,300	152,000	273,000	1,560,000	1,750	2,890,000	8,020,000
Respiratory effects (TRACI, Kg PM2.5 eq.)	57	75	4.4	13	8.1	53	158	47	1.2	-20	397
Acidification (TRACI, moles of H+-Eq)	11,600	16,400	1,480	3,310	1,940	15,200	38,900	10,600	324	-3,020	96,700
Ecotoxicity (TRACI, Kg 2,4-D eq.)	71,600	99,600	2,030	3,690	4,070	23,200	82,100	201,000	175	2,730	490,000
Eutrophication (TRACI, Kg N)	20	46	2.6	5.8	3.4	12	19	8.9	0.56	6	124
Ozone depletion (TRACI, Kg CFC-11 eq)	0.0016	0.0019	0.00059	0.00095	0.00074	0.038	0.0049	0.017	0.000074	-0.0009	0.065
Photochemical oxidation (TRACI, Kg NOx eq)	156	229	31	62	30	201	349	121	7	-22	1,160
Human health, endpoint (IMPACT, DALYs)	0.035	0.056	0.0041	0.011	0.0059	0.038	0.082	0.029	0.0011	-0.0037	0.26
Ecosystem quality, endpoint (IMPACT, PDF•m2•yr)	9,420	13,000	1,370	1,510	1,370	9,610	49,600	13,200	104	-1,810	97,400
Resource depletion, endpoint (IMPACT, MJ Primary)	1,300,000	3,880,000	62,400	128,000	107,000	5,060,000	2,450,000	2,330,000	9,580	-277,000	15,000,000

The use of the home (which includes consumption of heating fuel, water and electricity) is clearly the most prominent stage in the life cycle for most environmental impact categories.

The transportation and construction-related stages (construction, maintenance and demolition) contribute a relatively small amount to most environmental impact categories (combining for 5% or less). For several impact categories, including Acidification, Eutrophication, Ozone Depletion, Photochemical Oxidation, Human Health (endpoint), and *Ecosystem* Quality (endpoint), these stages contribute a slightly larger portion, combining for between 8 and 15% of these categories.

Material production, including both of the original and replacement materials is somewhat more significant contribution, as high as 40% in the case of Resource Depletion (endpoint). In the case of several other categories, the contribution of material production is in the range of 25 to 30% (Non-renewable Energy Use, Photochemical Oxidation, Human Health (endpoint), and *Ecosystem* Quality (endpoint). For the remainder of the impact categories, the contribution of material production is in a range from approximately 10% to 20% (16% in the case of *Climate Change*).

Material end-of-life is relatively insignificant for a majority of the indicators, resulting in either a small impact or small benefit, depending on the balance of impacts occurring in each category and benefits that are achieved when materials are recycled or used for energy recovery. However, there are several categories, including Carcinogenic Human Toxicity, Non-Carcinogenic Human Toxicity where material end-of-life is more significant, contributing 20% to 30% of the total impact.28

Many professionals from the green building community will be familiar with the concept of "embodied energy" of a building, or the amount of energy needed to produce it, which can then be compared to the energy needed to operate it or other relevant factors. The impact category Non-renewable Energy Use, applied in the results here is similar in concept, although specifically limited to non-renewable sources of energy (e.g., fossil fuels). It is interesting to note that although in many cases results for *Climate Change* and Non-renewable Energy Use are very similar due to the prominence of fossil energy in most greenhouse gas emissions, Figure 10 shows a higher material-related contribution for Non-renewable Energy Use than for *Climate Change*. The explanation lies in the asphalt shingles, which contain a large amount of petroleum-based material that is accounted for as fossil energy, but for which greenhouse gas emissions only occur if they are burned as fuel.

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[28] Landfilling of all materials have been represented by a variety of life cycle inventory data obtained from the Ecoinvent database intended to represent generic landfilling conditions using modern European technology. Landfills in Oregon have been equipped with technology that is intended to substantially reduce or eliminate the emissions of nutrients (which would lead to eutrophication) in the landfill leachate and effluent. It is not clear to what extent, if any, the assumptions used in the Ecoinvent database landfill model accurately reflect landfill technology in place in Oregon. The importance of landfilling in this impact category could therefore be further validated by assessing local technology.

Sensitivity to Home Lifetime

About 45% (by weight) of the materials in question are produced for the home's original construction and the remaining 55% are used to maintain the home over its 70 year life. When comparing the environmental impact of materials (including their production, transport and disposal), the original materials of the home contribute in the range of one-third (ranging from 25% to 45%, depending on impact category) of the impact, while replacement materials account for the remainder. This is shown in Figure 14.

Both the total magnitude of the home's impacts and the relative distribution of impacts among stages are highly dependent on the life of the home (assumed here to be 70 years). While the use phase of the life cycle is entirely proportionate to the lifetime, other stages are also affected by the lifetime but to a lesser extent. If a longer lifespan were estimated, total Materials Production and

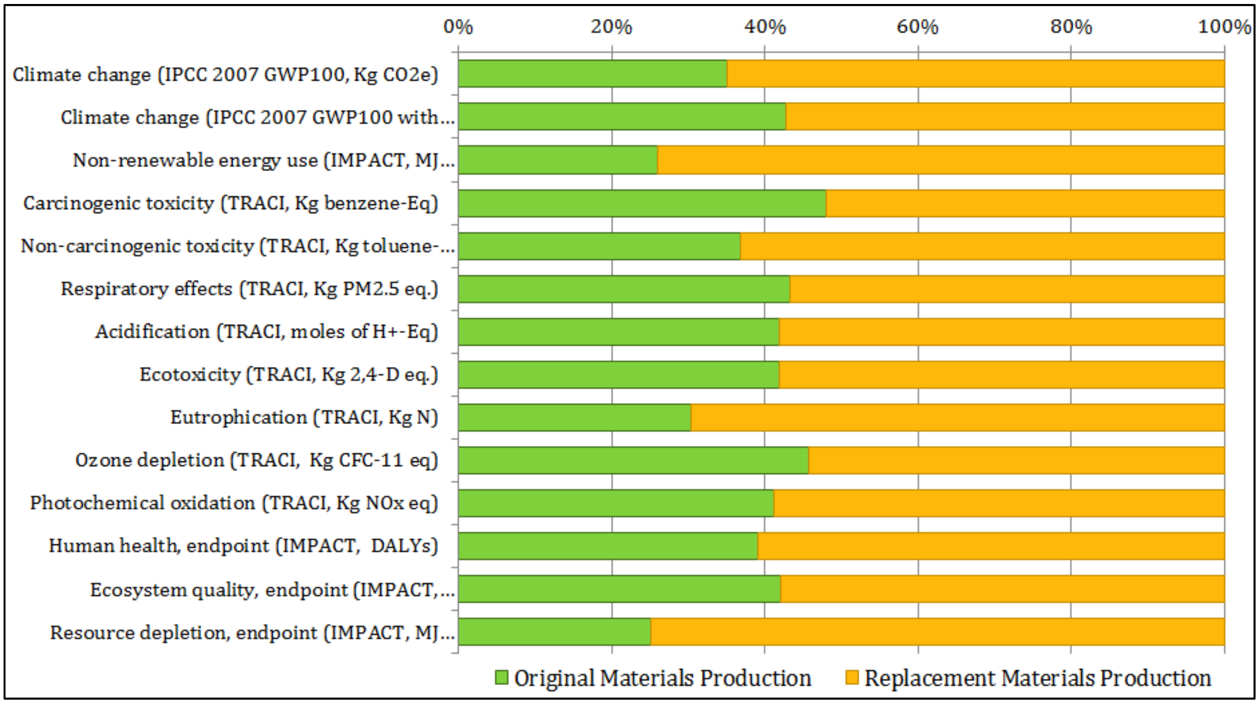

Figure 14: Proportion of material-related impact contributed by the original construction materials and replacement materials, assuming 70-year home life

associated Transportation and End-of-life impacts would increase due to the longer maintenance period. Figure 15 depicts the total and annualized *Climate Change* impact of the *Medium Standard Home* when the home lifetime is varied from 20 to 120 years.[29]

Many, though not all, aspects of the home's life cycle are strongly linked to the length of its life. As shown in Figure 15, because of the dominance of *Climate Change* impact by those components that are strongly determined by lifetime, the overall impact of the home changes in nearly a proportional manner with lifetime, showing only an approximately 10% difference in the annualized impact of a home lasting 120 years in comparison to one lasting 20 years.

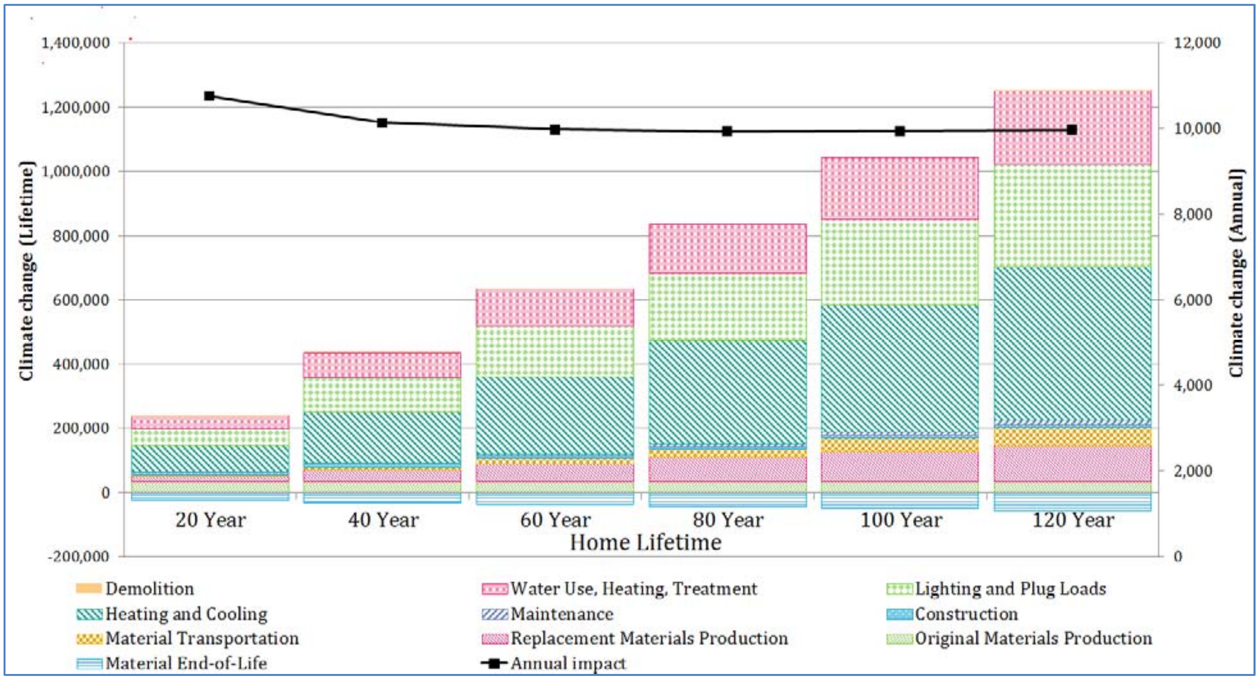

Figure 15: Variation in the total and annualized[30] *Climate Change* impact of the *Medium Standard Home* with home lifetime (70 years is the baseline assumption)

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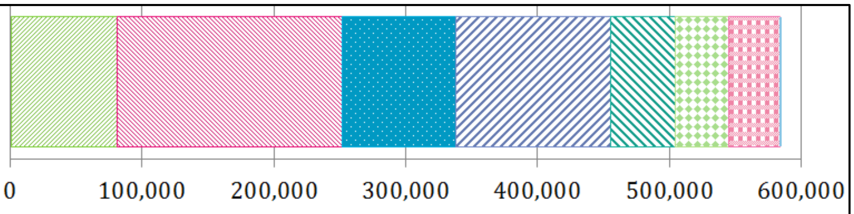
[29] It should be noted that all material replacement has been assumed to occur on an annualized basis, rather than in a stepwise fashion. For example, if a roof is replaced every 20 years, the replacement is represented as happening 1/20th in each of 20 years. Although this leads to an equivalent result over time, there may be a significant difference in the first decade(s) of a home's life when taking this approach. It may be less likely that maintenance would occur at the start of a home's life and this is not reflected in the present analysis. Results

Lifetime Cost

Figure 16 examines the contributions of each stage of the home's life cycle to the total Lifetime Cost of the *Medium Standard Home*[31].

The materials and labor involved in constructing and maintaining the home contribute the large majority to the lifetime cost of the home, with the energy use of the home contributing a total of only 15% to Lifetime Cost. The costs of material production are slightly higher than the costs of labor to build and maintain the structure, with the maintenance phase showing higher costs than original construction for both materials and labor.



	Lifetime cost (USD)
▨ Original Materials Production	80,600
▨ Replacement Materials Production	171,000
▩ Material Transportation	0
■ Construction	85,900
▨ Maintenance	118,000
▨ Heating and Cooling	48,400
▩ Lighting and Plug Loads	40,900
▩ Water Use, Heating, Treatment	38,800
■ Demolition	1,400
▤ Material End-of-Life	0
Total	585,000

Figure 16: Contribution to *Lifetime Cost* by stage of the life cycle for the *Medium Standard Home* Costs in categories with zero cost shown, are included within other categories (transportation in materials production and end-of-life in demolition)

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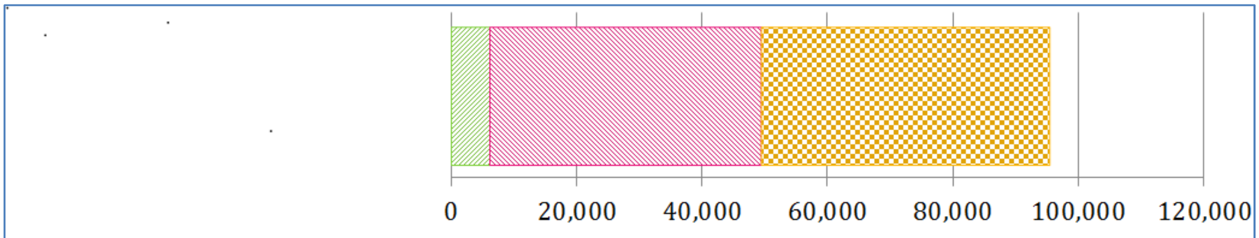
[30] Note that the axis for annual impact does not start at zero.

[31] Cost is not the primary focus of this study and is best described as a rough approximation (see more description of cost calculations in Appendix 5). The included costs are intended to be only those born by the home's occupants. Despite the long lifetime of the home, the costs of all aspects of the lifecycle have been estimated based on current costs and in 2010 dollars (i.e., no adjustments have been applied for inflation and no discounting had been applied to future costs).

Waste Generation

Figure 17 shows the amount of Waste Generation occurring over the lifetime of the *Medium Standard Home*, divided into the amount of waste material that is generated during the construction process, the amount that is generated during replacement activities, and the amount generated following demolition.

Only a small amount, approximately 5%, of the Waste Generation is predicted to occur at the time of the home's construction, with approximately 50% occurring over the course of the home's 70-year life and the remainder occurring at the time of demolition. This suggests that many of the waste prevention practices examined here may have a long delay between their implementation and the realization of the reduction in material entering the waste stream. Note that the maintenance-related waste is proportional to the life of the home, whereas the construction and demolition amounts are fixed. As a result, whereas it is shown above that the annual climate impact has only a small dependence on home lifetime, Figure 15 shows that for waste generation, a home with a 120 life has only 1/3 the annual waste generation of a similar home with 20-year lifetime. Further detail on the composition of the waste is shown in Table 9.



	Waste generation (Kg)
▨ Waste produced at construction	6,100
▧ Waste produced in maintanance	43,300
▦ Waste produced at demolition	46,100
Total	96,000

Figure 17: Waste Generation at the time of construction, during the home's life, and at the time of demolition for the *Medium Standard Home*

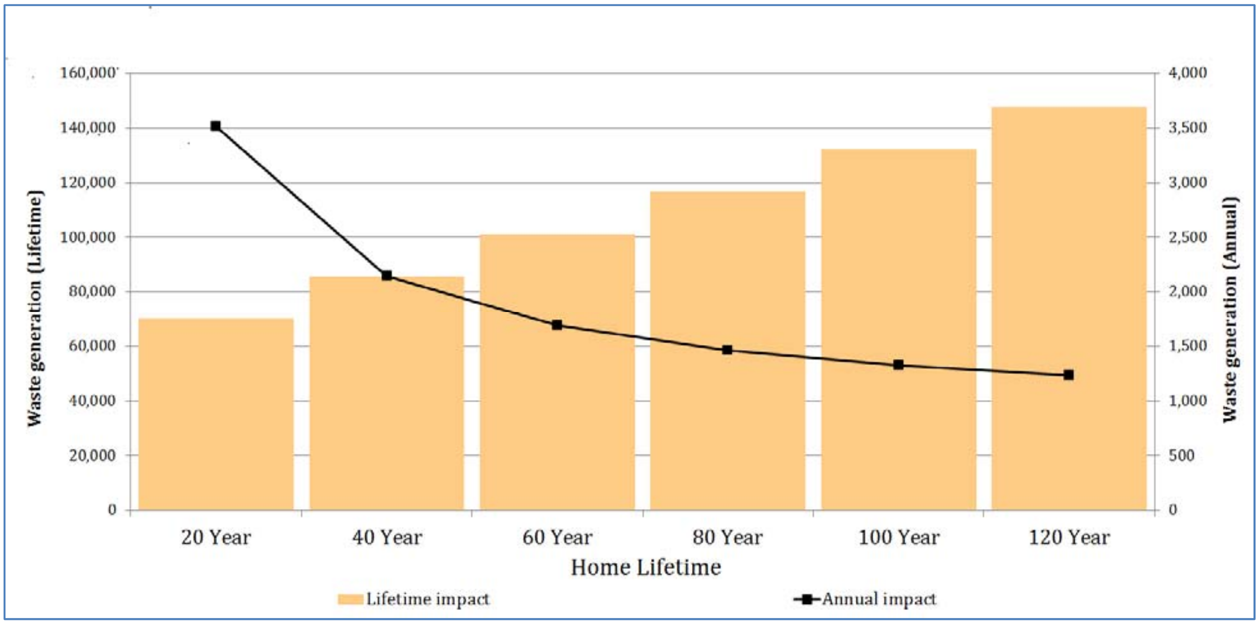
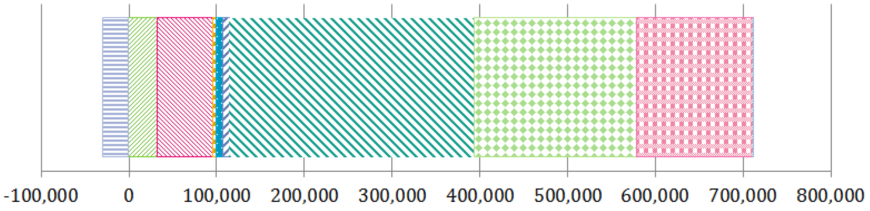


Figure 18: Variation in the total and annualized waste generation of the Medium Standard Home with home lifetime (70 years is the baseline assumption)

Climate Change

Figure 19 highlights the contribution to the *Climate Change* impact category.



	Climate change (IPCC 2007 GWP100, Kg CO2e)
▨ Original Materials Production	33,000
▨ Replacement Materials Production	62,500
▩ Material Transportation	3,800
■ Construction	8,400
▨ Maintenance	6,900
▨ Heating and Cooling	279,600
▩ Lighting and Plug Loads	185,200
▩ Water Use, Heating, Treatment	132,700
■ Demolition	600
▤ Material End-of-Life	-29,400
Total	684,000

Figure 19: Contribution to Climate Change impact by stage of the life cycle for the Medium Standard Home

For the *Climate Change* impact category, the use of the home contributes nearly 85% of the total. The materials production stages (including manufacture of original and replacement materials) contributes a significant amount of the remainder, at 14% overall, followed by the construction, maintenance, and demolition phases which contribute a combined 2%. Transportation of materials comprises less than 1%, while the end-of-life of materials results in a net benefit in *Climate Change* (4% of the total impact).

Within the use phase, the *Climate Change* impacts are chiefly from the energy use associated with space heating and cooling (including natural gas and electricity) and the use of electricity. These two factors represent 40% and 27% respectively of the life cycle *Climate Change* impacts. Water use and heating account for an additional 19% of *Climate Change* impacts. While the combination of space heating and cooling and electricity use dominates two thirds of the impact categories considered, their ratio relative to each other largely varies by type of impact.

Materials

The contribution of individual materials to Waste Generation and *Climate Change* impact (including from their production, transportation, and end-of-life) are shown in Table 9. The amount of each individual material within the listed material categories is provided in Appendix 9.

Table 9: *Waste Generation* and *Climate Change* impact for material production, transportation, and end-of-life by material for the *Medium Standard Home*

Item	*Mass (kg)*				*Climate Change Impact (KgCO$_2$e)*						
	Original Mass	***Replacement Mass***	***Lifetime Waste Generation***	***Percent of Waste***	***Material Production***	***Transport***	***Recycling***	***Landfilling***	***Waste-to-Energy***	***Total***	***Percent of Climate Change***
Carpeting	405	3300	3710	3.9%	21200	361	-191	235	95	21700	31%
Linoleum flooring	67	270	337	0.4%	452	33	-39	12	8.4	466	1%
Roofing (asphalt shingle)	2370	8170	10500	11%	11900	205	0	179	375	12700	18%
Insulation (glass fiber)	2060	1830	3890	4.1%	7890	379	0	28	0	8300	12%
Drywall	11200	7710	18900	20%	6660	368	-1.8	252	0	7280	10.5%
Doors/Windows	1240	2310	3550	3.7%	7840	345	-5660	89	-476	2140	3.1%
Plastics	772	488	1260	1.3%	4070	123	-103	37	-244	3880	5.6%
Lumber** *(with forestry land use)*	15800 *15800*	9390 *9390*	25200 *25200*	26.4% *26.4%*	9730 *52600*	691 *691*	-28 *-6820*	364 *364*	-9870 *-9870*	887 *37000*	1.3% *30.6%*
Hardware	637	286	923	1.0%	4370	87	-2620	1.6	-21	1820	2.6%
Electrical	115	84	199	0.2%	1100	19	-1.3	2.7	7	1130	1.6%
Foundation	14600	0	14600	15%	1110	113	0	10	0	1230	1.8%
Paints	53	393	446	0.5%	1190	43	-0.0015	0.019	55	1290	1.9%
Siding (wood shingle)** *(with forestry land use)*	1760 *1760*	6360 *6360*	8120 *8120*	8.5% *8.5%*	4280 *22100*	158 *158*	-9.2 *-2200*	117 *117*	-3190 *-3190*	1360 *17000*	2.0% *14.0%*
Other	1030	2750	3780	4.0%	13700	369	-8850	34	-2.2	5250	8%
Total** *(with forestry land use)*	52100 *52100*	43300 *43300*	95400 *95400*	100% *100%*	95500 *157000*	3290 *3290*	-17500 *-27500*	1360 *1360*	-13300 *-13300*	69400 *121000*	100% *174%*

*= Categories here are groups of smaller categories appearing elsewhere in the report. For example, "Lumber" here includes softwood lumber, plywood and MDF; Hardware describes various steel products, including nails, screws, bolts, brackets, etc.

**= Wood product categories are shown with and without the adjustment for forestry land use. This adjustment is intended to illustrate the magnitude of uncertainty due to not accounting for climate impacts associated with land use practices.

The materials contributing most to the *Climate Change* impact include flooring (the *Standard Home* has carpeting and linoleum flooring), roofing (asphalt shingle), drywall, appliances, insulation, and lumber. Combined, these materials contribute ¾ of the total material-related *Climate Change* impact. The addition of foundation, siding (wood), doors (aluminum exterior, wood interior), window, plumbing, and packaging bring the total to 98%. Paints, adhesives, ducts, and hardware are shown to contribute only a minimal amount. It is clear that in the case where the modification to include forestry land use is applied that wood products become a very important component of the material impact of the home.

Figure 20 through Figure 33depict the environmental impact (including both original and replacement materials) for the production, transportation[32] and end-of-life of various material classes for the *Medium Standard Home*, for each of the environmental impact categories that have been examined.

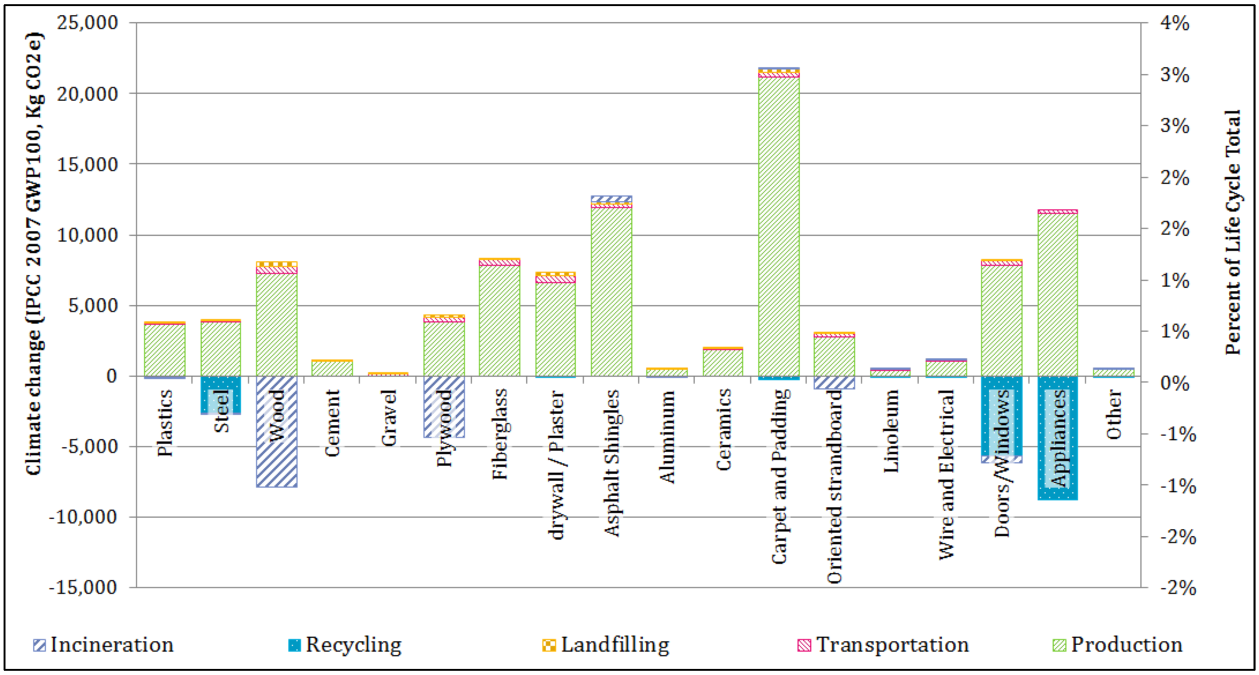


Figure 20: *Climate Change* impact for production, transportation and end-of-life of material types within the *Medium Standard Home*

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[32] Throughout this report, when a single category is shown for impacts at "End-of-Life," this category includes the hauling of materials from the home site to their point of waste treatment. However, to show the various end-of-life fates separately, the end-of-life hauling has been grouped here with the "Transportation" category instead.

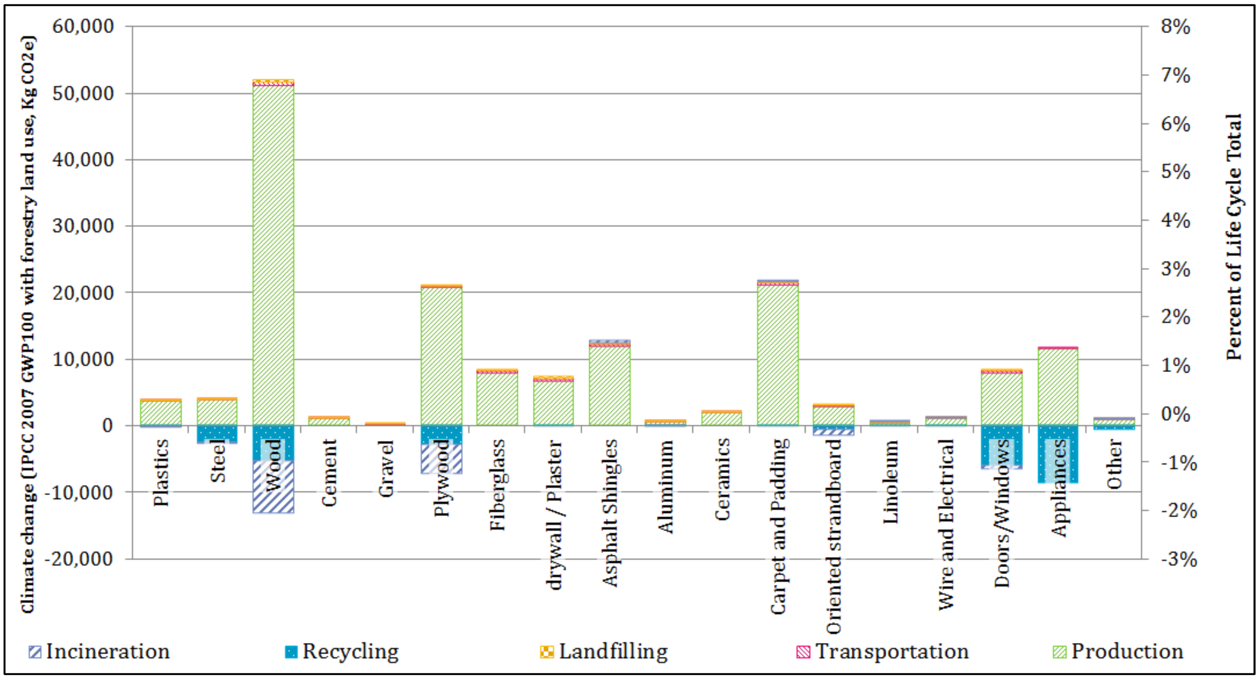


Figure 21: ***Climate Change*** **impact, including adjustment for forestry land use, for production, transportation and end-of-life of material types within the** ***Medium Standard Home***

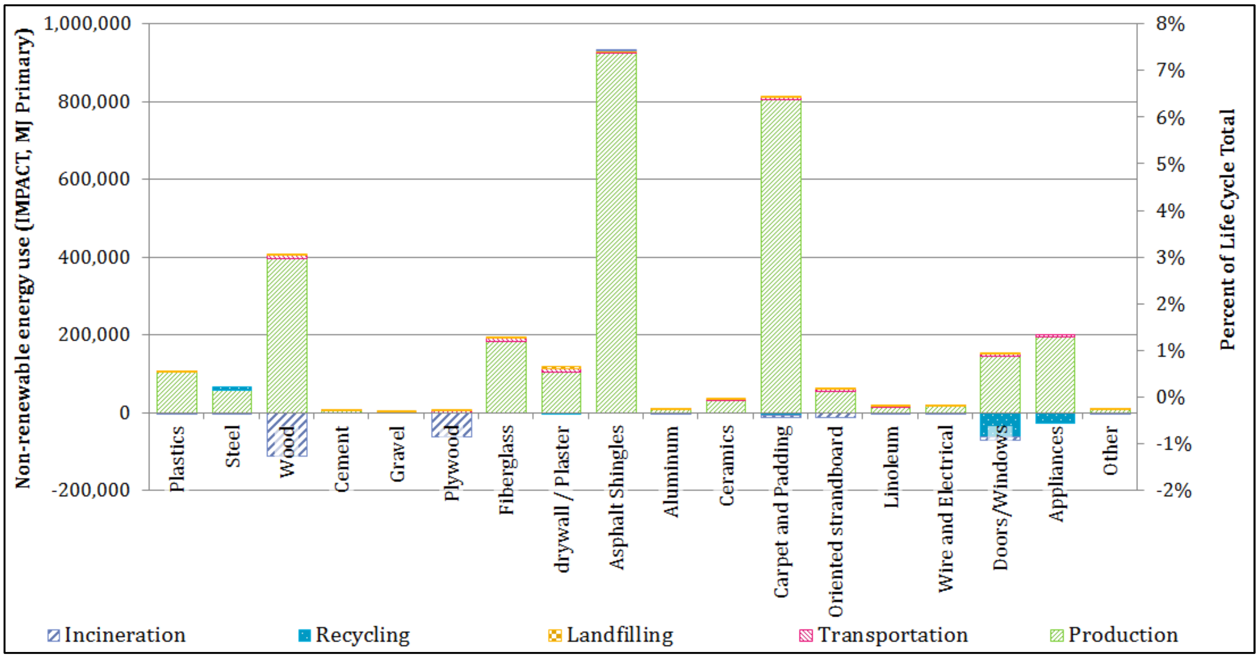


Figure 22: ***Non-renewable Energy Use*** **impact for production, transportation and end-of-life of material types within the** ***Medium Standard Home***

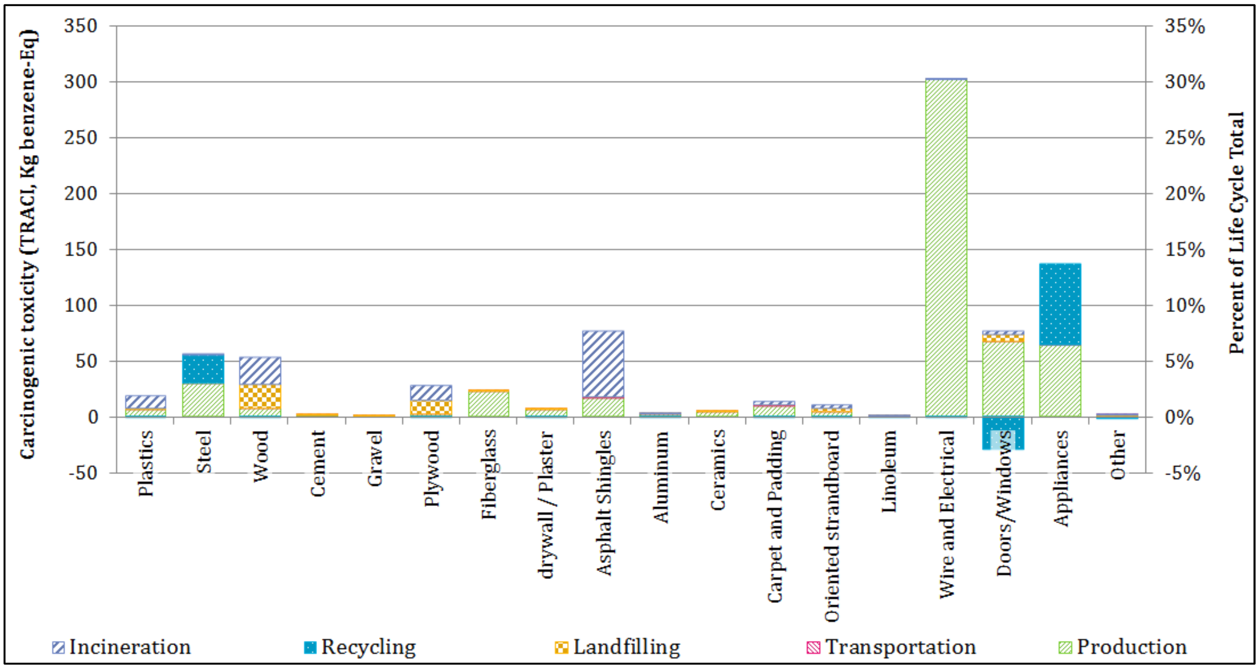


Figure 23: ***Carcinogenic Toxicity*** **impact for production, transportation and end-of-life of material types within the** ***Medium Standard Home***

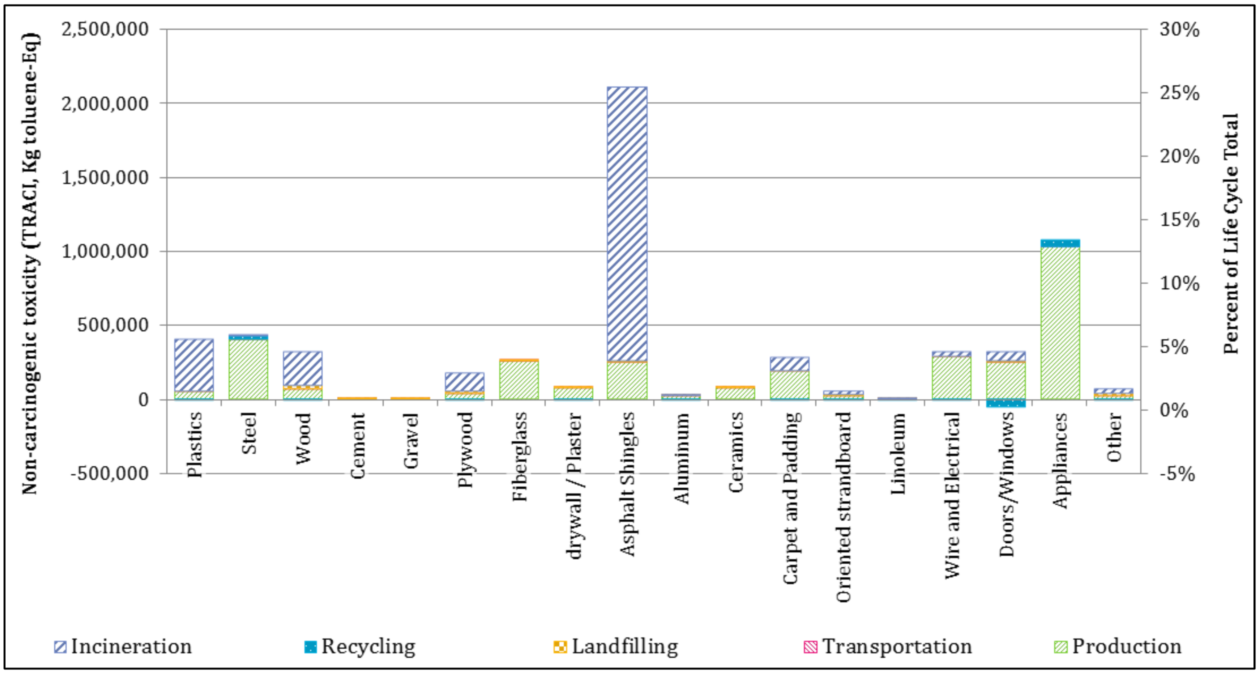


Figure 24: ***Non-Carcinogenic Toxicity*** **impact for production, transportation and end-of-life of material types within the** ***Medium Standard Home***

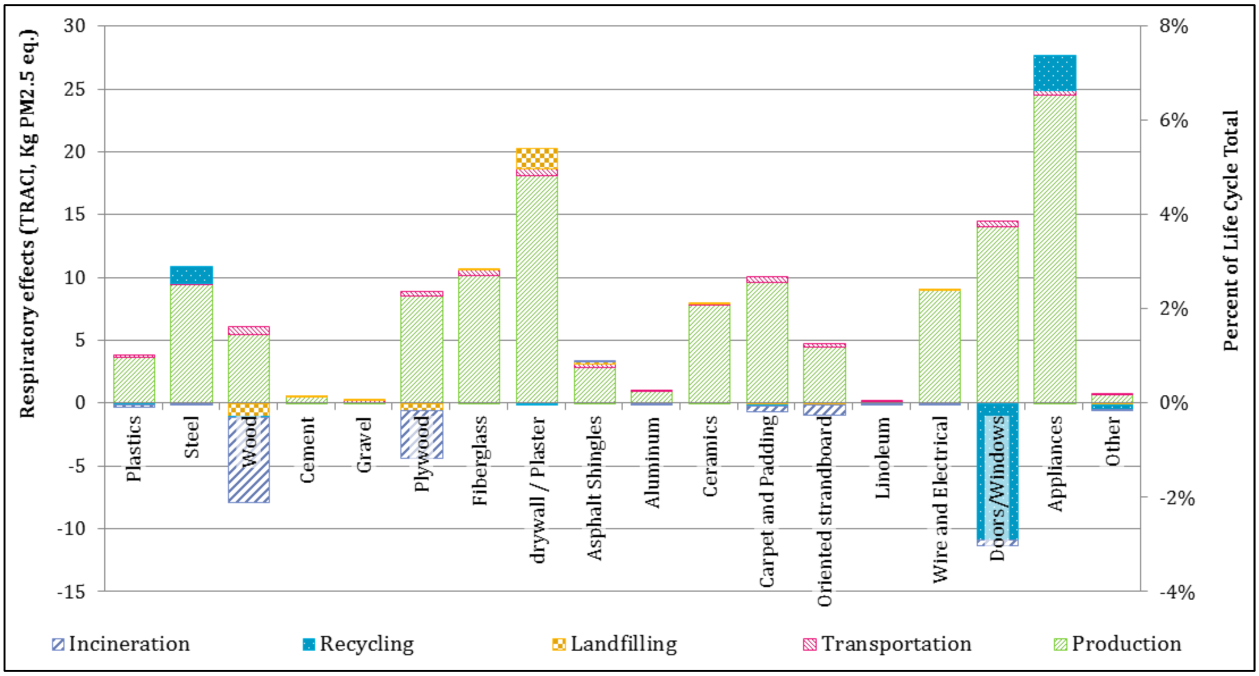


Figure 25: ***Respiratory Effects*** **impact for production, transportation and end-of-life of material types within the** ***Medium Standard Home***

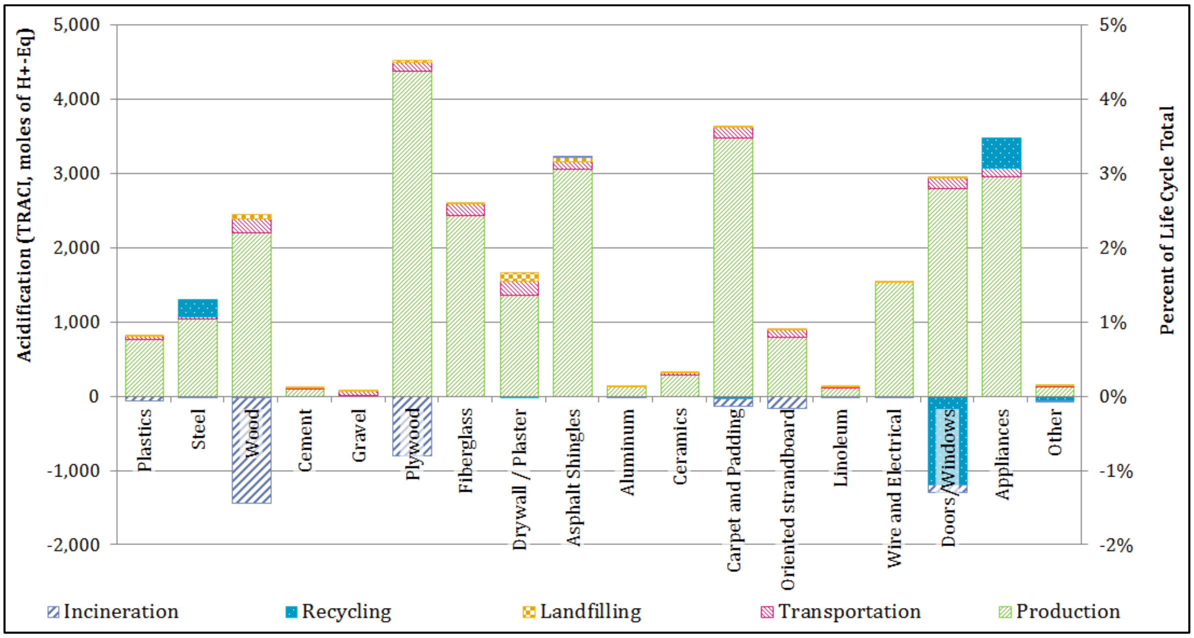


Figure 26: ***Acidification*** **impact for production, transportation and end-of-life of material types within the** ***Medium Standard Home***

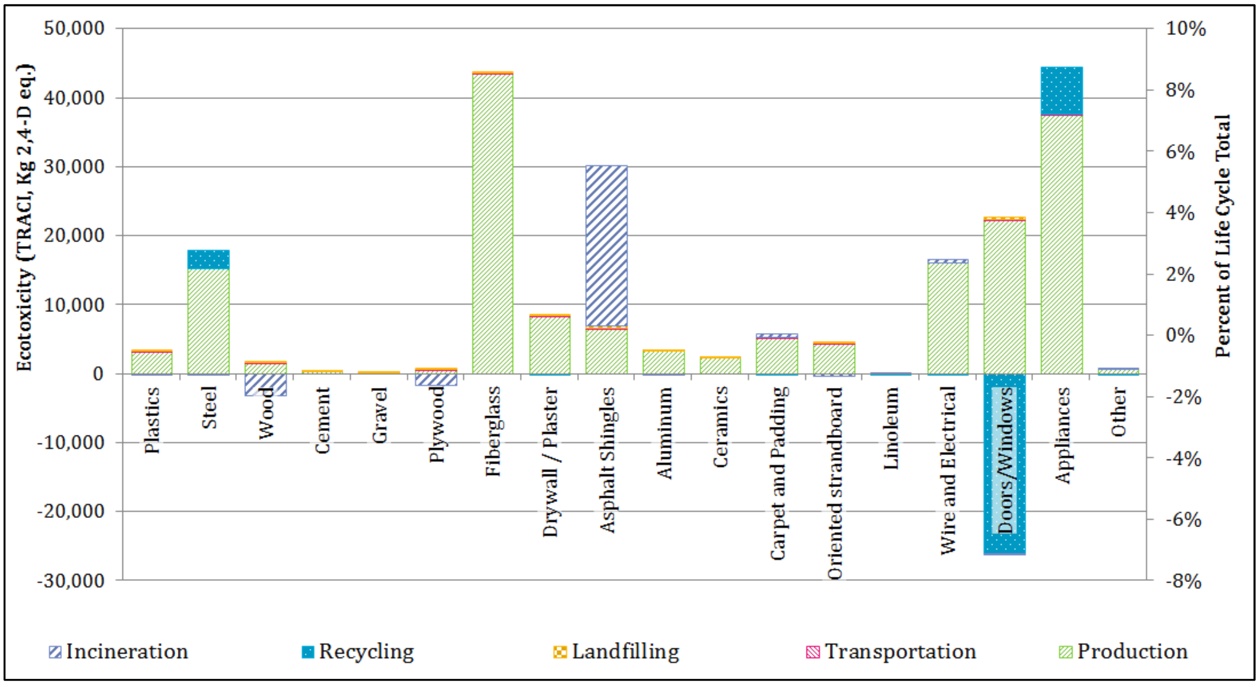


Figure 27: ***Ecotoxicity*** **impact for production, transportation and end-of-life of material types within the** ***Medium Standard Home***

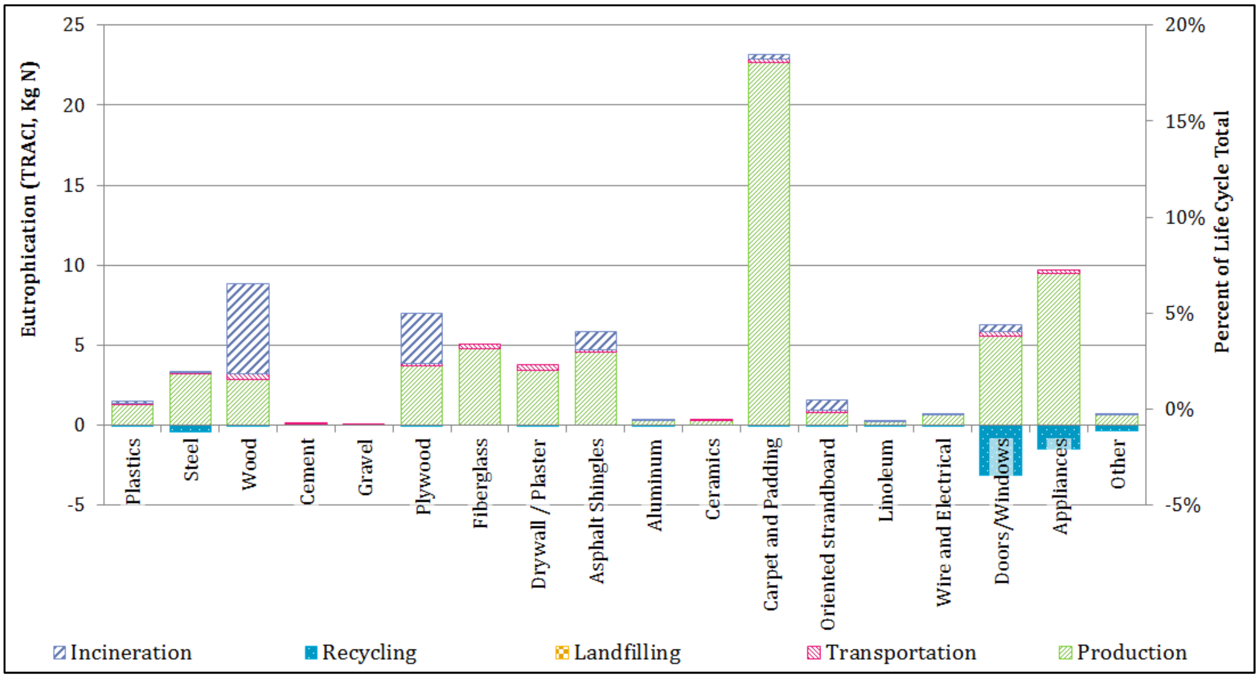


Figure 28: ***Eutrophication*** **impact for production, transportation and end-of-life of material types within the** ***Medium Standard Home***

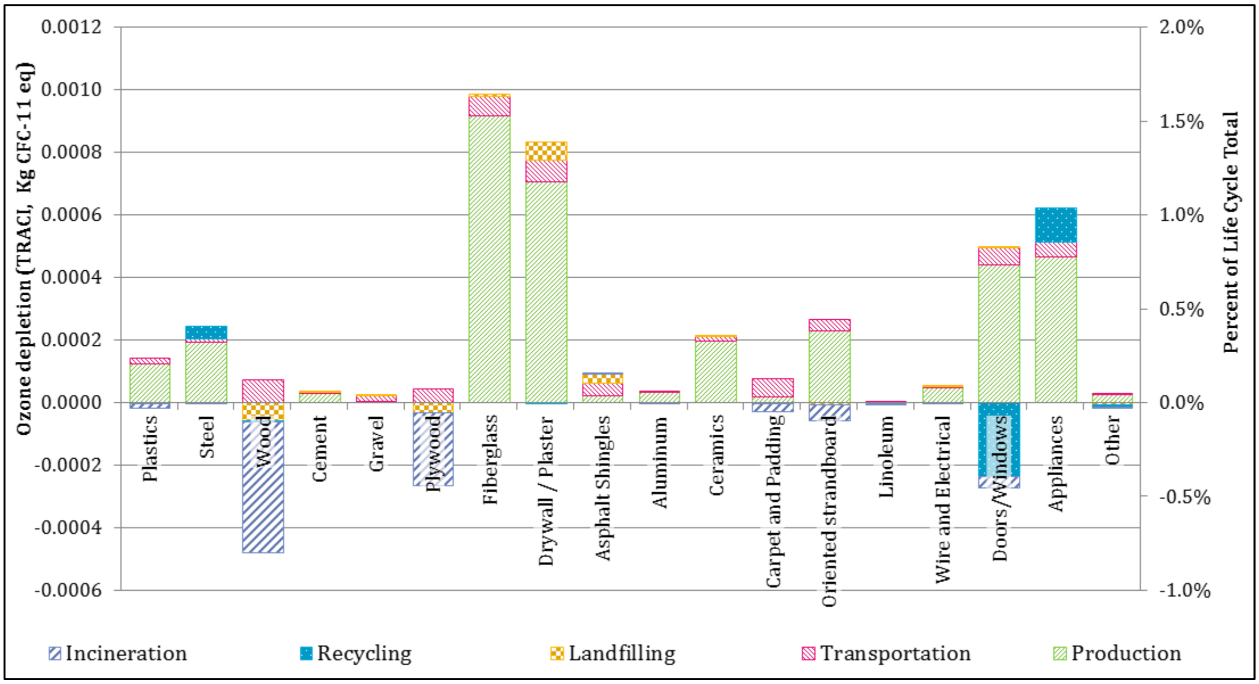


Figure 29: ***Ozone Depletion*** **impact for production, transportation and end-of-life of material types within the** ***Medium Standard Home***

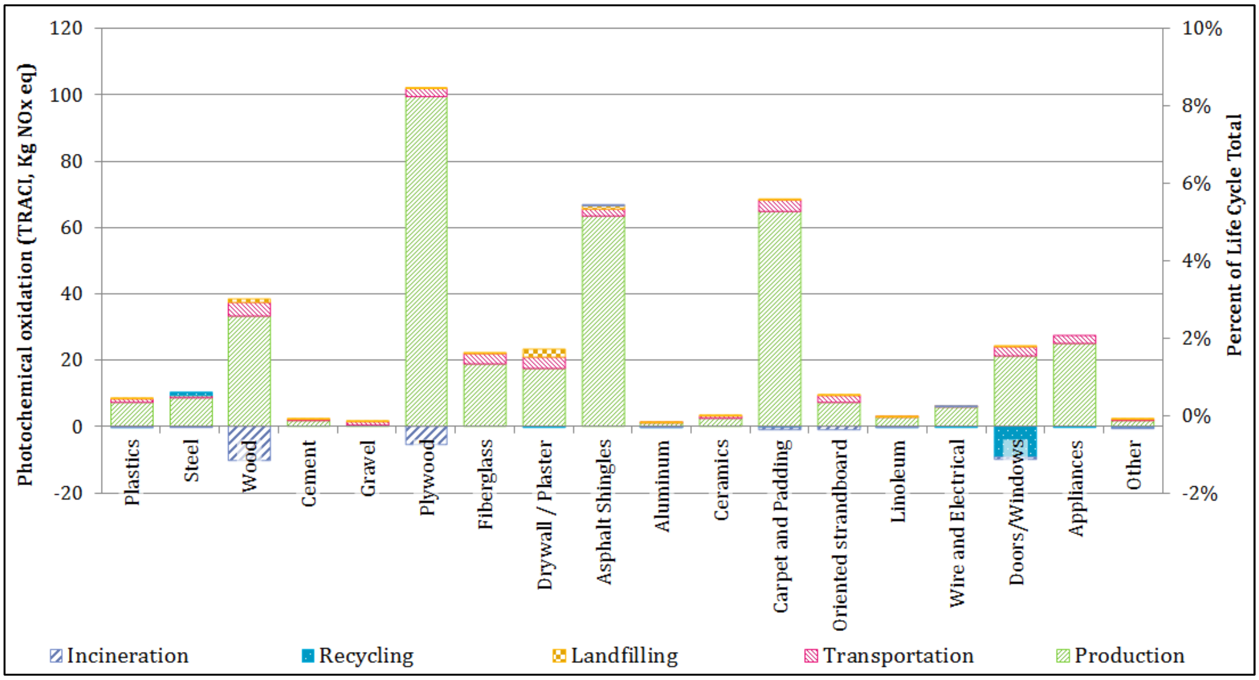


Figure 30: ***Photochemical Oxidation*** **impact for production, transportation and end-of-life of material types within the** ***Medium Standard Home***

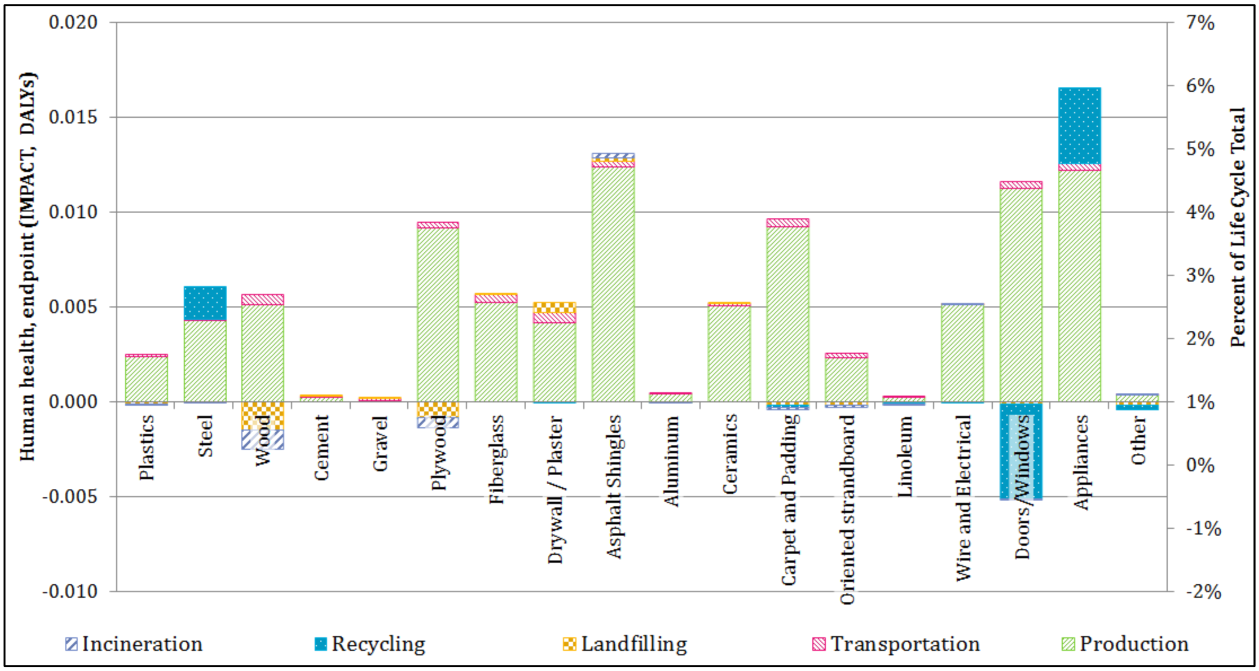


Figure 31: ***Human Health (endpoint)*** **impact for production, transportation and end-of-life of material types within the** ***Medium Standard Home***

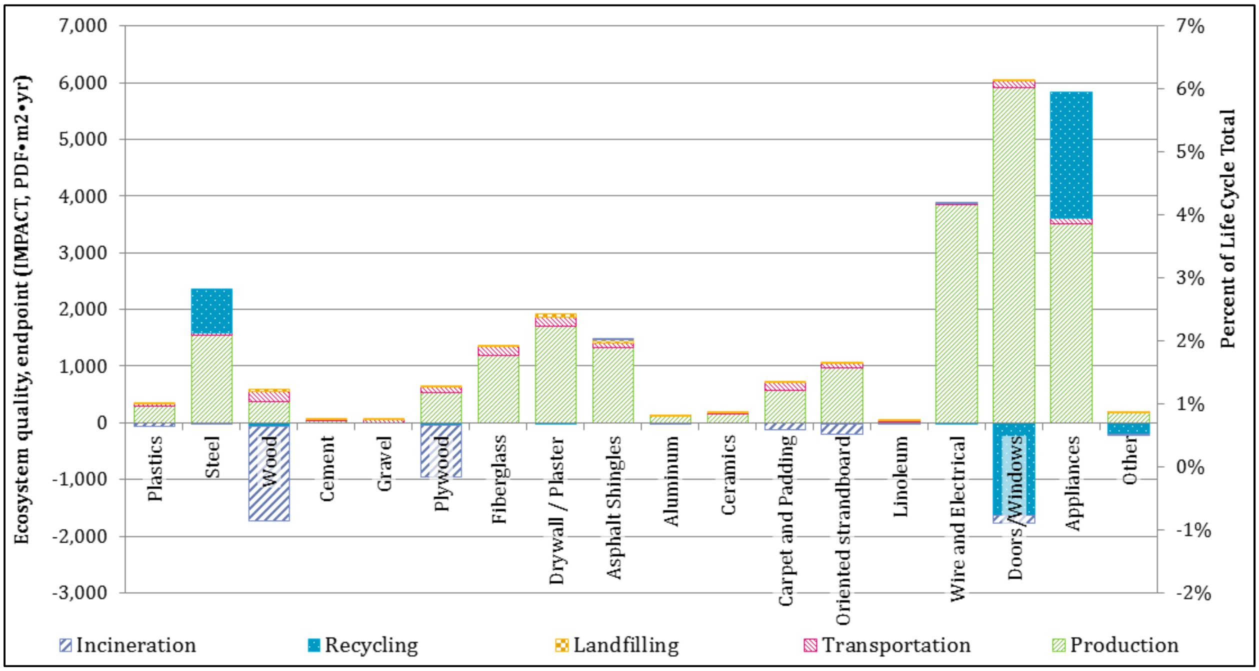


Figure 32: ***Ecosystem Quality (endpoint)*** **impact for production, transportation and end-of-life of material types within the** ***Medium Standard Home***

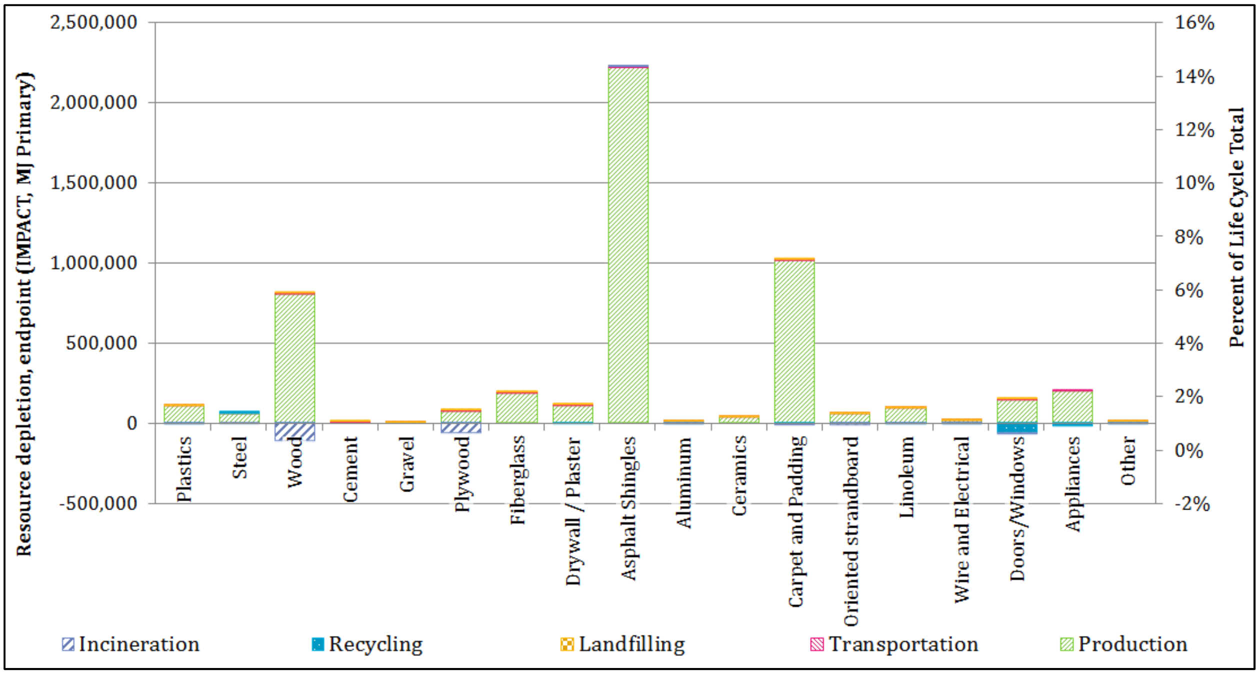


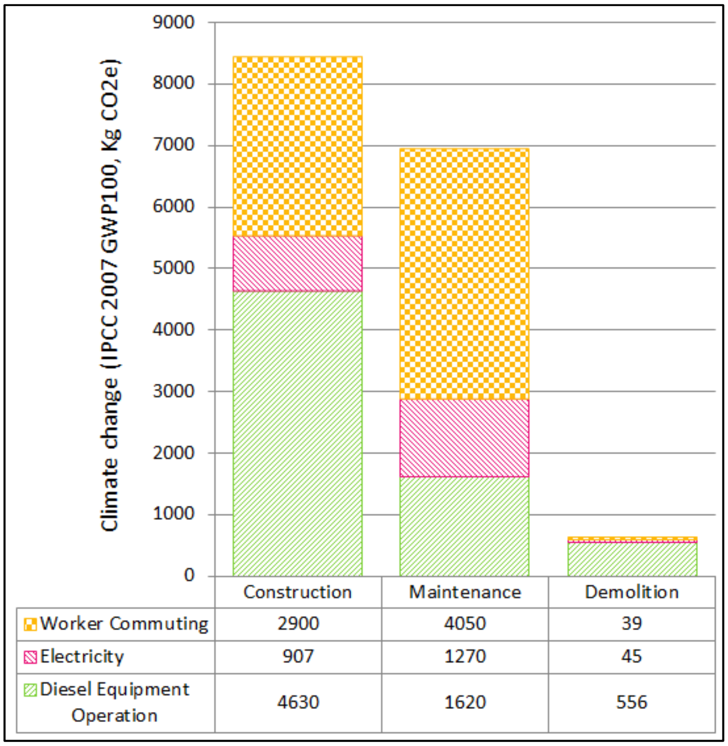
Figure 33: ***Resource Depletion (endpoint)*** **impact for production, transportation and end-of-life of material types within the** ***Medium Standard Home***

In Figure 19-32, where recycling or incineration are shown as a net benefit (i.e., a negative impact), this is due to the benefits of offsetting the production of materials or energy by conventional means being greater in magnitude than the impact incurred in recycling or incinerating. Clearly, the magnitude of such benefit varies considerably among material types and impact categories.

There is clearly a large variation among which material types are most substantial contributors to the environmental impact in each category. This finding underscores the importance of considering multiple environmental impact indicators when considering the combined impact of such a wide variety of materials. Across categories, the most substantial contributors among the material categories are carpeting, asphalt shingles, fiberglass insulation, wood, and steel/appliances (in addition to item labeled "steel", steel is also the primary component of the appliances.

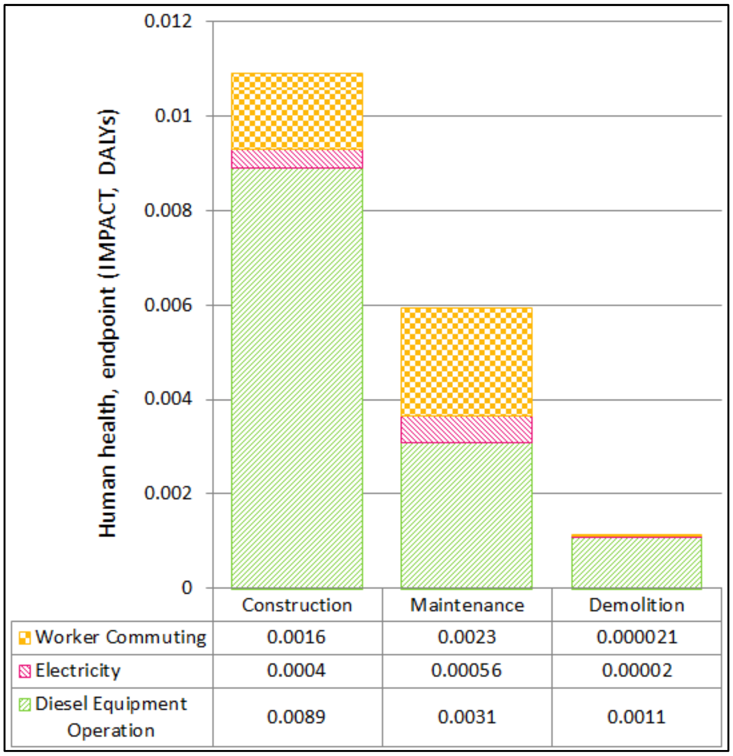
Construction, Maintenance and Demolition

The impacts of the processes of Construction, Maintenance, and Demolition are shown in Figure 36. Within these life cycle stages, it is the use of diesel equipment and the commuting of workers that contributes most significantly to the *Climate Change* impact, with electricity use contributing a less significant amount.



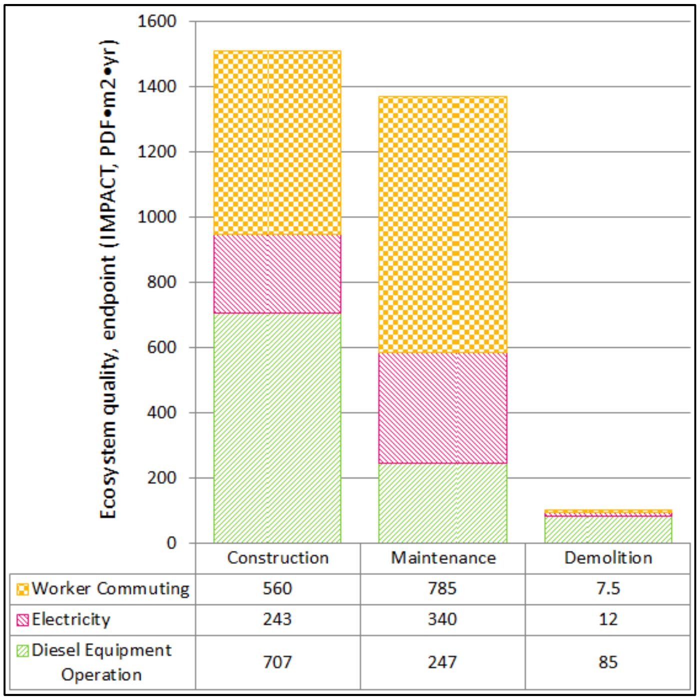
	Construction	Maintenance	Demolition
▨ Worker Commuting	2900	4050	39
▨ Electricity	907	1270	45
▨ Diesel Equipment Operation	4630	1620	556

Figure 34: *Climate Change* impact by component of the construction, maintenance and demolition stages for the *Standard Home*



	Construction	Maintenance	Demolition
▨ Worker Commuting	0.0016	0.0023	0.000021
▨ Electricity	0.0004	0.00056	0.00002
▨ Diesel Equipment Operation	0.0089	0.0031	0.0011

Figure 35: ***Human Health (endpoint)*** **impact by component of the construction, maintenance and demolition stages for the** ***Standard Home***



	Construction	Maintenance	Demolition
▨ Worker Commuting	560	785	7.5
▨ Electricity	243	340	12
▨ Diesel Equipment Operation	707	247	85

Figure 36: ***Ecosystem Quality (endpoint)*** **impact by component of the construction, maintenance and demolition stages for the** ***Standard Home***

Direct Land Use Impact of the Home

The present project has not explicitly considered the environmental implications of the land occupied by the home, although it is feasible that this is an important consideration. It is possible to make a quick assessment of its significance to the *Ecosystem* Quality endpoint result under the IMPACT 2002+ system, as the biodiversity impacts of land use are among the contributors to this endpoint indicator. If we assume that the home itself sets on a footprint of 100 m^2 (1076 ft^2) of impervious land (land use factor from IMPACT 2002+ = 1.15)and that it prevents the use of that land for habitat for the 70 year life of the home, the resulting impact would be 100 x 70 x 1.15 = 8,050 PDF*m^2*yr. This would represent slightly less than 10% of the total *Ecosystem* Quality impact of the whole lifetime of the home. In addition, one could consider that potential *Climate Change* impact of the use of the land for housing versus other purposes, as discussed further above for forestry practices, although it has not been possible to do so here. No aspect of the current project has considered the maintenance of a yard for the home, but this could be an additionally important consideration for land use.

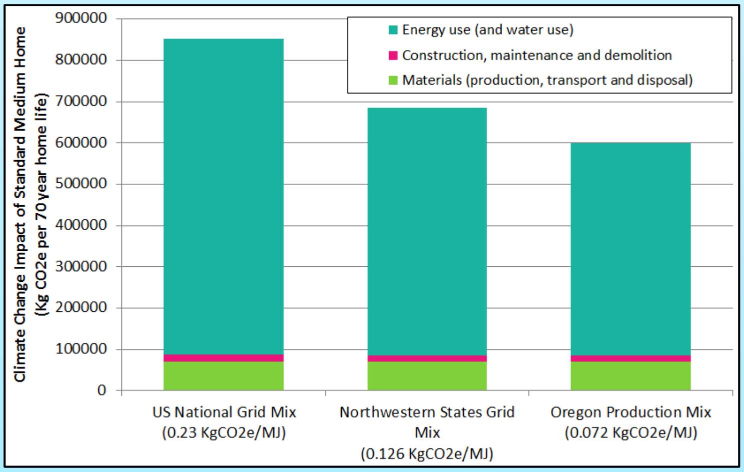
Results: State-wide Home Population

The annual and cumulative *Climate Change* impact for the population of homes is shown in Figure 37. These estimates include both the existing housing stock in 2010, as well as newly constructed homes through the year 2030 (see section above regarding Boundaries for Calculations Regarding the Statewide Home Population). Also shown, for purpose of comparison, is the result if the total impact were computed based only on the *Medium Standard Home* as a representation of all homes in the population. While the annual impact (shown in solid lines and measured against the right axis) indicates that total impact predicted for all homes within the study scope occurring within each year, the cumulative impact (shown in dashed lines and measured against the left axis, indicates the total amount of impact predicted for all homes within the study scope between 2010 and a given year.

It is estimated here that the annual *Climate Change* impact of the Oregon housing stock in 2010 is approximately 18 Tg (1 Teragram equals 10^{12} grams or one billion kilograms). It is anticipated that this will increase to nearly 23 Tg by 2030. Following 2030, the annual impact of homes *within the scope of the study* begins to decrease, as the homes built prior to 2030 are gradually removed from the population and the homes built beyond that point *are not included within the scope.* The cumulative impact shown, nearly 1600 Tg of CO_2 equivalents is therefore the total future *Climate Change* impact that is linked to homes that either exist now or will be built before 2030. As discussed above, it is considered that this coming 20-year window of home construction is reasonable to consider because it represents the homes that can reasonably be expected to be impacted by policy decisions, industry initiative or other actions taken today (2010) or in the near future. It should be noted that some home lives extend well beyond the 70 year life assumed for the *Medium Standard Home* due to the treatment of home loss among the population as an exponential decay, losing 3% of pre-existing homes each year. Therefore, while the *Average Home* in this population has a life in the range of 70 years, many are demolished sooner and many longer than at 70 years.

Characteristics of the Electricity Supply Mix

The present assessment has represented the production of electricity supplying the home as being derived from the Northwest states production (NWPP) mix (electricity within the supply chain of products is represented based on the US national average electrical grid). The choice of a representation of electricity production in such a project is not a simple matter. One might consider whether it is best to represent the actual source of the electricity that is being used, or the sources that would change if electricity use increased or decreased. In either case, it is challenging to pinpoint the exact mix of sources and production technologies and one might variously choose a very local or a quite broad (e.g., continental mix) in efforts to achieve what seems to be the most realistic representation. Added to uncertainty about the geographic extent of production is the temporal aspect. In the present case, current electrical production characteristics are being used to represent electricity production decades and more into the future. It is very unclear how this production will change over time and therefore impossible to make a highly accurate estimate of the environmental impacts of electrical production. One can, however, test the sensitivity of this issue in an effort to better understand and communicate on the potential implications of this issue. The figure below shows the *Climate Change* impact of the medium *Standard Home* under three alternative choices of electrical grid: the Oregon state production mix, the NWPP mix and the US national mix. While some may suggest the Oregon production mix is too local a representation to correctly indicate the impact of electricity use within the state, one might also consider that this lower level of impact per kWh might be considered to roughly represent an aggressive reduction in the electrical grid's impact over the lifetime of the homes in question.



As is seen in the figure, the impact of the electrical grid has an important influence on the total impact attributed to the Medium *Standard Home*. It should be noted that this home is modeled as having natural gas heat and so the influence will be even greater for homes with electric heat. The resulting implication is that results that depend highly on the electrical use of the home or on the proportional impact of electricity to other aspects of the life cycle should be viewed with an understanding that they may be highly sensitive the assumptions made about electricity, and especially to the uncertainty regarding future electricity production conditions.

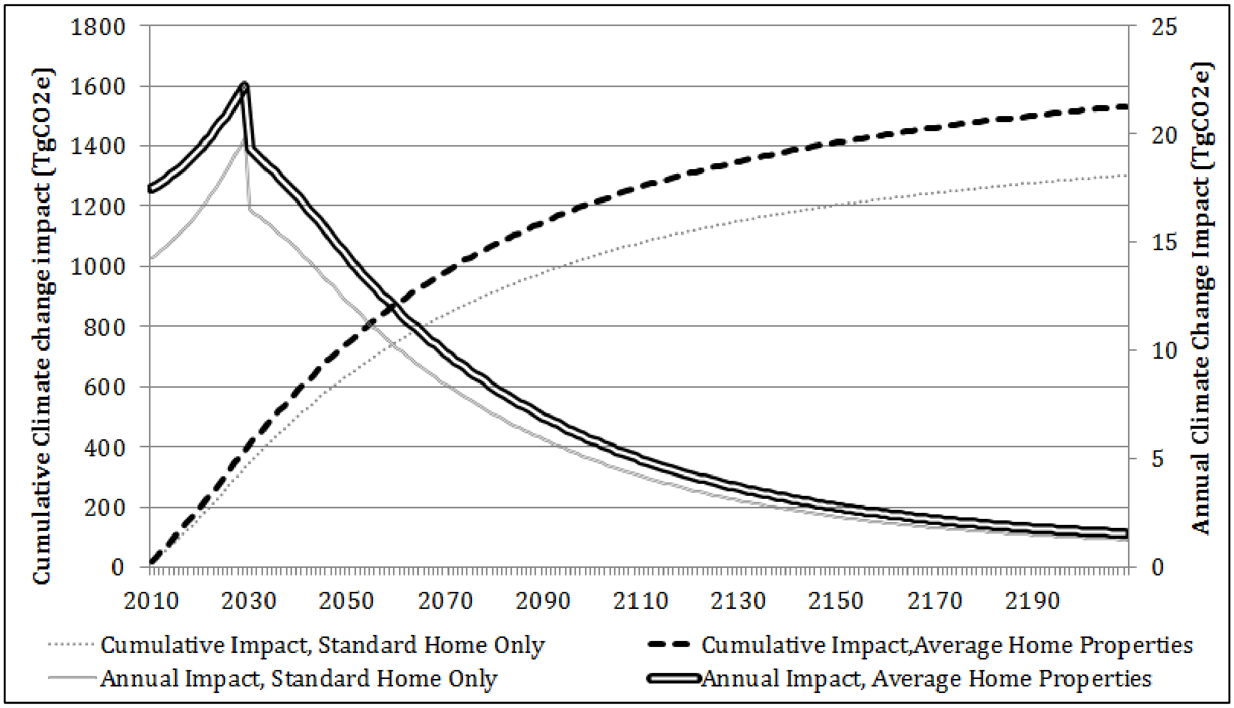


Figure 37: Comparison of statewide estimate made with 84 *Average Home* scenarios and with the *Medium Standard Home* only

Comparison with Oregon GHG Inventory

The State of Oregon has estimated the total GHG emissions from home fuel combustion and electricity use by residences with the state total 12 Tg CO_2e in 2005. This is roughly two-thirds of the 2010 estimate made above. Several reasons can be considered to explain this. One is a difference in scope. The Oregon inventory includes only the fuel and electrical use and does not include the material production, construction, maintenance, demolition or end-of-life of housing stock, which are included here. Certain things may not be included in the residential statistics within the inventory but they may be included elsewhere in the inventory. For instance, material production impacts may be included (as long as they were manufactured in Oregon) but they are not classified under residential, but under industrial.

The difference of five years in the timing of the estimate is likely to play a small role. Perhaps the most significant difference is a mismatch in which greenhouse gas emissions are included. The State of Oregon's estimate includes those greenhouse gasses emitted directly in the combustion of fuels or in the generation of electricity, but may not include the variety of other emissions that might occur upstream of combustion. In the life cycle approach considered here, emissions such as those occurring in mining and transporting fuels would also be included. When comparing the "life cycle" emissions from fuel combustion with the direct emissions, the percent difference will vary from one type of fuel to another. Finally, the estimates have been arrived at in two very different ways and so some disagreement it to be expected. Because it is derived from more accurate state-wide data on the quantities of fuel and electrical use, the State of Oregon's data should be seen as a more reliable estimate of the direct emissions from residential home heating/cooling within the state.

Table 10: Summary of cumulative environmental impact from pre-2010 and post-2010 homes (through 2210)

Impact Category	Unit	Cumulative impact from Pre-2010 homes	Cumulative impact from Post-2010 homes	Percent of impact from Pre-2010 homes	Percent of impact from Post-2010 homes
Waste generation	Kg	55,400,000,000	112,000,000,000	33%	67%
Climate Change *(with forestry land use)*	Kg CO2e	696,000,000,000 *(718,000,000,000)*	606,000,000,000 *(663,000,000,000)*	53% *(52%)*	47% *(48%)*
Non-renewable energy use	MJ Primary	11,800,000,000,000	10,500,000,000,000	53%	47%
Carcinogenic toxicity	Kg benzene-Eq	1,010,000,000	1,130,000,000	47%	53%
Non-carcinogenic toxicity	Kg toluene-Eq	7,100,000,000,000	7,720,000,000,000	48%	52%
Respiratory effects	Kg PM2.5 eq.	539,000,000	530,000,000	50%	50%
Acidification	moles of H+-Eq	131,000,000,000	123,000,000,000	52%	48%
Ecotoxicity	Kg 2,4-D eq.	382,000,000,000	418,000,000,000	48%	52%
Eutrophication	Kg N	114,000,000	128,000,000	47%	53%
Ozone depletion	Kg CFC-11 eq	41,100	34,600	54%	46%
Photochemical oxidation	Kg NOx eq	1,330,000,000	1,320,000,000	50%	50%
Human health, endpoint	DALYs	320,000	314,000	50%	50%
Ecosystem quality, endpoint	PDF•m2•yr	157,000,000,000	142,000,000,000	52%	48%
Resource depletion, endpoint	MJ Primary	13,600,000,000,000	12,400,000,000,000	52%	48%

Note that although Figure 37 shows a declining annual impact following 2030, the annual impact of the entire population of homes in Oregon is likely to continue increasing beyond this date. However, the newly constructed homes from 2030 onward are not considered within the scope of the assessment. As mentioned above, it is considered that beyond a 20-year period, new homes will be less subject to decisions made on the information assessed here and their materials, forms and efficiency may differ widely from the assumptions made here.

Note that while nearly two thirds of the waste that will be generated from these homes is from post-2010 homes, those homes account for roughly half of the total future environmental impact of all homes. This difference is due to the inclusion of the construction process and materials of the new homes, as well as an effect from the longer future life of the newly constructed homes.

Figure 37 above shows a comparison of modeling the home population with the series of *Average Homes* that have been created and with only the *Medium Standard Home*. Because many of the comparisons made throughout this report are in reference to the *Medium Standard Home* and/or to home models based upon it, this comparison provides a perspective on how closely this "standard" home, designed to be near the average size of new construction and with typical features, reflects the state of the population as a whole. The difference in the predicted cumulative total between the two approaches (for the *Climate Change* indicator) is approximately 15%. To the extent that these results are close lends some additional validation to the use of results based on the *Medium Standard Home* as a reasonable representative of the population as a whole.

Figure 38 depicts the *Climate Change* impact of the *Average Home* scenarios within each of the four single-family home sizes and three multi-family building sizes, including Pre-2010 and Post-2010 categories for each. These *Climate Change* impacts are divided among the pre-occupancy impact, occupancy impact and post-occupancy impact.33 Also shown is the contribution of each home category to the number of homes in the population over time, and the contribution of each home type to the cumulative *Climate Change* impact of the home population.

The greatest total contribution to *Climate Change* impact is expected among the medium and large single family homes. This can be attributed to both a larger number of these homes and also their higher *Climate Change* impact per home, as compared to the small and extra small homes. As can be seen in the result for contribution to home population, the assumption in the baseline scenario is a continuation of current trends resulting in a shift toward larger homes between 2010 and 2030, resulting in an increase in the most impacting segment of the home population.

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[33] Note that "Pre-occupancy" refers to activities occurring in the original construction of the home, "Occupancy" includes all energy, water, and maintenance during the homes' use, including disposal of materials removed during maintenance. "Post-occupancy" includes the demolition of the home and disposal of materials taken from the home at demolition.

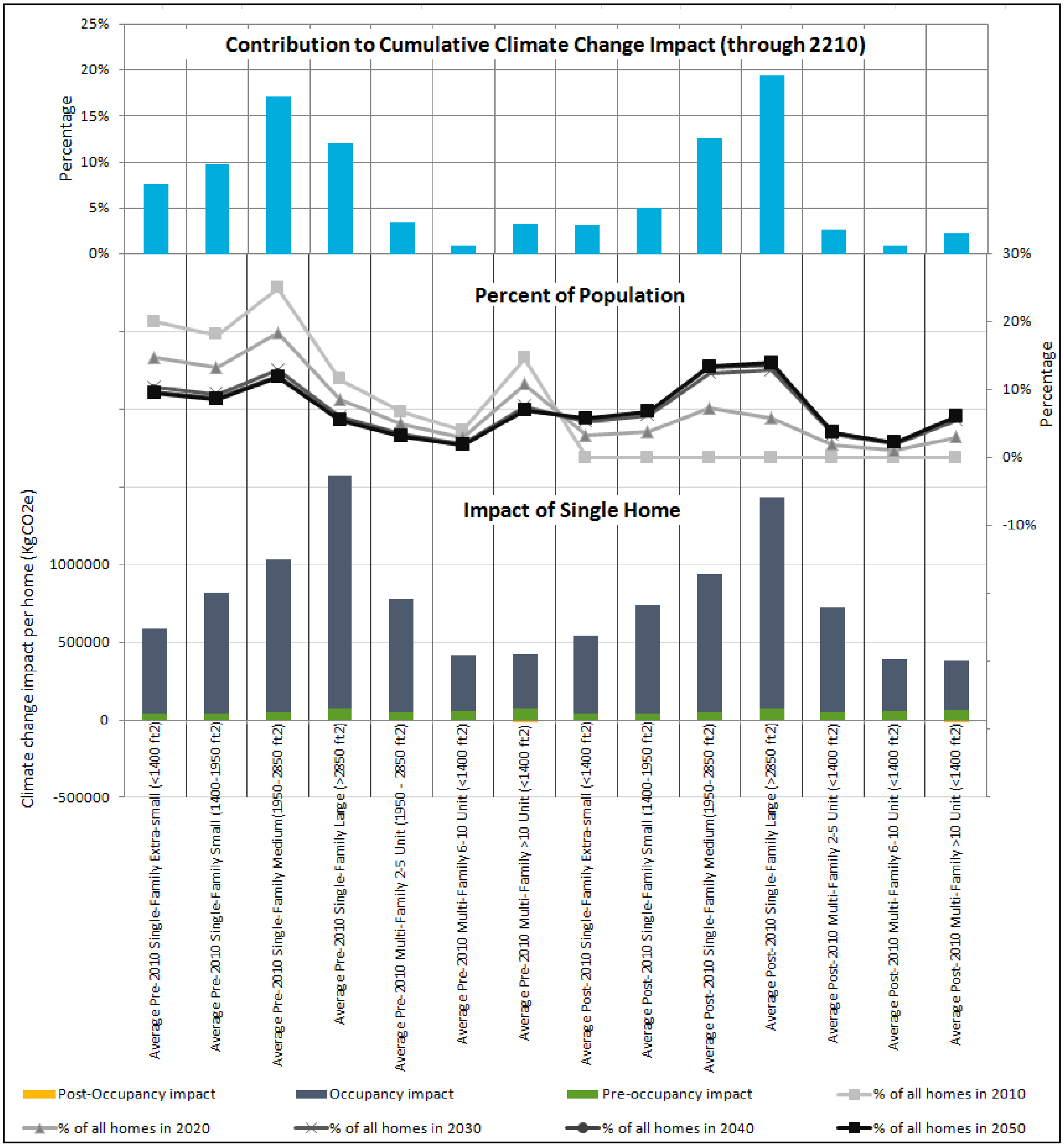


Figure 38: Impact of single homes, contribution to population and the contribution to cumulative *Climate Change* impact of size of single and multi-family residence

Results: Overview of Scenarios

Figure 39 shows the Waste Prevention benefit resulting from each of the scenarios evaluated. Note that positive values indicate an environmental benefit, whereas negative values indicate an environmental impact. For all scenarios, the value shown is the net difference from the *Medium Standard Home*.

The combined practices of the Waste Prevention home show the greatest benefit in this metric, followed by the material reuse scenario, multi-family housing, small home, green home certification and durable materials. In addition to the large home, insulating concrete forms and Strawbale each show a reasonably large net increase in waste generation, while SIPs and double wall show a small net increase.

Figure 40 shows the *Climate Change* benefit resulting from each of the scenarios evaluated. Note that positive values indicate an environmental benefit, whereas negative values indicate an environmental impact. For all scenarios, the value shown is the net difference from the *Medium Standard Home*. Figure 41 shows the same results when the sensitivity test of considering forestry land use is applied.

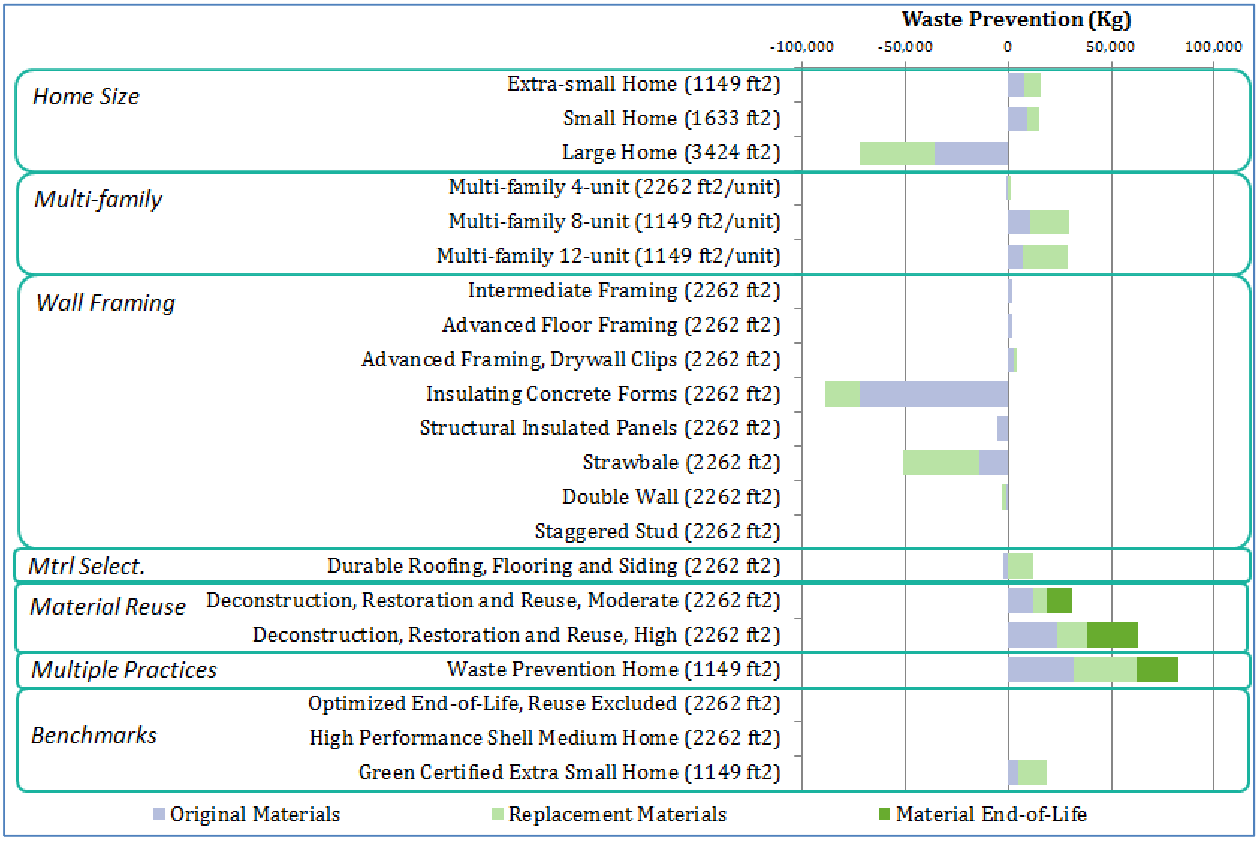


Figure 39: Waste Prevention benefit for each of the scenarios considered (net change from the *Medium Standard Home*,2262 sqft, which produces 92,000 kg waste in total)

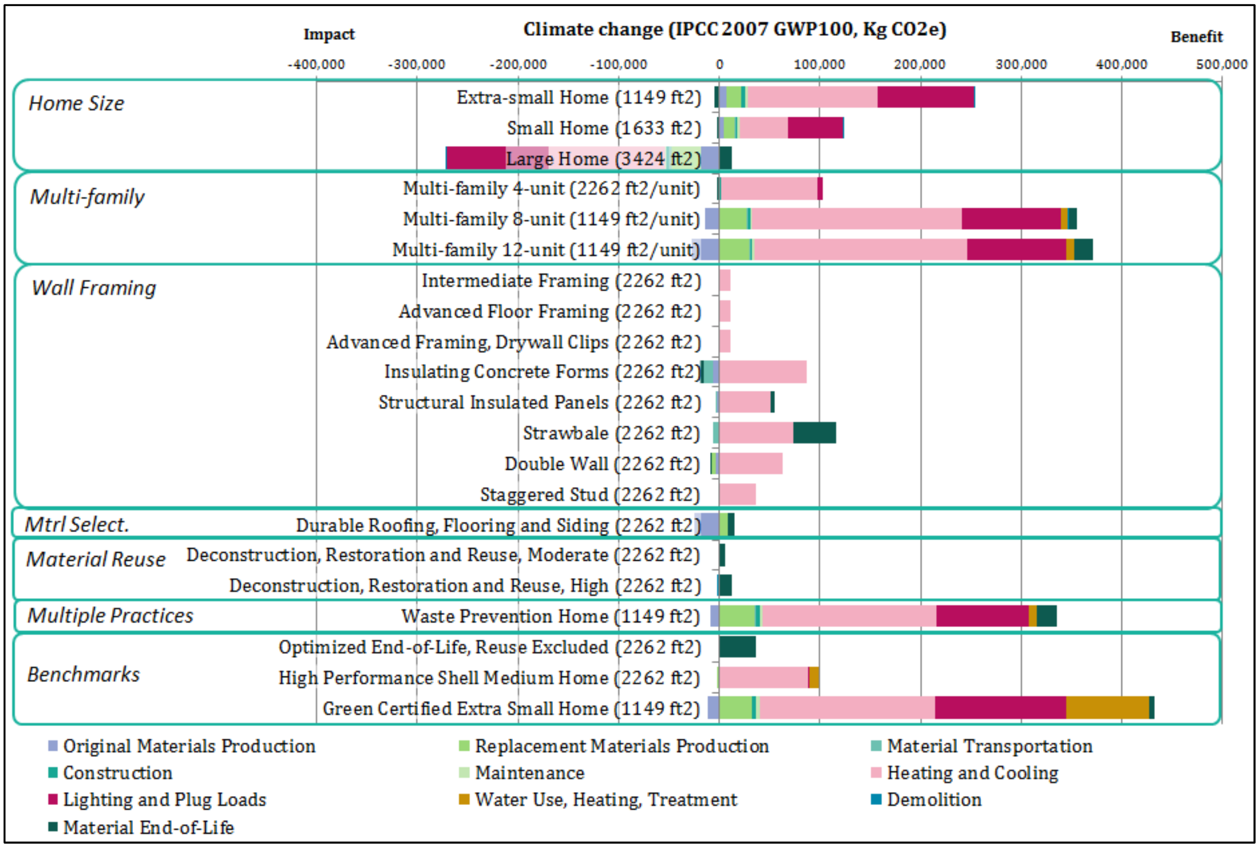


Figure 40: ***Climate Change*** **benefit for each of the scenarios considered (net change from the** ***Medium Standard Home, 2262 sqft*****)**

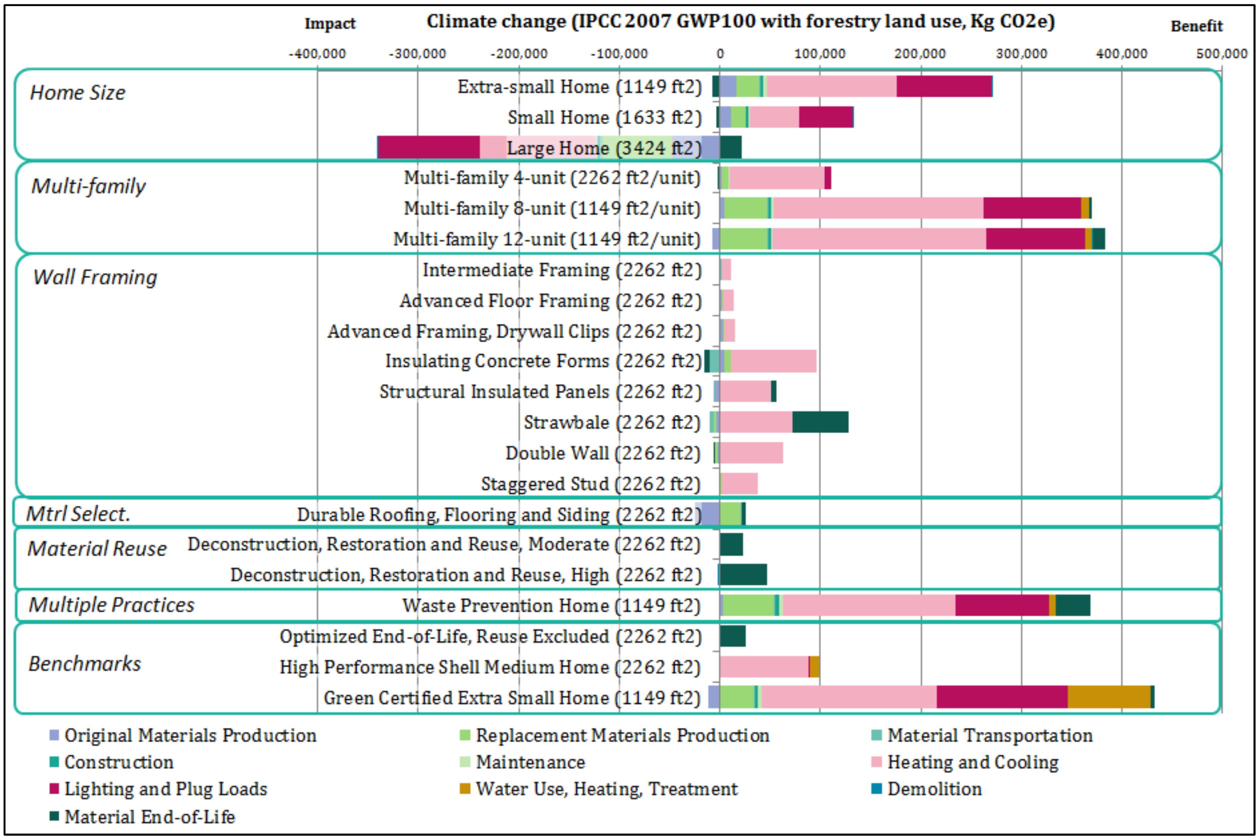


Figure 41: *Climate Change* benefit, including credit for forestry land use, for each of the scenarios considered (net change from the *Medium Standard Home, 2262 sqft*)

Table 11: *Climate Change benefit* for each of the scenarios considered (net change from the *Medium Standard Home*, 2262 sqft); The final column shows the total in the case that the sensitivity test for forestry land use is applied; the benefit is shown in units of kg CO_2e.

	Original Materials Production	Replacement Materials Production	Material Transportation	Construction	Maintenance	Heating and Cooling	Lighting and Plug Loads	Water Use, Heating, Treatment	Demolition	Material End-of-Life	Total	Total (with credit for forestry land use)
Extra-small Home (1149 ft2)	6200	13800	800	3800	3100	128800	94800	0	200	-3100	248400	255900
Small Home (1633 ft2)	4300	10000	500	2100	1700	48900	53500	0	100	-500	120600	120400
Large Home (3424 ft2)	-19300	-30200	-2300	-2800	-2300	-115000	-100900	0	-300	15600	-257500	-330300
Multi-family 4-unit (2262 ft2/unit)	-1400	-100	-100	800	700	95200	6100	0	0	500	101700	99400
Multi-family 8-unit (1149 ft2/unit)	-14000	26400	1300	2600	2100	208600	97600	7500	200	9400	341700	364400
Multi-family 12-unit (1149 ft2/unit)	-27200	29000	1400	2100	1700	212000	98700	7500	100	19100	344400	370100
Intermediate Framing (2262 ft2)	-500	-500	-100	0	0	10300	0	0	0	1900	11100	-100
Advanced Floor Framing (2262 ft2)	-400	-400	0	0	0	10500	0	0	0	1500	11200	3000
Adv. Framing, Drywall Clips (2262 ft2)	-300	-200	0	0	0	10500	0	0	0	1400	11400	4100
Insulating Concrete Forms (2262 ft2)	-6600	700	-8000	0	0	85500	0	0	0	-3000	68600	76200
Structural Insulated Panels (2262 ft2)	-3700	-200	-400	0	0	51000	0	0	0	5700	52400	41000
Strawbale (2262 ft2)	500	-900	-3200	0	0	72000	0	0	0	44800	113200	114100
Double Wall (2262 ft2)	-4400	-3900	-400	0	0	62700	0	0	0	1700	55700	48700
Staggered Stud (2262 ft2)	-800	-500	-100	0	0	36800	0	0	0	1800	37200	28500
Durable Roof/Floor/Siding (2262 ft2)	-26100	5000	0	0	0	0	0	0	0	8100	-13000	-12100
Decon., Rest. & Reuse, Mod. (2262 ft2)	-1000	-600	-900	0	0	0	0	0	-1200	8200	4500	14100
Decon., Rest. & Reuse, High (2262 ft2)	-1000	-600	-1700	0	0	0	0	0	-1600	14400	9500	40200
Waste Prevention Home (1149 ft2)	-8800	34000	200	3800	3100	172400	92000	7500	200	21100	325500	365600
Opt. End-of-Life, Reuse Excl.(2262 ft2)	-1000	-600	-100	0	0	0	0	0	0	41000	39300	16900
High Perf. Shell Med. Home (2262 ft2)	-1000	-600	-100	0	0	88100	1300	9600	0	2200	99500	88600
Green Cert. X-Small Home (1149 ft2)	-12300	32000	700	3800	3100	174900	129400	82600	200	5800	420200	416800

Figure 42 shows the predicted cost savings for each of the scenarios in comparison with the *Medium Standard Home*. Negative numbers represent cost reductions. Figure 43 shows the environmental impact or benefit for each scenario for each environmental impact scenario considered.

While the home size, multi-family and benchmark scenarios are reasonably consistent in the amount of benefit or impact among environmental impact categories, the wall framing, material selection, and material reuse scenarios are quite variable in their impact or benefit among categories. Each of these sets of scenarios is explored in more detail in the sections that follow.

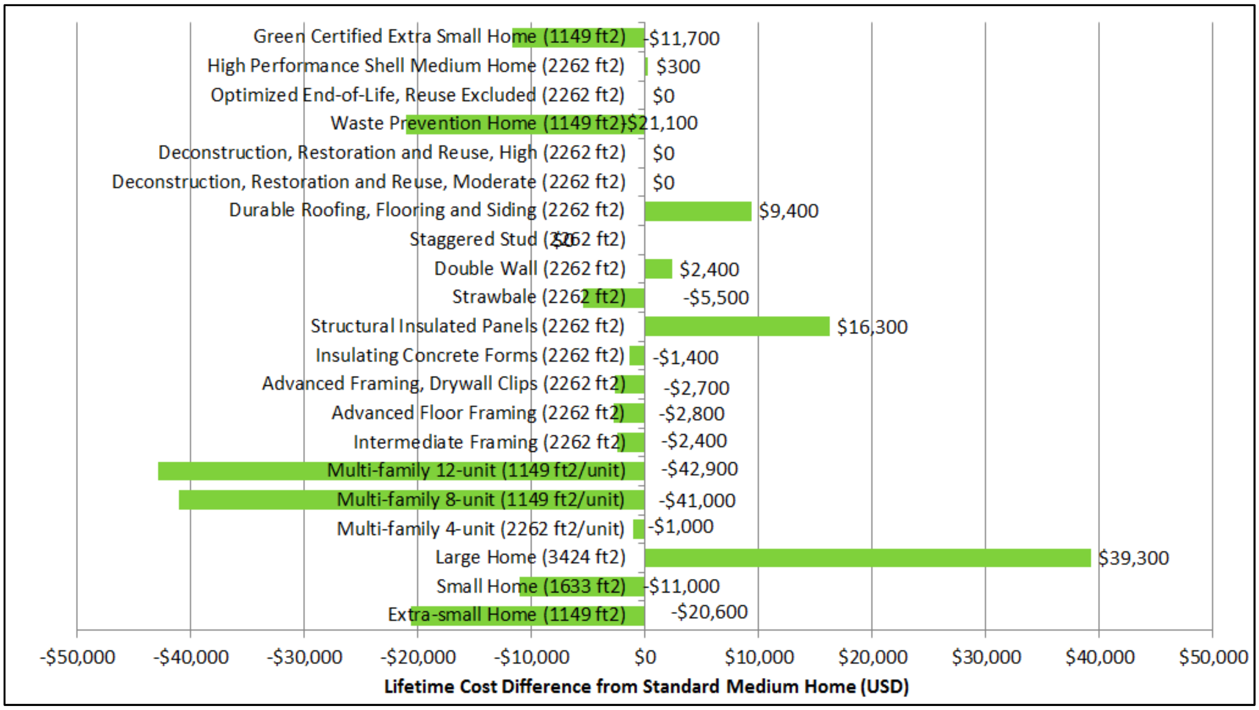


Figure 42: Predicted cost savings for each scenario relative to the *Medium Standard Home*

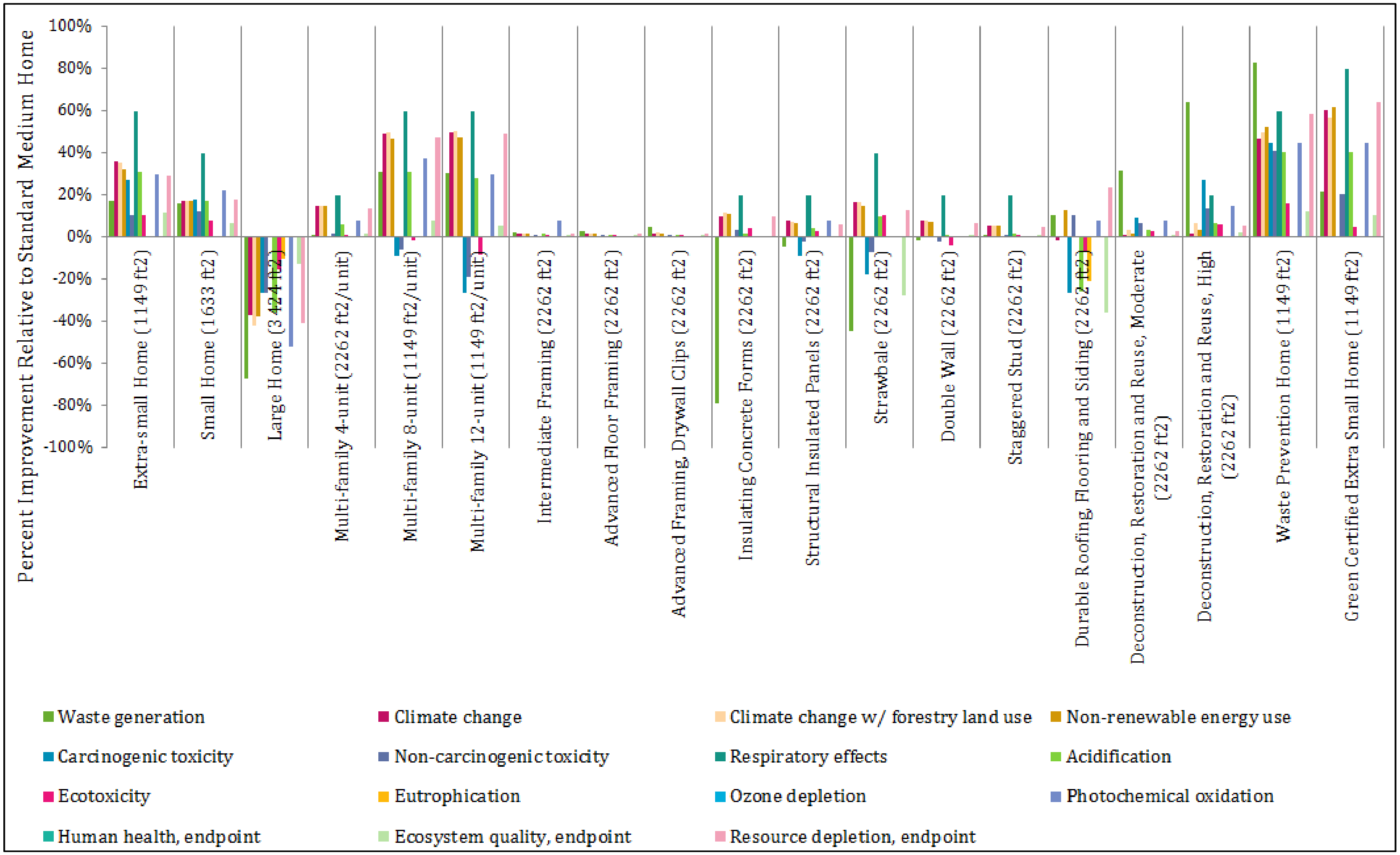


Figure 43: Environmental impact or benefit of each scenario (difference from the *Medium Standard Home*)

Results: Home Size

In considering the potential environmental benefits of smaller homes, it is important to identify the range of impacts incurred over the life cycle of homes of various sizes. A summary of the results for each of the sizes modeled here are show in Figure 44. Additional detail is shown in Figure 45 for *Climate Change* impact.

The impact of home size on environmental impact is dramatic and rather consistent among environmental categories. Across all categories, the environmental impact of the Extra-small Home in comparison to the Large home is between 40% and 60%, with a relatively steady decrease in impact with size among the home sizes considered. As it is shown for *Climate Change* impact, the benefits shown for smaller home sizes if achieved in most or all aspects of the home's life cycle, including material production, transportation, construction, and especially in energy used during the occupancy of the home.

Figure 46 shows the *Climate Change* benefit or impact of each of the home sizes examined, in addition to the comparison points of the Waste Prevention Home, the Green Certified Home, and the High Performance Shell Home. Figure 47 shows these benchmark scenarios in comparison to the home sizes for all impact categories. Recall that the Waste Prevention Home and Green Certified Home are designed to be the same size as the Standard Extra-small Home.

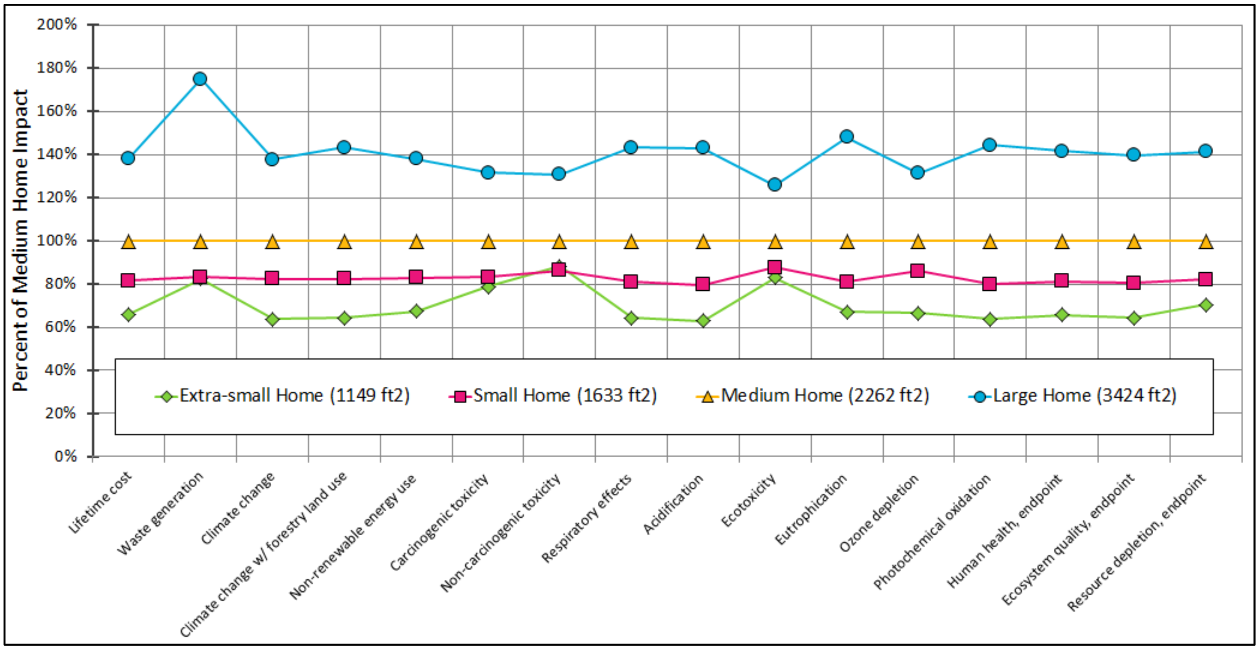
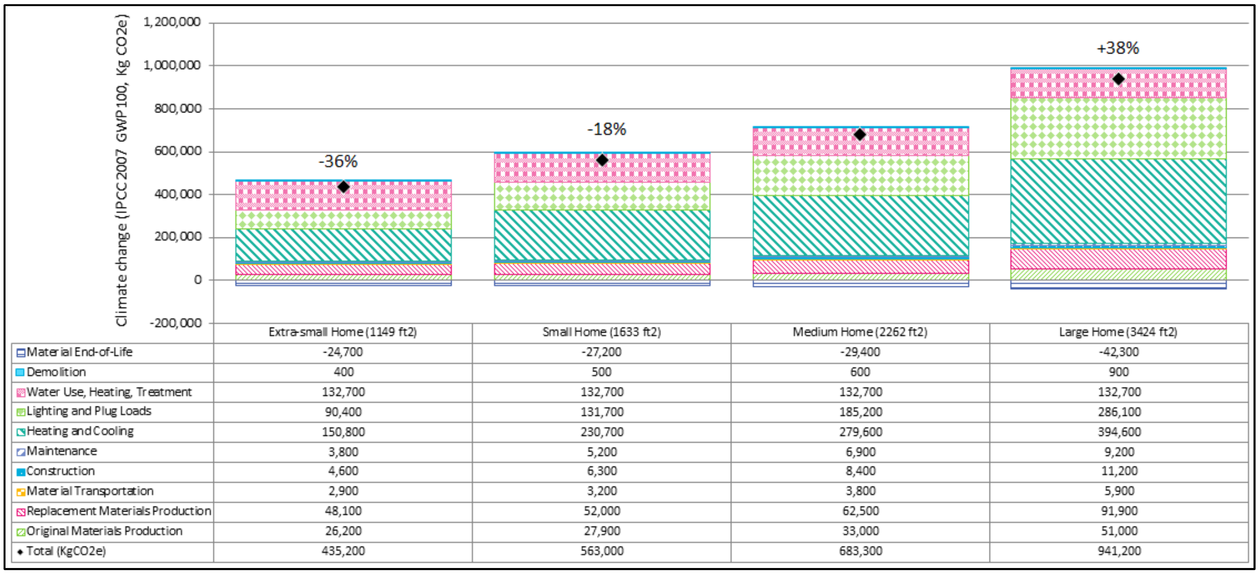


Figure 44: Comparison of environmental impacts, waste generation and cost for extra small, small, medium and large homes



	Extra-small Home (1149 ft2)	Small Home (1633 ft2)	Medium Home (2262 ft2)	Large Home (3424 ft2)
Material End-of-Life	-24,700	-27,200	-29,400	-42,300
Demolition	400	500	600	900
Water Use, Heating, Treatment	132,700	132,700	132,700	132,700
Lighting and Plug Loads	90,400	131,700	185,200	286,100
Heating and Cooling	150,800	230,700	279,600	394,600
Maintenance	3,800	5,200	6,900	9,200
Construction	4,600	6,300	8,400	11,200
Material Transportation	2,900	3,200	3,800	5,900
Replacement Materials Production	48,100	52,000	62,500	91,900
Original Materials Production	26,200	27,900	33,000	51,000
◆ Total (KgCO2e)	435,200	563,000	683,300	941,200

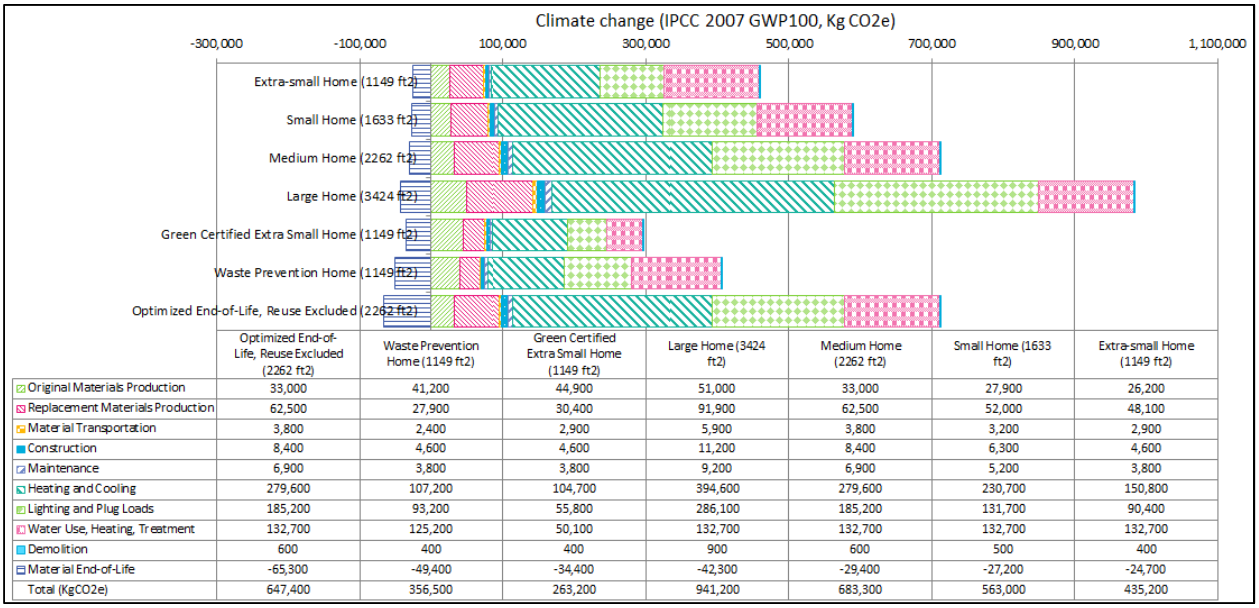
Figure 45: *Climate Change* impact over the life cycle of extra small, small, medium and large homes (percent change from medium is indicated)

Size and Function

Among the most prominent findings of the assessment of building types and building practices presented here is the large reduction in environmental impacts achieved by constructing smaller homes. A tenet of life cycle assessment is that comparisons of the environmental impact of systems should be made based on an equivalent ability to meet the defined function that is being compared (i.e., the functional unit). It is assumed here in comparisons among sizes that each home size under evaluation equally serves the defined function of “providing housing to a single family.” However, it can certainly be questioned whether houses across the wide range of sizes considered do indeed meet this function equally or whether additional qualities should be considered. Due to an inability to objectively and quantitatively evaluate such quality-of-life considerations, this study simply assumes that each home, no matter the size, provides the same quality of housing to a single family.

Although it might be interesting to consider the results based on an alternative functional unit, such as per area of home, there are several arguments suggesting this to not be a good measure of home function. One is that, though one might consider home “function” to increase with size, it may not do so consistently and/or linearly and it may therefore be problematic to assume each amount of area adds a similar increase in function. In fact, large home designs often dedicate more floor area to the same function. Larger designs also tend to include more circulation space. In every home, some areas are less used by the residents.

A further problem with measuring environmental impact per area is that it can mask the relationship of home size to energy efficiency. If divided by square footage, a larger home can appear to have a lower impact than a similar smaller home. At the level of the home population, increases in size have more than offset the gains made in efficiency in recent decades. In the United States, energy use per square foot has decreased over recent decades while overall household consumption (not to mention population numbers) continues to climb (Wigington, 2008; U.S. Department of Energy, 2008). This is a result of building larger, though more efficient, homes.



	Optimized End-of-Life, Reuse Excluded (2262 ft2)	Waste Prevention Home (1149 ft2)	Green Certified Extra Small Home (1149 ft2)	Large Home (3424 ft2)	Medium Home (2262 ft2)	Small Home (1633 ft2)	Extra-small Home (1149 ft2)
▨ Original Materials Production	33,000	41,200	44,900	51,000	33,000	27,900	26,200
▨ Replacement Materials Production	62,500	27,900	30,400	91,900	62,500	52,000	48,100
▨ Material Transportation	3,800	2,400	2,900	5,900	3,800	3,200	2,900
■ Construction	8,400	4,600	4,600	11,200	8,400	6,300	4,600
▨ Maintenance	6,900	3,800	3,800	9,200	6,900	5,200	3,800
▨ Heating and Cooling	279,600	107,200	104,700	394,600	279,600	230,700	150,800
▨ Lighting and Plug Loads	185,200	93,200	55,800	286,100	185,200	131,700	90,400
▨ Water Use, Heating, Treatment	132,700	125,200	50,100	132,700	132,700	132,700	132,700
■ Demolition	600	400	400	900	600	500	400
▤ Material End-of-Life	-65,300	-49,400	-34,400	-42,300	-29,400	-27,200	-24,700
Total (KgCO2e)	647,400	356,500	263,200	941,200	683,300	563,000	435,200

Figure 46: Comparison of *Climate Change* impact of each size of the standard single-family home, the *Waste Prevention Home*, the *Green Certification Home*, and the *High Performance Shell Home*

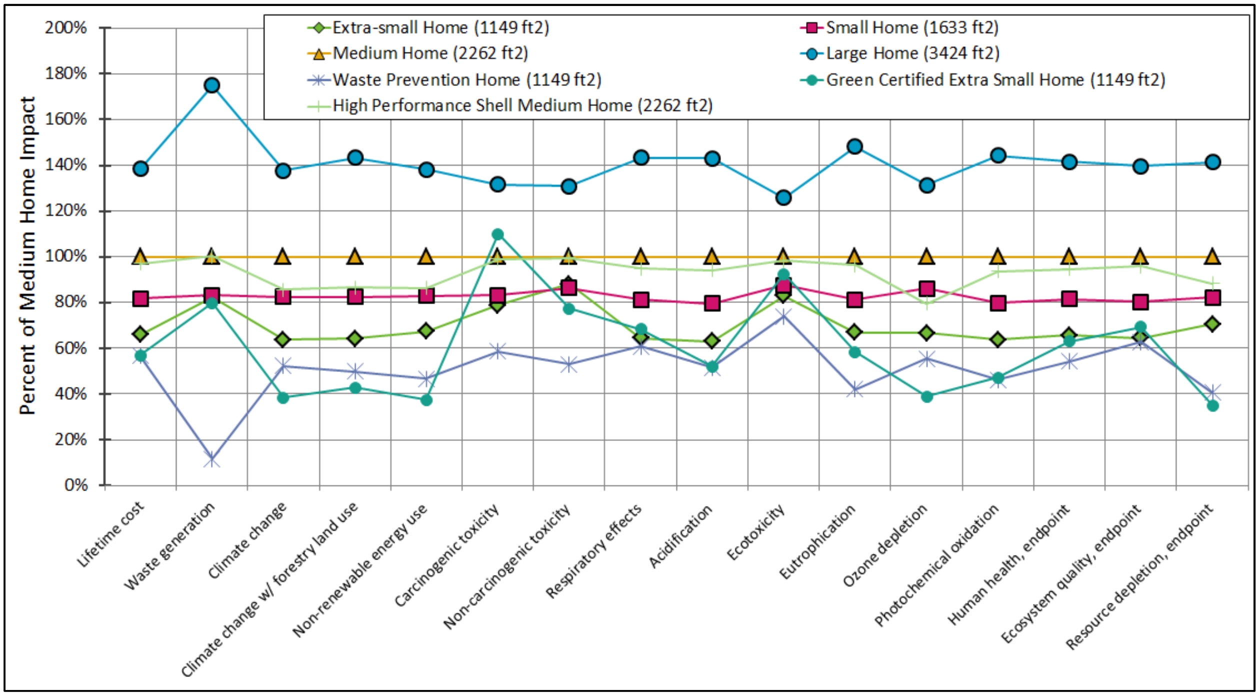


Figure 47: Comparison of environmental impact of each size of the standard single-family home, the *Waste Prevention Home*, the *Green Certification Home*, and the *High Performance Shell Home*

The benchmarks show, for example, that the impact of switching from a medium sized home (defined as 2262 ft2 in this case) to a small home (1633 ft2) is a more environmentally beneficial option than choosing a medium home with the High Performance Shell. Similarly, a switch from a medium to an extra-small home (defined here as 1149 ft2) is more environmentally beneficial than a complete switch of the home occupants from personal to public transportation. The Waste Prevention Home and the Green Certified Home results indicate that while there is indeed more benefit to be gained beyond that achieved by smaller home size, the size component is clearly a very large contributor to the benefits obtained in these benchmark homes.

Table 12: *Climate Change* impact (Kg CO_2e) by material or process category for each of the size options of the *Standard Homes* and in comparison to the *Waste Prevention Home*

Component of Home Life Cycle	Waste Prevention Home (1149 ft2)	Extra-small Home (1149 ft2)	Small Home (1633 ft2)	Medium Home (2262 ft2)	Large Home (3424 ft2)
Use - Natural Gas	206,000	255,000	332,000	379,000	488,000
Use - Electricity	98,700	97,500	142,000	197,000	304,000
Use - Water	12,100	12,100	12,100	12,100	12,100
Asphalt Shingles	0	12,300	8,730	11,900	18,300
Carpet	0	11,600	15,300	21,200	31,700
Appliances	11,500	11,500	11,500	11,500	11,500
Fiberglass Insulation	6,380	6,380	5,500	7,890	12,000
Drywall	4,680	5,240	6,100	6,660	15,000
Other Siding Mtl.	431	3,870	4,770	5,060	8,710
Windows	1,500	1,500	3,500	3,500	4,370
Electrical Fixtures	108	108	108	108	161
Wall Lumber	454	735	1,480	1,940	2,660
Other Roofing Mtl.	2,470	2,470	2,160	2,550	8,310
Doors (exterior)	2,200	2,200	2,200	2,200	1,910
Doors (interior)	1,790	1,790	2,150	2,150	3,590
Floor Engineered Wood	1,080	717	1,880	2,400	1,880
Packaging	972	1,940	1,940	1,940	1,940
Kitchen Cabinets	1,580	1,580	1,580	1,580	1,900
Wall Hardware	884	884	1,140	1,180	1,320
Sinks	878	878	1,330	1,330	2,070
Paints and Adhesives	991	991	1,170	1,180	645
Mouldings	227	578	1,100	1,290	892
Ducting	880	715	1,020	1,410	2,130
Foundation Concrete	1,050	1,260	833	1,110	1,520
Electrical Wire	828	828	747	1,040	1,240
Floor Lumber	707	886	503	600	2,910
Foundation Other Mtl.	837	794	614	741	1,590
Roof Lumber	411	450	436	507	647
Wall Engineered Wood	453	496	281	360	512
Linoleum Floors	0	339	326	452	904
Floor Hardware	147	147	294	294	294
Faucets	305	305	305	305	508
Toilets	283	283	566	566	1,130
Plumbing pipe	369	369	266	369	462
Porch Lumber	102	112	126	174	142
Cement Siding Shingles	3,870	0	0	0	0
Steel Roofing	20,100	0	0	0	0
Wood Flooring	424	0	0	0	0
Ceramic Tile	259	0	0	0	0
Transportation	2,370	2,940	3,190	3,760	5,940
Construction - Equipment	3,740	3,740	5,110	6,810	9,050
Construction - Commuting	3,840	3,840	5,240	6,990	9,290
Construction -	1,220	1,220	1,670	2,220	2,950

Component of Home Life Cycle	Waste Prevention Home (1149 ft2)	Extra-small Home (1149 ft2)	Small Home (1633 ft2)	Medium Home (2262 ft2)	Large Home (3424 ft2)
Electricity					
Material Waste-to-Energy	-2,440	-9,100	-11,300	-13,300	-26,500
Material Recycling	-14,000	-16,600	-17,000	-17,500	-18,200
Material Landfilling	343	1,000	1,130	1,360	2,420
Material Reuse	-33,300	0	0	0	0
Total	357,000	435,000	563,000	683,000	941,000

Table 13: Scenarios of Growth in Home Size

Scenario Home size growth rate	**Portion of new homes in 2030 that are extra-small**	**Portion of new homes in 2030 that are small**	**Portion of new homes in 2030 that are medium**	**Portion of new homes in 2030 that are large**
Size	(<1400 sqft)	1400 – 1950 sqft)	1950 - 2850 sqft	>2850 sqft sqft
Baseline (1% growth)	9.4%	10.7%	22.5%	34.2%
1% Shrinkage	20.6%	23.6%	32.4%	0.3%
2% Growth	6.7%	7.0%	15.5%	47.7%
2% Shrinkage	31.0%	30.7%	15.2%	0.0%
0% Change	13.8%	16.3%	29.6%	17.2%
Only extra-small	Homes built between 2010 and 2030 are 80% extra-small single family homes and 20% extra-small in 12-unit multi-family buildings			

Regarding the state-wide home population, a set of scenarios are conducted to examine the effect of altering the size of single-family homes that will be built within the coming 20-year period. An increase of 1% per year in *Average Home* size has been the baseline assumption. As shown in Figure 48, scenarios have been conducted representing a range of change in the average square footage of newly constructed homes of between -2% and +2%. For comparison, a scenario is also conducted in which only extra-small single-family homes are constructed. In each of the scenarios representing a change in *Average Home* size, only the single-family portion of the home population is affected. The multi-family portion of the population has not been represented with adequate gradation in size to represent such a change. However, in the only extra-small scenario, the total population of multi-family homes has been modeled as 12-unit (extra small) homes. Note that the results shown include both the existing housing stock as of 2010 and also the new construction between 2010 and 2030.

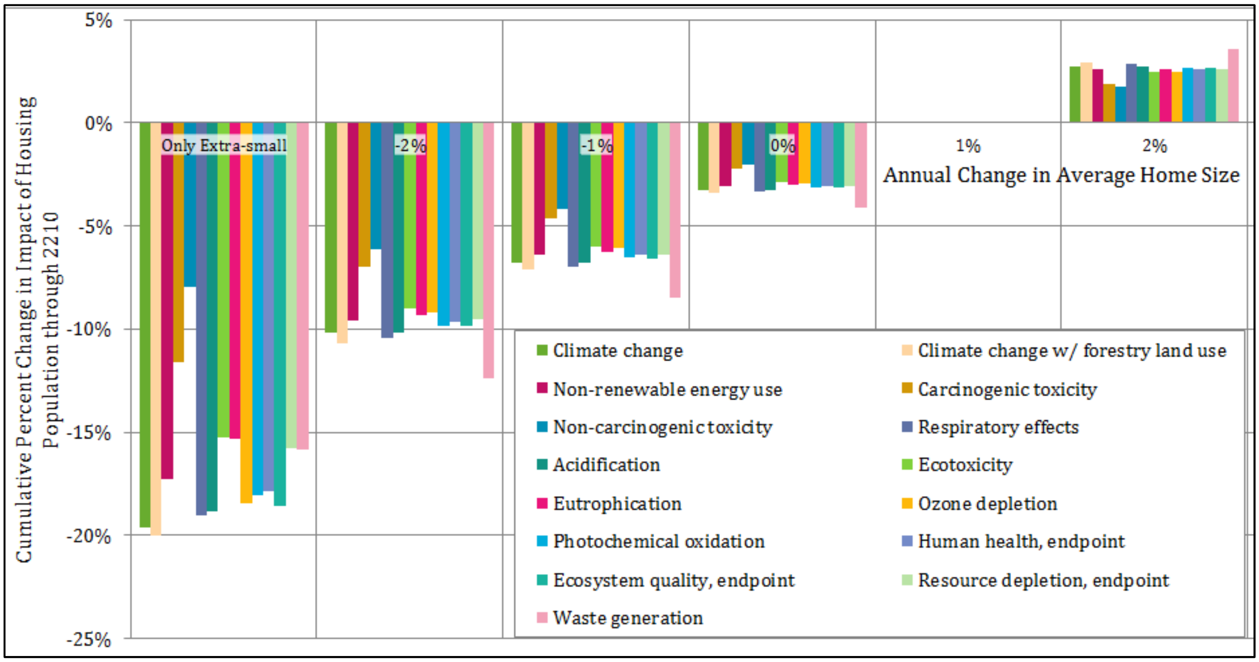


Figure 48: Comparison of environmental impact of alternative rates of change in the median home size during the period of action

Table 14: Cumulative environmental impact of the total housing population (including Pre-2010) under alternative rates of growth in new home size

	Unit	Only Extra-small	-2%	-1%	0%	1%	2%
Lifetime cost	USD	8.66E+11	9.51E+11	9.83E+11	1.02E+12	1.05E+12	1.07E+12
Waste generation	Kg	1.61E+11	1.68E+11	1.75E+11	1.83E+11	1.91E+11	1.98E+11
Climate Change* impact** ***(with forestry land use)	Kg CO_2e	1.07E+12 *(1.14E+12)*	1.20E+12 *(1.28E+12)*	1.24E+12 *(1.33E+12)*	1.29E+12 *(1.38E+12)*	1.33E+12 *(1.43E+12)*	1.37E+12 *(1.47E+12)*
Non-renewable energy use	MJ Primary	1.88E+13	2.05E+13	2.12E+13	2.20E+13	2.27E+13	2.33E+13
Carcinogenic toxicity	Kg benzene-Eq	1.93E+09	2.04E+09	2.09E+09	2.14E+09	2.19E+09	2.23E+09
Non-carcinogenic toxicity	Kg toluene-Eq	1.40E+13	1.42E+13	1.45E+13	1.49E+13	1.52E+13	1.54E+13
Respiratory effects	Kg PM2.5 eq.	1.03E+09	1.14E+09	1.19E+09	1.23E+09	1.28E+09	1.31E+09
Acidification	moles of H+-Eq	2.35E+11	2.60E+11	2.69E+11	2.80E+11	2.89E+11	2.97E+11
Ecotoxicity	Kg 2,4-D eq.	6.45E+11	6.93E+11	7.15E+11	7.39E+11	7.61E+11	7.80E+11
Eutrophication	Kg N	2.32E+08	2.48E+08	2.57E+08	2.65E+08	2.74E+08	2.81E+08
Ozone depletion	Kg CFC-11 eq	6.70E+04	7.46E+04	7.72E+04	7.98E+04	8.22E+04	8.42E+04
Photochemical oxidation	Kg NOx eq	2.46E+09	2.70E+09	2.80E+09	2.90E+09	3.00E+09	3.08E+09
Human health, endpoint	DALYs	5.52E+05	6.07E+05	6.29E+05	6.51E+05	6.72E+05	6.89E+05
***Ecosystem* quality, endpoint**	PDF•m2•yr	2.55E+11	2.82E+11	2.93E+11	3.03E+11	3.13E+11	3.22E+11
Resource depletion, endpoint	MJ Primary	2.22E+13	2.39E+13	2.47E+13	2.56E+13	2.64E+13	2.71E+13

Does House Size Influence the Consumption of Durable Goods? *[Supplemental research contributed by the Oregon DEQ]*

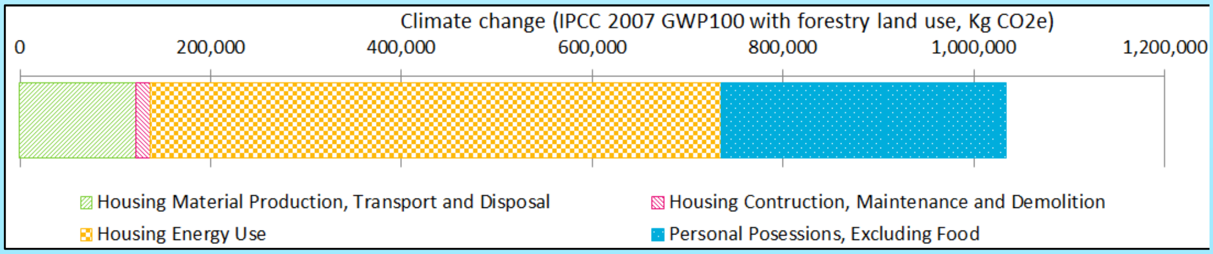
House size directly affects building material consumption and energy use and is one of the most important factors contributing to the lifecycle energy consumption and greenhouse gas emissions of homes. The effect house size has on the consumption patterns of the occupants, however, is rarely if ever quantified.

DEQ estimates that over the 70 year lifecycle of a home, the emissions associated with the "stuff" put into an average Oregon home may contribute an additional 35% to the life cycle greenhouse gas emissions associated with that home, as estimated elsewhere in this report. The "stuff" put in the home includes durable items like clothes, electronics, and furniture. This estimate does not include the "use phase" impacts of stuff. For example, the impact of producing and disposing of a television set is included in the 35% estimate, but the electricity plug load impact of using that TV is already included as a default assumption in the energy modeling efforts elsewhere in this report. Appliances, carpet, and other home contents already included in this *Average Home* modeling are not included in the 35% estimate either. Additionally, this estimate does not include the consumption of food, because the quantity of food is less likely to change with house size, whereas, the quantity of furniture and other goods purchased for someone's home is more likely to change with house size.

This estimate is very rough and is less accurate than other estimates related to house size contained in this report. DEQ derived this estimate using data from an unpublished draft report of Oregon's Consumption Based Emissions Inventory (CBEI), which is an effort currently underway to inventory the greenhouse gas emissions resulting from consumption in Oregon. The consumption inventory combines commodity-specific estimates of consumption (measured in dollars) by households and governments with a multi-regional input/output model and estimates of emissions intensities per commodity sector. In short, DEQ considered the emissions of those commodity sectors where household consumption would likely change as house size changes, summed these categories for one year of economic data, divided by the number of households in Oregon, and then multiplied by 70 years to match the lifecycle of the single home modeled elsewhere in this report.

Overall, this estimate suggests that reducing house size can also play a role in reducing the consumption-related impacts of the durable goods we put in our homes. The main body of this research report – which has not accounted for most of the contents of the home – has shown that as house size decreases, so do the environmental impacts associated with building materials and occupant energy use. Given our estimate that, for the *Average Home*, the purchase of home contents contributes an additional 35% to the lifecycle greenhouse gas emissions, if we assume that smaller homes will have fewer contents and larger homes will have more contents, then reducing house size has a supplemental environmental benefit associated with a smaller number of contents. Put differently, the environmental benefits of reducing house size is likely even greater than estimated elsewhere in this report.

There are numerous limitations to this estimate including the affect an occupant's income has on the type, quantity, and frequency of consumption and whether someone with less space will actually own fewer chairs, lamps, televisions, clothes, books, kitchen gadgets, etc., than someone with a larger home. Despite these limitations, there is real potential for home size to affect the occupants' consumption habits. Anecdotally, many Oregonians report that "stuff in the home seems to expand to fill the available space", although this dynamic has not been well studied or documented. Based on our rough estimate of the impacts of home possessions, these issues deserve more attention and research.



Results: Multi-family Homes

In addition to home size, it is anticipated that use of multi-family structures may offer important benefits both in the area of Waste Generation and other environmental impact categories. A summary of the results for all environmental impact categories for each of the Standard Multi-family Homes that have been modeled here are shown in Figure 49. Additional detail is shown in Figure 50 for *Climate Change* impact alone.

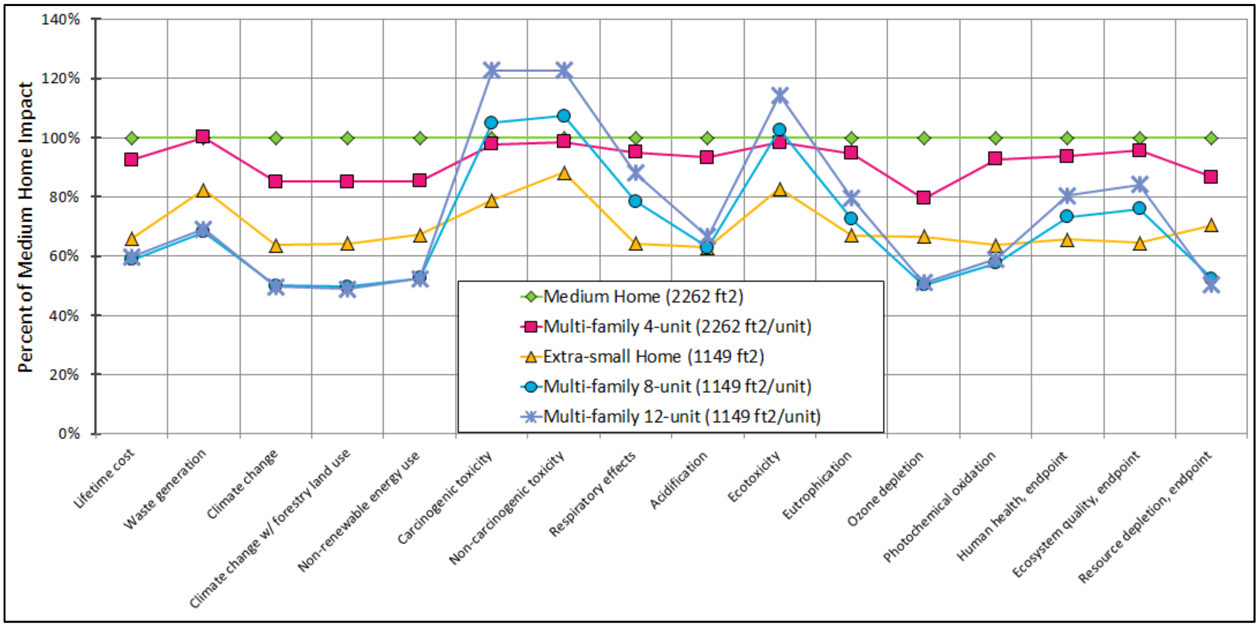
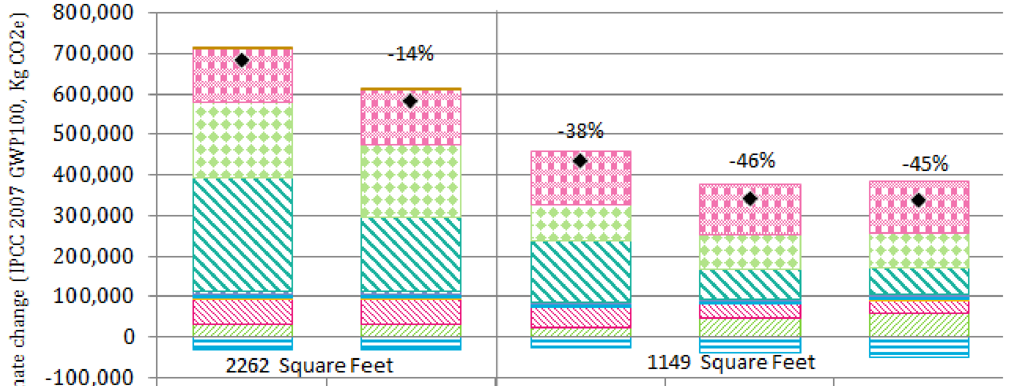


Figure 49: Environmental impact, cost and waste generation of multi-family homes in comparison to similarly sized single-family homes



	Medium Home (2262 ft2)	Multi-family 4-unit (2262 ft2/unit)	Extra-small Home (1149 ft2)	Multi-family 8-unit (1149 ft2/unit)	Multi-family 12-unit (1149 ft2/unit)
⊟ Material End-of-Life	-29000	-28000	-25000	-38000	-48000
▨ Demolition	1000	1000	0	0	0
▨ Water Use, Heating, Treatment	133000	133000	133000	125000	125000
▨ Lighting and Plug Loads	185000	179000	90000	88000	86000
▧ Heating and Cooling	280000	184000	151000	71000	68000
▨ Maintenance	7000	6000	4000	5000	5000
■ Construction	8000	8000	5000	6000	6000
▨ Material Transportation	4000	4000	3000	2000	2000
▧ Replacement Materials Production	62000	62000	48000	36000	33000
▨ Original Materials Production	33000	34000	26000	47000	60000
◆ Total	684000	583000	435000	342000	337000

Figure 50: *Climate Change* impact of multi-family homes in comparison to single-family homes

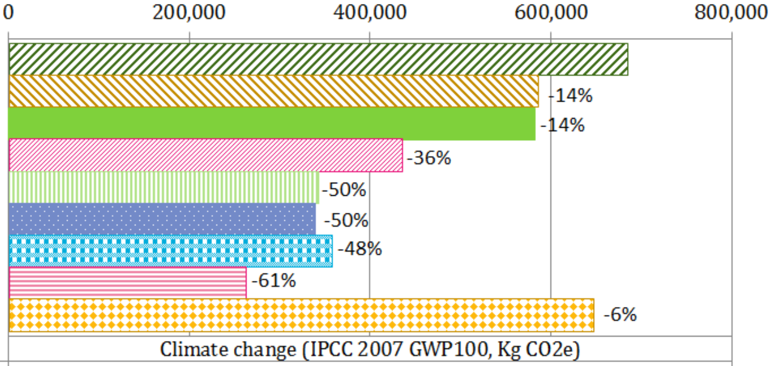
There is clearly an environmental benefit to multi-family housing, with an improvement shown for the multi-family option in comparison to the similarly-sized single family options in nearly all environmental impact categories. In most cases, the benefit of multi-family housing, independent of size difference, appears to in the range of 5 to 10%.

A very notable exception is the case of the Ecotoxicity impact category, where the 8-unit and 12-unit multi-family homes have substantially higher impact than the other homes shown. The cause of this higher impact is the exterior steel stairway and balcony that has been assumed to be included in this building design.

Although this increase in impact is very much specific to the design and material chosen for this external structure, it serves to highlight an important point regarding the impact of multi-family homes and their representation here. To maintain consistency and directly assess the influence of multi-family homes with minimal influence from changes in material, the multi-family structures examined here have all been wood-frame buildings. However, many multi-family structures may in fact have other material types used for the framing and exterior. The impact of such things as steel frame, cement frame, brick exterior, stone exterior, etc. have not been examined here. These material choices should not go unconsidered if promoting the environmental benefits of multi-family housing.

To provide context of the improvement in environmental performance, these results are compared with the Green Certified Home, and the High Performance Shell Home in Figure 51.

Currently, only 23% of homes in Oregon are multi-family, leaving a substantial room for growth in this type of housing. It is possible to consider, based on the information that has been generated here, what the environmental benefits would be of actions that promote additional growth in the multi-family housing portion of the population. Table 15 shows the characteristics of several scenarios of growth that have been assessed for the multi-family portion of housing during the period of action. The results of these scenarios are shown in Figure 52 for the full range of environmental impacts.



	Climate change (IPCC 2007 GWP100, Kg CO2e)
▨ Medium Home (2262 ft2)	684,000
▧ High Performance Shell Home (2262 ft2)	585,000
■ Multi-family 4-unit (2262 ft2/unit)	582,000
▨ Extra-small Home (1149 ft2)	435,000
▥ Multi-family 8-unit (1149 ft2/unit)	342,000
▦ Multi-family 12-unit (1149 ft2/unit)	339,000
▦ Waste Prevention Home (1149 ft2)	357,000
▤ Green Certified Home (1149 ft2)	263,000
▩ Optimized End-of-Life, Reuse Excluded (2262 ft2)	647,000

Figure 51: Comparison of the multi-family scenarios with the Green Certified Home and similarly sized single family homes

Table 15: Scenarios of Growth in Multi-Family Housing[34]

Scenario Name	Multi-family home growth rate	% of new homes as single-family in 2030	Portion of new-homes in 2030 that have 2-5 units	Portion of new homes in 2030 that have 5-10 units	Portion of new homes in 2030 that have >10 units
Assumed Size			1950 – 2850 sqft	<1400 sqft	<1400 sqft
Baseline (no change in % multifamily)	0%	76.9%	7.2%	4.3%	11.6%
1% Annual Increase in Multi-family	+1%	56.9%	13.4%	8.0%	21.6%
1% Annual Decrease in Multi-family	-1%	96.9%	1.0%	0.6%	1.6%
2% Annual Increase in Multi-family	+2%	36.9%	19.7%	11.7%	31.7%
2% Annual Decrease in Multi-family	-2%	100.0%	0.0%	0.0%	0.0%
Only Multi-family	Assumes that all homes build between 2010 and 2030 are multi-family structures, based on the current (baseline) division between <5 unit, 6-10 unit and >10 unit categories.				

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[34] The scenarios above are conducted under the assumption that growth in multi-family housing occurs only in the form of new construction and therefore at the expense of new single family units. It is also feasible that growth in multi-family housing could occur from the conversion of existing structures from single-family to multi-family through sub-divisions of pre-existing homes. The growth might therefore come partially at the expense of pre-existing single-family homes as well, or even at the expense of multi-family new construction. However, the process of conversion of a single-family home to a multi-family home may require substantial structural modifications that are not included here. The scenarios regarding material reuse may provide some additional input on this topic.

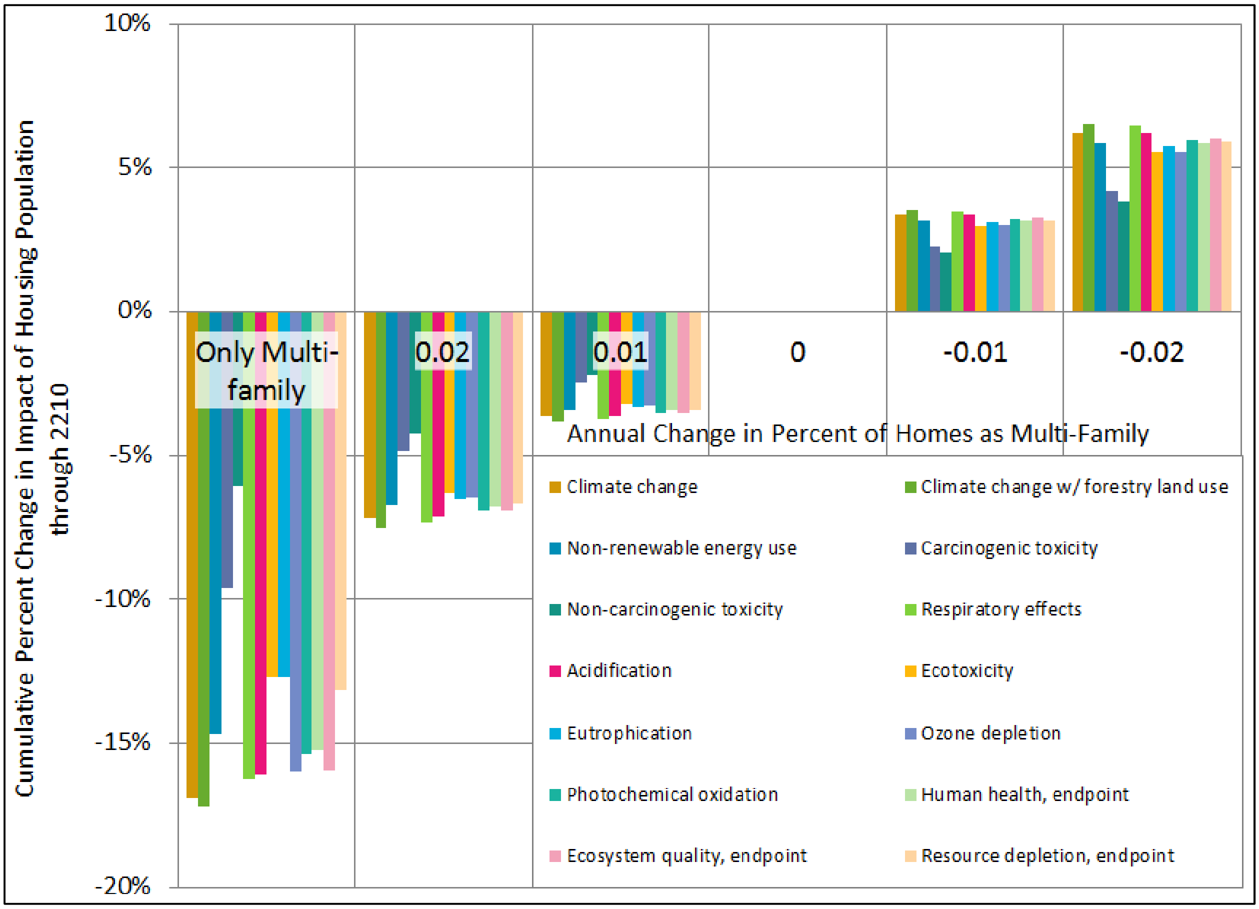

Figure 52: Environmental impact of the state housing population under various rates of growth in multi-family housing

Results: Material Durability and Material Selection

Table 16 shows the lifetime waste generation, *Climate Change* impact, human health impact and *Ecosystem* quality impact for the *Standard Home* by category of material. For the environmental impact information shown for each material class, the impact associated with production, transportation and end-of-life are included.

Table 16: Mass, Waste Generation, *Climate Change* Impact, Human Health Impact and *Ecosystem* Quality Impact for each class of material used in the *Standard Home*

Item	*Waste Generation*		*Climate Change Impact*		*Human Health Impact*		*Ecosystem Quality Impact*	
	Total (Kg)	*Percent of Total*	*Total (KgCO₂e)*	*Percent of Total*	*Total (DALYs)*	*Percent of Total*	*Total (PDF*m2*yr)*	*Percent of Total*
Carpeting	3,710	3%	21,500	28%	0.0091	9%	632	2%
Linoleum	337	0%	448	1%	0.00018	0%	26	0%
Roofing (asphalt shingle)	10,500	10%	12,700	17%	0.013	13%	1,460	5%
Fiberglass (fiberglass)	3,890	4%	8,300	11%	0.0057	6%	1,350	4%
Gypsum drywall	23,400	21%	9,000	11.9%	0.0064	6.6%	2,360	7.5%
Doors/Windows	3,550	3%	1,870	2.5%	0.006	6.2%	4,320	13.8%
Plastics	1,260	1%	3,760	5.0%	0.0023	2.4%	208	0.7%
Lumber	34,100	31%	-5,100	-6.8%	0.0086	8.9%	-268	-0.9%
(with forestry land use)			*(47,000)*	*32.9%*				
Hardware	982	1%	1,880	2.5%	0.0069	7.1%	2,640	8.4%
Electrical	199	0%	1,130	1.5%	0.0051	5.3%	3,870	12.4%
Foundation	14,600	13%	1,230	1.6%	0.00047	0.5%	104	0.3%
Paints	446	0%	1,280	1.7%	0.00087	0.9%	164	0.5%
Siding	8,120	7%	165	0.2%	0.0012	1.2%	-237	-0.8%
(with forestry land use)			*(15,800)*	*(11.0%)*				
Other	3,920	4%	17,300	23%	0.031	32%	14,700	47%
Total	109,000	100%	75,500	100%	0.097	100%	31,300	100%

A relatively small number of house components and/or materials contribute the majority of waste generation and environmental impact. Four material types (roofing, drywall, lumber and foundation) contribute 80% of the total waste generation. For *Climate Change*, five categories contribute 70% of the total. In some cases, the prominent contributors for human health and *Ecosystem* quality impact are different than for *Climate Change*. For example, human health impacts from lumber and *Ecosystem* quality impact from electrical components are each more than three times as large in its contribution to these categories as for *Climate Change*. Note that the selection of these components is based on their impact within the *Medium Standard Home* and it is very possible that some important components will have been missed due to the materials selected for this model home. An alternate design might lead to some differing conclusions regarding the importance of various materials.

For several environmentally important building component categories, a list of some alternatives currently used or available in the state of Oregon is shown in Table 17.

Table 17: Material options for most impacting building components

Category (assumed materials in *Standard Home*)	**Alternative Options**
Flooring (carpet and linoleum tile)	Ceramic tile Wood Earthen floor[35] Poured concrete Cork Natural linoleum
Roofing (20-year asphalt shingle)	40-year asphalt shingle Steel Fiber cement tile
Siding / Cladding (wood)	Fiber cement Aluminum siding Vinyl siding
Drywall (Gypsum board)	Wood Magnesium oxide board Plaster
Insulation (Fiberglass)	Cellulose
Foundation (Poured concrete)	No alternative considered

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[35] An earthen floor is typically made of a mixture of dirt, sand, straw and other natural materials. These materials are mixed and poured in layers. A top-layer of natural (e.g., linseed) oil is used to seal the surface.

For each of these materials, several prominent sources of information have been searched to determine the availability "cradle-to-gate" information of the environmental impacts of their production. The availability of such data is shown in Appendix 13.

For each of these materials, a comparison simply on the impact per weight of material is not a highly relevant metric of environmental performance for comparisons. Materials will vary in their durability and the impact of production should therefore be considered in the context of how long a service life is likely to be obtained for each material. Table 18 shows several example calculations of the durability needed to provide equal environmental performance in comparison to the standard materials. It should be noted that these examples consider only *Climate Change* impact and consider only the impact of material production. A more complete comparison would consider such things as transportation of the materials, their maintenance or use, and their disposal, as well as consider other types of environmental impact.

Table 18: Calculation of the durability necessary for each alternative material needed to provide equal performance in climate change impact to the standard material, based on material production only

Category	**Standard Material**	**Replacement Material**	**Replacement Material Impact (kgCO_2e per ft2)**	**Standard Material Impact (kgCO_2e per ft2)**	**Assumed Durability of Standard Material (years)**	**Needed Durability of Replacement (years)**	**Assumed Durability of Replacement materials (years)**
Flooring (Carpet and linoleum)	Carpeting	Wood*,**	0.19	1.2	10	***1.7***	Life of home (70 years)
	Linoleum tile	Ceramic tile	0.52	0.45	20	***23***	30
Roofing (20-year asphalt shingle)	20-year asphalt shingle	Steel	4.7	1.6	20	***58***	Life of home (70 years)
	20-year asphalt shingle	Fiber cement	0.59	1.6	20	***7.4***	31
	20-year asphalt shingle	40-year asphalt shingle	2.4	1.6	20	***30***	40
Cladding	Wood shingle*	Fiber cement	0.59	0.35	20	***34***	31
Insulation	Glass Fiber	Cellulose	0.15	0.30	80	***39***	No assumption made

*= When applying the 2 kgCO_2e / kg wood adjustment for forestry land use, the needed durability of wood flooring (to break even with carpet) is 17 years and of fiber cement (to break even with wood shingle) is 5 years

**= Once might also consider the impact of area rugs that are likely to be used with wool flooring. A preliminary attempt to represent this based on wool production data from Ecoinvent suggest that wool rugs may make the wood flooring an unfavorable option.

Material production is only one aspect of a product's life cycle. It is also important to consider the influence of product transport, use and end-of-life management. While Table 18 only considers the material production impact, a similar calculation is shown below in Table 20 considering also the transportation and disposal of selected materials.

Table 19: Calculation of the durability necessary for each alternative material needed to provide equal performance to the standard material, based on material production, transport and end-of-life management

Category	Standard Material	Replacement Material	Life Cycle Replacement Material Impact (kgCO$_2$e per ft2)	Life Cycle Standard Material Impact (kgCO$_2$e per ft2)	Assumed Durability of Standard Material	Needed Durability of Replacement (years)	Assumed Durability of Replacement materials (years)
Flooring (Carpet and linoleum)	Carpeting	Wood*	-0.078	0.90	10	--	55
	Linoleum tile	Ceramic tile	1.02	0.47	20	***43***	30
Roofing (20-year asphalt shingle)	20-year asphalt shingle	Steel	3.2	0.68	20	***94***	Life of home
	20-year asphalt shingle	Fiber cement	0.62	0.68	20	***18***	31
Cladding	Wood shingle*	Fiber cement	0.62	0.11	20	***112***	31

*= As shown here for wood flooring, within the scope of the present analysis, some products may show a negative impact (a net benefit) over the course of their lifecycle if the benefits achieved from their end-of-life management exceed the impact of their production and transportation. In the case of wood shown here, this results from the assumption that energy derived from fossil sources is not produced due to the production of energy from wood.

The example illustrates that it is best consider questions of alternative materials in terms of under what condition one material is environmentally preferable to another rather than in absolute terms. For example, in the case of steel roofing or ceramic tile, these results suggest that only if these materials last a period of 58 and 23 years respectively would they be preferable to the alternatives they replace (assuming a 20 year life for both linoleum flooring and asphalt shingle).

With regard to end-of-life, it is possible to examine the set of materials assumed to be used in the Standard Home and consider to what extent alternative end-of-life management would increase or decrease the total environmental impact associated with that material. In Table 20 and Table 21, the current end-of-life route of each material class is shown along with the associated Climate Change impact with treatment of the material by each route. An "optimal" end of life route for each is identified as the option among recycling, incineration and landfill that offer the best Climate Change profile.

The energy use implications of durable roofing / siding are negligible in the Oregon climate and are not considered.

Table 20: Assumed end-of-life routes for materials in the *Standard Home* based on DEQ data for current recycling practices in Oregon today

Material type	% recycled	% incinerated	% landfilled
Asphalt roofing	0%	7%	93%
Carpet	1%	7%	92%
Wood	10%	45%	45%
Fiberglass	0%	0%	100%
Appliance	100%	0%	0%
Gypsum Plasterboard	3%	0%	97%
Plywood/Oriented strandboard	10%	45%	45%
Other Plastic	5%	7%	88%
Steel	87%	0%	13%
Polystyrene	5%	7%	88%
Windows	1%	7%	92%
Ceramics	0%	0%	100%
Cement	0%	0%	100%
Paint	0%	7%	93%
Electrical	0%	7%	93%
LDPE	10%	6%	84%
Cardboard	79%	1%	20%
HDPE	5%	7%	88%
Gravel	0%	0%	100%
Sand	0%	0%	100%

Table 21: Assumed end-of-life associated *Climate Change* impact (in kg CO_2 eq.) for the materials in the *Standard Home*

Material type	Recycling impact or benefit (per Kg)	Incineration impact or benefit (per Kg)	Landfill impact (per Kg)	Reuse impact (per Kg)	Optimal treatment route (excluding reuse),	Ratio of minimal and maximal benefits to baseline scenario
Asphalt	-0.38	0.51	0.02	-1.13	Recycling	Min: 0.64 - 1.38
Carpet	-2.56	0.37	0.08	-6.04	Recycling	Min: 0.58 - 1.05
Wood	-0.01	-0.87	0.03	-0.49	Incineration	Min: -1.51 - 3.07
Fiberglass		0.03	0.01	-2.03	Landfill or Incineration	Min: 1 - 1.01
Appliance	-3.07	0.09	0.02	-4.04	Recycling	Min: 1 Max: 4.03
Gypsum drywall	0	0.03	0.01	-0.35	Landfill or Incineration	Min: 0.97 Max: 1.06
Plywood/oriented strandboard	-0.01	-0.87	0.03	-0.5	Incineration	Min: -2.14 Max: 3.62
Other Plastic	-2.34	0.37	0.04	-3.88	Recycling	Min: 0.41 Max: 1.1
Steel	-3.46	0.02	0.01	-4.35	Recycling	Min: 0.69 Max: 3
PS	-3.56	0.38	0.06	-5.31	Recycling	Min: 0.33 - Max: 1.08
Windows	-0.13	0.55	0.06	-2.67	Incineration	Min: 0.95 - Max: 1.16
Inert		0.51	0.01		Landfill	Min: 1 Max: 1
Ceramics	-0.003	0.03	0.01	-2.62	Recycling	Min: 1 Max: 1
Cement	-0.0004	0.03	0.001	-0.78	Recycling	Min: 1 Max: 1
Paint		1.81	0	-4.44		Min: 0.92 Max: 1.31
Electrical	-0.67	0.51	0.01	-5.45	Recycling	Min: 0.82 Max: 1.09
LDPE	-2.13	0.62	0.06	-2.78	Recycling	Min: 0.33 Max: 1.17
Cardboard	-0.63	-0.72	0.61	-1.34	Incineration	Min: 0.5 Max: 2

HDPE	-1.96	0.62	0.05	-2.62	Recycling	Min: 0.34 Max: 1.22
Gravel	-0.0002	0.03	0.001	-0.0038	Recycling	Min: 1 Max: 5
Sand	-0.00006	0.03	0.0002	-0.022	Recycling	Min: 1 Max: 4.11

Note that the "optimal treatment route" shown excludes reuse from consideration, as it is considered a form of waste prevention rather than treatment. With the exception of wood products, where incineration shows better climate change performance than reuse[36], all other materials show a greater benefit from reuse than any of the waste treatment options. For most non-wood materials, recycling is the preferred treatment option, with most exceptions being cases of only marginal differences among the options. The case of wood materials is discussed further below within the section on material salvage and reuse.

Transportation distance is another aspect of the life cycle of materials that could be important to consider in evaluating alternative options. Not all material alternatives will be available within the same range of distances and it is feasible that for some materials, added transportation could offset environmental benefits that might otherwise be seen. To examine the relative importance of transportation in the material lifecycle, it is possible to compare the environmental impact of transporting a given material to the impact incurred in producing and disposing of it. This comparison is shown in Table 22 for each of the environmental impact categories that have been considered.

Although for most impacts and for most materials the influence of transportation is relatively small in comparison to material production, in some cases, the influence of transportation can be highly influential and even surpass the impact of production and disposal. In particular, sand and gravel show a large influence of transportation, exceeding 60% of total impact for all but three of the environmental impact categories. In addition, wood, wood products and cement show a moderate influence of transportation, exceeding 10% in most impact categories.

Table 19 shows a comparison of the material durability needed for each of several example replacement materials to perform better with regard to Climate Change Impact than the material they are replacing, considering also the material's transport and end-of-life in addition to its production.37 Table 18, which presented similar information included only consideration of

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[36] The conclusion that energy recovery from wood is a preferable end-of-life route to re-use is dependent on the assumptions made regarding the impact of wood reuse on forestry land use and the impact of forestry land use on climate. Applying the adjustment described above from the U.S. EPA for the impact of forestry land use results in the conclusion that is it better to re-use wood than to recover energy from it.

material production impact. In this case, the life cycle of the material is considered38, including also its transportation and end-of-life management.

In comparison to the results presented earlier based on only material production impact, it is clear that consideration of the whole material life cycle can substantially influence the result and conclusions. Whereas wood flooring improves further (mostly due to beneficial end-of-life uses), steel roofing perform worse. The comparison between ceramic and linoleum changes relatively little, while cement fiber performs better in comparison to asphalt shingle for roofing, but worse in comparison to wood for siding. The mixture of results indicates that the material production impact alone is a relatively poor indicator of total environmental performance and that each stage of a material's life cycle must be assessed to understand the relative environmental benefit.

To examine the potential influence of material substitutions, a scenario has been conducted in which several materials in the *Standard Home* have been substituted with alternative materials that have greater durability and are therefore suspected of offering better environmental performance over their life cycle. These substitutions include the replacement of wood siding with fiber cement siding, the replacement of asphalt shingle roofing with steel roofing, the replacement of carpet with wood flooring and the replacement of linoleum tile with ceramic tile.

The *Durable Roofing, Flooring and Siding* scenario shows a modest environmental benefit in several environmental impact categories relative to the *Medium Standard Home*. However, many other categories show a net environmental impact of implementing the *Durable Roofing, Flooring and Siding* scenario. In each of these cases, it is the steel roofing that is responsible for the increased environmental impact.

Figure 53 shows the results for the same scenarios, but limited to only the material related portions of the life cycle (materials production, transport and end-of-life).

When considering only the material-related impact, the percentage improvement (or added impact) is comparatively larger. Many of the impact categories show an improvement of more than 20% in the material-related impacts by switching only these four materials within the home. Note that the material-related benefit of the *Durable Roofing, Flooring, and Siding* scenario is better in many cases than for the *Extra-small* home. In most instances, it is the flooring substitution (wood for carpet) that is responsible for the greatest part of this improvement.

Table 22: The ratio of environmental impact during transportation (including EOL transport) to environmental impact during material production and end-of-life for each of the environmental impact categories evaluated

	Climate Change impact	*(with forestry land use)*	Non-renewable energy use	Carcinogenic toxicity	Non-carcinogenic toxicity	Respiratory effects	Acidification	Ecotoxicity	Eutrophication	Ozone depletion	Photochemical oxidation	Human health, endpoint	*Ecosystem* quality, endpoint	Resource depletion, endpoint
Carpet	2%	*2%*	<1%	6%	2%	19%	5%	62%	1%	<1%	4%	6%	29%	<1%
Asphalt	2%	*2%*	<1%	<1%	<1%	<1%	<1%	<1%	3%	72%	3%	2%	7%	<1%
Fiberglass	5%	*5%*	4%	2%	<1%	5%	6%	<1%	N/A	7%	17%	8%	12%	4%
Wood	<1%	*2%*	6%	2%	1%	<1%	<1%	<1%	5%	<1%	25%	31%	20%	2%
Gypsum drywall	7%	*7%*	7%	6%	3%	3%	12%	3%	9%	9%	19%	10%	9%	7%
Appliance	11%	*11%*	3%	<1%	<1%	1%	3%	<1%	2%	8%	10%	2%	2%	3%
Plywood/oriented strandboard	<1%	*4%*	<1%	3%	2%	N/A	6%	<1%	5%	<1%	4%	8%	36%	85%
Other Plastic	3%	*3%*	2%	1%	<1%	3%	5%	2%	1%	206%	10%	4%	30%	1%
Steel	7%	*7%*	2%	<1%	<1%	<1%	3%	<1%	2%	6%	8%	2%	1%	2%
PS	2%	*2%*	2%	<1%	<1%	2%	4%	<1%	5%	21%	9%	4%	7%	2%
Windows	4%	*4%*	3%	<1%	<1%	3%	4%	<1%	4%	14%	12%	2%	4%	3%
Cement	3%	*3%*	12%	4%	9%	8%	12%	7%	N/A	17%	17%	13%	24%	12%
Paint	4%	*4%*	2%	<1%	<1%	3%	6%	2%	4%	8%	10%	6%	11%	2%
Electrical	2%	*2%*	2%	<1%	<1%	<1%	<1%	<1%	2%	6%	3%	<1%	<1%	2%
LDPE	4%	*4%*	2%	5%	2%	6%	8%	3%	10%	333%	18%	10%	31%	2%
Cardboard	11%	*10%*	14%	<1%	<1%	<1%	65%	4%	8%	37%	73%	<1%	<1%	14%
HDPE	4%	*4%*	2%	5%	2%	6%	8%	3%	11%	375%	19%	8%	31%	2%
Gravel	252%	*252%*	210%	91%	94%	157%	249%	98%	N/A	352%	344%	218%	353%	210%
Sand	339%	*339%*	304%	128%	119%	198%	310%	133%	N/A	514%	420%	279%	534%	302%

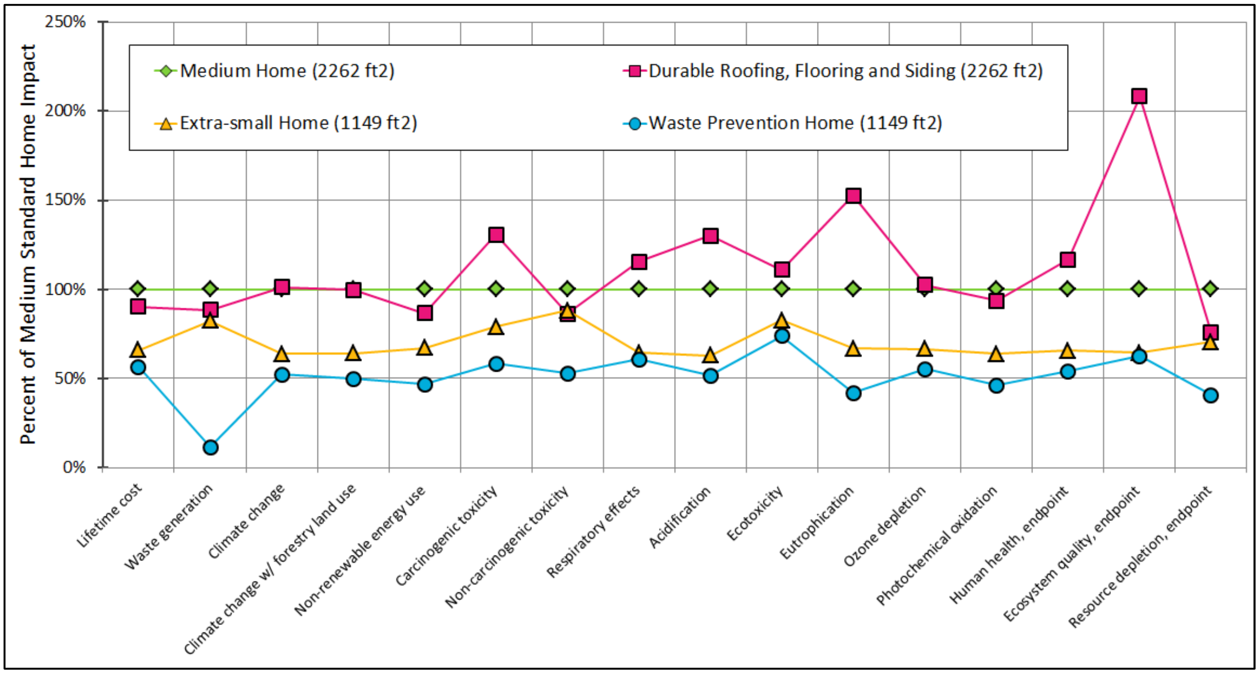


Figure 53: Material-related environmental impact of the Durable Roofing, Flooring and Siding home in comparison with the Medium home, Extra-small home and Waste prevention home.

Table 23: Comparison of the *Climate Change* impact (kg CO_2 eq.) by material type for the Durable Roofing, Flooring and Siding scenario, the Medium Home, Extra-small Home and Waste Prevention Home

Component of Home Life Cycle	Medium Home (2262 ft2)	Durable Roofing, Flooring and Siding (2262 ft2)	Extra-small Home (1149 ft2)	Waste Prevention Home (1149 ft2)
Foundation Other Mtl.	741	741	794	837
Foundation Concrete	1110	1110	1260	1050
Foundation Other Mtl.	741	741	794	837
Foundation Concrete	1110	1110	1260	1050
Floor Lumber	600	600	886	707
Floor Engineered Wood	2400	2400	717	1080
Floor Hardware	294	294	147	147
Paints and Adhesives	1180	1180	991	991
Fiberglass Insulation	7890	7890	6380	6380
Wall Lumber	1940	1940	735	454
Wall Hardware	1180	1180	884	884
Wall Engineered Wood	360	360	496	453
Drywall	6660	6660	5240	4680
Other Siding Mtl.	5060	781	3870	431
Cement Siding Shingles	0	5140	0	3870
Porch Lumber	174	174	112	102
Other Roofing Mtl.	2550	1190	2470	2470
Roof Lumber	507	507	450	411
Asphalt Shingles	11900	0	12300	0
Steel Roofing	0	19500	0	20100
Hardwood Flooring	0	771	0	424
Ceramic Tile	0	201	0	259
Carpet	21200	0	11600	0
Kitchen Cabinets	1580	1580	1580	1580
Mouldings	1290	1290	578	227
Linoleum Floors	452	0	339	0
Sinks	1330	1330	878	878
Toilets	566	566	283	283
Faucets	305	305	305	305
Plumbing pipe	369	369	369	369
Electrical Wire	1040	1040	828	828
Electrical Fixtures	108	108	108	108
Doors (exterior)	2200	2200	2200	2200
Doors (interior)	2150	2150	1790	1790
Windows	3500	3500	1500	1500
Packaging	1940	1940	1940	972
Appliances	11500	11500	11500	11500

Component of Home Life Cycle	Medium Home (2262 ft2)	Durable Roofing, Flooring and Siding (2262 ft2)	Extra-small Home (1149 ft2)	Waste Prevention Home (1149 ft2)
Ducting	1410	1410	715	880
Transportation	3760	3170	2940	2370
Construction - Equipment	6810	6810	3740	3740
Construction - Electricity	2220	2220	1220	1220
Construction - Commuting	6990	6990	3840	3840
Use - Natural Gas	379000	379000	255000	206000
Use - Electricity	197000	197000	97500	98700
Use - Water	12100	12100	12100	12100
Material Reuse	0	0	0	-33300
Material Recycling	-17500	-23600	-16600	-14000
Material Landfilling	1360	929	1000	343
Material Waste-to-Energy	-13300	-12800	-9100	-2440
Total	684000	654000	426000	348000

Figure 54 shows the relative benefit or impact in each environmental impact category of the replacement materials relative to the original materials.

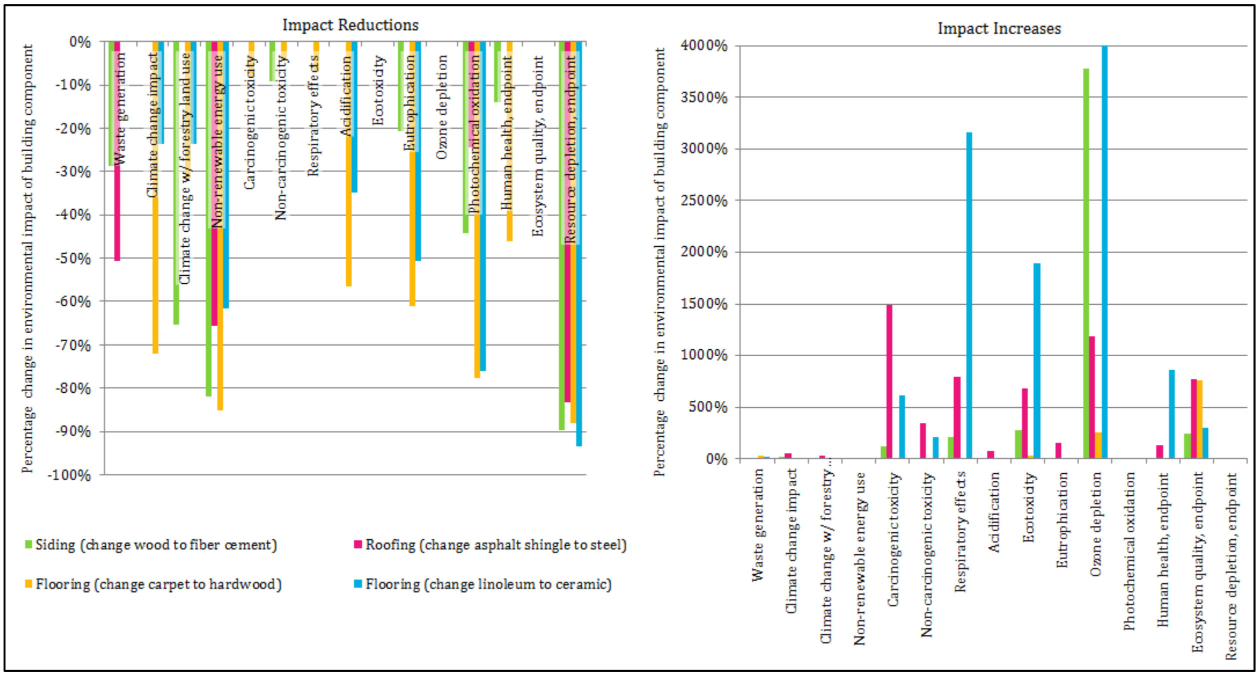


Figure 54: Net impact or benefit over the home life cycle of each of the material types substituted in the *Durable Roofing, Flooring and Siding* scenario

While in most cases the replacement materials offer an environmental benefit, there are many cases in which the replacement material shows a net impact relative to the material it is replacing. This is true most prominently in the case of steel roofing and ceramic tile, where roughly half of the environmental indicators point toward a net impact.

Results: Material Salvage and Reuse

Figure 55 shows the results for all impact categories considered among the two scenarios of *Deconstruction, Restoration and Reuse* that have been examined. As described above, for those materials that are anticipated to be able to be salvaged and reused within another home, the Moderate version of this scenario considers a rate of reuse of 33% of materials being reused (both entering and leaving the home), while the High version of the scenario considers a rate of 67%. The specific rates used for each material are listed in Appendix 3. The results for *Climate Change* impact are shown in Figure 56. Because of the dominance of the home's energy use, and the fact that it does not vary among these scenarios, the use phase energy has been removed from the chart in Figure 56, while being retained in the data table. Details of the scenarios are located in Appendix B.

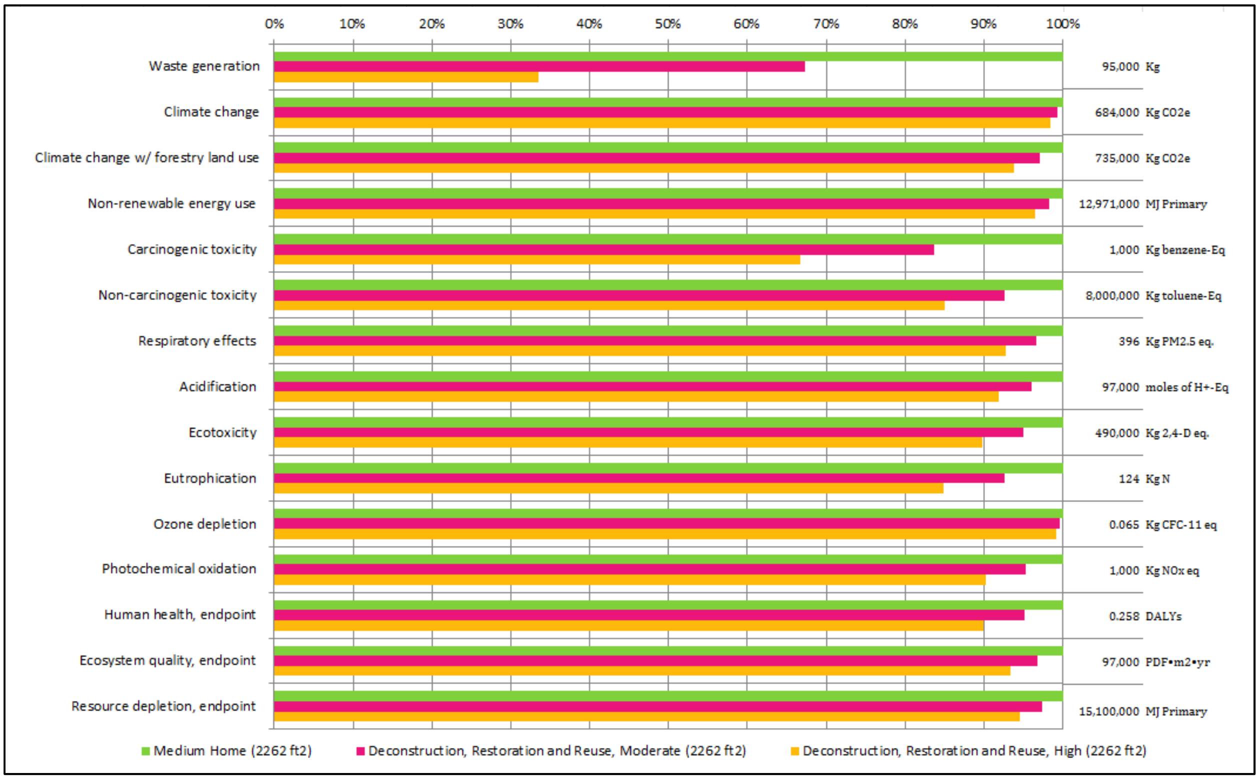
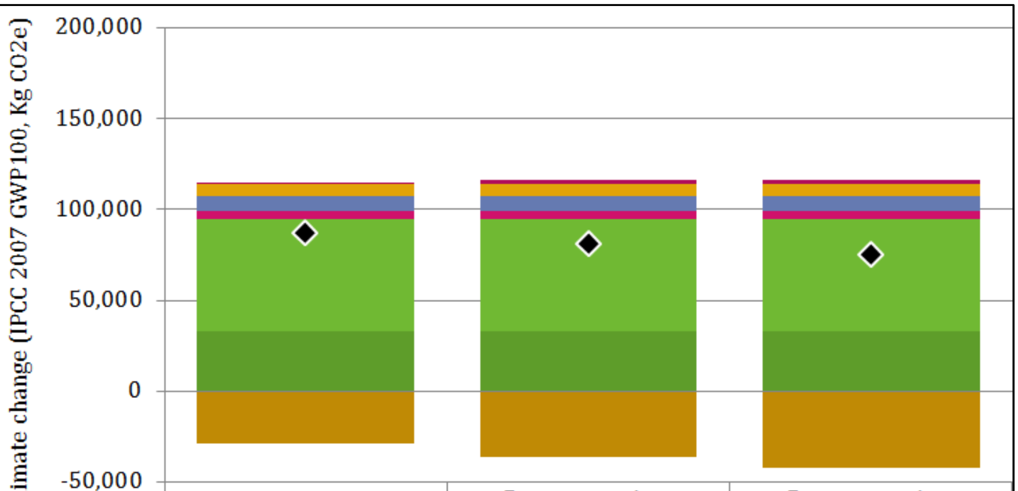
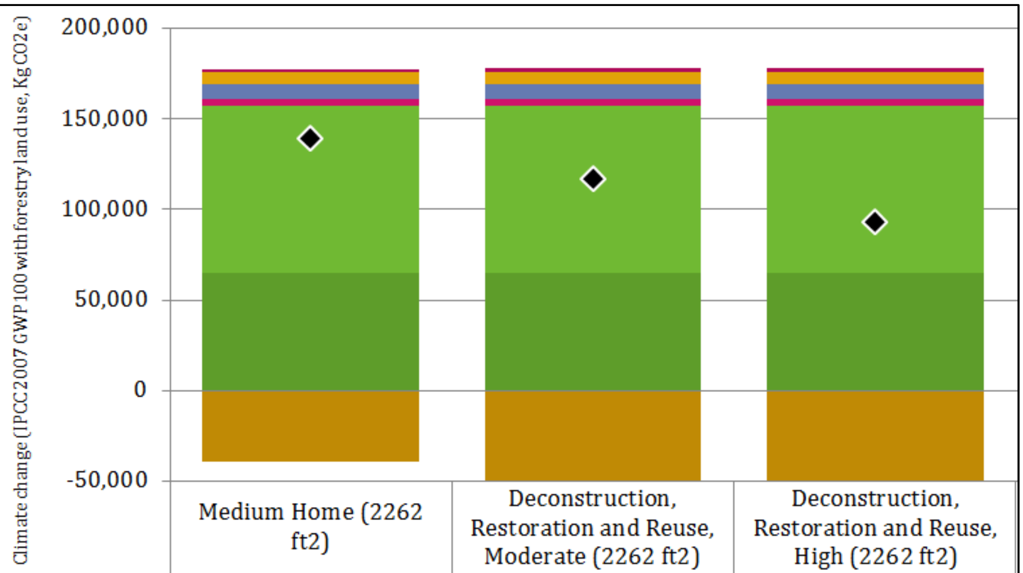


Figure 55: Comparison of the life cycle environmental impact and waste generation for various material re-use scenarios



	Medium Home (2262 ft2)	Deconstruction, Restoration and Reuse, Moderate (2262 ft2)	Deconstruction, Restoration and Reuse, High (2262 ft2)
Heating and Cooling	280000	280000	280000
Lighting and Plug Loads	185000	185000	185000
Water Use, Heating, Treatment	133000	133000	133000
🟧 Material End-of-Life	-29000	-36000	-42000
🟥 Demolition	1000	2000	2000
🟨 Maintenance	7000	7000	7000
🟦 Construction	8000	8000	8000
🟥 Material Transportation	4000	4000	4000
🟩 Replacement Materials Production	62000	62000	62000
🟩 Original Materials Production	33000	33000	33000
◆ Total (Excluding Use Phase)	86000	80000	74000
Total	684000	678000	672000
Waste Generation (Kg)	95000	64000	32000

Figure 56: Comparison of the life cycle *Climate Change* impact, excluding the home energy use, for various material re-use scenarios.



	Medium Home (2262 ft2)	Deconstruction, Restoration and Reuse, Moderate (2262 ft2)	Deconstruction, Restoration and Reuse, High (2262 ft2)
Heating and Cooling	280000	280000	280000
Lighting and Plug Loads	185000	185000	185000
Water Use, Heating, Treatment	133000	133000	133000
■ Material End-of-Life	-39000	-62000	-86000
■ Demolition	1000	2000	2000
■ Maintenance	7000	7000	7000
■ Construction	8000	8000	8000
■ Material Transportation	4000	4000	4000
■ Replacement Materials Production	92000	92000	92000
■ Original Materials Production	65000	65000	65000
◆ Total (Excluding Use Phase)	138000	116000	92000
Total	736000	714000	690000
Waste Generation (Kg)	95000	64000	32000

Figure 57: Comparison of the life cycle *Climate Change* impact, with the sensitivity test for consideration of *Climate Change* impact of forestry land use applied, excluding the home energy use, for various material re-use scenarios

Note that while benefit from material reuse is seen by lesser impact from material production and greater benefit at end-of-life, the benefit is mitigated somewhat by increased impact in some cases during construction and maintenance phases and from transportation[37].

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[37] The material transportation assumptions for the reuse scenarios are described in Appendix 3.

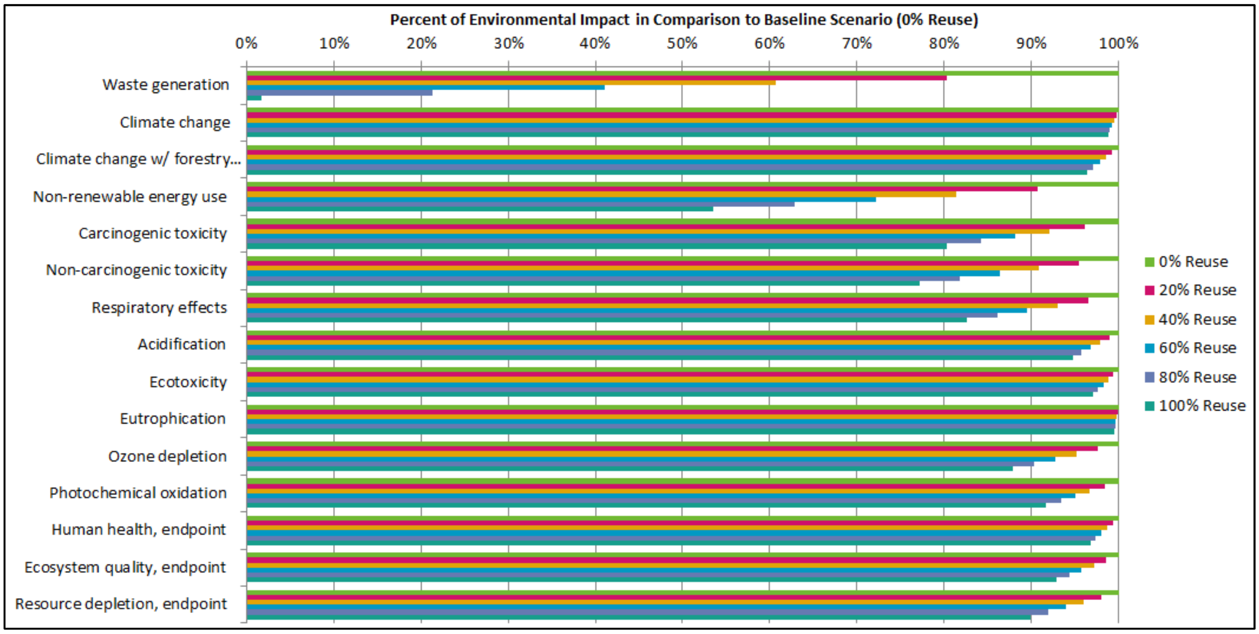

Figure 58: Percent reduction in environmental impact with varying percentages of reuse of materials within the home

The *High Reuse* assumptions have also been implemented within each of the *Average Home* scenarios to allow consideration of the extent of benefit if material reuse is aggressively pursued across the state shows the cumulative *Climate Change* impact for the housing stock of Oregon under the baseline set of assumptions and under the *Deconstruction, Restoration and Reuse (High)* scenario. This scenario assumes that of materials that have potential to be reused, 67% are salvaged and reused, both at the beginning and end of a home's life and during its maintenance. See Appendix 3 for detail on the rates of reuse assumed for specific materials. The total impact through 2210 for each impact category evaluated is shown in Figure 59.

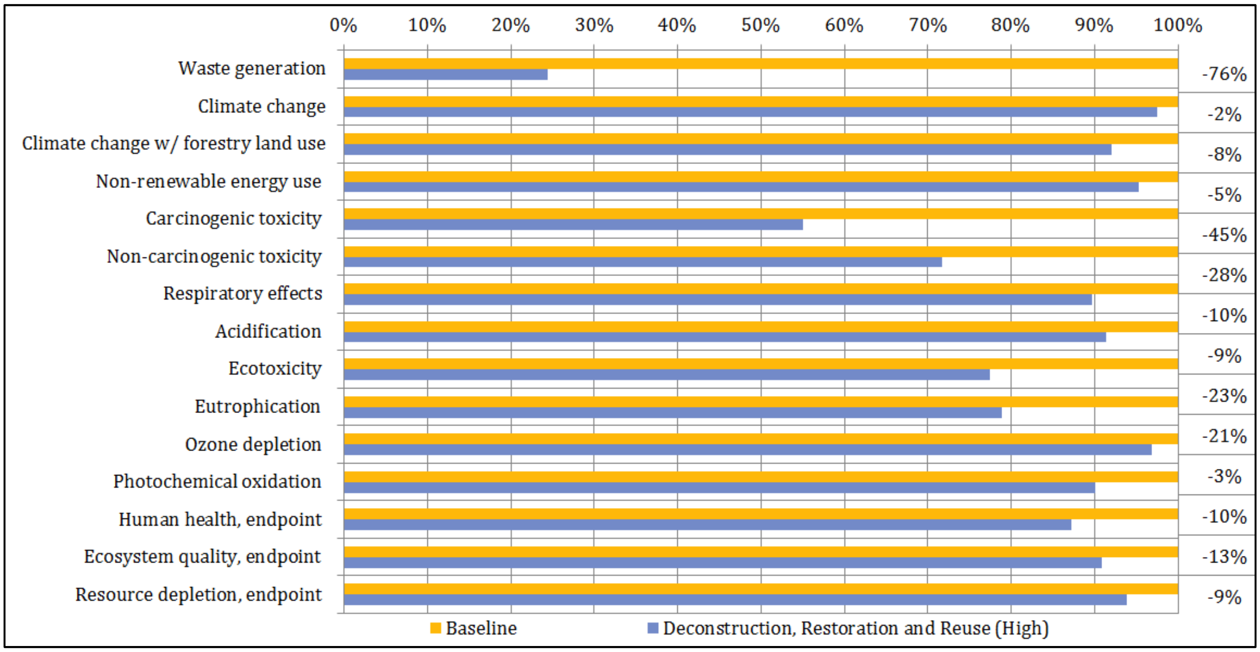

Figure 59: Comparison of the cumulative impact of the home population through 2210 under the baseline assumptions and under high material reuse

As with the individual home scenarios, there is a large variation among the indicators examined. For the majority of the indicators, a benefit in the range of 2 to 28 percent is seen.

For some materials, it is feasible that a significant amount of added transport for reused materials could offset the environmental benefit. It is assumed in the baseline results shown above that the transportation requirements for replacement materials are different than for new materials. For all material reuse, it has been assumed that a trip of 75 kilometers is required to move the material to a regional storehouse (identical to the transport to any other end-of-life fate), and when the materials are to be used in a new home, an additional trip of 75 kilometers is required by a half-loaded, light duty truck.

For each type of material in the home, Table 24 tabulates the amount of additional shipping distance (by a half-weighted smaller diesel truck, less than 16 ton in capacity) necessary to eliminate the benefit of reusing the material. This is calculated in two alternative ways. In one, the transportation distance needed to offset the *Climate Change* benefit of reuse (represented as the opposite of the impact of production) is considered. In the other, is the transportation distance necessary to offset the marginal *Climate Change* difference between reuse and the next best end-of-life option is considered (assuming that if the material is not reused, it will be sent to one of these fates). The same calculation for a weight-limited large-sized diesel truck is presented in

. The results of similar calculations for all the environmental impact indicators examined are shown in Figure 60, Figure 61, Figure 62, and Figure 63.

It should be noted that some materials, especially those relating to building envelope, may be unwise to reuse in some instances due to lesser energy efficiency. The present assessment is not able to fully evaluate such trade-offs. Similar considerations may occur with water use in some instances, such as in the reuse of older toilets.

Table 24: Added transportation distances necessary to offset benefits of material reuse, assuming a weight-limited large (>16 ton) truck.

Material Type	Impact of production Kg CO_2e per Kg	Benefit of reuse Kg CO_2e per Kg	Added transport needed to offset benefit (km)	Best waste management route	Benefit of best management route (Kg CO_2e per Kg)	Incremental benefit of reuse (Kg CO_2e per Kg)	Added transport needed to offset benefit (km)
PE (film)	2.7	2.7	42,000	Recycling	2	0.7	10,800
Steel Product	4.2	4.2	65,000	Recycling	3.5	0.7	10,800
Softwood	0.26	0.26	4,000	Waste to Energy	0.87	-0.61	-9,310
(with forestry land use)	*2.5*	*2.5*	*38,000*	*Waste to Energy*	*0.87*	*1.6*	*24,700*
Cement	0.78	0.78	12,000	Recycling	0.0038	0.78	12,100
Gravel	0.0038	0.0038	58	Recycling	0.0002	0.0036	127
Sand	0.0031	0.0031	48	Recycling	0.000061	0.003	118
Foamed PE	2.9	2.9	45,000	Recycling	2.3	0.6	9,300
Extruded PVC	5.1	5.1	78,000	Recycling	2.3	2.8	43,100
I-Joist	0.57	0.57	8,800	Waste to Energy	0.87	-0.3	-4,540
Plywood	0.26	0.26	4,000	Waste to Energy	0.87	-0.61	-9,310
(with forestry land use)	*2.5*	*2.5*	*38,000*	*Waste to Energy*	*0.87*	*1.6*	*24,700*
Kraft Paper	1.3	1.3	20,000	Recycling	0.61	0.69	10,700
Adhesive	4.6	4.6	71,000	Recycling	0	4.6	70,800
Fiberglass	2	2	31,000	Recycling	0	2	30,800
Gypsum drywall	0.38	0.38	5,800	Recycling	0.0038	0.38	5,920
Cement Fiber Facing	0.96	0.96	15,000	Recycling	0.0038	0.96	14,800
Wood Siding	0.53	0.53	8,200	Waste to Energy	0.87	-0.34	-5,160
(with forestry land use)	*2.7*	*2.7*	*42,000*	*Waste to Energy*	*0.87*	*1.8*	*27,800*
PE Fleece	3	3	46,000	Waste to Energy	0.87	2.1	32,400
HDPE	2.6	2.6	40,000	Waste to Energy	0.87	1.7	26,200
Asphalt Shingle	1.1	1.1	17,000	Recycling	0.38	0.72	11,100
Steel Product, Chrome	9.3	9.3	140,000	Recycling	3.5	5.8	89,300
Aluminum Product	13	13	200,000	Waste to Energy	0.87	12	185,000
Vinyl Acetate	2.5	2.5	38,000	Recycling	0	2.5	38,500
Hardwood	0.2	0.2	3,100	Waste to Energy	0.87	-0.67	-10,200
(with forestry land use)	*2.4*	*2.4*	*37,000*	*Waste to Energy*	*0.87*	*1.5*	*23,100*
Ceramic Tiles	0.91	0.91	14,000	Recycling	0	0.91	14,100
Carpeting	6	6	92,000	Recycling	2.6	3.4	52,400

Carpet Padding	4.9	4.9	75,000	Recycling	2.3	2.6	40,100
MDF	1.2	1.2	18,000	Waste to Energy	0.87	0.33	5,150
Ceramics	2.6	2.6	40,000	Recycling	0.0031	2.6	40,100
PEX (pipe)	2.5	2.5	38,000	Recycling	2.3	0.2	3,150
Wire	5.4	5.4	16,000	Recycling	0.67	4.7	13,700
Injected PS	5.2	5.2	15,000	Recycling	3.6	1.6	4,700
Electrical	9.3	9.3	27,000	Recycling	3.6	5.7	16,500
Outer Door	2.5	2.5	7,200	Recycling	7.3	-4.8	-13,800
Inner Door	1.6	1.6	4,600	Waste to Energy	0.87	0.73	2,180
Window	2.7	2.7	7,800	Recycling	0.13	2.6	7,590
Cardboard Box	1.3	1.3	3,800	Waste to Energy	0.72	0.58	1,750
LDPE (film)	2.8	2.8	8,100	Recycling	2.1	0.7	2,100
Stretch Blow Molded PS	5.2	5.2	15,000	Recycling	3.6	1.6	4,700
PP, Injection Molded	3.7	3.7	11,000	Recycling	2	1.7	4,990
SIP	1.3	1.3	3,800	Waste to Energy	0.87	0.43	1,310
ICF	0.14	0.14	400	Recycling	0.0038	0.14	477

Table 25: Added transportation distances necessary to offset benefits of material reuse, assuming a half-loaded small (<16 ton) truck

Material Type	Impact of production Kg CO_2e per Kg	Benefit of reuse Kg CO_2e per Kg	Added transport needed to offset benefit (km)	Best waste management route	Benefit of best management route (Kg CO_2e per Kg)	Incremental benefit of reuse (Kg CO_2e per Kg)	Added transport needed to offset benefit (km)
PE (film)	2.7	2.7	5,900	Recycling	2	0.7	1,590
Steel Product	4.2	4.2	9,100	Recycling	3.5	0.7	1,590
Softwood	0.26	0.26	560	Waste to Energy	0.87	-0.61	-1,250
(with forestry land use)	*0.78*	*0.78*	*2,300*	*Recycling*	*0.0038*	*0.78*	*2,330*
Cement	0.78	0.78	1,700	Recycling	0.0038	0.78	1,760
Gravel	0.0038	0.0038	8	Recycling	0.0002	0.0036	80
Sand	0.0031	0.0031	7	Recycling	0.000061	0.003	79
Foamed PE	2.9	2.9	6,300	Recycling	2.3	0.6	1,370
Extruded PVC	5.1	5.1	11,000	Recycling	2.3	2.8	6,140
I-Joist	0.57	0.57	1,200	Waste to Energy	0.87	-0.3	-578
Plywood	0.26	0.26	560	Waste to Energy	0.87	-0.61	-1,250
(with forestry land use)	*2.5*	*2.5*	*7,200*	*Waste to Energy*	*0.87*	*1.6*	*4,700*
Kraft Paper	1.3	1.3	2,800	Recycling	0.61	0.69	1,570
Adhesive	4.6	4.6	10,000	Recycling	0	4.6	10,000

Fiberglass	2	2	4,300	Recycling	0	2	4,410
Gypsum drywall	0.38	0.38	820	Recycling	0.0038	0.38	896
Cement Fiber Facing	0.96	0.96	2,100	Recycling	0.0038	0.96	2,150
Wood Siding	2.7	2.7	7,800	Waste to Energy	0.87	1.8	5,270
(with forestry land use)	2.7	2.7	42,000	Waste to Energy	0.87	1.8	27,800
PE Fleece	3	3	6,500	Waste to Energy	0.87	2.1	4,620
HDPE	2.6	2.6	5,600	Waste to Energy	0.87	1.7	3,760
Asphalt Shingle	1.1	1.1	2,400	Recycling	0.38	0.72	1,630
Steel Product, Chrome	9.3	9.3	20,000	Recycling	3.5	5.8	12,600
Aluminum Product	13	13	28,000	Waste to Energy	0.87	12	26,100
Vinyl Acetate	2.5	2.5	5,400	Recycling	0	2.5	5,490
Hardwood	0.2	0.2	430	Waste to Energy	0.87	-0.67	-1,380
(with forestry land use)	*2.4*	*2.4*	*6,900*	*Waste to Energy*	*0.87*	*1.5*	*4,410*
Ceramic Tiles	0.91	0.91	2,000	Recycling	0	0.91	2,040
Carpeting	6	6	13,000	Recycling	2.6	3.4	7,440
Carpet Padding	4.9	4.9	11,000	Recycling	2.3	2.6	5,710
MDF	1.2	1.2	2,600	Waste to Energy	0.87	0.33	787
Ceramics	2.6	2.6	5,600	Recycling	0.0031	2.6	5,710
PEX (pipe)	2.5	2.5	5,400	Recycling	2.3	0.2	506
Wire	5.4	5.4	12,000	Recycling	0.67	4.7	10,300
Injected PS	5.2	5.2	11,000	Recycling	3.6	1.6	3,540
Electrical	9.3	9.3	20,000	Recycling	3.6	5.7	12,400
Outer Door	2.5	2.5	5,400	Recycling	7.3	-4.8	-10,300
Inner Door	1.6	1.6	3,500	Waste to Energy	0.87	0.73	1,650
Window	2.7	2.7	5,900	Recycling	0.13	2.6	5,710
Cardboard Box	1.3	1.3	2,800	Waste to Energy	0.72	0.58	1,330
LDPE (film)	2.8	2.8	6,100	Recycling	2.1	0.7	1,590
Stretch Blow Molded PS	5.2	5.2	11,000	Recycling	3.6	1.6	3,540
PP, Injection Molded	3.7	3.7	8,000	Recycling	2	1.7	3,760
SIP	1.3	1.3	2,800	Waste to Energy	0.87	0.43	1,000
ICF	0.14	0.14	300	Recycling	0.0038	0.14	375

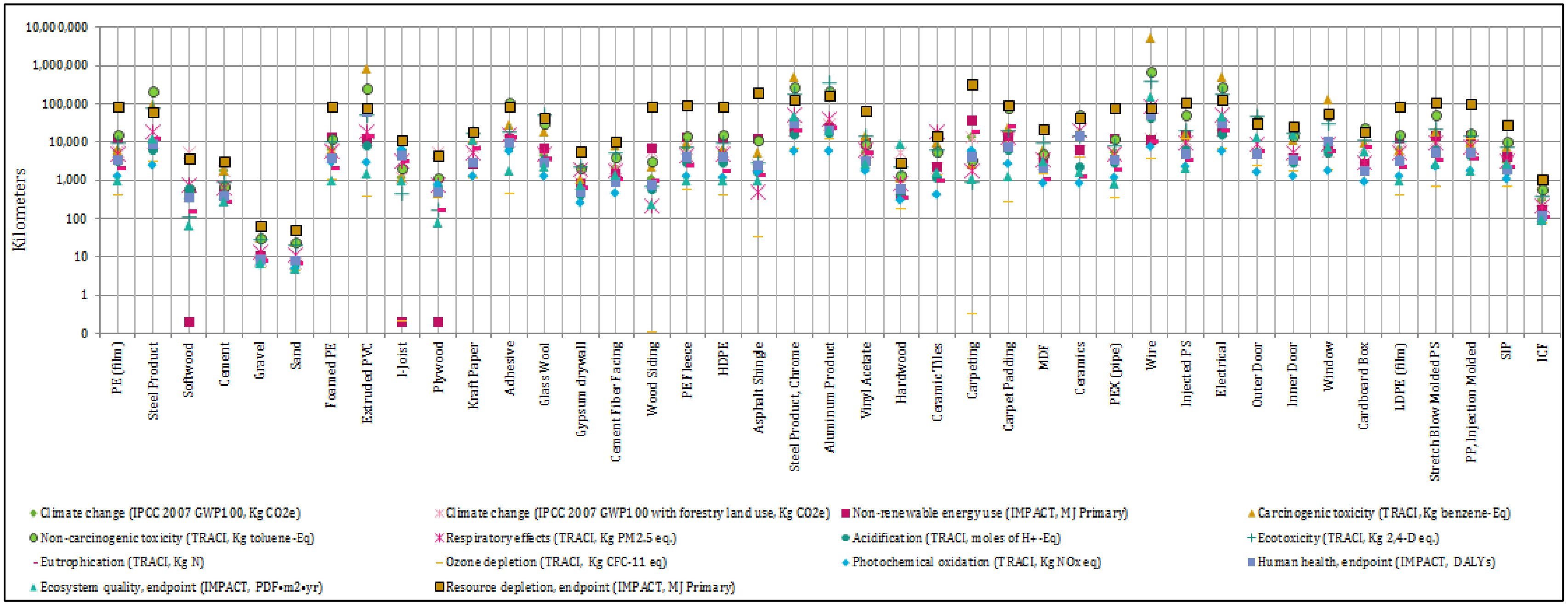

Figure 60: Transportation distance needed to offset benefit attributed to reuse (km by half-loaded small truck, <16 ton). Note that the scale is logarithmic.

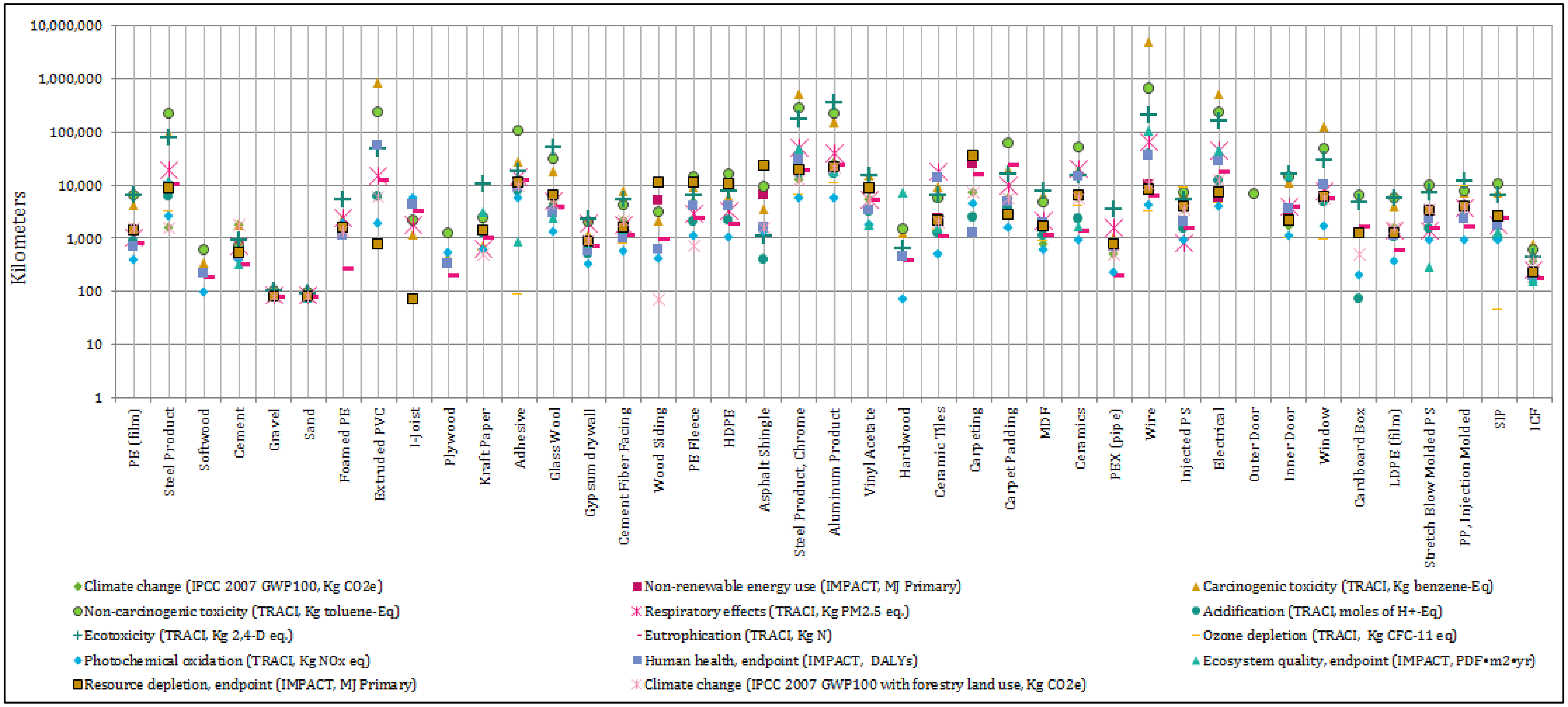

Figure 61: Transportation distance needed to offset incremental benefit of reuse versus best waste disposal (non-reuse) option (km by half-loaded small truck, <16 ton). [38] **Note that the scale is logarithmic.**

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[38] Note that for wood, many of the indicators used suggest that incineration, rather than reuse, is the optimal disposal route. These indicators are therefore not charted here because the amount of transportation needed to "break-even" is a negative value.

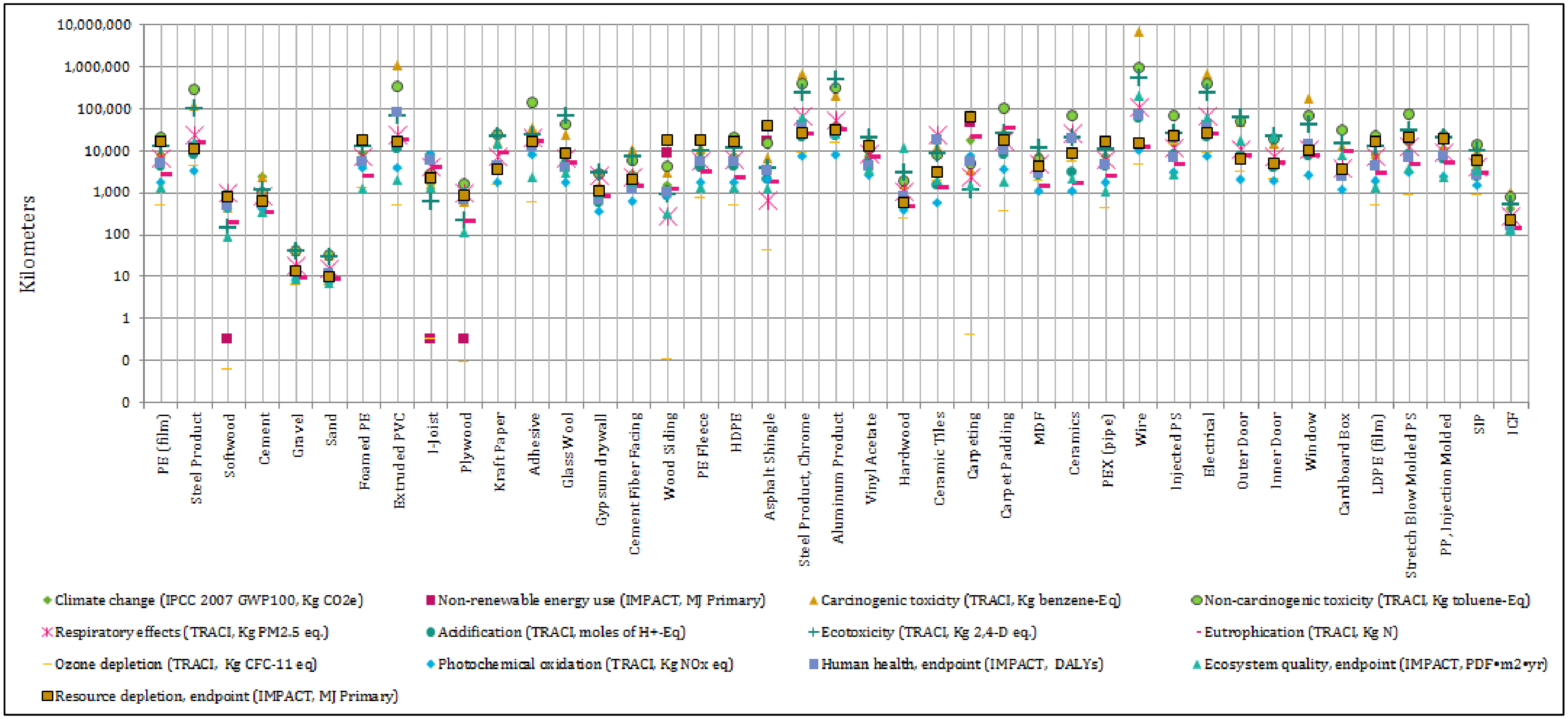

Figure 62: Transportation distance needed to offset benefit attributed to reuse (km by fully-loaded large truck, >16 ton). Note that the scale is logarithmic.

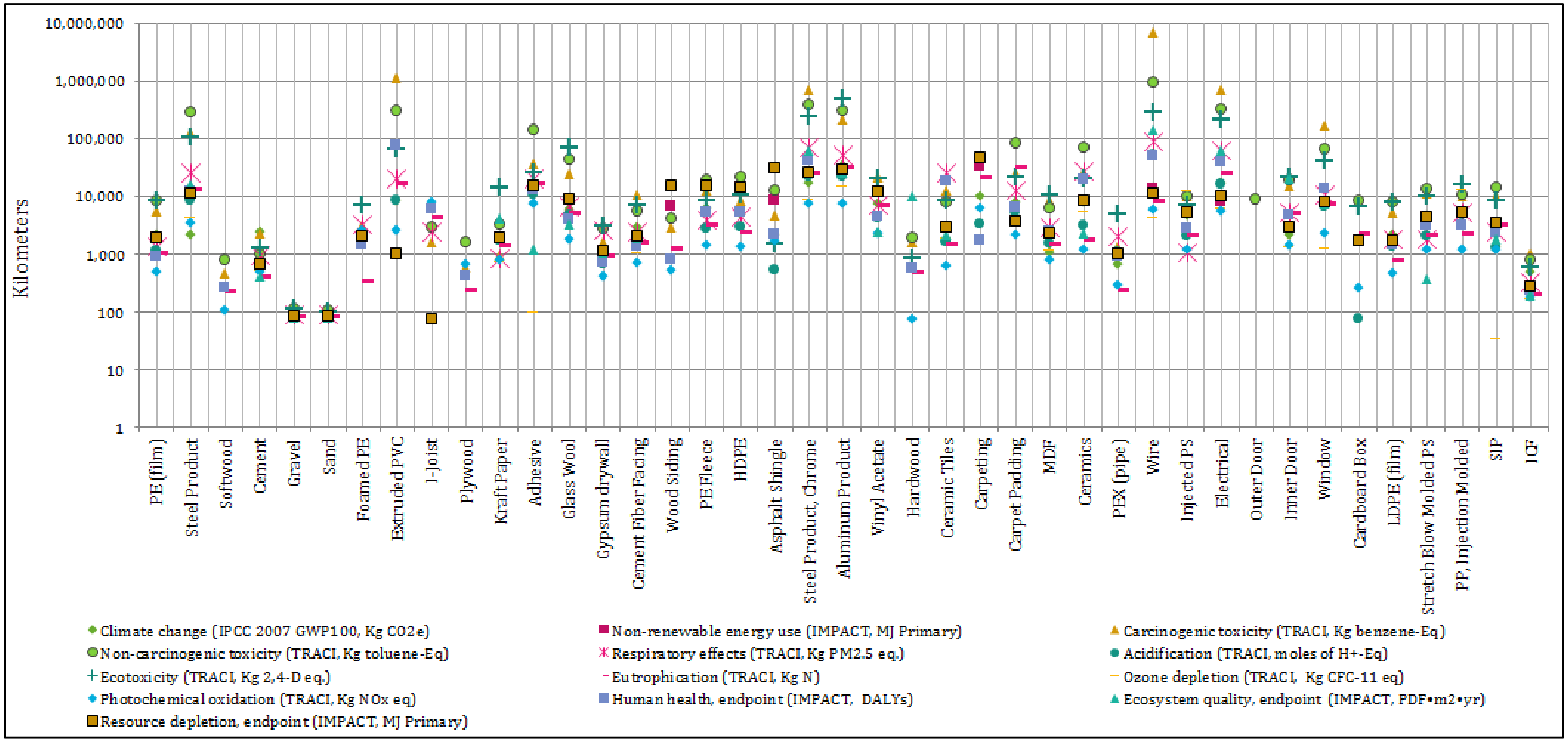

Figure 63: Transportation distance needed to offset incremental benefit of reuse versus best waste disposal (non-reuse) option (km by fully-loaded large truck, >16 ton).[39] Note that the scale is logarithmic.

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[39] Note that for wood, many of the indicators used suggest that incineration, rather than reuse, is the optimal disposal route. These indicators are therefore not charted here because the amount of transportation needed to "break-even" is a negative value.

The range of results suggests a high importance of considering materials independently when evaluating the importance of their transportation in reuse activities. In addition, the difference between the results for large and small trucks suggests that it is important to consider the transportation mode when considering limits of distance. Whereas with a large fully-loaded truck, the great majority of materials can be transported at least 1000 km before the benefit of reuse is depleted for the great majority of impact categories, for transportation by a half-loaded small truck this distance is closer to 100 km. For some materials, transport of 1000, or ever 10,000 km is not problematic.

Note that in several of the figures, the Non-renewable Energy result for wood and wood products show relatively short distances needed to offset any benefit of reusing this material. Because wood is a renewable material, it has a relatively low Non-renewable Energy impact at the time of production and therefore relatively little benefit at the time of reuse. This leads to a lesser distance needed to recover that benefit. Relative to other materials, it also shows a relatively low impact for Ozone Depletion. Therefore, a similar trend is seen for that indicator.

Across nearly all material categories, some trends can be seen in the relative position in the results of some environmental indicators relative to others. For example, Photochemical Oxidation and Ozone Depletion tend to require shorter distances to offset reuse benefits, while Non-renewable Energy Use and Ecotoxicity tend to require longer distances. Such overall trends are due to the relative impact of transportation in these impact categories. Photochemical Oxidation and Ozone Depletion, for example, are impact categories where transportation systems tend to contribute a higher proportion of environmental impact than for other categories.

In addition, several materials emerge as significant outliers of this trend. For sand, gravel and concrete, it appears that transporting these materials any more than 100 km is likely to be unfavorable to the environment. If by a small truck, even an excess distance of 10km may be sufficient to erase any environmental advantage of reuse., Electrical parts, wire, steel and aluminum products and extruded PVC appear to be materials where distances of 1000 km still result in a benefit from re-use and 10,000 would not be out of the question.

The text box on page 46 describes considerations regarding the inclusion of effects of forestry management practices on the flux of carbon to and from forest systems. While the assessment of wood production applied here considers the direct processes contributing to the growth of the wood being used, indirect effects on the forest system as a whole have not been considered. Results from elsewhere (e.g., US EPA, 2006) suggest that, if included, these considerations would show a large added *Climate Change* impact from marginal wood production. The effect on the current results of including those findings would be an emphasis on reusing wood rather than recovery of energy.

As shown above in Table 21, the approach taken to accounting for end-of-life impact in the present assessment results in a preferable outcome for *Climate Change* impact when wood is incinerated rather than being re-used. This is the only material in the *Standard Homes* for which this is the case for *Climate Change* impact. Table 26 presents the end-of-life impact in other categories associated with reuse and incineration of reuse of softwood lumber.[40] The *Climate Change* impact is shown both with and without the inclusion of sequestration of biogenic CO_2.

Regarding *Climate Change*, the inclusion of impact from forestry land use clearly has a potential to effect the decision on wood end-of-life management. Regarding other categories than *Climate Change*, with the exception of eutrophication and the non-carcinogenic toxicity category, all other categories also show a greater benefit to incinerating wood than reusing it. In the case of the exceptions mentioned, a net impact for incineration is shown that is up to several orders of magnitude higher than the benefit shown for reuse.

As is noted in the Methodology section above, the beneficial uses of materials at end-of-life has been attributed 100% to the system donating the materials and 0% to the system receiving the materials. This is just one of a number of possible ways of assigning the environmental benefits of

Table 26: Comparison of the impact of incineration and reuse of softwood lumber among multiple environmental impact categories (preferable route in bold *italics*)

Impact Category	Impact of Incineration, per kilogram	Impact of Reuse, per kilogram
Climate Change impact (IPCC 2007 GWP100, Kg CO_2e)	-0.87	-0.26
Climate Change with forestry land Use (Kg CO_2e)	-0.87	-2.5
Non-renewable energy use (IMPACT, MJ Primary)	-12	-0.0018
Carcinogenic toxicity (TRACI, Kg benzene-Eq)	0.0026	-0.00011
Non-carcinogenic toxicity (TRACI, Kg toluene-Eq)	25	-1.2
Respiratory effects (TRACI, Kg PM2.5 eq.)	-0.00076	-0.00039
Acidification (TRACI, moles of H+-Eq)	-0.16	-0.11
Ecotoxicity (TRACI, Kg 2,4-D eq.)	-0.34	-0.024
Eutrophication (TRACI, Kg N)	0.00063	-0.000047
Ozone depletion (TRACI, Kg CFC-11 eq)	-0.000000047	-3E-12
Photochemical oxidation (TRACI, Kg NOx eq)	-0.0011	-0.0012
Human health, endpoint (IMPACT, DALYs)	-0.00000011	-0.00000018
Ecosystem quality, endpoint (IMPACT, PDF•m2•yr)	-0.19	-0.0092
Resource depletion, endpoint (IMPACT, MJ Primary)	-12	-4.2

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[40] Note that in Table 21, the information shown for wood reflects the mix of all wood products used in the *Medium Standard Home*, while the data in Table 26 refers specifically to the underlying data for softwood lumber.

reuse. This methodological choice will affect the relative benefit of the material reuse scenarios, providing more benefit to some and less to others under different allocation methods.

Figure 64 shows the *Climate Change* results for the life cycle impact of each of the material reuse scenarios when modifying the allocation between the material-providing and material-receiving systems. Three options are shown here: providing all benefit to the material receiving system (0/100), providing all benefit to the material donating system (100/0, the baseline methodology applied throughout), and splitting the benefit evenly between them (50/50). It should be noted that in addition to the material re-use scenarios, the *Standard Home* is also sensitive to this assumption due to recycling and incineration at the end-of-life of many of its components. Similar results for *Ecotoxicity*, which shows a higher benefit for the material reuse scenarios, are shown in Figure 64.

As might be expected, it is clear that the comparative results among material reuse scenarios are highly sensitive to this choice of allocation methodology.

Table 27 provides a summary of the environmental benefits obtained from each material class within the *Maximal Reuse* scenario. Table 29 lists the benefit recovered per kilogram of material, better highlighting those materials which may be important to salvage but are small contributors to the home mass.

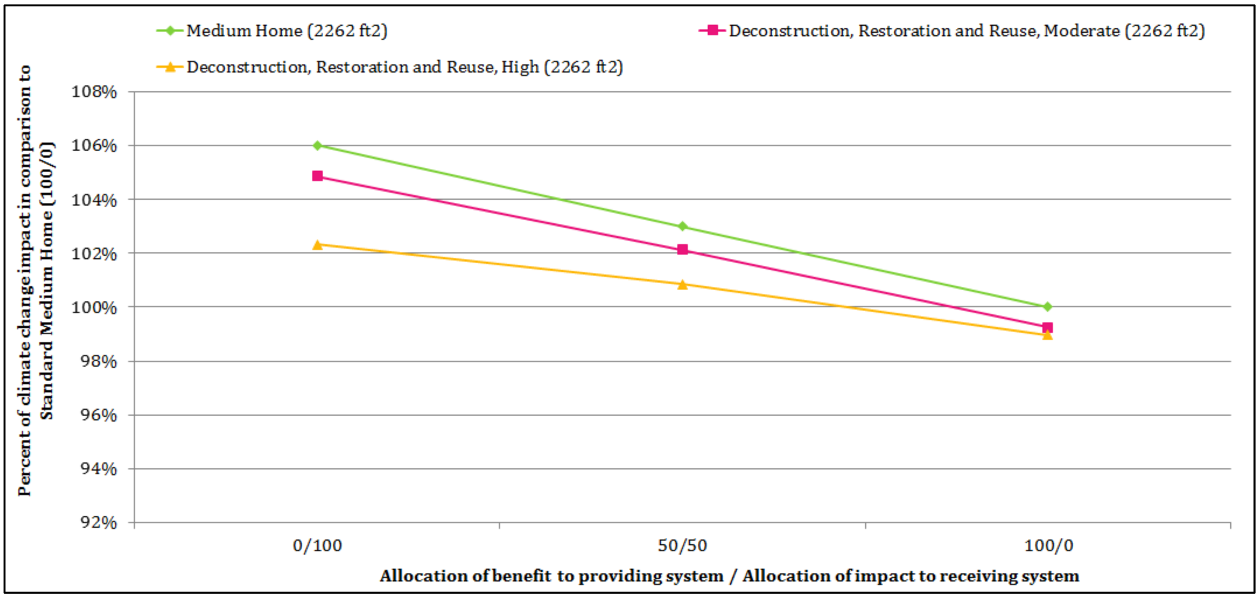

Figure 64: Variation in *Climate Change* impact among materials reuse scenarios with changes in allocation between material-providing and material-receiving systems

Table 27: Total environmental benefit of salvaged material obtained from the *Deconstruction, Restoration and Reuse, High* scenario, based on the amount of each material that is potentially reused

	Amount in life cycle of home (Kg)	Amount potentially reused (Kg)	Climate change (IPCC 2007 GWP100, Kg CO2e)	Climate change (IPCC 2007 GWP100 with forestry land use, Kg CO2e)	Non-renewable energy use (IMPACT, MJ Primary)	Carcinogenic toxicity (TRACI, Kg benzene-Eq)	Non-carcinogenic toxicity (TRACI, Kg toluene-Eq)	Respiratory effects (TRACI, Kg PM2.5 eq.)	Acidification (TRACI, moles of H+-Eq)	Ecotoxicity (TRACI, Kg 2,4-D eq.)	Eutrophication (TRACI, Kg N)	Ozone depletion (TRACI, Kg CFC-11eq)	Photochemical oxidation (TRACI, Kg NOx eq)	Human health, endpoint (IMPACT, DALYs)	Ecosystem quality, endpoint (IMPACT, PDF*m2*yr)	Resource depletion, endpoint (IMPACT, MJ Primary)
Steel Product	847	567.49	2360	35300	16	258000	5.7	637	9350	2	0.00012	5.3	0.0026	902	35800	2360
Softwood	11830	7926.1	2040	14	0.87	9670	3.1	902	192	0.37	2.4E-08	9.2	0.0015	73	32900	19500
Gravel	11270	7550.9	28	535	0.072	483	0.055	12	46	0.018	0.0000025	0.16	0.000035	6.8	537	28
Foamed PE	1.38	0.9246	2.7	86	0.0018	24	0.0028	0.62	1.9	0.00056	6.2E-08	0.0098	0.0000018	0.12	86	2.7
Extruded PVC	5.95	3.9865	20	349	1.1	2090	0.039	6	43	0.017	0.0000001	0.042	0.00011	0.8	349	20
I-Joist	3330	2231.1	1270	4	0.82	9820	3.7	2330	206	2.2	3.2E-08	52	0.0049	305	26200	1270
Plywood	7676	5142.92	1320	9.3	0.74	13000	2	611	173	0.26	2.5E-08	14	0.0012	56	23500	12600
Kraft Paper	1.16	0.7772	0.99	15	0.003	30	0.0022	0.41	2.7	0.0016	6.1E-08	0.0038	0.0000012	1.1	15	2.7
Adhesive	40.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Glass Wool	3888	2604.96	5290	124000	15	175000	6.8	1630	29100	3.2	0.00062	13	0.0035	803	124000	5290
Gypsum drywall	17320	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Wood Siding	8118	5439.06	2870	266000	3.7	35400	0.59	577	776	1.6	3.8E-08	13	0.002	178	508000	14800
PE Fleece	506	339.02	1000	32500	1	9960	0.77	173	556	0.25	0.000013	1.7	0.00069	48	32500	1000
Asphalt Shingle	10540	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Steel Product, Chrome	32.9	22.043	204	2950	3.5	13200	0.62	63	823	0.14	0.0000095	0.47	0.00033	141	3210	204
Aluminum Product	43	28.81	362	4840	1.4	13500	0.64	89	2180	0.21	0.000022	0.64	0.00029	79	4900	362
Plaster	1556	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Vinyl Acetate	405	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Carpeting	2652	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Carpet Padding	1052	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MDF	2314	1550.38	1890	37500	3	15100	3	539	2920	0.52	0.00015	4.7	0.0016	651	37600	1890
Linoleum	338	226.46	303	10400	0.11	1040	0.077	82	17	0.17	2.2E-09	1.7	0.00017	14	60800	303
Ceramics	724	485.08	1270	22100	2.9	52100	5.2	193	1550	0.19	0.00013	1.5	0.0034	107	22100	1270
Wire	191	127.97	694	10600	202	191000	5.9	1010	10600	0.4	0.000031	3.7	0.0034	2550	10900	694
Injected PS	7.43	4.9781	26	595	0.027	523	0.024	5.4	21	0.0054	0.0000037	0.044	0.000012	1.4	595	26
Electrical	7.43	4.9781	46	667	0.78	2970	0.14	14	186	0.031	0.0000022	0.11	0.000075	32	724	46
Outer Door	892	597.64	1470	21000	7	48000	2.7	576	5950	1.1	0.00009	3.6	0.0014	1060	21100	1470
Inner Door	1340	897.8	1440	25400	3.2	27100	2.6	464	3210	1.1	0.0001	4.5	0.0016	2000	25400	1440
Window	1311	878.37	2340	50300	35	93000	4.1	834	5710	1.6	0.0001	6.1	0.0045	908	50600	2340

Table 28: Environmental benefit of salvaged material obtained from the *Maximal Reuse* scenario on a per kilogram basis

	Amount in life cycle of home (Kg)	Amount potentially reused (Kg)	Climate change (IPCC 2007 GWP100, Kg CO2e)	Climate change (IPCC 2007 GWP100 with forestry land use, Kg CO2e)	Non-renewable energy use (IMPACT, MJ Primary)	Carcinogenic toxicity (TRACI, Kg benzene-Eq)	Non-carcinogenic toxicity (TRACI, Kg toluene-Eq)	Respiratory effects (TRACI, Kg PM2.5 eq.)	Acidification (TRACI, moles of H+-Eq)	Ecotoxicity (TRACI, Kg 2,4-D eq.)	Eutrophication (TRACI, Kg N)	Ozone depletion (TRACI, Kg CFC-11 eq)	Photochemical oxidation (TRACI, Kg NOx eq)	Human health, endpoint (IMPACT, DALYs)	Ecosystem quality, endpoint (IMPACT, PDF•m2•yr)	Resource depletion, endpoint (IMPACT, MJ Primary)
Steel Product	847	567.49	4.2	62	0.028	455	0.01	1.1	16	0.0035	2.1E-07	0.0093	0.0000046	1.6	63	4.2
Softwood	11830	7926.1	0.26	0.0018	0.00011	1.2	0.00039	0.11	0.024	0.000047	3E-12	0.0012	1.9E-07	0.0092	4.2	2.5
Gravel	11270	7550.9	0.0037	0.071	0.0000095	0.064	0.0000073	0.0016	0.0061	0.0000024	3.3E-10	0.000021	4.6E-09	0.0009	0.071	0.0037
Foamed PE	1.38	0.9246	2.9	93	0.0019	26	0.003	0.67	2.1	0.00061	6.7E-08	0.011	0.0000019	0.13	93	2.9
Extruded PVC	5.95	3.9865	5	88	0.28	524	0.0098	1.5	11	0.0043	2.5E-08	0.011	0.000028	0.2	88	5
I-Joist	3330	2231.1	0.57	0.0018	0.00037	4.4	0.0017	1	0.092	0.00099	1.4E-11	0.023	0.0000022	0.14	12	0.57
Plywood	7676	5142.92	0.26	0.0018	0.00014	2.5	0.00039	0.12	0.034	0.000051	4.9E-12	0.0027	2.3E-07	0.011	4.6	2.4
Kraft Paper	1.16	0.7772	1.3	19	0.0039	39	0.0028	0.53	3.5	0.0021	7.8E-08	0.0049	0.0000015	1.4	19	3.5
Adhesive	40.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Glass Wool	3888	2604.96	2	48	0.0058	67	0.0026	0.63	11	0.0012	2.4E-07	0.005	0.0000013	0.31	48	2
Gypsum drywall	17320	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Wood Siding	8118	5439.06	0.53	49	0.00068	6.5	0.00011	0.11	0.14	0.00029	7E-12	0.0024	3.7E-07	0.033	93	2.7
PE Fleece	506	339.02	2.9	96	0.0029	29	0.0023	0.51	1.6	0.00074	3.8E-08	0.005	0.000002	0.14	96	2.9
Asphalt Shingle	10540	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Steel Product, Chrome	32.9	22.043	9.3	134	0.16	599	0.028	2.9	37	0.0064	4.3E-07	0.021	0.000015	6.4	146	9.3
Aluminum Product	43	28.81	13	168	0.049	469	0.022	3.1	76	0.0073	7.6E-07	0.022	0.00001	2.7	170	13
Plaster	1556	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Vinyl Acetate	405	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Carpeting	2652	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Carpet Padding	1052	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MDF	2314	1550.38	1.2	24	0.0019	9.7	0.0019	0.35	1.9	0.00034	9.7E-08	0.003	0.000001	0.42	24	1.2
Linoleum	338	226.46	1.3	46	0.00049	4.6	0.00034	0.36	0.075	0.00075	9.7E-12	0.0075	7.5E-07	0.062	268	1.3
Ceramics	724	485.08	2.6	46	0.006	107	0.011	0.4	3.2	0.00039	2.7E-07	0.0031	0.000007	0.22	46	2.6
Wire	191	127.97	5.4	83	1.6	1490	0.046	7.9	83	0.0031	2.4E-07	0.029	0.000027	20	85	5.4
Injected PS	7.43	4.9781	5.2	120	0.0054	105	0.0048	1.1	4.2	0.0011	7.4E-07	0.0088	0.0000024	0.28	120	5.2
Electrical	7.43	4.9781	9.2	134	0.16	597	0.028	2.8	37	0.0062	4.4E-07	0.022	0.000015	6.4	145	9.2
Outer Door	892	597.64	2.5	35	0.012	80	0.0045	0.96	10	0.0018	1.5E-07	0.006	0.0000023	1.8	35	2.5
Inner Door	1340	897.8	1.6	28	0.0036	30	0.0029	0.52	3.6	0.0012	1.1E-07	0.005	0.0000018	2.2	28	1.6
Window	1311	878.37	2.7	57	0.04	106	0.0047	0.95	6.5	0.0018	1.1E-07	0.0069	0.0000051	1	58	2.7

These results provide an indication of which material classes provide the most potential within the home for benefit by salvaging them. By weight, metal product, including electrical systems, wires, hardware, etc. show the most potential, followed by plastic products, especially PVC. When considering the amount in the home in total, several other materials, including fiberglass insulation, doors, windows, and I-joists, among others show a high potential for benefits from reuse.

Results: Wall Framing

Figure 65 shows the results for the *Climate Change* impact of the various framing practices considered in comparison to the *Medium Standard Home*. Figure 66 shows the same results as a net difference from the *Medium Standard Home*.

With regard to the *Climate Change* impact, it is clear that the *ICF Home*, *SIP Home*, *Strawbale Home*, *Double Wall Home* and the *Staggered Stud Home* have a larger potential to provide benefits than the intermediate and advanced framing options. However, with the exception of the *Staggered Stud Home*[41], each of these other wall framing options are shown to be net generators of waste in comparison to the *Medium Standard Home,* which is designed with wall framing practices meeting the minimum requirements of the Oregon building code. Note that even though 80% of the straw within the *Strawbale Home* has not been counted as waste generated (assuming it would have been disposed of to begin with), the amount of additional material used is still sufficient for this home to be a net waste generator in comparison to the *Medium Standard Home.* Note that for the *ICF Home* and the *Strawbale Home* a significant amount of additional transportation is required.

Table 29 shows a division of these results by types of materials and processes within the life cycle of the home. Figure 67 shows the results for the other environmental impact categories considered.

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[41] An unexpected finding is that the staggered stud practice may in fact be waste preventing. Although studs are placed more closely together, the use of 2x4 lumber rather than 2x6 lumber and the configuration of boards appears to provide a slight waste savings, at least in this particular example.

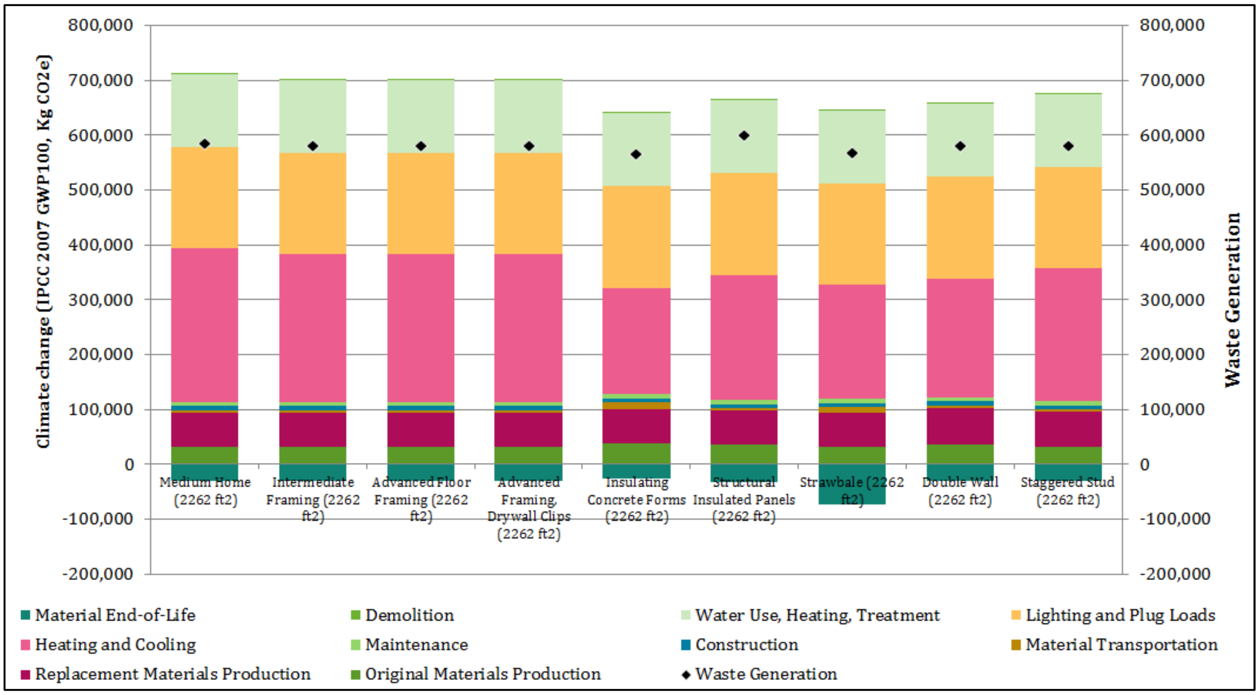
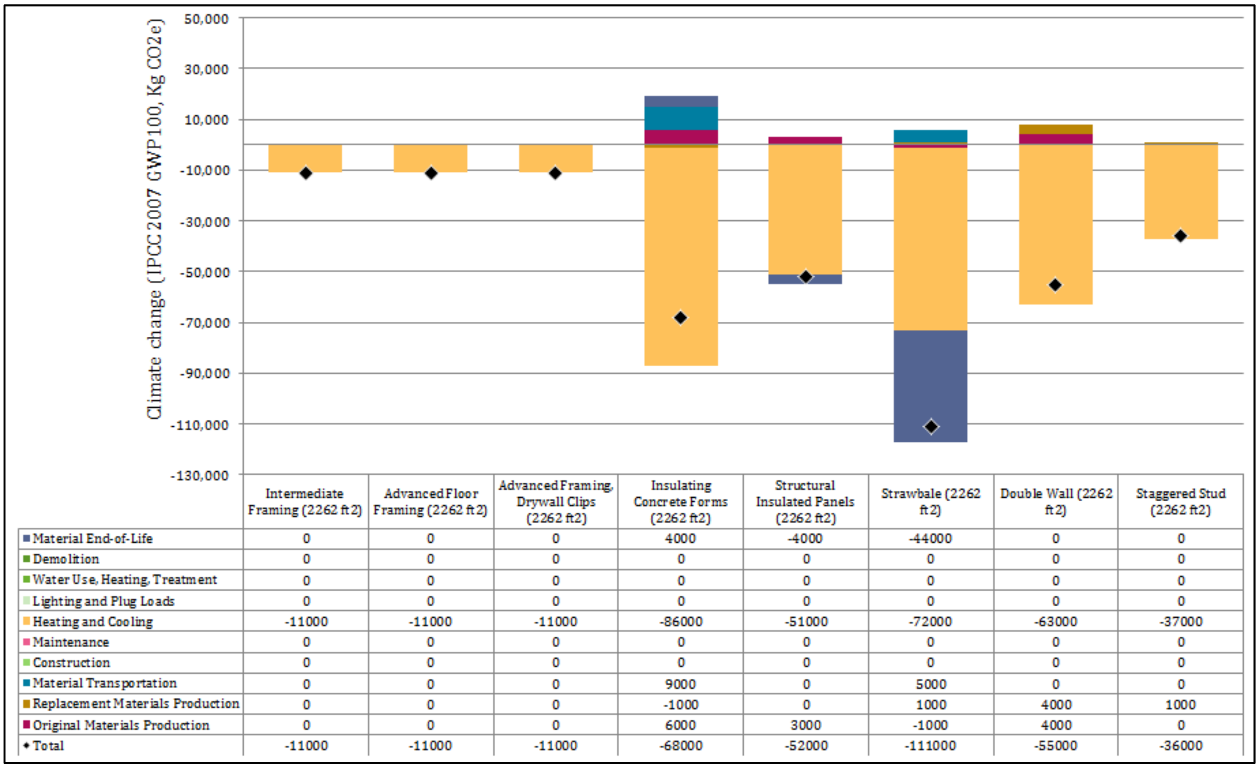


Figure 65: ***Climate Change*** **impact and waste generation for the wall framing options in comparison with the** ***Medium Standard Home***



	Intermediate Framing (2262 ft2)	Advanced Floor Framing (2262 ft2)	Advanced Framing, Drywall Clips (2262 ft2)	Insulating Concrete Forms (2262 ft2)	Structural Insulated Panels (2262 ft2)	Strawbale (2262 ft2)	Double Wall (2262 ft2)	Staggered Stud (2262 ft2)
■ Material End-of-Life	0	0	0	4000	-4000	-44000	0	0
■ Demolition	0	0	0	0	0	0	0	0
■ Water Use, Heating, Treatment	0	0	0	0	0	0	0	0
■ Lighting and Plug Loads	0	0	0	0	0	0	0	0
■ Heating and Cooling	-11000	-11000	-11000	-86000	-51000	-72000	-63000	-37000
■ Maintenance	0	0	0	0	0	0	0	0
■ Construction	0	0	0	0	0	0	0	0
■ Material Transportation	0	0	0	9000	0	5000	0	0
■ Replacement Materials Production	0	0	0	-1000	0	1000	4000	1000
■ Original Materials Production	0	0	0	6000	3000	-1000	4000	0
◆ Total	-11000	-11000	-11000	-68000	-52000	-111000	-55000	-36000

Figure 66: Net ***Climate Change*** **impact for each wall framing practice in reference to the** ***Standard Home***

Table 29: *Climate Change* impact (Kg CO_2e) by process or material type for each of the wall framing alternatives

Component of Home Life Cycle	Medium Home (2262 ft2)	Intermediate Framing (2262 ft2)	Advanced Floor Framing (2262 ft2)	Advanced Framing, Drywall Clips (2262 ft2)	Insulating Concrete Forms (2262 ft2)	Structural Insulated Panels (2262 ft2)	Strawbale (2262 ft2)	Double Wall (2262 ft2)	Staggered Stud (2262 ft2)	High Performance Shell Home (2262 ft2)
Use - Natural Gas	379,000	368,000	368,000	368,000	296,000	329,000	309,000	318,000	343,000	286,000
Use - Electricity	197,000	197,000	197,000	197,000	195,000	196,000	195,000	196,000	196,000	191,000
Use - Water	12,100	12,100	12,100	12,100	12,100	12,100	12,100	12,100	12,100	12,100
Asphalt Shingles	11,900	11,900	11,900	11,900	11,900	11,900	11,900	11,900	11,900	11,900
Carpet	21,200	21,200	21,200	21,200	21,200	21,200	21,200	21,200	21,200	21,200
Appliances	11,500	11,500	11,500	11,500	11,500	11,500	11,500	11,500	11,500	11,500
Fiberglass Insulation	7,890	7,890	7,890	7,890	724	724	724	15,100	8,120	8,120
Drywall	6,660	6,660	6,660	6,580	6,660	6,660	6,660	6,660	6,660	6,660
Other Siding Mtl.	5,060	5,060	5,060	5,060	5,060	5,060	8,730	5,060	5,060	5,060
Windows	3,500	3,500	3,500	3,500	3,500	3,500	3,500	3,500	3,500	3,500
Electrical Fixtures	108	108	108	108	108	108	108	108	108	108
Wall Lumber	1,940	1,800	1,800	1,730	488	1,720	902	1,640	1,750	1,940
Other Roofing Mtl.	2,550	2,550	2,550	2,550	2,550	2,550	2,550	2,550	2,550	2,550
Doors (exterior)	2,200	2,200	2,200	2,200	2,200	2,200	2,200	2,200	2,200	2,200
Doors (interior)	2,150	2,150	2,150	2,150	2,150	2,150	2,150	2,150	2,150	2,150
Floor Engineered Wood	2,400	2,220	1,890	1,890	2,400	541	2,400	2,400	2,400	2,400
Packaging	1,940	1,940	1,940	1,940	1,940	1,940	1,940	1,940	1,940	1,940
Kitchen Cabinets	1,580	1,580	1,580	1,580	1,580	1,580	1,580	1,580	1,580	1,580
Wall Hardware	1,180	1,180	1,180	1,300	738	3,690	1,180	1,180	1,180	1,180
Sinks	1,330	1,330	1,330	1,330	1,330	1,330	1,330	1,330	1,330	1,330
Paints and Adhesives	1,180	1,180	1,180	1,030	1,180	1,180	1,180	1,180	1,180	1,180
Mouldings	1,290	1,290	1,290	1,290	1,290	1,290	1,290	1,290	1,290	1,290
Ducting	1,410	1,410	1,410	1,410	1,410	1,410	1,410	1,410	1,410	1,410
Foundation Concrete	1,110	995	995	995	1,110	1,460	1,110	1,110	1,110	1,110

Component of Home Life Cycle	Medium Home (2262 ft2)	Intermediate Framing (2262 ft2)	Advanced Floor Framing (2262 ft2)	Advanced Framing, Drywall Clips (2262 ft2)	Insulating Concrete Forms (2262 ft2)	Structural Insulated Panels (2262 ft2)	Strawbale (2262 ft2)	Double Wall (2262 ft2)	Staggered Stud (2262 ft2)	High Performance Shell Home (2262 ft2)
Electrical Wire	1,040	1,040	1,040	1,040	1,040	1,040	1,040	1,040	1,040	1,040
Floor Lumber	600	422	693	693	600	2,020	600	600	600	600
Foundation Other Mtl.	741	741	741	741	741	745	741	741	741	741
Roof Lumber	507	507	507	507	507	507	507	507	507	507
Wall Engineered Wood	360	360	360	360	0	0	360	360	360	360
Linoleum Floors	452	452	452	452	452	452	452	452	452	452
Floor Hardware	294	294	294	294	294	163	294	294	294	294
Faucets	305	305	305	305	305	305	305	305	305	305
Toilets	566	566	566	566	566	566	566	566	566	566
Plumbing pipe	369	369	369	369	369	369	369	369	369	369
Porch Lumber	174	174	174	174	174	68	174	174	174	174
SIPs	0	0	0	0	0	7,900	0	0	0	0
ICFs	0	0	0	0	14,400	0	0	0	0	0
Strawbales	0	0	0	0	0	0	2,110	0	0	0
Wood Beams	0	0	0	0	0	0	1,750	0	0	0
Transportation	3,760	3,720	3,700	3,660	13,400	4,080	8,870	4,100	3,750	3,770
Construction - Equipment	6,810	6,810	6,810	6,810	6,810	6,810	6,810	6,810	6,810	6,810
Construction - Commuting	6,990	6,990	6,990	6,990	6,990	6,990	6,990	6,990	6,990	6,990
Construction - Electricity	2,220	2,220	2,220	2,220	2,220	2,220	2,220	2,220	2,220	2,220
Material Waste-to-Energy	-13,300	-12,900	-12,600	-12,500	-10,500	-15,000	-57,300	-12,900	-13,000	-13,300
Material Recycling	-17,500	-17,500	-17,500	-17,600	-17,200	-19,200	-17,500	-17,500	-17,500	-17,500
Material Landfilling	1,360	1,350	1,340	1,310	2,520	1,410	2,040	1,380	1,350	1,360
Total	684,000	663,000	663,000	663,000	608,000	622,000	563,000	620,000	637,000	575,000

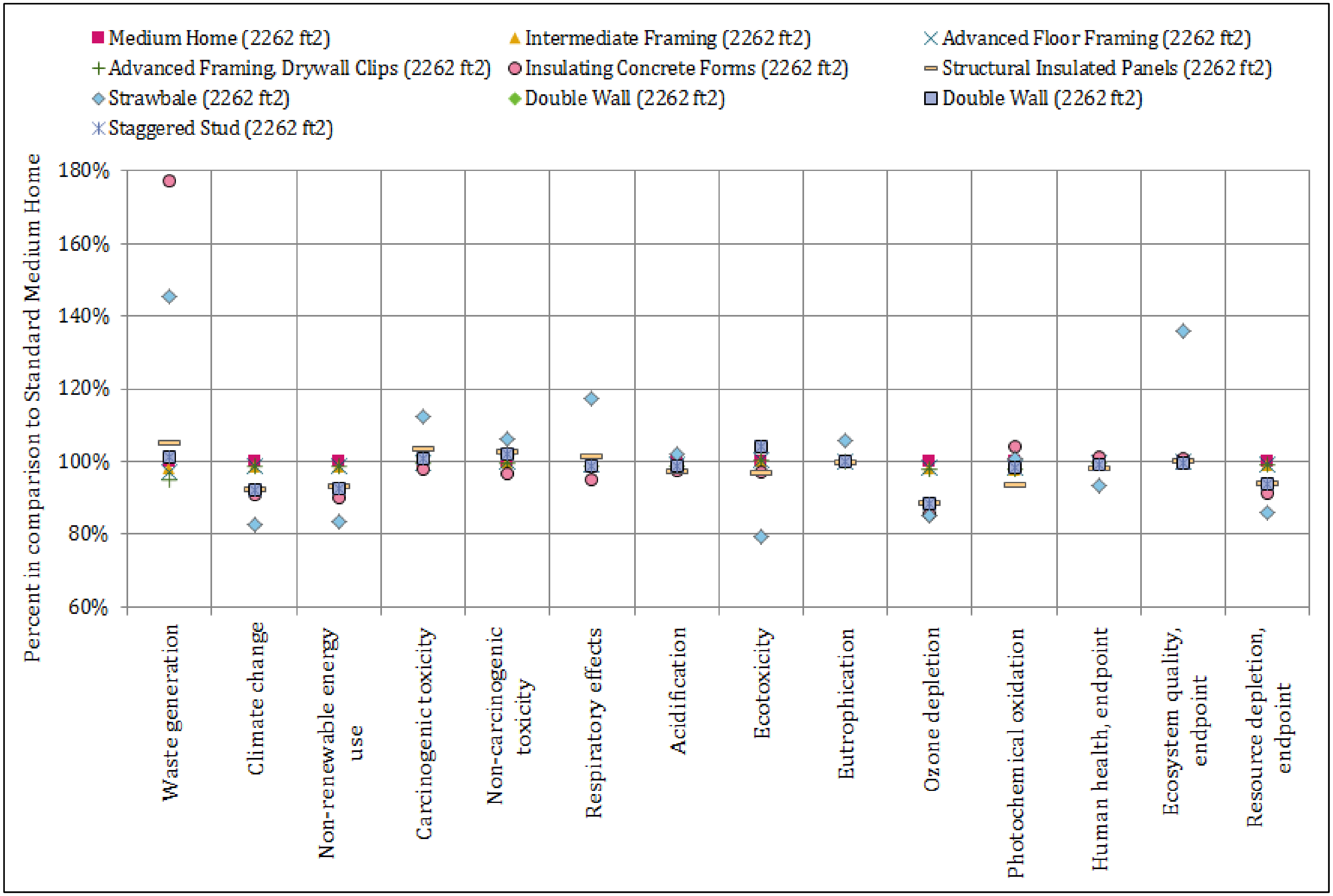
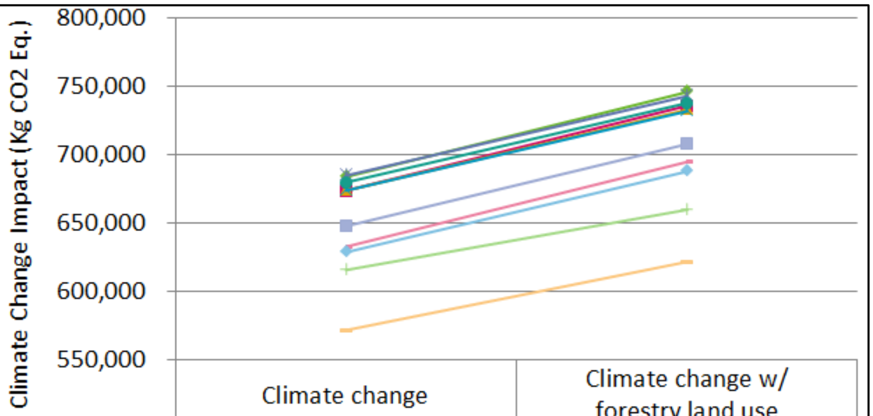


Figure 67: Comparison of environmental indicators for the wall framing options considered, presented as a percentage of the value for the *Standard Home*

Both the *ICF Home* and the *Strawbale Home* show substantially increased impacts in several environmental impact categories. These are due to the use of concrete and straw, respectively. In the case of straw, some of the impact categories, such as *Eutrophication* and the *Human Toxicity* categories, are strongly linked to disposal, whereas the *Ecosystem Quality (endpoint)* impact is linked to straw production.



	Climate change	Climate change w/ forestry land use
◆ Medium Home (2262 ft2)	684,000	746,000
■ Intermediate Framing (2262 ft2)	674,000	736,000
▲ Advanced Floor Framing (2262 ft2)	674,000	733,000
✕ Advanced Framing, Drywall Clips (2262 ft2)	674,000	732,000
✱ Detailed Framing Cut List (2262 ft2)	685,000	743,000
● Off-site Pre-fabricated Components (2262 ft2)	680,000	738,000
+ Insulating Concrete Forms (2262 ft2)	616,000	660,000
— Structural Insulated Panels (2262 ft2)	633,000	695,000
— Strawbale (2262 ft2)	572,000	622,000
◆ Double Wall (2262 ft2)	629,000	688,000
■ Staggered Stud (2262 ft2)	648,000	708,000

Figure 68: Comparison of *Climate Change* impact with and without the adjustment for forestry land use for the wall framing options considered

Results: Combined Waste Prevention Practices

Figure 69 shows the results for the *Waste Prevention Home* in comparison to both the *Medium Standard Home* and the *Standard Extra-small Home* to illustrate the high importance of the home size in the benefit achieved by the *Waste Prevention Home*. Figure 70 shows additional detail for the *Climate Change* impact.

In total, the *Waste Prevention Home* provides a reduction in *Climate Change* impact of nearly 50% when compared with the *Standard Home*. The majority of this benefit can be attributed to the size of the home, which alone is estimated to provide a 37% decrease in the *Climate Change* impact of the home. However, there is an additional 22% improvement in comparison to the *Standard Extra-small Home* as a result of the remaining practices implemented. The results in comparison to the *Medium Standard Home* are relatively similar among environmental impact categories, ranging from a 40% to 60% improvement. In comparison to the *Standard Extra-small Home*, the benefits are more variable among categories, ranging from only a very small added benefit in the case of *Respiratory Effects* and *Ecotoxicity* to a very large improvement (nearly 50% or more) in the cases of *Resource Depletion*, *Eutrophication* and the *Human Toxicity* categories. A description of the waste prevention home is provided in Table 3.

Table 30 shows the percent benefit of the in comparison to the *Medium Standard Home* and the *Standard Extra-small Home*.

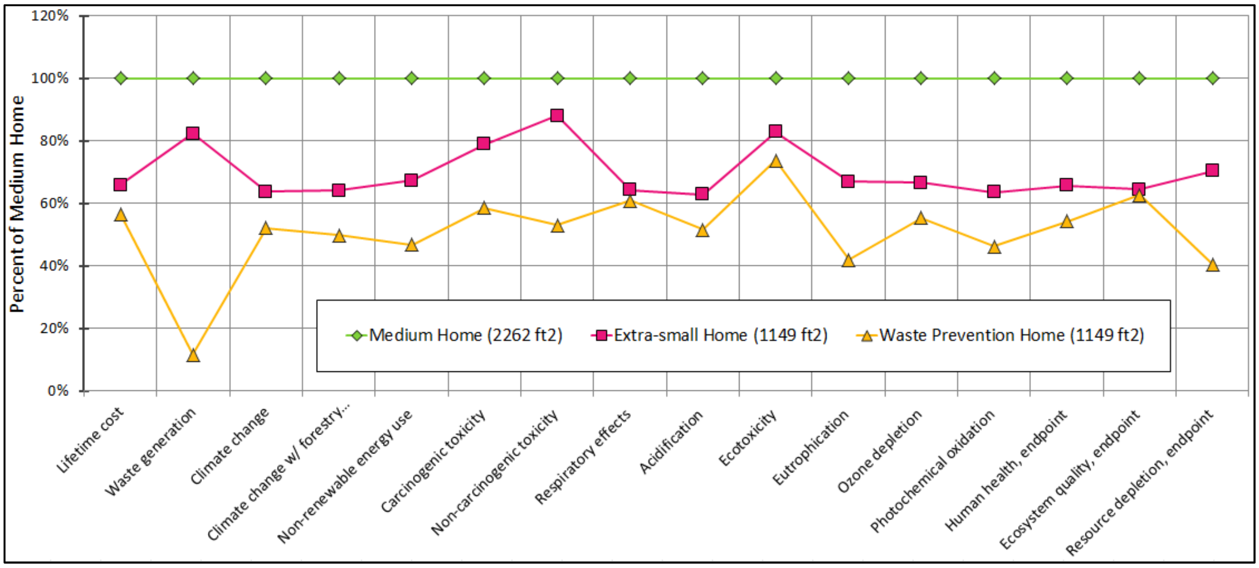
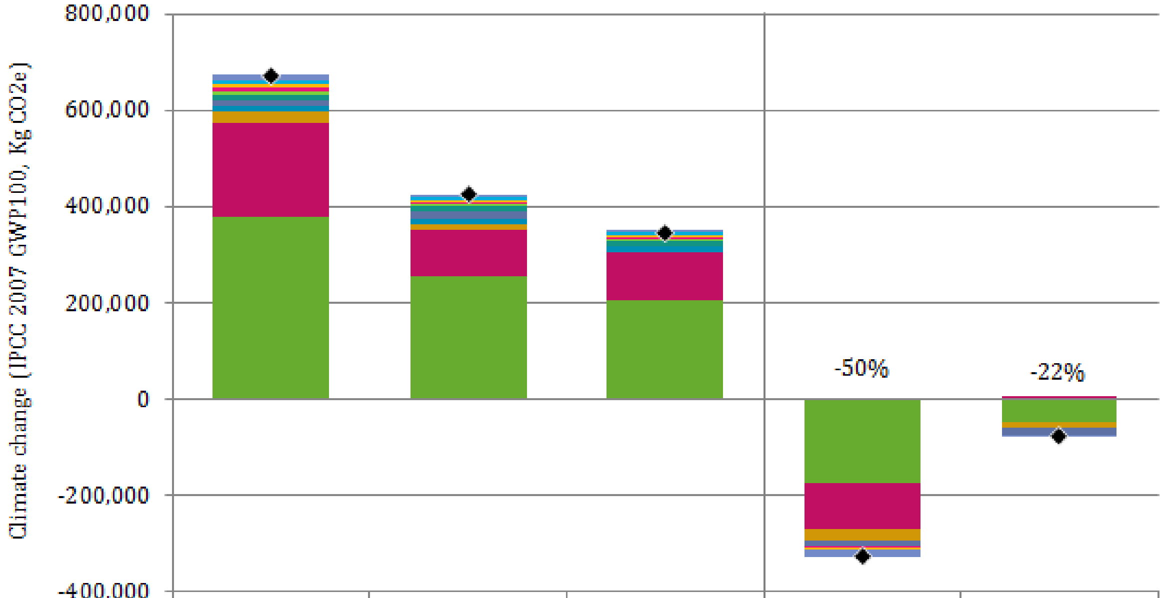


Figure 69: Environmental impact of the *Medium Standard Home*, the *Standard Extra-small Home*, and the *Waste Prevention Home*



	Medium Home (2262 ft2)	Extra-small Home (1149 ft2)	Waste Prevention Home (1149 ft2)	Net Benefit of Waste Prevention Home (from Medium)	Net Benefit of Waste Prevention Home (from Extra-small)
🟦 Other	12,900	6,900	800	-12,100	-6,100
🟦 Drywall	6,700	5,200	4,700	-2,000	-500
🟧 Construction - Equipment	6,800	3,700	3,700	-3,100	0
🟥 Construction - Commuting	7,000	3,800	3,800	-3,200	0
🟩 Fiberglass Insulation	7,900	6,400	6,400	-1,500	0
🟩 Appliances	11,500	11,500	11,500	0	0
🟦 Asphalt Shingles	11,900	12,300	0	-11,900	-12,300
🟦 Use - Water	12,100	12,100	12,100	0	0
🟧 Carpet	21,200	11,600	0	-21,200	-11,600
🟥 Use - Electricity	197,500	97,500	98,700	-98,800	1,200
🟩 Use - Natural Gas	378,600	255,000	205,500	-173,100	-49,500
◆ Total	674,100	426,000	347,200	-326,900	-78,800

Figure 70: ***Climate Change*** **impact of the** ***Medium Standard Home*****, the** ***Standard Extra-small Home*****, and the** ***Waste Prevention Home***

Table 30: Percent benefit of the *Waste Prevention Home* in comparison to the *Standard Medium* and *Extra-small Homes*

Environmental Impact Category	% Benefit vs. *Medium Standard Home*	% Benefit vs. Standard Extra-small Home
Waste generation (Kg)	88%	86%
Climate Change impact (IPCC 2007 GWP100, Kg CO_2e)	48%	18%
Climate Change impact with forestry land use (Kg CO_2e)	50%	22%
Non-renewable energy use (IMPACT, MJ Primary)	53%	31%
Carcinogenic toxicity (TRACI, Kg benzene-Eq)	41%	26%
Non-carcinogenic toxicity (TRACI, Kg toluene-Eq)	47%	40%
Respiratory effects (TRACI, Kg PM2.5 eq.)	39%	5%
Acidification (TRACI, moles of H+-Eq)	48%	18%
Ecotoxicity (TRACI, Kg 2,4-D eq.)	26%	11%
Eutrophication (TRACI, Kg N)	58%	37%
Ozone depletion (TRACI, Kg CFC-11 eq)	45%	17%
Photochemical oxidation (TRACI, Kg NOx eq)	54%	27%
Human health, endpoint (IMPACT, DALYs)	46%	17%
Ecosystem quality, endpoint (IMPACT, PDF•m2•yr)	37%	3%
Resource depletion, endpoint (IMPACT, MJ Primary)	59%	42%

Results: Summary of Population-level results

Table 31 summarizes the results of predictions of benefit for the *Climate Change* impact made at the level of the statewide population of homes. For practices that have not been modeled within the whole state population, an estimate of benefit is made by applying the results based on the results in comparison to the *Standard Homes*, divided among material-related impact and energy-related impact and based on the expected ability of each practice to effect both pre-2010 homes and post-2010 homes.[42]

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[42] For most practices, it has been assumed here that pre-existing homes are not effected. For example, the promotion of high performance shell homes is represented here as only effecting new construction homes. The exceptions are material reuse, where it is assumed that materials from pre-existing homes are available to be salvaged and reused, and material selection, where it is assumed that 25% of the total material burden for existing homes is from materials that are not yet installed and therefore subject to benefitting through better material selection. This assumption is based on an approximation that materials replaced during

Table 31: Summary of the predicted state-wide *Climate Change* benefit of various waste prevention practices and benchmarks

Practice or Scenario	Percent of Material Impact Reduction	Percent of Energy Impact Reduction	Influence on Pre-2010 homes	Influence on Post-2010 homes	Amount of Benefit (Kg CO_2e)	Percent Benefit
High Performance Shell Homes	1%	-9%	0%	100%	3.05E+10	4.3%
Green Certified Homes[43], with reduced size	-5%	-57%	0%	100%	1.88E+11	26.5%
Waste Prevention Practices	-8%	-40%	0%	100%	1.32E+11	18.7%
Reduced size (1% annual shrinking)	Modeled				2.26E+11	9.8%
Reduced size (only small homes)	Modeled				4.66E+11	20.2%
Multi-family (1% annual increase)	Modeled				1.64E+11	7.1%
Multi-family (only multifamily)	Modeled				4.86E+11	21.1%
Material Reuse	Modeled				2.07E+10	0.9%
Material Selection	-50%	0%	0.25	1	4.71E+10	6.6%

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occupation represent in the range of 50% of a home's material impact and that 50% of the life of existing homes, on average, has occurred. For all scenarios, the analysis shown here has assumed that 100% of new construction homes could be affected by each practice.

[43] It should be noted that a large environmental benefit of the green certification home evaluated here is based on its smaller size. The result shown should therefore be interpreted as being based on a strong influence of green certification programs on home size. Without such influence, the benefits of certification programs could potentially be much smaller than suggested here.

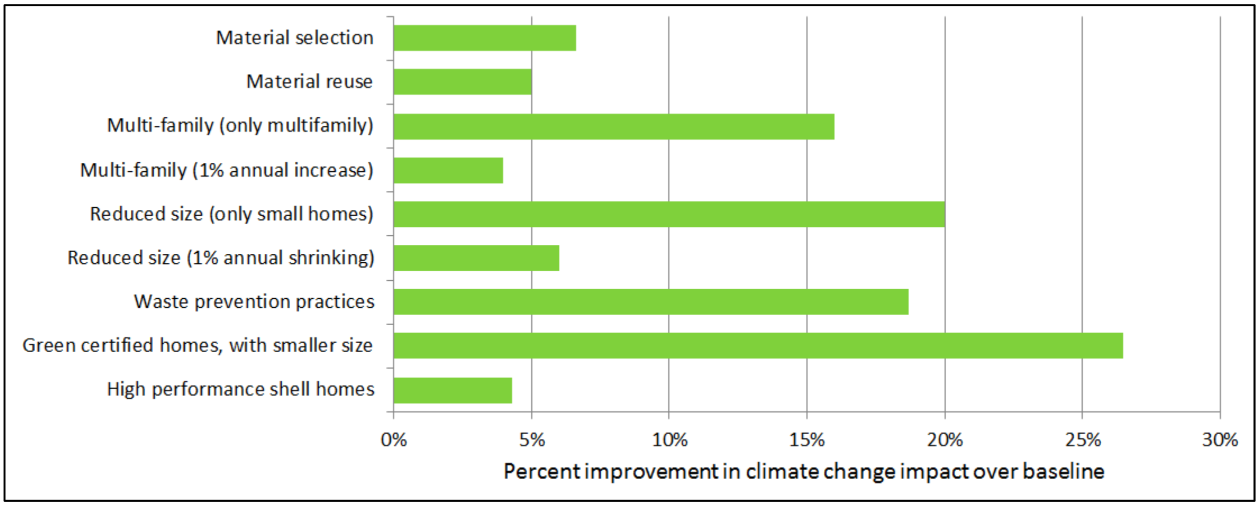

Figure 71: Summary of the predicted state-wide *Climate Change* benefit of various waste prevention practices and benchmarks

The results indicate a high potential benefit for promoting the use of waste prevention practices, smaller homes and multi-family housing, as well as material selection.

Note that a practice included to provide a benchmark with waste prevention—green certified homes—is shown here to be the leading option, outperforming each of the categories of waste prevention considered. While the present study is not intended to assess certification programs directly, it is important to highlight this result as a potential future direction. It should also be pointed out that the results here are based upon just a single example of a home that would meet several prominent certification schemes. However, there are a very wide variety of options for meeting these schemes, as well as many other schemes that might be followed. Prior results have shown that alternative means of meeting a point-based green certification scheme could vary in their true impact by more than an order of magnitude (see for example the evaluation of environmental benefits associated with credits under the LEED system by Humbert et al., 2007). This indicates a need for caution in viewing the present finding as an indication that all green certified homes will achieve such a high level of benefit (similarly, some may achieve even more). By highlighting the potential benefit of such programs, it also highlights a need to continually improve such programs to ensure they are driving toward those building practices and features that provide the greatest level of environmental benefit.

V. Discussion of Results

Discussion: Size

It is clear from Figure 44 that there is a substantial environmental benefit in the use of smaller residential structures. For the range of environmental impact categories considered for the range of different size *Standard Homes*, the lifetime environmental benefit of the *Standard Extra-small Home*, in comparison to the *Medium Standard Home*, ranges from approximately 20% to 40%. The construction and use of smaller homes has a substantial potential to reduce not only waste generation but also the full range of the environmental impacts linked with housing. As seen in Figure 45, this benefit is derived largely from reduced demands for heating and cooling energy during the occupation of the home.

In a comparison with a variety of benchmarks (see Figure 46 and Figure 47), the results indicate that energy efficiency, building practices and home size are all highly influential factors. It appears that home size is at least as important, if not more so, than the specifics of home construction type (e.g., types of wall framing, selection of materials, etc.) in determining the level of environmental impact caused by housing. While both the *Waste Prevention Home* and *Green Certified Home* offer substantial benefits in addition to the environmental gain achieved by the *Standard Extra-small Home*, it is clear that the smaller size of these options is highly important, contributing more than half of the improvement in environmental performance between these homes and the *Medium Standard Home*.

Several important implications of such a comparison exist, both for the public and for those in the building industry and government. Among the relevant conclusions are that when looking for an environmentally friendly home, or when implementing a certification or rating system, home size should be among the factors considered. Further, for those families which require or choose more living space, environmentally friendly building features can be an effective means of reducing the impact of the larger structure.[44] Both the *Waste Prevention Home*'s set of building practices and the *Green Certified Home* show substantial additional benefits (excluding the size feature), which could also be expected to be achieved in larger homes.

Figure 48 illustrates that actions that would reduce the rate of growth in home size will achieve a positive impact on the environment. If a 1 or 2% annual shrinkage can be achieved in the average size of newly constructed homes, an improvement of between 5 and 10% can be achieved across all impact categories in the total environmental impact of the Oregon homes within the scope of the present project. Compared to the overall impact of the housing sector, the percent of improvement is less than that seen in the single home comparisons made above due to the ability of this change to

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[44] Although an efficient larger home may have more impacts than a smaller code/regular house.

act only on newly constructed homes and that the change is implemented as a gradual increase or decrease over time, rather than an instantaneous shift to smaller homes.

The steady growth in house size has been arrested by the recent recession. Housing costs and consumer caution have caused a slight reduction in average house size. Nevertheless, history suggests that the trend to larger houses may likely return as economic growth returns. It is therefore reasonable to think that without specific actions encouraging smaller homes, home size will continue to grow. There is, perhaps, an upper bound on how large *Average Home* size can go, but that is unlikely to be a limiting factor within the 20-year timeframe and growth rates examined here.

There may be some potential actions that influence consumer preferences or place incentives on smaller homes or disincentives on larger homes and could thereby influence the market. Home heating costs may be another factor that indirectly influences a future preference for smaller residences. It is therefore interesting to consider the potential benefit of a widespread reduction in the typical size of newly constructed homes. The results indicate that if successful influence could be made in this area, there are substantial environmental benefits to be gained.

Discussion: Multi-Family

Compared to single-family homes of a similar size, it is clear that multi-family homes show a significant environmental advantage. The benefit is largely in the area of building energy, where homes in multi-family structures benefit from the overall thermal efficiency per area of these structures.[45] Across all impact categories, the use of a multi-family home is shown to reduce environmental impact by as much as 15% in comparison with a single-family home of similar size.

For the medium sized home (2262 square feet), approximately the same *Climate Change* benefit is seen from using the *High Performance Shell* as for locating the home within a 4-family structure. A similar finding is true for a comparison of the *Waste Prevention Home* and the *Standard Extra-small Homes* (1149 square feet), where location in an 8-family or 12-family structure achieves approximately as much benefit as the combination of waste prevention practices in the *Waste Prevention Home*.

As seen for home size, the improvement for the whole population of homes is limited by the ability to impact only new-construction homes and by the assumption that a change in the population would be a gradual process rather than an instant change. As with home size, the potential benefit

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[45] Possible additional benefits of multi-family home through influences on land use and reduction of sprawl have not been assessed here.

over time is on the order of billions of kg CO_2equivalents. This result is compared above (Figure 71) to population-level results of other practices.

As pointed out by the potential importance of the added metal balcony on the *Standard 8-Unit and 12-Unit Multi-family Homes,* it is also of potential importance to consider large-scale changes in materials that might occur during a shift to multi-family structures. A reasonable portion of multi-family homes are likely to be much larger than the largest (12-unit) building assessed here and are likely to be constructed in a fundamentally different manner than the wood-frame construction that characterizes all the *Standard* and *Average Home*s assessed in this study. This might include such thing as a steel support frame, concrete supports or exterior brick, or a very wide variety of other materials. The sections below on material selection provide some insights on the challenges of assessing such changes in material and home construction type.

Multi-family housing may also have other benefits that the present project is not properly framed to address. For example, the impact of a home's yard maintenance has not been included in the scope, neither has the transportation patters of occupants, which may be different among typical single-family and multi-family residences. In addition, most multi-family residences will either be owned by a management company, or managed by an association of multiple owners (e.g., condominiums). These ownership changes could have an important influence on the maintenance schedule, material selection and even choices effecting energy efficiency and electricity use within the structures. It is unclear what such effects may exist. In cases like this, as well as with regard to transportation distances, it is also important to consider whether such differences are causal or simply correlational. This can be an important difference if one is making a conclusion that promoting multi-family housing would bring benefits in any of these corresponding areas. That is, if it were found that inhabitants of multi-family housing drive less than occupants of single-family housing, this would not necessarily imply that movement of someone from single-family to multi-family housing would alter at all their transportation habits.

Discussion: Material Durability and Material Selection

Selecting the most environmentally preferable materials is a complicated matter, with many aspects to consider and a constantly increasing range of products on the market for many components of a home. However, the exploratory results examined above indicate that a high potential exists to reduce both waste and overall environmental impact through the careful consideration of materials. While materials are shown here to be a less impacting aspect of the home life than energy use, as energy efficiency increases, materials are likely to become of proportionately greater importance. Indeed, in the results shown here for such scenarios as the *Green Certification Homes*, the materials show a proportionally larger percent of impact than for the *Standard Homes*.

Identification of the relative preference of materials in a given category and the conditions under which each is preferable is, however, a very large task and well beyond the scope of the present analysis. Nevertheless, several interesting trends emerge from the information that has been examined here. It appears that, at least in the case of the *Standard Home*, a relatively small number of materials and home components provide the majority of the material-related impact. For example, with the impact categories of *Climate Change*, human health and *Ecosystem* quality, five or less building components represent more than half (and in the case of *Climate Change* as much as 80%) of the total material impact of the home. Those components that appear to be most prominent for environmental impact include the roofing (asphalt shingle), flooring (carpet), insulation (fiberglass), wallboard, and foundation. As is seen in the case of the *Ecosystem* quality impact of electrical components, it is possible that a component that may have relatively small impact in some categories can have a highly significant impact in others. It is therefore important to consider a wide range of environmental information when selecting material components.

It should be recognized that the materials chosen for representation in the *Standard Home* may bias the present analysis toward or away from an emphasis on certain components. For example, in the results of the *Standard Home*, the wall framing (softwood lumber) shows only a moderate contribution to the environmental impact (3.5% of the total material-related *Climate Change* impact, although 11% for human health). However, in the case that the same component is made of other materials, the environmental impact may be more significant.

While the present results clearly indicate a high potential benefit for carefully choosing building materials, they also suggest that there are several complicated issues that must be considered in making a good material selection. These include not only the environmental impact of producing each alternative, but also the durability/longevity of the material, the associated transportation impacts, and the impacts incurred during use of the material and occupancy of the home and in managing the end-of-life of the material.

As is shown for several example materials, the impact of material production should be considered in the context of the durability of the material or, perhaps more properly, the expected longevity of the material. If substantial differences exist in the longevity, it is of almost no use to compare information on the basis of an amount of material (e.g., mass, volume, area) alone. Although it is useful to consider the durability of materials, it is important not to overemphasize the potential for a material to remain in service longer than it is actually likely to. Materials reaching the end of their useful service life is just one among many reasons they may be replaced and for some building components, aesthetic or other reasons may be an important limiting factor to how long materials are likely to be retained. While an attempt has been made here to reflect the multi-component nature of material replacement, this is clearly an area where further research is needed to support good life-cycle based decisions regarding materials.

While transportation is a relatively insubstantial contributor (less than 10% of the total) to the life cycle impact for most environmental impact categories for most of the materials examined in the *Standard Home*, there are several cases where transportation is a significant factor (sand, gravel and to a lesser extent wood), as well as several environmental impact categories, where the contribution of transportation is more pronounced for a larger number of materials (respiratory effects, ozone depletion and photochemical oxidation). This suggests that the influence of transportation cannot be disregarded and considerations of sourcing distance must be taken into account, especially for those materials present in the home at higher masses.

The results shown here indicate that end-of-life management is also a significant aspect that must be considered in selecting materials. The following section discusses specifically the case of material reuse, which is considered here a form of waste prevention rather than waste management. In addition to reuse, options of landfilling, incineration and recycling must also be considered. For many materials, the results show that the lifetime environmental impact associated with the material can vary by 25% or more depending on the end-of-life management route that it is likely to undergo. While this information might be used by waste managers to optimize systems for waste sorting and treatment, it can also be useful for those managing building design, construction and material selection, as these choices will determine what materials will need to be handled at the end-of-life stage. It should also be noted that many of the materials being chosen today will not be sent to end-of-life management for several decades and the treatment routes for some materials may differ in the future from the present context. This adds additional uncertainty to the end-of-life component of the life cycle.

An additional stage of the life cycle, and potentially the most important, that should be considered in making material selection is the usage of the product and home. While some building materials may have a direct environmental impact during their lifetime, such as lighting or appliances, it may be most important to consider the potential influence of those materials that impact the thermal efficiency of the home. As shown in the results for the *Standard Home*, the heating and cooling energy of a typical home produces an environmental impact several-fold larger than the materials used to build and maintain it. There is therefore a potential that improvements or impairments in building energy efficiency may surpass gains or losses in the materially-related environmental impacts. The *Insulated Concrete Forms* scenario provides a convenient example of this, where a net *Climate Change* benefit is seen over the building's life even though the material-related impact is increased (note that not all environmental indicators show an improvement for this scenario, see Figure 67). It is therefore recommended that for those building components affecting the building energy efficiency, a determination of environmental preference never be attempted without also considering the impact during the use of the building.

Just as the longevity of materials is noted above as an important consideration, in cases where building energy is affected, the building lifetime also becomes an important factor. In the case of a short-lived home, the *Insulating Concrete Forms* scenario shows significantly worse performance, while in the case of a long-lived home, its performance is much better. Because a large portion of the impact of the home is linked to its annual occupation (energy use and replacement materials combine for more than 90% of total impact), instances where the lifetime of the home influences key conclusions have been found to be relatively scarce despite its strong influence on the total life cycle impact of a given home.

In the case of the *Durable Roofing, Flooring and Siding* scenario, several examples are provided of material substitution. These examples indicate that there is a very high potential to decrease both waste generation and the material-related impacts of homes through well-informed material selection. For many environmental impact categories, these material substitutions show a large benefit, in many cases decreasing the environmental impact of a material by more than half. However, for many other impact categories some of the material alternatives show a substantial increase in environmental impact associated with that building component (in many cases more than a 400% increase). The cases of ceramic tile and steel roofing show a large number of such conflicting results, while wood flooring shows very few. The use of end-point indicators presents a potential to resolve some such conflicts. For example, fiber-cement siding shows an increased impact for the ozone depletion indicator. It is very rare that when evaluating human health outcomes in LCA that this impact category is a large contributor in comparison to respiratory effects or toxic chemical impacts. Indeed, the human health endpoint indicator shows a net benefit for fiber cement siding, despite a greater impact for ozone depletion. However, it remains possible that the various endpoint indicators (e.g., human health, *Ecosystem* quality) will still be in conflict and so it is not possible to ensure a clear answer to such questions in all cases.

While the above information provides guidelines for considering material selection, it is not possible to definitively recommend materials based on the assessment made here. Rather, a comprehensive approach is needed to evaluate the material options for various building components. It is possible based on the results obtained here to provide some recommendations for making good material selection choices. The key principle is that *the full life cycle of the material must be considered*, including production, transportation, use and disposal. The expected longevity of the material must be accounted for. In cases where the material affects building energy use, the energy use of the building must be included in the assessment. A valuable framework for comparing materials is provided by the guidelines in the ISO 14040/14044 standards dealing with comparative assertions. Ideally, information would be available following those guidelines and considering each of the reasonable alternatives for a given component of the home.

The current state of available information makes decision-making in this area, even for knowledgeable experts, very difficult. As is shown in Appendix 13, the availability of life cycle inventory information on building components is limited and much of the best information is in proprietary databases, such as the Ecoinvent database that has been used extensively here. The data that is available is likely to have some questionable aspects regarding its temporal, geographic or technological relevance to the context in question and it is very likely to be intended to represent generic product categories rather than specific products. There has been an effort on the part of many product producers to provide their own product information in the form of an Environmental Product Declaration (EPD). However, where these exist it can be difficult to judge consistency between EPDs from various companies (or even within companies) and there are few, if any, categories where such information is available for even a majority of the options on the market.

Discussion: Material Salvage and Reuse

Material salvage and reuse show a potential for substantially reducing the materially-related impact of the Oregon home population. However, because these practices impact only material impact and benefit, their overall influence on the life cycle impact of Oregon homes is somewhat limited. As is seen in Figure 55 and Figure 59, the benefit in some impact categories of material use is quite substantial, reaching into the range of a 40% improvement in the total lifecycle impact. In several other environmental impact categories, the benefit is smaller, being in the range of 10% of the total life cycle impact. Modeling of the *Deconstruction, Restoration and Reuse (High)* assumptions within the statewide population (see Figure 59) indicate that benefits similar to those seen at the level of single-home *Deconstruction, Restoration and Reuse (High)* scenario might be obtained.

For each of the material reuse scenarios, the same home energy use is assumed, so there is no net impact or benefit shown for these scenarios in home energy use. The benefits shown in all environmental impact categories are due to changes in the production and end-of-life handling of materials, and are mitigated somewhat by changes in construction and transportation activities. In addition, the low benefit in some impact categories is in part caused by a net environmental *impact* from reuse in some material categories resulting from a switch away from other end-of-life treatments, especially waste-to-energy.

In addition to identifying which materials are of most benefit to recover and reuse from homes, it is also important to consider which materials, if any, are unwise to reuse. As is described above, converting wood to energy can be preferable in some impact categories as compared to reusing it within another home. This finding is somewhat dependent on the methods of accounting for *Climate Change* impact within the project and warrants further consideration and validation with a specific focus on wood. The life cycle inventory data used here indicate a benefit for incineration of wood in the range of 0.9 $KgCO_2e$ per Kg of wood. For wood reuse to be favorable, an indirect impact of wood use, such as from effects of land use, of at least this magnitude would be needed. The EPA has estimated such a benefit to be in the range of 2 $KgCO_2e$ per Kg of wood.

Although not represented by the present methodology, there are some other considerations that should be made regarding reuse of materials. One is their effect on the durability of both the materials that are being reused, as well as other components of the home that might be affected by the deterioration of those components or by the process of their replacement. For example, if reused roofing is more likely to allow water infiltration, this brings not only a need to replace the roof earlier than a new roofing material, but also brings potential for replacing other materials impacted by the damage. In the present approach, consideration has not been given to a reduced durability of reused materials. In some cases, certain materials have been assumed to not be reused in the present assessment due to such issues. However, it is unclear to what extent the lifetime of those materials that are reused might differ from virgin materials.

Further, due to diminished structural integrity, some materials many not be permitted for reuse as structural components of homes. For instance, salvaged lumber may not pass ASTM standards for use as loading-bearing elements. In this study, it is assumed that there are no such limits, but this may cause an overestimate of, for instance, the amount of wood that can be reused.

Further, a building's energy efficiency must be considered when using reclaiming materials. As seen throughout the results of this project, in a climate like Oregon's, it is the home energy use rather than materials that are the most substantial aspect of the environmental impact. If constructing with salvaged materials results in a substantially decreased energy performance of a home, an overall environmental benefit—at least with respect to energy consumption and global warming potential—is unlikely. For example, the reuse of salvaged single pane windows from older homes, which are likely to have much worse energy performance than even the minimal new production window, not to mention high efficiency windows, is likely to be unadvisable. Reuse of any components that effect building envelope and energy use should be done with caution and with assurance that building energy efficiency is not impaired.

Finally, it is important to consider potential limits of supply and demand and the relationship of this issue with material transportation. The *Deconstruction, Restoration and Reuse (High)* scenario considered here assumes a very high rate of material reuse (67% for all materials types that are assumed to generally be reusable). In a case of a growing housing stock, new construction will eventually exceed the number of older homes and will probably be larger in size than houses being disassembled. It may therefore be unlikely that an adequate supply of salvaged materials will be available for new construction of homes using this rate of salvaged material from solely within Oregon. In fact, import to the state of building supplies from elsewhere could be needed to fulfill the demand. In such cases, the discussion above regarding the relationship of transportation and material reuse benefits becomes relevant and may provide additional limits on which materials are sensible to reuse, at least within a very aggressive program to promote reuse.

It is shown here that several materials, such as sand and gravel, are unwise to transport more than perhaps an additional 100 km to allow reuse. Many other materials may allow transport of an additional 1000 km or more by truck and still provide an environmental benefit, but as such distances, the added transport will have significantly eroded the amount of environmental benefit of the reuse. If reuse is to be promoted, it is therefore important to set up an aggressive system where materials can be stored and sourced locally, rather than necessitating transportation from across the state or beyond. The information provided here can be referred to assess the relative importance of keeping various materials local in their reuse.

It is clear from the *Waste Generation* results of the material reuse scenarios that this is among the best performing set of practices for achieving waste prevention. However, there are risks that if not done following careful guidelines, material reuse could provide little environmental benefit, or even an environmental impact in cases of long transport or diminished energy efficiency. As more builders participate in material reuse, transportation distances are likely to be decreased and guidelines regarding which materials are most sensible to reuse and in what applications can be more easily disseminated. The materials in this report provide some initial guidance for promoting a program of material reuse within the state:

- Identify the most essential materials to recover and reuse from existing homes. The results here indicate that metal components, followed by some plastics and fiberglass insulation are among materials with high reuse benefit. Not all possible materials have been considered here within the *Standard Homes* developed for this project. The information here could therefore be built on to create a complete set of guidance for material recovery specialists.
- Identify materials that it is unwise to reuse, or applications in which it is unwise to reuse certain materials. Examples may be older and inefficient building envelope components, heating and cooling systems and lighting, materials that have a preferred alternative fate

than reuse, or materials for which there is a toxic health concern (lead paint, asbestos, etc.). Regarding the reuse of wood, additional verification might be sought of the relative benefit of reuse and energy recovery.

- Establish reuse networks and infrastructure that ensure as efficient transportation system for reused materials as possible. Use and/or build upon the information presented here to establish guidelines regarding how far certain material should be shipped.

Discussion: Wall Framing

In the first phase of the project, several of the wall framing options show preferable performance in several impact categories, including *Climate Change*, even though the assessment calls into question whether they are truly waste preventing. For example, the *ICF Home* and *Strawbale Home* were found to be potentially more waste generating than the *Medium Standard Home.* In addition, the juxtaposition of the waste prevention aspect and other environmental impacts of wall framing options raises an important question of whether an emphasis on waste prevention is wise within an area with such a potentially strong influence on other aspects of environmental impact.

The results of this second phase add several additional wall framing options and confirm many of the findings of the first phase. Within the numerous wall framing options considered, there is not a strong relationship between the *Waste Generation* impact and other categories of environmental impact. In contrast, some of the wall framing options that perform best in *Climate Change,* for example, are in fact waste generating options rather than waste preventing options. Because of the potential importance of building envelope in determining the energy efficiency of homes, it is suggested that wall framing options be selected based on their overall environmental profile and not necessarily with regard to whether they prevent or generate waste. The Staggered Stud Home does provide one option within the study that prevents waste and offers a significant advantage in energy efficiency.

In comparing all environmental impacts among framing options, the majority of indicators remain within a close margin of the *Medium Standard Home* (within 10 to 20%) for most practices. However, there are some notable exceptions. The *ICF Home* shows substantially higher (double or more) impact in the toxicity categories, in addition to somewhat higher (a 50% or less increase) in several other categories. The *Strawbale Home* practice shows a much higher impact for *Ecosystem Quality (endpoint)* (nearly triple the *Standard Home*).

Discussion: Combined Waste Prevention Practices

While the first phase of the project has considered the environmental benefit of a variety of waste prevention practices in isolation, it is important to recognize that many of these practices are not mutually exclusive and may be implemented in combination. Among the scenarios evaluated in the second phase was therefore a *Waste Prevention Home*, incorporating a wide range of the waste prevention practices.

Green Certified Home with Passive Solar

In addition to modeling a Green Certified home the project team examined the same Green Certified home with some extra added passive solar features was also examined. What the two models revealed was that there was a limited difference between the two homes, well within the margin of error of the energy modeling and LCA modeling software. These results, however, are misleading as they do not fairly characterize the full benefits of passive solar home design.

The three fundamental aspects of passive solar design are load reduction, energy conservation and utilization of direct and indirect solar heat gain. Sun tempered design features are a category of design features that utilize solar energy but without the use of added thermal mass. A full passive solar house includes the use of thermal mass to store heat to warm the house at a later time. When all these design techniques are used in combination, and according to the specific site solar resource, a home can be designed with such low load demands that remaining energy loads can be effectively met with passive solar techniques.

The Green Certified home presented in the study fully incorporates load reduction and energy conservation design principles as well as utilizing some direct and indirect solar energy through sun tempering design. The project team also modeled the same small modifications on the examined Green Certified (and sun tempered) home with a home utilizing the extra additional passive solar feature of thermal mass. Specifically, the design for the passive solar home included were to vary varying the solar heat gain coefficient on the windows, adding some thermal mass to the floor of the living room and kitchen, increasing the south facing glazing and including additional thermal mass in an internal wall. While it is the ultimate goal of a passive solar design, the model examined did not completely eliminate heating loads making it necessary to have supplemental heat.

While the results of the passive solar home show the design medications se actions provided slight energy use and life cycle benefits in the sunnier central Oregon climate, the fact that the home was built to such high efficiency standards to begin with meant that the differential of these added actions was very small. In the course of analysis it became clear that it was not a fair comparison to examine the benefits of passive solar home design by examining the results of the Green Certified home alongside the Green Certified home with passive solar because the Green Certified home already incorporated so much of the passive solar design principles.

To illustrate this, consider the passive solar design principle of 'cutting losses.' Essentially, a passive solar home should be well sealed and well insulated, reducing heat loss and gain. Approaches that contribute to minimizing heating and cooling loads include using advanced framing guidelines, properly installing insulation, high insulation levels, reducing duct losses, and tightening the building envelope. All of these features were incorporated into the Green Certified home.

When considering the benefits of a more comprehensive inclusion of direct and indirect solar gain utilization, it becomes apparent that specific details of siting are important. As this was not a factor that can be universally applied, as compared to increased insulation, staggered stud walls or duct placement inside conditioned space (for example) the study focuses on more universally applicable building techniques and does not attempt to examine the nuances of passive solar siting issues.

In conclusion, the project team found that the Green Certified home provided an optimal combination of design features aimed to significantly reduce the life cycle of a residential home as compared to the modeled *Standard Home*. The team determined that there are significant benefits associated with passive solar home design, however, this study did not isolate those benefits to allow for a fair comparison to a *Standard Home*.

A comparison to the *Waste Prevention Home* to any one of the practices alone clearly demonstrates the added benefit of applying a large number of waste prevention practices at once. Although the benefit of the Waste Prevention Home is contributed most prominently by its smaller size, the remaining practices that are incorporated combine to provide a very significant level of added environmental benefit. Clearly, incorporation of this range of building practices into new—and, to the extent feasible, existing—homes would provide important environmental benefits for the state of Oregon's housing stock.

Because many of these building practices can be implemented in combination, it is suggested that numerous waste reducing building practices be promoted simultaneously. Possible means for promoting these practices include creation of model homes, and creation of educational materials or programs for builders.

VI. Conclusions

The ultimate objective of this work is to assist the Oregon DEQ and interested parties in better understanding a spectrum of environmental benefit or impact associated with a wide variety of waste prevention practices applicable to residential buildings. The use of LCA provides a comprehensive view of the environmental implications of more than 30 building-related practices or activities, in addition to several benchmarking activities. In this second phase of the project, specific questions focused on several key topics are explored and resolved. The major conclusions of the project are summarized as follows:

Home size

Overview:

On a per-home basis, constructing smaller residences is among the most influential options for preventing waste and reducing a variety of environmental impacts, including Climate Change. Increased density and fewer home possessions were not explicitly included in the scope of this study and could further contribute to the benefit of small homes. A very clear result is that reducing home size is among the best tier of options for reducing waste generation in the Oregon housing sector, while simultaneously achieving a large environmental benefit across many categories of impact.

Additional Conclusions:

- There is a strong decline in environmental impact as home size decreases. Compared to the medium size (2262sqft) class considered, the extra-small (1149sqft) class shows a reduction in most environmental impact categories of nearly 40%. This implies both that even modest decreases in home size are likely to produce important environmental outcomes and also that the benefits of this practice will not diminish as further reductions in house size are achieved.
- If the change in *Average Home* size were shifted from a 1% annual growth to a 2% annual decrease, the cumulative impact over the entire stock of homes constructed before 2030 would be nearly 10%, depending on the category of impact considered.
- Considering more dramatic changes, even if unrealistic, shows that an immediate switch to constructing only homes in the "extra small category" (less than 1450 square feet) would result

in a decrease of 20% in cumulative *Climate Change* impact (including both the existing and new housing stock).

- Families who choose or require more living space may mitigate a larger home's impact by adding green building practices. The relationship between home size and environmental impacts suggests that larger homes be held to a more stringent building standard.[46] The larger the home, the more absolute benefit of each percentage gain in energy efficiency or in material impact. A system like this could be considered in future building code revisions or Oregon's new Reach Code, which will become a statewide green building code. Among those practices examined here, obtaining green certification, following a combined set of waste prevention practices and occupying multi-family buildings are among those that could be implemented effectively with larger home size.
- Reduction in home size may be a more effective impact reduction measure than achieving "green certification." Some certification programs include size as a criteria, such as LEED for Homes and Earth Advantage. Programs that do not consider home size should take this aspect into account. A review of the most prominent rating systems used statewide may be warranted to ensure size is taken into account adequately.
- All homes modeled in this study were assumed to provide housing for the average Oregon household of 2.5 people. Adding more people to a home may increase gross emissions of a housing unit (e.g. more electricity and hot water use) but will decrease the per person emissions. A square foot per person range can be helpful in right-sizing a home.[47] Incentive programs could be envisioned to promote smaller homes.
- If "larger" homes are still desired, one could consider designing an Accessory Dwelling Unit (ADU) directly into the new home. Providing flexibility and adaptability for different family configurations over time can provide more density of people within the home, thereby reducing the overall impacts of the home on a per person basis. ADU spaces can also act as office spaces to allow telecommuting and potentially reduce transportation impacts of work commuting. Finally, ADU can be income generating rentals which may be an attractive option to homebuyers in today's market.[48]
- Finally, it should be emphasized that despite its importance, size is only one of several important determinants of a home's environmental performance. While it may be questionable

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[46] For example, the City of Boulder, CO has a tiered building code based on home size.

[47] McLennan (2009) suggests example target sizes for homes intended to house a given number of people. Such targets could be adopted by certification programs, promoted through outreach activities or incentivized within building programs.

[48] For remodelers, adding an internal ADU to existing homes could be an excellent option with high environmental benefits although it was not directly modeled in this study. Basically, internal ADU's that do not expand the conditioned space of the home can achieve the "small home" benefits and the "multifamily" benefits of shared walls and materials.

whether it is possible for a 4,000 square foot home housing four people to be "environmentally friendly," there are certainly opportunities for many small residences to be made more "environmentally friendly," such as through updating energy efficiency of their building envelope.

Multi-family Homes

Overview:

In comparison to single-family homes of similar sizes, multi-family homes reduce environmental impact by as much as 30%, depending on the category of impact. Multi-family housing appears as effective in reducing environmental impacts as achieving "green certification" or qualifying as an "Oregon High Performance Shell Home" within a single-family home of the same size. As with smaller homes, it has a large benefit in both waste prevention and also in a wide variety of environmental impact categories. Some potential benefits of multi-family homes, such, such as higher potential for use of public transportation and greater sharing of various types of infrastructure have not been evaluated here and could lead to further benefits.

Additional Conclusions:

- Although the impact of an increase in multi-family housing is limited to new housing stock, an annual increase in the percent of new construction that is multi-family housing stock of 1% achieves approximately a 3% improvement in the total cumulative carbon footprint of the entire housing stock. An immediate switch to only multi-family housing for all new construction would result in a decrease of total carbon footprint of the housing stock built before 2030 (including that already built) of more than 15%.
- The small and multi-family concepts have been successfully combined in many "co-housing communities" that have been established in various cities throughout the US. These communities can realize the environmental benefits of smaller units, shared walls, and common space. This may also facilitate consuming less material due to space limitations and the community benefits of sharing things like lawnmowers, tools, and even cars. For further information, see DEQ's supplemental analysis on the impacts of the home's possessions in the Housing Size section above.

Material Durability and Selection

Overview:

A relatively small number of home components (e.g., roofing, flooring, lumber, appliances, drywall and insulation) are responsible for a large proportion of the environmental impact of homes. This indicates that a focused effort on key building components may allow a large amount of benefit to be gained from material selection with reasonable effort. However, experimentation with choice of several materials based on a seemingly preferable attribute such as durability reveals that identifying environmentally preferable materials requires a sophisticated life cycle approach and understanding of key information, such as the likely replacement time for components and consideration of any impact they may have on home energy efficiency.

Additional Conclusions:

- When considering environmental performance comparisons of materials, the entire lifecycle of materials must be considered. This includes not only production, but also transportation, maintenance and disposal of the materials. In addition, the expected longevity of the material must be considered.
- Further, for any building component potentially affecting the energy efficiency of the home, the influence on the use-phase of the home must be considered. Even relative small changes to the thermal efficiency of the home may overshadow other material-related impacts.
- When considering material changes, it is very important to consider a wide variety of environmental impact categories, as it is not uncommon for these to be in conflict with each other when materials are compared. Although the causes of conflicting findings should be carefully considered and validated, it may not be possible to arrive at an option that is universally the best and in such cases, a full explanation of a materials decision should be disclosed.
- The overall state of availability of information to support decision-making regarding material selection is fairly weak, with data that does exist often being somewhat inconsistent or lacking

specificity. Substantial efforts are needed to both produce additional data regarding the life cycle of building materials and to also organize this information so that it is more readily accessible for decision makers.

- Although the informational challenges are significant, the potential waste prevention and environmental benefits from material selection appear substantial in comparison to many other waste practices evaluated.
- With regard to material selection for durability, which was evaluated here through the implementation of several example material substitutions, the results do not indicate a consistent environmental benefit of selecting for this attribute and indicate a necessity to consider each material substitution on its total lifecycle performance rather than on the basis of an individual product attribute, which it appears can lead to benefits in some cases, but potentially to net impacts in others.

Waste Prevention

Overview:

A combination of waste prevention practices is shown here to result in reducing not only waste generation, but also a wide variety of environmental impacts. While most of the benefit shown could be attributed to the modeled reduction in home size, the remainder are due to a variety of other practices that were implemented in the design, each of which on its own might produce only a modest benefit, but as a package provide a reasonably large impact reduction.

Additional Conclusions:

- Among the best performing practices in waste prevention were those representing smaller homes and material reuse, with several others showing substantial but lesser benefits.
- Some practices evaluated in the first and second phase of the project were shown to be net waste producers, yet had environmental benefits in many other categories of impact. In most cases, these were wall assembly practices, such as insulated concrete forms or double walls, which use more mass of material, yet save energy in comparison to the standard "code" home.
- Similarly, some practices were successful in reducing waste, such as the promotion of reuse, but had comparatively minor benefits in other areas of environmental impact.
- Compared to the benefits of individual practices evaluated in the first phase of the project, implementing many waste prevention practices at once has a large benefit.
- While most of the benefit in the combined waste prevention scenario is from the decrease in home size, the remaining practices combine to provide a 20% reduction in *Climate Change* compared to the *Standard Extra-small Home*.
- Most of the environmental benefit supplied from implementing the waste prevention practices are due to reductions in energy use, although there are also important savings in material-related impact.

Material Reuse

Overview:

Regarding Climate Change, material reuse shows only a moderate influence over a home's life cycle environment impact, even in a scenario of high reuse where approximately 2/3 of the home's materials are reused. Explanations for this include that many materials are being handled in a way at end of life that already achieves at least a portion of the benefit that would be obtained by reuse and that re-use does not directly address the greatest driver of Climate Change impact, which is the home's energy use. It is therefore confined to acting only on that portion of the home impact attributable to the materials. It might therefore be considered that material reuse could become of increased relative importance in the future, as it is anticipated that the impact of home energy use will decline over time, resulting in a greater contribution by materials. For several other environmental impact categories, a benefit is achieved through material reuse, with a reduction from the standard scenario of as much as nearly 30% for some categories, depending on the amount and type of material reused.

Additional Conclusions:

- For some materials, it is possible to transport materials at least 100 km (62 miles) and for many materials, transport of 1000 km (620 miles) or more is feasible without completely removing the environmental benefit. There are some significant exceptions, such as sand and gravel that should not be transported more than tens of km. Acceptable transportation distances can change dramatically depending on the mode of transport, which makes generalizing results very difficult.
- The materials in the *Standard Home* that show the greatest environmental benefit to reuse include metal products, insulation, and plastic products. If considering the EPA's approach to considering land use of forestry land use, wood may also be among the most beneficial materials for which to avoid new virgin production through reuse.
- Based on waste generation, since remodeling and repairs creates 45% of the lifetime waste generated, it makes sense to salvage materials from the remodeling sector and to use salvaged materials primarily in the remodeling sector due to the lack of adequate supply for larger projects. While there are many challenges to material reuse which include supply, quality, cost, prep time, and hazardous material, reuse still represents an excellent way to reduce material-related impacts, incorporate a story connected to reused materials in a home, and encourage a thriving culture of conservation and not consumption.

Wall Framing

Overview:

There is not a good correlation between waste prevention and other environmental indicators in wall framing; waste prevention may be a poor consideration for selecting among wall framing options. However, several of the wall options evaluated showed substantial improvements in total life cycle environmental performance of the home. It is therefore important to make a complete evaluation of wall framing options and to promote those options that show the greatest total benefit. Results here indicate that, while energy efficiency rather than waste prevention is likely to be a driving factor, a more focused life cycle assessment in this area is warranted to fully examine the topic.

Additional Conclusions:

- Several of the wall framing options (including the *ICF Home, SIP Home, Strawbale Home, and Double Wall Home)* generate a net increase of waste. However, many of these wall framing options also show benefits in *Climate Change* impact and other environmental impact categories.
- For the *ICF Home* and the *Strawbale Home*, some other impact categories show a large increase in impact. This should be further evaluated before promoting either of these practices.
- Besides advanced framing, staggered stud framing was the only framing practice that prevented waste. Only a small amount of waste was prevented by using slightly less wood. By staggering the studs the wall cavity was thicker and additional insulation was added to the home. Modeling results indicate that despite the impacts of additional insulation, the staggered stud home still had *Climate Change* benefits over the life of the home by creating better thermal efficiency in the wall.

Other Key Findings

- The existing housing stock will play a major role in contributing to *Climate Change* over the next 20 years. Modeling shows the existing stock will contribute as much total impact over the remainder of its life as the total of all homes built in the coming 20 years. Since the use phase of a building contributes to 80% of the lifecycle GHG impacts, the efficiency of the existing housing stock is critically important for short-term *Climate Change* mitigation strategies.
- Our optimized recovery benchmark show that even if we were able to recycle or burn for energy all of the waste produced over the lifecycle of a home, the benefits would equate to only 37% recovery of the *Climate Change* impact of producing these materials (5% in comparison to the impact of the home's total life cycle). Programs that only pursue recycling will have much smaller environmental impact reductions than programs that pursue waste prevention options.

The results indicate that among the practices evaluated the most beneficial action for overall improvement in environmental performance of the housing stock is to reverse the past trend toward increasing size of homes. Similarly, multi-family housing presents a substantial level of environmental benefit and could be similarly promoted.

In addition, promotion and adoption of a wide variety of practices that prevent waste generation, as exemplified in the example *Waste Prevention Home* examined here show a large potential to reduce not only waste generation, but also a wide range of environmental impacts.

Beyond preventing the use of materials, it is possible to address the environmental impact of those materials that *are* used by selecting materials for environmental performance and by reusing materials. While material substitution may be logistically simple in many cases, material *selection* is a very complicated manner. Better data and a thorough analysis is needed in each case to determine material preference. The LCA framework contained in the ISO standards and employed here provides a roadmap for handling material selection. The case of wall framing, examined in detail here, is shown to be an issue for which waste prevention is not a good guide for selecting the best environmental performing options. Similarly, selecting for a feature such as durability is shown to not guarantee a high overall environmental performance.

Material reuse presents logistical challenges and ensuring a benefit for such programs requires ensuring that sufficient scale is achieved locally to avoid long transportation distances of materials. Guidelines about transport of reused materials could be set based on material type. The results here present some initial guidance upon which material reuse programs could be further developed and more complete guidance could be produced with targeted focus on this area.

This study presents a novel approach to understanding the lifecycle environmental impacts of a Standard newly constructed home in Oregon. The waste prevention practices evaluated here represent a wide range of potential environmental benefits and in a few cases show potential for net environmental impact, depending on the specifics of implementation. Original and replacement material production, end-of-life and transportation contributes approximately 15% to the lifecycle *Climate Change* impacts to the home while the occupancy phase of the home contributes approximately 85%. Material impacts are relatively more important in several of the other environmental impact categories examined. As residential buildings become more efficient the relative impact of materials will get larger. Waste prevention practices and the continuously growing field of appropriate material selection represent substantial opportunities to reduce a home's lifecycle environmental impacts.

Achieving Oregon's Greenhouse Gas Reduction Goals for the Residential Housing Sector [Supplemental Analysis Contributed by The Oregon DEQ]

In 2007, Oregon adopted Greenhouse Gas (GHG) reduction goals (HB 3543) . The goals are to: arrest the growth of Oregon's GHG emissions and begin to reduce greenhouse gas emissions by 2010; achieve GHG levels that are 10 percent below 1990 levels by 2020; and achieve GHG levels that are at least 75 percent below 1990 levels by 2050.

Oregon's current GHG emissions inventory reports emissions from residential direct combustion (such as natural gas use for heating) and residential electricity consumption to represent impacts of the residential housing stock. The lifecycle GHG impact of producing, using, and disposing of residential building materials is not explicitly included in the current inventory. Instead, the material-related impacts are divided among the industrial, transportation, and waste sectors. Additionally, the impacts of consuming building materials that were not produced in Oregon are not included in the inventory at all (except waste-related emissions), since their production would not be captured in the geographic-based State inventory. Either way, as the main body of this research has shown, the addition of the material-related impacts would, on average, increase the residential GHG impacts of the residential housing sector by approximately 15%.

If Oregon's GHG reduction goals are considered on a per-person basis, one can think of every Oregonian as having a "carbon budget". Housing can be thought of as a single line item in the larger budget. If every line item is reduced by an equal percentage, then the housing portion of an Oregonian's carbon budget would need to decrease 50% and 90% to meet the State's 2020 and 2050 GHG reduction goals, respectively, based on projected population growth. The percent reduction targets are expressed relative to Oregon's 2005 residential GHG emissions, which is the most recent data available. The actual reductions needed may be smaller or larger depending on how residential energy consumption trended between 2005 and today.

The main body of this research shows that reducing a newly constructed home's size from 2262ft2 to 1149ft2 (49% reduction) reduces the lifecycle GHG impacts by approximately 40% over a 70 year lifecycle. The "waste prevention home" (1149ft2) reduces lifecycle GHG impacts by 50% by implementing a number of other waste prevention practices in addition to being a smaller home. For new construction, building a 1149ft2 home for the average Oregon family of 2.5 people achieves a 40% reduction per person (compared to the average newly constructed home size in Oregon today) and nearly achieves the 50% reduction goal for 2020. This information suggests that the size of newly constructed homes can play a significant role in decreasing the GHG impacts of the people living in that home. Additionally, reducing the size of a home is not a practice that requires any additional technologies or expenses. In fact, it will likely cost less money to build and maintain a smaller home.

Even if all newly constructed homes were built and operated to have zero GHG impacts between now and 2020, the State would still need to address energy use by the existing housing stock to meet its goals. This research did not reveal any material-selection (durability) or handling practices (reuse/deconstruction) that could even come close to achieving a 50% reduction in lifecycle GHG impacts of an existing home. One option, which was not specifically evaluated, is to add density (people) to the existing housing stock without expanding the conditioned space of the home. Remodelers could either reconfigure a home to fit more people or divide a larger home into smaller and separate dwellings, called Accessory Dwelling Units (ADU). Internal ADUs that do not expand the conditioned space of the home can add density and realize the environmental benefits of both small home living and multifamily living while adding flexibility for changing family needs and potential rental income to the homeowner. Adding an internal ADU could lead to substantial alterations of an existing home, which could also present an excellent opportunity to upgrade the energy efficiency of the home through air sealing, insulating, and upgrading to a more efficient HVAC system.

In order to achieve the state's 2050 goals Oregonians will need to reduce their housing carbon budget by approximately 90%. This is a significant task that will not only require more efficient homes, cleaner sources of energy, and behavior change of the occupants, but will also require taking a closer look at the embodied energy and greenhouse gas emissions of materials. Since the production and transportation of materials in the average newly constructed home in Oregon today account for approximately 15% of the lifecycle GHG emissions, a 90% reduction in total lifecycle GHG emissions will require that more attention be paid to the emissions associated with the lifecycle of materials. Especially as Oregonians make their homes more efficient, they may become more materially intensive to achieve that efficiency. Practices evaluated in this study, such as deconstruction and reuse, and material durability will become increasingly important as we strive for the 2050 goals. While there is no clear path for achieving 90% reduction in per-capita housing carbon budget, the Living Building Challenge, of the International Living Building Institute, offers one of the most comprehensive approaches to building standards that could help the State achieve its 2050 GHG reduction goals for the residential buildings sector.

In the last few years, the issue of house size – and the benefits of smaller homes – has received increased attention in both the popular and professional literature. What has been lacking has been good, science-based analysis of potential house sizes that are consistent with a 'carbon budget'. A number of confounding factors make it challenging to estimate or recommend a budget expressed on the basis of square feet per person. However, there may be significant value in doing so, as it would ground the discussion of house size in the context of a clear vision of sustainability (at least from the perspective of carbon). Rather than talking in incremental terms ("smaller houses are less bad"), a recommended value (or range) expressed on the basis of square feet per person tied to a carbon budget would provide for a clear target to aim for and a positive, achievable standard of sustainability. It could also help to illustrate some of the trade-offs between efficiency and size, and how the current standard of carbon neutrality (applied only to consumptive energy use) is incomplete.

Appendices

Appendix 1: Oregon Home Builders Association Modeling Methodology

The basis for the LCA baseline home is a design from a concurrent Oregon Home Builders Association study. To capitalize on the previously designed home, the partners opted to adjust the OHBA model home to better meet the assumptions of this study. The resulting baseline home scenario is intended to represent a typical, not optimal, new construction home in Oregon. There are myriad possible formats for such a typical baseline home. While it is acknowledged that alternative baseline layouts could slightly modify the results of the present study, it is not possible to quantify the magnitude of this influence on the study. It is assumed that the conclusions of the study are not sensitive to layout variations within the range of typical homes.

The Size

The first change was to enlarge the model home's square footage to the current 2,262 square feet. This size more accurately represents the median home size for new construction within the state. While adjusting the size, the group allowed the original width of the home to remain intact. The width of the model is 35', and was used to denote an important design hurtle within multistory buildings. The 2008 Oregon Residential Specialty Code details prescriptive braced wall requirements, sheer walls, for the predominant seismic zone within Oregon. In this code provision, the spacing of braced wall lines must be 35 feet on center for all homes. The provision does allow for an exemption for one- and two-story homes to extend those requirements to 50 feet. While the model could have been designed with that exception, it was important to highlight this challenge since homes may be more than two stories.

Braced wall lines are a path of shear panels, or a continuously sheathed diaphragm that has minimal offsets to create a structure that can resist lateral and seismic loads. Structures that do not account for the required prevision will require additional materials. If the model were increased to 36 feet, to stay on module, an additional braced wall line would have been needed to comply with the sheer design requirements. If the structure required an interior braced wall line, that wall would need to be supported by a concrete foundation or doubled floor joists. If one were to use the exception and extend the spacing to 50 feet on center, the model would still be required to accommodate the required sheer amount within the allotted walls. This option may be less desirable if a building is designed with extensive glazing to accentuate a natural feature or view.

A narrower product was designed also to better meet the land use laws and city zoning requirements. When designing the model it was important to balance the dimensions to practical application. Oregon has a unique land use policy that limits sprawl. This policy leads to the predominant number of newly constructed homes to be built within the urban growth boundary. Of these homes, local zoning and economic factors often result in smaller lots and higher density.

The Shape

When designing the model it was important to keep the home simple but complex enough to simulate basic and middle scale homes. While the basic shape of the home is a rectangle, there are various indentions and bump-outs to offer visual changes. These offsets when practical continue the perimeter braced wall line. The ORSC specifies the offset of a braced wall line to 4' offsets and an 8' overall offset. It is important to note that additional material may have been needed to construct this home if those provisions were not observed during the design phase.

The Walls

The height of the model was determined by the framing stud. For this study a 92-5/8" stud was used for the wall framing. When coupled with a single sole plate and a double top plate, the overall wall height is approximately 8'-1 5/16". That is assuming the dimensional lumber's actual size is 1-9/16" X 5-9/16". When making this assumption, it was determined depending on moisture content. Dimensional lumber could vary approximately 1/8" since Oregon uses a large amount of green, non-dried lumber. It is important to note this trend may shift as the ORSC now requires the framing components to have moisture content below 19% prior to installation of interior finishes. There are various ways to achieve that benchmark, starting with a kiln dried product that may increase its market share.

For the baseline home, all interior and exterior walls have headers. As can happen in the field, similarly sized headers were used interchangeably within the home. This often happens with little or no regard to sizing to meet the design needs. Due to business practices, interior nonbearing headers are often removed. In this case, the group felt it was important to rely on what is permitted within the code language since builders could still include interior nonbearing headers.

The Floor System

For the baseline model, a traditional post and beam system was used for the main level floor system. The group believed that this practice still held a large market share. While the market may be moving to dimensional or engineered lumber, the group felt that the post and beam should be used in the baseline with dimensional and engineered joists modeled in some of the methods.

An engineered sheeting product was chosen for the subflooring in the home. While there are homes being built with boards, the majority of homes use plywood sheeting.

The Process

Once the design criteria were established, the original OHBA home was redesigned using computer aided drafting and design software. In the software, 2D and 3D models of the baseline home were created. With these models, material takeoffs were extrapolated for the baseline home. Along with materials, wall details were exported to spreadsheet software to be incorporated into the energy modeling. This data included the wall lengths, heights, wall cavity volume, window and door surface area, framing volume, and the relative percentages of each component to the overall wall.

When looking at each individual measure, various resources were used. These resources included product installation and design material, building codes, industry standards, and best practices. When available, existing research was used as supportive material. It is important to note that material mass, spans, and characteristic can vary from that of this study depending on manufacture, species, moisture content, and installation technique.

Appendix 2: REM/RATE Energy Modeling Methodology

Operational energy use was modeled using the REM/Rate software tool. REM/Rate is published by Architectural Energy Corporation of Boulder, Colorado, and complies with Residential Energy Services Network (RESNET) protocols for modeling home energy ratings. It is used nationally to qualify homes for the ENERGY STAR® home program. Energy modeling seeks to predict energy use by calculating heat loss and gain through each building component, such as wall, floor, and roof assemblies, as well as windows. REM/Rate also incorporates heating and cooling system types and efficiencies along with lights and appliance use. Finally, active solar systems, such as solar water heaters and photovoltaic systems, can be included.

Predictive energy models will always be inaccurate to some degree. The biggest factor is occupant behavior, which includes temperature settings, hot water consumption, and usage of lights and appliance. A recent study of three modeling methodologies titled Energy Performance Score 2008 Pilot compared three modeling methodologies. While REM/Rate was not the most accurate overall, its accuracy in predicting energy use for recently-constructed homes was comparable to the other two methodologies.

Since the same model is used across all scenarios, any inaccuracies are consistent and should therefore not affect the relative ranking of the practices.

For this study, the OHBA model house was used as a baseline. The house was modeled as if built to the 2008 Oregon Residential Specialty Code with the following characteristics:

- Weather: Portland, Oregon
- Conditioned floor area: 2,262 sq. ft.
- Conditioned building volume: 20,358 cu. ft.
- Bedrooms: 3
- Bathrooms: 2
- Foundation: vented crawlspace
- Framed floors: R30
- Walls: R21, framing factor 26%
- Windows: typical double-glazed, low-e, vinyl frame, U-0.35, 374 square feet windows area. Windows oriented to minimize solar gain.
- Doors: 2.25-inch solid wood, R2.8
- Ceiling: R38

- Heating: 90% efficient gas furnace
- Duct leakage: RESNET/HERS default, all duct leakage outside the thermal envelope
- Water heating: 58% efficient gas storage tank
- Building Air Leakage: 6.5 ACH at 50 Pascals

Energy use for lights and appliances was determined by REM/Rate based on its database of information on the actual energy use by a wide variety of homes. The program matches each scenario to the information in its database to determine the most likely energy use for that scenario. It should be noted that differences in energy use are based on associations or correlations and not necessarily causal relationships.

Many of the LCA scenarios gained significant benefits from improvements in operational energy. These scenarios were modeled by making specific changes to the base case characteristics. Other scenarios did not have an energy use impact, so modeling was not performed.

1 Intermediate framing

While the base case home was designed to represent a traditional framing approach, many builders already incorporate framing practices that reduce framing members not strictly required for structural purposes. Much of this additional wood framing serves to support interior gypsum board, sometimes called “nailers”. Phase 1 evaluated several of these steps independently. Intermediate framing eliminates many nailers in exterior corners and re-orients others to provide proper support for gypsum board. This eliminates uninsulated areas of exterior walls and reduces the amount of lumber used. In the energy model, the “framing factor” is the percentage of the wall’s surface area occupied by lumber. Wood has an insulating value of only about R1 per inch, while fiberglass insulation is typically rated at R3.5 per inch. Framing is called a “thermal bridge” because the lower insulating value of lumber allows greater heat loss through the framing than the insulated portions of the assembly. Framing is a very sensitive factor in the overall heat loss of the wall assembly. In Phase 1, the base case house was designed with a framing factor of 26%, while the intermediate scenario reduced this to 23%. It is noted that framing factors vary widely by housing design. In Phase 1, the design identified the location of each framing member to support the calculation of the framing factor.

2 I-joist floor

Full dimensional lumber used in floor framing is 1.5 inches wide by 9.25 inches deep and spaced 16 inches on-center. In the I-joist floor system, dimensional “2x” material is replaced with wood I-joists, which use less lumber and allow spacing to be increased to 24 inches. Although it is possible to achieve greater spacing (e.g. 36” on center) with I-joists, the current home design was such that this greater spacing might compromise structural integrity.

3 Advanced Framing

The term advanced framing refers to a collection of practices that eliminate structurally unnecessary wood framing from the building. The concept was originally developed for the National Association of Home Builders in the 1970s when it was called Optimum Value Engineering.

For the purposes of Phase 1, advanced framing has been restricted to practices that builders would be able to apply to almost any building design. The starting point is the Intermediate Framing practices in scenario 1a plus the I-joist floors from scenario 1b. The principal addition is increasing stud spacing to 24-inch on-center which reduces the framing factor to 18%.

17 Small House

The small house scenario is redesigned from the base case home to reduce overall floor area while retaining all the same functions. The conditioned floor area drops to 1633 square feet with a corresponding decline in window area from 374 square feet (16.5% window to floor area) in the base case to 301 square feet (18.4% window to floor area) in the small house. The framing factor also drops slightly from the base case to 25%.

19 Structural Insulated Panels

Many of the limitations of wood-frame construction are overcome with structural insulated panels (SIPS). Roof, wall and floor structures are assembled in a factory into a sandwich of oriented strand board (OSB) surfaces and a core of rigid foam insulation. In Phase 1, this core material is expanded polystyrene (EPS), generally considered to be one of the foam plastics with lower overall environmental impact. The insulating value of each panel is determined by the thickness of the EPS core. One clear advantage of SIPS is the radical reduction or elimination of wood framing and the associated thermal bridges. For this scenario, insulation values were increased a modest amount to reflect this benefit of the technology. Wall panels are specified at 6.5 inches overall thickness for an insulating value of R-23. Roof panels are 12.25 inches for R-46. Using roof panels increases the conditioned volume by 5,555 cu. ft. and the ceiling surface by 294 square feet. Air leakage is reduced to 5.0 air changes per hour (ACH) @50 Pascals. This value is 23% lower than the base case. While many SIPS houses obtain even more impressive air leakage reductions, such savings result from careful installation and attention to detail that is not inherent in the use of this material. In other words, it is possible to build a leaky SIPS house, so the team selected a mid-level air leakage rate. The thermal boundary was moved from the ceiling to the roof which would have been an ideal opportunity to model the heating ducts within the conditioned space. In order to show a clear result of the SIPs alone, the duct locations were not changed from the base case. These two factors slightly increase heat loss relative to what could be envisioned. However, the overall performance of SIPS still exceeds the base case by a considerable margin.

18 Insulating Concrete Forms

Another alternative to wood-frame construction is a system of stay-in-place concrete forms that also provide insulation. Called insulating concrete forms (ICFs), this product is most commonly used for walls, but systems are available to build floors and even roofs. Phase 1 focuses on ICF wall construction. ICF units can take several forms, but are generally formed blocks or sheets held together at a set distance by ties. This creates two layers of insulation and a void into which concrete is placed. For the purposes of this assessment, the ICF is assumed to have 2.5 inches of foam insulation on each side for an assembly insulating value of R-24. As with SIPS, ICF does not have thermal bridges so this insulation is continuous across the entire wall surface. The ceiling and floor construction has not been changed from the base case. Air leakage has been set at 5.0 ACH@50 Pa using the same rationale as was used with SIPs.

8-inch Staggered Stud Wall

Of the major building components, walls are most limiting. Oregon code requires R-21 insulation leading to walls with 5.5 inches thick (2x6). Builders are beginning to experiment with 7.25-inch thick walls. The thickness is established by 2x8 top and bottom plates. Two-by-four studs are placed 12-inches on-center, but are staggered. Every other stud aligns with the interior wall plane while the alternating studs align with the exterior. This allows nailing support for interior and exterior surfaces every 24 inches. The 7.25 inch wall cavity is filled with loose fiberglass or cellulose insulation at a density sufficient to prevent settling. A small amount of water or adhesive may be blown with the insulation as a binder. In addition to the extra thickness, this wall assembly reduces the thermal bridging, because the 2x4 studs don't extend through the entire thickness of the wall. However, plates and the framing around openings do create thermal bridges. The nominal insulating value in the wall cavity is R-30. Parallel path calculations determined the overall heat loss rate of this assembly to be U-0.041 or R-25 for the entire assembly, including framing.

Double Wall

Another option for breaking the 2x6 wall limitation is a 2x4 structural wall and then a second 2x4 wall inside. The distance between the walls is determined by the desired insulation value. In this case, the wall is modeled as 10 inches thick. The nominal insulation value in the cavity is R-40 and the overall heat loss rate for the entire assembly (including framing) is U-0.0274 or R-36 overall.

Extra small house

This home represents a very small economical home, on the order of an income qualified project. It's the kind of home that would be built by Habitat for Humanity, with the addition of a garage. Windows are only 204 sq. ft., but that makes the WFA slightly higher than the base house at 17.7%. Insulation levels are identical to the base house.

Large house

This home represents a larger than *Average Home* typical of many new developments. The conditioned floor area is 3424 sq. ft. Windows were held proportional to the smaller designs at about 16% window-to-floor area.

Multifamily

The multifamily scenario tests the idea of aggregating living units of roughly the same size as the extra small house (1149 sq. ft.).).) into one building. Common walls reduce the surface area exposed to ambient conditions and therefore the heat loss that occurs through those surfaces. All energy elements are modeled at code level in order to assess the impact of the arrangement. Two different scenarios were modeled. One is an 8-unit building with two stories. Four units occur on the ground floor, and four units on the upper floor. A 12-unit building was also modeled. This building was three stories with four units on each level. Each living unit had the identical floor area, but some floor plans were mirror images of others.

Waste Prevention House

The energy features of this home were set to meet the Oregon building code minimum requirements. The major elements include: R-38 ceiling, R21 walls, R30 floor, U-0.35 windows, 90% efficient furnace and 58% efficient gas-fired water heater. In addition, to these basic energy-use features, this waste prevention home has been designed so that the entire forced air heating system, including ducts, exists within the conditioned space of the home. While not common, this "ducts inside" home represents significant potential for saving use phase energy and reducing overall life cycle impacts. This home design tests the impact of a home with the primary intention of reducing waste.

High Performance Shell

The State of Oregon offers an income tax credit for homes that reach a certain threshold of performance. The elements of the building required to reach this threshold include: R-49 attics, wall heat loss of U-0.050 (which is equivalent to R-24), R-38 floor and windows at U-0.32. In addition, duct losses must be eliminated by locating ducts entirely within the conditioned space or an equivalent practice, such as a heating system with hydronic delivery. This package of energy efficiency measures was used for this scenario because it represents an increasingly popular threshold of performance. One element of the HPH package was omitted from the model. It was the on-site renewable energy system.

Green Certified

This home represents another step toward the green end of the spectrum. The building is oriented so that the long axis runs east and west, providing a long south-facing wall. Living areas, including the living room, kitchen and den, are located along the south wall. The home contains 197 square feet of windows, with 117 square feet located on the south-facing wall. These south windows represent 60 percent of the home's glazing with a heat loss rate ofUofUof U-.30. This combination of features makes good use of solar energy with virtually no investment in additional materials. It could be called "sun tempered."

Walls are 8 inches thick and constructed with a staggered stud approach (described above) that reduces thermal bridges in the wall. The wall plates are 7.25 inches with 2x4 studs set 12 inches apart. Alternating studs are positioned to the inside and outside of the wall, giving nailing for siding on the outside and drywall on the inside at 24-inch intervals.

Instead of building with roof trusses that create an empty attic, this design captures additional building volume within the conditioned space by insulating the rafters. Rafter framing comprises 14-inch I-joists with blow-in insulation giving an insulating value of R-50. Building air leakage is 4.0 air changes per hour (ACH50), representing a level of air tightness that is commonly achieved with careful attention to detail.

Because of the home's small size and highly-efficient thermal envelope, the design heating load is only about 17,000 btu/hr -- far smaller than any central forced air furnace. Instead of a central system, a "furnace-rated" fireplace was chosen as the main space heating appliance. Attached to a thermostat, this fireplace operates automatically and easily meets the design heating load of the house with an Annual Fuel Utilization Efficiency of 74%. The open floor plan and ceiling fans promote internal mixing of air heated by the fireplace. To maintain occupant comfort under extremely cold conditions small electric heaters are located in the bedrooms and bathrooms. The total connected load of these heaters is 2 KW.

Domestic water heating is an ENERGY STAR gas-fired water heater supplemented by a solar water heater sized to a family of four. The refrigerator and dishwasher are ENERGY STAR. A heat pump version of this house was also modeled, which assumes a 2-ton ductless heat pump. The gas water heater was replaced with a 50-gallon electric water heater with an efficiency rating of 93%. - This version also has 2 KW of electric resistance heat for bedrooms and bathrooms, although it could be argued that they would not be necessary.

The home with electric zonal heat also has a 50-gallon electric water heater with an efficiency rating of 93%. This one would not meet ENERGY STAR or Earth Advantage standards, because of the main heating fuel is electric resistance.

Green Certified with Passive Solar

This final scenario takes one more step toward green by adding passive solar elements to the green certified package. Windows were rearranged slightly to add even more emphasis on south glass. Windows already in the plan were lengthened. A window from the bedroom was removed. A clerestory was added for additional south windows. Total window area for this scenario is 218 sq. ft. for 18.6% window-to-floor area. Of this total 138 sq. ft. occurs on the south, comprising 63% of the total window area.

Windows on the south façade have high Solar Heat Gain Coefficient (SHGC), which means they allow more solar heat to penetrate the window. Windows with this characteristic typically have higher U-values as well, owing to the close relationship between heat loss and heat gain through the glazing. These south-facing windows were set to U-0.38 and SHGC 0.60. Windows on the east, west and north were set to U-0.30 and SHGC 0.30.

Thermal mass was added in the form of an internal concrete wall four inches thick. The wall is positioned to be in the direct sunlight from windows on the south wall and clerestory. A small amount of mass also was added for the earthen floor.

Appendix 3: Reuse Rates, Waste Factors and Availability of Salvaged Materials by Material Type

See the attached MS Excel file

Appendix 4: Material Replacement Rates

See the attached MS Excel file

Appendix 5: Home Materials for *Standard Home* and Waste Prevention Practices

See the attached MS Excel file

Appendix 6: Summary of LCI Data Used

See the attached MS Excel file

Appendix 7: Results by Process for the Standard Scenario

See the attached MS Excel file

Appendix 8: Cost Data

See the attached MS Excel file

Appendix 9: End-of-life Fates of Material Types

See the attached MS Excel file

Appendix 10: Home Design Information

See attached file

Appendix 11: Energy Modeling Results

See attached file

Appendix 12: Oregon DEQ Advisory Committee

See attached file

Appendix 13: Availability of LCI Data for Building Materials

See attached file

Appendix 14: Life Cycle Impact Assessment Factors

See attached file

Appendix 15: Data Quality and Uncertainty

As discussed in the report, understanding the quality if input data is essential to interpreting the quality and uncertainty of the results of the project. The breadth of the subject matter and the handling of events taking place relatively far into the future result in a necessarily high level of uncertainty in the project outcomes. To assist the reader in making an assessment of the magnitude of the uncertainty and how it might influence their interpretation of results, the following tables present an overview of the major types of input data with an assessment of their quality and a summary of key areas of uncertainty within the project, as identified by the report authors. Statements about the importance of various uncertainty sources are subjective opinions given by the report authors.

Data Category	Source	Data precision	Internal consistency	Geographic relevance	Temporal relevance	Technological relevance	Summary relative to goal
Home materials	Produced within project by CAD modeling of OHBA	Very High; the modeling allows precise counts of most materials	High; all scenarios modeled with same tools and personnel	High; models created to reflect Oregon conditions by OHBA	High for 2010; diminishing for homes built far in the past or future	High for 2010; diminishing for homes built far in the past or future	Very good data quality and consistency, exceeding any available elsewhere.
Home energy use	Produced with REM/Rate professional home energy modeling software	High; REM/Rate is a commercial software considered to be as accurate for this purpose as others that might be available	High; all scenarios modeled with same tools and personnel	High; models created to reflect Oregon conditions by leading home energy certifier in the state.	High for 2010; diminishing for homes built far in the past or future	High for 2010; diminishing for homes built far in the past or future, as the heating and cooling technologies change over time	Very good data quality and consistency, exceeding any available elsewhere.
Data Regarding Construction and Material Replacement	Materials replacement extrapolated from American Home Survey data; Construction activities created as general estimates, not validated for each scenario	Moderate for AHS data, as extrapolation is needed from survey results. Low for construction, as scenario-specific estimates were not made	High; all scenarios modeled based on same assumptions and data sources	High; AHS data is available specific to Oregon	Mid-to-High; AHS data is from within the past decade; Relevance decreases for representing future conditions	High for AHS data, as it reflects homes actually in place in Oregon; Low for construction data, as machinery and equipment is not highly specified.	Material replacement data is believed to be as good as exists or that could be obtained. Construction activity data is of poor quality and conclusions that require accuracy within a factor 2 for this data should be seen as suspect.
Data regarding material transport distances and modes	Based on distance estimates made by team	Expected to be representative of distances that in actuality will be highly variable	High; all scenarios modeled based on same assumptions and data sources	High; assumptions were made based on expected distances to Oregon (e.g., wood shipments expected to be short)	High for 2010; diminishing slightly for homes built far in the past or future	High for 2010; diminishing slightly for homes built far in the past or future.	Given the wide variation that will occur in actuality, the approximations made are as good as can be obtained.
Data regarding	Provided by	High	High; all scenarios	High; data is from	High for 2010;	High for 2010;	Very good data

Data Category	Source	Data precision	Internal consistency	Geographic relevance	Temporal relevance	Technological relevance	Summary relative to goal
material end-of-life fates	Oregon DEQ based on current fates for construction and demolition debris in their state		modeled based on same assumptions and data sources	Oregon state agency	diminishing for disposal taking place far in the future	diminishing for disposal taking place far in the future	
Home population characteristics and growth	Drawn or extrapolated from sources such as the AHS, NAHB and US Census.	High for current population, moderate for future projections	High; all scenarios modeled based on same assumptions and data sources	High; data are from Oregon wherever possible, with use of US data to supplement or validate	High; most survey and census data are from within 5 years. Relevance diminishes for future years.	High for 2010; diminishing slightly for homes built far in the past or future.	Good data, given the impossibility to predict future growth with any known precision. Inaccuracies are likely to affect more the absolute values of future projections rather than comparative conclusions.
Data representing environmental impacts of material and energy flows (life cycle inventory)	Data taken primarily from Ecoinvent 2.0, with updates to the database to reflect US electricity production for all background processes. Wood data from CORRIM/USLCI. Carpet and linoleum data from BEES. A handful of data from Ecoinvent 2.2 included.	High; Ecoinvent, CORRIM and BEES are quality sources of data.	High, as the great majority of data is represented by a single database, Ecoinvent. The CORRIM data has been checked against results for similar materials taken from Ecoinvent and found to be reasonably similar in result. BEES data, where it is used, may be suspect for poor consistency.	Mid-high; Ecoinvent updated to reflect US electrical grid in background. CORRIM data and BEES data are collected from US industries.	Mid-high; most data are from within 5 to 10 years. Relevance will diminish for representing impacts occurring far in the future.	Varying from high to mid, depending on the material being represented. Many materials and processes are excellent matches. In other cases, such as steel roofing, the input materials (e.g., steel sheets) have been modeled, but final product manufacturing has not been considered. No materials or processes exist for which at least proxy data has not been used.	Adequate to meet project goals. The ability to take most data from a single data source increases internal consistency and supports comparative results to a greater extent than if data were taken from a wider range of sources, with better individual data relevance, but lesser consistency within the project.

Uncertainty Source	Consideration of Importance
Mismatch of future conditions and technologies with those data and assumptions used to represent them	Highly important source of uncertainty for many results.
Mismatch of geographic relevance of data sources	Relatively little importance for most results.
Data regarding impacts of building materials	Important source of uncertainty for conclusions that involve comparison of materials; the project is not intended to support direct comparisons of individual materials or products.
Data regarding building material replacement rates	Moderate importance for those conclusions that are highly dependent on material impact.
Assumptions regarding transportation distances, modes and impacts	Relatively little importance for most results.
Assumptions and data regarding construction and demolition activities	Relatively little importance for most results; high uncertainty in cases where differences in construction/demolition practices could be expected to differ substantially among scenarios.
Life cycle impact assessment methodologies	High importance for many conclusions and impact categories. Comparative results within several tens of percent may be seen as inconclusive without further investigation into specific uncertainties and causes.
Mismatch of actual technologies with that of data (LCI) used to represent environmental impact	Low importance in the case of most conclusions. Where individual materials or product types are important determinants of results, variability in product impact or less-then-ideal matching of LCI data may significantly effect uncertainty.
Assumptions about home lifetime	Relatively low source of uncertainty for most conclusions. However, some specific results, such as the comparative benefit of insulated concrete forms, may be highly affected by this uncertainty.
Consideration of land use impact on *Climate Change*	Modest impact on most results and conclusions. In some

Uncertainty Source	Consideration of Importance
	cases, especially where the impact of wood data is very prominent, the uncertainty may be very substantial.
Lack of consideration of the land used by the home itself and of the home yard, driveway, etc.	Expected to contribute equally to most scenarios; some influence on the results for various home sizes and single/multi-family.
Choice of allocation of benefits and impacts between systems providing reused materials and those receiving them.	Relatively low uncertainty for most conclusions.
Assumption that conclusions regarding only wood frame homes are relevant to all residential homes	Moderate uncertainty, as some conclusions may be very different for other types of construction
Lack of consideration of influence of home on occupant lifestyle or possessions	Relatively low uncertainty for most conclusions, but moderate uncertainty in cases where a strong influence may exists, such as that of home size on furnishings and possessions or that of singe/multi-family on transportation habits.
Mismatch of home designs used within project to the set of homes they are intended to represent.	Relatively low impact for most conclusions; may be important in some cases, such as where the addition of a steel fire escape adversely effects the performance of multi-family homes, or in cases where the population of options from which the example chosen has very high variability, such as for green certification or durable materials.

Appendix 16: Example Calculation

The following table shows an example calculation to illustrate how the various information sources are combined to compute the relative environmental profile of each scenario. This example shows the impacts in:

- one environmental impact category, for
- one substance, emitted to
- one environmental compartment, from the production of
- one type of material within the home, to calculate the net impact for
- one of the building practices.

To compute the overall results, such calculations are carried out for (1) each of the materials or energy uses in the home's life cycle, (2) each of the pollutants emitted to each environmental compartment (e.g., air, water, soil),(3) each of the impact categories considered, and (4) each of the building practices being modeled.

The impacts are calculated by first identifying the amount of the material in the home, which is supplied by the OHBA. This information is multiplied by an emission factor that indicates the amount of a pollutant emitted when producing that product or supplying that energy. In the case of resource consumption, the factor describes the amount of resource used rather than pollutants emitted. These factors are gathered from existing data sources as described in the above section. multiplying the quantity of the material required by the emission factor for a given emission provides the amount of the pollutant emitted in producing the material for the home.

Impact assessment is then applied to the emissions of pollutants. The methods used here provide factors that are used to evaluate the importance of emissions of various substances. These factors are multiplied by the amount of each substance emitted to determine the impact of emissions of that substance. To determine the impact of the house as a whole, this is carried out for each material or energy use within the home and for each pollutant or resource usage for which there is available information for its inclusion.

The net impact or benefit of the scenarios is then determined as the difference in the total among the impact caused by each of the components of the home's life cycle.

Table 32: Example calculation of the ecotoxicity impacts associated with the emissions of lead to air caused by the use of fiberglass insulation in the Medium (A) and smaller (B) home scenarios.

	Item of Information	Unit of Measure	A	B	How Information is calculated or determined
			Medium	Small	
1	Amount of fiberglass in life cycle of home	kg fiberglass	6874	4792	Determined based on home design and density of material
2	Amount of lead emitted to air per kg fiberglass produced	mg lead / kg fiberglass	0.95	0.95	Taken from preexisting data sources regarding the production of fiberglass; in this case, the ecoinvent database

3	Total amount of lead emitted to air in producing fiberglass for home (g)	g lead	6.53	4.55	Line 1 multiplied by line 2
4	Impact of lead emission to air on ecotoxicity	g 2,4-D equivalents per g lead emitted to air	1.44	1.44	Taken from the documentation of the appropriate impact assessment method, in this case the TRACI ecotoxicity method
5	Impact of producing the fiberglass for this home	g 2,4-D equivalents	9.40	6.56	Line 3 multiplied by line 4
6	Net ecotoxicity impact from lead emission to air of added fiberglass insulation for smaller home	g 2,4-D equivalents	-2.85		Item B5 minus item A5

Appendix 17: Evaluation of “Green Certified Homes”

See attached files

Appendix 18: Peer Review

The project report has been peer reviewed by a panel of three external LCA experts to validate the methodologies used, relevance of conclusions and conformance with the ISO LCA standards (ISO 14040 and 14044). The panel consisted of:

Arpad Horvath, Ph.D. (Chairperson)
Greg Keoleian, Ph.D. (Panelist)
Tom Gloria, Ph.D. (Panelist)

Their comments regarding the draft report are listed below, with responses of the report authors listed in ***bold italics***.

The review panel found that the report generally follows the ISO 14044/14044 principles, but more detail, explanation or discussion is warranted in places noted in the detailed peer review.
Comment is addressed as specific issues are discussed below.

Please state explicitly that the intended audience is the Oregon DEQ, or that it will eventually be disclosed to the public, and if the study intends to support comparative assertions.
A statement of the intended audience has been added to the goal and scope section of the report. Clarification on the type of comparative assertions has similarly been added.

Sensitivity analysis should be performed for the parameters that drive the results.
The following parameters have been examined through sensitivity tests, either within the original draft or as additional results included in the updated report. These cover the majority of the features identified as being the most prominent contributors to uncertainty in the added appendix on this topic.

- ***Lifetime of home***
- ***End-of-life fate of individual materials***

- ***Rate of material reuse within reuse scenarios***
- ***Transportation distances by material for reuse scenarios***
- ***Multiple home sizes and multi-family building sizes***
- ***Green certification home with and without passive solar features***
- ***Rate of change of Average Home size within population***
- ***Rate of change of percentage of multi-family homes within population***
- ***Consideration of Climate Change with and without potential influence of forestry land use***
- ***Effect of choice of allocation of benefit and impact for reused and beneficially used materials or energy***

Data quality assessment and quality goals, as well as treatment of missing data need to be stated.
A statement of the data quality goals has been added, along with an assessment of the data quality and a description of how missing data has been handled. See the added appendix on this topic and the section on project goals.

The goals and objectives of the study were clearly defined, including what had been left out of the analysis. The system boundaries and life cycle stages modeled were clearly outlined.
No comment required.

Delivery of water was included in the analysis, but it was not clear whether sewage or treatment of wastewater was included.
This was not included in the original analysis, but upon this suggestion, we have included it and have clarified in the report that it is included.

The modeled scenarios were clearly stated. However, it was not clear what home models were used to represent existing and new homes except that a 20% difference in energy efficiency was used.
New and existing homes have been represented as being identical in their material composition. The 20% difference in energy use mentioned, along with a different distribution of home sizes, is therefore the only difference in how these pools of homes have been represented in the population modeling. Although there have been changes in typical homebuilding practices over the course of the last century when most Oregon homes have been built, the variation within both the old and new pools of homes is substantial and perhaps greater than the differences between old and new. It has therefore been determined to not be feasible to distinguish between the material composition of typical older homes in comparison to typical new homes, with the exception of the trend in homesize influencing the proportion of homes in various size categories in these populations. Clarification of these points has been added to the report.

The assumptions are generally clearly identified and reasonable, with a few exceptions.
No comment required.

The study did not take into account technology improvements in materials production, construction, appliances and other systems. The only modeling of improvements is related to thermal energy efficiency, where pre-existing homes are assumed, on average, to have a 20% lesser thermal energy efficiency. Efficiencies will continuously improve, driven by new standards (appliance standards and codes). The analysts should indicate how the use of static models and data to represent life-cycle impacts across several decades would affect the results.
Language has been added to the report to further clarify and emphasize the limitations of the modeling approach in representing future conditions. A section has been added to the methodology section specifically identifying this as an important source of uncertainty.

For electricity production, the average U.S. grid dataset is employed. This will not be representative of electricity supply in Oregon. Either a State profile or NERC grid profile should be used.
The data used to represent electricity use has been modified to include a representation of the production mix within the Northwest Power Pool (NWPP), a regional pool containing the state of Oregon and other states in the Northwestern portion of the United States. This representation is done using Ecoinvent data to represent the impact of power production by each of the several different production technologies and a weighting is applied to these technologies based on their proportional contribution to the regional supply, as detailed in reports of the U.S. EPA's e-grid model. This NWPP electricity production data has been applied to the use of electricity in the foreground of the model, which includes electricity-demanding events known to occur in Oregon such as the construction and maintenance of the home, and most especially the use of electricity for heating/cooling and supplying plug loads. Because the location of material production is not known with certainty, the US national grid mix has been retained in the background of the life cycle inventory. For example, when electricity is used in the production of concrete, it is assumed this electricity is supplied by the US national average electricity grid.

"Most materials are assumed to travel 1,500 km (932 miles) from the site of production to the building site." No source was given for the distance; was this assumption supported by OHBA? It seems that 1,500 km is too arbitrary a distance. Most materials are likely to travel less, while some materials might travel much more."
The cited statement is vague and has been clarified. Because so many homes are being represented over such a lengthy period, it is impossible to know precisely the distances that materials will travel. The project team, including OHBA and others, have made assumptions about distances of material delivery based on their experience in the industry. These assumptions are based on broad categories of materials. Specifically, sand and gravel are assumed to be sourced from 100 km away, softwood lumber is assumed to be shipped from 300 km, and remaining materials, such as fiberglass insulation, doors, windows, etc. are assumed to be shipped 1500 km.

The service life of a home is a critical parameter impacting the results. At one point the report states that the service life is 70 years, but then elsewhere lifetime is determined using a demolition rate. The service life needs greater description and explanation for modeling.
This is indeed a critical parameter for the absolute value of impacts shown for a home's life and in many cases, it is also critical to the relative results drawn from comparison of home scenarios. The crucial nature of this variable is shown in the sensitivity test done on this parameter. The explanation of the home life in the prior draft, especially with regard to the home population was not fully clear and has been modified. To explain in brief, the analysis is divided among a comparison of scenarios on the basis of a single home and among the whole population of homes. When considering a single home, the 70 year lifetime mentioned has been assumed. When considering the population, it is more accurate to consider home loss from the population as a rate. Our assumption has been that no homes are lost in the first 20 years of their life and then are lost at a 2% rate. This gives a typical home life in a similar range to the 70 year lifetime used for single homes. However, under these assumptions some homes will live far less than 70 years and some are still existing after the 200-year timeframe that has been considered in the future projections.

The data sources were clearly identified, but the representativeness of some of the data needs to be explored and explained better. The ecoinvent database includes datasets that range in data quality, technological and geographical representativeness, and year. This study seeks to describe residential buildings in Oregon over several decades. There is major limitation of modeling a dynamic system with limited static data. Systems impacting the material production and construction are evolving as well as the technologies and energy mixes that impact the use phase and end-of-life management of a residential building.
As noted above, a section has been added to the appendices in which the quality of the data used has been systematically assessed.

The report is generally complete, consistent, and transparent, with a few exceptions.
Given the length of the report and number of scenarios evaluated, the Executive Summary should be expanded. As many readers will just look at the Executive Summary and not the rest of the report, it is recommend to add section headings and provide more key findings and conclusions. You should not expect the reader to draw the key findings and conclusions from just the figures provided alone.
This suggestion has been implemented.

The study did not account for design and technological changes or other changes in life-cycle performance of homes built in the future (e.g., 2030).
It is unknown what design and technological changes would occur in these future years and so the assumption has been made that the typical homes designed based on the current practices are equally applicable homes build in in future years through 2030. Because of the likelihood that this assumption will be progressively more wrong as the years go on, 2030 has been chosen as the limit at which newly constructed homes are considered in the population

analysis. There is admittedly high uncertainty regarding how closely homes built in 2030 will resemble today's homes.

More description is needed on how material recovery (for reuse and recycling) during demolition was modeled.
For those scenarios in which materials are recovered from the home for reuse, an assumption has been made that the electricity used in demolishing the home and the number of worker-days are each increased more than 10-fold. This has been based on information provided by a company specializing in home deconstruction. Heavy machinery usage (i.e., diesel) has not been changed in these scenarios because it is assumed that most of the additional work is done by hand or light machinery. The rates of recovery have been updated in this final version based on feedback from various reviewers regarding the handling of allocations at end of life (see below). In the current version, amount of material reuse is represented as a moderate (1/3) and high (2/3) rate of recovery and reuse within the home of all materials except those that are specifically identified as being very unlikely to be reused (e.g., drywall). These rates of materials reuse are reflected in both the materials used in construction and those taken away from the home during and after its life. Recycling of materials is based on input from the Oregon DEQ's Waste Division regarding the amounts of various construction debris sent to various fates within their state. No specific accounting of recovery activities for recycling have been assumed, but rather than that are embedded within the demolition activities and waste management activities represented. Further clarification of these points has been added to the text.

The review panel is unanimous that the final conclusions drawn from this study should be preceded by a detailed uncertainty analysis. The inventory and impact assessment models and the data used to arrive at the results all carry significant and differing uncertainties that should be catalogued and quantified to the extent feasible.
We agree that the uncertainties entailed in the study are significant. However, a formal quantitative uncertainty assessment of the results is not feasible within our scope of work. As noted above, we have included a section on data quality and included within this section a catalogue of some significant sources of uncertainty. This qualitative assessment is the most that is able to be provided here.

It would be useful to indicate about the robustness of the results and conclusions if more detailed modeling was conducted (e.g., accounting for future improvements in energy efficiency).
The study does not account for improvements in life-cycle performance of homes built in the future (e.g., 2030). In general, as homes become more efficient, the material production and construction phases will have a larger contribution to life-cycle impacts. This factor should be discussed with respect to the specific waste prevention strategies.
This is an excellent point made also by members of the project team during throughout the project. It was not thoroughly reflected in the initial draft and some discussion of it has been include in the project conclusions.

It would be useful to compare high level results from this study with previous life-cycle studies of residential buildings.

A detailed literature review has been conducted and appended, which includes a variety of other life cycle assessments of residential homes. There are very few assessing impacts of home populations, but a variety examining the life cycle of individual homes. A survey of the results indicates that variation in building practices and materials among geography and climate (which influences home energy use) is a strong influence. The high importance of energy use is a common theme among published studies, with a significant (but usually not dominating) influence of building materials. Which materials are most important varies widely, as dissimilar materials are used among many of the homes studied. Because conclusions here are primarily drawn in regard to comparative scenarios that have not been made elsewhere, there is not further ability to benchmark the conclusions with such prior findings.

The Northwest Power Pool was selected as the grid system to represent Oregon's electricity mix. The EIA provides the description of the electricity mix for the state as: "Hydroelectric power dominates the electricity market in Oregon, providing nearly two-thirds of the power generated in the State. Oregon's four largest electricity generation facilities, all located on the Columbia River, are hydroelectric plants. Smaller hydroelectric plants generate power along several rivers flowing from the Cascade Mountains. Natural gas-fired power plants are located along major gas transmission lines and supply about one-quarter of the electricity market. The Boardman plant in the north central part of the State is Oregon's lone coal plant and supplies most of the rest of Oregon's electricity needs. Oregon also imports electricity from coal-fired plants in Utah, Wyoming, and Montana." It could be useful to compare this with the NWPP.

A text box has been added to the main discussion of results for the single family home to explore this issue and to present a scenario assessment with alternate grid mixes. The finding is that the choice of grid mix is a rather important choice for the overall result of the total impact of a residential home. Whether certain outcomes and conclusions are sensitive to this will depend upon whether a difference conclusion might be reached in cases where a different environmental impact profile for electricity is used.

The Review Panel also addressed two additional issues raised by the Oregon DEQ:

DEQ's Question : Allocation of end-of-life benefits. Currently, the report assigns a 50/50 allocation for the benefits of using salvaged materials, recycling at end of life, incineration with energy recovery, or the act of salvaging materials (deconstruction) for future reuse. For example, the benefits of recycling are split between the home that recycles the material and the manufacturer that uses that recycled content. Similarly, the benefits of deconstruction (the act of salvaging a material) are only given 50% of the avoided production credit. The problem with this approach, as DEQ sees it, is that ultimately, this information will be used to support decisions by Oregon DEQ and others in their efforts to form programs, policies, and actions to prevent waste generation from the residential building sector in a way that maximizes overall environmental benefits. Showing only 50% of the potential benefits does not inform decision makers of the FULL potential of an action. Additionally, since we're not trying to assign any unique ownership of credits, DEQ wasn't sure why we couldn't show the full benefits rather than 50%. DEQ, therefore, has pushed for a 100/100 allocation where, for example, a home would receive the 100% benefit of building with reused materials and then another 100% if those materials were either salvaged again, recycled, or incinerated. I know there are potential double counting issues, but considering the way the data is intended to be used, DEQ thinks a 100/100 allocation may better inform full lifecycle benefits of certain practices. Your thoughts are greatly appreciated.

Panel's Response: EPA LCI Guidance Manual (1993) allocation method 2 indicates that if the original product is recycled the solid waste burden for that product is reduced by the amount of waste diverted from the disposal phase. The product system that uses the recycled material picks up the burdens for processing of the secondary material but avoids virgin material production burdens. I think this is the most logical method and least arbitrary. It also provides motivation in new construction to incorporate many waste prevention strategies. The 50:50 allocation is also one of the options presented by EPA. The quality of recovered materials can vary widely and you could argue different allocation ratios based on differences in quality of recovered materials and many other factors. The 100/100 allocation has a double-counting problem.

Quantis' response: It is strongly agreed that there are many methods employed in current practice and little consensus on a best global approach, or even suggestion of best approaches for specific cases. This is among the reasons that we have included a sensitivity test on this methodological decision. Things that we think are clear on this topic and would be largely agreed upon are that 1) when a benefit is obtained at end-of-life and included within the scope of the project, 100% and not more or less of the benefit should be assigned in total to the systems upstream and downstream of the recycling or reuse event; 2) to the extent that important conclusions hinge on the methodological choice, a clear demonstration and statement of that dependence should be made.

A potential problem with the suggestion to assign all the benefit to the system receiving the material in the present cases is that we illustrate several analyses that compare different end-of-life management options for materials. Such analysis is more problematic if no benefits for materials or energy recovery are assigned at end-of-life, as it becomes then only an analysis of the treatment processes without consideration of the beneficial co-products of some of those processes. In an attempt to best meet DEQ's concern on this topic while staying within what we believe to be reasonable methods, we have chosen in our revision to not change the allocation, but to modify the system in question for some of the home types where this is of most concern. Our original analysis included comparisons of, for example, a home from which material is salvaged to one which uses the salvaged material. This leads to the question of which practice is better, to salvage or to reuse the salvaged material. We believe this was an ill-conceived question in the first place, as they are really the same action seen from different angles.

One way we have dealt with this in our initial draft is to expand the scope to avoid allocation, which is a recommendation of the ISO guidance. By taking a state-wide view and considering hundreds of thousands of homes, much of the issue is internalized within the system. The issue still exists, but only on the fringes of population of homes and not within each individual exchange of material. Further, the statewide modeling includes both the donation and receipt of materials at an approximate steady-state approach. So, the influence of the allocation problem at the 2010 end of the scope is roughly offset by that at the end happening in 2031 and afterward. We have revised our single home scenarios to take a similar approach. Rather than comparing homes that only donate or only receive materials from a reuse program, we have created two new scenarios that are doing both, at different levels of intensity. This resolves DEQs concern that the 50/50 allocation method puts the reuse scenarios at a disadvantage by only representing half the potential benefit.

Finally, because of the focus in some sections in comparing among end-of-life options for materials, a change was made to allocate 100% of the materials processing impact and resulting benefit to the system donating the material and 0% to the system receiving the material. As described above, this change results in no change in results for the new scenarios of material reuse within the home life cycle, but does have the change of showing more benefit when viewing the result of waste management practices. In discussing with the DEQ their interpretation of results, it was found that this is a more useful viewpoint for them and avoids then needing to account for the 50% allocation when comparing to other internal data sources they keep.

DEQ Question: Forest carbon sequestration credit. This one gets me particularly confused but Jon and I have had some very good but inconclusive discussions about how to address this issue. This issue came up when the recovery and incineration of wood for energy recovery showed higher benefits than wood reuse. After looking into it, I realized that DEQ typically uses EPA's WARM data on the benefits of waste management options (http://www.epa.gov/climatechange/wycd/waste/calculators/Warm_home.html). The WARM dataset (which is widely used by waste managers) assigns a carbon sequestration benefit for recycling or source reducing forestry related products (paper and lumber). Essentially, the credit recognizes that if you are using less virgin material (due to use of recycled content or reduced demand for a product) trees that would have normally been harvested will stay standing and continue to sequester carbon as they grow. The credit, therefore, is the increased carbon storage that can be realized if we leave more trees standing. To put things in perspective for GHG impact, we are using a production impact for softwood lumber of .26 kgCO$_2$e/kg wood. EPA assigns a similar number (0.2 kgCO$_2$e/kg) for production impact but assigns a source reduction credit of -2.2 kgCO$_2$e/kg, which recognizes that reducing the demand for lumber by using less or reusing lumber can increase carbon storage. EPA's analysis was conducted by USFS and in my opinion represents a marginal contribution analysis of what could happen on the margins of the wood industry if a change in construction practices that emphasize reduction and reuse actually decrease the number of trees harvested. There are clearly a number of assumptions in this credit but the underlying point that Jon and I have been debating is whether that same credit for reuse should be assigned as an impact to the lumber production phase. As such, does the act of cutting trees and not allowing them to live longer and sequester more carbon deserve an impact for that "lost" opportunity? Currently, the report does not really address carbon sequestration credits with the exception of a few footnotes and 1 table. I am very undecided on the issue and at the very least would like to present both sides of the debate in the report. Your thoughts are greatly appreciated.

Panel Response: The Review Panel members make several somewhat different points about this issue, all worthy of consideration and pointing to the same conclusion, a forest carbon sequestration credit should not be included in the analysis.

Keoleian: "The argument you make is valid, but the study does not apply a marginal analysis methodology. This study was an attributional analysis rather than a consequential (marginal) analysis, and therefore should be consistent throughout."

Gloria: "… if a credit is given for source reduction, likewise an impact should be given to production. Market forces are generally not contained within this LCA so the EPA credit should not be included, and likewise the loss factor. … Further, the CO_2 in question is short cycle CO_2, versus fossil carbon."

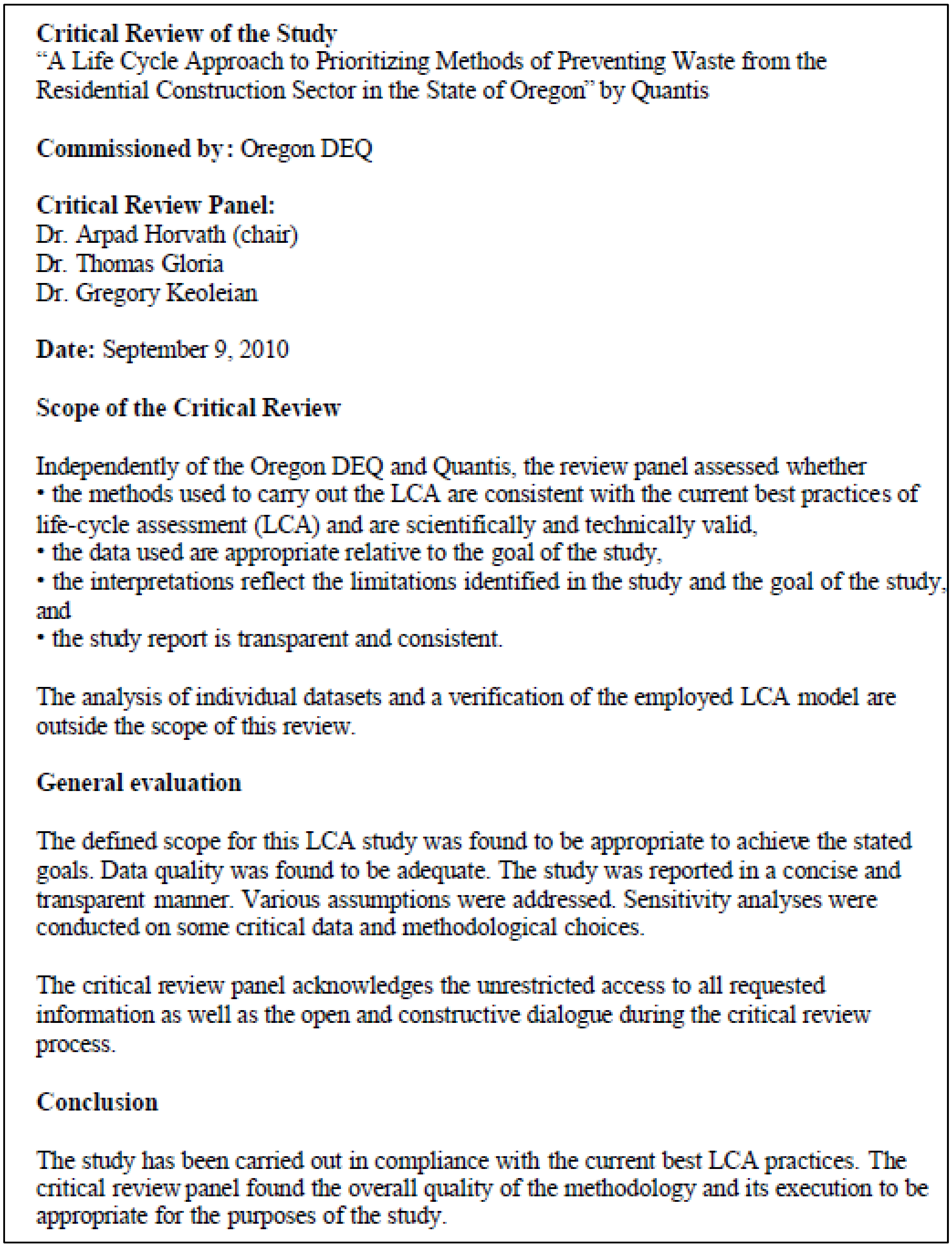
Horvath: "Biogenic carbon, as is the case here, presents some challenges in emissions accounting, but only in the short term. My preference is to leave out biogenic carbon from this inventory because what is released from combusted or degraded biomass is most likely (with correct biomass stewardship) to be sequestered by new biomass in an endless cycle, if not in 20, 50 or 70 years, then in 100 years, which is within the planning horizon for global warming effects. Of course, in reality this is not always the case, e.g., when tropical rainforests are turned into pasture and the carbon sequestration capacity is thus greatly diminished. But for commercial timber in North America and many other countries that embrace forest stewardship, biogenic carbon is not a deciding factor in emissions accounting. How much carbon would a tree left standing (rather than cut down for paper or timber) continue to sequester relative to a newly planted tree is not at all clear. Neither is the recycling or reuse fate of wood in these houses."

Quantis Response: Being a Swiss-based company, it is our inclination to agree with both sides of the argument and such is the case here. We strongly agree with the points made by the reviewers regarding inconsistency of this consideration with the overall study approach, with the invalidity of representing the environmental benefit of not using something in any way other than in relation to the impact of using it and to the incredibly high uncertainties regarding the available information to consider the impacts of forest product consumption on the economics and land stewardship of the forestry industry as a whole, including incomplete knowledge about patterns of global timber trade that affect the market of wood for Oregon homes. We would add to this list the issue that even the best available knowledge is based on relatively current economic data and forestry practice and we are looking at a scope of study which includes wood in homes built in the distant past, as well as wood that will be added to homes decades from now. It is also not clear to us that, while the

analysis mentioned considers forestry land use practices within that industry, that it makes any consideration of competing demands for land and to what extent forestry economics may interact to keep land forested, rather than being deforested for another higher-economic-value use. Further, there are other land uses within the project's life cycle inventory, including that the home sits on, which would not have been treated in a consistent way.

At the same time, we recognize that what information that is available suggests that this is potentially a very important consideration. A quick consideration of the numbers DEQ cites makes it clear that the impact in question could be very significant in comparison to the rest of the *Climate Change* impact of materials production and management within the scope of the study. It may even compete with home energy use as the dominant aspect of the home life cycle. We feel it is therefore imperative to call attention to this topic and make a clear statement regarding its importance and explore potential implications.

In selected figures and tables, we have therefore added in a second *Climate Change* result, labeled as "with forestry land use," which adds the 2.2 kgCO$_2$e / kg wood factor from the U.S. EPA reference as both an impact of wood production and a benefit of its recovery and reuse. We believe that the uncertainty in this 2.2 number is extremely high and see the value of including it as similar to the inclusion of an error bar on the *Climate Change* results that indicate how wrong those results might be if full consideration of this land use question is made. In addition to pointing out several conclusions for which this consideration is of crucial importance, such as in the comparisons of wood end-of-life fates, it also serves the very valuable purpose of pointing out many conclusions where this factor is not a substantial influence on the confidence of results.



Critical Review of the Study
"A Life Cycle Approach to Prioritizing Methods of Preventing Waste from the Residential Construction Sector in the State of Oregon" by Quantis

Commissioned by: Oregon DEQ

Critical Review Panel:
Dr. Arpad Horvath (chair)
Dr. Thomas Gloria
Dr. Gregory Keoleian

Date: September 9, 2010

Scope of the Critical Review

Independently of the Oregon DEQ and Quantis, the review panel assessed whether
- the methods used to carry out the LCA are consistent with the current best practices of life-cycle assessment (LCA) and are scientifically and technically valid,
- the data used are appropriate relative to the goal of the study,
- the interpretations reflect the limitations identified in the study and the goal of the study, and
- the study report is transparent and consistent.

The analysis of individual datasets and a verification of the employed LCA model are outside the scope of this review.

General evaluation

The defined scope for this LCA study was found to be appropriate to achieve the stated goals. Data quality was found to be adequate. The study was reported in a concise and transparent manner. Various assumptions were addressed. Sensitivity analyses were conducted on some critical data and methodological choices.

The critical review panel acknowledges the unrestricted access to all requested information as well as the open and constructive dialogue during the critical review process.

Conclusion

The study has been carried out in compliance with the current best LCA practices. The critical review panel found the overall quality of the methodology and its execution to be appropriate for the purposes of the study.

Appendix 19: Annotated Bibliography

Short Citation	Full Citation	Potential Use/Annotation
Abeysundara, Babel, & Gheewala, 2007a	Yasantha Abeysundara, U. G., Babel, S., & *Gheewala, S. (2007). A decision making* matrix with life cycle perspective of materials for roofs in Sri Lanka. *Materials and Design, 28, 2478–2487.* Retrieved from http://www.sciencedirect.com.	Compares the environmental and social impacts of 2 types of roofs considering their LCA in Sri Lanka.
Abeysundara, Babel, Gheewala, & Sharp, 2007	Yasantha Abeysundara, U. G., Babel, S., Gheewala, S., & *Sharp, A. (2007). Environmental, economic* and social analysis of materials for doors and windows in Sri Lanka. *Building and Environment, 42, 2141–2149.* Retrieved from http://www.sciencedirect.com.	Compares the environmental and social impacts of windows and doors considering their LCA in Sri Lanka.
Abeysundara, Babel, & Piantanakulchai, 2009	Yasantha Abeysundara, U. G., Babel, S., & *Piantanakulchai, M. (2009).* A *matrix for* selecting sustainable floor coverings for buildings in Sri Lanka. *Journal of Cleaner Production, 17: 231–238*, from www.elsevier.com/locate/jclepro.	Method to facilitate the decision making process in selecting sustainable floors (elements) for buildings in Sri Lanka using LCA.
Allione, 2007	*Allione,* C. *(2007). Building life cycle. Tools* for building components and industrial products. *Politecnico di Torino. 2007 Life Cycle Management Conference,*	Assessment of Ecodesign Ecotools that help improve architectural design.
Althaus, Kellenberger, Doka, & Künniger, 2004	Althaus, H. J., Kellenberger, D., Doka, G., & Künniger, T. (*November 2004). Manufacturing and disposal of building* materials and inventorying infrastructure in ecoinvent. *ecoinvent: Materials and Agriculture, 10 (1), 35 – 42.* Retrieved from http://dx.doi.org/10.1065/lca2004.11.181.4	Describes the goal and scope of building material inventories in the ecoinvent database and gives an overview of the database's content.
Asif, Muneer, & Kelley, 2007	*Asif, M., Muneer, T., & Kelley,* R. (2007). Life cycle assessment: A case study of a dwelling home in Scotland. *Building and Environment*, *42*, 1391–1394.	Life cycle assessment (LCA) of a 3-bedroom semi-detached house in Scotland. Detailed LCA of five main construction materials (wood, aluminum, glass, concrete, and ceramic tiles) provided to determine their respective embodied energy and associated environmental impacts.
Baczedk, Yost, & Finegan, 2006	Baczedk, S., *Yost, P., & Finegan,* S. (2006). Using wood efficiently: From optimizing design to minimizing the dumpster. *Building Science Press.*	Report on the benefits of using wood. Addresses some newer, innovative construction techniques that improve thermal properties, strengthen structures, reduce waste, etc. Includes case studies.
Baldo, Rollino, Stimmeder, & Fieschi, 2002	Baldo, G. L., Rollino, S., Stimmeder, G., & Fieschi, M. (2002*). The use of LCA to develop eco-label criteria for hard floor* coverings on behalf of the European Flower. International *Journal of Life Cycle Assessment, 7 (5), 269 - 275.* Retrieved from http:/Idx.doi.ora110.1065/Ica2002.08.093	Describes eligibility development criteria using LCA for eco-labeling wood flooring.
Bare, Norris, Pennington, & McKone, 2003	Bare, J. C., Norris, G. A., Pennington, D. W., & *McKone, T. (2003). TRACI: The Tool for the Reduction* and Assessment of Chemical and Other Environmental Impacts. *Journal of Industrial Ecology, 6, Nos. 3-4.* Retrieved from http://mitpress.mit.edu/jie	Describes the tool for the reduction and assessment of chemical and other environmental impacts (TRACI), including its history, the research and methodologies it incorporates, and the insights it provides within individual impact categories. Originally developed by the U.S. Environmental Protection Agency for LCA, TRACI facilitates the characterization of environmental stressors that have potential effects, including ozone depletion, global warming, acidification, eutrophication,

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		tropospheric ozone (smog) formation, ecotoxicity, human health criteria–related effects, human health cancer effects, human health non-cancer effects, fossil fuel depletion, and land-use effects.
Bare & Gloria, 2005	Bare, J., & Gloria, *Ph.D., T. (November 2005). Li*fe cycle impact assessment for the building design and construction industry. *building design & construction*. Retrieved from http://www.bdcnetwork.com	Using EPA's TRACI to evaluate LCA of building design and construction.
Borg, Paulsen, & Trinius, 2001	Borg, M., Paulsen, J., & Trinius, W. (200*1). Proposal of a method for allocation in* building-related environmental LCA based on economic parameters. *International Journal Life Cycle Assessment*, *6 (4)*, 219 - 230.	Application and development of the LCA methodology to the building sector is different than other typical LCA sectors, as some key characteristics of products in the building sector differ considerably from those of other industrial sectors. The largest difference is that the service life of a building can stretch over centuries, rather than decades or years, as seen with consumer products
Boustead, 2002	Boustead, I. (November 2002). *Eco-profiles of silicones*. Brussels, Belgium: Cefic - The European Chemical Industry Council.	Eco-profile of silicone products, including sealants. Eco-profiles for silicones are a cradle-to-factory-gate summation of the consumption of energy and raw materials and of the solid, liquid and gaseous emissions during their manufacture when the starting materials are raw materials in the earth.
Campioli & Lavagna, 2007	*Campioli, A., & Lavagna*, M. (2007). Life cycle design in building and construction sector. *Politecnico di Milano, Dipartimento BEST*. LCM 2007	Addresses the LCA of operation phase of buildings, which needs to be considered when designing sustainable architecture. Better choices in the design phase will be made when operation LCA impacts are understood.
Cascadia Consulting Group, Inc., 2004	Cascadia Consulting Group, Inc. (December 2004). *A plan for distributing SPU's* Green Home Remodel *guides*. Seattle, Washington: Seattle Public Utilities.	Report to Seattle Public Utilities (SPU) by the Cascadia Consulting Group on developing a target market for the *Green Home Remodel* guides and developing the marketing plan for distribution of the guides. The guides focus on home remodeling & help homeowners and their contractors make informed decisions about the environmental, health, and economic costs and benefits of available remodel choices. Guides cover the following topics: Green Home Remodel Overview Guide, Roofing, Kitchen, Bath and Laundry, Paints and Finishes, Landscape Materials, Salvage and Recycling, and Hiring a Professional.
Chen, Burnett, & Chau, 2001	Chen, T. Y., B*urnett, J.,* & Chau, C. K. (2001). Analysis of embodied energy use in the residential building of Hong Kong. *Energy*, *26*, 323-340. Retrieved from http://www.elsevier.com/locate/energy.	Paper presents a study on the energy embodied in the residential building envelope of Hong Kong. Until recently, studies have primarily focused on energy conservation in building operation, even though recent research has indicated that the embodied energy used in residential buildings could account for up to 40% of the life cycle energy used in residential buildings.

Short Citation	Full Citation	Potential Use/Annotation
Citherlet & Defaux, 2007	Citherlet, S., & Defaux, T. *(2007). Energy and environmental comp*arison of three variants of a family house during its whole life span. Building and Environm*ent, 42, 591-598.* Retrieved from http://www.elsevier.com/locate/buildenv. doi:10.1016/j.buildenv.2005.09.02.	Study analyzes and compares three variants of a family house in order to evaluate the total environmental impacts produced during the whole building life cycle.
Energy Information Administration, 20011	Energy Information Administration. (2001). OTP/MDU exhibit 347 average per-household energy consumption, 2001. Retrieved from the Energy Information Administration Web site: http://www.eia.doe.goy/emeu/states/sep sum/html/sum btu res.html	Data on household energy consumption/state
Earth Advantage Institute, 2009a	Earth Advantage Institute. (2009). *Energy Performance Score horizontal*. Portland, Oregon: Earth Advantage Institute.	Description & graphic of the EPS process with example energy & carbon bar graph
Earth Advantage Institute, 2009b	Earth Advantage Institute. (2009). *Energy Performance Score vertical*. Portland, Oregon: Earth Advantage Institute.	Description & graphic of the EPS process with example energy & carbon bar graph
Gorr6e, Guin, Huppes, & van Oers, 2002	G*orr6e, M., Guin, J. B., Huppes, G., & van Oers, L. (2002). Envir*onmental life cycle assessment of linoleum. International *Journal of Life Cycle Assessment, 7 (3), 158 – 166.* Retrieved from http://dx.doi.org/10.1065/lca2001.12.072	LCA of linoleum flooring. Goal of LCA, assess the environmental performance of linoleum floors, identification of potential options for improving product.
Griffiths, Eames, Lo, & Norton, 1996	Griffiths, P. W., E*ames*, P. C., Lo, S., & Norton, B. (1996). Energy and environmental life-cycle analysis of advanced windows. *WREC*, 219-222.	Environmental consequences of options for the manufacture, application, disposal, reuse and recycling, applicable to the full range of currently conceived advanced window systems.
Guy & Ciarimboli, 2005	*Guy, B., & Ciari*mboli, N. (2005). Design for disassembly in the bu*ilt environment: A guide to closed-loop design & building.* Seattle, Washington: City of Seattle, Washington.	Issues related to designing buildings for disassembly (DfD). Addresses DfD principles, strategies, materials that can be DfD, benefits of, values, planning, materials, model deconstruction planning, and case studies.
Habitat, 2000	Habitat for Humanity of Wake County ReUse Center, (March 2000). *Final report.* Wake County, North Carolina: Habitat for Humanity of Wake County.	Synopsis of activities funded by a grant (Solid Waste Reduction Assistance Grant) from N.C. Department of Environment and Natural Resources, Division of Pollution Prevention and Environmental Assessment. Grant supported building deconstruction activities performed by Habitat for Humanity ReUse Center.
Harris, 1999	Harr*is, H. (1999). A quantit*ative approach to the assessment of the environmental impact of building materials. *Building and Environment*, *34*, 75, I-758.	An analysis of environmental impacts (locally, through the effects of activities such as quarrying; globally, by GHG emissions from using energy used to manufacture the materials; and internally, in the effects on the health of the occupants of the Building).
Hellweg et al., 2009	Hellweg, S., Demou, E., Bruzzi, R., Meijer, A., Rosenbaum, R., Huijbre*gts, M., et al. (2009) Integrating h*uman indoor air pollutant exposure within life cycle impact assessment. *Environmental Science and Technology*, *43*(6), 1670-1679	An evaluation and set of recommendations for the inclusion of indoor air exposures within life cycle impact assessment, based on the outcomes of a SETAC / UNEP working group.
Hondo, Moriizumi, & Sakao, 2006	Hondo, H., Moriizumi, Y., & Sakao, T. (2006). A method for technology selection considering envir*onmental and socio-economic impacts: Input-*output *o*ptimization model and its application to housing policy. *International*	Article addresses Japanese household CO_2 abatement. States that conventional LCA methodology can effectively evaluate environmental impacts of high insulation

Short Citation	Full Citation	Potential Use/Annotation
	Journal Life Cycle Assessment, *11 (6)*, 383-393.	technologies, while not necessarily providing sufficient information to support policymaking because of its analytical perspective. The study goal is to first develop a new methodology to examine the optimal use of high insulating technologies to formulate an environmental policy by considering dynamic socioeconomic conditions. Second, as a demonstration, such the new methodology is applied to explore an environmentally conscious housing policy for CO_2 abatement in Japan.
Humbert, Abek, Bali, & Horvath, 2007	Humbert, S., Abeck, H., Bali, N., & Horvath, A. (2007). Leadership i*n Energy and Environmental Design (LEED): A cr*i*ti*cal evaluation by LCA and recommendations for improvement. *International Journal of Life Cycle Assessment*, *12*, 46-57.	LCA of LEED credits are qualitatively analyzed to evaluate the actual extent of benefits and burdens of LEED, identify critical credits, and develop a new scale that corrects miscorrelations, which under current LEED point system implies the higher scores lower environmental impact.
Johnson, Lippke, Marshall, & Comnick, 2005	Johnson, L. R., Lippke, B., Marshall, J.D., & Comnick, J. (20*05). Life-cycle impact*s *of* forest resource activities in the Pacific Northwest and Southeast United States. *Wood and Fiber Science*, *37*, 30–46.	LCA assessment of environmental impacts associated with the life cycle of forest resource activities in the Southeastern U.S. and Pacific Northwest supply regions as a component of a broad analysis of life cycle inventory data on wood products produced in these regions.
Johnstone, 2001	Johnstone, I. M. (2001). Energy and mass flows of housing: A model and example. *Building and Environment*, *36*, 27-41.	Paper develops a model to estimate the energy flows of a typical subpopulation of New Zealand housing stock. The energy and mass flows of key building materials are estimated and the energy flows of alternative cladding systems are compared.
Jolliet, Margni, Charles, Humbert, Payet, & Rebitzer, 2002	Jolliet, O., Margni, M., Charles, R., H*umbert, S., Payet, J., & Rebitzer, G. (2002*). IMPACT 2002+: A new life cycle impact assessment methodology. *International Journal Life Cycle Assessment*, (6), 324–330.	Discusses IMPACT 2002+ database upgrade, focusing on the comparative assessment of human toxicity and ecotoxicity. Human damage factors are calculated for carcinogens and non-carcinogens, employing intake fractions, best estimates of dose-response slope factors, as well as severities.
Keoleian, Blanchard, & Reppe, 2001	Keoleian, G. A., Blanc*hard, S., & Reppe, P. (2001). Life-*cycle energy, costs, and strategies for improving a single-family house. *Journal of Industrial Ecology*, *1 (2)*, 135-156.	Analyzes the life cycle energy, greenhouse gas emissions, and costs of a contemporary 2,450 sq ft (228 m3) U.S. residential home (the *Standard Home*, or SH) identify opportunities for conserving energy throughout pre-use (materials production and construction), use (including maintenance and improvement), and demolition phases.
Kline, 2005	*Kline*, *D.* E. (2005). Gate-to-gate life-cycle inventory of oriented strandboard production. *Wood and Fiber Science*, *37*, 74 – 84.	Life-cycle inventory (LCI) for Southeast oriented strandboard (OSB) manufacturing by surveying four OSB manufacturing plants in the Southeast US.
Kofoworola & Gheewala, 2008	Kofoworola, O. F., *& Gheewala, S. H. (2008). Environmental life* cycle assessment of a commercial office building in Thailand. *International Journal of Life Cycle Assessment*, *13*, 498-511.	Article provides an environmental life cycle assessment (LCA) of a typical commercial office building in Thailand.
Krogmann, Minderman,	*Krogmann, U., Minderman, N., Senick, J., & Andrews, C. (2008). Life-Cycle ass*essment of the New Jersey	LCA of large institutional building

Short Citation	Full Citation	Potential Use/Annotation
Senick, & Andrews, 2008	meadowlands, Commission Center for Enviro*nmental and Scientific Education Building*. New Brunswick, New Jersey: The Rutgers Center for Green Building.	
Kulongoski, 2008	Kulongoski, T. (November 2008). *Answering the Oregon challenge: Climate Change.* Salem, Oregon: Oregon Governor's Office.	Description of governor's *Climate Change* legislative agenda for Oregon 2009 Legislative Session.
Laquatra and Pierce, 2002	*Laquatra, J and Pierce, M. 2002. Waste Management at the Construction Site. Cornel University, Ithaca New York.*	Contains information on materials in construction waste stream.
Lippiatt & Boyles, 2001	*Lippiatt, B. C., & Boyles, A. S. (*2001). Using BEES to select cost-effective green products. *International Journal of Life Cycle Assessment*, *6*(2), 76-80.	Describes the BEES ((Building for Environmental and Economic Sustainability) software, which allows assessment of the environmental and economic performance of building products.
Lippke, Wilson, Perez-Garcia, Bowyer, & Meil, 2004	Lippke, B., Wilson, J., Perez-Garcia, J., Bowyer, *J., & Meil, J. (June* 2*004*). CORRIM: Life-cycle environmental performance of renewable building materials. *Forest Products Journal*, *54*(6), 8-19.	Describes how the Consortium for Research on Renewable Industrial Materials (CORRIM) to undertake research on the use of wood as a renewable material. Describes development of a life-cycle assessment (LCA) for residential structures and other wood uses.
Lippke & Edmonds, 2005	Lippke, B., & Edmonds, L. (October 2005). Environm*ental performance improvement in* residential construction: The impact of products, biofuels, and processes. *Forest Products Journal*, *55 (10)*, 59-63.	Previous study by Consortium for Research on Renewable Industrial Materials (CORRIM) evaluated the life cycle environmental impacts of building materials used in residential construction. This report builds upon those findings by examining the environmental burdens of each component used to construct wall and floor subassemblies in residential homes. Evaluating components and subassemblies illuminates how the environmental burdens from different products, designs, and processes compare.
Louisiana-Pacific Corporation, 2008	*Louisi*ana-Pacific Corporation. (2008). LP® *SolidStart® I-JOISTS LPI® 18 Technical guide, floor & roof applications.* USA: Louisiana-Pacific Corporation.	I-Joist Factsheet, LP SolidStart
Lstiburek, 2005	Lstiburek, J. (October/November 2005). The future of framing. *Fine Homebuilding*, 50-55.	Extols the benefits of wood in building construction. Discusses recent improvements in building design and construction that use wood.
Meil, Lucuik, O'Connor, & Dangerfield, 2006	Meil, J., Lucuik, M., O'Connor, J., & Dangerfield, J. (*September 2006). A life cycle* environmental and economic assessment of optimum value engineering in houses. *FOREST PRODUCTS JOURNAL*, *56 (9)*, 19-25.	Study tests the hypothesis that reducing or substituting forest products (mainly wood) for alternative, non-wood materials provides an environmental benefit. Uses LCA approach to compare a conventional Canadian house to two case study houses: 1. house using up to 50% less wood; 2. house that combined some elements of efficient framing with maximum use of renewable content (e.g., cellulose insulation in place of fiberglass, wood windows in place of aluminum windows, and wood siding in place of vinyl siding). House 1 had little or no environmental benefit. House 2 exhibited significant environmental benefit, suggesting that maintaining, not decreasing renewable content in building construction is important.

Short Citation	**Full Citation**	**Potential Use/Annotation**
METRO: Solid Waste Department, 1993a	METRO: Solid Waste Department. (July 1993). *Characterization of construction site waste (*Contract No. 902906). Portland, Oregon: METRO.	Assessment of solid waste from new residential and commercial construction within the Portland metro area.
METRO: Solid Waste Department, 1993b	METRO: Solid Waste Department. (July 1993). *Construction industry recycling project.* Portland, Oregon: METRO.	Assessment of an educational, promotional campaign on resource-efficient building practices & materials.
METRO, 1993	METRO. (June 1993). *Residential remodeling waste reduction demonstration project* (Contract No.902741). Portland, Oregon: METRO.	Report on a project to develop, document, and teach cost effective waste reduction techniques for residential remodeling projects. Three project types assessed: Kitchen, Family Room/Kitchen, Bathrooms. Wastes generated during each project's demolition and construction phases were audited to determine the weight and type according to standard classifications used by METRO. Materials that could be diverted were identified and their disposition was recorded. Diversion was defined as source separation, salvage and reuse, and recycling. No effort was made to affect the design or construction of the projects to reduce waste generation.
Milota, West, & Hartley, 2005	Milota, M. *R., West, C. D., & Hartley*, I. D. (2005). Gate-to-gate life-cycle inventory of softwood lumber production. *Wood and Fiber Science, 37*, 47 – 57.	Life cycle inventory of softwood lumber in the Western and Southern United States.
Mithraratne & Vale, 2004	Mithraratne, N., & Vale, B. (2004). Life cycle analysis model for New Zealand houses. *Building and Environment. 39*, 483-492.	Paper describes a method that has been developed at the University of Auckland for a detailed life cycle analysis of an individual house in New Zealand based on the embodied and operating energy requirements and life cycle cost over the useful life of the building.
EPA, 1997	*U.S. Environmental Protection Agency: The Urban and Economic Development* Division. (June 1997). Deco*nstruction - Building disassembly and material salvage: The Riverdale case study*. Upper Marlboro, Maryland.	Deconstruction and disassembly of 2,000 sq. ft. multifamily (4 unit) building in 27-acre Riverdale neighborhood, urban area of Baltimore.
NAHBRC, 1997	*National Association of Home Builders R*esearch Center. (1997). *Deconstruction -Building disassembly and material salvage: The Riverdale case study.*	Information on disassembly and use of salvaged materials
NCSC, 200	North Carolina Solar Center. (2002, June). *Passive solar home design checklist*. Raleigh, North Carolina: North Carolina Solar Center.	Extols the benefits of passive solar design. Discusses important design requirements to maximize passive solar benefits.
NEEA, 2007a	*Northwest* Energy Efficiency Alliance. (2007, August). *Single-family residential existing construction stock assessment.* Sonoma, California: RLW Analytics.	Single-family residential existing construction stock characteristics
NEEA, 2007b	*Northwest Energy Efficiency Alliance.* (2007, March). Single-family residential new *construction characteristics and practice study: Final report* [Brochure]. Sonoma, California: RLW Analytics.	Single-family residential new construction stock characteristics and practices study
NEEA, 2007c	*Northwest Energy* Efficiency Alliance. (2007, October). Residential new construc*tion (single and multifamily) billing analysis* [Brochure]. Sonoma, California: RLW Analytics: RLW Analytics	Residential New Construction (Single and Multifamily) Billing Analysis - contains average new construction energy
NPCC, 2005	*Nor*thwest Power and Conservation Council. (2005, May). The fifth Northwest electric power and conservation *plan.*	Comprehensive plan for electric power generation in Northwest US. The

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	Portland, Oregon: NPCC. Retrieved online from http://www.nwcouncil.org/energy/powerplan/5/Default.htm	appendices contain a wealth of data.
O'Brien, Guy, & Linder, 2006	O'Brien, E., Guy, B., & Linder, A. (2006). Life cycle analysis of the deconstruction of military Barracks: Ft. McClellan, Anniston, AL. *Journal of Green Building, 1*(4), 166-183.	Report on the LCA for manual deconstruction of military barracks at Ft. McClellan in Anniston, Alabama. Several manual deconstruction scenarios were compared. Study compared manual deconstruction to mechanical demolition. Found materials salvaged using either 100% or 44% manual deconstruction and reused within a 20-mile radius of the deconstruction site yielded the most favorable environmental and health impacts.
ODEQ, 2007	*Oregon Department of Environmental* Quality (2007, February). *Waste prevention strategy – Background paper #1 solid waste generation in Oregon*. p. 2	
ODEQ, 2002	*Oregon Department of Environmental Quality* (2002). *2002 Waste Composition Study.* http://www.deq.state.or.us/lq/sw/disposal/wastecompositionstudy.htm	Categorizes waste types collected in the state.
Ortiz, Francesco, & Sonnemann, 2009	Ortiz, O., Francesco, C., & Sonnemann, G. (2009). *Sustainability in* the construction industry: A review of recent developments based on LCA. *Construction and Building Materials, 23*. Retrieved from http://www.sciencedirect.com	LCA of construction practices in the construction industry
Osman & Ries, 2007	Osman, A., *& Ries, R. (2007). Life cycle assessment of electrical* and thermal energy systems for commercial buildings. *International Journal of Life Cycle Assessment. 12 (5)*, 308–316.	Article addresses developing LCA models for energy systems in order to assess the potential environmental impacts that might result from meeting energy demands in buildings. The scope of the study includes LCA models of the average electricity generation mix in the USA, a natural gas combined cycle (NGCC) power plant, a solid oxide fuel cell (SOFC) cogeneration system; a microturbine (MT) cogeneration system; an internal combustion engine (ICE) cogeneration system; and a gas boiler.
Passer, Cresnik, Schulter, & Maydl, 2007	Passer, A., Cresnik, G., Schulter, D., & Maydl, P. (2*007). Life cycle assessment of buildings* comparing structural steelwork with other construction techniques. *2007 Life Cycle Management Conference.*,	LCA shows the results of a pre-feasibility study to identify future calls for actions for the construction industry towards sustainability: Three office buildings with load bearings systems made of reinforced concrete, steel and timber were compared.
Paulsen & Borg, 2003	Paulsen, *J. H., & Borg, M. (2003). A building sector* related procedure to assess the relevance of the usage phase. *International Journal of Life Cycle Assessment, 8 (3)*, 142-150.	Concern that there is a lack of structured procedures to include a building's use-phased impacts in LCA studies. Article develops a procedure for assessing the relevance and the possibility to include the usage. Phase 1 is proposed in a structured way. Considerable effort has also been put into explaining the underlying obstacles of today's practice in handling the connection between the choice of building products and its resulting impacts in the usage phase.

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Pennington et al., 2004	Pennington, D. W., Potting, J., Finnveden, G., Lindeijer, E., Jolliet, O., Rydberg, T., et al. (2004). Current impact assessment practice. *Life cycle assessment Part 2: Environment International*, *30* pp. 721-739.	Article highlights how practitioners and researchers from many domains have come together to provide indicators for the different impacts attributable to products in the life cycle impact assessment (LCIA) phase of life cycle assessment (LCA).
Perez-Garcia, Lippke, Briggs, Wilson, Bowyer, & Meil, 2005	Perez-Garcia, J., Lippke, B., Briggs, D., Wilson, J.B., Bowyer, J., & Meil, J. (2005). *The Environmental perfor*mance of renewable building materials in the context of residential construction. *Wood and Fiber Science. 37*, 3 – 17.	Life cycle assessment (LCA) of alternative building materials from forest resource regeneration or mineral extraction through product manufacturing, the assembly of products in constructing a residential home, occupancy and home repairs, and the eventual disposal or recycle.
Peuportier, 2001	Peuportier, B. L. P. (2001). *Life cycle assessme*nt *a*pplied to the comparative evaluation of single family houses in the French context. *Energy and Buildings*, *22*, 443-350.	Life cycle simulation tool is developed and linked with thermal simulation. Using the LCA simulation tool, three houses are evaluated: the present construction standard in France (reference), a solar, and a wooden frame house.
Puettmann & Wilson, 2005a	Puettmann, M. E., & Wilson, J. *B. (2005). Life-cycle* an*al*ysis of wood products: Cradle-to-gate LCI of residential wood building materials. *Wood and Fiber Science*, *37*, 18-29.	Compares cradle-to-gate total energy and major emissions for the extraction of raw materials, production, and transportation of the common wood building materials from the CORRIM 2004 reports. A life cycle inventory identified the raw materials, including fuel resources and emission to air, water, and land for glued-laminated timbers, kiln-dried and green softwood lumber, laminated veneer lumber, softwood plywood, and oriented strandboard.
Puettmann & Wilson, 2005b	Puettma*nn, M. E., & Wilson, J. B.* (2005). Gate-to-gate life-cycle inventory of glued-laminated timbers production. *Wood and Fiber Science*, *37*, 99 – 113.	Full gate-to-gate life cycle inventory for the production of glued-laminated timbers (glu-lam) produced in two regions of the United States: the Pacific Northwest and Southeast. Data collected from surveys of manufacturers are presented for energy requirements, raw materials use, and emissions to land, water, and air allocated for one cubic meter and 1,000 cubic feet of glu-lam.
Rebitzer et al. 2004	Rebitzer, G., Ekvall, T., Frischknecht, R., Hunkeler, D., Norris, G. Rydberg, T., et al. (2004*). Life cycle assessment Part* 1: Framework, goal and scope definition, inventory analysis, and applications. *Environment International*, *30*, 701-720.	Part 1 in a series of two, this paper introduces the LCA framework and procedure, outlines how to define and model a product's life cycle, and provides an overview of available methods and tools for tabulating and compiling associated emissions and resource consumption data in a life cycle inventory (LCI). It also discusses the application of LCA in industry and policy making.
Sartori & Hestnes, 2007	Sartori, I., & Hest*nes, A. G. (2007). E*nergy use in the life cycle of conventional and low-energy buildings: A review article. *Energy and Buildings*, *39*. Retrieved from http://www.sciencedirect.com.	Literature review of a building's LCA energy use. Includes review of 60 buildings in 9 countries.

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Schenck, R. 2009	Schenck, R. (2009). *The Outlook and Opportunity for Type III Environmental Product Declarations in the United States of America: A Policy While Paper.* Institute for Environmental Research and Education.	Discussion of the context of ecolabelling and environmental product declarations.
Scheuer & Keoleian, 2002	Scheuer, C. W., & Keoleian, G. A. (2002). *Evaluation of LEED using life cycle assessment methods.* Gaithersburg, Maryland: U.S. Department Of Commerce.	Detailed & lengthy report on using LCA to evaluate LEED.
Schmidt, Jensen, Clausen, Kamstrup, & Postlethwaite, 2004	Schmidt, A. C., Jensen, A. A, Clausen, A. U., Kamstrup, O., & Postlethwaite, D. (2004). A comparative life cycle assessm*ent of building insulation products made of sto*ne *woo*l, paper wool and flax - Part 2 Comparative assessment. *International Journal of Life Cycle Assessment, 9(2)*, 122-129.	LCA information on insulation materials
Shah, Col Debella, & Ries, 2008	Shah, V.P., Col Debella, D., & Ries, R.J. (20*08). Life cycle assessment of res*idential heating and cooling systems in four regions in the United States. *Energy and Buildings, 40: 503-513*. Retrieved from http://www.sciencedirect.com.	Home HVAC systems responsible for most energy consumption & emissions of all home systems. Compares LCA impacts of 3 types HVAC in 4 U.S. locations over 35 year life.
Shami, 2006	Shami, M. *(2006). A comprehensive review of building deconstruction and salvage:* Deconstruction benefits and hurdles. *International Journal Environmental Technology and Management, 6 (3/4)*, 236-291.	Paper addresses the benefits of building deconstruction as an alternative to building demolition. Discusses technical, environmental, and socioeconomic issues of deconstruction.
Sharrard, 2007	Sharrard, A. (2007) Greening Construction Processes Using an Input-Output-Based Hybrid Life Cycle Assessment Model. PhD Thesis, Carnegie Mellon University	Thesis includes a wide variety of information regarding construction practices, combined with an economic input-output approach to quantifying environmental impacts
University of Alaska, 2006	*University of* Alaska, Fairbanks Cooperative Extension Service. (2006, November). *Passive solar heating: An energy factsheet* (EEM-01258). Fairbanks, Alaska: University of Alaska.	Brochure debunks the misconception that passive solar building design cannot be accomplished in Alaska. Provides information on the value of passive solar design in Alaska as an efficient & inexpensive method to heat buildings.
Unknown, 2006	*Unknown. (2006, Dec*ember). *Design for disassembly in the built environment: DfD case study home: 71 Boulevard, Atlanta, GA 30312*.	Case study of a house that has been designed for future disassembly. Includes recommendations and advice on what to consider when designing a building for disassembly.
University of Florida, 2003	*University of Florida: Powell* Center for Construction and Environment. (2003, January). *Final report: Design for deconstruction and reuse.* Gainesville, Florida: University of Florida.	Report on the benefits of designing buildings for deconstruction. Addresses the dangers of current building design process & application. Assessed old building waste & new building design. Used cases studies for deconstruction of an old building and a new building using deconstructed materials from the old building.
Upton, Miner, Spinney, & Heath, 2008	Upton, B., Miner, R., Spinney, M., & Heath, L. S. (2008). The greenhouse gas *and energy impacts o*f *using woo*d instead of alternatives in residential construction in the United States. *Biomass and Bioenergy*, *32m, 1-10.* Retrieved from http://www.elsevier.com/locate/biombioe	Article estimates savings of greenhouse gas emissions and energy consumption associated with use of wood-based building materials in residential construction in the United States. Using LCA for energy consumption & GHG emissions compares wood based building construction to other construction materials (masonry, steel).

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US DOE, 2000a	U.S. Department of Energy, Office of Building T*echnology, State and Community Programs, Office of Energy Efficiency and Rene*wable Energy. (2000, October). Advanced wall frami*ng: Build efficiently, use less material, and save energy!* (DOE/GO-102000-0770). Washington, D.C.: U.S. DOE.	Advanced framing techniques
US DOE, 2000b	*U.S. Dep*artment of Energy, Office of Energy Efficiency and Renewable Energy. (2000, November). *Passive solar design:* (DOE/GO-102000-728). Golden, Colorado: US Department of Energy.	Brochure on incorporation of passive solar measures in federal facilities.
US DOE, 2000c	*U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. (2000, December). Passive* solar design: Increase energy efficiency and co*mfort in homes by incorporating passive solar design features* (DOE/GO10099-790). Washington, D.C.: U.S. DOE.	Booklet with information on passive solar design benefits & design requirements.
US DOE, 2001	*U.S. Dep*artment of Energy, National Renewable Energy Laboratory. (2001, February). *Passive solar design for the home* (DOE/GO-102001-1105). Washington, D.C.: U.S. DOE.	Brochure with information on passive solar design for houses.
US EPA, 1998	*U.S. Environmental Protection Agency: Municipal and Industrial Solid Waste Division.* (1998, June). Characterization of building-related construction and demolition *debris in the United States.* Office of Solid Waste (Report No. EPA530-R-98-010). Washington, D.C.: U.S. EPA.	Report characterizes the quantity and composition of building related construction and demolition (C&D) debris generated in the United States, and summarizes the waste management practices for this waste stream. C&D debris is produced when new structures are built and when existing structures are renovated or demolished.
US EPA, 2003	*U.S. Environmenta*l Protection Agency. (2003). *Estimating 2003 building-related construction and demolition materials amounts.* Washington, D.C.: U.S. EPA.	The purpose of this study is to determine the amount of building-related C&D (construction and demolition) materials generated and recovered in the U.S. during 2003, and updating the findings of the 1998 EPA report, *Characterization of Building-Related Construction and Demolition Debris in the United States* (EPA 530-R-98-010). C&D materials are generated when new structures are built and when existing structures are renovated or demolished (including deconstruction activities).
US EPA, 2006	*U.S. Environmenta*l Protection Agency. (2006). *SOLID WASTE MANAGEMENT AND GREENHOUSE GASES: A Life-Cycle Assessment of Emissions and Sinks.* Third Edition. Washington, D.C.: U.S. EPA.	Provides estimates of the impact of disposing of various materials by a variety of routes.
US HUD, 2000	U.S. *Department of Housing a*nd Urban Development, Office of Policy Development and Research. (February 2000). *A guide to deconstruction.* Washington, D.C.: U.S. Department of Housing and Urban Development.	Report on building deconstruction opportunities as a way to reduce waste as well as provide economic benefits, job training, environmental improvement, etc.
Utama & Gheewala, 2008	Utama, *A., & Gheewala, S. H.* (2008). Influence of material selection on energy demand in residential houses. Journal M*aterials and Design*. Retrieved from http://www.elsevier.com/locate/matdes. doi:10.1016/j.matdes.2008.08.046.	Article using LCA assesses utilizing local materials for improving the energy demand in the single landed houses in Indonesia.
Werner & Richter, 2007	*Werner, F., & Richter, K. (2007). Wooden building products* in *compar*ative LCA: A literature review. *International Journal of Life Cycle Assessment: A Literature Review. 12*	Review LCA literature on results of approximately 20 years of international research on the environmental impact of

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	(7), 470–479.	the life cycle of wood products used in the building sector compared to functionally equivalent products from other materials.
Wilson & Dancer, 2005a	Wilson*, J. B., & Dancer, E. R.* (2005). Gate-to-gate life-cycle inventory of laminated veneer lumber production. *Wood and Fiber Science*, *37*, 114-127.	A life cycle inventory (LCI) study of laminated veneer lumber (LVL) manufacturing. Gate-to-gate study includes all environmental impacts from the logs to produce either veneer or parallel laminated veneer (PLV) as input to the LVL process, through production of the LVL. The study includes all materials, fuels, and electricity inputs to produce LVL and related co-products and emissions.
Wilson & Dancer, 2005b	*Wilson, J. B., & Dance*r, E. R. (2005). Gate-to-Gate life cycle inventory of I-joist production. *Journal of Wood and Fiber Science*, *37*, 85-94.	LCI data on I-joist beams.
Wilson & Sakimoto, 2005	*Wilson, J. B., & Saki*moto, E. T. (2005). Gate-to-gate life-cycle inventory of softwood plywood production. *Wood and Fiber Science*, *37*, 58-73.	Article on life cycle inventory (LCI) of softwood plywood manufacturing. Gate-to-gate study includes all materials, fuels, and electricity inputs to produce plywood, co-products, and emissions.
Winistorfer, Chen, Lippke, & Stevens, 2005	Winistorfer, P., Chen, Z., Lippke, B., & Stevens, N. (2005). Energy consump*tion and greenhouse gas em*issions related to the use, maintenance, and disposal of a residential structure. *Wood and Fiber Science*, *37*, 128-139.	Virtual residential houses in Atlanta, Georgia, and Minneapolis, Minnesota, were analyzed to determine energy consumption and greenhouse gas emission during the building use, maintenance, and demolition phases of their life cycle.
Wittstock, Makishi, Braune, Kreissig, Gallon, & Wetzel, 2007	Wittstock, B., Makishi, C., Braune, A., Kreissig, J., *Gallon, N., & Wetzel, C. (2007). Iden*tifying environmental improvement potentials of residential buildings. *2007 Life Cycle Management Conference.*	Addresses options to reduce the environmental impacts from residential dwellings throughout their entire life cycle. The main objective of the study is to outline the current situation of residential buildings in the EU-25, to assess environmental improvement options for new and existing buildings and to evaluate the improvement potentials from a European perspective.
Washington State University, 2006	Washington State University Extension Energy Program. (2006). "Framing," in *WSEC builder's field guide* (7th ed.). Washington State University Extension Energy Program.	Discussion of different kinds of framing techniques and construction materials, as well as doors & windows.
AHS Web site a	U.S. Census Bureau. (2009). *American housing survey.* Retrieved June, 10, 2009, from http://www.census.gov/hhes/www/housing/ahs/ahs.html	Website with data and information on the US Census Bureau's American Housing Surveys
AHS Web site b	U.S. Census Bureau. (2009). 2002 AHS metropolitan alterations and replaceme*nts*. Retrieved June, 10, 2009, from http://www.census.gov/hhes/www/housing/ahs/ahs02alt/portland/tab1-3.html	AHS page on home remodeling data.
BECRC Web site a	Building Energy Codes Resource Center. (2009). Drywall clips - code *notes*. Retrieved June, 10, 2009, from http://resourcecenter.pnl.gov/cocoon/morf/ResourceCenter/article//133	Web site with an article on the use of drywall clips in wall construction.
BECRC Web site b	Building Energy Codes Resource Center. (2009). Advanced fr*aming*. Retrieved June, 10, 2009, fromhttp://resourcecenter.pnl.gov/cocoon/morf/ResourceCenter/article/1399.	Web site with an article on the use of advanced framing in building construction.

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EAI Web site	Energy Information Administration. (2009). Consumption, price and expenditure estimates: State energy data system (SEDS). Retrieved June, 10, 2009, from http://www.eia.doe.gov/emeu/states/_seds.html.	Official energy statistics from U.S. government.
ICFA Web site	Insulating Concrete Form Association. (2009). Retrieved June, 10, 2009, from http://www.forms.org/index.php.	Trade association Web site providing resources regarding ICFs.
McCoy's Web site a	McCoy's Building Supply. (2009). What is deconstruction? Retrieved June, 10, 2009, from http://www.mccoys.com/library/construction-and-demolition-debris-management-deconstruction. I	Article that explains building deconstruction with links to other related articles.
McCoy's Web site b	McCoy's Building Supply. (2009). Advanced fr*aming techniques*. Retrieved June, 10, 2009, from http://www.mccoys.com/Library/Advanced-Framing-Techniques.	Article that explains advanced framing techniques with links to other related articles.
McCoy's Web site c	McCoy's Building Supply. (2009). Using passive solar heating in you*r home*. Retrieved June, 10, 2009, from http://www.mccoys.com/library/using-passive-solar-heating-your-home.	Article on passive solar heating in homes.
McCoy's Web site d	*McCoy's* Building Supply. (2009). Less is more: Demand a house with less framing, less waste, and better performance. Retrieved June, 10, 2009, from http://www.mccoys.com/library/Less+is+More%3A+Demand+a+House+with+Less+Framing%2C+Less++Waste%2C+and+Better+Performance+	Article on using fewer materials to build a house.
PCA Web site	Portland Cement Association. (2009). Concrete home*s*. Retrieved June, 10, 2009, from http://www.cement.org/homes/ch_bs_icf.asp. Internet; accessed 10 June 2009	Trade association providing information on the benefits of Portland cement in the building industry.
SIPA Web site	Structural Insulated Panel Association. (2009). SIP R-values (Calcu*lated R-Values).* Retrieved June, 10, 2009, from http://www.sips.org/content/technical/index.cfm?PageId=159.	Trade association Web site addressing the benefits of SIPs.
UM Web site	Center for Sustain*able Building Research, College of Architecture and Landscape Architecture, Univ*ersity of Minnesota (2009). Minnesota building materials database: A tool for selec*ting sustainable materials*. Retrieved June, 10, 2009, from http://www.buildingmaterials.umn.edu/index.html.	Web page providing resources, links, and a tool for selecting sustainable building materials
VC Web site	Ventura County, California. (2009). Commercial recycling, green business. Retrieved June, 10, 2009, from http://portal.countyofventura.org/portal/page?_pageid=876,1708604&_dad=portal&_schema=PORTAL	Article on Ventura's experience with recycling building construction and demolition waste.
Wikipedia, 2009	Insulating concrete forms. (June 2009). In Wikipedia, *the free encyclopedia*. Retrieved June 10, 2009, from http://en.wikipedia.org/wiki/Insulated_concrete_forms.	Wikipedia article on ICFs.