ANALYSIS OF THE LIFE CYCLE IMPACTS AND POTENTIAL FOR AVOIDED IMPACTS ASSOCIATED WITH SINGLE-FAMILY HOMES

United States
Environmental Protection
Agency

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BACKGROUND

The construction sector is a key industrial economic sector engaged to construct, modify, renovate, and demolish buildings and infrastructure. It is composed of establishments that build and prepare sites for residential, industrial and commercial buildings as well as sewers, roads, bridges, and other infrastructure projects. The construction sector responds to the nation's population and economic growth pressures, produces needed buildings and infrastructure, provides diverse jobs and incomes, and helps maintain the economic vitality of the small business sector.

Benefits of Construction

In 2008, construction yielded over 9 million jobs, making it one of the United States' largest industrial and economic sectors.[1] Construction provides an array of jobs to individuals of diverse educational and technical backgrounds, including truck drivers, accountants, engineers, economists, contractors, managers, and business owners.[2] Construction is a robust industry partly due to the existence of a variety of market niches that enable small businesses to thrive. For example, in 2007, 62% of establishments within the construction sector employed fewer than five employees.[3]

The vitality of the construction sector is also a key indicator of the health of the U.S. economy. The Economics and Statistics Administration (ESA) recognizes twelve Principal Federal Economic Indicators, two of which examine construction activity: *Construction Spending* and *New Residential Construction*. The U.S. Census Bureau and Bureau of Economic Analysis tracks overall construction, but also, the construction of private residential structures, such as single-family homes and apartment buildings.[4] This information can be used to identify national economic trends or to estimate the vitality of single-family home construction.

Single-family home construction in the U.S. is a significant economic activity. In 2007, single-family home construction accounted for 33% of the overall work value in the construction sector.[5] Single-family home construction provides economic benefits similar to those of the building construction sector at large, such as job creation and the generation of tax revenues from worker incomes, business owner profits, material sales, building permit approvals and extensions of utility services.[6]

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[1] Career Guide to Industries, 2010-11 Edition, Bureau of Labor Statistics, United States Department of Labor, http://www.bls.gov/oco/cg/cgs003.htm#emply, Accessed May 04, 2011

[2] Ibid.

[3] Sector 23: EC0723SG02: Construction: Summary Series: General Summary: Selected Statistics for Establishments by Employment Size Class: 2007, 2007 Economic Census, U.S. Census Bureau, http://factfinder.census.gov/servlet/IBQTable?_bm=y&-_clearIBQ=Y&-ds_name=EC0723SG02&-ib_type=NAICS2007&-_lang=en, Accessed May 04, 2011

[4] About Economic Indicators, Economics and Statistics Administration, United States Department of Commerce, http://www.esa.doc.gov/about-economic-indicators, Accessed May 04, 2011

[5] Sector 23: EC0723SG05: Construction: Summary Series: General Summary: Value of Construction Work for Establishments by Geographic Area and Type of Construction: 2007, 2007 Economic Census, U.S. Census Bureau, http://factfinder.census.gov/servlet/IBQTable?_bm=y&-_clearIBQ=Y&-ib_type=NAICS2007&-ds_name=EC0723SG05&-NAICS2007=236115&-_lang=en), Accessed May 04, 2011

[6] Economic Benefits of New Home Construction, Housing's Economic Impact, National Association of Home Builders, http://www.nahb.org/fileUpload_details.aspx?contentID=155811, Accessed May 04, 2011

The Green Building Movement

While construction meets economic growth demands and provides an array of economic and societal benefits, it is also a resource-intensive activity. The environmental impacts associated with buildings do not end with their construction, but continue throughout their use, renovation, and end of life. At end of life, building demolition materials embody all the upstream impacts associated with delivering and operating buildings, including soil erosion, top soil loss, habitat disruption, natural resource depletion, water and air pollution, climate disruption and land expenditure. Since the early 1990s, stakeholders have been investing efforts to conceptualize and guide ways in which to lessen building impacts. Early milestones in the U.S. include:

- Committee on the Environment, formed by the American Institute of Architects (AIA) (1989)
- Environmental Resource Guide, published by the AIA, funded by the EPA (1992)
- ENERGY STAR program, launched by the EPA & the U.S. Department of Energy (1992)
- First local green building program, introduced in Austin, TX (1992)
- U.S. Green Building Council (USGBC), founded (1993)
- "Greening of the White House", launched by the Clinton administration (1993)
- Leadership in Energy and Environmental Design (LEED) version 1.0 pilot program, launched by the USGBC (1998)[7]

Green building introduced the concept of sustainability into the design, construction, operation, maintenance, renovation, and demolition processes. The result has been high-efficiency structures derived through more sustainable processes. Green buildings consume less energy, water and other resources, protect occupant health, pollute less, and generate less waste. For example, green buildings may incorporate sustainable materials in their construction (e.g., reused, recycled-content, or made from renewable resources); create healthy indoor environments with minimal pollutants (e.g., reduced product emissions); and/or feature landscaping that uses less water (e.g., native plants that survive without extra watering).[8]

In 2006, the Associated General Contractors of America (AGC; http://www.agc.org) created an Environmental Agenda, which lists seven goals. Four of these goals relate directly to materials management:

1. Encourage environmental stewardship through education, awareness and outreach.
2. Recognize environmentally responsible construction practices.
3. Identify opportunities to reduce the impact that construction practices have on the environment, including:
    - Facilitating members' efforts to recycle or reduce construction and demolition debris.
    - Identifying and maximizing the contractor's role in "green" construction

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[7] Green building, U.S. Environmental Protection Agency, http://www.epa.gov/greenbuilding/pubs/about.htm, Accessed May 06, 2011

[8] Ibid.

4. Identify ways to measure and report environmental trends and performance indicators of such trends.

In 2010, AGC released its *Building a Green Future* report, which "outlines measures designed to stimulate demand for green construction projects, boost infrastructure capacity, improve building efficiency and green construction practices." Other efforts undertaken by the construction industry to reduce the impacts of the sector include the following:

- **The National Association of Home Builders** (NAHB; http://www.nahb.org) issued Green Home Building Guidelines that contractors can follow to make their homes more "green," including reducing, reusing, and recycling construction waste. They also host an annual Green Building Conference that brings together contractors and researchers to discuss new "green" construction techniques. The NAHB Research Center also pursued research in the area of C&D materials recycling, such as using the material on-site.

- **The Building Materials Reuse Association** (BMRA; http://www.buildingreuse.org) facilitates building deconstruction and the reuse and recycling of recovered building materials. They produce information on deconstruction techniques and information on how to make a successful deconstruction or reuse business. They convene annually to transfer this knowledge among contractors, government representatives, and researchers.

- **The Construction Materials Recycling Association** (CMRA; http://www.cdrecycling.org) aids their members in the appropriate methods for processing material to ensure environmental protectiveness, as well as producing a high-value product. They have developed websites to reach out to any recyclers, users of recycled materials, and regulators in order to provide a better understanding of C&D materials recycling. They have developed websites that contain research and practical information for the recycling of concrete (http://concreterecycling.org), drywall (http://drywallrecycling.org), and asphalt shingles (http://shinglerecycling.org).

- **The National Demolition Association** (NDA; http://www.demolitionassociation.com) actively promotes recycling and reuse of the materials generated during a demolition. They released a report titled, "Demolition Industry Promotes C&D Recycling," in which they describe ways that the industry and government can work together to overcome recycling barriers. The "members of the National Demolition Association are committed to increasing the recycling and reuse of the material generated" on their jobsites. They state that "recycling is good for the environment, good for the nation's economy, a positive use of valuable commodity, and good for the country."

Today, various LEED initiatives including legislation, executive orders, resolutions, ordinances, policies and incentives can be found in 45 states, including 442 localities, 35 state governments, 14 federal agencies or departments, and numerous public school jurisdictions and institutions of higher education across the United States.[9] In addition, green building was projected to contribute $554 billion to the U.S.

[9] USGBC: Policy and Government Resources: http://www.usgbc.org/DisplayPage.aspx?CMSPageID=1779, Accessed October 03, 2011

gross domestic product between 2009 and 2013, and the green building industry was expected to generate 7.9 million jobs through 2013.[10]

Environmental Justice

While the impacts that buildings cast on human health and natural environment have been largely recognized, their meaning for low-income strata has not consistently stayed in the forefront. Pursuing green building goals with awareness and regard for the implications on low-income households can advance environmental justice in the future.

The concept of environmental justice calls for the protection of vulnerable populations by preventing environmental threats. Unfair land use patterns place some people in proximity to pollution from industrial and non-industrial facilities. The lack of affordable housing opportunities for low-income households in new-construction markets tends to keep them in these polluted environments and/or older, existing structures. A negative effect of residing in older structures is the increased exposure to toxic building materials, mold and allergens. Prior to 1978, lead was commonly used for products such as home paint or plumbing and furniture. Chipping lead-based paint is the most common source of lead poisoning in children because of how easily it is ingested. If in good condition, lead paint may not be an issue, but under substandard conditions where paint is peeling or chipping around windows and doors, railings and fences, the presence of lead is a genuine risk.[11]

Considering that the means of exposure of low-income strata include proximity to pollution from industrial and non-industrial facilities and exposure to potentially toxic materials, mold, and allergens inside older homes, green building goals become even more important. Reducing the demand for new materials, minimizing the production of new materials through salvage and recycling, producing materials that are derived through cleaner production processes, and phasing out the use of toxic materials target some of the environmental injustices described above. Additional environmental justice goals met by the practice of green building may include safe distancing of residential land uses from polluting facilities and landfills, educating vulnerable communities about potential hazards and ways to protect themselves, educating home dwellers on proper home operation and maintenance, and better positioning minority and low-income households in new construction markets.

EPA & Sustainable Materials Management: The Road Ahead

In 1976, Congress enacted the Resource Conservation and Recovery Act (RCRA) to initiate efforts to manage municipal and industrial solid waste generated nationwide. RCRA's goals are:

- To protect human health and the environment from the potential hazards of waste disposal
- To conserve energy and natural resources
- To reduce the amount of waste generated; and
- To ensure that wastes are managed in an environmentally sound manner.

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[10] USGBC: Information: https://www.usgbc.org/ShowFile.aspx?DocumentID=1991, Accessed October 03, 2011
[11] http://www.epa.gov/lead/pubs/leadinfo.htm#

Over its initial two decades, RCRA programs have accomplished considerable achievements. For example, post-consumer municipal and industrial solid waste recycling rates have risen, uncontrolled dumping of hazardous waste had been curtailed, and a large portion of contaminated sites have been cleaned up.[12] However, critics of RCRA have indicated that the program has not sufficiently focused on actions to prevent upstream pollution.[13]

In 2003, in *Beyond RCRA: Prospects for Waste and Materials Management in the year 2020* (2020 Vision), after a joint analysis with state environmental officials, EPA introduced a new direction for RCRA. RCRA's focus was to shift from *waste* management to *materials* management. The rationale for the change stood in the need to become more resource efficient, and the efficient use of resources would require wastes under RCRA to become resources (materials), where possible. Thus, within such a system, RCRA programs would need to focus on managing materials, not wastes, to ensure the protection of human health and the environment. Life cycle analysis would become the main feature of materials management since it would provide insight into where in the life cycles of these resources, risks from the chemicals could emerge or how and when materials would truly become waste.

In 2009, EPA released *Sustainable Materials Management: The Road Ahead*, which provides an analysis of the major materials, products, and services in the U.S. economy and their associated environmental impacts. The report ranks 480 materials, products and services based on 17 environmental impact categories (EPA, 2009). EPA identified the construction of new single-family homes as one of the most significant sources of life cycle environmental and resource use impacts in the U.S. To better understand this finding and identify strategic opportunities for reducing or avoiding the life cycle impacts associated with single-family homes, EPA conducted a further detailed analysis of the sources, types, and relative magnitudes of these impacts.

About this Study[14]

The purpose of this study, *Analysis of the Life Cycle Impacts and Potential for Avoided Impacts Associated with Single-Family Homes,* was to identify strategic opportunities for reducing or avoiding life cycle impacts associated with single-family homes. It is documented that the dominant contributor to most environmental impacts of single-family homes across a life cycle is energy use (Oregon DEQ, 2010). Energy efficiency has long been a topic of research and an area of focus when identifying opportunities for reducing the impacts of single-family homes.[15] However, materials also matter.

The first objective for this study was to quantify the environmental impacts embodied in materials, products and services consumed during the life cycle of single-family homes, and rank-order these inputs

[12] Beyond RCRA, Waste and Materials management in the Year 2020, United States Environmental Protection Agency, Office of Solid Waste, 2003, http://www.epa.gov/osw/inforesources/pubs/vision.pdf, Accessed on May 9, 2011

[13] Ibid.

[14] This study focuses on single-family housing, but in July 2010, the EPA funded development of another follow-on report to the Sustainable Materials Management Relative Ranking Analysis that analyzes the life cycle impacts associated with "new office, industrial and commercial building construction." The full report is included in Appendix H.

[15] Two examples at the federal level include the Energy Star program and associated Energy Star Qualified New Homes, which was launched by the U.S. EPA and the Department of Energy (DOE) to recognize homes that were substantially more energy efficient than the model energy code. DOE developed a number of other programs through the Office of Energy Efficiency and Renewable Energy (EERE). See Homes: energy.gov, http://www.energy.gov/energyefficiency/homes.htm, Accessed May 13, 2011

according to the magnitude of their embodied impacts. Several of the top-ranked materials and products were analyzed to pinpoint the specific supply-chain processes where their most significant impacts in the context of single-family homes were occurring. In addition to analyzing the upstream processes for a select group of top-ranking materials and products, EPA analyzed the impacts of all of the supply-chain processes needed to deliver and operate new single-family homes in the U.S.

The second objective for this study was to propose example changes and reveal the potential for reducing impacts across diverse environmental impact categories if these changes were to be incorporated on a national scale. Proposed changes encompassed optimizing the end-use energy efficiency of homes as well as increasing recycling and reuse of select building materials.

The third objective for the study was to state environmental justice and affordable housing issues as they pertained to the results of the analysis. Increasing the recycling and reuse of building materials may reduce the pollution burdens that disadvantaged households face due to their proximity to polluting facilities. This environmental strategy also helps reduce housing costs, which in turn, should increase low-income households' access to sustainable, green housing. The environmental justice discussion also relayed potential human health and worker safety considerations involved with providing green homes at a lower cost.

EXECUTIVE SUMMARY

Over 110 million residences exist in the United States, almost 70% of which are single-family homes. The range of materials, goods, and services used to construct, maintain, repair, and renovate these homes is complex, involving—directly or indirectly—almost every sector of the U.S. economy. In the report *Sustainable Materials Management: The Road Ahead*, EPA identified the construction of new single-family homes as one of the most significant sources of life cycle environmental and resource use impacts in the U.S.

To better understand this finding and identify strategic opportunities for reducing the life cycle impacts associated with single-family homes, EPA conducted a more detailed analysis of the sources, types, and relative magnitudes of these impacts. This detailed analysis considers all of the life cycle phases—pre-occupancy, occupancy, and post-occupancy—and provides a national, economy-wide strategic view of the environmental impacts associated with single-family homes.[16]

Methodology

An I-O LCA tool was used to analyze life cycle environmental impacts associated with each life cycle phase of single-family homes and to quantify the potential for avoiding those impacts. Life cycle impacts were characterized using the following 17 environmental impact categories from the 2020 Vision Relative Ranking Analysis (EPA, 2009):

1. Abiotic depletion potential (ADP)
2. Land use competition (LUC)
3. Global warming potential (GWP)
4. Stratospheric ozone depletion potential (ODP)
5. Human toxicity potential (HTP)
6. Freshwater aquatic ecotoxicity potential (FAETP)
7. Marine aquatic ecotoxicity potential (MAETP)
8. Terrestrial ecotoxicity potential (TETP)
9. Freshwater sediment ecotoxicity potential (FSETP)
10. Marine sediment ecotoxicity potential (MSETP)
11. Photochemical ozone creation potential (POCP)
12. Acidification potential (AP)
13. Eutrophication potential (EP)
14. Energy consumption (EC)
15. Water consumption (WC)
16. Material input (MTL)
17. Waste (WST)

The analysis consisted of the following general steps:

[16] This analysis also provides a method for scaling-up the results of site- or unit-focused analyses to evaluate their potential to have a nationally significant impact. The analysis did not attempt to assess the effects of unit- or site-level changes in residential building methods. Rather, it was used to develop insights into where such additional analyses could best be focused.

1. **Identification and analysis of top-ranked supply chain processes, materials, products, and services:**
    - Input contribution analysis was used to evaluate and identify the materials, products, and services directly consumed during the construction and use of single-family homes (“direct inputs”) that contribute most significantly to overall life cycle environmental impacts.
    - Supplemental contribution analyses were conducted for selected direct inputs to characterize the supply chain processes contributing most significantly to the life cycle impacts associated with these selected direct inputs.
    - An output contribution analysis was conducted to holistically identify the upstream supply chain processes in the economy where the most significant sources of life cycle environmental impacts associated with new single-family homes occur.
    - In conjunction with input and output analyses, vector analyses were used to rank order either the direct inputs based on their relative contributions to the overall life cycle impacts of single-family homes, or the upstream supply chain processes associated with the delivery and operation of new single-family homes in the U.S.
2. **Estimation of the potential for avoided impacts:**
    - Results of the I-O LCA, supplemental contribution analyses, and vector analyses were reviewed and hypothetical scenarios for avoided impacts were identified based on their potential to reduce material and resource intensity and/or illustrate the range of policy actions available to address the environmental footprint of single-family homes. The analyzed scenarios can be grouped into two broad groups: energy-efficiency improvement scenario and increased recovery and utilization of recovered materials scenario.

Summary of Findings

Overall Lifecycle Impacts

The analysis of the overall life cycle impacts associated with single-family homes indicates the following:

- The majority of life cycle impacts associated with single-family homes occurs during the occupancy phase. The one exception to this finding is that the majority of life cycle *material input* occurs during the pre-occupancy phase.
- Life cycle impacts associated with the post-occupancy phase are relatively insignificant for all but the waste impact category. However, this finding should not be interpreted to imply that choices regarding the management of building demolition/deconstruction material have an insignificant effect. In fact, when viewed across the life cycle or product boundaries, the recycling and reuse of construction and demolition materials can significantly offset impacts associated with the input of virgin material into construction and renovation of single-family homes, other buildings and infrastructure. Section 5.3 of the report explores several pathways by which increased recycling and reuse of products and materials recovered from single-family homes offset impacts of various other products and industries.
- For the pre-occupancy and occupancy phases, most of life cycle impacts associated with single-family homes are indirect—they result from upstream supply chain processes and are embodied

in the direct inputs to the single-family home. Thus, a policy perspective focused solely on direct inputs (e.g. brick, concrete, wood) without an understanding of the upstream supply chain processes (e.g. manufacturing, distribution) and the associated connections may miss opportunities to effectively reduce the environmental impacts of single-family homes.

Input Contribution Analysis of Life Cycle Impacts of Direct Inputs[17]

The input contribution analysis was conducted to estimate the life-cycle impacts of direct inputs to the pre-occupancy and occupancy phases of single-family homes. The direct inputs were ranked based on their relative contributions to the overall life cycle impacts associated with single-family homes.

- **Pre-Occupancy Phase**
  A diverse mix of direct inputs contributes to the overall life cycle impacts of single-family homes, including building materials (e.g., *brick and structural clay tile*, *ready-mixed concrete*, *reconstituted wood products*), more highly engineered products (e.g., *miscellaneous plastic products*), and services (e.g., *trucking and courier services*).

  Depending on the impact category, impacts associated with the top 10 inputs account for anywhere from just below 2% to just above 16% of the total life cycle impact associated with single-family homes . For some impact categories, the overall life cycle impacts associated with inputs into this phase are the accumulation of impacts across a diverse range of inputs. For other impact categories, the overall life cycle impacts are embodied in a more limited set of inputs.

- **Occupancy Phase.**
  The input contribution analysis for the occupancy phase of single-family homes was focused on energy and water inputs and materials and products replaced during the life span of homes. The analysis highlighted *electric services* and *natural gas distribution* as well as *insulation* and *siding* as some of the top most highly ranked direct inputs.

  Depending on the impact category, top 6 most highly ranked direct inputs contribute anywhere from 20% to 90% of the total life cycle impact associated with single-family homes, with *electric services (utilities)* typically contributing the highest percentage. Thus, opportunities exist to significantly reduce overall life cycle impacts of single-family homes by focusing on a narrow set of inputs used in the occupancy phase, and the most significant reductions could be realized through reductions in electricity consumption and/or impacts associated with upstream supply processes needed for electricity generation and distribution.

Supplemental Analyses of Selected Materials and Products

Select materials, products, and services representing direct inputs to single-family homes were identified for further supplemental analyses based on the results of the input contribution and vector analyses and whether they represented a clearly-defined material or product—i.e., a material or product for which an SMM-oriented policy response could be feasible.

[17] Contribution analyses were conducted for the pre-occupancy and occupancy phases. They were not conducted for the post-occupancy phase due to the limited scope and contribution of impacts associated with this phase relative to the overall life cycle impact associated with single-family homes. See Section 2.3 for additional discussion.

- Fiberglass and mineral wool insulation - The input contribution analyses highlight the significant contribution of *fiberglass and mineral wool insulation* to the overall stratospheric ozone depletion potential (ODP) life cycle impacts of single-family homes. The supplemental analysis suggests that nearly half of the ODP impacts associated with these products occur as a result of the manufacturing phase of *fiberglass and mineral wool insulation*.

- Ready-mixed concrete - The input contribution analysis suggests that *ready-mixed concrete* contributes significantly to a diverse set of life cycle impacts associated with single-family homes, including global warming, photochemical ozone creation, acidification, eutrophication, abiotic depletion, energy consumption, material input, and waste. The supplemental contribution analysis suggests that *hydraulic cement* manufacturing is a key source of embodied impacts in the upstream supply chain, as well as that the manufacture of *ready-mixed concrete* itself is significant due to the associated direct emissions.

- Wood Shingle Siding- The occupancy-phase input contribution analysis suggests that *wood shingle siding* contributes to the life cycle impacts associated with single-family homes primarily based on the land use competition (LUC) factor. *Forestry products* and related services contribute most significantly to the LUC impacts embodied in wood shingle siding, reflecting the geographic footprint of forests managed for wood production. Other embodied impacts of *wood shingle siding* are associated with *electric services* and *sawmills and planing mills*.

- Reconstituted wood products - The input analysis suggests a broad range of impacts associated with *reconstituted wood products*, particularly across the natural resources and land use and pollution impacts. The supplemental analysis suggests that energy consumption and waste impacts can be attributed to the *reconstituted wood products* manufacturing process. Embodied natural resources and land use impacts can be attributed to *forestry products* and related services and *electric services*.

- Brick & Structural Clay Tile - The input contribution analyses suggest that *brick and structural clay tile* contribute significantly to the overall life cycle toxicity impacts associated with single-family homes, particularly human toxicity, marine aquatic ecotoxicity, and freshwater sediment ecotoxicity. The supplemental contribution analysis suggests that direct emissions from the manufacturing of *brick and structural clay tile* account for close to half of these toxicity impacts.

Output Contribution Analysis of Upstream Supply Chain Processes

Whereas the input contribution analysis focuses on the relative contribution of direct inputs to the overall life cycle impacts, the output contribution analysis disaggregates these impacts to their original sources in the upstream supply chain of single-family homes. The output contribution analysis was conducted for the pre-occupancy and occupancy phases of single-family homes, and it highlights energy and related supply chain processes across both of these life cycle phases of single-family homes.

- **Pre-Occupancy Phase**
  The pre-occupancy phase output contribution analysis highlights the supply chain processes of materials, products and services associated with new building construction (e.g., *brick and structural clay tile, sand and gravel, mineral wool, electric services, trucking and courier services, crude petroleum and natural gas* and *coal*).

Depending on the impact category, impacts associated with the top 10 supply chain processes utilized in the pre-occupancy phase account for anywhere from less than 3% to almost 60% of the total life cycle impact associated with single-family homes. The analysis highlights the relative differences in perspectives offered by input and output contribution analysis. The output contribution analysis highlights that about 10% of the overall abiotic depletion potential (ADP) impacts associated with the supply-chain processes of the pre-occupancy phase can be attributed to crude petroleum and natural gas and coal production. From an input contribution perspective, around 2% of the overall ADP impacts associated with the inputs into the pre-occupancy phase can be explained by the top 10 ranked ones. This suggests that petroleum, natural gas, and coal production are part of a number of different supply chains.

- **Occupancy Phase**
  The occupancy phase output contribution analysis highlights supply chain processes associated with replacement materials, e.g., *agriculture, forestry, and fishery services*, *paper and paperboard mills*, and *plastics materials and resins* as inputs to replacement wood products. *Fiberglass and mineral wool insulation* is a rare example of a product for which supply chain processes were highlighted by both pre-occupancy and occupancy phase output analysis; this impactful product is used not only in new construction but also for home maintenance and renovation. Broadly, however, materials associated with new building construction are less important in the supply chain associated with home use. Both pre-occupancy and occupancy phase analyses highlight energy services and related materials.

  Depending on the impact category, impacts associated with the top 10 supply chain processes utilized in the occupancy phase account for anywhere from about 15% to 95% of the total life cycle impacts of single-family homes.

Potential for Avoided Impacts Scenarios

Environmental Impact

Additional analyses were conducted to analyze the potential for avoiding impacts through reduced material and resource use. Included were the following scenarios:

Table ES-1
Avoided Impacts Scenarios Analyzed

Product Category	Scenario	Improvements
End-use electricity	Efficiency improvements associated with electric water heating, space heating, space cooling, refrigeration, and lighting	Efficiency improvements ranging from 12% to 50%, depending on end use
End-use natural gas	Efficiency improvements associated with natural gas water heating and space heating	Efficiency improvements ranging from 6% to 12%, depending on end use
Ready-mixed concrete	Ready-mixed concrete from demolished/ deconstructed single-family homes processed and used as aggregate for roadway construction.	20% increase in recycling of ready-mixed concrete from current levels, resulting in 1% reduction in sand and gravel used as aggregate for roadway construction
Carpets and Rugs	Carpets and rugs removed from single-family homes as a result of renovation and/or demolition/deconstruction processed and used as resin for manufacturing of various synthetic materials.	5% increase in recycling of carpets and rugs from current levels, resulting in a 0.65% reduction in resin from other sources used to manufacture various synthetic materials

Brick and structural clay tile	Brick from demolished/deconstructed single-family homes reused in new construction	15% increase in reuse of old brick in new buildings relative to current levels
Reconstituted wood products	Reconstituted wood products from demolished/ deconstructed single-family homes burned as fuel for power generation in paper and wood products industry	Wood recovery rates increased to a level equivalent to replacing 5% of coal currently consumed by wood and paper products industry

The results of the avoided impacts analysis suggest the following:

- Combined, the energy efficiency improvements and material reuse/recycling scenarios considered in the avoided impacts analysis could result in 5-28% reductions in the life cycle impacts associated with single-family homes.
- Improving efficiencies in lighting, space heating, space cooling and water heating could result in reductions of 12-27% in the life cycle impacts associated with single-family homes across a range of natural resource use, toxicity, and pollution impact categories. The most significant contributions to avoided impacts would result from the efficiency improvements in natural gas water and space heating, lighting, and electric space cooling.
- Improvements in material reuse and recycling rates considered in the analysis could result in reductions of 6-14% in life cycle impacts associated with single-family homes across a range of natural resource, toxicity, and pollution impact categories. The recycling of *carpets and rugs* into resin for various synthetic materials accounted for most of the potential avoided impacts, including 9-13% reductions in life cycle stratospheric ozone depletion potential (ODP) and three categories of ecotoxicity impacts. The increased recycling of salvaged reconstituted wood products as an energy source could offset 7% of life cycle abiotic depletion potential (ADP) and 5% of the life cycle waste (WST) impacts associated with single family homes. While reductions in life cycle impacts could be achieved through increased recycling of concrete and reuse of brick, the contribution of the scenarios considered to reducing overall life cycle impacts associated with single-family homes would be small. However, it is important to note that even if an offset impact for a single material could be small, the sum of such small impacts across the many materials used in single-family homes should result in more significant environmental savings overall.

Environmental Justice & Equity

The avoided impact scenarios quantified the environmental benefits that can accrue from using recovered materials as replacements for virgin materials and improving energy efficiency. The analysis demonstrated how these strategies can help single-family homes perform better environmentally over their life cycles. However, the benefits from implementing the two strategies extend beyond those benefits that can be measured purely by environmental impact categories; use of recovered materials in construction and improvements to home energy efficiency reduce housing costs and environmental pollution and thus, provide social, economic and health benefits to disadvantaged communities. Other co-benefits that result from increasing the recycling and reuse of materials include job creation in local deconstruction and recycling/reuse industries as well as overall community revitalization from any associated economic activity.

Recovered materials are often less expensive than traditional construction materials and their increased incorporation can help reduce both upfront and renovation housing costs in attempts to provide and maintain affordable, green homes. However, for recovered materials to be of service to low-income households, they need to be chosen judiciously. One caution is that potentially harmful materials that had historically circulated in the construction and maintenance of buildings could be reintroduced. The U.S EPA works to promote safe reuse and has gathered useful information, e.g., on how reuse stores and their customers can safely manage older building materials that may contain lead-based paint.[18] Second concern is that depending on the application, the structural and energy-efficiency performance of certain recovered materials may not be adequate. For example, building codes may not allow salvaged lumber for structural applications due to concerns over structural integrity, or a salvaged single-pane window for exterior applications due to energy inefficiency. [19] Finally, for repair and maintenance costs not to overcome the upfront savings, recovered materials need to be sufficiently durable. Materials salvaged from the structures of periods that boasted construction of better quality may be preferential.[20]

Conclusions

The national-scale life cycle analysis uses the I-O LCA approach to consider all of the life cycle phases and provides a national, economy-wide strategic view of the nature, source, and locus of life cycle impacts associated with a key economic activity – construction of single-family homes. The I-O LCA approach provides a method for scaling-up the results of site- or unit-focused analyses to evaluate their potential to have a nationally significant impact.

Broadly, the analysis demonstrates relationships among supply chain processes and suggests the interconnectivity among producers, service providers, and consumers—individuals, businesses, and governments—in the economy. Policy interventions require integrated environmental decision making so as to occur at multiple points in a supply chain, involve multiple stakeholders and policy instruments.

Varying levels of coordination across environmental programs could be necessary to address life-cycle impacts associated with specific inputs. For example, if a material, product, or service contributes significantly to overall life cycle impacts through impact categories that encompass diverse environmental media, a coordinated response among environmental programs, using different authorities, could yield the best approaches. Conversely, if an input contributes significantly to overall life cycle impacts through impact categories affecting a limited number of environmental media, a directed response through a single program or a limited set of authorities might be more effective.

From the perspective of life cycles and products, it is important to consider opportunities to preserve natural capital by reusing and recycling materials at the end-of-life as inputs to upstream supply chain processes associated with production or use phases (e.g., reuse of bricks or hardwood flooring). It is also

[18] U.S EPA, Pollution Prevention and Toxics, 2011, Frequent Questions, General Information about Lead, 2011: http://toxics.supportportal.com/link/portal/23002/23019/Article/32411/Building-material-reuse-stores-sometimes-accept-older-materials-which-have-been-coated-with-lead-based-paint-and-could-pose-a-lead-poisoning-hazard-In-particular-older-windows-and-doors-are-likely-to-, Accessed August 15, 2011.

[19] King County Department of Natural Resources and Parks, Solid Waste Division & City of Seattle Department of Planning and Development, 2006. {Green home remodel} salvage & reuse: http://your.kingcounty.gov/solidwaste/greenbuilding/documents/Green_home_remodel-salvage.pdf, Accessed August 15, 2011.

[20] Ibid.

important to consider opportunities for avoiding impacts in another economic sector (e.g., recycling of carpets and rugs into resin for various synthetic products or recycling of wood panels as fuel).

The affordability and environmental justice discussions suggest that policies or strategies that involve reducing material or energy inputs into single-family homes have the potential to result in co-benefits for low-income communities. These environmental strategies provide meaningful ancillary benefits to help resolve social problems and as such should garner interest and support of various public entities.

1. INTRODUCTION

The U.S. housing stock includes over 110 million units, almost 70% of which are single-family homes.[21] The range of materials, goods, and services used to construct, maintain, repair, and renovate these homes is complex, involving—directly or indirectly—almost every sector of the U.S. economy. In the report *Sustainable Materials Management: The Road Ahead*[22], EPA ranked the construction of new residential 1-unit structures[23] among the top 10 products of the U.S. economy in terms of relative life cycle environmental and resource use impact.[24] The analysis supporting this conclusion considered the life cycle impacts associated with single-family home construction. Additional impacts are associated with the occupancy and demolition or deconstruction of these buildings.

To better understand these findings and identify strategic opportunities for reducing or avoiding the life cycle impacts associated with single-family homes, EPA conducted a more detailed analysis of the sources, types, and relative magnitudes of these impacts. This more detailed analysis considers all of the life cycle phases—pre-occupancy, occupancy, and post-occupancy—and provides a national, economy-wide strategic view of the environmental impacts associated with single-family homes. It identifies the supply-chain processes, materials, products, and services associated with the greatest life cycle impacts and begins to quantify the impacts that could be avoided by reducing the amount of material and resources consumed over the life cycle of a single-family home.

The following report provides additional context, describes the methodology and data sources, and presents results of analyses of the life cycle impacts and the potential for avoided impacts associated with single-family homes. The remainder of this section provides additional background regarding the materials and resources used throughout the life cycle of the "typical" single-family home and describes the general sources of the life cycle impacts. Section 2 describes the methodology and data sources used for the life cycle impact analyses, Sections 3 and 4 respectively, present the results of input and output, more detailed life cycle impact analyses, of the national stock of single-family homes; Section 5 describes the methodology and

[21] According to the American Community Survey (ACS), the U.S. housing stock as of 2009 included 112 million housing units, 63.1% of which were 1-unit detached structures and 5.8% of which were 1-unit attached structures. Attached structures include "town homes or row homes where each housing unit is separated by a ground-to-roof wall and where no housing units are constructed above or below." (DOC, 2009)

[22] For a copy of the report, visit: http://www.epa.gov/epawaste/inforesources/pubs/vision.htm

[23] The U.S. Bureau of Economic Analysis (BEA) input-output tables refer to the economic sector that is the subject of this report as "new residential 1-unit structures" (BEA code 110101). This report uses the term "single-family homes" interchangeably with the BEA definition.

[24] The findings of the report were based on the 2020 Vision Relative Ranking Analysis, which ranked the relative impact of the 480 materials, products, and services included in the U.S. Economic Accounts based on 13 environmental impact categories, including, for example, climate impacts, human toxicity, and ecological toxicity, and four other categories of impact, specifically, material use, waste, water use, and energy use (EPA, 2009).

results of the avoided impacts analysis, and Section 6 summarizes this information and concludes the report.

1.1 DEFINITION OF AVERAGE 1-UNIT RESIDENTIAL STRUCTURE

The 2020 Vision Relative Ranking Analysis, the study used to develop the conclusions of the Sustainable Materials Management report, used an input-output life cycle analysis (I-O LCA) methodology employing economic data available from the U.S. Bureau of Economic Analysis (BEA), as described in Section 1.2. This current analysis adopts a similar approach. The most recent year for which BEA data were available in the Comprehensive Environmental Data Archive (CEDA) tool used to conduct the analysis, was 1998.[25] Therefore, 1998 was used as the reference year for the analysis of life cycle impacts associated with single-family homes.

1.1.1 New Home Construction

In 1998, there were an estimated 104 million residential homes in the U.S., 1.16 million of which were newly built in that year.[26] Wooden structures dominated and continue to dominate the U.S. single-family housing stock. The average size single-family home built in 1998 was 2,190 square feet (sf). In comparison, the average size home built in 1973 was 1,660 sf, and the average size home built in 2009 was 2,392 sf (DOC, 2010). The average size of a single-family home has generally increased over this period, though since a peak in 2007-2008, the average home size has trended downward.

The types and quantities of materials used in single-family home construction vary widely, influenced by factors such as local conditions (e.g., climate, cultural history), building codes, architectural trends, and economic factors (e.g., cost of building materials). Table 1-1 presents a summary of the average quantity of materials used in a single-family home built around 1998.

Table 1-1
Average Quantities of Materials Used in Construction of a Single-family Home in 2000

Item	Average Quantity
Lumber	13,837 board feet
Sheathing	13,118 square feet
Concrete	19 tons
Exterior siding material	3,206 square feet
Roofing material	3,103 square feet
Insulation	3,061 square feet
Wall material	6,050 square feet
Ceiling material	2,335 square feet
Ducting	226 linear feet
Windows	19 units

[25] Although the 2002 BEA data are available now, they were still under development at the time this analysis was conducted.
[26] DOE (2011), Tables 2.2.1 and 2.5.1.

Table 1-1
Average Quantities of Materials Used in Construction of a Single-family Home in 2000

Item	Average Quantity
Exterior doors	4 units (3 hinged, 1 sliding)
Flooring material	2,269 square feet
Interior doors	12 units
Closet doors	6 units
Garage doors	2 units
Fireplace	1 unit
Bathroom fixtures	3 toilets, 2 bathtubs, 1 shower, 3 sinks
Kitchen fixtures	1 sink
Kitchen appliances	1 range, 1 refrigerator, 1 dishwasher, 1 garbage disposal, 1 range hood
Laundry appliances	1 washer, 1 dryer
Heating and cooling system	1 system

Source: NAHB (2004)

In addition to material inputs, single-family home construction involves labor, engineering and inspection services, financial services (e.g., banking, insurance), services associated with employee benefits, etc. Table 1-2 summarizes information provided by NAHB regarding the cost breakdown of the average 2,150 sf single-family homes built around 1998.

Table 1-2
1998 Cost Breakdown of a 2,150-Square-Foot, New Single-Family Home[27]

Cost Component	Cost	
	USD ($2009)	Contribution to total
Finished Lot	64,622	24%
Construction Cost		
Inspection/Fees	4,223	2%
Shell/Frame		
Framing	30,925	11%
Windows/Doors	10,271	4%
Exterior Finish	11,304	4%
Foundation	16,130	6%
Wall/Finish Trim	28,210	10%
Flooring	7,210	3%
Equipment		
Plumbing	8,837	3%
Electrical Wiring	5,638	2%

[27] Based on a NAHB Survey asking builders to provide a detailed breakdown of the cost of constructing a 2,150 SF home with 3 or 4 bedrooms on a 7,500 to 10,000 sf lot. For a comparison, average sales price of a new home in 42 surveyed markets was $226,680 in $1998 (DOE, 2011a, Table 2.5.8), which is the price paid by the consumer including profit, fees and commissions. The actual average price of a single-family home built in 1998 was $158,620 in producer's price, which does not include profit, fees and commissions (calculated based on the BEA 1998 input-output table). Differences among the NAHB survey, DOE data and BEA data are due to differences in the scope of the sample and in the price definitions (i.e., consumer vs. producer price) as well as differences in base years.

Table 1-2
1998 Cost Breakdown of a 2,150-Square-Foot, New Single-Family Home[27]

Cost Component	Cost	
	USD ($2009)	Contribution to total
Lighting Fixtures	1,560	1%
HVAC	6,170	2%
Appliances	2,165	1%
Property Features	17,566	6%
Other Costs		
Financing	5,151	2%
Overhead & General Expenses	15,644	6%
Marketing	3,840	1%
Sales Commission	9,238	3%
Profit	25,161	9%
Total	**273,865**	**100%**

1.1.2 Occupancy and Demolition/Deconstruction

NAHB data indicate that the average lifespan of a single-family home in the U.S. is on the order of 50 years. In their analysis of the residential construction sector, the Oregon Department of Environmental Quality (DEQ), assumed an average lifespan of 70 years for homes built in the Portland, OR area. This assumption was based on a scan of American Housing Survey data, which indicated that lifespan is a function of the period when the home was built and typically ranges from 50 to 200 years (Oregon DEQ, 2010). In the absence of definitive statistics on the life-spans of single-family homes, the analysis adopted O'Connor's (2004) results of a survey on service lives for non-residential North American buildings. These buildings were demolished between 2000 and 2003 in a major North American city of Minneapolis/St. Paul. According to the survey, service life of non-residential wood structures was 51.6 years. This life span was adopted as a proxy for the life span of U.S. single-family homes because of the similarity between the non-residential wood structures and U.S. single-family homes in the use of wood as the dominant construction material. Nevertheless, just as 70 years was admittedly an uncertain number in the Oregon DEQ study, so is 51.6 years here. Firstly, a meaningful relationship between home age and likelihood of demolition does not exist (Oregon DEQ, 2010). For example, even when a home is not old, but is small, raising land values may motivate a developer to demolish it and replace it with a new, bigger and more expensive home so as to maximize his potential for profit. Conversely, in certain circumstances, homebuyers may find older homes aesthetically appealing or extremely affordable for the neighborhood and through continuous resale extend their service lives. In both examples, longevity is independent of the reasonably anticipated durability of a structure obscuring the relationship between home age and likelihood of demolition. It should be recognized, however, that the purpose of the lifespan figure is to obtain an overall average, and not the range of lifespans associated with individual circumstances.

Secondly, these factors that affect service lives and extend beyond just longevity of structural materials, e.g. functional obsolescence, community planning or neighborhood conditions, may not equally affect non-residential and residential structures (O'Connor, 2004). This limits the applicability of the non-residential service life to residential structures. However, since the analysis aims to project into the future and anticipate future longevity of homes, data on *residential* structures that have *already* been demolished would not be fully applicable either (Oregon DEQ, 2010).

During the occupancy phase of a single-family home, the period after the home has been built and before it is demolished or deconstructed, resource inputs, such as electricity, natural gas, and water, are required to operate appliances and other systems. In addition, materials are used to replace worn out or outdated components of the home and remodel or renovate the structure. Table 1-3 describes examples of the types of components typically replaced in a single-family home and average lifespans of common components, which correspond to replacement periods. Based on information provided in the study by the Oregon DEQ (2010), costs for replacements during the life-time of a standard residential home are on the order of $180,000 ($2010) (see Appendix A1). By comparison, the life-time energy costs for operating the average home built in 1998 would be on the order of $90,000 ($2010).[28]

Table 1-3
Examples of Average Life Expectancies of Home Components

Home Component	Avg. Years to Replacement*	Ref.	Home Component	Avg. Years to Replacement*	Ref.
Appliances and HVAC			Footings and Foundations		
Dishwasher	9	(1)	Poured concrete	Lifetime	(1,2)
Range	13-15	(1)	Concrete block	Lifetime	(1,2)
Clothes washer/dryer	10-13	(1)	Waterproofing	10	(1)
Water heaters	10-11	(1)	Framing, engineered lumber		
Boilers and furnaces	13-21	(1)	Timber frame homes	Lifetime	(1,2)
Cabinetry			Engineered trusses	Lifetime	(1,2)
Kitchen and other cabinets	38	(2)	Wood Panels		
			Oriented Strand Board	25-30	(1)
Medicine cabinets	32	(2)	Plywood	>50	(1)
Doors and Windows			Insulation		
Exterior doors	33	(2)	Cellulose	>50	(1,2)
Aluminum windows	15-20	(1)	Fiberglass	>50	(1,2)
Wood windows	30+	(1)	Roofing		
Electrical and lighting			Asphalt	20	(1,2)
Wiring	Lifetime	(1,2)	Slate	>50	(1)
Electrical fixtures	38	(2)	Siding, trim and accessories		
Electrical controls	10+	(1)	Brick siding	Lifetime	(1)
Flooring			Cement shingle siding	31	(2)
Hardwood floors	>50	(1,2)	Other siding materials	19	(2)
Carpet	8-10	(1,2)	Trim	25	(1)
Linoleum flooring	17	(2)	Shutters (wood exterior)	20	(1)
Vinyl flooring	26	(2)	Walls, Ceilings and Finishes		
Tile flooring	>50	(2)	Standard gypsum	Lifetime	(1) (1)

[28] From DOE (2011a), Table 2.3.9. The average annual energy expenditure associated with a home built in 1998 is $1,671 in $2009. Assuming a 51.6-year lifespan and adjusting for inflation, this equates to a life-time energy cost of $87,600 in $2010.

* Lifetime means for the full lifespan of the home.
Sources: (1) NAHB and Bank of America (2007)
(2) Oregon DEQ (2010), Appendix 4

In addition to the materials and resources associated with construction and use, additional materials and resources are required when a single-family home is demolished and/or deconstructed[29]. These include the equipment and labor inputs required to remove the building, stabilize the site, and landfill or recycle demolition waste.

Construction and demolition (C&D) materials are generated during all 3 phases of a single-family home, construction, renovation, and demolition/deconstruction. EPA estimated that nationwide, renovation generated the majority of C&D materials associated with residential buildings in 2003. EPA further estimated that approximately 14.4 million tons of material was generated from demolition/deconstruction of single-family homes in 2003. On a weight basis, concrete contributed the largest fraction of this material, comprising as much as 68% of the total weight of C&D materials for homes with a full basement and garage (EPA, 2003a). Recovered and recycled C&D materials can be a source of material for single-family home construction and renovation. Table 1-4 lists typical components of C&D materials.

Table 1-4
Typical Components of C&D Materials

Material Components	Content Examples
Wood	Forming and framing lumber, stumps/trees, engineered wood
Drywall	Sheetrock (wallboard)
Metals	Pipes, rebar, flashing, wiring, framing
Plastics	Vinyl siding, doors, windows, flooring, pipes, packaging
Roofing	Asphalt, wood, slate, and tile shingles, roofing felt
Masonry	Cinder blocks, brick, masonry cement
Glass	Windows, mirrors, lights
Miscellaneous	Carpeting, fixtures, insulation, ceramic tile
Cardboard	From newly installed items such as appliances and tile
Concrete	Foundations, driveways, sidewalks, floors, road surfaces
Asphalt pavement	Sidewalks and road structures made with asphalt binder

Source: EPA 2003a

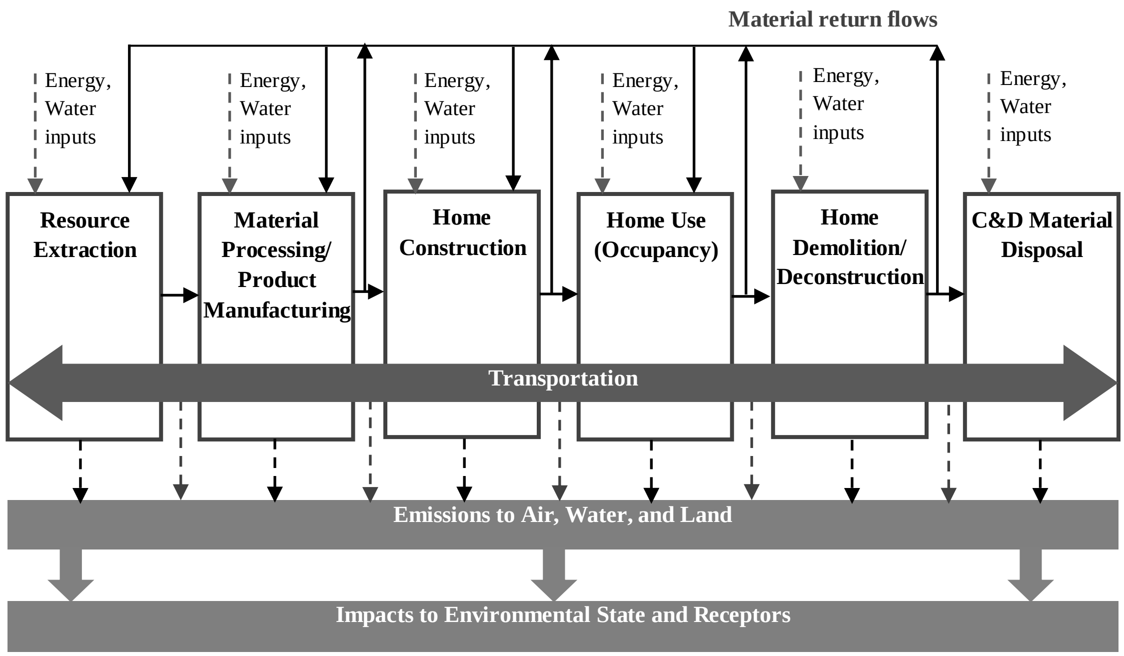
[29] Deconstruction, the systematic dismantling of a structure, can be used in various degrees in order to salvage usable materials. Techniques can range from reuse of an entire structure or foundation, to select assemblies and systems, to the careful removal of specific materials or items. See: http://www.epa.gov/osw/conserve/rrr/imr/cdm/reuse.htm

1.2 ESTIMATING LIFE CYCLE ENVIRONMENTAL IMPACTS

1.2.1 Life Cycle Assessment – An Overview

Life Cycle Assessment (LCA) is a tool used to quantify the environmental impacts of a product system throughout its life cycle—from raw material acquisition, manufacturing, transportation, assembly, use and disposal. LCA can be used to assess impacts in terms of a single environmental concern, such as climate change, or across multiple environmental impacts. Figure 1-1 illustrates the concept of a product life cycle, where the "product" in this case is the single-family home.

Figure 1-1
Material Flows, Resource Withdrawals, and Emissions
In the Life Cycle of a Home



Source: Adapted from EPA (2009)

Construction of a single-family home includes the delivery and installation of a variety of materials. For example, construction could include pouring a concrete foundation or slab; framing with lumber and engineered wood products; constructing exterior elements including the roof, siding, windows, and doors; installing electrical, plumbing and other systems; finishing the interior with floors, walls, carpet, cabinets and trim; and installing appliances. During construction the builder will use natural resources, such as petroleum and electricity to power equipment, and the construction activity could generate "emissions" in the form of pollution and waste.[30] These emissions translate into impacts to the environmental state (e.g., contaminated air or water) and impacts to receptors (e.g., health effects, ecosystem degradation).

In Figure 1-1, resource withdrawals (i.e., energy and water inputs) and emissions are represented by the dotted arrows entering and exiting the box labeled “home construction.” Material flows, which in this case represent materials, products, and services delivered to the job site—are represented by the solid arrows entering this box.

More traditional perspectives on the residential construction sector would characterize the resource use and emissions associated with home construction as only those directly used and created by the construction activity, respectively—i.e., the arrows directing entering and exiting the “home design and construction” box. LCA, on the other hand, looks at the resources used and emissions associated with the “supply chain” of materials, products, and services used to build the home, which includes emissions generated in order to extract, manufacture, and deliver these materials, products and services to the job site.

For example, whereas a more traditional view would suggest that installation of kitchen cabinets generates a limited scope of emissions (e.g., to run power saws to cut trim for the cabinets), a life cycle view would consider a much broader scope. In LCA, the scope considers all of the emissions generated in the cabinet supply chain. These “upstream” emissions would include those associated with harvesting timber, milling, assembling the cabinets, and delivering the cabinets to the job site, including emissions associated with transportation during all of these steps. A similar view would apply to the resources used to manufacture and deliver the cabinets. LCA looks at all of the materials, products, and services used to build the home—the “direct inputs” to the construction—and conducts a similar analysis of all of the upstream resource withdrawals and emissions associated with these inputs.

In addition to assessing the impacts associated with manufacturing, delivering, and installing home components, LCA assesses the resources used and emissions associated with the use and end-of-life of those components, where the latter could include reuse, recycling, or disposal. For example, if during the life of a home, the kitchen cabinets were replaced, LCA would consider the emissions associated with removing and disposing of the old cabinets and the emissions associated with manufacturing, delivering, and installing the new cabinets in the home. If the cabinets were simply refinished, LCA would consider the emissions associated with stripping the original finish and applying a new finish. This could include the stripping waste and upstream emissions associated with the chemicals used to strip the finish as well as the upstream emissions associated with the new finish.

In this way, LCA attempts to characterize the full impact of a product system. Environmental emissions and natural resource withdrawals quantified using LCA represent the environmental pressures created by the consumption of a product system. These environmental pressures result in changes in environmental state and eventually result in impacts to receptors, which can be

[30] In this report and in LCA in general, the term “emissions” is used generally to describe the release of material back to the environment via air emissions, discharges to water, disposal of waste on land, etc.

measured in terms such as human health, ecosystem health, and natural resources degradation. LCA uses "characterization models" to quantify the relative environmental impact of different environmental pressures. For example, the impact of greenhouse gas (GHG) emissions is quantified based on the radiative forcing of GHGs, known as their Global Warming Potential (GWP).[31]

The use of characterization models is particularly important when assessing the life cycle impacts of a complex product system like the single-family home. By expressing impacts using a common metric (e.g., GWP), direct and upstream impacts can be summed across disparate materials, products, and services. For example, the use of the radiative forcing approach allows for summing the impacts from emissions associated with the timber extraction, milling, and delivery of original and replacement kitchen cabinets, emissions associated with the original cabinet finish, stripping chemicals, and new finish, transportation of removed cabinets for processing or disposal, etc. These summed impacts represent the "embodied" GWP impacts associated with kitchen cabinets.

1.2.2 LCA Alternatives

To provide a national, economy-wide strategic view of the environmental impacts associated with materials, products, and services consumed in the U.S., an input-output life cycle analysis (I-O LCA) approach was used, but supplemented with additional information to address use and end-of-life phases and help quantify the potential for avoided impacts.

A number of methods are used for conducting LCA. They include "process" LCA, input-output LCA, and hybrids of these methods. "Process," or "bottom-up," LCA is performed by gathering and analyzing process-specific data on inputs (resources, materials, goods and services) and outputs (products and emissions) of the target product system over its life cycle. An alternative to process LCA is input-output life cycle analysis (I-O LCA). I-O LCA incorporates detailed data describing the economic transactions between industries within an economy. In the U.S., these data are available through BEA and are used, for example, by the Federal Reserve to formulate monetary policy and the U.S. Government to formulate fiscal policy (DOC, 2006).

A reasonably complex product system can involve several hundred inputs and outputs, particularly when viewed from a life cycle perspective, which includes all upstream supply chain processes and associated resource withdrawals and emissions. Collecting data on each input and output is a challenge and leads to a long-standing issue in process LCA known as the "truncation problem" (Lave et al., 1995; Joshi, 1999; Lenzen, 2001; Suh and Huppes, 2002; Suh et al., 2004; Suh and Huppes, 2005). Given the economy-wide scope of the I-O data, I-O LCA results in

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[31] Radiative forcing is the change in the balance between solar radiation entering the atmosphere and the Earth's radiation going out. On average, a positive radiative forcing tends to warm the surface of the Earth while negative forcing tends to cool the surface. Greenhouse gases have a positive radiative forcing because they absorb and emit heat (http://www.epa.gov/climatechange/science/recentac.html). For a more detailed technical definition, including practical issues with this definition, see IPCC (2001), Chapter 6.

practically no truncation and is capable of characterizing inputs and impacts associated with complex and variable product systems.

In addition, where there is great variation among methods used in a product system, it can be difficult to draw general conclusions based on a limited set of process LCAs. For example, adjustments would need to be made to generalize the results of a process LCA that assumes one type of residential building construction to the full range of construction methods actually used. I-O LCA accounts for this variation. However, as a trade-off, the economic I-O data used in I-O LCA is generally more aggregated than is necessary to hone in on specific issues or mitigating actions. Also, I-O LCA focuses on impacts associated with delivering a product to the consumer and does not explicitly address use and disposal phases associated with a product system.

The limitations of I-O LCA can be addressed by using multiple perspectives and focused supply chain analyses and by using hybrid approaches that selectively integrate within the I-O LCA model process-specific data for key inputs and processes (Suh et al., 2004). Process LCA and input-output LCA share a common analytical approach and, when integrated thoughtfully (e.g., where the interfaces between the models use consistent product definitions, the models use the same data sources or sources of similar quality, etc.), they are complementary. Combining these approaches can improve the quality of the analysis.

Given the objectives of the analysis of life cycle impacts associated with single-family homes, an I-O LCA approach was used, employing multiple perspectives and focused supply chain analyses, supplemented with additional information to address use and end-of-life phases and help quantify the potential for avoided impacts. I-O LCA provides a national, economy-wide strategic view of the environmental impacts associated with product systems and has been used in the U.S. and Europe for similar purposes. The specific methodology used and the results of the analyses are described in the following sections.

2. LIFE CYCLE ANALYSIS METHODOLOGY

2.1. OVERVIEW

An I-O LCA approach was used to develop a national, economy-wide strategic view of the life cycle environmental impacts associated with single-family homes. This method focused on identification and analysis of top-ranked supply chain processes, materials, products, and services used in the pre-occupancy, occupancy and post-occupancy phases of single-family homes and the potential for avoiding impacts through reductions in material and resource intensity. The analysis did not attempt to assess the effects of unit- or site-level changes in residential building methods. Rather, it was used to develop insights into where such additional analyses could best be focused. It also provides a method for scaling-up the results of site- or unit-focused analyses to evaluate their potential to have a nationally significant impact.

The analysis consisted of the following steps:

- Identification and analysis of top-ranked supply chain processes, materials, products, and services:
  - Sources were researched and data were collected regarding occupancy and post-occupancy phases of single-family homes; data were integrated with I-O data to support the analysis of the full life cycle of single-family homes.
  - I-O LCA of residential 1-unit structures were conducted using input and output contribution analysis methods, where impacts were characterized using the 17 environmental impact categories used in the 2020 Vision Relative Ranking Analysis (EPA, 2009).
  - A vector analysis was used to rank supply chain processes, materials, products, and services based on their relative contributions to the overall life cycle impacts associated with single-family homes.
  - Supplemental, focused output contribution analyses were conducted to identify supply chains processes contributing most significantly to the life cycle impacts associated with selected materials, products and services.
- Avoided impacts analysis:
  - Results of the I-O LCA, supplemental output contribution analyses, and vector analyses were reviewed and hypothetical scenarios for avoided impacts were identified based on their potential to reduce material and resource intensity and/or illustrate the range of policy actions available to address the environmental footprint of single-family homes.
  - Supplemental data were collected regarding key determinants of avoided impacts (e.g., recycling rates, energy consumption associated with recycling, etc.) and were

integrated with the pre-occupancy, occupancy, and post-occupancy data to support analysis of the overall avoided life cycle impacts.

– I-O LCA was conducted for each of the scenarios and the potential for avoided impacts was quantified.

Additional information regarding the LCA methodologies used to identify and analyze top-ranked supply chain processes, materials, products, and services is presented in the remainder of this section. Sections 3 and 4 present the results of the input and output life cycle impact analyses and Section 5 describes the methodology and results of the avoided impacts analysis.

2.2. I-O LCA AND CONTRIBUTION ANALYSIS

At the heart of the analysis is the I-O model used to characterize material flows throughout the life cycle of the single-family home, including flows associated with the pre-occupancy, occupancy, and post-occupancy phases of the home. These flows form the structure by which emissions and impacts are characterized through the supply chain processes associated with single-family homes. This section reviews the methods used to construct the basic I-O model, including defining the system scope and boundaries, specifying impacts of interest, and incorporating supplemental use and end-of-life data.

2.2.1 Scope and System Boundary

The life cycle of a single-family home encompasses the following phases:

- *Pre-occupancy phase* – This phase includes all inputs to the construction of a single-family home (e.g., framing lumber, windows and doors, cabinets and carpets), including all upstream supply-chain processes that provide inputs (e.g., forestry and milling, glass and synthetic fibers manufacturing, transportation) to residential building construction. It also includes on-site activities during the residential building construction, capturing the energy and other resource inputs required to construct the building, install components, etc. and the associated emissions.
- *Occupancy phase* – The use, or occupancy phase, includes all resources and materials used in the components of the home (e.g., heating systems, plumbing fixtures, kitchen and laundry appliances) and to maintain the structure and components, including repairs and renovations. It also includes all upstream supply-chain processes associated with these inputs (e.g., electricity generation, replacement cabinet manufacturing) and emissions associated with the use and maintenance of the home.
- *Post-occupancy phase* – This phase includes building demolition and/or deconstruction. It includes the C&D materials, where those materials that are disposed of are considered “waste” and those that are recycled or reused are considered “products” of this phase. It also includes the upstream supply-chain processes that provide inputs (e.g., demolition equipment, energy) to demolish or deconstruct the home and the emissions and waste generated by this on-site activity.

Figure 2-1 illustrates the scope and system boundaries associated with each of these phases. Combined, these represent the overall scope and system boundary of the life cycle of a single-family home considered in this analysis.

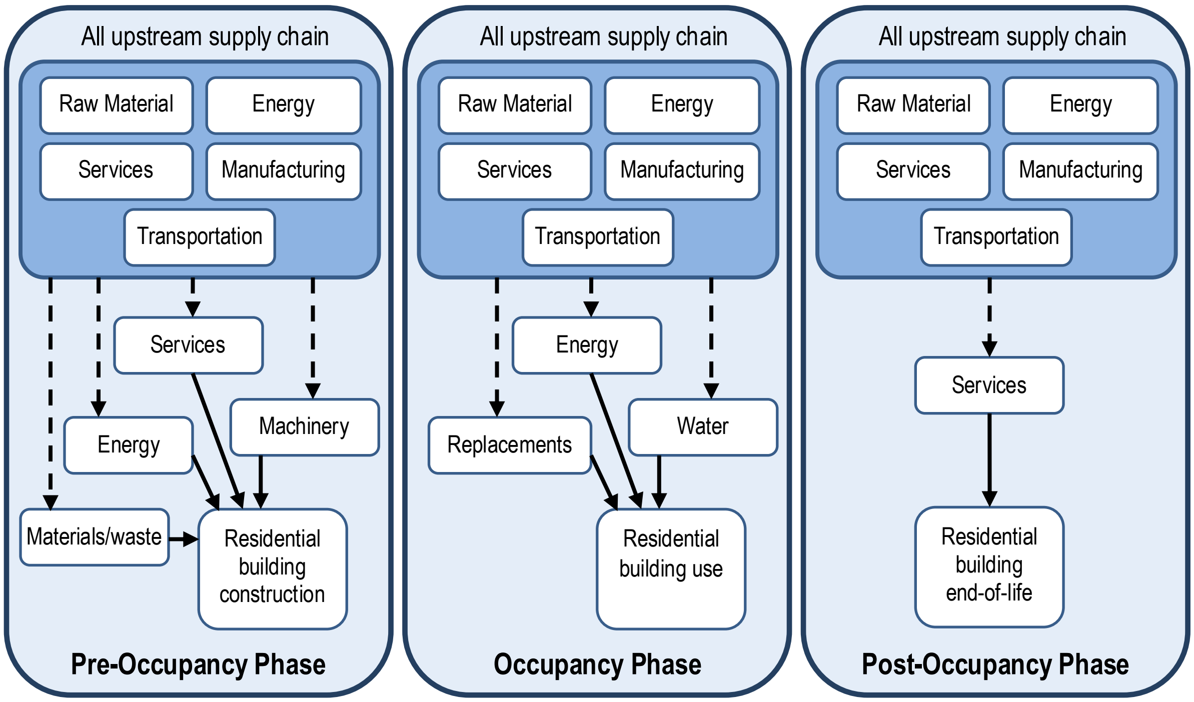

Figure 2-1. The scope of the analysis: system boundary

2.2.2 Impact Categories

The 17 impact categories used in the 2020 Vision Relative Ranking Analysis were used to conduct this analysis. These include 13 environmental impact categories evaluated using the CML[32] characterization models incorporated in the Comprehensive Environmental Data Archive (CEDA)[33] and four additional categories addressing material use and waste and resource consumption. Table 2-1 lists the environmental impact categories used in this study. Detailed descriptions of each impact category are included in Appendix B1.

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[32] Leiden University, Institute of Environmental Sciences (Centrum voor Milieuwetenschappen, CML).
[33] Characterization of the 13 environmental impact categories (the 17 categories used in this analysis exclusive of energy and water consumption, material input and waste) is based on the characterization models developed by the Leiden University Institute for Environmental Sciences (CML). See Suh (2004) and Guinée et al. (2002).

Table 2-1
Impact Categories and Units Used in This Study*

Impact category	**Units**
Abiotic depletion potential (ADP)	kg antimony eq.
Land use competition (LUC)	million m^2*yr
Global warming potential (GWP)	kg CO_2 eq.
Stratospheric ozone depletion potential (ODP)	kg CFC-11 eq.
Human toxicity potential (HTP)	kg 1,4-dichlorobenzene eq.
Freshwater aquatic ecotoxicity potential (FAETP)	kg 1,4-dichlorobenzene eq.
Marine aquatic ecotoxicity potential (MAETP)	mton 1,4-dichlorobenzene eq.
Terrestrial ecotoxicity potential (TETP)	kg 1,4-dichlorobenzene eq.
Freshwater sediment ecotoxicity potential (FSETP)	mton 1,4-dichlorobenzene eq.
Marine sediment ecotoxicity potential (MSETP)	kg 1,4-dichlorobenzene eq.
Photochemical ozone creation potential (POCP)	kg ethylene eq.
Acidification potential (AP)	kg SO_2 eq.
Eutrophication potential (EP)	kg PO_4 eq.
Energy consumption (EC)	million BTU
Water consumption (WC)	thousand gallons
Material input (MTL)	mton
Waste (WST)	mton

* See Appendix B1 for definitions of impact categories.

2.2.3 LCA Methodology: Contribution Analysis

Based on the objectives of the analysis, a contribution analysis was conducted to better understand the sources of significant life cycle impact associated with single-family homes and help identify strategic opportunities for reducing or avoiding these impacts. Contribution analysis examines the relative contributions of different inputs to a product system, including direct inputs and upstream supply chain processes, to the overall life cycle impact associated with the product system. In this way, contribution analysis can highlight those inputs and supply chain processes that contribute most significantly to the overall impact of single-family homes and, thus, can provide useful insights for developing strategic actions to address these impacts.

One of the hallmarks of I-O LCA is its ability to support analysis from multiple perspectives once the fundamental relationships among material flows, emissions, and impacts have been defined. Taking advantage of this attribute, two types of contribution analysis were completed for this study: 1) input contribution analysis and 2) output contribution analysis. Input contribution analysis analyzes the relative contribution of direct inputs to the overall life cycle impacts of the product system. Output contribution analysis, on the other hand, associates impacts with their original source in the upstream supply chain of the product system. The two approaches offer different ways to disaggregate the overall life cycle impact and can provide different insights into sources of impact and approaches for addressing impact.

For the single-family home "product system," input contribution analysis includes impact estimates and resource withdrawals associated with each of the "direct inputs" to the home. This includes an estimate of the impacts and resource use associated with each of the materials and products delivered to the job site (pre-occupancy phase) and/or delivered to the home as replacements (occupancy phase). It also includes each of the services provided in support of the home construction and/or renovation and work completed on the job site and/or during the renovation. These include, for example, the impacts associated with wood kitchen cabinets delivered to the site plus impacts associated with running the machinery to install the cabinets in the home (e.g., to run power saws to cut trim for the cabinets).

In the results of the input contribution analyses, the impacts and resource use associated with each direct input are a compilation of all of the impacts and resources embodied in those inputs. For example, in the case of wood kitchen cabinets, all of the impacts associated with the upstream supply chain processes used to manufacture and deliver the cabinets to the job site would roll-up to the wood kitchen cabinet product category (BEA code 200502). This would include, for example, all of the impacts and resources used in association with harvesting timber, milling, assembling the cabinets, and transporting the cabinets to the job site.

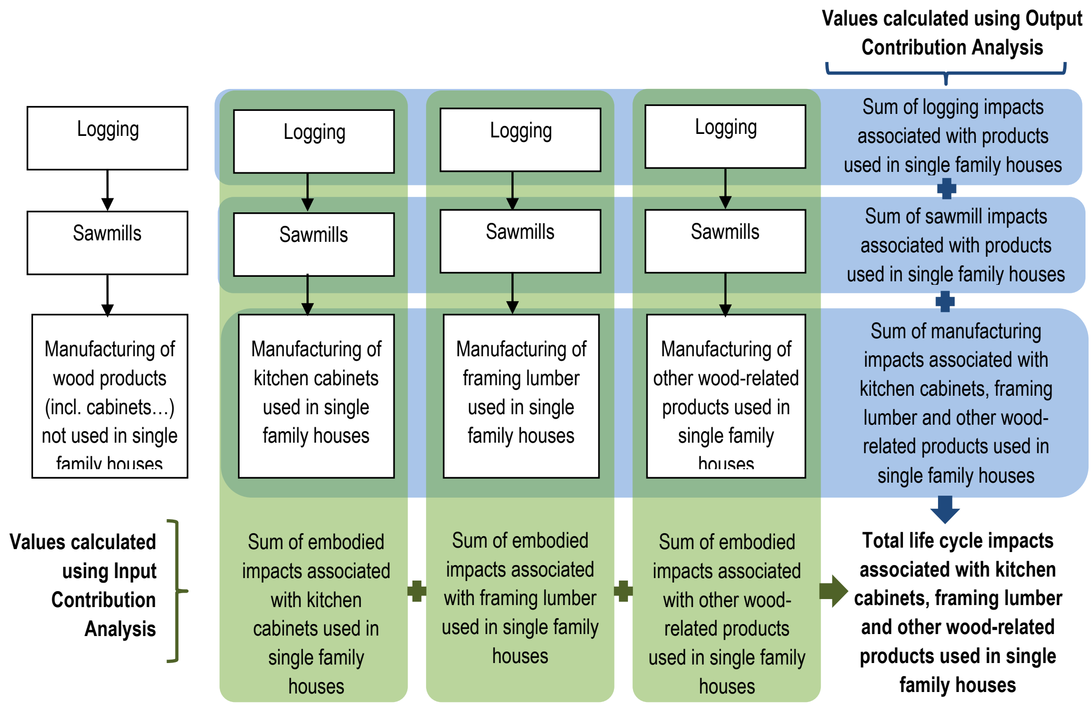
In contrast, the output contribution analysis disaggregates, or separates out, the impacts and resource withdrawals to their original source in the supply chain. In the case of wood kitchen cabinets, all of the impacts upstream of the cabinet manufacturer would be disaggregated—e.g., impacts associated with logging would be included in BEA category 200100, logging; impacts associated with transporting the logs to planning mills would be included in BEA category 650301, trucking and courier services; impacts associated with sawing/planing the logs would be included under BEA category 200200, sawmills and planing mills, etc. In the results of the output contribution analysis, the only impacts associated with the wood kitchen cabinets category would be those associated with emissions generated and resources used during the actual cabinet manufacturing operations.

In a product system as complex as a single-family home, some upstream supply chain processes will be associated with more than one direct input. For example, sawmills could be a process in the supply chain for both framing lumber and wood kitchen cabinets. In the input contribution analysis, the impacts associated with operating the sawmill would be distributed to framing lumber and kitchen cabinets (and other products associated with sawmills) in proportion to the contribution of these direct inputs to the overall home construction. In the output contribution analysis, these impacts would not be disaggregated but, rather, would be reported together in association with the sawmill category.

Figure 2-2 illustrates these two approaches to contribution analysis and the relationships of input and output contribution analysis to total life cycle impacts associated with a product system.

This dual approach to the analysis was selected to help elucidate the possible effects of different policy options and/or external trends on the overall life cycle impact associated with single-family homes. Input contribution analysis provides a perspective on materials selection in single-family home construction, use, and end-of-life and highlights those materials used by the residential construction industry that embody the greatest impacts. Output contribution analysis, on the other hand, highlights how changes in a supply-chain process, (e.g. emissions associated

Figure 2-2
Illustration of Input and Output Contribution Analyses



with sawmill operations), could affect the life cycle impacts associated with single-family homes.

2.2.4 Defining "Direct" and "Indirect" Impacts

As discussed above, the input contribution analysis of, for example, the pre-occupancy phase of a single-family home includes impact estimates and resource withdrawals associated with each of the materials and products delivered to the job site and each of the services provided in support of the home construction. The output contribution analysis disaggregates these impacts and resource withdrawals to their original source in the supply chain.

The I-O LCA described herein labels impacts and resource withdrawals that take place during the construction or use of the home as "direct" impacts or resource withdrawals. Impacts and resource withdrawals associated with upstream supply chain processes are labeled "indirect." For example, sediment runoff from the site during the construction of a home could result in eutrophication impacts, which would be classified as "direct" impacts in this analysis. On the other hand, eutrophication impacts embodied in ready-mixed concrete used to build the foundation for the home (e.g., impacts associated with nitrogen-containing compounds emitted during cement production) would be considered "indirect." [34]

[34] Eutrophication describes a condition where nutrient enrichment causes shifts in species composition and elevated biomass production in aquatic and terrestrial ecosystems (see Appendix B1). Run-off from

Impacts associated with some direct inputs, are represented in the I-O LCA in terms of both an "environmental impact" and a "resource withdrawal." For example, when diesel fuel is combusted in construction vehicles on-site, the I-O LCA accounts for this in terms of both the environmental impact associated with combustion emissions and energy consumption, which is a resource withdrawal. In addition, to prevent double-counting the I-O LCA measures energy consumption based on the point of combustion. Diesel fuel combusted in construction vehicles on site is considered "direct" energy consumption. The combustion of coal and other fossil fuels to generate electricity that is used during construction is considered "indirect" energy consumption. The consumption of these fossil fuels is embodied in the *electric services* input to single-family home construction. For additional information and figures illustrating the relationships among the direct and indirect impacts in the pre-occupancy and occupancy phases, see Appendix B2.

2.3 VECTOR ANALYSIS

The vector analysis approach developed for the 2020 Vision Relative Ranking Analysis was used to rank the supply chain processes, materials, products and services based on their contributions to the overall life cycle impacts of single-family homes. Vector analysis provides a transparent approach for characterizing impacts across multiple and disparate impact categories without embedded weighting. It tends to highlight those supply chain processes, materials, products and services whose impacts differ significantly from the average across one or more impact categories and provides readily available information regarding the impact categories driving the ranking.

A more detailed discussion of the vector analysis methodology and rationale for each of these steps is included in EPA (2009). An overview of how the vector analysis was used in this analysis of single-family homes is presented below. Appendix C provides additional technical detail, an applied example of vector analysis in the context of this LCA as well as a brief discussion of strengths and weaknesses of the vector analysis approach.

2.3.1 Pre-Occupancy

For the purpose of assessing the life cycle impacts associated with single-family homes, separate vector analyses were conducted on the input contribution analysis results and output contribution analysis results for the pre-occupancy phase. The following steps were employed:

- CEDA output data (see section 2.5.1) were compiled for each of the supply chain processes, materials, products, and services and for each impact category. Supply chain processes, materials, products, and services that did not indicate contribution to life cycle impacts associated with the pre-occupancy phase of single-family homes were eliminated from the analysis.

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construction sites can contain nitrogen that can affect the nutrient balance in nearby water bodies. It can also result in sedimentation, which can affect the biomass balance by affecting sunlight penetration of the water column. Emissions of nitrogen-containing compounds during cement production, such as nitrogen oxides (NO_x) and ammonia (NH_3) can affect the nitrogen load in terrestrial and aquatic ecosystems.

- The average (mean value) for each criterion was computed and subtracted from the criterion value for each of the supply chain processes, materials, products, and services retained in the analysis, the standard deviation for each impact category was calculated, and the mean-centered values were normalized by the standard deviation.
- Vector magnitudes were calculated by taking a square root of the sum of the individual standard deviations squared; vector magnitudes were calculated as the basis for ranking supply chain processes, materials, products and services.

Vector analyses were conducted for all 17 impacts - the 13 environmental impact categories from the Comprehensive Environmental Data Archive (CEDA) and four additional categories addressing material use and waste and resource consumption. In addition, for the pre-occupancy phase, vector analyses were also conducted for the following groupings of impacts:

1. *Natural Resources and Land Use* – waste (WST), abiotic depletion potential (ADP), energy consumption (EC), water consumption (WC), land use competition (LUC), and material input (MTL);
2. *Toxicity* – human toxicity potential (HTP), freshwater aquatic ecotoxicity potential (FAETP), marine aquatic ecotoxicity potential (MAETP), terrestrial ecotoxicity potential (TETP), freshwater sediment ecotoxicity potential (FSETP), and marine sediment ecotoxicity potential (MSETP); and
3. *Pollution Impacts* – stratospheric ozone depletion potential (ODP), global warming potential (GWP), acidification potential (AP), euthrophication potential (EP), and photochemical ozone creation potential (POCP).

2.3.2 Occupancy

For the occupancy phase, 13 specific products/materials and one “other” material/product category were considered in the analysis of life cycle impacts associated with replacement of home components during the occupancy phase (see Section 2.5). In addition, the occupancy-phase analysis considered overall life cycle impacts associated with electric services, natural gas distribution, and petroleum refining used during occupancy. Therefore, the input contribution analysis of the occupancy phase considered the embodied impacts associated with these 17 direct inputs. The output contribution analysis, on the other hand, disaggregated these impacts to upstream supply chain processes, and indicated that 450 upstream supply chain processes are associated with the production and delivery of these 17 occupancy-phase inputs.

Vector analysis is an appropriate methodology for providing insights when the array of inputs and impacts is too broad to be understood using simpler techniques. The output contribution analysis for the occupancy phase of a single-family home generated 7,650 impact estimates (450 supply chain processes over 17 impact categories). Therefore, the full vector analysis methodology, as described above for the pre-occupancy phase, was used to analyze the occupancy-phase output contribution results.

The input contribution analysis generated 289 impact estimates (17 supply chain processes over 17 impact categories). The initial vector analysis of these results suggested that certain supply chain processes consistently ranked other than the rest across impact categories and that the conditions under which vector analysis works most effectively in this context were not met.[35] Therefore, for the input contribution analysis of the occupancy phase, the contribution of each input to the life cycle impacts associated with this phase was considered on a factor-by-factor basis.

2.3.3 Post-Occupancy

For the inputs used in the post-occupancy phase, neither the input contribution analysis nor the vector analysis was conducted. Existing literature suggests that the impacts of inputs used in the post-occupancy phase represent a relatively small percentage of the overall life cycle impacts associated with single-family homes (Ramesh et el., 2010; Oregon DEQ, 2010). Based on this and the limited scope of impacts considered, a separate output contribution analysis also was not completed for the processes used in the post-occupancy phase. Post-occupancy phase impacts were only included in the overall analysis of life cycle impacts associated with single-family homes (see Section 3.2). For more detailed explanation of the assumptions associated with the post-occupancy phase, see Section 2.5.5.

2.4 SUPPLEMENTAL CONTRIBUTION ANALYSIS OF SELECTED DIRECT INPUTS

The results of the vector analysis of the input contribution results were reviewed to identify highly ranked direct inputs to single-family homes for further review. Supplemental contribution analyses were conducted to identify the "hotspots" in the supply chains of these direct inputs, where "hotspots" were defined as the supply chain processes contributing most significantly to the overall life cycle impact of the direct input.

The data sources and methodologies used to analyze the life cycle impacts associated with these inputs were the same as those used to analyze life cycle impacts associated with single-family homes. See Sections 2.2.3 through 2.5 for more detailed descriptions of applicable data sources and methodologies.

[35] As part of the 2020 Vision Relative Ranking Analysis, the distributions of impact estimates about the mean for each impact criterion were analyzed to evaluate whether one or more criteria imparted an inordinate influence on the overall vector ranking results (EPA, 2009, pp. 19-20). The analysis indicated that the estimates within each impact category tended to cluster around the mean impact estimate and that the materials, products, and services that differed most significantly from the mean did so in a positive direction (i.e., estimated impact was much greater than the average). This allows for the efficient interpretation of vector analysis results, as the criteria driving relatively high rankings represent criteria for which the material, product, or service is relatively more impactful. For the occupancy-phase input contribution analysis, impact estimates were more normally distributed around the mean, and, thus, the conditions that lend clarity to the vector analysis approach in multiple dimensions were violated.

2.5 DATA SOURCES

The contribution analyses were conducted using the environmentally extended input-output databases incorporated in CEDA, supplemented with additional data to incorporate material use and waste impact categories and occupancy and post-occupancy phases of single-family homes.

2.5.1 Comprehensive Environmental Data Archive (CEDA)

CEDA covers a comprehensive list of environmental interventions[36] for a range of natural resource types (e.g., fossil fuels, water, metals ores and minerals), and emissions of a range of substances to air, water and soil.[37] CEDA quantifies natural resource use and environmental emissions of products throughout their pre-consumer life cycles by connecting input-output tables, which represent the entire supply-chain network of an economy, with a comprehensive list of environmental interventions. The U.S. version of CEDA contains over 3 million data points, distilled from raw data sources containing tens of millions of data points using a consistent and rigorous quality control process (Suh 2004).

2.5.2 Supplemental Material Use and Waste Data

The CEDA databases were supplemented with material use and waste data developed for the 2020 Vision Relative Ranking Analysis using World Resources Institute (WRI) Materials Flow Analysis (MFA) data. MFA data were developed by WRI as a comprehensive estimation of material flows for over 160 primary materials consumed in the U.S. economy from 1975 through 2000, covering four principal sectors: agriculture, forestry, non-renewable organic materials (e.g., fossil fuels), and metals and minerals (WRI 2008). For the 2020 Vision Relative Ranking Analysis, material waste was defined to be consistent with the direct process output (DPO) measure used by WRI, which includes all materials that are consumed in the U.S. economy and "exit" (e.g., through disposal in a landfill) within 30 years after entry.[38] The WRI MFA data were captured in the 2020 Vision Relative Ranking Analyses by cross-walking the WRI material classification system with the BEA-defined industries included in CEDA (EPA 2009).

2.5.3 Occupancy-phase Energy Use, Water Consumption, and GHG Emissions Data

Energy use, water consumption, and GHG emissions during the occupancy phase of residential homes were estimated based on information available through the U.S. Department of Energy.

[36] In the context of CEDA and similar LCA tools, the term "environmental intervention" is a general term used to capture a range of interactions between humans and the environment, including resource extraction, land use, and emissions to air, water, and land. See ISO (1997).
[37] For additional detail, see Suh (2004), Appendix B.
[38] DPO is equal to direct material consumption (DMC), which is used as the measure of "material use," less material that remains in the economy for over 30 years, less material that is recycled (WRI 2008).

(DOE). The DOE Buildings Energy Data Book (DOE 2010) provides data regarding energy use and GHG emissions from 1980 through 2008 and projects future energy use and GHG emissions through 2035. The following assumptions were made to estimate the energy use, water consumption, and GHG emissions associated with homes built in the reference year of 1998 based on the DOE data and projections:

- *Energy use* – DOE projects that residential homes in the U.S. will consume a quintillion Btu of energy over the 50-year period from 1980 to 2030 (DOE 2011a, Table 2.1.1). In 1998, single-family homes newly built in that year comprised 1.12% of the total housing stock (DOE 2011a Tables 2.2.1 and 2.5.1). Based on this proportion, 1.12% of the total projected energy consumption, or 11 quadrillion Btu, was ascribed to the single-family homes built in 1998. An emissions factor was used to derive direct emissions and 1998 energy price data were used to monetize energy use. CEDA was then applied to calculate indirect emissions associated with energy use during the home occupancy phase.
- *Water consumption* – DOE data support two ways to estimate total water consumption by residential homes: (1) using time-series survey data and (2) based on per-capita water consumption per use categories (DOE 2011a, Tables 8.2.1 and 8.2.2). Using these approaches total water use by residential homes for the 50-year period from 1985-2035 is estimated to be 5.7 and 5.9 trillion gallons, respectively. For the purpose of this analysis, an average of the two numbers, or 5.8 trillion gallons was used. Consistent with the approach for energy use, 1.12% of this total was attributed to homes built in 1998.
- *GHG emissions* –DOE projects that residential homes will be responsible for 56 billion metric tons of CO_2e GHG emissions during the 50-year period from 1985 to 2035. For the purposes of this analysis, it was assumed that the homes built in 1998 produce average amount of GHGs relative to the overall housing stock during this period. Based on the approach used above, the life-time GHG emission from the single-family residential homes built in 1998 was estimated to be 1.12% of 56 billion metric tons, or 628 million metric tons of CO_2e.

These estimates are rough and are subject to uncertainty due to, for example, trends in technology and efficiency in the future. However, these estimates are considered adequate to help rank-order supply-chain processes, materials, products and services and quantify avoided impacts potential for possible, more detailed analysis.

2.5.4 Occupancy Phase Material Replacement Data

Life cycle impacts associated with the materials replaced during the occupancy phase of a residential home were estimated by incorporating data regarding the types and value of materials replaced into the CEDA database. This approach was used to take advantage of the computing capabilities of CEDA and to maintain maximum consistency between pre-occupancy and occupancy LCA results.

A number of statistics and reports were reviewed to develop estimates of replacement requirements during the occupancy phase of a single-family home. Among others, the Oregon DEQ has conducted a comprehensive LCA study providing valuable information on the types and quantities of materials replaced during this phase (Oregon DEQ, 2010). Given the quality of the Oregon study, the data were used as the basis for this present study with modifications to monetize the data for use in CEDA and to account for uncertainties in the use of these data for a national-scale LCA, as follows:

- The scope of material replacements was limited to the following 13 specific products commonly replaced or used in the renovation of a single-family home over its life span and/or for which adequate data were available: carpeting, linoleum flooring, asphalt shingle roofing, glass fiber insulation, drywall, doors and windows, plastics, lumber, hardware, electrical fixtures, foundation, paints, and wood shingle siding.
- In order to utilize I-O LCA approach, physical unit data for replacements were monetized using the price data provided in the Oregon report. The original installation data for building materials in an average 1-unit residential building in the Oregon State study were converted into monetary units. The unit cost data were scaled up to provide nationwide estimates based on the number of homes built in 1998. Monetary conversions are summarized in Appendix A1.
- In 1998, new single-family homes cost $184 billion according to the BEA 1998 input-output data. Using this figure and the BEA input-output data, nationwide cost estimates for each replacement item were derived. These estimates were compared with the scaled-up figures from the Oregon study, adjusting inflation. In general, both sets of figures were in the same order of magnitude, though reasonably significant discrepancies were observed for some items, most notably carpet—figures based on the Oregon study were more than 10 times higher than those based on I-O data—and paint— estimates based on the Oregon study were less than 10% of the I-O-derived estimates.
- To further evaluate the replacement assumptions generated using the Oregon data and address these apparent discrepancies, a similar study done by Harvard University (2009) was reviewed. Figures from the Harvard University study are summarized in Appendix A2. The Harvard University figures also indicated that the scaled-up carpet replacement figures from the Oregon state study might be an overestimation; there was no comparable data on paint in the Harvard University study. Based on this, the monetary value of carpet replacement was estimated for this study as the ratio between the value derived from BEA I-O data and the scaled-up Oregon study for original installation. The Oregon assumptions regarding carpet replacement were not used directly.
- For the purposes of estimating waste associated with material replacement, it was assumed that there is one-to-one correspondence between the amount of materials replaced and the amount of waste generated due to the replacement during the occupancy phase.

Overall, the data used as the basis for this LCA suggest the costs of replacements over the lifespan of a single-family home built in 1998 range from $122 billion (Harvard University study) to $208 billion USD (Oregon state study), in $1998. Given that total new residential building construction in 1998 cost $184 billion ($1998), replacements over the lifespan of residential buildings are estimated to be comparable to the cost of new residential buildings for the purposes of this study. Appendix A1 summarizes the itemized replacement costs derived from the Oregon State study with modifications based on review of the BEA I-O data and Harvard University study.

2.5.5 Post-Occupancy Phase Data

For the purpose of the analysis, the "end-of-life" of residential structures was defined as the point when buildings are demolished or deconstructed. Based on information available in the literature, impacts associated with the post-occupancy phase of residential homes are small relative to the overall life cycle impacts associated with a single-family home. Of the post-occupancy impacts, those associated with energy consumption, combustion-related emissions and waste generation are most significant (Sára et al., 2001; Boyano Larriba and Wolf, 2010). Therefore, the scope of the post-occupancy impacts analysis was limited to these factors.

Post-occupancy impacts were calculated using a number of different sources. Information regarding GHG emissions associated with the demolition phase was adopted from the Oregon DEQ (2010) study. Oregon DEQ (2010) estimates that demolition of an average residential home generates about 600 kg of CO_2-eq. GHG emissions – this number includes emissions of carbon dioxide, carbon monoxide, dinitrogen monoxide and sulfur hexafluoride from diesel equipment operation and use of electricity, but excludes worker commuting. The GHG emissions associated with the landfilling of organic materials, e.g., wood, have not been allocated to the post-occupancy phase in this study, and consequently, the GWP environmental impact of the post-occupancy phase is somewhat underrepresented. If we assume a 49.5% contribution of wood to the C&D waste from residential demolition sites,[39] and 1.6 mton CO2-eq per mton of waste,[40] the GWP associated with wood waste emissions in landfills are 39,600 kg CO2-eq. Allocating this GWP impact from wood waste emissions to the post-occupancy phase would have raised its contribution to the life cycle GWP impacts associated with single-family homes from .0007% to 4.3%.

Energy consumption data were derived from average diesel fuel consumption associated with the post-occupancy phase of wood-frame structures in Minnesota and Atlanta, referring to Winistorfer et al. (2005). Waste generated during the post-occupancy phase was calculated as the difference between the total life-cycle waste generation per a unit residential home and the amount of replacement, assuming that replacement generates the same mass amount of wastes during the occupancy phase. The basic data for life-cycle waste generation and replacement were

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[39] Table A-13, http://www.epa.gov/wastes/hazard/generation/sqg/cd-rpt.pdf, accessed January 31, 2013
[40] Exhibit 6, p.7, http://www.epa.gov/climatechange/waste/downloads/Landfilling.pdf, accessed January 31, 2013

derived from Oregon DEQ (2010), where the replacement volume per standard house was scaled up by multiplying the number of housing units built in 1998 (1.16 million).

3. RESULTS: LIFE CYCLE IMPACT ANALYSIS OF DIRECT INPUTS TO SINGLE-FAMILY HOMES

3.1 OVERVIEW

The following section presents the results of the input contribution analyses of the national housing stock of single-family homes. Section 3.2 reviews the estimates of overall life cycle impacts associated with single-family homes, and Section 3.3 disaggregates these impacts based on the input contribution perspective, summarizing the results of the input contribution analysis. Section 3.4 presents the more detailed analysis of the supply chain processes contributing most significantly to the life cycle impacts associated with selected, highly ranked direct inputs identified using the input contribution analysis.[41]

3.1.1 About Carpets and Rugs and *Cotton*[42]

The input contribution analyses highlighted the contribution of *carpet and rugs* to the land use competition, freshwater aquatic ecotoxicity potential, and terrestrial ecotoxicity potential lifecycle impacts associated with single-family homes. The supplemental analysis for *carpets and rugs* highlighted that these impacts were associated with cotton cultivation to produce cotton fibers. However, the Carpet and Rug Institute shows that carpet fibers used in single-family homes are dominated by synthetics followed by wool at 0.4%, and does not attribute any content to cotton.[43]

Similarly, the output contribution analyses, which are presented in Section 4, highlighted the contribution of *cotton* as the significant contributor to the life-cycle impacts associated with single-family homes. Again, this impact was primarily attributed to the assumed consumption of cotton within the Carpet and Rug Mills industry as a whole. For example, Carpet and Rug Mills (314110), which indeed does not have any direct cotton input, uses significant textile- related products such as Textile and Fabric Finishing (313320), Other textile products (314990), Nonwoven fabric mills (313230), and Narrow fabric mills (313220) that do consume a significant amount of cotton. Due to the aggregation of non-cotton based and cotton-based products within these sectors, *carpet and rugs* endowed contribution from cotton and the embodied impacts associated with cotton cultivation despite cotton not being their direct input.

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[41] The material/product category "feed grains" has been removed from the relative ranking results presented herein. This category tended to be ranked highly based on impacts associated with land use, terrestrial ecotoxicity, and impacts associated with agricultural run-off (i.e., freshwater aquatic ecotoxicity and eutrophication). However, it is posited that the contributions of feed grains to single home construction relate to feeding workers (e.g., via mobile canteens). The relevance of this category to the current analysis is considered limited and its elimination improved the presentation of results.
[42] Input Contribution Analysis, which is presented here, highlighted *Carpets and Rugs*, and Output Contribution Analysis, which is presented in Section 4, highlighted *Cotton*. Considering that both findings revolve around an assumed cotton input, a common explanation is provided herein.
[43] The Carpet & Rug Institute's *Carpet Primer* indicates that carpet doesn't contain cotton - the majority of carpet fiber is nylon at 57%, followed by olefin at 36%, polyester at 7% and wool at 0.4%: http://www.carpet-rug.org/residential-customers/resources/carpet-primer.cfm, Accessed October 21, 2011

The EPA finds this type of aggregation to be a limitation of the I-O LCA high-level approach and has attempted to cautiously interpret the findings. In that respect, the EPA dismisses the finding that in the context of single-family homes, *carpets and rugs* and *cotton* contribute significantly to the land use competition, freshwater aquatic ecotoxicity potential and terrestrial ecotoxicity potential life-cycle impacts.

The figures in this report will include *carpets and rugs* and *cotton* as such are the results of the I-O LCA, but the discussions associated with the figures will not acknowledge and validate their contribution to the lifecycle impacts of single-family homes; the EPA finds that such a conclusion would be flawed.

3.2 OVERALL LIFE CYCLE IMPACT

3.2.1 Total Life Cycle Impacts and Impacts by Phase

Table 3-1 summarizes the results of the I-O life cycle analysis for typical single-family home built in 1998. The results are broken down in terms of life cycle phase—pre-occupancy, occupancy, and post-occupancy, as described in Section 2.2.1. The information is also summarized in Figure 3.1 in terms of the relative contribution of each phase to the overall life cycle impact of a typical single-family home. Appendix D presents the results of the overall life cycle analysis broken-down further by phase and locus of impact (i.e., direct or indirect).

The I-O LCA analysis indicates that the majority of life cycle impacts associated with single-family homes occur during the occupancy phase. This finding holds for all of the measures of toxicity-related impact and pollution impact and all but one of the measures of land and resource use impact. The one exception in this last category is material use, where the majority of impact occurs during the pre-occupancy phase.

The I-O LCA methodology used for this analysis indicates that the life cycle impacts associated with the post-occupancy phase are relatively insignificant for all but the waste impact category. This finding reflects the phase boundaries used in the analysis and should not be interpreted to imply that choices regarding the management of building demolition/deconstruction material have an insignificant effect on the overall life cycle of a single-family home. Rather, this finding reflects the fact that far greater inputs (i.e., resources and materials) are consumed during the construction and use of a single-family home than during its demolition or deconstruction.
The recycling and reuse of C&D waste as input for new single-family home construction or renovation can offset the use of virgin material and, thus, can contribute to a reduction in the impacts associated with single-family homes, when this "product category" is viewed in aggregate. The recycling and reuse of C&D material from one home can decrease the pre-occupancy phase impacts associated with one or more others. In addition, the recycling and reuse of C&D material from single-family homes can be reused in a manner that lessens the life cycle impacts associated with other "product" categories, such as commercial building or highway construction. For example, Section 5.3 quantifies the potential of the reconstituted wood products

from demolished or deconstructed single-family homes to offset environmental impacts of paper and pulp industries when used to replace a portion of coal needed in paper production. Section 5.3 also explores and documents the types of impacts that can be offset through an increased processing of carpets and rugs into resin for synthetic materials and ready-mixed concrete into aggregate for use in road construction.

Table 3-1
Summary of Estimated Life Cycle Impacts of Typical Single-family Homes[44]
(1998 Basis)

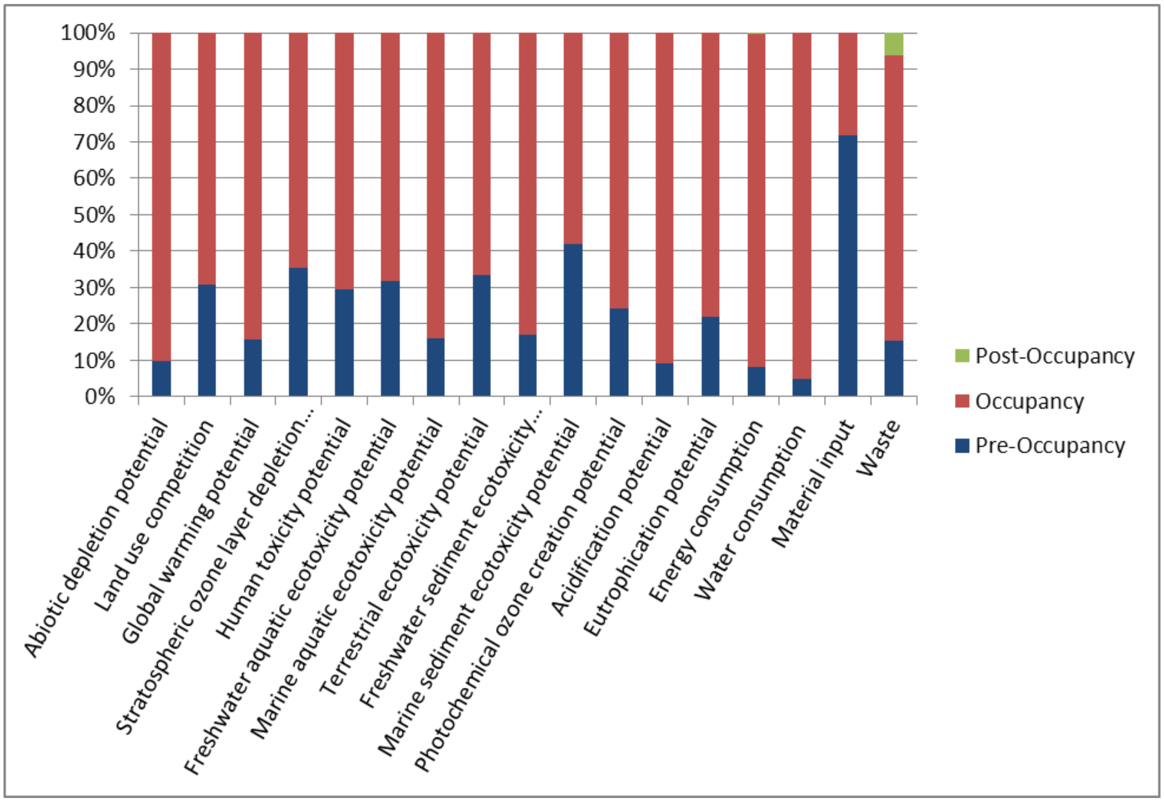
Impact category	Units	Estimated Impact by Life Cycle Phase			
		Pre-Occupancy	Occupancy	Post-Occupancy	Total Life Cycle[45]
Abiotic depletion potential (ADP)	kg Sn eq.	500	4,700	0	5,200
Land use competition (LUC)	m^2*yr	11,000	25,000	0	36,000
Global warming potential (GWP)	kg CO_2 eq.	140,000	760,000	600	900,000
Stratospheric ozone depletion potential (ODP)	kg CFC-11 eq.	620	1,100	0	1,800
Human toxicity potential (HTP)	kg p-DCB eq.	16,000	39,000	0	55,000
Freshwater aquatic ecotoxicity potential (FAETP)	kg p-DCB eq.	2,600	5,500	0	8,000
Marine aquatic ecotoxicity potential (MAETP)	mton p-DCB eq.	47,000	250,000	0	290,000
Terrestrial ecotoxicity potential (TETP)	kg p-DCB eq.	3,100	6,300	0	9,400
Freshwater sediment ecotoxicity potential (FSETP)	mton p-DCB eq.	17,000	84,000	0	100,000
Marine sediment ecotoxicity potential (MSETP)	kg p-DCB eq.	30,000	42,000	0	72,000
Photochemical ozone creation potential (POCP)	kg C_4H_4 eq.	90	250	0	330
Acidification potential (AP)	kg SO_2 eq.	500	5,000	0	5,500
Eutrophication potential (EP)	kg PO_4 eq.	70	250	0	320
Energy consumption (EC)	10^6 BTU	1,200	14,000	20	15,000
Water consumption (WC)	10^3 gallons	13,000	250,000	0	270,000
Material input (MTL)	mton	2,700	1,100	0	3,700
Waste (WST)[46]	mton	120	620	50	790

[44] To understand the relative significance of the life cycle impacts of single-family homes, see the overall vector magnitude for single-family homes as related to the whole U.S. economy, in the Relative Ranking Technical Support Document, the appendix to *Sustainable Materials Management: The Road Ahead* (EPA, 2009).

[45] Values across the rows in the table may not add up due to the rounding off to two significant digits.

[46] The life cycle waste associated with single-family homes does not equal the life cycle material input for the following reasons: 1) some material inputs leave the system not as a waste but as something else, and vice versa (e.g., coal is converted to CO_2 and water and is emitted during combustion; less than 10% of mass is counted as waste); 2) there are losses and additions to urban/industrial stock throughout the supply-chain that are not counted as waste; 3) imprecisions associated with the methods used to collect economic and environmental data do not allow for a complete mass balance.

Figure 3-1
Contribution of Different Life Cycle Phases of a Typical Single-family Home to Overall Life Cycle Impact

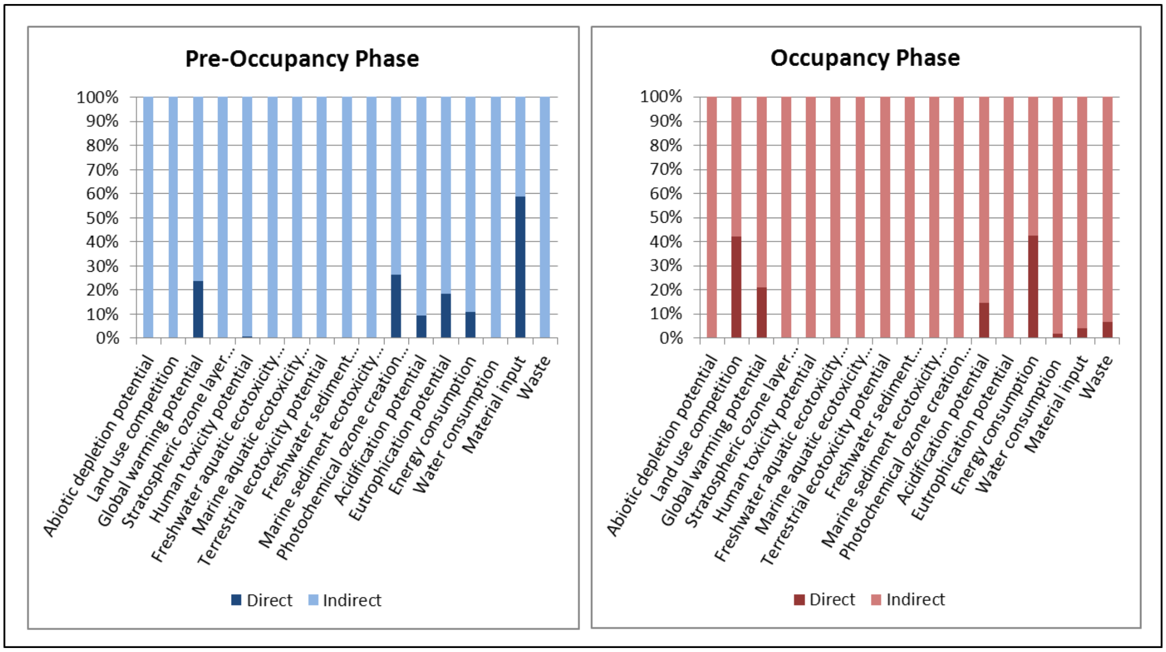


For some impact categories, the estimated occupancy-phase impacts exceed the estimated pre-occupancy phase impacts by close to an order of magnitude or more. These include the abiotic depletion potential, marine aquatic ecotoxicity potential, freshwater sediment ecotoxicity potential and acidification potential impact categories and energy and water consumption. These impacts are attributable to electric services, and the relative differences in impact estimates for these and the energy consumption categories likely reflect significantly higher energy consumption during the home occupancy phase (see Section 3.3.2 for further discussion of occupancy-phase life cycle impacts).

3.2.2 Locus of Impact: Pre-Occupancy and Occupancy Phases

Figure 3-2 presents a more detailed view of the life cycle impacts associated with the pre-occupancy and occupancy phases of the typical single-family home. Each of the charts breaks down the total life cycle impacts shown in Figure 3-1 for the respective phase based on the locus of impact, direct or indirect, as defined in Section 2.2.4.

Figure 3-2
Locus of Impact - Pre-Occupancy and Occupancy Phases



The input contribution analysis indicates that for the pre-occupancy phase the majority of impacts are indirect – i.e., they are embodied impacts associated with upstream supply chain processes. This is true for all impact categories with the exception of material input. The material input category is measured in terms of mass, and construction of single-family homes involves significant material use on a mass basis, with materials such as sand and gravel, concrete, and stone being reflected as direct impacts. Other categories of where there are significant direct impacts include those in the pollution impacts grouping and energy consumption. These likely reflect on-site energy use, including fuel combustion (e.g., by construction vehicles), and surface water impacts associated with land disturbance and re-vegetation.

The input contribution analysis for the occupancy phase highlights the direct impacts associated with the use of the land upon which the home is situated, energy and water consumption, impacts associated with emissions from fuel combustion, material input associated with replacement products, and waste. The indirect impacts are associated with the upstream supply chain processes embodied in energy production and delivery to the home as well as manufacturing and the delivery of material/product replacements during the occupancy phase of the home. Similar to the pre-occupancy phase, indirect impacts dominate the total occupancy phase life cycle impacts.

3.2.3 Comparison with Previous Studies

The estimates of overall life cycle impacts produced using the I-O LCA approach described herein generally agree with the findings of the Oregon DEQ (2010) study. The Oregon study differed from the present analysis in terms of methodology, system definition, scope (i.e., state-specific vs. national), measures of impact, data sources, and assumptions. Nonetheless, both indicate that the majority of life cycle impacts associated with single-family homes occur during the occupancy phase. This agreement between the two analyses holds across measures of abiotic depletion potential, global warming potential, stratospheric ozone depletion potential, human and ecological toxicity potentials, photochemical ozone creation potential, acidification potential, eutrophication potential, energy consumption, and water consumption. Both analyses attribute these occupancy-phase impacts to energy use and life cycle impacts associated with material replacement.

In terms of the magnitude of the life cycle impact associated with single-family homes, the results of the current analysis are also consistent with prior research. For example, the Oregon DEQ (2010) study reported life cycle GHG emissions of 684,000 kg CO_2 eq. and 12,300 million Btu of primary energy consumption on a per home basis. This national-scale analysis estimates life cycle GHG emissions of 900,000 kg CO_2 eq. and life cycle primary energy consumption of 15,000 million Btu per home. Given the differences in the methodologies employed, the agreement between these estimates is relatively strong.

3.3 INPUT CONTRIBUTION ANALYSIS

Input contribution analysis quantifies the relative contribution of direct inputs to the overall life cycle impacts associated with a single-family home. This includes estimates of embodied impacts associated with materials, products, and services used directly in building, renovating, and demolishing or deconstructing a single-family home. The input contribution analysis was completed for the pre-occupancy and occupancy phases, as described in Sections 2.2 through 2.5. The results of the input contribution analysis are summarized below. Detailed results are presented in Appendix F.

3.3.1 Pre-Occupancy Phase

Figure 3-3 highlights the top ten most highly ranked materials, products, and services used in the pre-occupancy phase of single-family homes from an input contribution perspective. The analysis indicates that when all factors are considered equally (no weighting or grouping), a diverse mix of direct inputs contributes to the overall life cycle impacts of single-family homes. The analysis highlights building materials (e.g., *brick and structural clay tile*, *ready-mixed concrete*, *reconstituted wood products*), more highly engineered products (e.g., *miscellaneous plastic products*), and services (e.g., *trucking and courier services*).

Figure 3-3
Highest Ranked Materials, Products, and Services
Full Scope (all impact categories)
Input Contribution Basis – Pre-Occupancy Phase

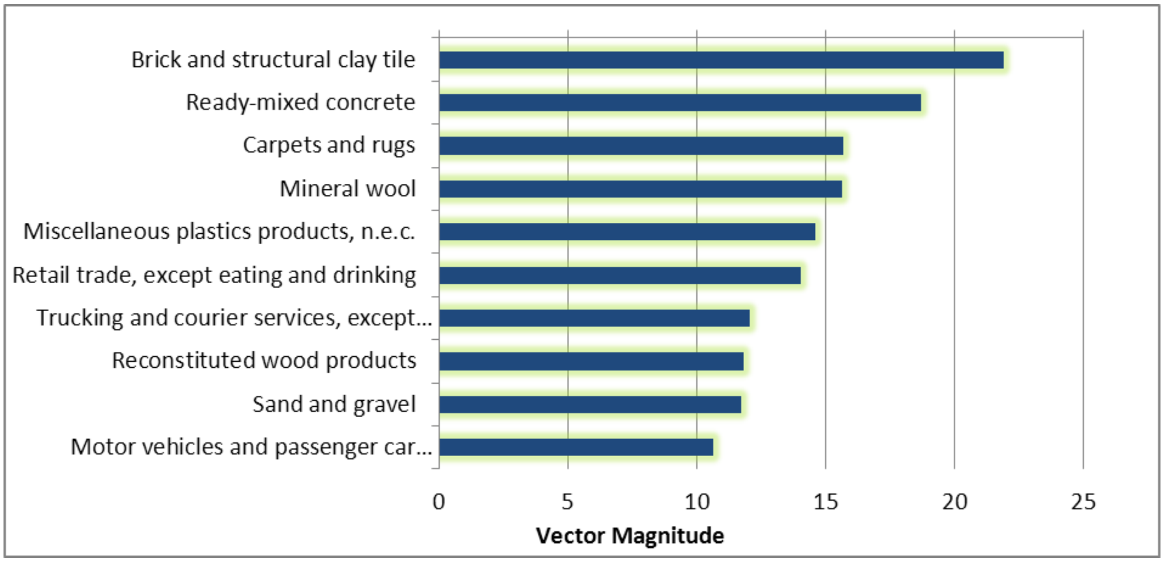


Table 3-2 further explores these results by analyzing the impact categories behind the relatively high rankings developed using the vector analysis approach. The table lists the 10 most highly ranked direct inputs contributing to the life cycle impacts associated with the pre-occupancy phase of single-family homes, considering all of the impact categories. The values associated with each impact category in the table represent the change in vector orientation, in degrees, from the vector magnitude that would have been calculated in absence of the respective category, providing an indication of the extent to which individual categories or combinations of categories drive the overall vector magnitude and overall ranking. Appendix C provides additional technical detail as well as an applied example of vector analysis, including the type of analyses used to derive Figure 3-3, Table 3-2, and similar figures and tables in subsequent sections of this report.

Where only one or two impact categories associated with a high-ranking input have relatively strong influence on the overall vector magnitude (i.e., as indicated by dark orange shading), this indicates a situation where the high ranking is driven by a limited range of impacts (e.g., ozone depletion potential impacts associated with *mineral wool*). Where moderate influence on the overall vector magnitude exists across several categories, this suggests a diverse range of life cycle impacts associated with the input (e.g., *ready-mixed concrete*).

Table 3-2
Top Ranked Direct Inputs to Single-Family Home Construction (Pre-Occupancy Phase) Based on Input Contribution Analysis

				Factor Influence (change in vector orientation introduced by factor in degrees)																
Rank	BEA Code	BEA Description	Vector Mag.	ADP	LUC	GWP	ODP	HTP	FAETP	MAETP	TETP	FSETP	MSETP	POCP	AP	EP	EC	WC	MTL	WST
1	360200	Brick and structural clay tile	21.89	2	0	2	0	25	0	40	-1	40	-1	0	0	0	0	0	0	1
2	361200	Ready-mixed concrete	18.68	13	3	25	1	5	2	1	2	1	4	20	27	26	11	9	17	17
3	170100	Carpets and rugs	15.65	0	9	0	0	1	48	0	39	0	2	0	0	8	0	1	-1	0
4	362000	Mineral wool	15.62	10	4	11	58	8	6	1	8	1	13	10	6	7	7	9	0	5
5	320400	Miscellaneous plastics products, n.e.c.	14.57	15	9	13	11	19	14	2	18	3	31	15	13	15	10	14	0	9
6	690200	Retail trade, except eating and drinking	14.02	17	9	16	2	9	7	3	9	3	10	14	19	13	23	36	1	7
7	650301	Trucking and courier services, except air	12.01	10	37	15	0	2	2	0	3	0	2	30	12	23	16	4	0	4
8	200904	Reconstituted wood products	11.79	16	13	16	3	7	5	2	6	2	10	13	13	12	36	21	2	18
9	90002	Sand and gravel	11.69	2	-1	2	-1	0	-1	0	-2	0	-2	0	0	0	3	3	46	43
10	590301	Motor vehicles and passenger car bodies	10.62	14	12	16	5	16	21	3	23	4	14	17	14	16	16	15	0	7

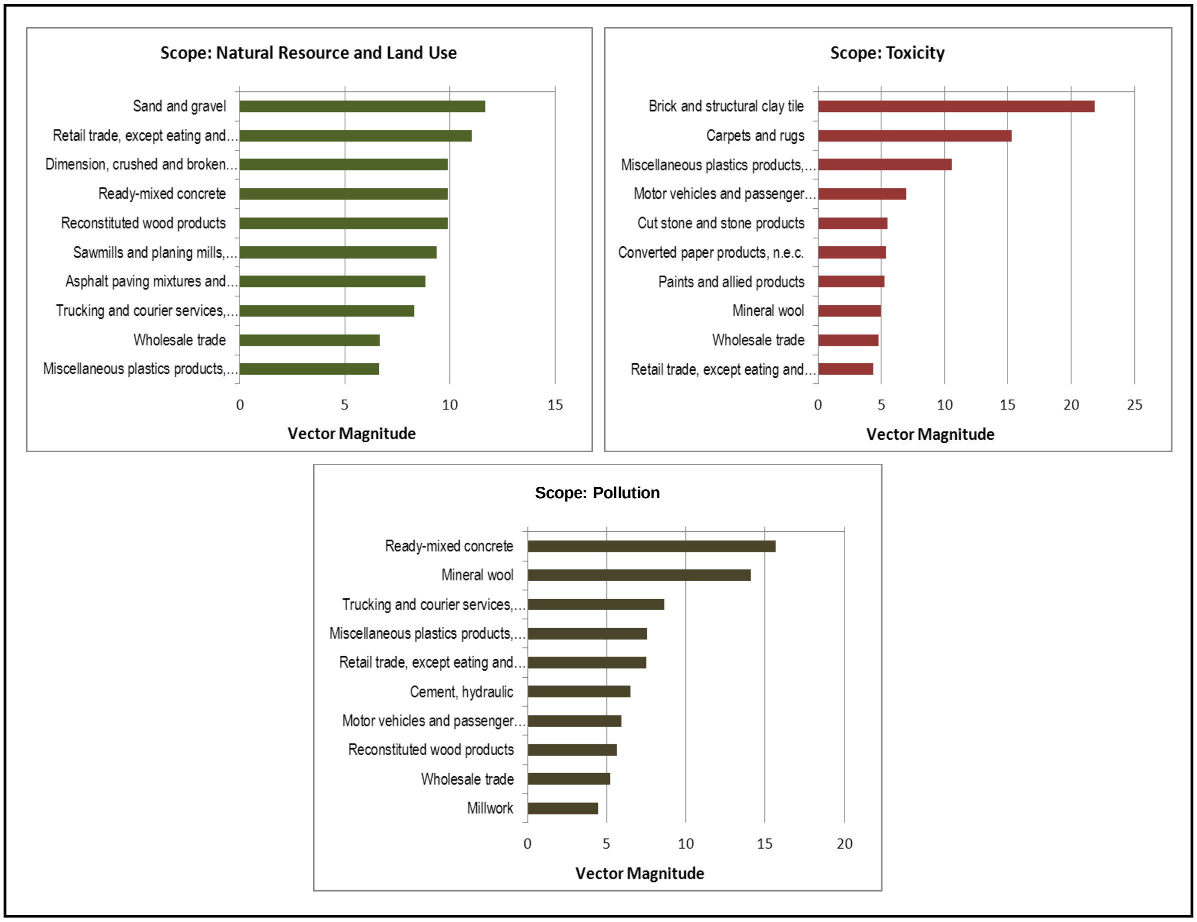
Key: Cells are shaded using a gradient, where orange-shaded cells indicate that the impacts associated with the material/product/service are above the mean for all materials/products/services and blue-shaded cells indicate that the impacts associated with the material/product/service are below the mean. Darker shading indicates relatively stronger influence of the impact category on the overall vector magnitude.

This more detailed review suggests that some direct inputs to single-family home construction are ranked highly based on related impact categories. For example, the relatively high ranking associated with brick and structural clay tile derives from its relatively high impact along three potentially related dimensions: human toxicity potential (HTP), marine aquatic ecotoxicity potential (MAETP), and freshwater sediment ecotoxicity potential (FSETP). This clustering of impacts and drivers was further explored by conducting vector analyses on groups of impact categories described in Section 2.3 and summarized below.

1. *Natural Resources and Land Use* – waste (WST), abiotic depletion potential (ADP), energy consumption (EC), water consumption (WC), land use competition (LUC), and material input (MTL);
2. *Toxicity* – human toxicity potential (HTP), freshwater aquatic ecotoxicity potential (FAETP), marine aquatic ecotoxicity potential (MAETP), terrestrial ecotoxicity potential (TETP), freshwater sediment ecotoxicity potential (FSETP), and marine sediment ecotoxicity potential (MSETP); and
3. *Pollution Impact* – stratospheric ozone depletion potential (ODP), global warming potential (GWP), acidification potential (AP), euthrophication potential (EP), and photochemical ozone creation potential (POCP).

Figure 3-4 summarizes the results of these analyses of factor groupings and highlights the nature of the impact categories driving the rankings behind the top-ranked materials, products, and services identified in Figure 3-3. For example, the analysis by groupings indicates that the high ranking associated with *sand and gravel* is driven primarily by resource use; high ranking associated with *brick and structural clay tile* is driven by toxicity impacts; and high rankings associated with some materials and products, such as *ready-mixed concrete*, *reconstituted wood products*, and *miscellaneous plastics products* are driven by a range of impact types.[47]

Figure 3-4
Highest Ranked Materials, Products and Services Based on Different Scopes
Input Contribution Basis – Pre-Occupancy Stage



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[47] Through possible correlations in their supply-chains, inputs that are ranked highly within the same groupings of environmental impacts could point to industry sectors within their supply-chains that contain "hotspots" for those groups of impact categories. Those sectors could then be examined for the appropriateness of a mitigation measure. For example, *ready-mixed concrete* and *reconstituted wood products* are ranked as top 10 inputs for their high impacts in both Natural Resource and Land Use and Pollution groupings. The supplemental contribution analyses, pages 38- 41, provide a glimpse into the sectors within their supply-chains that cast the highest impacts. If mitigating impacts of *ready-mixed concrete* and *reconstituted wood products* within Natural Resource and Land Use and Pollution groupings were of high priority, targeting those sectors that are highlighted within Natural Resource and Land Use and Pollution groupings that are in common for the two products could be effective. Since sector data are

Summary – Input Contribution Analysis, Pre-Occupancy Phase

The input contribution analysis for the pre-occupancy phase suggests the following findings:

- Material use as a dominant factor – The relatively high ranking of certain construction materials can be attributed to the influence of the material use factor, which measures impact in terms of weight. This includes materials and products such as *ready-mixed concrete* and *sand and gravel*. In the case of *sand and gravel*, this and the waste factor (which is also weight-based) are the principal drivers of the high ranking. The relatively high ranking of *ready-mixed concrete* reflects a more complex set of embodied impacts, not just material use. The material use factor provides an indication of physical land and/or ecosystem disturbance, distinct from pollution or toxics-based disturbance. By highlighting sand, gravel, and similar materials, the material use factor appears to be serving this function.

- Toxicity factors as primary drivers – The relatively high ranking of some direct inputs used in the pre-occupancy phase of a single-family home is driven by toxicity factors, including human and ecological toxicity factors. Direct inputs falling into this category include *brick and structural clay tile*. Section 3.4.5 reviews the potential sources of toxic impacts associated with *brick and structural clay tile*.

- Diverse embodied impacts reflective of diverse products categories – Some product and service categories encompass a diverse set of inputs used directly in single-family home construction and embody a diverse set of upstream processes. The complexity of these product/service categories and upstream processes is reflected in the results, where they are ranked relatively highly based on moderate effects across diverse sets of impact categories. Products and services that fit this profile include *miscellaneous plastic products*, *retail trade*, *trucking and courier services*, and *motor vehicles and passenger car bodies*.

- Narrowly defined products with diverse mix of impacts – In contrast to the diverse products and service categories described above, some product categories are relatively narrowly defined but, nonetheless, the analysis indicates impacts across diverse sets of categories. This is reflective of a situation whereby the relatively high ranking is driven by the complex ways in which a limited set of upstream processes impact the environment. The ranking is a result of the complexity of the product-environment interactions rather than the complexity of the product category. Products that fit this profile include *ready-mixed concrete* and *reconstituted wood products*.

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aggregated, sectors that are common for the two should be analyzed so that correct supply-chain products and processes are identified for a mitigation measure.

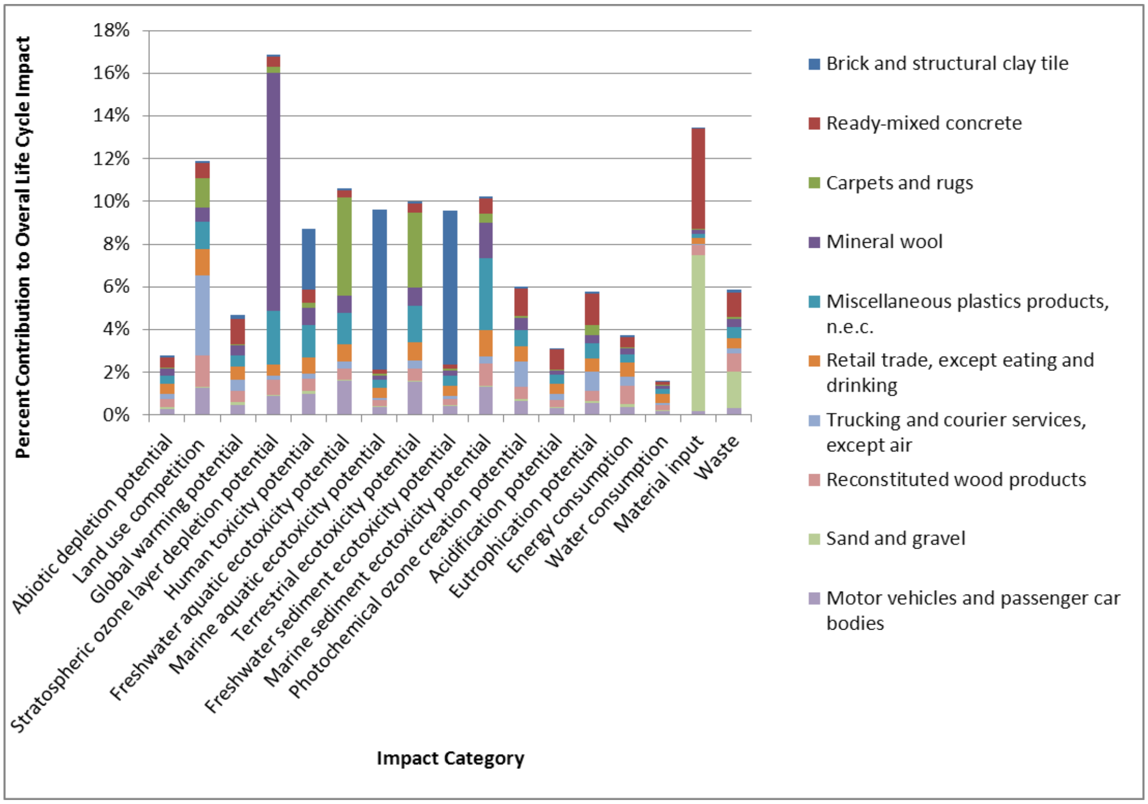
- Fiberglass and mineral wool – The product category *mineral wool*[48] does not fit neatly into any of the above categories. It is a narrowly defined product with a relatively high ranking that is driven primarily by a single factor, stratospheric ozone depletion potential (ODP). In terms of single-family home construction, *mineral wool* is associated with fiberglass and mineral wool insulation.

Finally, Figure 3-5 shows the percentage of the total estimated life cycle impacts associated with the top 10 ranked direct inputs used in the pre-occupancy phase of single-family homes. Depending on the impact category, impacts associated with the top 10 inputs account for anywhere from just below 2% to just above 16% of the total life cycle impact of single-family homes. This suggests that for some impact categories, the overall life cycle impacts associated with inputs used in this phase are distributed across an array of inputs. For example, the top 10 inputs account for less than 2% of the overall life cycle water consumption (WC) of single-family homes. Reductions in the water consumption associated with any one of the top-ranked inputs may have little effect on the overall life cycle impact.

However, for other impact categories, the overall life cycle impacts are embodied in a more limited set of inputs. In these situations, opportunities exist for significantly reducing selected impacts by focusing on a narrow set of inputs. Stratospheric ozone depletion potential and material input are examples of this, where one or two of the top-ranked inputs account for a significant percentage of the overall life cycle impact (e.g., *mineral wool* accounts for an estimated 11% of the life cycle stratospheric ozone depletion impacts associated with single-family homes).

[48] The "mineral wool" product category (BEA commodity 362000) encompasses a range of products, including fiberglass insulation, mineral wool insulation, and related fiberglass and mineral wool products (e.g., insulating bats). See section 3.4.2 for additional discussion.

Figure 3-5: Contribution of 10 Most Highly Ranked Direct Inputs to Life Cycle Impacts Associated with Single-family Home Construction (Pre-occupancy Phase)



3.3.2 Occupancy Phase

The input contribution analysis of the occupancy phase of the life cycle of a single-family home focused on:

- Impacts associated with energy and water consumed in the home, including indirect impacts associated with the production and delivery of electricity and water to the home by utilities;
- Impacts associated with GHG emissions and acidifying substance emissions generated by fuel combustion (e.g., natural gas for heating) in the home; and
- Direct and indirect impacts associated with the 13 specific products and an "other product" category included to capture materials replaced during the life span of the home.

For replacement materials, direct and indirect impacts were rolled up and expressed as embodied impacts. As a result, a total of 17 direct inputs were considered in this analysis: 13 specific products and one "other" product category representing replacement materials, electric services, natural gas distribution, and petroleum refining. Given this relatively narrow scope, vector analysis was not used for ranking the materials, products, and services, as several of the key conditions necessary for efficient operation of this approach were not met (e.g., skewed distribution of mean-centered impact estimates).

Rather, a single-factor vector analysis was conducted for each impact category. Using this approach, six direct inputs were identified where at least one impact estimate exceeded one standard deviation above the mean impact value for all 17 materials, products, and services analyzed. The results are summarized in Table 3-3.

Table 3-3: Top Ranked Direct Inputs to Single-Family Home Construction (Occupancy Phase) Based on Input Contribution Analysis

BEA Code	BEA Description	ADP	LUC	GWP	ODP	HTP	FAETP	MAETP	TETP	FSETP	MSETP	POCP	AP	EP	EC	WC	MTL	WST
170100	Carpeting		●				●		●									
362000	Insulation (glass fiber)				●													
200200	Siding (wood shingle)		●															
540700	Other				●						●							
680100	Electric services (utilities)	●		●		●		●		●	●	●	●	●	●	●	●	●
680202	Natural gas distribution	●															●	●

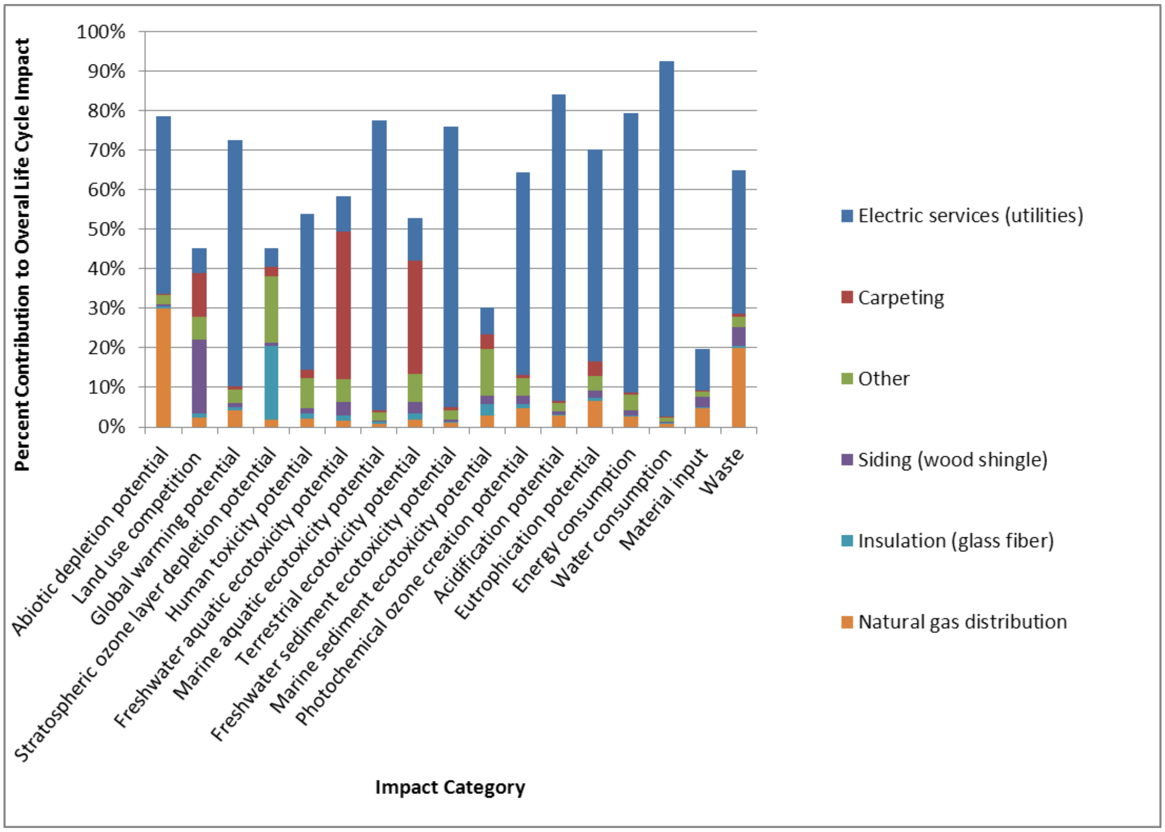
<u>**Summary – Input Contribution Analysis, Occupancy Phase**</u>

The input contribution analysis for the occupancy phase of single-family homes suggests the following findings:

- <u>Energy consumption and related impacts</u> – As Figure 3.6 shows, energy consumption and the impacts associated with electricity generation and delivery dominate the life cycle impacts associated with the inputs into the occupancy phase of single-family homes. *Electric services* represent more than half of the overall life cycle impact of single-family homes for 8 of the 17 impact categories analyzed and represent the highest contributor to occupancy-phase life cycle impacts for 11 of the impact categories.
- <u>Replacement materials</u> –In the case of highly ranked replacement materials—*wood shingle siding* and *glass fiber insulation*—significant contributions to life cycle impacts are associated with a single impact category.

Finally, Figure 3-6 shows the contribution of these six direct inputs to the life cycle impacts associated with single-family homes. Depending on the impact category, these six inputs contribute anywhere from 20% to 90% of the total life cycle impact of single-family homes. This analysis suggests that opportunities exist for significantly reducing the overall life cycle impacts of single-family homes by focusing on a narrow set of inputs into the occupancy phase. The most significant reductions in life cycle impacts of single-family homes could be realized through reductions in electricity consumption and/or impacts associated with upstream supply processes associated with electricity generation and distribution. Improvements in these areas could result in reduced impacts across multiple natural resource and land use, toxicity, and pollution impact categories.

Figure 3-6: Contribution of 6 Most Highly Ranked Direct Inputs to Life Cycle Impacts Associated with Single-family Home Use (Occupancy Phase)



3.4 Supplemental Contribution Analysis for Selected Inputs

Select materials, products, and services representing direct inputs to single-family homes were identified based on the results of the input contribution and vector analyses as well as whether they were among the top 20 highest ranked inputs used in the pre-occupancy and/or occupancy phase. Direct inputs meeting these criteria were further reviewed based on whether they represented a clearly-defined material or product—i.e., a material or product for which an SMM-oriented policy response could be feasible. Twenty-one direct inputs met these criteria, and the following five direct inputs were identified for further supply-chain analysis based on the rationale outlined in Appendix F:

- Fiberglass and mineral wool (insulation)
- Ready-mixed concrete
- Reconstituted wood products
- Brick and structural clay tile
- Siding (wood shingle)

This subsequent analysis was conducted using supplemental contribution analysis to identify the processes in the supply chains of these direct inputs that contribute most significantly to their associated life cycle impacts. While these supplemental analyses were conducted using the same methodology as other life cycle analyses described herein, interpretation of the results focused primarily on the sets of impacts for which the direct input was identified as significant in the context of the life cycle impacts of single-family homes. For example, the interpretation of results of supplemental analysis of fiber glass and mineral wool focused on embodied stratospheric ozone depletion potential (ODP) impacts. This approach was adopted to maintain the focus on the life cycle of single-family homes.

The results of these supplemental supply chain analyses are presented below. Section 5 of this report discusses the potential for avoided impacts for some of these materials, including *brick and structural clay tile*, *ready-mixed concrete*, and *reconstituted wood products*, and closely related upstream supply chain processes.

3.4.1 Fiberglass and Mineral Wool (Insulation)

Life cycle impacts associated with fiberglass and mineral wool insulation used in single-family homes are captured in the BEA *mineral wool* product category.[49] In newer homes, fiberglass and mineral wool insulation is typically installed when the home is built (pre-occupancy phase). For older homes, fiberglass and mineral wool insulation may be installed during the occupancy phase of the home for weatherization and to improve energy efficiency. New residential construction, renovation, and the manufacturing of products used in single-family homes (e.g., appliances) accounted for more than half of the demand for products in the *mineral wool* category in 1998 (DOC 2010b). Once installed, fiberglass and mineral wool insulation typically last for the lifespan of the home (see Table 1-3).

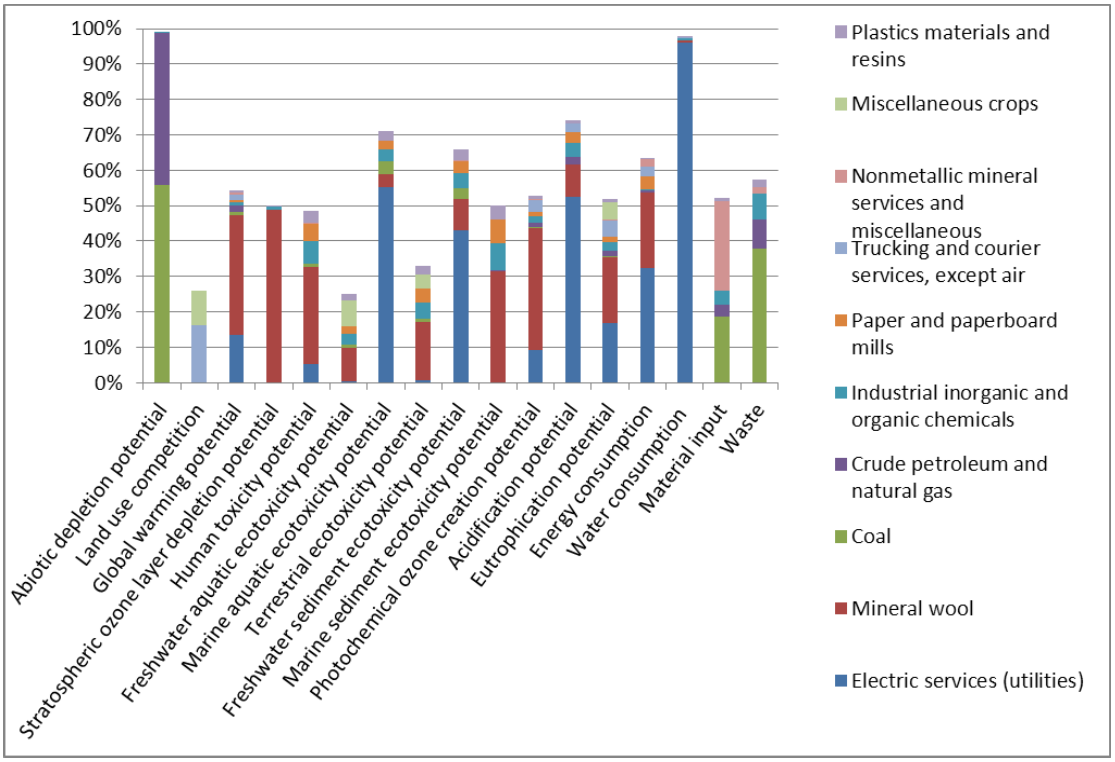
The pre-occupancy-phase input contribution analysis suggests that *mineral wool* contributes significantly to the overall life cycle impacts associated with single-family homes primarily due to stratospheric ozone depletion potential (ODP) impacts, though the analysis also suggests contributions to other embodied impacts across all of the impact groupings (see Table 3-2). The occupancy-phase input contribution analysis highlights the significant contribution of *mineral wool* to the overall ODP life cycle impacts associated with single-family homes.

Figure 3-7 presents the results of the supplemental contribution analysis of fiberglass and mineral wool used in the insulation of single-family homes. For the ODP impact category, nearly half of the impacts are associated with the *mineral wool* product category itself, suggesting that direct emissions of stratospheric ozone layer depleting substances during the manufacture of *mineral wool*, rather than upstream supply chain processes, are the principal contributor to this impact.[50]

[49] The “mineral wool” product category (BEA commodity 362000) encompasses a range of products, including fiberglass insulation, mineral wool insulation, and related fiberglass and mineral wool products (e.g., insulating bats). See, for example, NAICS category 327993, Mineral Wool Manufacturing (http://www.census.gov/cgi-bin/sssd/naics/naicsrch?code=327993&search=2007%20NAICS%20Search), which is the analog of BEA commodity.

[50] Output contribution analysis disaggregates the impacts embodied in a material, product, or service to the upstream supply chain processes where the emissions associated with the impacts occur. The portion of the total embodied life cycle impact that is not disaggregated to upstream supply chain processes represents the impacts associated with the production of the material, product, or service being analyzed.

Figure 3-7: Supplemental Contribution Analysis of Fiberglass and Mineral Wool (Insulation) Used in Single-family Homes



3.4.2 Ready-mixed Concrete

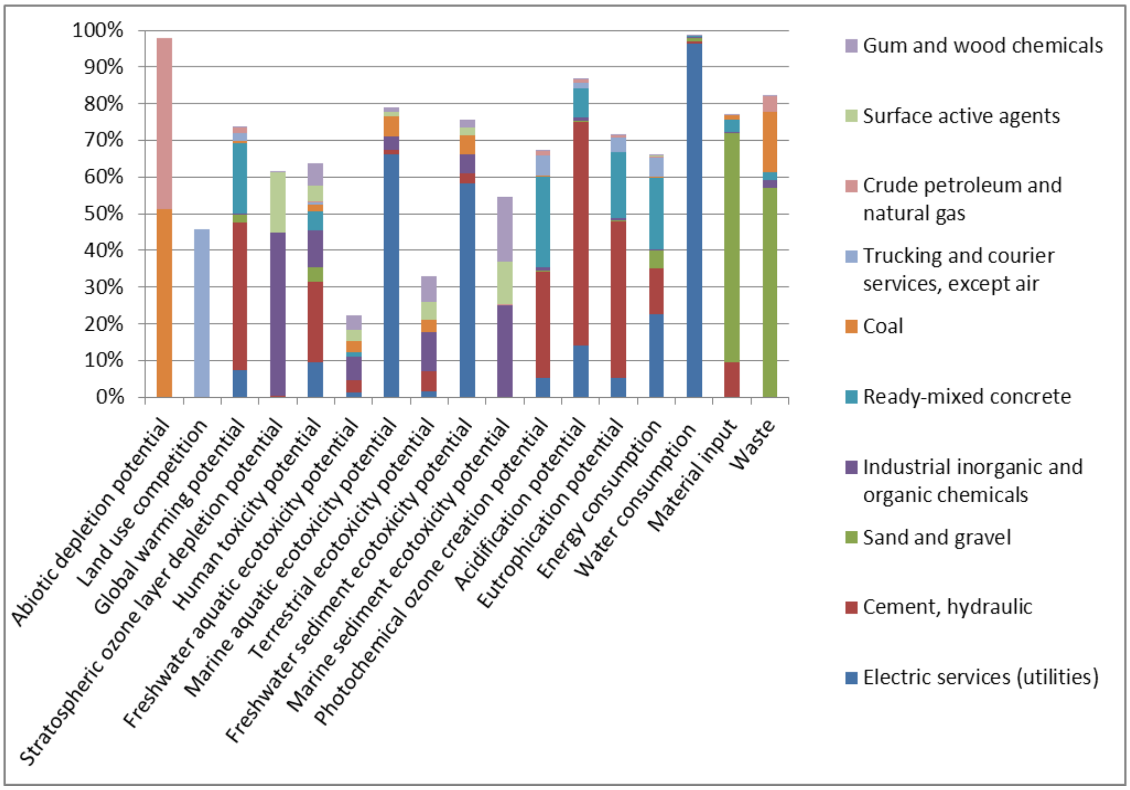
Ready-mixed concrete is a direct input to newly constructed single-family homes, used to construct foundations, footings and basement walls, architectural and hard landscape elements, driveways, etc. Approximately 19 tons of concrete were used to build the average home in 2000 (see Table 1-1). When used for foundations and footings, *ready-mixed concrete* typically lasts for the lifespan of the home (see Table 1-3).

The pre-occupancy-phase input contribution analyses suggests that *ready-mixed concrete* contributes significantly to the overall life cycle impacts associated with single-family homes through four of the five impact categories included in the "pollution impacts" grouping: global warming potential, photochemical ozone creation potential, acidification potential, and eutrophication potential. It is the highest-ranked direct input based on this grouping (see Figure 3-4). The analysis also suggests that *ready-mixed concrete* contributes to the overall life cycle impacts of single-family homes through several other impact pathways, including abiotic depletion potential, energy consumption, material input, and waste (see Table 3-2).

Figure 3-8 presents the results of the supplemental contribution analysis of *ready-mixed concrete*. For the four pollution impacts categories for which *ready-mixed concrete* contributes significantly to the overall life cycle impact, *hydraulic cement* was identified as the primary source of embodied impacts within the *ready-mixed concrete* supply chain. This likely reflects direct emissions associated with quarrying and cement kilns. For example, cement manufacturing is the second-leading source of CO_2 after fossil fuel consumption (DOE 2009). The analysis also suggests that direct emissions during the manufacture of *ready-mixed concrete* are a significant source of impact in this grouping.

Sand and gravel was identified as the most important upstream supply chain process associated with relatively significant material use and waste life cycle impacts embodied in the ready-mixed concrete used to build single-family homes. *Electric services* also contribute significantly to embodied impacts across multiple impact categories.

Figure 3-8: Supplemental Contribution Analysis of Ready-Mixed Concrete Used in Single-family Homes

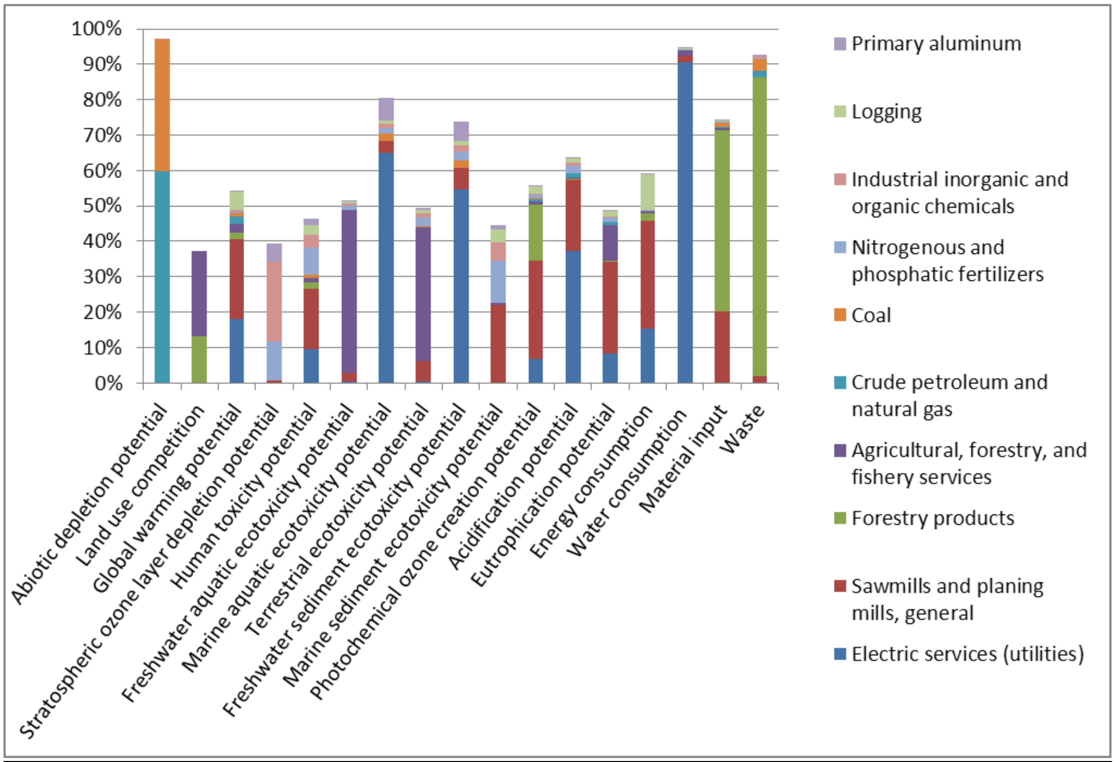


3.4.3 *Wood Shingle Siding*

Wood shingle siding was considered in the analysis of material replacement during the occupancy phase of a single-family home based on information presented in the Harvard University (2009) study on the home remodeling market and replacement data available in the Oregon DEQ (2010) study. In addition, wood shingle siding is the most frequently replaced of the materials commonly used in North America for siding in single-family homes (Athena Institute, 2002). The occupancy-phase input contribution analysis suggested that *wood shingle siding* contributes to the life cycle impacts associated with a single-family home primarily based on the land use competition (LUC) factor.

Figure 3-9 presents the results of the supplemental contribution analysis of *wood shingle siding* used in single-family homes. *Forestry products* and *agricultural, forestry and fishery services* supply chain processes contribute most significantly to the LUC impacts embodied in wood shingle siding, reflecting the geographic footprint of forests managed for wood production. Other supply chain processes contributing significantly to embodied impacts associated with *wood shingle siding* include *electric services* and *sawmills and planing mills*.

Figure 3-9
Supplemental Contribution Analysis of Siding (Wood Shingle) Used in Single-family Homes



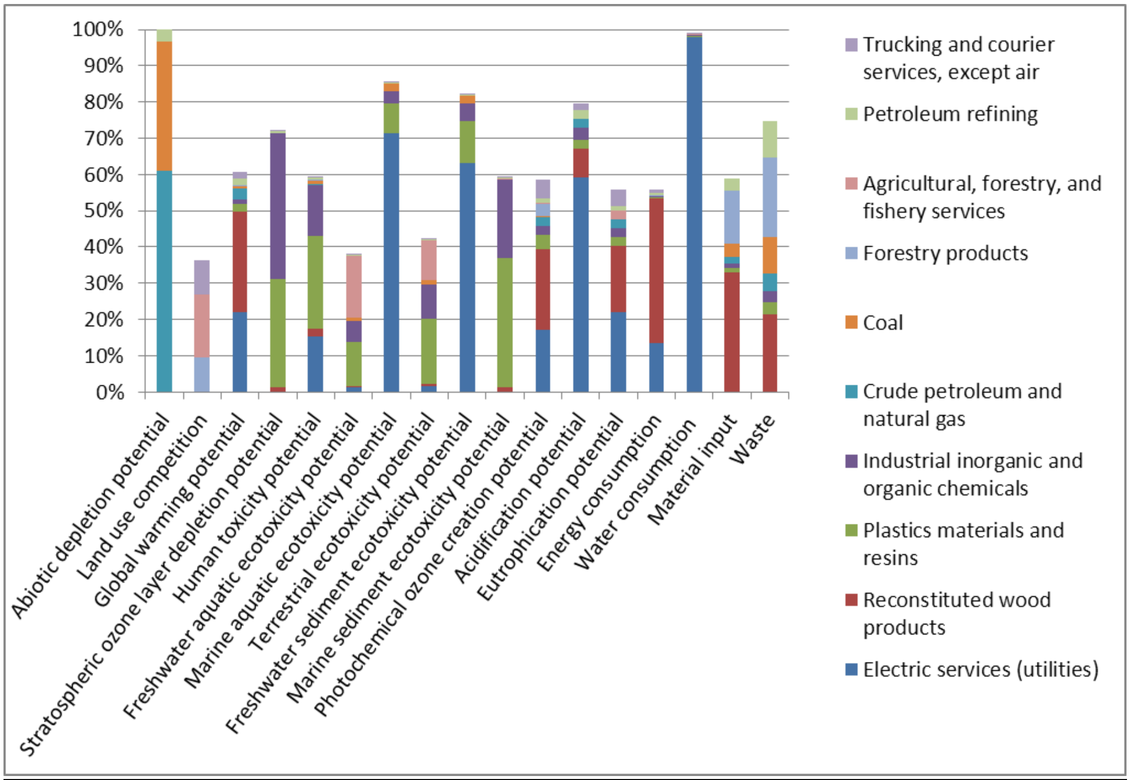
3.4.4 *Reconstituted Wood Products*

The reconstituted wood products category includes wood panels (e.g., particleboard, oriented strand board) made from wood chips and particles and used in a variety of ways in home construction and renovation (e.g., exterior wall sheathing, subfloors, etc.). *Reconstituted wood products* were highlighted in the pre-occupancy-phase input contribution analysis, with a broad range of impacts associated with this direct input particularly across the natural resources and land use and pollution impacts groupings. Reconstituted wood products are ranked among the top 10 most significant contributors to the overall life cycle impact associated with single-family homes based on both of these groupings (see Figure 3-4).

Figure 3-10 presents the results of the supplemental contribution analysis of *reconstituted wood products*. Within the natural resources and land use grouping, the analysis suggests that the *reconstituted wood products* manufacturing process contributes significantly to energy consumption and waste impacts. Upstream supply chain processes contributing significantly to the embodied natural resources and land use impacts of this input include *forestry products* and *agricultural, forestry, and fishery services* (land use competition) and *electric services* (water consumption), the former reflecting the geographic footprint of forests managed for wood production.

For the four pollution impacts categories for which *reconstituted wood products* contributes significantly to the overall life cycle impact associated with single-family homes, *electric services* was identified as consistently significant source of embodied impacts within the *reconstituted wood products* supply chain. The analysis also suggests that direct emissions during the manufacture of *reconstituted wood products* are a significant source of impacts within this grouping.

Figure 3-10: Supplemental Contribution Analysis of Reconstituted Wood Products Used in Single-family Homes

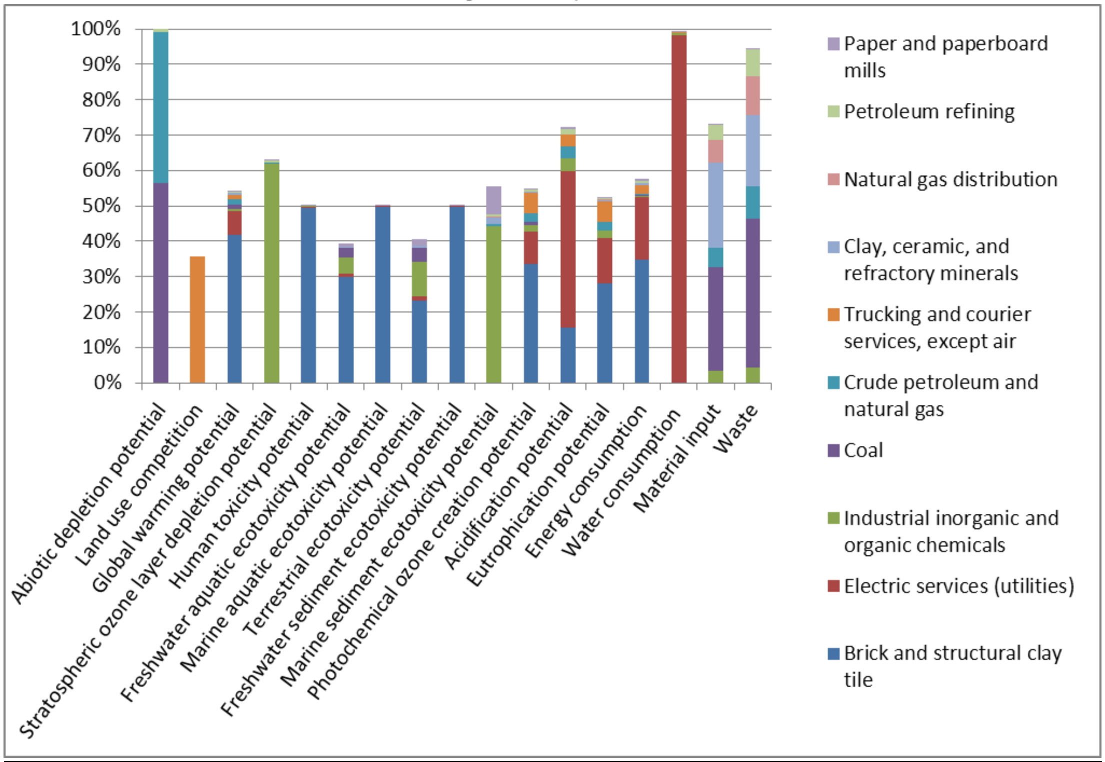


3.4.5 Brick and Structural Clay Tile

Brick and structural clay tile are important direct inputs to newly constructed single-family homes, primarily used as durable siding materials and architectural and structural elements. New residential construction and renovation accounted for about a third of the demand for products in the *brick and structural clay tile* category in 1998 (DOC 2010b). These materials typically last for the lifespan of the home (see Table 1-3). The pre-occupancy-phase input contribution analysis suggests that *brick and structural clay tile* contribute significantly to the overall life cycle toxicity impacts associated with single-family homes, particularly in the human toxicity potential, marine aquatic ecotoxicity potential, and freshwater sediment ecotoxicity potential categories (see Table 3-2). It is the highest-ranked direct input based on the toxicity grouping (see Figure 3-4).

Figure 3-11 presents the results of the supplemental contribution analysis of *brick and structural clay tile*. The analysis suggests that direct emissions from the manufacture of *brick and structural clay tile* account for close to half of this direct input's contribution to the overall life cycle impact in the human toxicity, marine aquatic ecotoxicity, freshwater sediment ecotoxicity potential impact categories. Toxic impacts associated with *brick and structural clay tile* likely derive from the release of naturally occurring in toxic compounds during mining and high heat production processes.[51]

Figure 3-11: Supplemental Contribution Analysis of Brick and Structural Clay Tile Used in Single-family Homes



<u>**Summary – Supplemental Contribution Analysis**</u>

The supplemental contribution analyses indicate different patterns of impact with respect to the supply chains of the product categories that were analyzed. These patterns demonstrate the importance of a life cycle approach to the development of policy responses that are well-tailored to address environmental impacts. These patterns include:

1. <u>Life cycle impacts attributable to the direct inputs</u> – The analyses of *fiberglass and mineral wool insulation* and *brick and structural clay tile* suggest that a significant portion of their life cycle impacts in the context of single-family homes is directly associated with production of these inputs, rather than upstream processes. Almost half of the stratospheric ozone depletion potential impacts associated with *fiberglass and mineral wool insulation* and almost half of the human toxicity potential, marine sediment ecotoxicity potential, and freshwater sediment ecotoxicity potential impacts associated with *brick and structural clay tile* are attributable to the manufacture of these respective products. This suggests the following:

[51] See, for example, EPA (1995) and EPA (2003b) and Toxicity Release Inventory (TRI) 2009 dataset for NAICS category 327 Brick/Clay/Glass.

a. Policy responses intended to reduce the life cycle impacts associated with these direct inputs and direct inputs exhibiting similar supply chain impact patterns could be effectively focused on the product categories themselves (i.e., rather than upstream supply chain processes).

b. Policy responses associated with these and similar materials and products could also focus effectively on those processes that directly consume these products. For example, because single-family homes and other residential structures account for a significant percentage of the demand for *fiberglass and mineral wool insulation* and *brick and structural clay tile*, policy responses focused on residential housing (i.e., design, construction, renovation, C&D waste management) could be an effective avenue for encouraging reductions in the impacts associated with these products.

2. Life cycle impacts attributable to energy intensive supply chain processes – *Ready-mixed concrete* and *reconstituted wood products* also fall into the category above (life cycle impacts attributable to direct inputs). In addition, the analyses of these products suggest that a significant portion of their life cycle impacts in the single-family home context derive from energy inputs, primarily *electric services*. This suggests that policy responses associated with these and other products exhibiting similar supply chain impact patterns could be most effective if conducted as integrated energy- and emissions- focused responses. SMM concepts and strategies present a framework for such an integrated approach.

3. Wood products and forestry – Forestry and related forestry services processes account for almost 40% of the life cycle land use competition impacts embodied in *wood shingle siding* and almost 30% of the life cycle impacts embodied in *reconstituted wood products*. Depending on how they are managed, forests can represent an important carbon sink. In the United States, forests account for the majority of the carbon sequestration experienced over the past two decades due primarily to a net increase in carbon accumulation in forest stocks (EPA 2011). This illustrates the connectivity of the impacts included in this life cycle analysis and the importance of weighing multiple factors when evaluating policy responses. For example, efforts to reduce the land dedicated to forestry for single family homes could have implications for the life cycle global warming potential impacts associated with single family homes.[52]

4. Material Input and Waste –The supplemental analysis indicates that upstream supply chain processes associated with s*and and gravel* contribute significantly to the material use and waste life cycle impacts embodied in the ready-mixed concrete used to build single-family homes. Similarly, the manufacturing of *reconstituted wood products* contributes significantly to the waste life cycle impacts associated with this input to single-family homes. Policy responses focused on feeding industrial waste back into the manufacturing and upstream supply chain processes (e.g., the use of concrete from demolished buildings as aggregate in ready-mixed concrete, the recycling of wood panels back into the reconstituted wood products manufacturing process) as well as policy responses focused on residential housing

[52] The implications in terms of the direction of global warming potential impact would depend on several factors, including forest management practices, demand effects for forest products on the forest biomass, waste generated in producing inputs from harvested wood and the management of that waste, etc.

(i.e., design, construction, renovation, C&D waste management) could be effective avenues for encouraging reductions in the impacts associated with these products.

4. RESULTS: OUTPUT CONTRIBUTION ANALYSIS

4.1 OVERVIEW

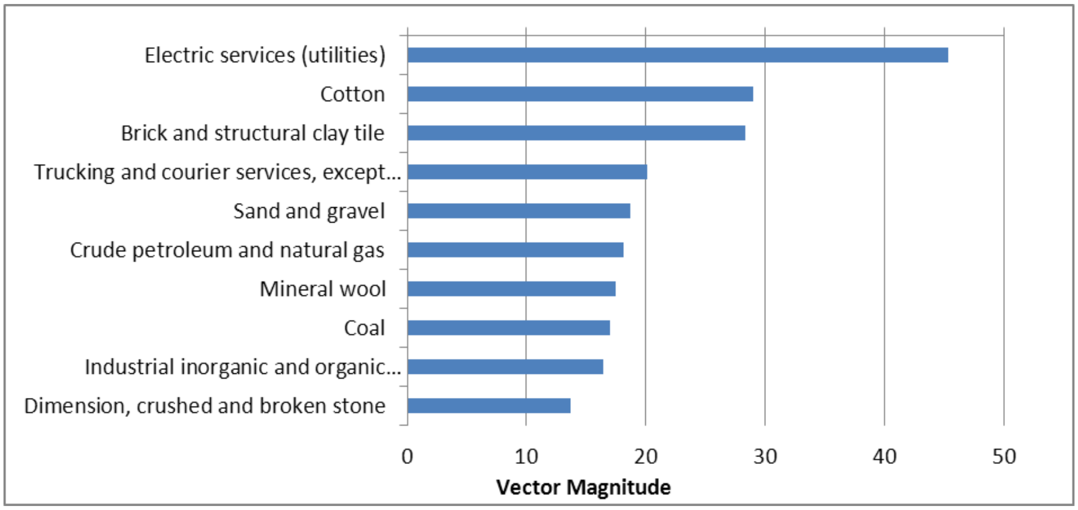
The following section presents the results of the output contribution analyses of the national housing stock of single-family homes. Whereas the input contribution analysis described in the previous section focused on the relative contribution of direct inputs to the overall life cycle impacts associated with a single-family home, the output contribution analysis disaggregates these impacts to their original sources in the upstream supply chain of the product system. Whereas the supplemental contribution analyses in the previous section focused on the upstream supply-chain processes for specific inputs, the output contribution analysis included here will focus on the supply-chain processes necessary to construct and operate all single-family homes built in 1998 across the nation.

Section 4.2 presents the results of the output contribution analysis for the pre-occupancy phase of the single-family home, Section 4.3 presents the output contribution results for the occupancy phase, and Section 4.4 summarizes the overall findings from the output contribution analysis. Appendix G presents detailed results of the output contribution analysis.

4.2 PRE-OCCUPANCY PHASE

Figure 4-1 highlights the top ten most highly ranked supply chain processes used to provide and deliver inputs into the pre-occupancy phase of single-family homes from an output contribution perspective. The analysis indicates that when all factors are considered equally (no weighting or grouping), a relatively diverse mix of supply chain processes contributes to the overall life cycle impacts of single-family homes. The analysis highlights energy services and related supply chain process (e.g., *electric services*, *coal*), raw material extraction/production processes (e.g., *sand and gravel*, *dimension, crushed and broken stone*), and transportation (i.e., *trucking and courier services*).

Figure 4-1: Highest Ranked Materials, Products, and Services, Full Scope (all impact categories), Output Contribution Basis – Pre-Occupancy Phase



In addition, comparing these results to the results of the input contribution analysis (see Figure 3-3) highlights the differences in these two perspectives. Whereas the input contribution analysis emphasized the contribution of more finished products to the overall life cycle impacts of home construction, the output contribution analysis highlights the energy- and materials-related supply chain processes contributing most significantly to the impacts embodied in the more direct construction inputs. The two perspectives emphasize some of the same materials and products and services. This is the case for:

- Materials and products where the supply chain from extraction to direct input to home construction is relatively direct (e.g., *sand and gravel*);
- Products where the locus of impact is concentrated at the manufacturing stage of the material/product (e.g, *mineral wool*, *brick and structural clay tile*); and
- Services that are ubiquitous throughout the supply chain (e.g., *transportation and courier services*).

Table 4-1 further explores these results by analyzing the impact categories behind the relatively high rankings developed using the vector analysis approach. The table lists the 10 most highly ranked supply chain processes contributing to the life cycle impacts associated with single-family-home pre-occupancy phase, considering all of the impact categories. As with Table 3-2, the values associated with each impact category in the table provide an indication of the extent to which individual categories or combinations of categories drive the overall vector magnitude and overall ranking.

Where only one or two impact categories associated with a high-ranking input have relatively strong influence on the overall vector magnitude (i.e., as indicated by dark orange shading), this indicates of a situation where the high ranking is driven by a limited range of impacts (e.g., the abiotic depletion impacts associated with *crude petroleum and natural gas*). Where influence on the overall vector magnitude exists across several categories, this suggests a diverse range of life cycle impacts associated with the input (e.g., *electric services*).

Table 4-1: Top Ranked Supply Chain Processes Associated with Single-family Home Construction (Pre-Occupancy Phase), Based on Output Contribution Analysis

				Factor Influence (change in vector orientation introduced by factor in degrees)																
Rank	BEA Code	BEA Description	Vector Mag.	ADP	LUC	GWP	ODP	HTP	FAETP	MAETP	TETP	FSETP	MSETP	POCP	AP	EP	EC	WC	MTL	WST
1	680100	Electric services (utilities)	45.35	0	0	22	0	8	0	11	0	11	0	17	26	18	25	28	0	0
2	20100	Cotton	28.97	0	9	0	0	0	45	0	42	0	0	0	0	10	0	0	0	0
3	360200	Brick and structural clay tile	28.30	0	0	1	0	21	0	41	0	41	0	0	0	0	0	0	0	0
4	650301	Trucking and courier services, except air	20.11	0	41	11	0	0	0	0	0	0	-1	35	5	24	10	0	0	0
5	90002	Sand and gravel	18.66	0	0	1	0	0	0	0	0	0	-1	0	0	0	2	0	59	31
6	80001	Crude petroleum and natural gas	18.10	71	0	9	0	0	0	0	0	0	0	7	3	5	1	0	1	14
7	362000	Mineral wool	17.46	0	0	4	81	3	0	0	1	0	5	5	0	1	1	0	0	0
8	70000	Coal	16.97	47	0	3	0	2	1	1	1	1	-1	1	0	-1	0	0	3	42
9	270100	Industrial inorganic and organic chemicals	16.40	0	0	3	38	23	4	1	9	3	38	7	4	6	0	0	1	9
10	90001	Dimension, crushed and broken stone	13.66	0	-1	2	-1	-1	0	0	-1	0	-1	0	0	0	2	0	87	0

Key: Cells are shaded using a gradient, where orange-shaded cells indicate that the impacts associated with the material/product/service are above the mean for all materials/products/services and blue-shaded cells indicate that the impacts associated with the material/product/service are below the mean. Darker shading indicates relatively stronger influence of the impact category on the overall vector magnitude.

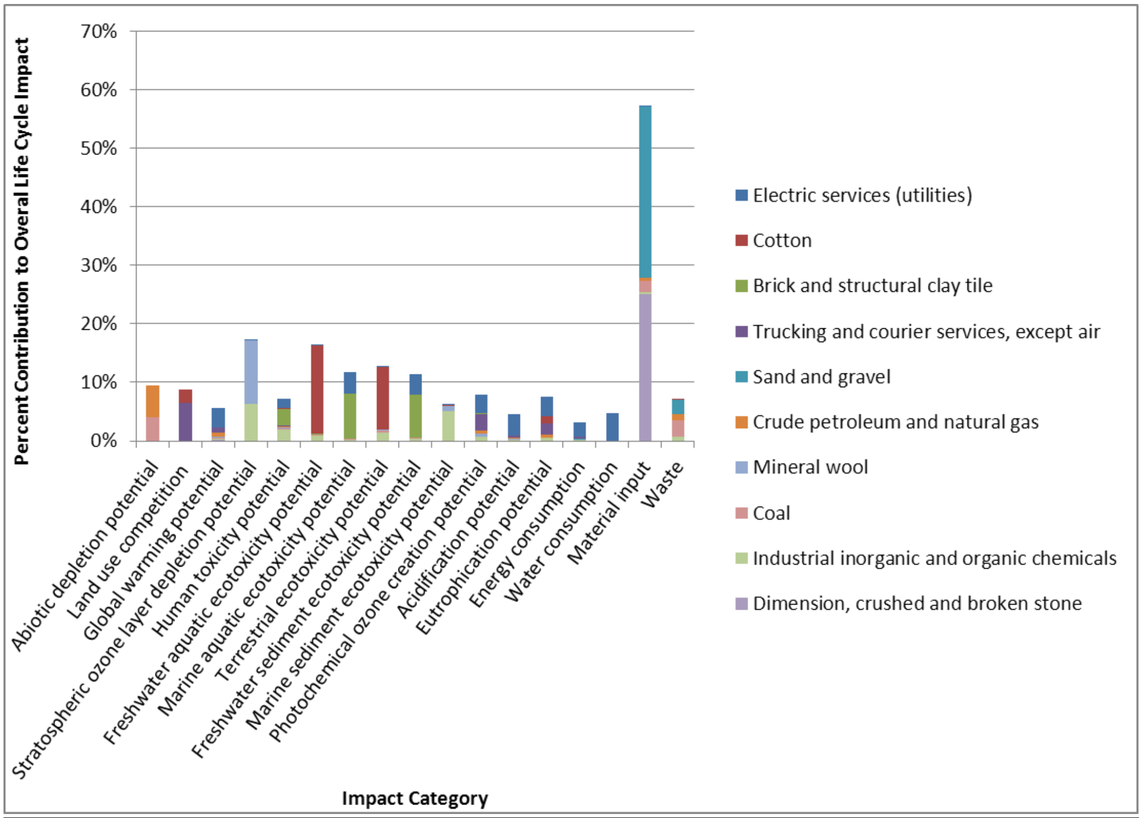
For most of the supply chain processes highlighted in the output contribution analysis, the relatively high rankings are based on related impact categories. Referring to the impact groupings described in Section 2.3:

1. Supply chain processes associated with *sand and gravel*, *crude petroleum and natural gas*, *coal*, *and dimension*, *crushed and broken stone* are ranked highly based on the impact categories in the natural resources and land use grouping;
2. Supply chain processes associated with *brick and structural clay tile* are ranked highly based on the impact categories in the toxicity grouping; and
3. Other supply chain processes are ranked relatively highly based on a more diverse mix of impacts that cut across groupings, including those associated *electric services* and *trucking and courier services* (pollution impacts and natural resources and land use) and those associated with *industrial organic and inorganic chemicals* (toxicity and pollution impacts).

A more complete summary of the output contribution vector analysis is presented in Appendix G.

Figure 4-2 shows the percentage of the total estimated life cycle impacts of single-family homes represented by the top 10 ranked pre-occupancy supply chain processes. Depending on the impact category, impacts associated with the top 10 supply chain processes account for anywhere from just above 3% to almost 60% of the total life cycle impacts of single-family homes. This finding also highlights the relative differences in perspectives offered by input and output contribution analysis, with implications for how these different analyses can inform SMM policy decision processes.

Figure 4-2: Contribution of 10 Most Highly Ranked Supply Chain Processes to Life Cycle Impacts Associated with Single-family Home Construction (Pre-occupancy Phase)



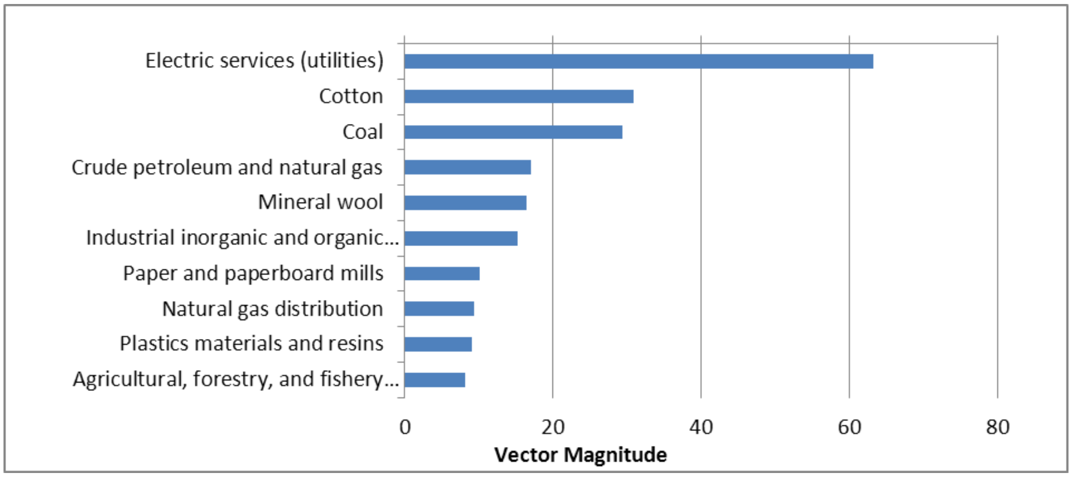
For example, the output contribution analysis highlights that almost 10% of the overall abiotic depletion potential (ADP) impacts of single-family homes can be attributed to supply chain processes associated with crude petroleum and natural gas and coal production (note that this is the majority of lifecycle ADP impacts cast by inputs/processes used in the pre-occupancy phase, see Table 3-1). From an input contribution perspective, around 2% of the ADP impacts associated with the inputs into the pre-occupancy phase of single-family homes can be explained by the top 10 ranked direct inputs (see Figure 3-5). This suggests that petroleum, natural gas, and coal production are part of a number of different supply chains, and embodied ADP impacts are widely dispersed among a diverse set of direct inputs to the pre-occupancy phase of single-family homes.

From an SMM perspective, if life cycle ADP impacts associated with the pre-occupancy phase of single-family homes were considered a high priority for mitigation efforts, actions might best be targeted to the primary consumers of petroleum, natural gas, and coal (e.g., power plants), rather than consumers of direct inputs to home construction (e.g., builders).

4.3 OCCUPANCY PHASE

Figure 4-3 highlights the top ten most highly ranked supply chain processes used to provide and deliver inputs into the occupancy phase of single-family homes from an output contribution perspective. As noted in Section 3.3.2, the occupancy phase of the life cycle of a single-family home focused on energy and water consumption and replacement materials. The output contribution analysis distributes the impacts associated with these direct inputs to associated upstream supply chain processes.

Figure 4-3
Highest Ranked Materials, Products, and Services
Full Scope (all impact categories)
Output Contribution Basis – Occupancy Phase



The analysis reflects the make-up of the inputs used to analyze the occupancy phase of single-family homes. It highlights the contributions to the overall life cycle impact of upstream supply chain processes associated with replacement materials, *agriculture, forestry, and fishery services*, *paper and paperboard mills*, and *plastics materials and resins* as inputs to wood products.[53] Like the pre-occupancy phase analysis, the occupancy phase output contribution analysis identifies *fiberglass and mineral wool insulation* as a significant contributor to life cycle impacts because: 1) it was included in the scope of replacement materials and 2) the locus of impact is concentrated at the manufacturing stage of the product (see Section 3.4.2).

The analysis differs from the output contribution analysis for the pre-occupancy phase in that it does not highlight materials associated with new building construction (e.g., *brick and structural clay tile*, *sand and gravel*, and *dimension, crushed and broken stone*). This in part reflects the definition of the scope of replacement materials and in part reflects the fact that these materials are less important in the supply chain associated with the occupancy phase of single-family

[53] Products in the plastics materials and resins category are an important input to the manufacturing of reconstituted wood products (DOE 2010b).

homes. The two analyses are similar in that they highlight the importance of energy services and related materials throughout the life cycle of single-family homes.

Table 4-2: Top Ranked Supply Chain Processes Associated with Single-family Home Construction (Occupancy Phase), Based on Output Contribution Analysis

			Factor Influence (change in vector orientation, in degrees)																	
Rank	BEA Code	BEA Description	Vector Mag.	ADP	LUC	GWP	ODP	HTP	FAETP	MAETP	TETP	FSETP	MSETP	POCP	AP	EP	EC	WC	MTL	WST
1	680100	Electric services (utilities)	63.23	0	0	19	0	19	1	20	2	20	0	19	20	19	20	20	0	0
2	20100	Cotton	30.91	0	18	0	0	0	43	0	42	0	1	0	0	2	0	0	0	0
3	7000	Coal	29.42	30	0	1	0	2	2	1	3	1	0	1	0	0	0	0	37	38
4	80001	Crude petroleum and natural gas	17.05	64	0	5	0	0	0	0	0	0	1	5	1	3	0	0	15	19
5	362000	Mineral wool	16.38	0	-1	0	84	1	0	0	0	0	6	1	0	0	0	0	0	0
6	270100	Industrial inorganic and organic chemicals	15.16	0	-1	0	37	7	2	0	5	0	51	1	0	1	0	0	2	2
7	240800	Paper and paperboard mills	10.14	0	-1	0	0	7	2	0	6	0	80	1	0	0	1	0	-1	0
8	680202	Natural gas distribution	9.40	0	-1	0	-1	0	0	0	0	0	2	0	0	0	0	0	39	51
9	280100	Plastics materials and resins	8.98	0	-1	0	18	9	3	0	7	1	68	1	0	0	0	0	1	1
10	40001	Agricultural, forestry, and fishery services	8.12	0	79	0	-1	-1	8	0	7	0	-1	0	0	1	0	0	-1	-1

Key: Cells are shaded using a gradient, where orange-shaded cells indicate that the impacts associated with the material/product/service are above the mean for all materials/products/services and blue-shaded cells indicate that the impacts associated with the material/product/service are below the mean. Darker shading indicates relatively stronger influence of the impact category on the overall vector magnitude.

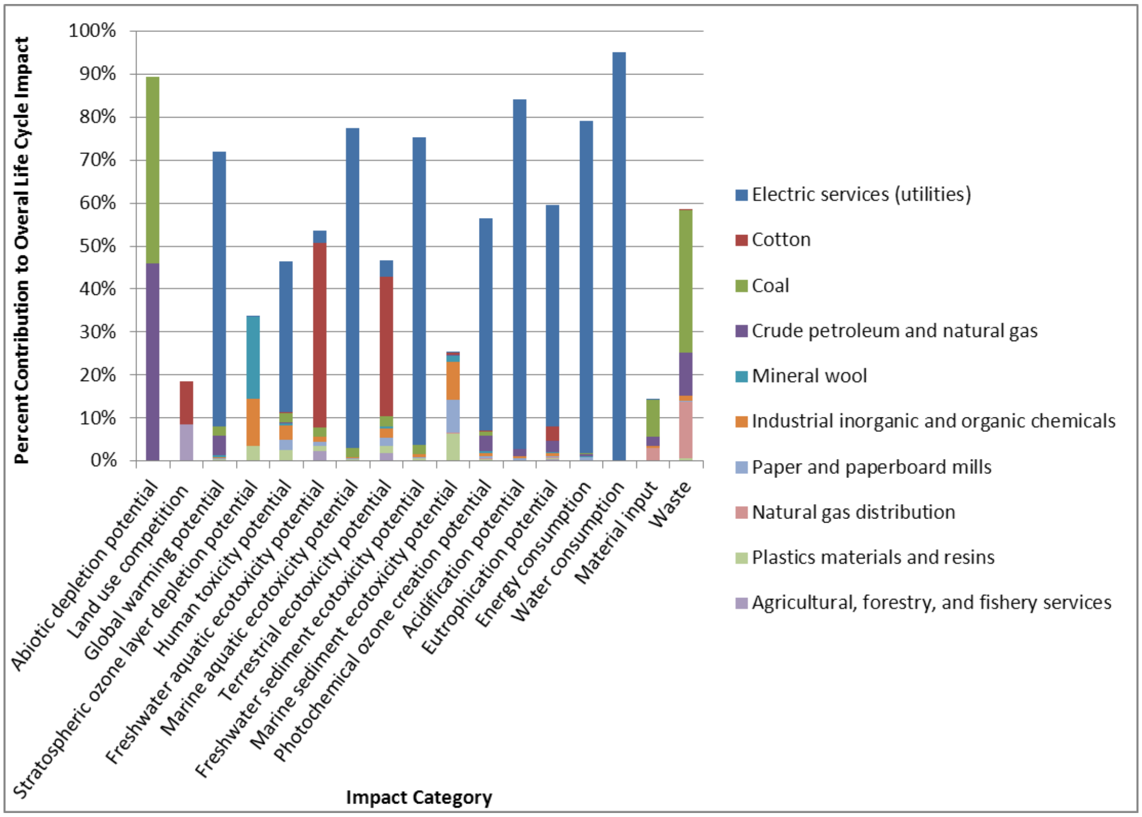
The analysis of the impact categories behind the highly ranked supply chain processes of the home occupancy phase highlights the following:

- Energy-related inputs (e.g., *electric services*, *coal*, and *crude petroleum and natural gas*), and forestry services contribute most significantly to the natural resource and land use life cycle impacts, reflecting the scope of energy inputs and replacement materials used during the occupancy phase;
- *Electric services*, chemicals, and pulp and paper mills contribute most significantly to the toxicity-related impacts; and
- *Electric services* and *fiberglass and mineral wool insulation* contribute most significantly to pollution life cycle impacts.

Detailed results are presented in Appendix G.

Figure 4-4 shows the percentage of the overall life cycle impacts of single-family homes attributable to the top 10 ranked supply chain processes needed for single-family homes' maintenance and operation. Depending on the impact category, impacts associated with the top 10 supply chain processes account for anywhere from about 15% to almost 95% of the total life cycle impact of single-family homes.

Figure 4-4
Contribution of 10 Most Highly Ranked Supply Chain Processes to Life Cycle Impacts Associated with Single-family Home Construction (Occupancy Phase)



4.4 Summary of Results – Output Contribution Analysis

The output contribution analysis for the pre-occupancy and occupancy phases suggests the following findings:

- Energy and energy-related impacts – A significant portion of the life cycle environmental impacts and resource withdrawals associated with single-family homes can be attributed to energy consumed in the upstream supply chain. The impacts associated with *electric services* delivered directly to homes or through the supply chains contribute significantly to the life cycle use of natural resources, toxicity impacts, and pollution impacts associated with single-family homes. In addition, fossil fuels (i.e., *crude petroleum and natural gas* and *coal*) are highlighted in the analysis as the primary contributors to life cycle abiotic depletion potential and as significant contributors to the life cycle waste generated by single-family homes.

- Direct inputs for which the manufacturing phase dominates – The relatively high ranking of some materials and products based on both the input and output contribution analyses indicates that those direct inputs contribute significantly to the life cycle impacts associated with single-family homes through predominantly their manufacturing processes. Materials/products that fall into this category include *brick and structural clay tile* (pre-occupancy phase) and *mineral wool* (pre-occupancy and occupancy phases)

- Ecotoxicity factors as primary drivers –A relatively few highly ranked supply chain processes contribute significantly to life cycle ecotoxicity impacts. These include supply chain processes associated with *electric services*, *brick and structural clay tile*, *paper and paperboard mills*, *pulp mills*, *industrial organic and inorganic chemicals*, and *plastics materials and resins*.
- Construction materials – Construction materials, including *sand and gravel* and *dimension, crushed and broken stone* contribute significantly to the material inputs consumed in the life cycle of single-family homes, either directly during construction or indirectly as building blocks for other materials (e.g., concrete). The supply-chain processes of construction materials were highlighted for their contribution to the overall life cycle impacts of single-family homes mainly through the pre-occupancy output analysis. This is understandable being that over the home life cycle, construction materials are predominantly used during initial construction, i.e., pre-occupancy phase.
- Transportation – The importance of *transportation services* in terms of the life cycle impacts associated with single-family homes is highlighted by the relatively high ranking in the output contribution analysis. Fuel combustion related to *transportation services* contributes significantly to the life cycle energy consumption and air emissions-related impacts associated with single-family homes. *Transportation services* also represent significant contributions to life cycle land use and eutrophication potential impacts, most likely due to impacts associated with surface transportation systems.

5. AVOIDED IMPACTS ANALYSIS

5.1 OVERVIEW

The input and output contribution analyses, relative ranking, and supplemental contribution analyses, indicated that a diverse mix of inputs and that energy (in the form of direct and indirect electricity consumption and direct consumption of fossil fuels) contribute significantly to the life cycle impacts associated with single-family homes. Based on the findings from these analyses, the following environmental mitigation scenarios were tested to analyze the potential for avoided impacts through reduced material and resource use:

- Improving end-use efficiency of electricity
- Improving end-use efficiency of natural gas
- Increasing reuse of major input materials, where the *brick and structural clay tile* product category was used to explore this scenario
- Increasing recycling of major input materials, where the product categories *ready-mixed concrete*, *carpets and rugs*, and *reconstituted wood products* were used to explore this scenario

In addition to their significance to the life cycle impacts associated with single-family homes, these scenarios were selected to illustrate SMM concepts using options that are technologically feasible and are familiar to a broad range of readers. The approach for analyzing potential avoided environmental impacts associated with these scenarios and the results of the analysis are described below.

5.2 METHODOLOGY FOR ANALYSIS OF POTENTIAL FOR AVOIDED IMPACTS

5.2.1 End-Use Energy Efficiency

The first two scenarios considered the effects of energy efficiency improvements associated with five residential electrical end use categories—space heating, space cooling, water heating, refrigeration, and lighting—and two natural gas end use categories—space heating and water heating. Estimates of potential energy efficiency improvement potentials were derived from the Energy Information Agency's (EIA) Annual Energy Outlook (AEO) 2011 (DOE 2011b) and assumptions based on other sources.

Table 5-1 shows the total electricity purchased by households in 2008 for the five end use categories considered in the analysis, share of the electricity delivered that is represented by these end uses, and potential efficiency improvements incorporated into the analysis. The end use categories included in the analysis represent 59% of the total electricity delivered.

Table 5-1
Electricity Efficiency Improvement Potential by End Use Categories

	Purchased Electricity, 2008 (quadrillion Btu)[1]	Share in the total electricity delivered	Efficiency improvement potential (2008-2030)[2]	Source
Space Heating	0.28	6%	14%	EIA, 2011
Space Cooling	0.87	22%	19%	EIA, 2011
Water Heating	0.43	9%	12%	EIA, 2011
Refrigeration	0.37	7%	28%	EIA, 2011
Lighting	0.72	14%	50%[3]	Assumption
Sum	2.68	59%	27%	

[1] DOE 2011b,Table A4, p. 124

[2] Derived from the reference case for the Residential Sector Equipment Stock and Efficiency scenario, DOE 2011b (electronic dataset)

[3] An efficiency scenario for lighting was not available from the Residential Sector Equipment Stock and Efficiency scenario. The Energy Independence and Security Act 2007, specifies that general purpose light bulbs should be at least 30% more efficient by 2014 than then-current incandescent light bulbs. There are a few states that mandate phase-out of incandescent light bulbs. LEDs consume about 10% of the energy used by equivalent incandescent light bulbs. Given the pace of efficiency improvement, 50% of efficiency gain by 2030 was considered to be reasonable.

Table 5-2 shows the total amount of natural gas purchased by households in 2008 for the two end use categories considered in the analysis, share of the natural gas delivered that is represented by these end uses, and potential efficiency improvements incorporated into the analysis.

Table 5-2
Natural Gas Efficiency Improvement Potential by End Use Categories

	Purchased NG, 2008 (quadrillion Btu)[1]	Share in the total NG delivered	Efficiency improvement potential (2008-2030)	Source
Space Heating	3.40	67%	6%	EIA, 2011
Water Heating	1.33	27%	12%	EIA, 2011
Sum	4.73	95%	8%	

[1] DOE 2011b,Table A4, p. 124

Using these estimates, the avoided environmental impacts associated with improvements in electricity and natural gas end use efficiency were estimated considering both indirect impact (supply-chain impact) and direct impact (combustion emissions and direct resource use).

Note that DOE (2011b) forecasts reductions in per capita household energy use due to efficiency gains in space heating, water heating, and lighting equipment and population shifts to warmer and drier climates. However, DOE forecasts that overall energy consumption by residential homes will rise due more-than-offsetting growth in population, the number of homes, and the average square footage of homes. Therefore, the potential reductions associated with energy efficiency improvements estimated herein are an indication of the magnitude of the environmental impact reduction that could be attained with energy efficiency improvements relative to the DOE forecast. They do not represent an estimate of absolute reduction in energy consumption.

5.2.2 Material Reuse and Recycling

Carpets and rugs and three of the five direct inputs with supplemental supply chain analyses described in Section 2.4, were analyzed based on reuse and recycling potential: *ready-mixed concrete*, *brick and structural clay tile*, and *reconstituted wood products*. The *fiberglass and mineral wool insulation* product category was not included, as little information was available suggesting that the reuse or recycling of this material on a large scale has been considered. The findings associated with the *reconstituted wood products* recycling scenario are illustrative of the types and relative magnitude of impacts that could be avoided by comparable recycling of *wood shingle siding*.

Table 5-3 lists the materials/products considered in the analysis of the potential for avoided impacts, specific reuse/recycling scenarios, and assumptions regarding increased reuse and recycling rates. The bases for these scenarios and assumptions are described below.

Table 5-3
Material Recycling/Efficiency Improvement Potential for Selected Direct Inputs

Product Category	Reuse/recycling scenario	Increased reuse or recycling rate
Ready-mixed concrete	Ready-mixed concrete from demolished/ deconstructed single-family homes processed and used as aggregate for roadway construction.	20% increase in recycling of ready-mixed concrete from current levels, resulting in 1% reduction in sand and gravel used as aggregate for roadway construction
Carpets and Rugs	Carpets and rugs removed from single-family homes as a result of renovation and/or demolition/deconstruction processed and used as resin for manufacturing of various synthetic products.	5% increase in recycling of carpets and rugs from current levels, resulting in a 0.65% reduction in resin from other sources used to manufacture various synthetic products
Brick and structural clay tile	Brick from demolished/deconstructed single-family homes reused in new construction	15% increase in reuse of old brick in new buildings relative to current levels
Reconstituted wood products	Reconstituted wood products from demolished/ deconstructed single-family homes burned as fuel for power generation in paper and wood products industry	Wood recovery rates increased to a level equivalent to replacing 5% of coal currently consumed by wood and paper products industry

The scenarios described in Table 5-3 were developed based on the following considerations:

- *Ready-mixed concrete* – Avoided environmental impacts associated with increased recycling of concrete waste from single-family homes was calculated as follows:
    - Scenario: At the end of its life, ready-mixed concrete is often crushed and used in place of aggregate in the base course for road construction. This recycling scenario was assumed for the purpose of this analysis.
    - Recycling rate: In 2002, approximately 370 million tons of concrete waste from building projects was generated in the United States (Cochran and Townsend, 2010). By comparison, the United States consumed an estimated 1.13 billion metric tons of

construction sand and gravel and 1.51 billion metric tons of crushed stone (USGS, 2003a; USGS, 2003b) in 2002. Approximately 65% of that concrete waste generated in 2002 was recycled, which represents only 4% of the aggregate demand for 2002. Given this potential demand, it was assumed that a 20% increase in the recycling rate (to 85%) would be plausible.

- Material replacement rate: If the amount of concrete recycled increased to 85%, recycled concrete from buildings would represent about 5% of the aggregate demand, or an increase of 1%.
- Recycling vs. landfilling process substitution: The process for recycling concrete involves crushing, sizing and transportation. Some research suggests that the transportation load and environmental impact is reduced by recycling rather than landfilling (USACE, 2004). There is no clear evidence that recycling processes require more energy and generate greater environmental impact relative to landfilling. Therefore, the impacts associated with recycling were assumed to be the same as those associated with landfilling the same amount of waste concrete.
- Overall net change: Based on an assumption of no net change in impact associated with recycling versus landfilling, the overall reduction in impact was calculated as the reduced impact associated with a 1% reduction in use of sand and gravel in roadways.

- *Carpets and rugs* – Avoided environmental impacts associated with increased recycling of carpets and rugs salvaged from single-family homes was calculated as follows:
  - Scenario: For the purposes of this analysis, it was assumed that resins derived from processing salvaged carpets and rugs would be used to replace resins made from virgin materials. Actual recycling pathways for carpets and rugs are more diverse (CARE, 2010).
  - Recycling rate: The U.S. Green Building Council's (USGBC's) proposed LEED for Homes 2012 certification program provides an incentive for replacing 25% of needed construction materials with salvaged materials. If the USGBC is able to change the housing market such that 30% of new housing construction meets this standard, approximately 7.5% of materials used for housing construction will be of environmentally preferable source (including salvaged materials or recycled content materials). In the absence of more detailed research, this was used as the basis for assuming a 5% increase in the demand for salvaged *carpets and rugs* (comparable to a 5% increase in recycling rate) between now and 2030.
  - Replaced materials: Lave et al (1998) estimate that nylon carpet recycling can reach a 16.9% yield rate (i.e., 16.9 pounds of nylon can be produced from 100 pounds of salvaged carpet). In the absence of more detailed research, it was assumed that similar yield rates could be achieved for other types of carpets and rugs. In 2002, the plastic materials and resins product category was a $45.4 billion business and the *carpets and rugs* product category was a $11.7 billion business. Assuming that nylon and carpets are priced on the same per unit mass, recycling all of the carpet produced in 2002 as resin would replace 4.4% of resin [(11.7/45.4)*16.9%]. A 5% increase in the carpets and rugs recycling rate would replace 0.22% of the resin produced. For the purpose of this analysis, a factor of 3 was used to account for technological improvements in the yield ratio between now and 2030, and the analysis assumed a replacement rate of 0.65%.

- Recycling vs. landfilling process substitution: Available literature and data regarding the energy consumed and environmental impacts associated with producing resin from salvaged carpets and rugs are limited. For the purposes of this analysis, it was assumed that the amount of energy needed and impacts associated with recycling would be similar to those associated with landfilling. No difference in transportation was assumed.
- Overall net change: Based on an assumption of no net change in impact associated with recycling versus landfilling, the overall reduction in impact was calculated as the reduced impact associated with replacing 0.65% of resin made from virgin material with resin made from salvaged carpets and rugs.

- *Brick and structural clay tile* – Avoided environmental impacts associated with increased recycling of brick salvaged from single-family homes was calculated as follows:
  - Scenario: For this product category, a reuse scenario was analyzed. It was assumed that brick salvaged from single-family homes would be used to replace brick made from virgin materials.
  - Recycling rate: The market for used brick for reuse in new construction has been steadily rising while the market for new brick has been declining. This reflects in part shifts in the availability of alternatives to new brick and changes in construction techniques and styles. In 2002, the United States consumed approximately 15 million tons of brick (BIA, 2006). That same year, the country generated approximately 17 million tons of brick as waste (Cochran and Townsend, 2010). If 5% of that is currently reused as new bricks, it would represent approximately 5% of the brick consumption. If demand for brick continues to stagnate and demand for used brick continues to increase, reused brick could represent 20% of brick consumption, an increase of 15%. This increased reuse rate of 15% was assumed for the purpose of this analysis.
  - Replaced materials: For this product category, a reuse scenario was analyzed. Therefore, used brick would replace new brick on a one-to-one basis.
  - Recycling vs. landfilling process substitution: For the purposes of this analysis, it was assumed that the amount of energy needed and impacts associated with recycling would be similar to those associated with landfilling. No difference in transportation was assumed.
  - Overall net change: Based on an assumption of no net change in impact associated with recycling versus landfilling, the overall reduction in impact was calculated as the reduced impact associated with replacing 15% of brick made from virgin material with salvaged bricks.

- *Reconstituted wood products* – Avoided environmental impacts associated with increased recycling of reconstituted wood products salvaged from single-family homes was calculated as follows:
  - Scenario: Reconstituted wood products (e.g., wood panels) can be salvaged and burned as fuel. For the purposes of this analysis, it was assumed that salvaged reconstituted wood products would be used to replace coal combusted by the paper and wood products industries to produce energy for manufacturing.

- Recycling rate: In 2002, the wood products and paper products industries (NAICS codes 321 and 322, respectively) consumed approximately 11.5 million tons of coal to produce 237 trillion Btu of energy (DOE, 2006). Assuming a heating value of 7,400 Btu/lb for C&D wood waste (Jambeck et al., 2007), replacement of 5% of coal consumption would require approximately 0.7 million mtons. McKeever (2004) estimates that 25.2 million mtons of demolition waste wood was generated in 2002. Based on these estimates, a 3% increase in recycling of C&D wood waste would be required to replace 5% of the coal consumed by the wood and paper products industries.
- Replaced materials: An increase in the recycling reconstituted wood products in an amount equal to 3% of C&D wood waste (0.72 million mtons/year), would replace approximately 5% of the coal used for energy generation by the wood and paper products industries.
- Recycling vs. landfilling process substitution: For the purposes of this analysis, it was assumed that the amount of energy needed and impacts associated with recycling C&D wood waste would be similar to those associated with landfilling. No difference in transportation was assumed.
- Overall net change: Based on an assumption of no net change in impact associated with recycling versus landfilling, the overall reduction in impact was calculated as the reduced impact associated with replacing 5% of the coal consumed by the wood and paper products industries by reconstituted wood products salvaged from single-family home demolition.

5.3 RESULTS

Figure 5-1 presents the results of the avoided impacts analysis aggregated by type of scenario—i.e., end-use electricity efficiency, end-use natural gas efficiency, and material recycling rate/use efficiency improvements. Figures 5-2 and 5-3 present the results for the different types of scenarios. In terms of energy efficiency improvements, percentages used to express avoided impacts can be interpreted in a straightforward manner—they represent reductions in life cycle impacts associated with more efficient energy use during the occupancy phase of the single-family home life cycle.

In terms of material reuse and recycling scenarios, the results can be interpreted in terms of offsets to life cycle impacts associated with single-family homes. For example, the reductions in material input impacts associated with substituting salvaged concrete for sand and gravel in roadways do not reduce the actual life cycle impacts associated with the universe of homes considered in this analysis. Rather, the recycling of concrete as road base material reduces material inputs required by the roadway construction sector. These reductions in material input are then used to offset the life cycle impacts associated with the single family homes from which the concrete was salvaged. Percentages in the following figures can be interpreted as the percentage of the original life cycle impacts of single-family homes offset by reuse and recycling of salvaged materials.

Figure 5-1: Potential Avoided Impacts Associated with Energy Efficiency Improvements and Material Reuse/Recycling Scenarios (Composite View)

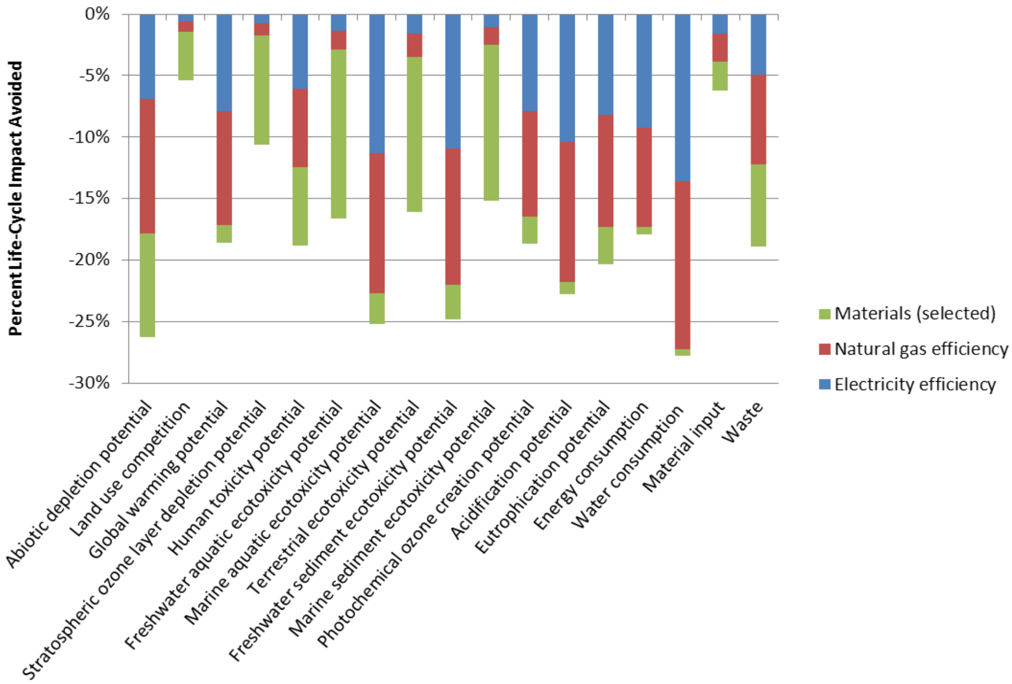


Figure 5-2: Potential Avoided Impacts Associated with Energy Efficiency Improvements Considered for Single-family Homes

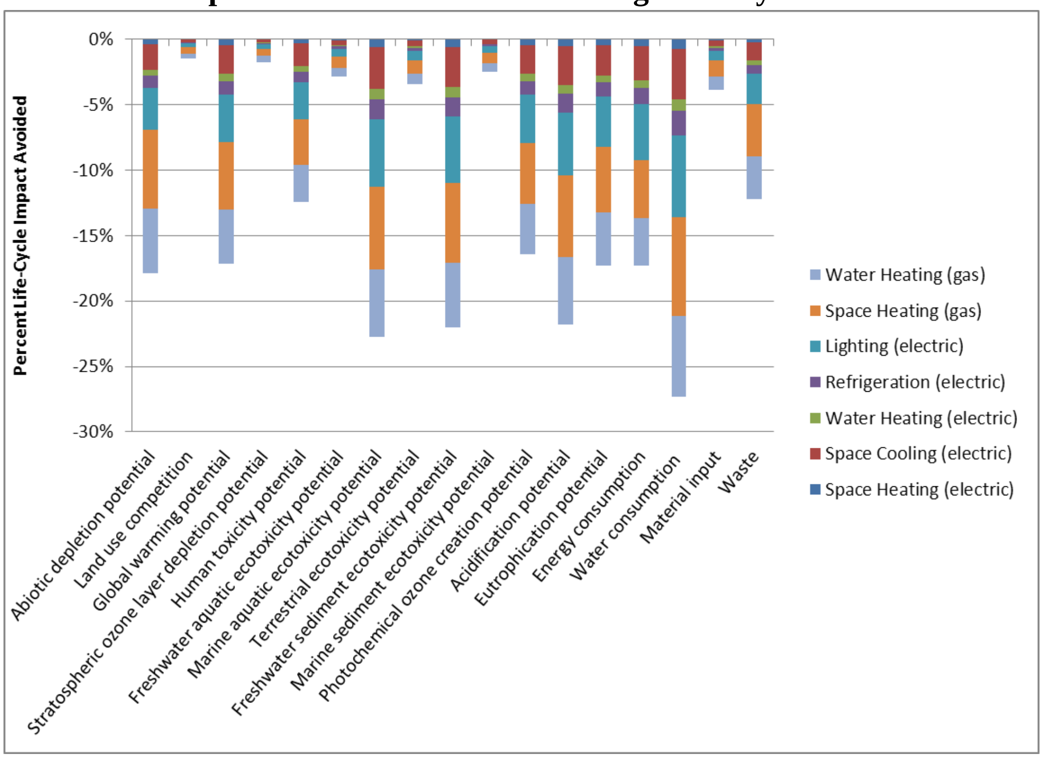
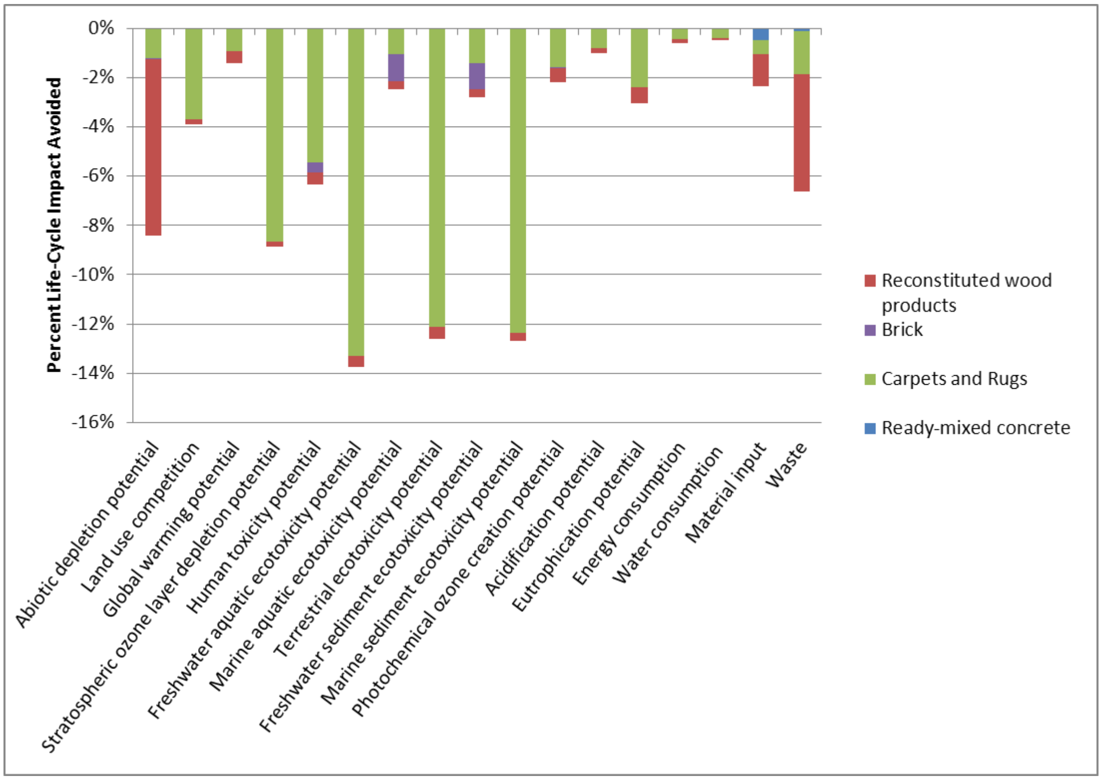


Figure 5-3: Potential Avoided Impacts Associated with Material Reuse/Recycling Scenarios Considered for Single-family Homes



The analysis suggests the following findings:

- *Combined scenarios:* The analysis indicates that combined, the energy efficiency improvements and material reuse/recycling scenarios considered in the avoided impacts analysis could result in 5-28% reductions in life cycle impacts associated with single-family homes. These include reductions in life cycle land use competition of 5% at the low end up to reductions in life cycle water consumption of 28% at the high end.

  In terms of the relative importance of energy efficiency and materials reuse/recycling scenarios to the overall, combined results, the analysis suggests the following:

  - The analysis suggests that energy efficiency improvements would represent the majority of avoided impacts in the following categories: global warming potential, marine aquatic ecotoxicity potential, freshwater sediment ecotoxicity potential, photochemical ozone creation potential, acidification potential, and eutrophication potential, energy consumption and water consumption.
  - Material reuse and recycling improvements would represent the majority of avoided impacts in the following areas: land use competition, stratospheric ozone depletion potential, freshwater aquatic ecotoxicity potential, terrestrial ecotoxicity potential, and marine sediment ecotoxicity potential.

- The contribution of the different scenarios to avoided impacts in other categories—abiotic depletion potential, human toxicity potential, material input, and waste —is fairly balanced.

  The analysis again highlights an important quality of multi-criteria LCA, previously discussed in Section 3.4.1 of this report. Specifically, the analysis indicates that though the energy efficiency and material reuse/recycling scenarios account for a relatively small reduction in material input (6%), reduced impacts associated with these scenarios could be substantially greater (up to 28%). This highlights the finding that impacts may not correlate with measures of material input and that some materials may have an inordinate effect on an impact category, pound-for-pound.

- *Electricity efficiency improvements:* The analysis indicates that overall, improving efficiencies in lighting, space heating, space cooling and water heating could result in reductions of 12-27% in the life cycle impacts associated with single-family homes across the following range of impact categories: abiotic depletion potential, global warming potential, human toxicity potential, marine aquatic ecotoxicity potential, freshwater sediment ecotoxicity potential, photochemical ozone creation potential, acidification potential, eutrophication potential, water consumption, and waste. The analysis suggests that the most significant contributions to avoided impacts would result from the efficiency improvements in natural gas water and space heating, lighting, and electric space cooling.

- *Material reuse and recycling scenarios:* The analysis indicates that the improvements in material reuse and recycling rates considered herein could result in reductions of 6-14% in life cycle impacts associated with single-family homes in the following impact categories: abiotic depletion potential, stratospheric ozone layer depletion potential, human toxicity potential, freshwater aquatic ecotoxicity potential, terrestrial ecotoxicity potential, marine sediment ecotoxicity potential, and waste. The analysis suggests that meaningful reductions could also be achieved in other life cycle toxic impacts, eutrophication potential, material input and waste.

  In terms of the relative importance of material reuse and recycling scenarios to these avoided impacts the analysis suggests the following:

  - For all but three of the impact categories, avoided impacts associated with recycling *carpets and rugs* into resin for various synthetic materials accounts for most of the potential avoided impacts. The exceptions are abiotic depletion potential, material input, and waste. Recycling of carpets and rugs account for 9-13% reductions in life cycle impacts associated with single family homes across the stratospheric ozone depletion potential, freshwater aquatic ecotoxicity potential, terrestrial ecotoxicity potential, and marine sediment ecotoxicity potential impacts categories.
  - The analysis suggests that the increased recycling of salvaged reconstituted wood products as an energy source for the wood and paper products industries could offset

7% of the life cycle abiotic depletion potential and 5% of the life cycle waste impacts associated with single family homes.

- The analysis indicates that the scenarios analyzed for concrete recycling and brick reuse would have little effect on the overall life cycle impacts associated with single-family homes.
  - For concrete, this is likely because even significant increases in concrete recycling could replace only a relatively small percentage of aggregate and also, because impacts associated with aggregate materials are of relatively limited scope (primarily material input and waste).
  - For brick, while the absolute reductions in life cycle impacts could be significant, the relative reduction in life cycle impacts associated with a 15% increase in reuse rates would translate to a 1% reduction in categories where brick and structural clay tile contribute significantly to the life cycle impacts of single family homes—human toxicity potential, marine aquatic ecotoxicity potential (MAETP), and freshwater sediment ecotoxicity potential. For example, the life cycle MAETP impacts associated with single family homes, though this product category still only accounts for 7.5% of the total MAETP impacts. While a 15% increase in reuse decreases the MAETP impacts associated with brick and structural clay tile by 15%, this translates into a 1.1% reduction in total life cycle MAETP impacts associated with single family homes (7.5% of total * 15% reduction).

5.4 EXTENDED SUSTAINABILITY BENEFITS – ENVIRONMENTAL JUSTICE AND EQUITY

Environmental Justice and Equity[54]

The two avoided impact scenarios discussed above quantify the environmental benefits that can accrue from improving energy efficiency of single-family homes and using recycled/reused materials as replacements for virgin materials in their construction. The analysis was focused on how these strategies can help single-family homes perform better environmentally over their life cycles. However, the benefits from implementing these two strategies extend beyond those that can be measured purely by environmental impact categories to include economic and social benefits.

As part of the U.S. EPA's commitment to integrate environmental justice principles and priorities into the analyses, this section offers a discussion on how improving home energy efficiency and increasing the recycling and reuse of materials associated with single family home construction could positively affect disadvantaged communities. Improving the energy efficiency of homes mitigates environmental pollution associated with electric utility services and also, can deliver long-term savings to home owners and renters on energy bills. Increasing the recycling and reuse of materials reduces the pollution associated with both the production of new materials and

[54] For a narrative discussing opportunities to reduce housing costs in green construction, see Appendix I

disposal of materials at their end of life, supports job creation and community revitalization, and can reduce housing costs for low-income families.

5.4.1. Energy Efficiency

Increasing the energy efficiency of single family homes has the potential to mitigate environmental pollution associated with electricity production and its effect on proximate, typically low-income, communities. In addition, increasing energy efficiency of homes delivers long-term savings on energy bills. For illustrative purposes, compared to standard homes, Energy Star homes, which feature effective insulation, high-performance windows, tight construction and ducts, efficient equipment and appliances, use substantially less energy for home heating, cooling, and water heating and deliver $200 to $400 in annual savings on just these expenses.[55]

While some of the energy efficiency measures such as optimizing home-orientation or window positioning may not come at additional costs, others, such as increasing the amount of insulation or including more-efficient windows, may. However, Habitat for Humanity Metro Denver partnered with the U.S Department of Energy's Building America Project and the National Renewable Energy Laboratory to create affordable, energy-efficient demonstration homes which shows that certain energy efficiency features can be incorporated in cost-effective ways.[56]

5.4.2. Recycled and Reused Materials

Increasing the recycling and reuse of materials reduces the pollution associated with both the production of new materials and disposal of materials at their end of life, supports job creation and community revitalization, and can reduce housing costs for low-income families.

Pollution Reduction.
Material recovery diverts waste and intercepts the emissions associated with either the incineration or the material break-down in landfills. In addition, the recovered materials replace raw materials or finished products; thereby, the recovery intercepts the pollution associated with the extraction and processing of virgin materials and the manufacture of new products.[57] Even though the pollution reduction improves the environment for all, benefits are the greatest for disadvantaged, low-income communities that are often in the closest proximity to waste and manufacturing facilities. These low-income households typically face cumulative pollution risks as various waste and manufacturing facilities are often grouped together.

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[55] ENERGY STAR, Features & Benefits of ENERGY STAR Qualified New Homes: http://www.energystar.gov/index.cfm?c=new_homes.nh_features; Accessed September 19, 2011.

[56] Building America, U.S Department of Energy case studies: http://www.nrel.gov/docs/fy05osti/36102.pdf and http://www.nrel.gov/docs/fy08osti/42591.pdf, Accessed September 19, 2011.

[57] U.S. EPA, Is recycling worthwhile: http://waste.supportportal.com/ics/support/kbAnswer.asp?deptID=23023&task=knowledge&questionID=19159, Accessed August 12, 2011.

Job creation and community revitalization.
Incorporating recycled and reused materials supports the recycling and reuse industry, which creates jobs[58]. According to The U.S. Recycling Economic Information Study, more than 56,000 recycling and reuse establishments in the United States employ approximately 1.1 million people.[59] Building materials recovery generally involves substantial activities around deconstruction, sorting, salvage, value adding, stocking, and resale. Therefore, the contribution of building material-recovery jobs to the overall recycling industry is significant.

Equally significant is the fact that recovered materials are typically sourced locally and that therefore, any associated economic activity should directly benefit local communities. These benefits range from creating local deconstruction, recovery, or resale jobs and providing low-cost materials for local residents, to creating tax revenues and revitalizing communities at large.

Reduced housing costs.
The market for recovered materials primarily emerged from the growing awareness of the life cycle impacts of *new* building materials. However, since recovered materials can function as financial assets to lower construction and renovation costs for low-income-home builders and home-owners, their value extends beyond just environmental protection. Pursuing affordable, sustainable materials can improve the builder's bottom line and be an effective mechanism to lower the upfront home or renovation costs for the owner.

The Building Material Reuse Association recently gathered industry representatives together at its 2011 convention, Decon '11 to speak about the value of deconstruction and material reuse. Participants included appraisers and reuse consultants and designers. One of the repeatedly mentioned benefits supported by industry examples was that deconstruction provided sustainable, low-cost building materials.[60] Along the same lines, the City of Seattle's Department of Planning and Development published that recycling or reusing salvaged building materials as well as

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[58] The Tellus Institute in its report *More Jobs, Less Pollution: Growing the Recycling Economy in the U.S.*, compared two hypothetical 2030 waste management scenarios; the baseline scenario that was developed on continuing current practices to reach about 37-percent C&D waste diversion by 2030, and the Green Economy scenario reflecting 75-percent C&D diversion through significantly enhanced recycling and composting efforts. The Green Economy scenario generated more than twice the amount of jobs of the baseline scenario demonstrating that the recycling jobs gained through enhanced diversion outnumber any loss of jobs in C&D waste disposal. In addition, in its study *2008 Employment Trends in N.C.'S Recycling Industry*, the state of North Carolina looked at the recycling industry at large and found that job losses in waste disposal and virgin materials mining and manufacture that directly result from recycling program success, in North Carolina, were balanced or outweighed by job creation in the recycling sector.
[59] U.S. EPA: http://waste.supportportal.com/link/portal/23002/23023/Article/18602/If-there-is-plenty-of-landfill-space-then-why-should-I-recycle, Accessed August, 12, 2011.
[60] For more information and copies of presentation slides, please see http://www.bmra.org/about-bmra/newsupdates/323-decon-11-presentations-are-available .

minimizing materials and packaging, reduces material expenses.[61] Reduced material expenses translate into lower upfront housing costs as well as lower renovation/maintenance costs.

Differences in cost that exist between various recycled and reused materials reflect the value added through the recovery process. In limited cases, this difference can result in a higher cost for a recycled or reused material. However, funding may be available through the Low Income Housing Tax Credit program to offset this incremental cost. State and local governments provide funds based on how many points from their Qualified Allocation Plans the projects are able to meet. States allocate points for green building practices, and a number of them allocate points for recycled/reused materials.[62] In such a case, incorporating recovered materials may help the project qualify for funding that would in turn help the project team afford more sustainable material choices for the needed applications.

Other Considerations

Health and safety considerations for recycled or reused materials.

Although building material reuse and recovery affords needed economic, social and environmental benefits to society, concerns regarding human health and safety do exist. For example, with material reuse and recycling, potentially harmful materials that had historically circulated in the construction and maintenance of buildings (e.g. lead-based paint) could be reintroduced into the housing stock, if not properly managed. From an environmental justice perspective, of those materials, particular attention has been given to lead-based paint. Fighting childhood lead-based paint poisoning has become one of the Department of Housing and Urban Development (HUD)'s primary environmental justice initiatives.[63] Through this initiative, HUD provides public outreach and technical assistance and conducts technical studies to help protect children and their families from health and safety hazards in the home.[64]

The U.S EPA also works to promote safe reuse and has gathered useful information to communicate these issues.[65] For example, in its Pollution Prevention and Toxics website, the EPA specifically addresses the question of how reuse stores and their customers can manage the lead-based paint hazards in older building materials. As a primary matter, the EPA notes that states may have laws or regulations addressing the management, handling or sale of materials

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[61] Department of Planning and Development, City of Seattle, June 2005: Construction Waste Management Guide for Architects, Designers, Developers, Facility Managers, Owners, Property Managers & Specification Writers, p.2. http://www.seattle.gov/dpd/cms/groups/pan/@pan/@sustainableblding/documents/web_informational/dpds_007173.pdf, August 11, 2011.

[62] Global Green USA, http://www.globalgreen.org/greenurbanism/affordablehousing/, Accessed August 15, 2011

[63] U.S. Department of Housing and Urban Development, March 1995, Achieving Environmental Justice – a Departmental Strategy: http://www.hud.gov/offices/cpd/environment/library/subjects/justice/deptstrategy.cfm#b, Accessed August 15, 2011.

[64] U.S. Department of Housing and Urban Development, Healthy Homes and Lead Hazard Control, http://portal.hud.gov/hudportal/HUD?src=/program_offices/healthy_homes, Accessed August 15, 2011.

[65] U.S EPA, Pollution Prevention and Toxics, 2011: http://www.epa.gov/opptintr/, Accessed August 15,2011.

containing lead-based paint, which would give very specific directions. Otherwise, the EPA recommends that reuse stores at a minimum label suspect items to indicate that they may contain lead, educate staff about lead hazards, and provide outreach materials to customers about lead-safe work practices. The EPA also lists useful resources. [66] While lead has taken center stage, health and safety concerns may revolve around other materials and products as well. Unsafe materials include asbestos, mercury, PCBs or arsenic.

It is also important to ensure that the chosen materials and products suit the application they are intended to fill. For example, unless properly treated, salvaged lumber may not be suitable for structural applications.[67] Using recovered materials because of their low-cost, but without due regard for functional suitability, could result in unsafe applications in affordable homes. Additionally, some products may not be sufficiently efficient to provide healthy indoor conditions or long-term cost-savings. For example, a single-pane window may be inexpensive and in usable condition, but meanwhile, it is energy-inefficient in certain climates and thus, not a good, affordable thermal solution for a home-owner in the long-run. However, such a window could still be used in interior applications, e.g. a transom, where it could allow penetration of light into secondary spaces such as hallways. Using salvaged materials in certain applications might not meet the requirements of local building codes and it is most practical and protective for builders and home-owners to consult local building officials and codes early.

Therefore, builders and home-owners who purchase building products for reuse should select them judiciously in order to capitalize on their lower cost without jeopardizing the health and/or safety of home-occupants. In that respect, additional inquiries and/or inspections may be warranted around certain types of materials. The Department of Planning & Development of the City of Seattle and the Department of Natural Resources and Parks of King County have created a material index that lists various building items, recommends which ones should be recycled, reused or disposed, and notes the associated environmental, health and safety concerns that justify such recommendations.[68]

Durability and maintenance.

Interest in using recovered materials in new construction is not uniformly present across the country. One common concern is that recycled or reused materials are inferior in quality and may not be as durable. This perception is limiting the development of needed infrastructure to increase the availability of these materials for affordable housing projects.

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[66] U.S EPA, Pollution Prevention and Toxics, 2011, Frequent Questions, General Information about Lead, 2011: http://toxics.supportportal.com/link/portal/23002/23019/Article/32411/Building-material-reuse-stores-sometimes-accept-older-materials-which-have-been-coated-with-lead-based-paint-and-could-pose-a-lead-poisoning-hazard-In-particular-older-windows-and-doors-are-likely-to-, Accessed August 15, 2011.

[67] King County Department of Natural Resources and Parks, Solid Waste Division & City of Seattle Department of Planning and Development, 2006. {Green home remodel} salvage & reuse: http://your.kingcounty.gov/solidwaste/greenbuilding/documents/Green_home_remodel-salvage.pdf, Accessed August 15, 2011.

[68] Ibid.

However, the U.S EPA has published that recycled materials contain similar chemical and physical properties as the virgin materials they replace, and when used according to appropriate environmental regulations engineering specifications, provide comparable—and in some cases, superior—performance at a lower cost.[69]

The Department of Planning & Development of the City of Seattle and the Department of Natural Resources and Parks of King County both advocate that salvaged materials cost less and last longer: their longevity is especially evident when building materials are salvaged from the structures of the periods that boasted construction of better quality.[70]

The USGBC consistently encourages the use of salvaged or reused building materials in single family home construction. The USGBC does not specifically recommend any additional operations and maintenance considerations pertaining to reused materials.[71] However, the USGBC does point out that the recycled-content materials may require different maintenance than conventional products. Homeowners should be made aware of any specific maintenance requirements in order to delay and minimize repairs. However, the USGBC's caution that recycled-content materials may require specific upkeep should not be interpreted to imply that these materials would not last long or perform as is expected.

The performance requirements of building codes may on the outset determine the expected levels of maintenance and durability for the materials that are alternative to conventional. Accordingly, the recycled/reused product suppliers may warranty the product performance to ensure a customer base. Such warranties might sufficiently address any durability concerns for designers, builders and owners. In any case, designers, builders and owners must ensure that recovered materials meet applicable building codes and laws.

Planning considerations.

If the process to include reclaimed materials is to be successful, so that any benefits for low-income households could accrue, builders and homeowners should be aware that the construction process is not traditional and that additional planning steps are needed. Guidelines from industry practitioners and local governments and technical assistance are available to make this process more predictable. For example, considering that the material availability fluctuates, guidelines suggest that it is necessary to keep a flexible design and schedule. Flexibility will allow the designers/builders to investigate the market and capitalize on the safe, affordable materials as they become available. However, because the prospective materials will not all come at the same time, the designers/builders will need to provide spaces for their proper storage on-site. On the

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69 U.S. EPA, Office of Resource Conservation and Recovery, March 2009. Estimating 2003 *Building Related* Construction and Demolition Materials Amounts, p. 21.

70 King County Department of Natural Resources and Parks, Solid Waste Division & City of Seattle Department of Planning and Development, 2006. {Green home remodel} salvage & reuse: http://your.kingcounty.gov/solidwaste/greenbuilding/documents/Green_home_remodel-salvage.pdf, Accessed August 15, 2011.

71 U.S. Green Building Council, Green Building Design and Construction, LEED Reference Guide for the Design, Construction and Major Renovations of Commercial and Institutional Buildings Including Core and Shell and K-12 School Projects, 2009 Edition (Updated June 2010), p. 367 and 375.

side of design though, reliance on random local materials that are available during construction will most likely result in unique structures and creative material patterns and applications[72] that could be aesthetically valuable in affordable housing.

[72] Olivia Chen, Affordable Housing Made of Recycled Materials: http://inhabitat.com/low-income-housing-made-of-recycled-materials/, Accessed September 16, 2011.

6. Summary of Findings and Conclusions

This life cycle analysis presents a national, economy-wide strategic view of the environmental impacts associated with the construction, use, and demolition/deconstruction of single-family homes. The input contribution analysis identified the materials, products, and services directly consumed during the construction and use of single-family homes ("direct inputs") that contribute most significantly to overall life cycle environmental impacts. The output contribution analysis holistically identified the upstream supply chain processes in the economy where the most significant sources of life cycle environmental impacts associated with single-family homes occur.

The supply chains associated with selected direct inputs to single-family homes were explored in greater detail to provide further insights into the sources of embodied environmental impacts associated with these inputs. In addition, the potential for avoiding life cycle impacts associated with single-family homes was assessed by analyzing the energy efficiency and recycling/reuse scenarios. A brief summary of the results of these analyses is presented below. More in-depth summaries are presented in Sections 3 through 5.

6.1 Summary of Findings

6.1.1 Overall life cycle impacts of single-family homes

The analysis of overall life cycle impacts associated with single-family homes indicates the majority of life cycle impacts associated with single-family homes occur during the occupancy phase. This finding holds across all impact categories with the exception of the material input category, where the majority of impacts occur during the pre-occupancy phase. Life cycle impacts associated with the post-occupancy phase are relatively insignificant for all but the waste impact category. However, this should not be interpreted as a finding that choices regarding the management of building demolition/ deconstruction material have an insignificant effect on the life cycle impacts of single-family homes. Rather, the finding reflects a definitional issue, and the recycling and/or reuse of C&D material can result in significant avoided impacts when used as an input in the residential building and other sectors of the economy.

For the pre-occupancy and occupancy phases, most of life cycle impacts associated with single-family homes are indirect—they result from upstream supply chain processes and are embodied in the direct inputs to the single-family home. This suggests that a policy perspective focused solely on direct inputs without an understanding of the upstream supply chain processes and the economic linkages among inputs and upstream processes may miss opportunities for effectively reducing the environmental impacts associated with single-family homes.

6.1.2 Direct Inputs – Pre-Occupancy and Occupancy Phases[73]

The input contribution analysis for the pre-occupancy phase of single-family homes suggests that when all factors are considered equally (no weighting or grouping), a diverse mix of direct inputs contributes to the overall life cycle impacts of single-family homes, including building materials (e.g., *brick and structural clay tile*, *ready-mixed concrete*, *reconstituted wood products*), more highly engineered products (e.g., *miscellaneous plastic products*), and services (e.g., *trucking and courier services*).

Construction materials, including *sand and gravel*, *dimension, crushed and broken stone*, *ready-mixed concrete*, and *reconstituted wood products*, tend to contribute most significantly to the life cycle natural resource and land use impacts. *Brick and structural clay tile* contributes most significantly to the toxicity-related life cycle impacts associated with single-family homes. *Ready-mixed concrete*, *fiberglass and mineral wool insulation*, and *reconstituted wood products* accounted for significant contributions to the life cycle pollution impacts associated with single-family homes.

The input contribution analysis for the occupancy phase of single-family homes was focused on energy and water inputs and materials and products replaced during the life span of the home. Energy consumption and impacts associated with electricity contribute the most to the life cycle impacts associated with the occupancy phase of single-family homes. More than half of the overall life cycle impact of single-family homes for 8 of the 17 impact categories is associated with *electric services*. In terms of replacements, *wood shingle siding*, and *fiberglass and mineral wool insulation* contribute significantly to life cycle impacts of single-family homes.

6.1.3 Supplemental Analysis of Selected Inputs

Supplemental supply chain analyses focused on *fiberglass and mineral wool insulation*, *ready-mixed concrete*, *wood shingle siding*, *reconstituted wood products*, and *brick and structural clay tile*. The analysis identified a close relationship between the upstream supply chain processes associated with *forestry products* and the land use impacts associated with *wood shingle siding* and the upstream supply chain processes associated with *hydraulic cement* and the pollution impacts associated with *ready-mixed concrete*.

The analysis also found that for some products categories, the manufacturing phase of the product itself accounted for a significant portion of the life cycle impacts associated with the product. It is estimated that the manufacturing of *fiberglass and mineral wool insulation* accounts for almost half of the ODP impacts associated with these products, the manufacturing of *ready-mixed concrete* is an important source of pollution impacts, and the manufacturing of *brick and structural clay* tile accounts for almost half of important life cycle toxicity impacts of single-family homes.

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[73] Contribution analyses were not conducted for the post-occupancy phase due to the limited scope and constribution of impacts associated with this phase relatively to the overall life cycle impact associated with single-family homes. See Section 2.3 for additional discussion.

The analysis highlighted the significance of electric services and other energy-related upstream supply chain processes to the life cycle impacts embodied in direct inputs to single-family homes. This contribution was particularly evident in the analyses of the *ready-mixed concrete* and *reconstituted wood products* product categories. Finally, the findings with respect to the contribution of forestry to land use competition impacts and the potential for managed forests to sequester carbon highlighted the importance of weighing multiple factors (e.g., land use and global warming potential) when evaluating policy responses.

6.1.4 Upstream Supply Chain Processes

Whereas the input contribution analysis focused on the relative contribution of direct inputs to the overall life cycle impacts, the output contribution analysis disaggregated these impacts to their original source in the upstream supply chain of single-family homes. The output contribution analysis was conducted for the pre-occupancy and occupancy phases of single-family homes. Relative to the input contribution analysis, the output contribution analysis highlighted energy and related supply chain processes, raw construction and other materials used in single-family homes and transportation, for their contribution to the overall life cycle impacts of single-family homes.

The pre-occupancy phase output contribution analysis highlighted materials associated with new building construction (e.g., *brick and structural clay tile, sand and gravel*, and *dimension, crushed and broken stone*). The occupancy phase output contribution analysis differed in that it highlighted supply chain processes associated with replacement materials, *agriculture, forestry, and fishery services*, *paper and paperboard mills*, and *plastics materials and resins* as inputs to wood products. Both analyses identify *fiberglass and mineral wool insulation* as a significant contributor to the overall life cycle impact of single-family homes.

Processes contributing significantly to the overall natural resource and land use impacts of single-family homes included, in the pre-occupancy phase, *sand and gravel, crude petroleum and natural gas*, *coal*, *and dimension, crushed and broken stone*, and in the occupancy phase, energy-related inputs (e.g., *electric services*, *coal*, and *crude petroleum and natural gas*), and forestry services. Processes contributing significantly to the overall toxicity impacts of single-family homes included, in the pre-occupancy phase, *brick and structural clay tile*, and in the occupancy-phase, *electric services*, chemicals, and pulp and paper mills. Both the pre-occupancy- and occupancy-phase output contribution analyses highlight *electric services* as a primary contributor to impacts included in the pollution grouping.

6.1.5 Potential for Avoided Impacts

The input and output contribution analyses indicated that a diverse mix of inputs contribute significantly to the life cycle impacts associated with single-family homes. Additional analyses were conducted to analyze the potential for avoiding impacts through reduced material and resource use. These included analysis of avoided impacts associated with the following scenarios:

- Improving end-use efficiency of electricity use for space heating, water heating, space cooling, refrigeration, and lighting;
- Improving end-use efficiency of natural gas use for space heating and water heating;
- Increasing the recycling of ready-mixed concrete from single-family home demolition as roadway aggregate;
- Increasing the recycling of carpets and rugs salvaged during the renovation or demolition/ deconstruction of single-family homes as resin for various synthetic materials;
- Increasing the reuse of brick salvaged from single-family homes for new construction; and
- Increasing the recycling of reconstituted wood products as a source of energy for the wood and paper products industries.

The results of the avoided impacts analysis suggest that, combined, the energy efficiency improvements and material reuse/recycling scenarios considered in the avoided impacts analysis could result in 5-28% reductions in the life cycle impacts associated with single-family homes. Improving efficiencies in lighting, space heating, space cooling and water heating could result in reductions of 12-27% in the life cycle impacts associated with single-family homes across a range of natural resource use, toxicity, and pollution impact categories. The analysis suggests that the most significant contributions to avoided impacts would result from the efficiency improvements in natural gas water and space heating, lighting, and electric space cooling.

Improvements in material reuse and recycling rates considered in the analysis could result in reductions of 6-14% in life cycle impacts associated with single-family homes across a range of natural resource, toxicity, and pollution impact categories. The analysis suggests that the recycling scenario analyzed for *carpets and rugs* accounted for most of the potential avoided impacts, including 9-13% reductions in life cycle stratospheric ozone depletion and three categories of ecotoxicity impact. The analysis suggests that the increased recycling of salvaged reconstituted wood products as an energy source could offset 7% of life cycle abiotic depletion and 5% of the life cycle waste impacts associated with single family homes. The analysis suggested that while reductions in life cycle impacts could be achieved through increased recycling of concrete and reuse of brick, the contribution of the scenarios considered to reducing overall life cycle impacts associated with single-family homes would be relatively small. However, it is important to note that even if an impact for a single material could be small, the sum of such small impacts across the many materials used in building a home should result in more significant environmental savings overall.

6.1.6 Environmental Justice

The two avoided impact scenarios quantified the environmental benefits that can accrue from using recycled/reused materials as replacements for virgin materials and improving energy efficiency. The analysis demonstrated how these strategies can help single-family homes perform better environmentally over their life cycles. However, the benefits from implementing the two strategies extend beyond ones that can be measured purely by environmental impact categories. Broadly, through the reduction of pollution that most affects low-income households and their potential to reduce housing costs, incorporation of recovered materials and energy efficiency improvement strategies provide social, health and economic benefits to disadvantaged communities. Other co-benefits that result from increasing the recycling and reuse of materials include job creation in local deconstruction and recycling/reuse industries as well as overall community revitalization from any associated economic activity.

Recovered materials are often cheaper and their increased incorporation can help reduce both upfront and renovation housing costs in attempts to provide and maintain affordable, green homes. However, for recovered materials to be of service to low-income households in affordable housing, they need to be chosen judiciously. One concern is that potentially harmful materials that had historically circulated in the construction and maintenance of buildings could be reintroduced. The U.S EPA works to promote safe reuse and has gathered useful information on how reuse stores and their customers can safely manage older building materials that may contain lead-based paint.[74]

Further, depending on the application, the structural and energy-efficiency performance of recovered materials may be other important criteria for their selection. Building codes may not allow salvaged lumber for structural applications due to safety concerns, or a salvaged single-pane window for exterior applications due to energy inefficiency.[75]

Finally, for repair and maintenance costs not to overcome the upfront savings, recovered materials need to be sufficiently durable. Materials salvaged from the structures of periods that boasted construction of better quality may be preferential.[76]

6.2 CONCLUSIONS

The analysis of the life cycle impacts associated with single-family homes demonstrates the importance of considering a broad range of life cycle impacts in the evaluation of environmental issues and mitigation responses.

6.2.1 The Use of Life Cycle, Multi-Impact Analysis in Support of SMM

This analysis demonstrates the importance of approaching environmental issues from a life cycle perspective and the importance of considering multiple impacts of concern. The analysis provides insights that could not be gleaned from a more narrow perspective—e.g., insights regarding

[74] U.S EPA, Pollution Prevention and Toxics, 2011, Frequent Questions, General Information about Lead, 2011: http://toxics.supportportal.com/link/portal/23002/23019/Article/32411/Building-material-reuse-stores-sometimes-accept-older-materials-which-have-been-coated-with-lead-based-paint-and-could-pose-a-lead-poisoning-hazard-In-particular-older-windows-and-doors-are-likely-to-, Accessed August 15, 2011.
[75] King County Department of Natural Resources and Parks, Solid Waste Division & City of Seattle Department of Planning and Development, 2006. {Green home remodel} salvage & reuse: http://your.kingcounty.gov/solidwaste/greenbuilding/documents/Green_home_remodel-salvage.pdf, Accessed August 15, 2011.
[76] Ibid.

relationships among life cycle phases, across environmental media, and across human and ecological receptors.

For example, in the context of life cycle impacts associated with single-family homes, the analysis demonstrates:

- Different patterns emerge when analyzing impacts across the supply chain. For example:
    - For some materials, products and services, a very clear link exists between embodied impacts and upstream supply chain processes (e.g., *reconstituted wood products* and *forestry products* and wood milling processes).
    - In other cases, the patterns are less clear reflecting situations where an end-product embodies impacts derived from a diverse range of upstream supply chain processes (e.g., *miscellaneous plastic products*) or situations where a supply chain process contributes to overall life cycle impact through a diverse set of direct inputs (e.g., *electrical services*).
    - Still in other cases, the manufacturing of the product itself creates much of the impact with little contribution from upstream supply chain processes (e.g., *fiberglass and mineral wool insulation*).
- Different patterns emerge when analyzing impacts across different impact categories. For example:
    - Some materials, products, and services contribute significantly to overall life cycle impact due to one or two dominant impacts (e.g., *sand and gravel* and the material input and waste impact categories).
    - Some materials, products, and services contribute significantly to overall life cycle impacts through a diverse set of impacts (e.g., *electrical services*, *reconstituted wood products*).
    - Other materials, products, and services contribute to overall life cycle impacts based on a diverse but related set of impacts (e.g., *ready-mixed concrete* and pollution impacts).
- Different patterns emerge when analyzing impacts across life cycle phases. For example:
    - The relative significance of different materials, products, and services to overall life cycle impact may change depending on life cycle phase (e.g., construction materials contribute more significantly to life cycle impacts in the pre-occupancy phase). Other materials continue to contribute to the overall life cycle impacts of single-family homes through the life cycle (e.g., *wood shingle siding* used in original construction and replaced during the life span of a home).
    - Different life cycle phases can contribute more or less significantly to different life cycle impacts. For example, energy consumption during the occupancy phase accounts for the majority of overall life cycle energy consumption associated with single-family homes. Material input during the pre-occupancy phase

accounts for the majority of overall life cycle material inputs associated with single-family homes.

6.2.2 Opportunities for Integrated Environmental Decision-Making in Support of SMM

The analysis also suggests the potential for multiple, reinforcing environmental benefits that could be achieved when mitigation is approached from an integrated environmental decision-making perspective. It demonstrates relationships among supply chain processes and suggests the interconnectivity among producers, service providers, and consumers—individuals, businesses, and governments—in the economy. The life cycle perspective suggests that policy interventions could occur at multiple stages in a supply chain and involve multiple actors and policy instruments. The multi-impact perspective suggests that government programs focused on different objectives could work in tandem to address disparate issues with common solutions. A multi-impact life cycle perspective provides a foundation for integrated environmental decision-making.

For example, in the context of single family homes, the analysis demonstrates the following insights with respect to integrated environmental strategies:

- Impact patterns across supply chains suggest the types of policy responses. For example:
    - Where direct or embodied impacts tend to accumulate around a limited set of supply chain processes, a set of policy responses directed specifically at those points in the supply chain might be more effective than a cross-supply chain response.
- Different impact patterns across impact categories suggest different type of policy responses. For example:
    - Where a material, product, or service contributes significantly to overall life cycle impacts through a diverse set of impact categories, a coordinated response among environmental programs, using different authorities, could yield efficiencies in addressing impacts and avoid the shifting of impacts from one medium/receptor to another.
    - Where a material, product, or service contributes significantly to overall life cycle impacts through a limited set of impact categories, a directed response through a single program or using a more limited set of authorities might be more effective.
- When analyzing potential approaches to more sustainable materials management, it is important to consider inter-relationships across life cycle boundaries. For example:
    - Where the analysis indicates significant impacts associated with the use phase, it is important to consider not only policy strategies focused on use but also opportunities to avoid use phase impacts through, for example, improvements in

product design (e.g., use of more durable construction), alternative product-service systems, etc.

- o It is important to consider opportunities to preserve natural capital by reusing and recycling materials at the end-of-life as inputs to upstream supply chain processes associated with production or use phases (e.g., reuse of bricks or hardwood flooring) and to consider opportunities for avoiding impacts in another economic sector (e.g., recycling of concrete as roadway aggregate, recycling of wood panels as fuel).

6.2.3 Analytical Tools in Support of SMM

Input-Output Life Cycle Analysis (I-O LCA) is inclusive of an infinite number of production processes and circular effects along their way. The data that the I-O LCA approach uses are the most detailed and complete US life cycle inventory data. Consequently, the I-O LCA is increasingly becoming part of decision-making processes.

However, input-output data as detailed as they may be, generally, have some limitations that could reduce the certainty of findings of I-O LCA models. Examples of such data limitations include source data uncertainties, aggregation uncertainties and international production uncertainties:[77]

1. **Source data uncertainties.** Input-output data are publicly available data that were collected through business surveys and later transformed; the standard error typically linked to surveys is obscured with these later data transformations.[78]

   In addition, not all possible environmental impacts are represented by the data. For example, to minimize reporting burdens, information such as the use of fertilizers is not collected at the national level.[79] This being the case, nutrient and organic matter fluxes associated with forestry will be omitted and the impacts embodied in e.g., dimensional lumber will not be completely characterized.

2. **Aggregation uncertainties.** Products are grouped in a single sector if their making requires similar processes. In instances in which data for dissimilar products are aggregated in one sector, one product may incorrectly endow contributions and embody impacts of upstream processes of another product. For example, non-cotton-based and cotton-based products are aggregated in Carpet and Rug Mills Industry. Because of the aggregation, non-cotton-based products such as residential carpets and rugs, embody environmental impacts of cotton cultivation; see Section *3.1.1 About Carpets and Rugs*

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[77] For an expanded list of uncertainties and further explanation, see: 1. Manfred Lenzen, *Errors in Conventional and Input-Output–based Life-Cycle Inventories,* Journal of Industrial Ecology, Volume 4, Number 4; and 2. Eric D. Williams, Christopher L. Weber, and Troy R. Hawkins, *Hybrid Framework for Managing Uncertainty in Life Cycle Inventories*, Journal of Industrial Ecology, Volume 13, Number 6
[78] Manfred Lenzen, *Errors in Conventional and Input-Output–based Life-Cycle Inventories*, Journal of Industrial Ecology, Volume 4, Number 4

[79] Carnegie Mellon, Green Design Institute: Limitations of the EIO-LCA Method and Models, http://www.eiolca.net/Method/Limitations.html , Accessed January 03, 2013.

and *Cotton*. This occurrence makes it difficult to model a specific product. In addition, data may also be combined based on similar end-products even if the production processes are different, and such occurrence makes it difficult to model a specific industry.

3. **International production uncertainties.** US input-output tables detail environmental impacts of manufacturing processes of US facilities. The I-O LCA approach assigns those same impacts to imports also, if the modeled applications are based in the US; e.g., Chinese drywall used in US single-family homes. However, globally, technology, manufacturing processes and environmental regulations differ. Accordingly, uncertainty is associated with the assumption that an imported product will use the same resources and create same environmental releases as its US counterpart.

In addition, I-O data are averaged out across the national economy so that I-O LCA findings are not applicable in local contexts.

Importantly though, data uncertainties do not imply that I-O LCA studies are unreliable;[80] however, to present and interpret the findings, these uncertainties should be understood and the ultimate nature of the I-O LCA results recognized. In this particular case, instead of governing a specific, sustainable way to produce a single-family home, I-O LCA points to where additional efforts could be focused so as to begin to develop approaches to a sustainable management of single-family homes. For example, where a product category that encompasses a diverse range of products contributes significantly to life cycle impacts (e.g., *miscellaneous plastic products*), the analysis suggests that supplemental research, comparison with previous studies and complementary analyses (e.g., process LCA) be conducted to better understand the nature of these impacts. Where the analysis shows significant potential for avoided impacts, it suggests additional research, stakeholder convening, and/or other activities to validate the finding and understand the feasibility and possible strategies for capturing this potential. The feasibility analysis may include assessment of the availability of techniques to produce less impactful inputs, e.g., a less-impactful ready-mixed concrete.

6.2.4 Additional Studies Others Could Undertake

I-O LCA provides a unique and thorough perspective in support of national-level, strategic studies of the nature, source, and locus of life cycle impacts associated with a key area of economic activity. I-O LCA allows for an effective and efficient analysis based on thorough sets of economic data and a multi-perspective, multi-impact view and is increasingly becoming part of decision-making processes.

Nevertheless, I-O LCA can and should be improved. Providing certainty analyses in association with I-O LCA studies could help identify specific I-O data limitations so they could be corrected. For example, follow-on studies focusing on uncertainty others could undertake could result in the disaggregation of the Carpet and Rug Mills Industry in the I-O table into cotton-based and non-

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[80] Eric D. Williams, Christopher L. Weber, and Troy R. Hawkins, *Hybrid Framework for Managing Uncertainty in Life Cycle Inventories*, Journal of Industrial Ecology, Volume 13, Number 6

cotton-based products made by the sector. This would improve the I-O data and the certainty associated with the data going forward.

Follow-on tasks others could undertake are to:

1. Provide complementary analyses using process-based LCA datasets and software such as EcoInvent, GaBi, and/or BEES, and critically compare findings to the findings included herein;
2. Research literature for other more narrowly focused studies, e.g., another LCA study could have the scope that is a subset of the scope of this report, and critically compare findings to the findings included herein;
3. For products of interest, examine specific life cycle elementary flows that are contributing to the high impact as well as the original data sources used to characterize those impacts, and identify if data may be generating overestimates;
4. Research I-O database independently to identify potential areas of data aggregation that could be influencing findings of interest, and highlight if the data that may be generating spurious findings.

Glossary of Key Terms

Abiotic depletion potential (ADP) – the annual rate of depletion of the stock of minerals and fossil fuels (natural resources that are regarded as non-living) relative to ultimate reserves. See also Appendix B1.

Acidification potential (AP) – impact of human emissions of acidifying substances (e.g., SO_2, NO_x, NH_x) on soil groundwater, surface waters, biological organisms, ecosystems, and built infrastructure. See also Appendix B1.

Characterization – modeling life cycle impacts. Characterization models are used to express impacts in terms of common characterization factors that allow aggregation of environmental emissions using equivalent terms (Suh, 2004; EPA, 2006).

Construction and demolition (C&D) materials – materials are generated when new structures are built and when existing structures are renovated or demolished (including deconstruction) (EPA, 2003a).

Contribution analysis – analysis of the contribution of impacts associated with *direct inputs* or *upstream supply chain processes* to the overall life cycle impact of the material, product, or service under study, within or across life cycle phases (Heijungs and Suh, 2002). See also *input contribution analysis* and *output contribution analysis*.

Cradle-to-gate – the life cycle of a product or service from the point of resource extraction to the "factory gate," or the point at which it is sold or, in some cases, consumed (Heijungs and Suh, 2002). For this analysis, it is equivalent to the *pre-occupancy phase*.

Deconstruction – the systematic dismantling of a building in an attempt to recover as much material as possible (EPA 2003a). Compare to *demolition*.

Demolition – the removal of the building through mechanical means in an attempt to remove the building as quickly and inexpensively as possible (EPA 2003a). Compare to *deconstruction*.

Direct environmental impact – impact that results during the extraction of material, production of the product, or delivery of service under study or impact that occurs during the life cycle phase under study. Used to describe specific direct environmental impacts (e.g., global warming, human toxicity) or a combination of direct environmental impacts and *direct resource withdrawals* (e.g., water consumption). Compare to *indirect impact*. See also Appendix B2.

Direct input – material, product or service directly consumed by the material, product, or service under study. Compare to *indirect input*. See also Appendix B2.

Direct resource withdrawal – resource withdrawal (e.g., water consumption, material input) that occurs during the extraction of the material, production of the product, or delivery of the service under study. Compare to *indirect resource withdrawal*. See also Appendix B2.

Ecotoxicity – the effects of chemical emissions on fish, wildlife, plants, and other wild organisms.

Embodied environmental impact – environmental impacts associated with *upstream supply chain processes* (i.e., *indirect impacts*) plus impacts associated with the extraction of the material, production of the product, or delivery of the service under study (i.e., *direct impacts*). Used to describe specific environmental impacts (e.g., global warming, human toxicity) or a combination of environmental impacts and *resource withdrawals* (e.g., water consumption).

Embodied resource withdrawal – resource withdrawal (e.g., energy consumption, material input) associated with *upstream supply chain processes* (i.e., *indirect resource withdrawals*) plus resource withdrawals associated with the extraction of the material, production of the product, or delivery of the service under study (i.e., *direct resource withdrawal*).

Energy consumption (EC) – total net primary energy consumption, including consumption of fossil fuels, nuclear energy, and renewable energy (not including geothermal energy). See also Appendix B1.

Eutrophication potential (EP) – impact of high environmental levels of macronutrients, the most important of which are nitrogen (N) and phosphorus (P), in terms of excessive nutrient enrichment and shifts in species composition and elevated biomass production in aquatic and terrestrial ecosystems. See also Appendix B1.

Freshwater aquatic ecotoxicity potential (FAETP) – impact of toxic substances on freshwater aquatic ecosystems. See also Appendix B1.

Freshwater sediment ecotoxicity potential (FSETP) – impact of toxic substances on the sediment of freshwater aquatic ecosystems. See also Appendix B1.

Global warming potential (GWP) – impact of human emissions on the *radiative forcing* of the atmosphere. See also Appendix B1.

Human toxicity potential (HTP) – impact on human health of toxic substances present in the environment (i.e., excluding workplace exposures). See also Appendix B1.

Indirect environmental impact – impact associated with upstream supply chain processes. Used to describe specific indirect environmental impacts (e.g., global warming, human toxicity) or a combination of indirect environmental impacts and *indirect resource withdrawals* (e.g., water consumption). Compare to *direct impact*. See also Appendix B2.

Indirect input – upstream supply chain process associated with the material, product, or service under study. Compare to *direct input*. See also Appendix B2.

Indirect resource withdrawal – resource withdrawal (e.g., water consumption, material input) associated with upstream supply chain processes associated with the material, product, or service under study. Compare to *direct resource withdrawal*. See also Appendix B2.

Input contribution analysis – analysis of the contribution of impacts associated with *direct inputs* to the overall life cycle impact of the material, product, or service under study, within or across life cycle phases (Suh 2003). See also *contribution analysis* and *output contribution analysis*.

Input-output life cycle analysis (I-O LCA) – life cycle analysis employing detailed input-out data regarding the economic transactions between industries within an economy to model supply chain resource requirements, environmental emissions, and environmental impacts associated with a particular material, product, or service

Integrated environmental decision-making – an approach to environmental problems that involves holistic thinking, informed synthesis and elicitation of public environmental values, and application of tools and procedures to evaluate multi-dimensional risks, in order to maximize the efficient reduction of aggregate risk to populations or ecological systems (EPA 2000).

Land use competition (LUC) – loss of land as a resource, in the sense of being temporarily unavailable for other uses, due to human use. See also Appendix B1.

Life cycle analysis (LCA) – an approach for estimating the cumulative environmental impacts resulting from all stages of the life cycle of a material, product, or service from the perspective that they are interdependent (EPA 2006).

Life cycle emissions – the releases of chemical substances to air, water, or land aggregated over the life cycle of a material, product, or service. In this context, the term "emissions" extends beyond air emissions and includes water discharges, land disposal, etc.

Life cycle environmental impact – impact associated with *life cycle environmental emissions* and/or impacts associated with a combination of *life cycle environmental emissions* and *life cycle resource withdrawals*.

Life cycle resource withdrawal – resource withdrawal (e.g., water consumption, land use, energy consumption, material consumption) aggregated over the life cycle of a material, product, or service.

Marine aquatic ecotoxicity potential (MAETP) – impact of toxic substances on marine aquatic ecosystems. See also Appendix B1.

Marine sediment ecotoxicity potential (MSETP) – impact of toxic substances on the sediment of marine aquatic ecosystems. See also Appendix B1.

Material input (MTL) – raw materials required to produce a commodity, including domestically extracted and imported raw materials, less processing wastes and exports of processed materials. See also Appendix B1.

Occupancy phase – the phase of the life cycle of a single-family home when the home is in use, extending from the end of the *pre-occupancy phase* to the time at the beginning of the *post-occupancy phase*, including periods when the home is vacant between occupants.

Output contribution analysis – analysis of the contribution of impacts associated with *upstream supply chain processes* to the overall life cycle impact of the material, product, or service under study (Suh, 2003). See also *contribution analysis* and *input contribution analysis*.

Photochemical ozone creation potential (POCP) – impact of human emissions of volatile organic compounds (VOCs) and carbon monoxide (CO) in the presence of nitrogen oxides (NO_x) resulting in the formation of reactive chemical compounds, including ozone, by the action of sunlight. See also Appendix B1.

Post-occupancy phase – the period when the single-family home is *demolished* or *deconstructed,* extending from the end of the *occupancy phase* to the end-of-life of the materials that previously constituted the structure.

Pre-occupancy phase – the period extending from the extraction of raw materials associated with the supply chain of a single-family home through the time when the home is being built and ending at the start of the *occupancy phase*.

Process life cycle analysis (LCA) – an approach to life cycle analysis that involves summing life cycle impacts across unit process models to obtain total life cycle impact, where unit processes are defined as the smallest portion of a product system for which data are collected (Hendrickson et al., 2006).

Radiative forcing – the change in the balance between solar radiation entering the atmosphere and the Earth's radiation going out. On average, a positive radiative forcing tends to warm the surface of the Earth while negative forcing tends to cool the surface. Greenhouse gases have a positive radiative forcing because they absorb and emit heat (IPCC, 2001).

Replacements – materials and products substituted for materials and products originally installed in the single-family home or providing/enhancing the function of the original materials and products, after these original materials and products have been removed, including parts of the structure (e.g., roofing shingles, doors and windows), materials used to protect and/or improve the function of structure (e.g., rugs, insulation), and appliances (e.g., washing machines, heaters).

Stratospheric ozone depletion potential (ODP) – Impact of anthropogenic emissions on the thinning of the stratospheric ozone layer, resulting in a greater fraction of solar UV-B radiation reaching the earth's surface. See also Appendix B1.

Supply chain process – a process in the supply chain of a material, product, or service provided to the end consumer, where the supply chain consists of the network of all materials extraction processes, product production processes, and services required to meet the consumer's need. See also *upstream supply chain process*.

Sustainable materials management (SMM) – an approach to promote sustainable materials use, integrating actions targeted at reducing negative environmental impacts and preserving natural capital throughout the life-cycle of materials, taking into account economic efficiency and social equity (OECD, 2005).

Terrestrial ecotoxicity potential (TETP) – Impact of toxic substances on terrestrial ecosystems. See also Appendix B1.

Upstream environmental impact – impact associated with upstream supply chain processes. Used to describe specific indirect environmental impacts (e.g., global warming, human toxicity) or a combination of indirect environmental impacts and *upstream resource withdrawals* (e.g., water consumption). Compare to *direct impact*. See also *indirect environmental impact*.

Upstream resource withdrawal – resource withdrawal (e.g., water consumption, material input) associated with upstream supply chain processes associated with the material, product, or service under study. Compare to *direct resource withdrawal*. See also *indirect resource withdrawal*.

Upstream supply chain process – a process in the supply chain of a material, product, or service provided to the end consumer, where the supply chain consists of the network of all materials extraction processes, product production processes, and services required to meet the consumer's need. See also *supply chain process.*

Waste (WST) – Materials that are consumed in the U.S. economy and exit (e.g., through disposal in a landfill) within 30 years after entry. See also Appendix B1.

Water consumption (WC) – Total water used by operation or facility, including: for agriculture, total water used in irrigation; for commercial/industrial sectors, net intake plus water re-circulated; and for electricity generation, total water used in thermoelectric (in-stream and off-stream) and hydropower facilities (in-stream). See also Appendix B1.

Units of Measure Used in This Report

Btu – British thermal units

C_4H_4 eq. – ethylene equivalents, expressed in terms of kilograms (kg C_4H_4 eq.)

CFC-11 eq. – trichlorofluoromethane (also known as CFC-11) equivalents, expressed in terms of kilograms (kg CFC-11 eq.)

CO_2 eq. – carbon dioxide equivalents, expressed in terms of kilograms (kg CO_2 eq.)

p-DCB eq. – 1,4-dichlorobenezene (also known as p-dichlorobenzene) equivalents, expressed in terms of kilograms (kg p-DCB eq.) or metric tons (mton p-DCB eq.)

MJ – megajoules

kg - kilograms

*m^2*yr* – square meter years

mton – metric ton, equivalent to 1,000 kilograms

PO_4 eq. – phosphate equivalents, expressed in terms of kilograms (kg PO_4 eq.)

Sn eq. – antimony equivalents, expressed in terms of kilograms (kg Sn eq.)

SO_2 eq. – sulfur dioxide equivalents, expressed in terms of kilograms (kg SO_2 eq.)

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APPENDICES

APPENDIX A - SINGLE-FAMILY HOME CONSTRUCTION AND RENOVATION DATA

Appendix A1 – Mass and Cost of Replacement Materials/Products during the Occupancy Phase of a Single-Family Home

Appendix A2 – Remodeling expenditures in the US in 1998-1999

Appendix A3 – Specification of Average Residential Building for Occupancy-Phase Analysis

APPENDIX A1 – MASS AND COST OF REPLACEMENT MATERIALS/PRODUCTS DURING THE OCCUPANCY PHASE OF A SINGLE-FAMILY HOME

	Mass (kg)	Monetization		Cross-check with the Harvard University study	
	Replacement Mass (kg)[(1)]	Replacement in USD per 1 standard residential home[(2)]	Total in million USD[(3)]	Corresponding/related item (may duplicate)	Total in million USD[(4)]
Carpeting	3,300.00	65,476.19	5,222.03[(5)]	Flooring/Paneling/Ceiling	12,334.94
Linoleum flooring	270	2,534.13	2,939.59	Flooring/Paneling/Ceiling	12,334.94
Roofing (asphalt shingle)	8,170.00	10,235.24	11,872.88	Roofing	11,486.02
Insulation (glass fiber)[(a)]	1,830.00	3,816.88	4,427.58	Insulation	901.29
Drywall[(b)]	7,710.00	2,731.45	3,168.48	N/A	-
Doors/Windows[(c)]	2,310.00	12,043.12	13,970.02	Window/door	7,192.50
Plastics[(d)]	488	8,396.10	9,739.48	N/A	-
Lumber[(e)]	9,390.00	13,268.74	15,391.74	N/A	-
Hardware[(f)]	286	7,865.00	9,123.40	N/A	-
Electrical[(g)]	84	6,619.20	7,678.27	Electrical system	1,353.67
Foundation	-	-	-	N/A	-
Paints	393	715.39	829.86	N/A	-
Siding (wood shingle)	6,360.00	12,720.00	14,755.20	Siding	6,039.70
Other[(h)]	2,750.00	32,950.86	38,223.00	Other	19,247.16
Total	43,300.00	179,372.32	208,071.89		121,804.08

(1) Replacement weights from Oregon DEQ (2010), Table 9 (p. 59)
(2) Replacement weights monetized based on Oregon DEQ (2010), Appendix 8, Cost per unit data ($2010)
(3) Assuming 1.16 million homes built in 1998 (DOE 2011, Table 2.5.1)
(4) Assuming the same annual replacement expenditure will occur over the 51.6 years of average life-time for 1.16% of the homes exist in 1998-1999, where 1.16% is derived from DOE (2011a), Tables 2.2.1 and 2.5.1
(5) Adjusted based on 1998 IO table

Basis for unit cost assumptions:
(a) Assumed to be R25 fiberglass insulation
(b) Assumed to be 5/8-inch gypsum board
(c) Based on higher unit cost data included for “windows” in Oregon DEQ (2010), Appendix 8
(d) Based on highest unit cost data included in Oregon DEQ (2010), Appendix 8, for items that could be categorized as "plastics" (i.e., “PVC film” unit cost used)
(e) Assumed to be 4x12 lumber
(f) Based on highest unit cost data included in Oregon DEQ (2010), Appendix 8, for items that could be categorized as “hardware” (i.e., “faucet” unit cost used)
(g) Based on highest unit cost data included in Oregon DEQ (2010), Appendix 8, for items that could be categorized as “electrical” (i.e., “electrical boxes” unit cost used)
(h) The average price of all items included in Oregon DEQ (2010), Appendix 8, used as basis for unit price for this category.

APPENDIX A2 – REMODELING EXPENDITURES IN THE US IN 1998-1999 (Harvard University report)

Base year 1998-1999; over 1 year, total residential building		Million USD total expenditure
Kitchen	Minor remodeling	$ 7,595.00
	Major remodeling	$ 9,841.00
	Additions/Alterations	$ 1,376.00
Bath	Minor remodeling	$ 4,646.00
	Major remodeling	$ 6,036.00
	Additions/Alterations	$ 3,890.00
Other	Bedroom	$ 13,044.00
	Other room	$ 20,618.00
	Deck/Porch	$ 5,620.00
	Other interior	$ 3,203.00
	Disaster repairs	$ 7,693.00
Replacement	Roofing	$ 19,957.00
	Siding	$ 10,494.00
	Plumbing	$ 1,588.00
	Electrical system	$ 2,352.00
	Window/door	$ 12,497.00
	Plumbing fixtures	$ 2,938.00
	Insulation	$ 1,566.00
	Flooring/Paneling/Ceiling	$ 21,432.00
	HVAC	$ 14,487.00
	Appliances	$ 4,507.00
Exterior	Garage	$ 2,813.00
	Other	$ 33,442.00
Total		$211,635.00

Excerpted from: http://www.jchs.harvard.edu/publications/remodeling/remodeling_2003.pdf

APPENDIX A3 – SPECIFICATION OF AVERAGE RESIDENTIAL BUILDING FOR OCCUPANCY-PHASE ANALYSIS

- Base year: c.a. 1998
- Average size: 2,170 sf
- Total units built: 1,160,000
- Total cost: 184 billion USD (in 1998$)
- Expected longevity: 51.6 year
- Average physical material input to the single unit residential construction
  - 13,837 board-feet of lumber
  - 13,118 square feet of sheathing
  - 19 tons of concrete
  - 3,206 square feet of exterior siding material
  - 3,103 square feet of roofing material
  - 3,061 square feet of insulation
  - 6,050 square feet of interior wall material
  - 2,335 square feet of interior ceiling material
  - 226 linear feet of ducting
  - 19 windows
  - 4 exterior doors (3 hinged, 1 sliding)
  - 2,269 square feet of flooring material
  - 12 interior doors
  - 6 closet doors
  - 2 garage doors
  - 1 fireplace
  - 3 toilets, 2 bathtubs, 1 shower stall
  - 3 bathroom sinks
  - 15 kitchen cabinets, 5 other cabinets
  - 1 kitchen sink
  - 1 range, 1 refrigerator, 1 dishwasher, 1 garbage disposal, 1 range hood
  - 1 washer, 1 dryer
  - 1 heating and cooling system

Source: NAHB (2004)

APPENDIX B – INPUT-OUTPUT LIFE CYCLE IMPACT ANALYSIS DEFINITIONS

APPENDIX B1 – DEFINITIONS OF IMPACT CATEGORIES

Abiotic Depletion Potential:

Acronym: ADP

Units: kg antimony equivalent (kg Sn-eq.)

Definition: Abiotic resources are natural resources, such as iron ore, crude oil, and wind energy, which are regarded as non-living. For the purposes of this analysis, abiotic depletion potential is defined in terms of the annual rate of depletion of the stock of minerals and fossil fuels relative to ultimate reserves.

Reference: Baseline definition from Guinée et al. (2002), Part 2A, Section 4.3.3.1 (pp. 56-57)

Land Use Competition:

Acronym: LUC

Units: m^2*yr

Definition: Loss of land as a resource, in the sense of being temporarily unavailable for other uses, due to human use.

Reference: Baseline definition from Guinée et al. (2002), Part 2A, Section 4.3.3.3 (pp. 57-59)

Global Warming Potential:

Acronym: GWP

Units: kg carbon dioxide equivalent (kg CO_2-eq.)

Definition: Impact of human emissions on the radiative forcing (see glossary of terms) of the atmosphere, characterized using the model developed by the Intergovernmental Panel on Climate Change (IPCC), which defines the GWP of different greenhouse gases. Based on a 100-year time horizon (i.e., GWP100).

Reference: Baseline definition from Guinée et al. (2002), Part 2A, Section 4.3.3.5 (pp. 59-60)

Stratospheric Ozone Depletion Potential:

Acronym: ODP

Units: kg CFC-11 equivalent (kg CFC-11-eq.)

Definition: Impact of anthropogenic emissions on the thinning of the stratospheric ozone layer, resulting in a greater fraction of solar UV-B radiation reaching the earth's surface, characterized using the model developed by the World Meteorological Organisation, which defines the ozone depletion potential of different gases. Based on an infinite time horizon (i.e., ODP_∞).

Reference: Baseline definition from Guinée et al. (2002), Part 2A, Section 4.3.3.6 (pp. 60-61)

Human Toxicity Potential:

Acronym: HTP

Units: kg 1,4-dichlorobenzene equivalent (kg p-DCB-eq.)

Definition: Impact on human health of toxic substances present in the environment (i.e., excluding workplace exposures), characterized based on USES 2.0 (RIVM, 1997), describing fate, exposure, and effects of toxic substances, adapted to LCA. Based on an infinite time horizon (i.e., HTP_{∞}).

Reference: Baseline definition from Guinée et al. (2002), Part 2A, Section 4.3.3.7 (p. 61)

Freshwater Aquatic Ecotoxicity Potential:

Acronym: FAETP

Units: kg 1,4-dichlorobenzene equivalent (kg p-DCB-eq.)

Definition: Impact of toxic substances on freshwater aquatic ecosystems, characterized based on USES 2.0 (RIVM, 1997), describing fate, exposure, and effects of toxic substances, adapted to LCA. Based on an infinite time horizon (i.e., $FAETP_{\infty}$).

Reference: Baseline definition from Guinée et al. (2002), Part 2A, Section 4.3.3.8.1 (p. 62)

Marine Aquatic Ecotoxicity Potential:

Acronym: MAETP

Units: mton 1,4-dichlorobenzene equivalent (mton p-DCB-eq.)

Definition: Impact of toxic substances on marine aquatic ecosystems, characterized based on USES 2.0 (RIVM, 1997), describing fate, exposure, and effects of toxic substances, adapted to LCA. Based on an infinite time horizon (i.e., $MAETP_{\infty}$).

Reference: Baseline definition from Guinée et al. (2002), Part 2A, Section 4.3.3.8.2 (pp. 62-63)

Terrestrial Ecotoxicity Potential:

Acronym: TETP

Units: kg 1,4-dichlorobenzene equivalent (kg p-DCB-eq.)

Definition: Impact of toxic substances on terrestrial ecosystems, characterized based on USES 2.0 (RIVM, 1997), describing fate, exposure, and effects of toxic substances, adapted to LCA. Based on an infinite time horizon (i.e., $TETP_{\infty}$).

Reference: Baseline definition from Guinée et al. (2002), Part 2A, Section 4.3.3.8.3 (p. 63)

Freshwater Sediment Ecotoxicity Potential:

Acronym: FSETP

Units: mton 1,4-dichlorobenzene equivalent (mton p-DCB-eq.)

Definition: Impact of toxic substances on the sediment of freshwater aquatic ecosystems, characterized based on USES 2.0 (RIVM, 1997), describing fate, exposure, and effects of toxic substances, adapted to LCA. Based on an infinite time horizon (i.e., $FSETP_{\infty}$).

Reference: Baseline definition from Guinée et al. (2002), Part 2A, Section 4.3.3.8.4 (pp. 63-64)

Marine Sediment Ecotoxicity Potential:

Acronym: MSETP

Units: kg 1,4-dichlorobenzene equivalent (kg p-DCB-eq.)

Definition: Impact of toxic substances on the sediment of marine aquatic ecosystems, characterized based on USES 2.0 (RIVM, 1997), describing fate, exposure, and effects of toxic substances, adapted to LCA. Based on an infinite time horizon (i.e., $MSETP_{\infty}$).

Reference: Baseline definition from Guinée et al. (2002), Part 2A, Section 4.3.3.8.5 (p. 64)

Photochemical Ozone Creation Potential:

Acronym: POCP

Units: kg ethylene equivalent (kg C_4H_4-eq.)

Definition: Impact of human emissions of volatile organic compounds (VOCs) and carbon monoxide (CO) in the presence of nitrogen oxides (NO_x) resulting in the formation of reactive chemical compounds, including ozone, by the action of sunlight, characterized based on the United Nations Economic Commission for Europe (UNECE) Trajectory model.

Reference: Baseline definition ("high NO_x POCP") from Guinée et al. (2002), Part 2A, Section 4.3.3.9 (p. 65)

Acidification Potential:

Acronym: AP

Units: kg sulfur dioxide equivalent (kg SO_2-eq.)

Definition: Impact of human emissions of acidifying substances (e.g., SO_2, NO_x, NH_x) on soil groundwater, surface waters, biological organisms, ecosystems, and built infrastructure, characterized based on the International Institute for Applied Systems Analysis (IIASA) RAINS10 model, describing the fate and deposition of acidifying substances, adapted to LCA.

Reference: Baseline definition from Guinée et al. (2002), Part 2A, Section 4.3.3.10 (pp. 65-66)

Eutrophication Potential:

Acronym: EP

Units: kg phosphate equivalent (kg PO_4-eq.)

Definition: Impact of high environmental levels of macronutrients, the most important of which are nitrogen (N) and phosphorus (P), in terms of excessive nutrient enrichment and shifts in species composition and elevated biomass production in aquatic and terrestrial ecosystems, characterized based on the stoichiometric procedure applied to aquatic and terrestrial systems.

Reference: Baseline definition from Guinée et al. (2002), Part 2A, Section 4.3.3.11 (p. 66)

Energy Consumption:

Acronym: EC

Units: million BTUs

Definition: Total net primary energy consumption, including consumption of fossil fuels, nuclear energy, and renewable energy (not including geothermal energy), based on sector data provided by the Energy Information Agency (EIA). For fossil fuels, energy consumption is allocated to the point of combustion. For renewable and nuclear energy, energy consumption is allocated to the power-generating facility.

Reference: Equivalent to “energy use” as defined in EPA (2009), Appendix: Relative Ranking Technical Support Document (pp. 16-17)

Water Consumption:

Acronym: WC

Units: thousand gallons

Definition: Total water used by operation or facility, including: for agriculture, total water used in irrigation; for commercial/industrial sectors, net intake plus water re-circulated; and for electricity generation, total water used in thermoelectric (in-stream and off-stream) and hydropower facilities (in-stream), as defined by USGS (1998).

Reference: Equivalent to “water use” as defined in EPA (2009), Appendix: Relative Ranking Technical Support Document (pp. 12-15)

Material Input:

Acronym: MTL

Units: thousand kg or metric ton (mton)

Definition: Raw materials required to produce a commodity, including domestically extracted and imported raw materials, less processing wastes and exports of processed materials, consistent with the World Resources Institute (WRI) definition of direct material consumption (DMC) (WRI 2008).

Reference: Equivalent to “material use” as defined in EPA (2009), Appendix: Relative Ranking Technical Support Document (pp. 9-12)

Waste:

Acronym: WST

Units: thousand kg or metric ton (mton)

Definition: Materials that are consumed in the U.S. economy and exit (e.g., through disposal in a landfill) within 30 years after entry, consistent with the World Resources Institute (WRI) definition of direct process output (DPO) (WRI 2008).

Reference: Equivalent to “material waste” as defined in EPA (2009), Appendix: Relative Ranking Technical Support Document (p. 12)

Appendix B2- "Direct" and "Indirect" Impacts

Input contribution analysis of, for example, the pre-occupancy phase of a single-family home includes impact estimates and resource withdrawals associated with each of the materials and products delivered to the job site and each of the services provided in support of the home construction. Input contribution analysis of the occupancy phase includes impacts estimates and resource withdrawals associated with living in the home and operating appliances and other systems, as well as the impacts and resource withdrawals associated with replacement materials and products. Output contribution analysis disaggregates these impacts and resource withdrawals to their original source in the supply chain.

The I-O LCA described herein labels impacts and resource withdrawals that take place during construction or directly in the use of the home as "direct" impacts or resource withdrawals. Impacts and resource withdrawals associated with upstream supply chain processes are labeled "indirect." Figures 2-3 and 2-4 illustrate these distinctions for the pre-occupancy and occupancy phases of a single-family home, respectively.

Figure B-1
Direct and Indirect Impacts and Resource Withdrawals Associated with Single-family Home Construction

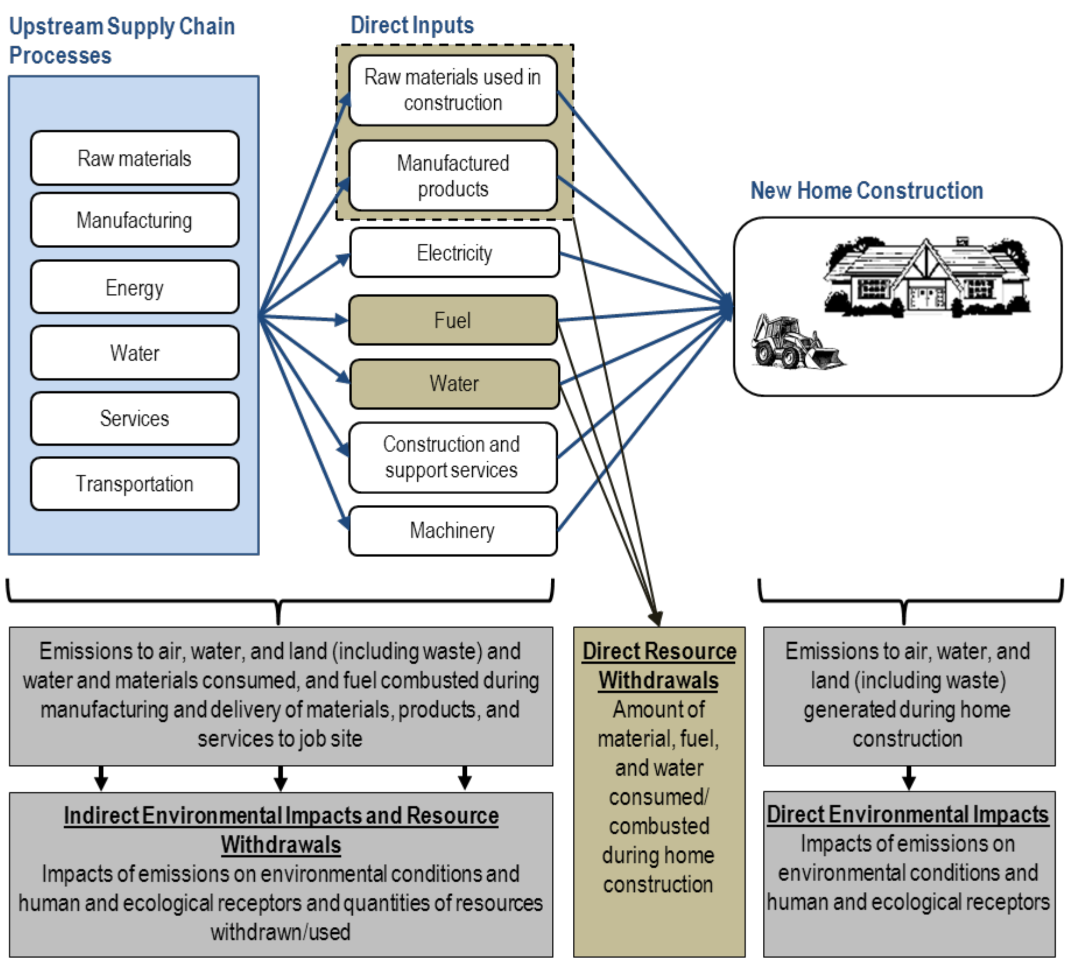
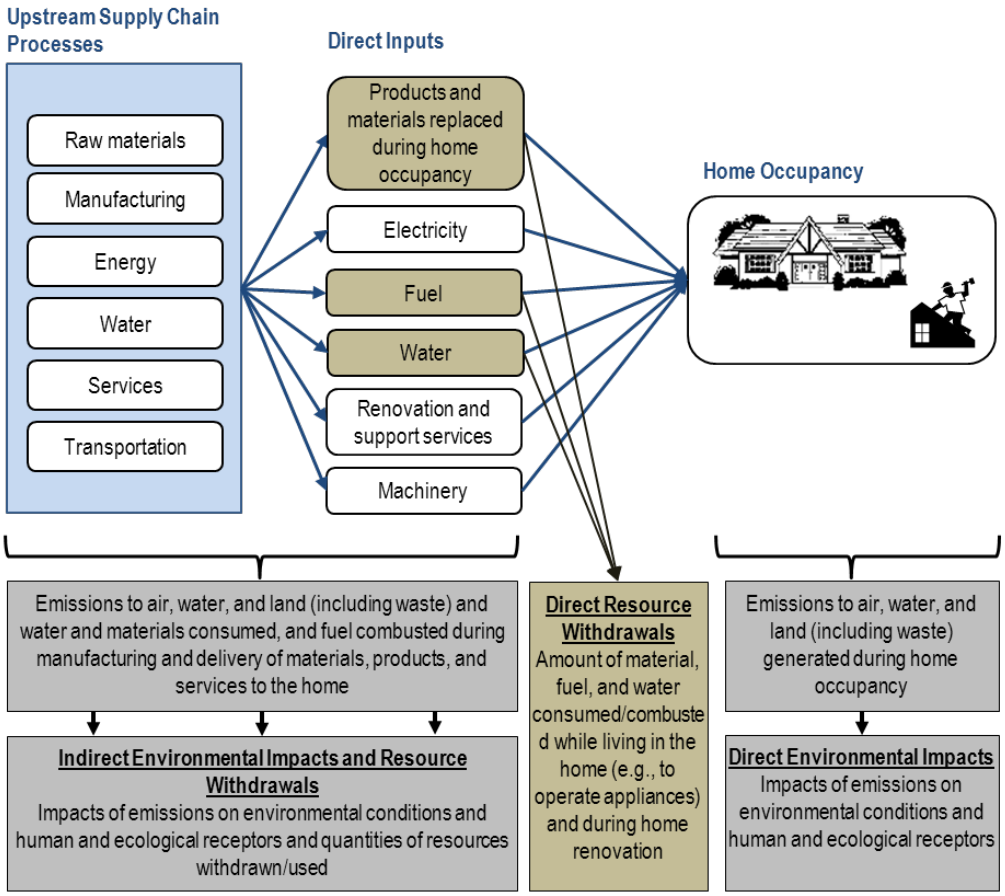


Figure B-2
Direct and Indirect Impacts and Resource Withdrawals Associated with Single-family Home Occupancy



These figures illustrate the following concepts:

Distinction between Environmental Impacts and Resource Withdrawals

The I-O LCA for single-family homes includes 17 "impact" categories. These include categories that express estimates of emissions to air, water, and land in terms of their environmental, human health, and ecological impacts and in terms of the withdrawal of natural resources from the environment. Table B-1 summarizes how the impact categories are grouped for this analysis. Note that some categories classified as "environmental impacts" could also be considered "resource withdrawals" (e.g., abiotic depletion). The distinction between environmental impacts and resource withdrawals is conceptual and does not affect the findings and conclusions of the I-O LCA.

Note that the consumption of some materials, products, and services represents both a resource withdrawal and an environmental impact, as those terms are defined herein. For example, water consumed during home construction to establish a new lawn would be accounted for in the water consumption (WC) factor. It represents a demand on this resource in terms of an out-of-stream use.

Depending on factors such as fertilizer application, erosion controls, and other hydrologic factors (e.g., ground water-surface water interaction in the area), this water use could also result in run-off ("emissions") of nutrients to nearby surface water, which could affect the nutrient balance and would be accounted for in the eutrophication potential (EP) impact category.

The distinction between environmental impacts and resource withdrawals is represented in Figures B-1 and B-2. Using the example above, water consumed during construction is shown on Figure B-1 as a brown arrow from the direct input "Water" to the "Direct Resource Withdrawals" text box. The impacts associated with the water use (impacts from run-off associated with establishing a lawn) occur through a more complex pathway, involving emissions and consequent changes to the environmental condition of the nearby waterbody. This is represented by the two text boxes under the home graphic, where the first represents the emissions (runoff) and the second, labeled "Direct Impacts," represents the environmental effects of this emissions.

From the standpoint of the LCA model, water consumption data are derived directly from reported data whereas eutrophication potential (EP) estimates are derived from both emissions data and a characterization model (see Appendix B-1 for a description of data and methods). These two pathways are not redundant. Rather, they represent two different types of impacts (in a broad sense) in which the water consumed during home construction can affect the environment. Similar concepts apply to energy consumption, material input, etc.

Table B-1
Classification of Impact Categories for LCA of Single-Family Homes

Environmental Impact Categories	Resource Withdrawal Categories
Abiotic depletion potential (ADP)	Land use competition (LUC)
Global warming potential (GWP)	Energy consumption (EC)
Stratospheric ozone depletion potential (ODP)	Water consumption (WC)
Human toxicity potential (HTP)	Material input (MTL)
Freshwater aquatic ecotoxicity potential (FAETP)	
Marine aquatic ecotoxicity potential (MAETP)	
Terrestrial ecotoxicity potential (TETP)	
Freshwater sediment toxicity potential (FSETP)	
Marine sediment toxicity potential (MSETP)	
Photochemical ozone creation potential (POCP)	
Acidification potential (AP)	
Eutrophication potential (EP)	
Waste (WST)	

Distinction between Direct and Indirect Impacts

From the perspective of the single-family home, direct impacts include those environmental impacts and resource withdrawals that occur over the life cycle of a single family home. For the pre-occupancy phase, these include, for example, impacts associated with emissions from construction vehicles, impacts associated with run-off from the job site, etc. Direct resource withdrawals during the pre-occupancy phase include materials, fuel, and water consumed during the construction of the home. For the occupancy phase, direct impacts include impacts associated with emissions generated by the operation of appliances and the care and maintenance of the home. Direct resource withdrawals during the occupancy phase include material inputs associated with replacements and fuel consumed in appliances, water used for bathing and laundry, etc. Direct impacts associated with the post-occupancy phase would include impacts associated with emissions from demolition equipment, water consumed during demolition/deconstruction, waste generated, etc.

Indirect impacts include environmental impacts and resource withdrawals associated with the production and/or delivery of the direct inputs required over the life cycle of the home. These include impacts associated with emissions generated during the manufacturing of products used to build or renovate the home, including embodied impacts associated with upstream supply chain processes. They also include resource withdrawals required to produce direct inputs (e.g., energy consumed), including resource withdrawals associated with all upstream supply chain processes.

Allocation of Energy Consumption and Energy-Associated Impacts

Energy consumption and associated impacts associated with the life cycle of a home are allocated to the point at which the fuel used to produce the energy is combusted (or, in the case of hyroelectric power, the point at which water is used). Fuel that is combusted in construction vehicles during the construction or renovation of a home, is considered a direct resource withdrawal and impacts associated with the vehicle emissions are considered direct impacts. Likewise, energy consumed by a gas stove or water heater in the home is considered a direct resource withdrawal.

Resources withdrawn and impacts associated with electricity used in home construction, occupancy, or demolition/deconstruction are considered indirect impacts. For example, coal used to produce electricity is combusted at the power plant and, thus, is allocated to the upstream supply chain associated with *electric services*. Likewise, energy consumed in the extraction of materials, manufacturing of products and equipment, etc. used in the life cycle of a single family home is considered an indirect resource withdrawal and associated impacts are considered indirect impacts.

APPENDIX C – VECTOR ANALYSIS METHODOLOGY

Background

Vector analysis, or spatial vector analysis, is a technique used to support multi-factor decision-making. Vector analysis involves analyzing the interactions between two or more variables by plotting measures of the variables in a graphical representation of the decision space. The resulting vector includes both measures of magnitude and direction. For the contribution analyses described in this report, vector analysis was used to derive:

- Vector magnitude, representing the extent to which the impacts associated with a material, product, or service differ from those associated with the rest of the materials, products, and services being considered.
- Change in vector orientation, describing the strength of influence of one impact category relative to all other impact categories being analyzed for a specific material, product, or service.

This approach was developed for the 2020 Vision Relative Ranking Analysis as a way to rank materials, products, and services across multiple impact criteria without weighting criteria and in a way that showed the influence of different criteria on the overall ranking. The *vector magnitude* calculated using this methodology does not represent an estimate of actual impact but, rather, they indicate the degree to which the material, product, or service is an "outlier," or how much it deviates from the mean relative to all materials, products, and services being measured. The *change in vector orientation* is an indicator of the criterion/criteria that has/have the greatest effect on magnitude.

Method

Upon completion of the contribution analyses based on individual environmental impact categories, the vector analysis was used to rank materials, products, and services across all impact categories and across the impact categories considered in the three impact subgroupings (i.e., natural resources and land use, toxicity, and pollution impacts). Specifically, the following steps were employed:

- <u>Step 1 – Compile CEDA data</u>: CEDA output data were compiled for each of the supply chain processes, materials, products, and services and for each impact category. Supply chain processes, materials, products, and services that did not indicate contribution to life cycle impacts associated with the pre-occupancy phase of single-family homes were eliminated from the analysis.
- <u>Step 2 – Calculate measure of variance</u>: The average (mean value) for each criterion was computed and subtracted from the criterion value for each of the supply chain processes, materials, products, and services retained in the analysis, the standard deviation for each impact category was calculated, and the mean-centered values were normalized by the standard deviation.
- <u>Step 3 – Calculate vector magnitude</u>: Vector magnitudes were calculated by "plotting" standard deviations on different axes corresponding to each of the different impact categories, vector

magnitudes were calculated as the basis for ranking supply chain processes, materials, products and services.

- Step 4 – Calculate criterion-specific change in vector orientation: To analyze individual impact categories' contributions to the overall ranking of a specific supply chain process, material, product, or service, the change in vector orientation associated with adding the standard deviation measure for a specific impact category to the vector plotted without the category was calculated.

Example

The following discussion uses the analysis of the relative ranking of *ready-mixed concrete* and *mineral wool* within the pollution impact grouping based on input contribution analysis of the pre-occupancy phase to illustrate the vector analysis methodology.

Step 1 – Compile CEDA data

Table C-1 shows the results of the input contribution analysis for the pre-occupancy phase for the criteria included in the pollution impact grouping:

Table C-1
CEDA Output for Ready-Mixed Concrete and Pollution Impact Categories
Input Contribution Analysis, Pre-Occupancy Phase

Material/product/service		Impact Categories in Pollution Impacts Grouping				
		GWP	ODP	POCP	AP	EP
		kg CO_2 eq.	kg CFC-11 eq.	kg C_4H_4 eq.	kg SO_2 eq.	kg PO_4 eq.
Ready-mixed concrete	Impact	$1.01x10^4$	$1.00x10^{-2}$	$4.97x10^0$	$5.15x10^1$	$5.28x10^0$
	# SD from the mean	7.96	0.39	6.54	8.62	8.09
Mineral wool (including fiberglass and mineral wool insulation)	Impact	$4.13x10^3$	$2.26x10^{-1}$	$2.21.x10^0$	$1.24x10^1$	$1.44x10^0$
	#SD from the mean	2.94	13.30	2.62	1.72	1.86
All other materials, products, and services identified as direct inputs to single-family homes, pre-occupancy phase	Sum of impacts	$8.47x10^5$	$2.02x10^0$	$3.87x10^2$	$5.51x10^3$	$3.56x10^2$
Mean impact estimate		$6.08x10^2$	$3.50x10^{-3}$	$3.55x10^{-1}$	$2.59x10^0$	$2.95x10^{-1}$
Standard deviation of impact estimates		$1.20x10^3$	$1.68x10^{-2}$	$7.06x10^{-1}$	$5.67x10^0$	$6.16x10^{-1}$

Step 2 – Calculate measure of variance

The measure of variance—number of standard deviations from the mean—is calculated for each impact category and each material, product, and service by subtracting the impact estimate for the specific material, product, or service from the mean for all materials, products, and services and dividing the result by the standard deviation. Table C-1 shows this calculation for *ready-mixed concrete* and *mineral wool*.

Step 3 – Calculate vector magnitude

Vector magnitudes and direction were calculated by "plotting" the number of standard deviation from the mean on different axes, each corresponding to a different impact category. Figure C-1 depicts how the vector magnitude and direction were calculated for the first two impact categories (GWP and ODP) for *ready-mixed concrete* and *mineral wool*.

Figure C-1
Vector Magnitude and Direction Plotted in 2 Dimensions (GWP and ODP)

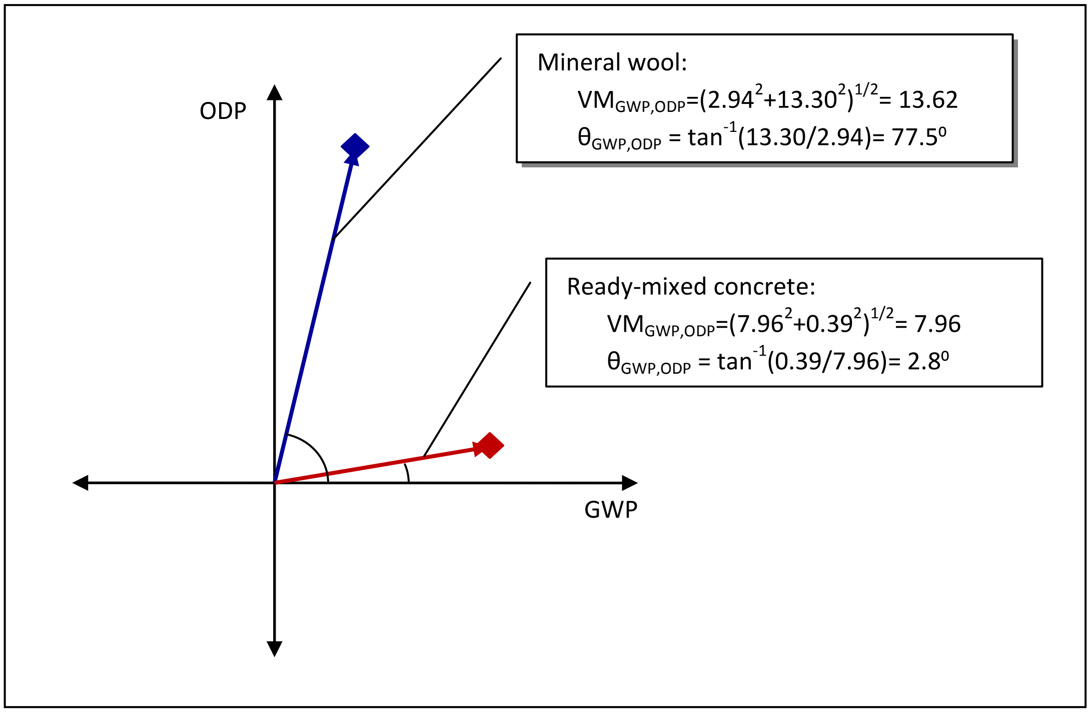


Figure C-1 illustrates two examples of how the vector magnitude and direction can provide information used for ranking materials, products and services on two dimensions and understanding the key driving factors behind the rankings. In this example, *mineral wool* would be ranked relatively higher than *ready-mixed concrete* when considering the two impact categories, GWP and ODP (the vector magnitude for *mineral wool* of 13.62 is higher than that for *ready-mixed concrete*, 7.96).

The orientation of the two vectors indicate that the vector magnitude associated with *ready-mixed concrete* is primarily a function of the relatively high GWP impact embodied in *ready-mixed concrete* when compared to other direct inputs to a single-family home. The orientation of the vector for *mineral wool* indicates that ODP impacts are the driving factor behind its relatively high ranking.

Further review indicates that *mineral wool* is ranked relatively higher than *ready-mixed concrete* on these two dimensions because of the relatively greater extent to which the ODP impacts associated with *mineral wool* differ from the average as compared to the extent to which the GWP impacts associated with *ready-mixed concrete* differ from the average.

The above analysis can be expanded to a third impact category by plotting the vector magnitude and direction in a third, orthogonal dimension. Additional impact categories can be included by plotting the vectors in additional, orthogonal dimensions. As long as each additional dimension is orthogonal, the basic calculus for vector magnitude in two dimensions can be projected to the number of dimensions (impact categories) of interest. The generalized equation for calculating vector magnitudes is as follows:

$$VM = \sqrt{\sum_{i=1}^{n} SD_i}$$

For *ready-mixed concrete* and *mineral wool*, the vector magnitudes calculated based on the pollution impacts grouping were calculated as follows:

Ready-mixed concrete: $VM_{poll} = (7.96^2+0.39^2+6.54^2+8.62^2+8.09^2)^{½} = 15.69$
Mineral wool: $VM_{poll} = (2.94^2+13.30^2+2.62^2+1.72^2+1.86^2)^{½} = 14.10$

Step 4 – Calculate criterion-specific change in vector orientation

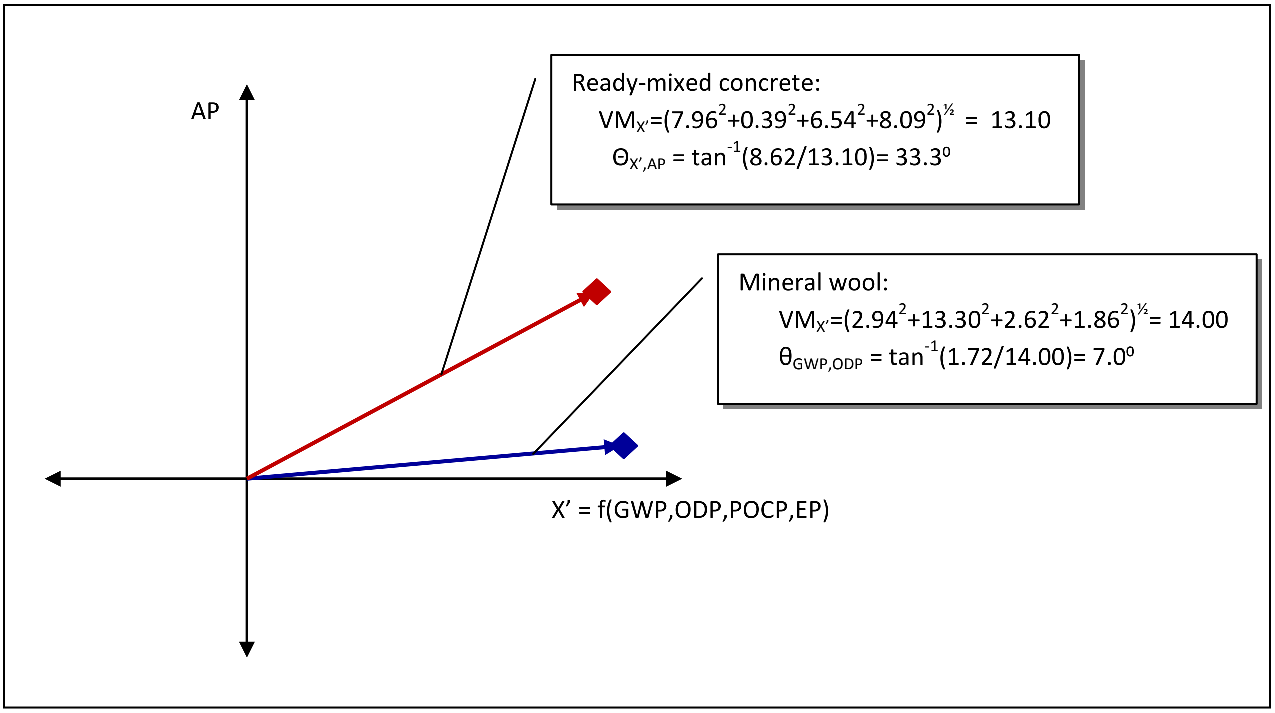
Ready-mixed concrete and *mineral wool* were the two most highly ranked product categories based on the input contribution analysis for single-family homes and the pollution impacts grouping (see Figure 3-4 in the main body of the report). A review of the vector magnitude calculations reveals that the relatively high ranking associated with *ready-mixed concrete* reflects a combination of the relatively significant impacts across several impact categories. By contrast, the vector magnitude calculated for *mineral wool* is dominated by the ODP impact category (which accounts for 80% of the total vector magnitude).

To identify driving factors behind the relative rankings of materials, products and services, the change in vector orientation associated with adding the standard deviation measure for a specific impact category to the vector plotted without the category was calculated. Figure C-1 shows this process in two dimensions, where the effect of the ODP category in terms of the change in vector orientation using the equation:

$\theta_{GWP,ODP}$ = tan-1($\#SD_{ODP}/\#SD_{GWP}$).

This approach can be projected into multiple dimensions by calculating the change in vector orientation resulting when the standard deviation associated with a new factor is added to the vector representing the combination of all other factors. Figure C-2 illustrates the approach for measuring the change in vector orientation when the standard deviation measures for acidification potential (AP) are plotted relative to the vector reflecting the combination of the other four impact categories associated with the pollution impact grouping. Note that the X′ axis represents the projection of the 4-dimensional vector calculated based on GWP, ODP, POCP and EP impact categories onto a plane surface.

Figure C-2
Change in Vector Orientation Resulting from Adding the AP Impact Category to All Other Impact Categories in the Pollution Impact Grouping



Review of the change in vector orientation indicates the AP impact category had a relatively strong effect on the relative ranking of *ready-mixed concrete* based on the pollution impact grouping. The effect of the AP category on the vector magnitude and relative ranking of *mineral wool* within this grouping was less pronounced. This is consistent with the conclusions drawn by reviewing the vector magnitude calculations. This approach was used to systematically analyze drivers behind relative rankings and is the basis for the information presented in Tables 3-2 and 4-1 in the main body of the report.

Strengths and Weaknesses

The vector analysis supports the I-O LCA by compiling and presenting the I-O LCA results in a format that is useful for subsequent policy analysis. Characteristics of the vector analysis approach are as follows:

- The Vector analysis considers the impact characterization results for the full range of materials, products and services that are either direct inputs to single family homes (input contribution perspective) or are included in the supply chain (output contribution perspective). This system of materials, products and services is not variable and thus, the vector analysis is not vulnerable to the issue of rank reversal.

- The internal normalization used in the vector analysis is intended to highlight significance. To fulfill its intended function, the vector analysis normalizes characterization results within an impact category in terms of number of standard deviations from the mean. From a descriptive standpoint, this is preferable to more common methods currently used in LCA (e.g., division by maximum or sum) in that it accounts for variability in the data.

- The vector analysis explicitly recognizes the theoretical and interpretational problems inherent in summing non-commensurate units. To address this, the vector analysis combines internally normalized results across impact categories using vector calculus and the assumption that the measures of impact are orthogonal. While this is clearly a simplifying assumption, vector addition is preferable to some of the more widely used compensatory methods in that it avoids the intuitively problematic assumption that units measuring different types of impact can be directly summed.

- As stated in the body of the report, the vector magnitude is descriptive and is not intended to convey a measure of relative impact. Rather, it is intended to help inform subsequent policy analysis and decision-making across a broad range of environmental policy contexts. The approach recognizes the uncertainties inherent in the underlying data and characterization methods and, as such, presents results in qualitative terms. Also, given its intended use, the approach does not assume that a single weighting scheme will be applicable across all decision contexts.

Primary sources of uncertainty in the single-family home analysis are the environmental and economic data and the assumptions used in the characterization methodologies. To evaluate the potential effect of uncertainty on the relative rankings obtained through the vector analysis, a perturbation analysis was conducted on the results of the input contribution analysis, pre-occupancy phase. Categorized impacts were randomly adjusted by ±5% and rankings were re-analyzed under different constraining conditions (i.e., ±10%, ±20% and no constraint on overall change in impact in any one category). The results of the analysis demonstrated that the vector analysis is robust at this level of potential random error, see Table C-2 below.

In addition, because the vector magnitude across categories is calculated by summing vectors (which squares the normalized result), the presence of materials, products and services that are significantly less impactful than the mean for the system - as expressed by their negative normalized value, could in theory increase the relative ranking of the material, product, service instead of lower it. A sensitivity analysis was conducted to test the practical implications of this concern. Because the number of supply chain processes associated with an material/product/service can vary (e.g., only 204 of the 480 materials, products and services included in the BEA commodity categories were identified as direct inputs to the pre-occupancy supply chain for single family homes), different sample sizes were analyzed. The sensitivity analysis found that given the structure of the data in the I-O LCA model, the vector analysis will consistently highlight the most impactful materials/products/services despite the theoretical possibility that negative normalization results will incorrectly rank less impactful materials, products and services more highly. As a practical matter, the vector analysis fulfills its intended function to help guide policy analyses and decisions, see Table C-3 below.

Table C-2
Analysis of Impact of Random Error on Relative Ranking Using Vector Analysis
Input Contribution Analysis, Pre-Occupancy Phase

Analysis of Impact of Random Error on Relative Ranking Using Vector Analysis
Analysis of Life Cycle Impacts Associated with Single Family Homes
Input Contribution Analysis, Pre-Occupancy Phase
January 7, 2013

		Perturbation = +/- 5% of Characterized Impact					
		Within-Impact Change <= 10%		Within-Impact Change <= 20%		Unconstrained Change	
Original Rank	Direct Input (Material/Product/Service)	Rank	Change in Rank	Rank	Change in Rank	Rank	Change in Rank
1	Brick and structural clay tile	1	0	1	0	1	0
2	Ready-mixed concrete	2	0	2	0	2	0
3	Carpets and rugs	3	0	4	-1	3	0
4	Mineral wool	4	0	3	1	4	0
5	Miscellaneous plastics products, n.e.c.	5	0	5	0	5	0
6	Retail trade, except eating and drinking	6	0	6	0	6	0
7	Trucking and courier services, except air	8	-1	7	0	7	0
8	Reconstituted wood products	7	1	8	0	8	0
9	Sand and gravel	9	0	9	0	9	0
10	Motor vehicles and passenger car bodies	10	0	10	0	10	0
11	Sawmills and planing mills, general	11	0	11	0	11	0
12	Dimension, crushed and broken stone	12	0	12	0	12	0
13	Wholesale trade	13	0	13	0	13	0
14	Asphalt paving mixtures and blocks	14	0	14	0	14	0
15	Millwork	15	0	15	0	15	0
16	Paints and allied products	16	0	16	0	16	0
17	Cement, hydraulic	17	0	17	0	17	0
18	Cut stone and stone products	18	0	18	0	18	0
19	Electric services (utilities)	19	0	19	0	19	0
20	Converted paper products, n.e.c.	20	0	20	0	20	0
21	Refrigeration and heating equipment	21	0	21	0	21	0
22	Wood kitchen cabinets	22	0	22	0	22	0
23	Construction machinery and equipment	23	0	23	0	23	0
24	Metal doors, sash, frames, molding, and trim	24	0	24	0	24	0
25	Wood preserving	25	0	25	0	25	0
26	Petroleum refining	26	0	26	0	27	-1
27	Sheet metal work	27	0	27	0	26	1
28	Gypsum products	28	0	28	0	28	0
29	Concrete block and brick	29	0	29	0	29	0
30	Wiring devices	30	0	30	0	30	0

Table C-3
Sensitivity Analysis of the Potential of the Vector Summation to Change the Relative Ranking of Materials, Products or Services (MPS)

	Number of MPS in Sample	
	300 MPS	200 MPS
Top 10 Ranked MPS		
Percent of samples where top 10 remained in Top 10	97%	100%
Percent of cases where top 10 remained in Top 20	100%	100%
Top 20 Ranked MPS		
Percent of cases where top 20 remained in Top 20	97%	90%
Percent of cases where top 20 remained in Top 30	100%	100%
Top 30 Ranked MPS		
Percent of cases where top 30 remained in Top 30	80%	63%
Percent of cases where top 30 remained in Top 40	100%	90%

APPENDIX D – OVERALL RESULTS SUMMARY

Life-Cycle Phase, Locus of Impact	ADP	LUC	GWP	ODP	HTP	FAETP
	kg Sn eq.	m2*yr	kg CO2 eq.	g CFC-11 eq.	kg p-DCB eq.	kg p-DCB eq.
Pre-Occupancy Phase - Indirect	499	11,002	107,889	617	15,925	2,552
Pre-Occupancy Phase - Direct	0	0	33,514	0	112	0
Subtotal, Pre-Occupancy Phase	499	11,002	141,404	617	16,038	2,552
Occupancy Phase - Indirect	4,651	14,199	597,995	1,138	38,712	5,483
Occupancy Phase - Direct	0	10,403	160,787	0	0	0
Subtotal - Occupancy Phase	4,651	24,602	758,782	1,138	38,712	5,483
Post-Occupancy Phase - Indirect	0	0	556	0	0	0
Post-Occupancy Phase - Direct	0	0	45	0	0	0
Subtotal - Post-Occupancy Phase	0	0	601	0	0	0
Total	5,150	35,604	900,786	1,755	54,750	8,035

Life-Cycle Phase, Locus of Impact	MAETP	TETP	FSETP	MSETP	POCD	AP
	mton p-DCB eq.	kg p-DCB eq.	mton p-DCB eq.	kg p-DCB eq.	kg C4H4 eq.	kg SO2 eq.
Pre-Occupancy Phase - Indirect	47,300	3,137	17,124	29,924	63	456
Pre-Occupancy Phase - Direct	0	0	0	0	22	47
Subtotal, Pre-Occupancy Phase	47,300	3,137	17,124	29,924	85	502
Occupancy Phase - Indirect	246,592	6,252	83,748	41,601	253	4,292
Occupancy Phase - Direct	0	0	0	0	0	730
Subtotal - Occupancy Phase	246,592	6,252	83,748	41,601	253	5,022
Post-Occupancy Phase - Indirect	0	0	0	0	0	0
Post-Occupancy Phase - Direct	0	0	0	0	0	0
Subtotal - Post-Occupancy Phase	0	0	0	0	0	0
Total	293,892	9,389	100,872	71,525	338	5,525

Life-Cycle Phase, Locus of Impact	EP	EC	WC	MTL	WST
	kg PO4 eq.	mBTU	103 gal	mton	mton
Pre-Occupancy Phase - Indirect	54	1,084	12,766	1,101	118
Pre-Occupancy Phase - Direct	12	133	38	1,568	0
Subtotal, Pre-Occupancy Phase	66	1,216	12,804	2,669	118
Occupancy Phase - Indirect	247	7,899	248,814	1,006	580
Occupancy Phase - Direct	0	5,885	4,993	43	43
Subtotal - Occupancy Phase	247	13,783	253,808	1,050	623
Post-Occupancy Phase - Indirect	0	0	0	0	0
Post-Occupancy Phase - Direct	0	20	0	0	52
Subtotal - Post-Occupancy Phase	0	20	0	0	52

APPENDIX E – INPUT CONTRIBUTION ANALYSIS RESULTS

Appendix E1 – Pre-Occupancy-Phase Results by Impact Category

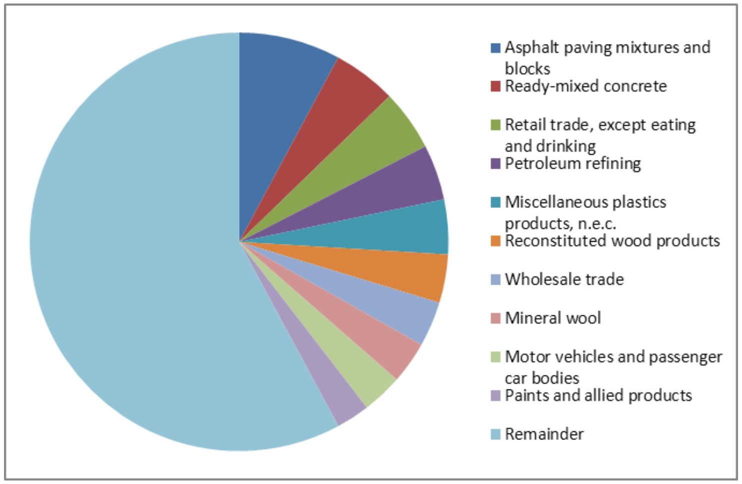
Appendix E2 – Vector Analysis Results, Input Contribution Basis, Pre-Occupancy Phase

Appendix E3 – Occupancy-Phase Results by Impact Category

APPENDIX E1 – PRE-OCCUPANCY-PHASE RESULTS BY IMPACT CATEGORY

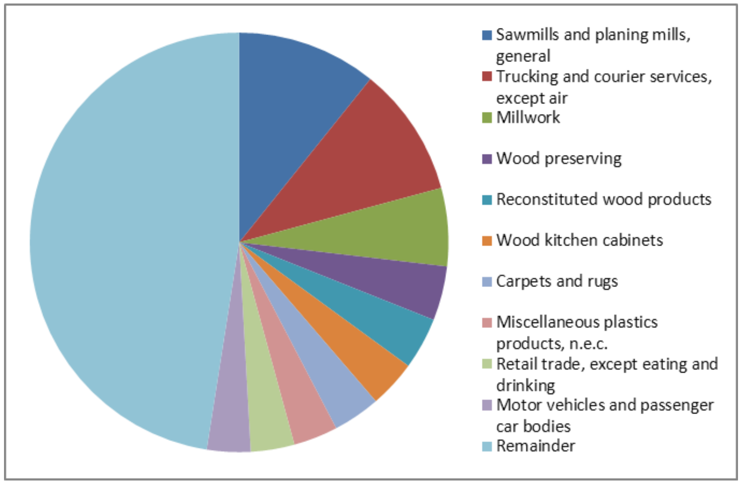
Abiotic Depletion Potential (ADP) – Input Contribution Analysis – Pre-Occupancy Phase

Rank	BEA Material/Product/Service Description	ADP (kg Sn eq.)	Contribution to Life Cycle ADP
1	Asphalt paving mixtures and blocks	39.15	7.85%
2	Ready-mixed concrete	24.46	4.90%
3	Retail trade, except eating and drinking	23.50	4.71%
4	Petroleum refining	21.32	4.28%
5	Miscellaneous plastics products, n.e.c.	21.07	4.22%
6	Reconstituted wood products	18.66	3.74%
7	Wholesale trade	17.34	3.48%
8	Mineral wool	16.22	3.25%
9	Motor vehicles and passenger car bodies	15.59	3.13%
10	Paints and allied products	12.87	2.58%
	Total Accounted for in Top 10 M/P/S	210.19	42.14%
	Total Life Cycle ADP impacts	498.78	100.00%
	Remainder	288.59	57.86%



Land Use Competition (LUC) – Input Contribution Analysis – Pre-Occupancy Phase

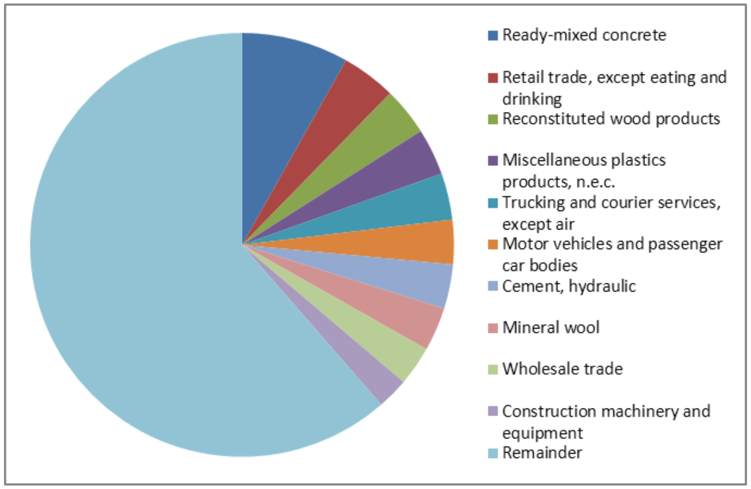
Rank	BEA Material/Product/Service Description	LUC (m2*yr)	Contribution to Life Cycle LUC
1	Sawmills and planing mills, general	1,187.03	10.79%
2	Trucking and courier services, except air	1,103.13	10.03%
3	Millwork	662.08	6.02%
4	Wood preserving	460.64	4.19%
5	Reconstituted wood products	440.08	4.00%
6	Wood kitchen cabinets	402.28	3.66%
7	Carpets and rugs	401.52	3.65%
8	Miscellaneous plastics products, n.e.c.	375.68	3.41%
9	Retail trade, except eating and drinking	371.28	3.37%
10	Motor vehicles and passenger car bodies	370.14	3.36%
	Total Accounted for in Top 10 M/P/S	5,773.87	52.48%
	Total Life Cycle LUC impacts	11,002.07	100.00%
	Remainder	5,228.20	47.52%



APPENDIX E1 (CONTINUED)

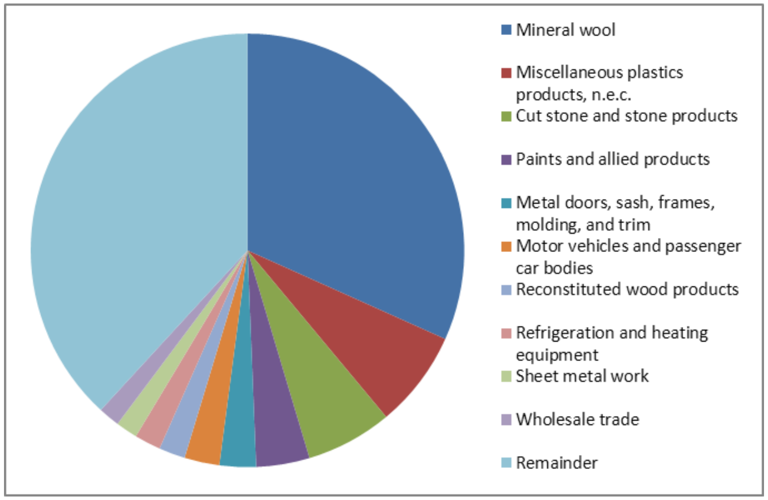
Global Warming Potential (GWP) – Input Contribution Analysis – Pre-Occupancy Phase

Rank	BEA Material/Product/Service Description	GWP (kg CO2 eq.)	Contribution to Life Cycle GWP
1	Ready-mixed concrete	11,549.88	8.17%
2	Retail trade, except eating and drinking	5,864.40	4.15%
3	Reconstituted wood products	5,182.87	3.67%
4	Miscellaneous plastics products, n.e.c.	5,029.22	3.56%
5	Trucking and courier services, except air	5,027.66	3.56%
6	Motor vehicles and passenger car bodies	4,784.99	3.38%
7	Cement, hydraulic	4,783.80	3.38%
8	Mineral wool	4,706.06	3.33%
9	Wholesale trade	4,251.64	3.01%
10	Construction machinery and equipment	3,387.25	2.40%
	Total Accounted for in Top 10 M/P/S	54,567.77	38.59%
	Total Life Cycle GWP impacts	141,403.66	100.00%
	Remainder	86,835.88	61.41%



Stratospheric Ozone Depletion Potential (ODP) – Input Contribution Analysis – Pre-Occupancy Phase

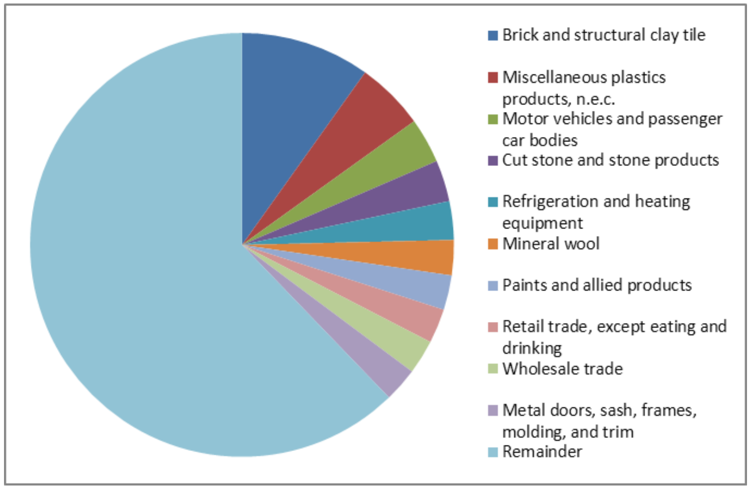
Rank	BEA Material/Product/Service Description	ODP (g CFC-11 eq.)	Contribution to Life Cycle ODP
1	Mineral wool	195.59	31.70%
2	Miscellaneous plastics products, n.e.c.	44.68	7.24%
3	Cut stone and stone products	39.72	6.44%
4	Paints and allied products	24.54	3.98%
5	Metal doors, sash, frames, molding, and trim	16.78	2.72%
6	Motor vehicles and passenger car bodies	16.09	2.61%
7	Reconstituted wood products	12.11	1.96%
8	Refrigeration and heating equipment	12.08	1.96%
9	Sheet metal work	10.03	1.63%
10	Wholesale trade	9.85	1.60%
	Total Accounted for in Top 10 M/P/S	381.48	61.83%
	Total Life Cycle ODP impacts	616.98	100.00%
	Remainder	235.50	38.17%



APPENDIX E1 (CONTINUED)

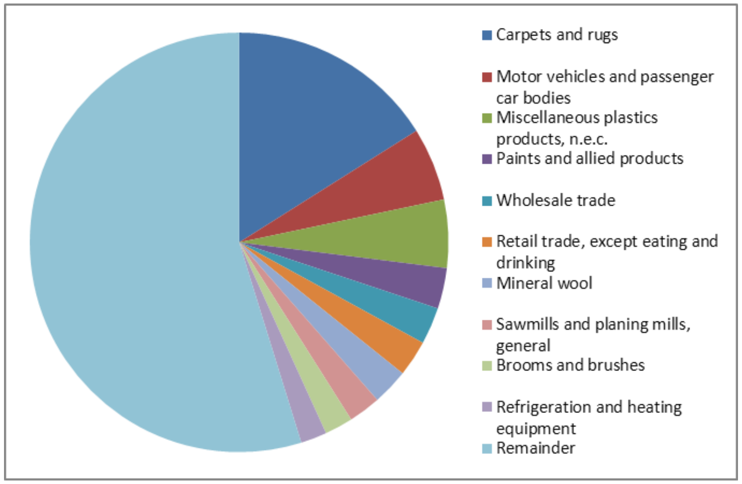
Human Toxicity Potential (HTP) – Input Contribution Analysis – Pre-Occupancy Phase

Rank	BEA Material/Product/Service Description	HTP (kg p-DCB eq.)	Contribution to Life Cycle HTP
1	Brick and structural clay tile	1,582.43	9.87%
2	Miscellaneous plastics products, n.e.c.	836.36	5.22%
3	Motor vehicles and passenger car bodies	552.86	3.45%
4	Cut stone and stone products	505.64	3.15%
5	Refrigeration and heating equipment	472.50	2.95%
6	Mineral wool	429.60	2.68%
7	Paints and allied products	424.00	2.64%
8	Retail trade, except eating and drinking	420.69	2.62%
9	Wholesale trade	419.58	2.62%
10	Metal doors, sash, frames, molding, and trim	418.00	2.61%
	Total Accounted for in Top 10 M/P/S	6,061.68	37.80%
	Total Life Cycle HTP impacts	16,037.52	100.00%
	Remainder	9,975.84	62.20%



Freshwater Aquatic Ecotoxicity Potential (FAETP) – Input Contribution Analysis – Pre-Occupancy Phase

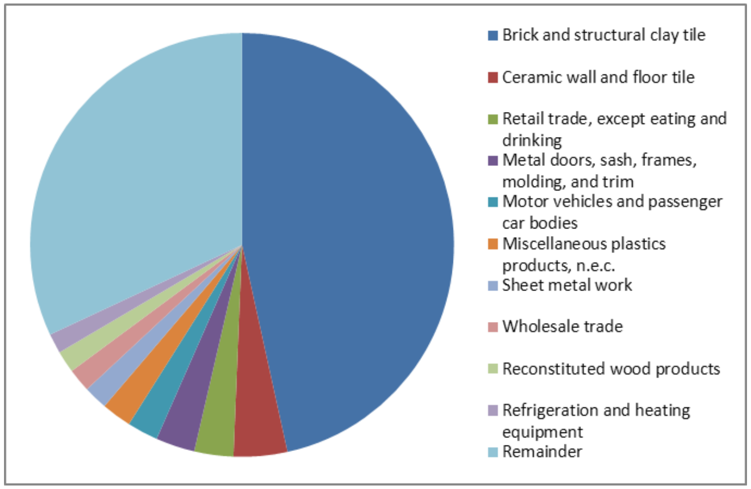
Rank	BEA Material/Product/Service Description	FAETP (kg p-DCB eq.)	Contribution to Life Cycle FAETP
1	Carpets and rugs	410.12	16.07%
2	Motor vehicles and passenger car bodies	144.03	5.64%
3	Miscellaneous plastics products, n.e.c.	133.92	5.25%
4	Paints and allied products	80.12	3.14%
5	Wholesale trade	72.61	2.85%
6	Retail trade, except eating and drinking	71.22	2.79%
7	Mineral wool	71.12	2.79%
8	Sawmills and planing mills, general	63.52	2.49%
9	Brooms and brushes	55.44	2.17%
10	Refrigeration and heating equipment	51.40	2.01%
	Total Accounted for in Top 10 M/P/S	1,153.50	45.20%
	Total Life Cycle FAETP impacts	2,552.07	100.00%
	Remainder	1,398.58	54.80%



APPENDIX E1 (CONTINUED)

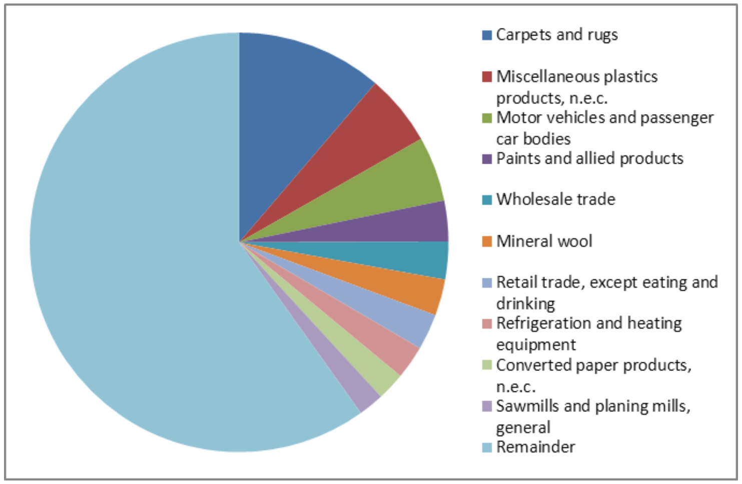
Marine Aquatic Ecotoxicity Potential (MAETP) – Input Contribution Analysis – Pre-Occupancy Phase

Rank	BEA Material/Product/Service Description	MAETP (mton p-DCB eq.)	Contribution to Life Cycle MAETP
1	Brick and structural clay tile	22,021.73	46.56%
2	Ceramic wall and floor tile	1,933.73	4.09%
3	Retail trade, except eating and drinking	1,410.17	2.98%
4	Metal doors, sash, frames, molding, and trim	1,409.93	2.98%
5	Motor vehicles and passenger car bodies	1,113.36	2.35%
6	Miscellaneous plastics products, n.e.c.	1,082.99	2.29%
7	Sheet metal work	861.55	1.82%
8	Wholesale trade	844.24	1.78%
9	Reconstituted wood products	791.14	1.67%
10	Refrigeration and heating equipment	715.49	1.51%
	Total Accounted for in Top 10 M/P/S	32,184.32	68.04%
	Total Life Cycle MAETP impacts	47,300.18	100.00%
	Remainder	15,115.86	31.96%



Terrestrial Ecotoxicity Potential (TETP) – Input Contribution Analysis – Pre-Occupancy Phase

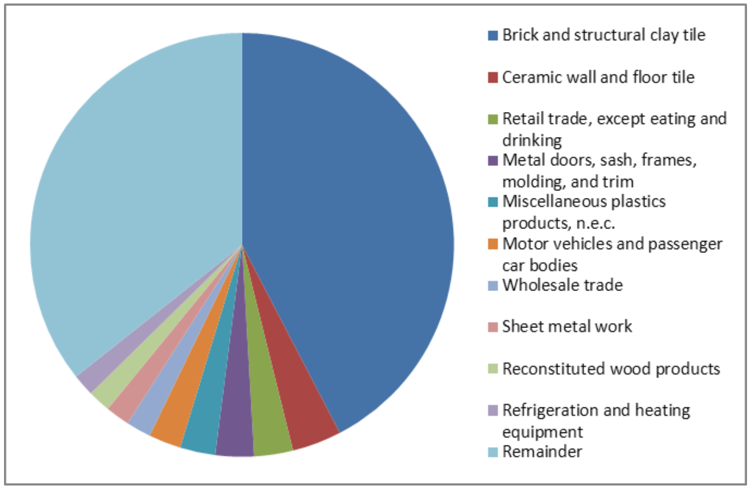
Rank	BEA Material/Product/Service Description	TETP (kg p-DCB eq.)	Contribution to Life Cycle TETP
1	Carpets and rugs	353.90	11.28%
2	Miscellaneous plastics products, n.e.c.	172.56	5.50%
3	Motor vehicles and passenger car bodies	157.09	5.01%
4	Paints and allied products	98.46	3.14%
5	Wholesale trade	91.26	2.91%
6	Mineral wool	87.95	2.80%
7	Retail trade, except eating and drinking	86.94	2.77%
8	Refrigeration and heating equipment	80.79	2.58%
9	Converted paper products, n.e.c.	67.79	2.16%
10	Sawmills and planing mills, general	61.76	1.97%
	Total Accounted for in Top 10 M/P/S	1,258.50	40.12%
	Total Life Cycle TETP impacts	3,136.84	100.00%
	Remainder	1,878.35	59.88%



APPENDIX E1 (CONTINUED)

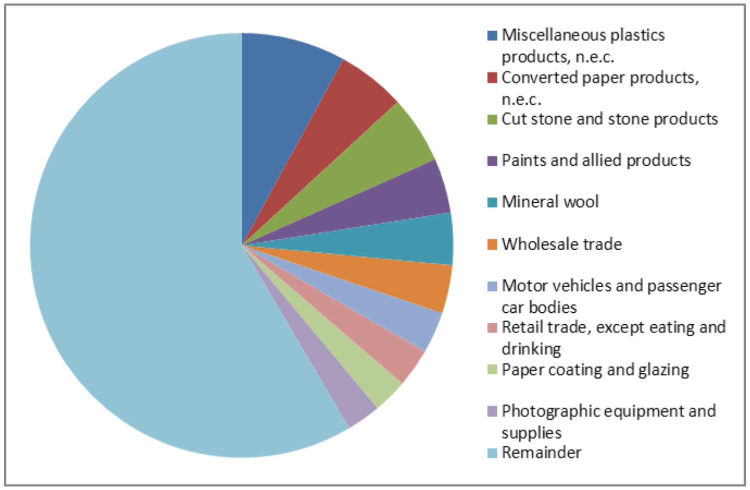
Freshwater Sediment Ecotoxicity Potential (FSETP) – Input Contribution Analysis – Pre-Occupancy Phase

Rank	BEA Material/Product/Service Description	FSETP (mton p-DCB eq.)	Contribution to Life Cycle FSETP
1	Brick and structural clay tile	7,254.15	42.36%
2	Ceramic wall and floor tile	644.28	3.76%
3	Retail trade, except eating and drinking	508.04	2.97%
4	Metal doors, sash, frames, molding, and trim	502.87	2.94%
5	Miscellaneous plastics products, n.e.c.	460.30	2.69%
6	Motor vehicles and passenger car bodies	422.08	2.46%
7	Wholesale trade	325.52	1.90%
8	Sheet metal work	315.45	1.84%
9	Reconstituted wood products	295.48	1.73%
10	Refrigeration and heating equipment	287.04	1.68%
	Total Accounted for in Top 10 M/P/S	11,015.21	64.33%
	Total Life Cycle FSETP impacts	17,124.15	100.00%
	Remainder	6,108.94	35.67%



Marine Sediment Ecotoxicity Potential (MSETP) – Input Contribution Analysis – Pre-Occupancy Phase

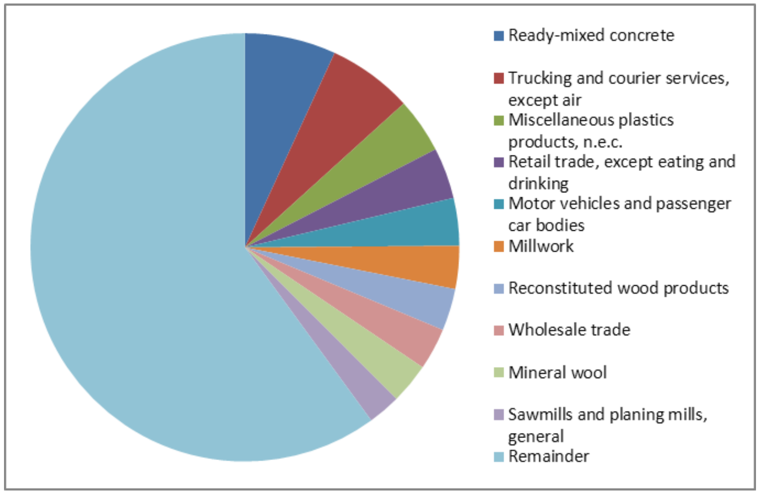
Rank	BEA Material/Product/Service Description	MSETP (kg p-DCB eq.)	Contribution to Life Cycle MSETP
1	Miscellaneous plastics products, n.e.c.	2,388.02	7.98%
2	Converted paper products, n.e.c.	1,561.77	5.22%
3	Cut stone and stone products	1,542.86	5.16%
4	Paints and allied products	1,246.47	4.17%
5	Mineral wool	1,189.26	3.97%
6	Wholesale trade	1,101.21	3.68%
7	Motor vehicles and passenger car bodies	947.63	3.17%
8	Retail trade, except eating and drinking	883.55	2.95%
9	Paper coating and glazing	782.29	2.61%
10	Photographic equipment and supplies	777.77	2.60%
	Total Accounted for in Top 10 M/P/S	12,420.83	41.51%
	Total Life Cycle MSETP impacts	29,923.75	100.00%
	Remainder	17,502.92	58.49%



APPENDIX E1 (CONTINUED)

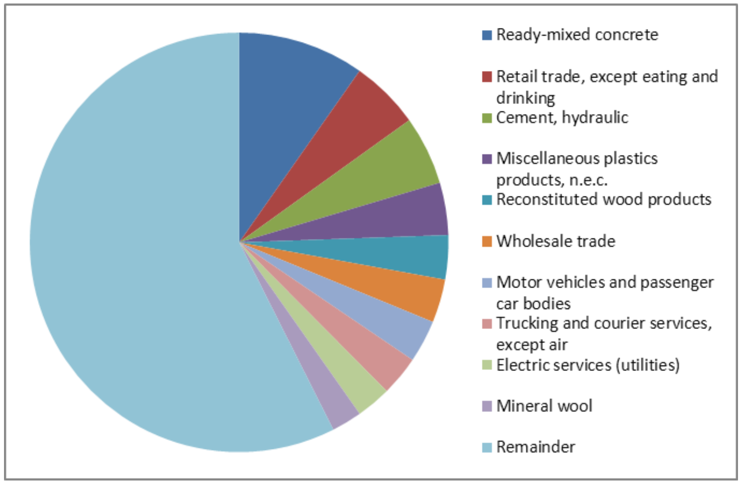
Photochemical Ozone Creation Potential (POCP) – Input Contribution Analysis – Pre-Occupancy Phase

Rank	BEA Material/Product/Service Description	POCP (kg C4H4 eq.)	Contribution to Life Cycle POCP
1	Ready-mixed concrete	5.84	6.87%
2	Trucking and courier services, except air	5.44	6.40%
3	Miscellaneous plastics products, n.e.c.	3.53	4.15%
4	Retail trade, except eating and drinking	3.28	3.86%
5	Motor vehicles and passenger car bodies	3.05	3.59%
6	Millwork	2.76	3.25%
7	Reconstituted wood products	2.69	3.17%
8	Wholesale trade	2.69	3.16%
9	Mineral wool	2.59	3.05%
10	Sawmills and planing mills, general	2.09	2.46%
	Total Accounted for in Top 10 M/P/S	33.96	39.97%
	Total Life Cycle POCP impacts	84.96	100.00%
	Remainder	51.00	60.03%



Acidification Potential (AP) – Input Contribution Analysis – Pre-Occupancy Phase

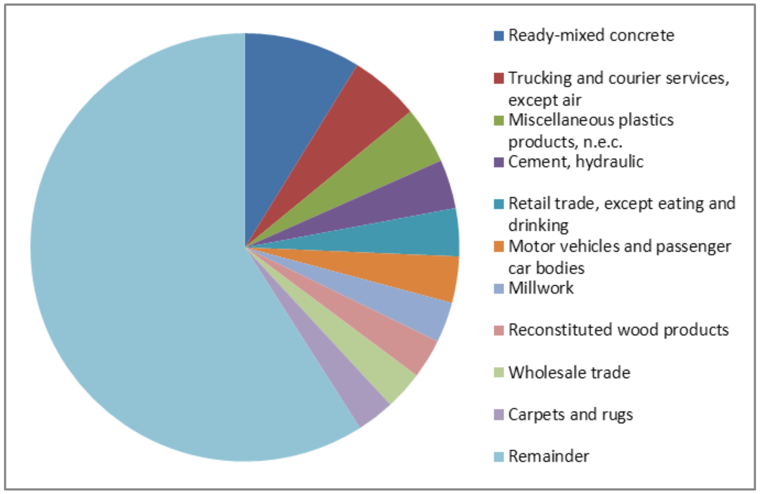
Rank	BEA Material/Product/Service Description	AP (kg SO2 eq.)	Contribution to Life Cycle AP
1	Ready-mixed concrete	49.01	9.76%
2	Retail trade, except eating and drinking	26.84	5.34%
3	Cement, hydraulic	26.68	5.31%
4	Miscellaneous plastics products, n.e.c.	20.26	4.03%
5	Reconstituted wood products	17.09	3.40%
6	Wholesale trade	16.81	3.35%
7	Motor vehicles and passenger car bodies	16.46	3.28%
8	Trucking and courier services, except air	15.45	3.08%
9	Electric services (utilities)	13.48	2.68%
10	Mineral wool	11.77	2.34%
	Total Accounted for in Top 10 M/P/S	213.85	42.57%
	Total Life Cycle AP impacts	502.36	100.00%
	Remainder	288.50	57.43%



APPENDIX E1 (CONTINUED)

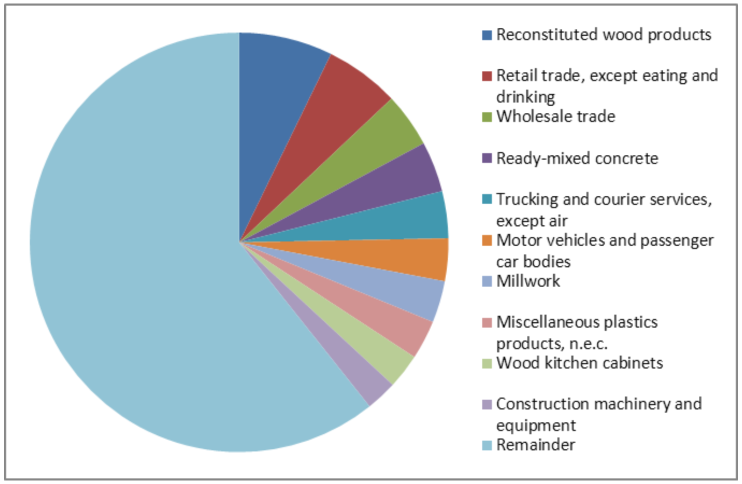
Eutrophication Potential (EP) – Input Contribution Analysis – Pre-Occupancy Phase

Rank	BEA Material/Product/Service Description	EP (kg PO4 eq.)	Contribution to Life Cycle EP
1	Ready-mixed concrete	5.81	8.78%
2	Trucking and courier services, except air	3.50	5.28%
3	Miscellaneous plastics products, n.e.c.	2.85	4.30%
4	Cement, hydraulic	2.45	3.70%
5	Retail trade, except eating and drinking	2.40	3.62%
6	Motor vehicles and passenger car bodies	2.32	3.50%
7	Millwork	2.02	3.05%
8	Reconstituted wood products	1.98	2.99%
9	Wholesale trade	1.93	2.92%
10	Carpets and rugs	1.88	2.85%
	Total Accounted for in Top 10 M/P/S	27.14	40.98%
	Total Life Cycle EP impacts	66.22	100.00%
	Remainder	39.09	59.02%



Energy Consumption (EC) – Input Contribution Analysis – Pre-Occupancy Phase

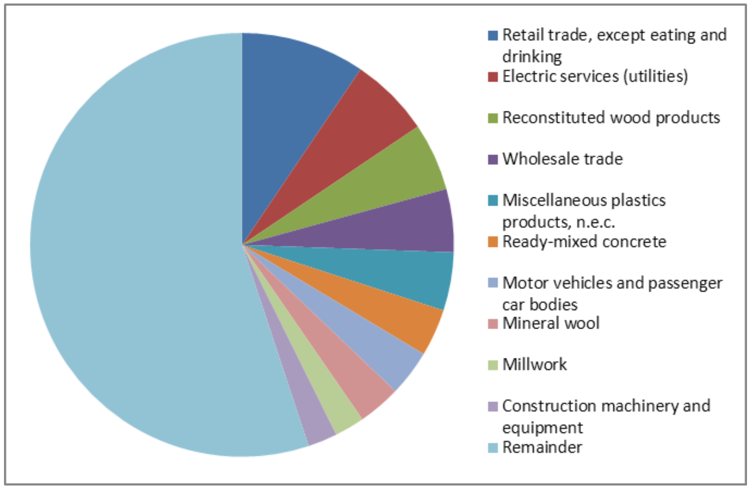
Rank	BEA Material/Product/Service Description	EC (mBTU)	Contribution to Life Cycle EC
1	Reconstituted wood products	87.99	7.24%
2	Retail trade, except eating and drinking	69.86	5.74%
3	Wholesale trade	50.94	4.19%
4	Ready-mixed concrete	47.48	3.90%
5	Trucking and courier services, except air	43.99	3.62%
6	Motor vehicles and passenger car bodies	39.94	3.28%
7	Millwork	39.13	3.22%
8	Miscellaneous plastics products, n.e.c.	36.67	3.02%
9	Wood kitchen cabinets	32.59	2.68%
10	Construction machinery and equipment	29.29	2.41%
	Total Accounted for in Top 10 M/P/S	477.90	39.29%
	Total Life Cycle EC impacts	1,216.21	100.00%
	Remainder	738.31	60.71%



APPENDIX E1 (CONTINUED)

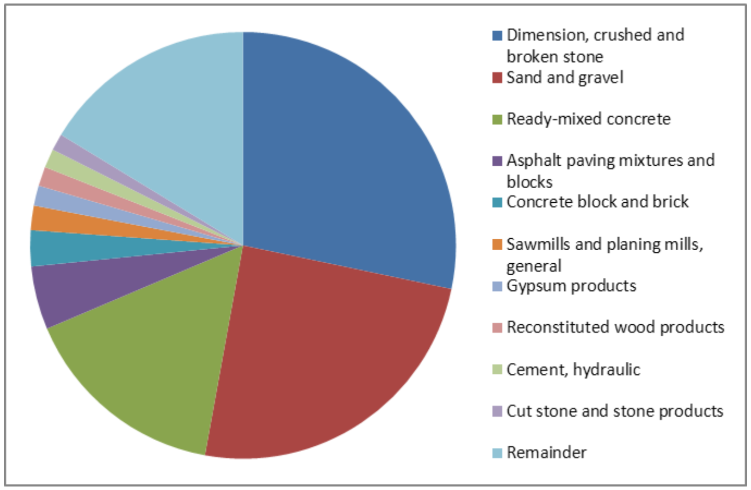
Water Consumption (WC) – Input Contribution Analysis – Pre-Occupancy Phase

Rank	BEA Material/Product/Service Description	WC (10^3 gal)	Contribution to Life Cycle WC
1	Retail trade, except eating and drinking	1,210.07	9.45%
2	Electric services (utilities)	784.47	6.13%
3	Reconstituted wood products	662.20	5.17%
4	Wholesale trade	616.75	4.82%
5	Miscellaneous plastics products, n.e.c.	568.87	4.44%
6	Ready-mixed concrete	461.51	3.60%
7	Motor vehicles and passenger car bodies	450.08	3.52%
8	Mineral wool	417.25	3.26%
9	Millwork	291.45	2.28%
10	Construction machinery and equipment	287.76	2.25%
	Total Accounted for in Top 10 M/P/S	5,750.41	44.91%
	Total Life Cycle WC impacts	12,804.20	100.00%
	Remainder	7,053.79	55.09%



Material Input (MTL) – Input Contribution Analysis – Pre-Occupancy Phase

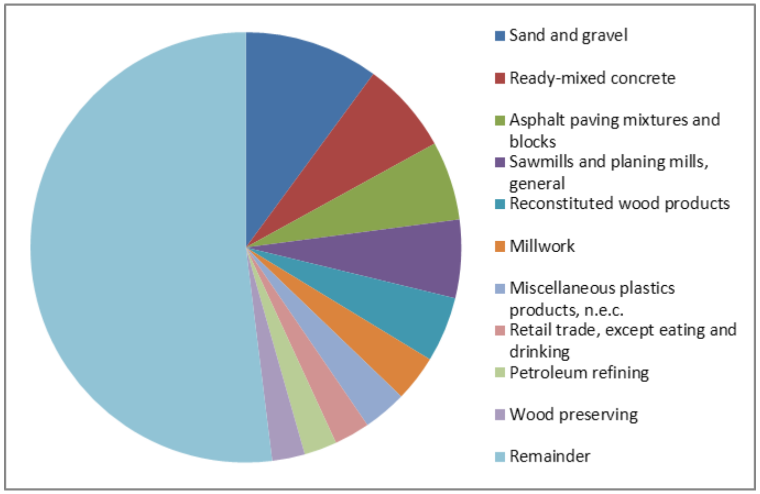
Rank	BEA Material/Product/Service Description	MTL (mton)	Contribution to Life Cycle MTL
1	Dimension, crushed and broken stone	754.64	28.28%
2	Sand and gravel	656.15	24.59%
3	Ready-mixed concrete	420.45	15.76%
4	Asphalt paving mixtures and blocks	127.94	4.79%
5	Concrete block and brick	72.88	2.73%
6	Sawmills and planing mills, general	49.37	1.85%
7	Gypsum products	40.79	1.53%
8	Reconstituted wood products	39.06	1.46%
9	Cement, hydraulic	37.98	1.42%
10	Cut stone and stone products	33.88	1.27%
	Total Accounted for in Top 10 M/P/S	2,233.14	83.68%
	Total Life Cycle MTL impacts	2,668.70	100.00%
	Remainder	435.55	16.32%



APPENDIX E1 (CONTINUED)

Waste (WST) – Input Contribution Analysis – Pre-Occupancy Phase

Rank	BEA Material/Product/Service Description	WST (mton)	Contribution to Life Cycle WST
1	Sand and gravel	11.88	10.07%
2	Ready-mixed concrete	8.15	6.91%
3	Asphalt paving mixtures and blocks	7.00	5.94%
4	Sawmills and planing mills, general	6.94	5.88%
5	Reconstituted wood products	5.79	4.91%
6	Millwork	4.09	3.47%
7	Miscellaneous plastics products, n.e.c.	3.86	3.28%
8	Retail trade, except eating and drinking	3.15	2.67%
9	Petroleum refining	2.90	2.46%
10	Wood preserving	2.90	2.46%
	Total Accounted for in Top 10 M/P/S	56.68	48.05%
	Total Life Cycle WST impacts	117.95	100.00%
	Remainder	61.28	51.95%



APPENDIX E2 –VECTOR ANALYSIS RESULTS, INPUT CONTRIBUTION BASIS, PRE-OCCUPANCY PHASE

<u>All Impacts</u>

		Number of Standard Deviations from the Mean																	
Rank	Description	ADP	LUC	GWP	ODP	HTP	FAETP	MAETP	TETP	FSETP	MSETP	POCP	AP	EP	EC	WC	MTL	WST	Vector Magnitude
1	Brick and structural clay tile	0.69	-0.18	0.60	-0.12	9.30	-0.17	14.02	-0.23	13.97	-0.28	0.09	-0.01	0.02	0.18	0.09	-0.12	0.21	21.89
2	Ready-mixed concrete	4.36	1.10	7.96	0.39	1.60	0.57	0.23	0.79	0.26	1.19	6.54	8.62	8.09	3.52	2.83	5.35	5.36	18.68
3	Carpets and rugs	0.06	2.41	0.04	0.11	0.40	11.61	-0.02	9.93	0.01	0.61	0.00	0.05	2.30	-0.07	0.16	-0.14	0.01	15.65
4	Mineral wool	2.73	0.99	2.94	13.30	2.17	1.71	0.24	2.13	0.32	3.45	2.62	1.72	1.86	1.97	2.52	0.04	1.45	15.62
5	Miscellaneous plastics products, n.e.c.	3.68	2.23	3.18	2.88	4.69	3.54	0.55	4.61	0.73	7.41	3.75	3.30	3.72	2.61	3.60	0.05	2.32	14.57
6	Retail trade, except eating and drinking	4.17	2.20	3.79	0.40	2.12	1.71	0.76	2.10	0.83	2.43	3.45	4.51	3.05	5.42	8.16	0.14	1.82	14.02
7	Trucking and courier services, except air	2.05	7.27	3.18	0.04	0.40	0.50	0.05	0.57	0.07	0.32	6.06	2.41	4.67	3.23	0.94	-0.07	0.86	12.01
8	Reconstituted wood products	3.21	2.67	3.29	0.63	1.50	1.01	0.36	1.30	0.41	1.99	2.75	2.71	2.43	6.96	4.26	0.34	3.69	11.79
9	Sand and gravel	0.40	-0.26	0.37	-0.16	-0.09	-0.27	-0.06	-0.33	-0.07	-0.36	-0.08	0.09	-0.10	0.59	0.56	8.45	8.00	11.69
10	Motor vehicles and passenger car bodies	2.60	2.19	3.00	0.90	2.93	3.84	0.57	4.16	0.66	2.65	3.17	2.59	2.94	2.88	2.75	0.02	1.31	10.62

		Factor Influence (change in vector orientation, in degrees)																
Rank	Description	ADP	LUC	GWP	ODP	HTP	FAETP	MAETP	TETP	FSETP	MSETP	POCP	AP	EP	EC	WC	MTL	WST
1	Brick and structural clay tile	2	0	2	0	25	0	40	-1	40	-1	0	0	0	0	0	0	1
2	Ready-mixed concrete	13	3	25	1	5	2	1	2	1	4	20	27	26	11	9	17	17
3	Carpets and rugs	0	9	0	0	1	48	0	39	0	2	0	0	8	0	1	-1	0
4	Mineral wool	10	4	11	58	8	6	1	8	1	13	10	6	7	7	9	0	5
5	Miscellaneous plastics products, n.e.c.	15	9	13	11	19	14	2	18	3	31	15	13	15	10	14	0	9
6	Retail trade, except eating and drinking	17	9	16	2	9	7	3	9	3	10	14	19	13	23	36	1	7
7	Trucking and courier services, except air	10	37	15	0	2	2	0	3	0	2	30	12	23	16	4	0	4
8	Reconstituted wood products	16	13	16	3	7	5	2	6	2	10	13	13	12	36	21	2	18
9	Sand and gravel	2	-1	2	-1	0	-1	0	-2	0	-2	0	0	0	3	3	46	43
10	Motor vehicles and passenger car bodies	14	12	16	5	16	21	3	23	4	14	17	14	16	16	15	0	7

APPENDIX E2 (CONTINUED)

Natural Resources and Land Use Impact Grouping

		Number of Standard Deviations from the Mean							Factor Influence (change in vector orientation, in degrees)					
Rank	Description	ADP	LUC	EC	WC	MTL	WST	Vector Magnitude	ADP	LUC	EC	WC	MTL	WST
1	Sand and gravel	0.40	-0.26	0.59	0.56	8.45	8.00	11.67	2	-1	3	3	46	43
2	Retail trade, except eating and drinking	4.17	2.20	5.42	8.16	0.14	1.82	11.02	22	12	29	48	1	10
3	Dimension, crushed and broken stone	0.92	-0.15	1.10	0.97	9.74	0.41	9.90	5	-1	6	6	80	2
4	Ready-mixed concrete	4.36	1.10	3.52	2.83	5.35	5.36	9.90	26	6	21	17	33	33
5	Reconstituted wood products	3.21	2.67	6.96	4.26	0.34	3.69	9.89	19	16	45	26	2	22
6	Sawmills and planing mills, general	0.72	7.85	1.97	1.16	0.48	4.50	9.37	4	57	12	7	3	29
7	Asphalt paving mixtures and blocks	7.26	0.06	1.22	0.84	1.51	4.55	8.82	55	0	8	5	10	31
8	Trucking and courier services, except air	2.05	7.27	3.23	0.94	-0.07	0.86	8.31	14	61	23	6	0	6
9	Wholesale trade	2.95	1.94	3.82	3.94	0.04	1.33	6.65	26	17	35	36	0	12
10	Miscellaneous plastics products, n.e.c.	3.68	2.23	2.61	3.60	0.05	2.32	6.61	34	20	23	33	0	21

Toxicity Impact Grouping

		Number of Standard Deviations from the Mean							Factor Influence (change in vector orientation, in degrees)					
Rank	Description	HTP	FAETP	MAETP	TETP	FSETP	MSETP	Vector Magnitude	HTP	FAETP	MAETP	TETP	FSETP	MSETP
1	Brick and structural clay tile	9.30	-0.17	14.02	-0.23	13.97	-0.28	21.87	25	0	40	-1	40	-1
2	Carpets and rugs	0.40	11.61	-0.02	9.93	0.01	0.61	15.29	1	49	0	40	0	2
3	Miscellaneous plastics products, n.e.c.	4.69	3.54	0.55	4.61	0.73	7.41	10.56	26	20	3	26	4	45
4	Motor vehicles and passenger car bodies	2.93	3.84	0.57	4.16	0.66	2.65	6.96	25	34	5	37	5	22
5	Cut stone and stone products	2.64	0.48	-0.02	1.22	0.07	4.61	5.48	29	5	0	13	1	57
6	Converted paper products, n.e.c.	2.00	0.77	0.04	1.54	0.13	4.68	5.37	22	8	0	17	1	61
7	Paints and allied products	2.14	1.97	0.16	2.44	0.25	3.63	5.26	24	22	2	28	3	44
8	Mineral wool	2.17	1.71	0.24	2.13	0.32	3.45	4.92	26	20	3	26	4	44
9	Wholesale trade	2.11	1.75	0.39	2.23	0.47	3.15	4.78	26	22	5	28	6	41
10	Retail trade, except eating and drinking	2.12	1.71	0.76	2.10	0.83	2.43	4.36	29	23	10	29	11	34

Appendix E2 (Continued)

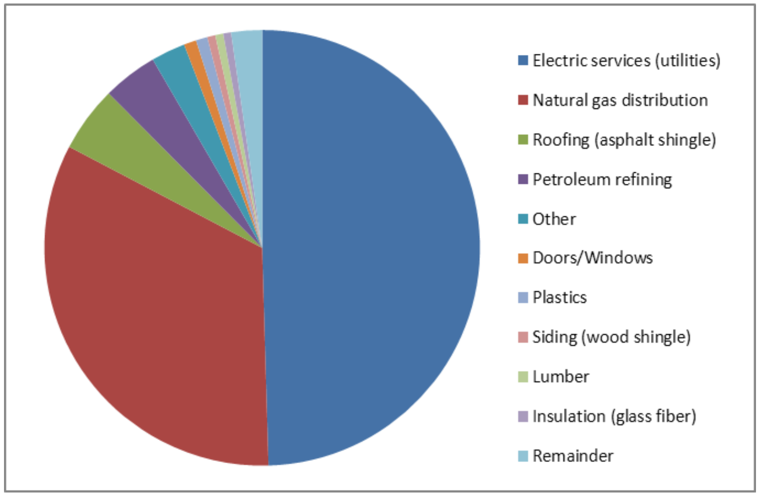
Pollution Impacts Grouping

		Number of Standard Deviations from the Mean						Factor Influence (change in vector orientation, in degrees)				
Rank	Description	GWP	ODP	POCP	AP	EP	Vector Magnitude	GWP	ODP	POCP	AP	EP
1	Ready-mixed concrete	7.96	0.39	6.54	8.62	8.09	15.69	30	1	25	33	31
2	Mineral wool	2.94	13.30	2.62	1.72	1.86	14.10	12	71	11	7	8
3	Trucking and courier services, except air	3.18	0.04	6.06	2.41	4.67	8.63	22	0	45	16	33
4	Miscellaneous plastics products, n.e.c.	3.18	2.88	3.75	3.30	3.72	7.56	25	22	30	26	29
5	Retail trade, except eating and drinking	3.79	0.40	3.45	4.51	3.05	7.49	30	3	27	37	24
6	Cement, hydraulic	3.00	-0.15	1.80	4.48	3.13	6.49	28	-1	16	44	29
7	Motor vehicles and passenger car bodies	3.00	0.90	3.17	2.59	2.94	5.94	30	9	32	26	30
8	Reconstituted wood products	3.29	0.63	2.75	2.71	2.43	5.66	36	6	29	29	25
9	Wholesale trade	2.61	0.47	2.74	2.66	2.37	5.21	30	5	32	31	27
10	Millwork	1.78	0.11	2.83	1.60	2.50	4.47	24	1	39	21	34

Appendix E3 – Occupancy-Phase Results by Impact Category

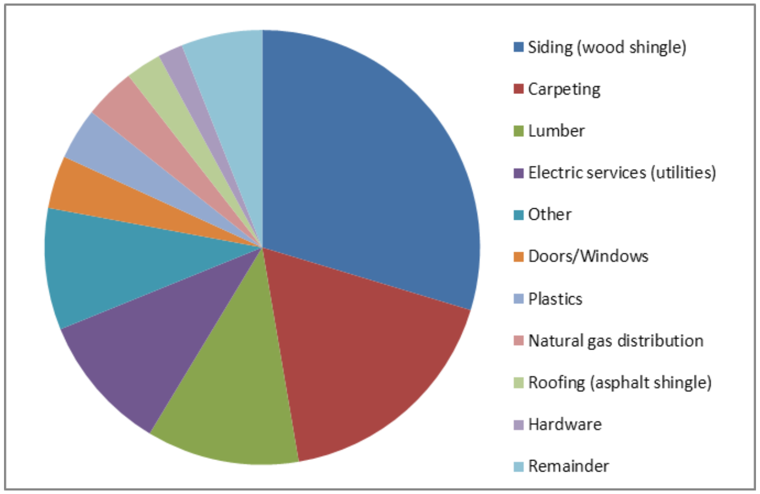
Abiotic Depletion Potential (ADP) – Input Contribution Analysis – Occupancy Phase

Rank	BEA Material/Product/Service Description	ADP (kg Sn eq.)	Contribution to Life Cycle ADP
1	Electric services (utilities)	2,304.47	49.54%
2	Natural gas distribution	1,540.98	33.13%
3	Roofing (asphalt shingle)	226.84	4.88%
4	Petroleum refining	189.29	4.07%
5	Other	118.23	2.54%
6	Doors/Windows	42.74	0.92%
7	Plastics	39.80	0.86%
8	Siding (wood shingle)	28.18	0.61%
9	Lumber	27.37	0.59%
10	Insulation (glass fiber)	27.13	0.58%
	Total Accounted for in Top 10 M/P/S	4,545.05	97.71%
	Total Life Cycle ADP impacts	4,651.36	100.00%
	Remainder	106.32	2.29%



Land Use Competition (LUC) – Input Contribution Analysis – Occupancy Phase

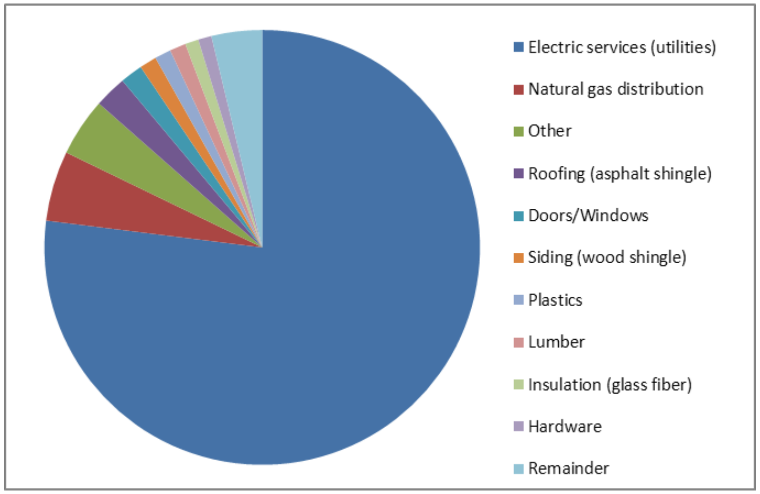
Rank	BEA Material/Product/Service Description	LUC (m2*yr)	Contribution to Life Cycle LUC
1	Siding (wood shingle)	7,297.21	29.66%
2	Carpeting	4,342.91	17.65%
3	Lumber	2,786.35	11.33%
4	Electric services (utilities)	2,513.70	10.22%
5	Other	2,227.95	9.06%
6	Doors/Windows	965.74	3.93%
7	Plastics	945.79	3.84%
8	Natural gas distribution	934.61	3.80%
9	Roofing (asphalt shingle)	648.91	2.64%
10	Hardware	458.06	1.86%
	Total Accounted for in Top 10 M/P/S	23,121.23	93.98%
	Total Life Cycle LUC impacts	24,601.79	100.00%
	Remainder	1,480.57	6.02%



APPENDIX E3 (CONTINUED)

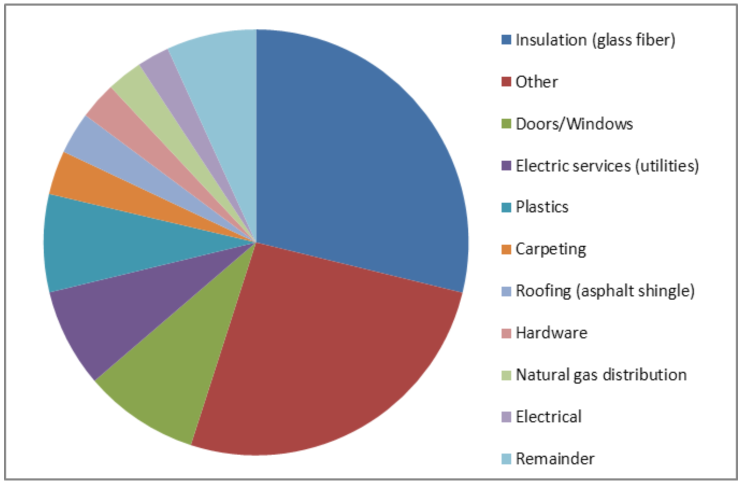
Global Warming Potential (GWP) – Input Contribution Analysis – Occupancy Phase

Rank	BEA Material/Product/Service Description	GWP (kg CO2 eq.)	Contribution to Life Cycle GWP
1	Electric services (utilities)	584,041.14	76.97%
2	Natural gas distribution	39,560.78	5.21%
3	Other	32,850.79	4.33%
4	Roofing (asphalt shingle)	18,175.33	2.40%
5	Doors/Windows	12,647.94	1.67%
6	Siding (wood shingle)	9,648.96	1.27%
7	Plastics	9,156.41	1.21%
8	Lumber	9,138.04	1.20%
9	Insulation (glass fiber)	7,586.78	1.00%
10	Hardware	7,501.54	0.99%
	Total Accounted for in Top 10 M/P/S	730,307.71	96.25%
	Total Life Cycle GWP impacts	758,781.76	100.00%
	Remainder	28,474.05	3.75%



Stratospheric Ozone Depletion Potential (ODP) – Input Contribution Analysis – Occupancy Phase

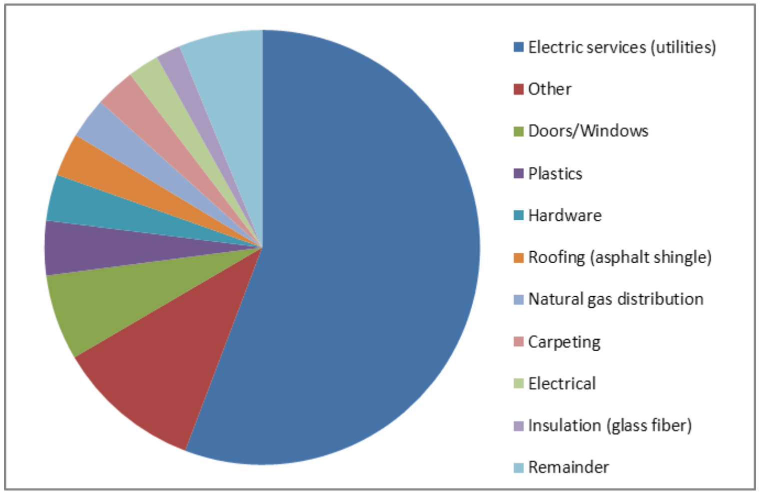
Rank	BEA Material/Product/Service Description	ODP (g CFC-11 eq.)	Contribution to Life Cycle ODP
1	Insulation (glass fiber)	327.77	28.80%
2	Other	297.77	26.16%
3	Doors/Windows	99.77	8.77%
4	Electric services (utilities)	85.30	7.49%
5	Plastics	84.57	7.43%
6	Carpeting	38.00	3.34%
7	Roofing (asphalt shingle)	36.19	3.18%
8	Hardware	32.41	2.85%
9	Natural gas distribution	30.79	2.71%
10	Electrical	27.87	2.45%
	Total Accounted for in Top 10 M/P/S	1,060.43	93.18%
	Total Life Cycle ODP impacts	1,138.08	100.00%
	Remainder	77.65	6.82%



APPENDIX E3 (CONTINUED)

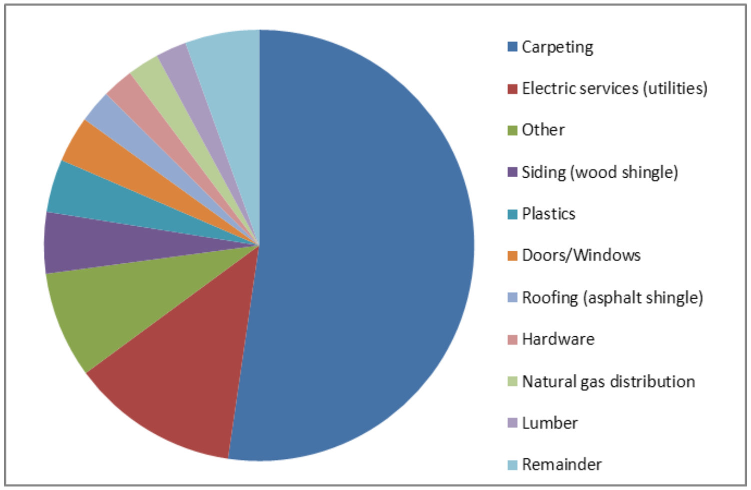
Human Toxicity Potential (HTP) – Input Contribution Analysis – Occupancy Phase

Rank	BEA Material/Product/Service Description	HTP (kg p-DCB eq.)	Contribution to Life Cycle HTP
1	Electric services (utilities)	21,585.86	55.76%
2	Other	4,181.72	10.80%
3	Doors/Windows	2,464.33	6.37%
4	Plastics	1,569.51	4.05%
5	Hardware	1,335.01	3.45%
6	Roofing (asphalt shingle)	1,243.25	3.21%
7	Natural gas distribution	1,172.09	3.03%
8	Carpeting	1,149.87	2.97%
9	Electrical	895.98	2.31%
10	Insulation (glass fiber)	713.86	1.84%
	Total Accounted for in Top 10 M/P/S	36,311.48	93.80%
	Total Life Cycle HTP impacts	38,712.02	100.00%
	Remainder	2,400.54	6.20%



Freshwater Aquatic Ecotoxicity Potential (FAETP) – Input Contribution Analysis – Occupancy Phase

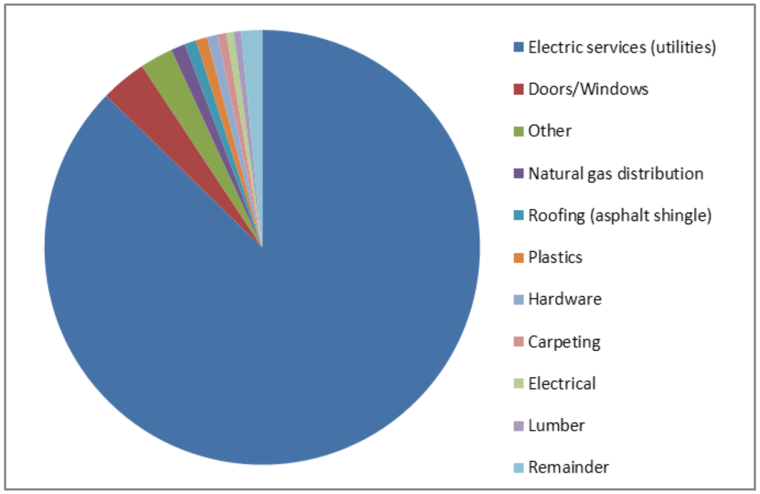
Rank	BEA Material/Product/Service Description	FAETP (kg p-DCB eq.)	Contribution to Life Cycle FAETP
1	Carpeting	2,868.24	52.31%
2	Electric services (utilities)	690.79	12.60%
3	Other	437.48	7.98%
4	Siding (wood shingle)	252.50	4.61%
5	Plastics	217.99	3.98%
6	Doors/Windows	189.95	3.46%
7	Roofing (asphalt shingle)	135.32	2.47%
8	Hardware	129.09	2.35%
9	Natural gas distribution	128.90	2.35%
10	Lumber	127.59	2.33%
	Total Accounted for in Top 10 M/P/S	5,177.87	94.44%
	Total Life Cycle FAETP impacts	5,482.93	100.00%
	Remainder	305.07	5.56%



APPENDIX E3 (CONTINUED)

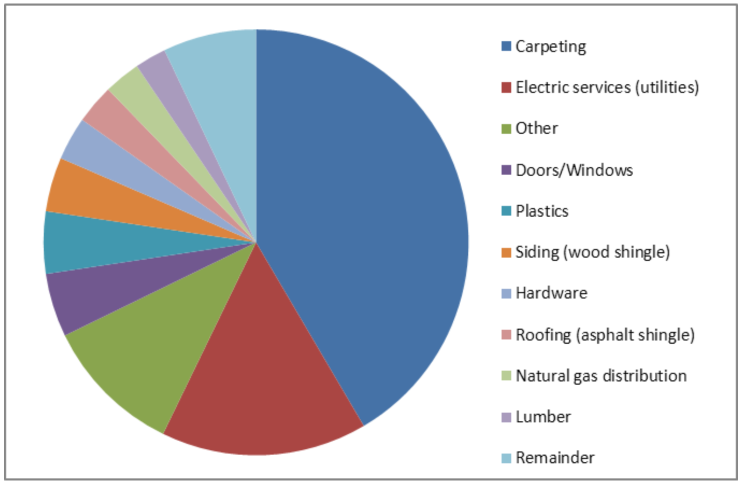
Marine Aquatic Ecotoxicity Potential (MAETP) – Input Contribution Analysis – Occupancy Phase

Rank	BEA Material/Product/Service Description	MAETP (mton p-DCB eq.)	Contribution to Life Cycle MAETP
1	Electric services (utilities)	215,239.91	87.29%
2	Doors/Windows	8,393.52	3.40%
3	Other	6,073.57	2.46%
4	Natural gas distribution	2,602.51	1.06%
5	Roofing (asphalt shingle)	2,162.07	0.88%
6	Plastics	2,052.19	0.83%
7	Hardware	1,919.52	0.78%
8	Carpeting	1,636.52	0.66%
9	Electrical	1,351.70	0.55%
10	Lumber	1,303.13	0.53%
	Total Accounted for in Top 10 M/P/S	242,734.65	98.44%
	Total Life Cycle MAETP impacts	246,592.22	100.00%
	Remainder	3,857.56	1.56%



Terrestrial Ecotoxicity Potential (TETP) – Input Contribution Analysis – Occupancy Phase

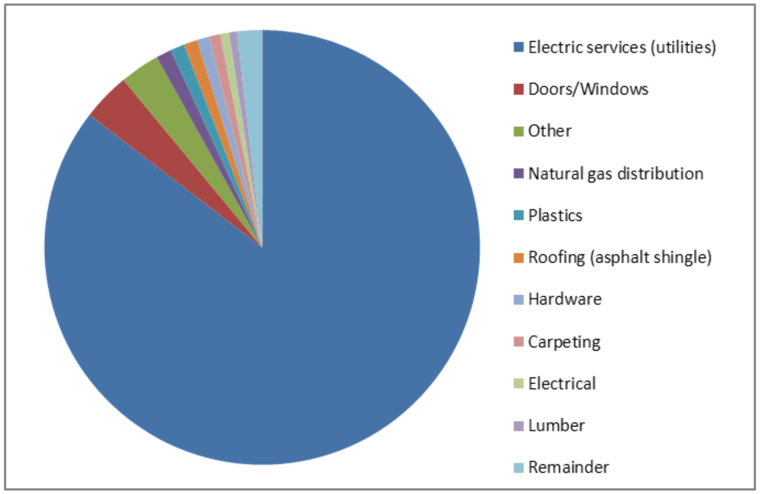
Rank	BEA Material/Product/Service Description	TETP (kg p-DCB eq.)	Contribution to Life Cycle TETP
1	Carpeting	2,596.85	41.54%
2	Electric services (utilities)	979.73	15.67%
3	Other	662.02	10.59%
4	Doors/Windows	302.41	4.84%
5	Plastics	294.73	4.71%
6	Siding (wood shingle)	257.56	4.12%
7	Hardware	206.05	3.30%
8	Roofing (asphalt shingle)	187.21	2.99%
9	Natural gas distribution	173.07	2.77%
10	Lumber	149.47	2.39%
	Total Accounted for in Top 10 M/P/S	5,809.11	92.91%
	Total Life Cycle TETP impacts	6,252.11	100.00%
	Remainder	443.00	7.09%



Appendix E3 (Continued)

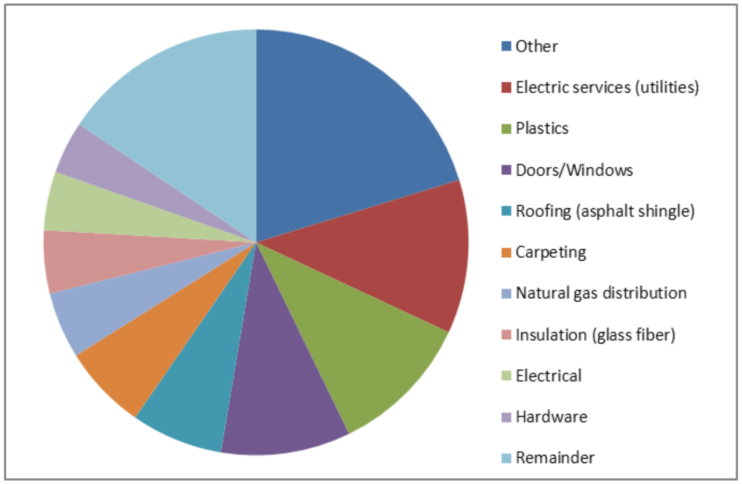
Freshwater Sediment Ecotoxicity Potential (FSETP) – Input Contribution Analysis – Occupancy Phase

Rank	BEA Material/Product/Service Description	FSETP (mton p-DCB eq.)	Contribution to Life Cycle FSETP
1	Electric services (utilities)	71,547.77	85.43%
2	Doors/Windows	2,993.18	3.57%
3	Other	2,472.46	2.95%
4	Natural gas distribution	959.44	1.15%
5	Plastics	872.10	1.04%
6	Roofing (asphalt shingle)	840.70	1.00%
7	Hardware	772.94	0.92%
8	Carpeting	704.60	0.84%
9	Electrical	543.12	0.65%
10	Lumber	493.40	0.59%
	Total Accounted for in Top 10 M/P/S	82,199.72	98.15%
	Total Life Cycle FSETP impacts	83,747.98	100.00%
	Remainder	1,548.26	1.85%



Marine Sediment Ecotoxicity Potential (MSETP) – Input Contribution Analysis – Occupancy Phase

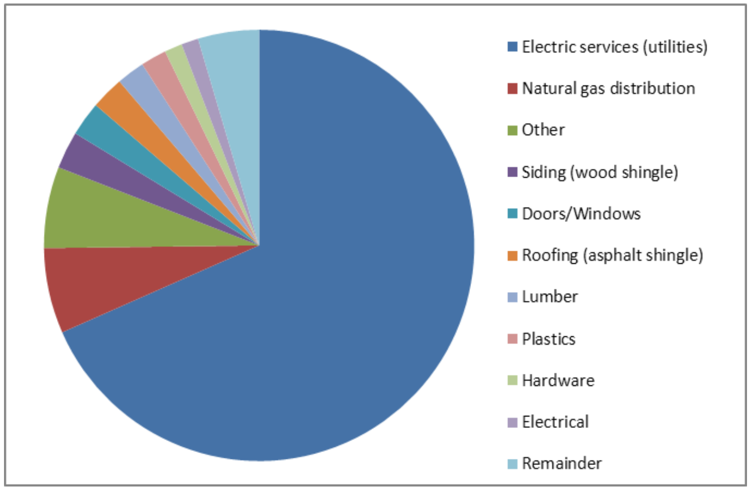
Rank	BEA Material/Product/Service Description	MSETP (kg p-DCB eq.)	Contribution to Life Cycle MSETP
1	Other	8,429.85	20.26%
2	Electric services (utilities)	4,856.76	11.67%
3	Plastics	4,513.11	10.85%
4	Doors/Windows	4,102.23	9.86%
5	Roofing (asphalt shingle)	2,905.98	6.99%
6	Carpeting	2,682.28	6.45%
7	Natural gas distribution	2,102.11	5.05%
8	Insulation (glass fiber)	1,990.18	4.78%
9	Electrical	1,852.87	4.45%
10	Hardware	1,657.96	3.99%
	Total Accounted for in Top 10 M/P/S	35,093.34	84.36%
	Total Life Cycle MSETP impacts	41,601.17	100.00%
	Remainder	6,507.83	15.64%



Appendix E3 (Continued)

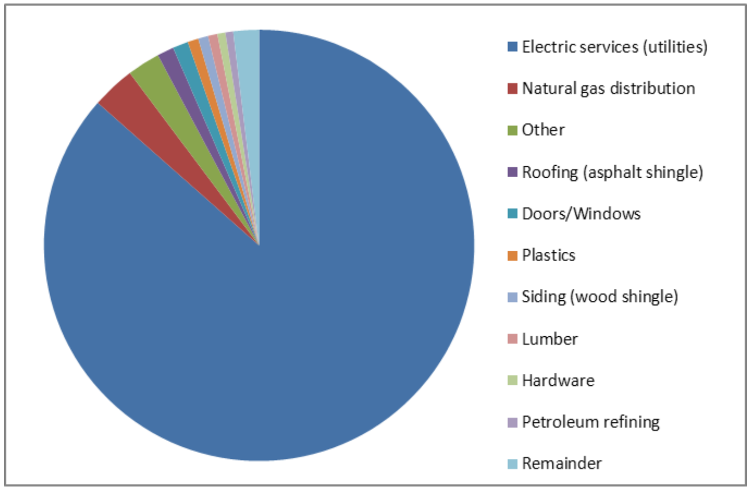
Photochemical Ozone Creation Potential (POCP) – Input Contribution Analysis – Occupancy Phase

Rank	BEA Material/Product/Service Description	POCP (kg C4H4 eq.)	Contribution to Life Cycle POCP
1	Electric services (utilities)	173.28	68.40%
2	Natural gas distribution	16.22	6.40%
3	Other	15.45	6.10%
4	Siding (wood shingle)	7.10	2.80%
5	Doors/Windows	6.53	2.58%
6	Roofing (asphalt shingle)	6.28	2.48%
7	Lumber	5.35	2.11%
8	Plastics	4.91	1.94%
9	Hardware	3.37	1.33%
10	Electrical	3.24	1.28%
	Total Accounted for in Top 10 M/P/S	241.72	95.41%
	Total Life Cycle POCP impacts	253.35	100.00%
	Remainder	11.62	4.59%



Acidification Potential (AP) – Input Contribution Analysis – Occupancy Phase

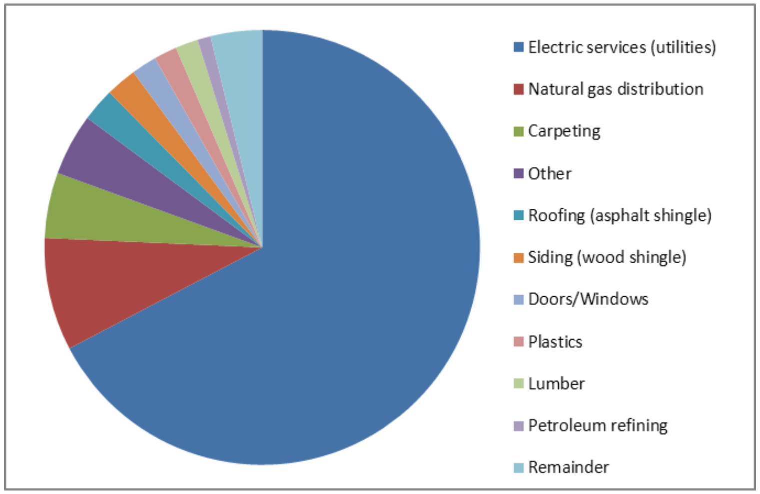
Rank	BEA Material/Product/Service Description	AP (kg SO2 eq.)	Contribution to Life Cycle AP
1	Electric services (utilities)	4,344.39	86.50%
2	Natural gas distribution	162.73	3.24%
3	Other	123.52	2.46%
4	Roofing (asphalt shingle)	62.87	1.25%
5	Doors/Windows	58.58	1.17%
6	Plastics	40.70	0.81%
7	Siding (wood shingle)	37.61	0.75%
8	Lumber	35.76	0.71%
9	Hardware	29.96	0.60%
10	Petroleum refining	29.50	0.59%
	Total Accounted for in Top 10 M/P/S	4,925.61	98.07%
	Total Life Cycle AP impacts	5,022.33	100.00%
	Remainder	96.73	1.93%



APPENDIX E3 (CONTINUED)

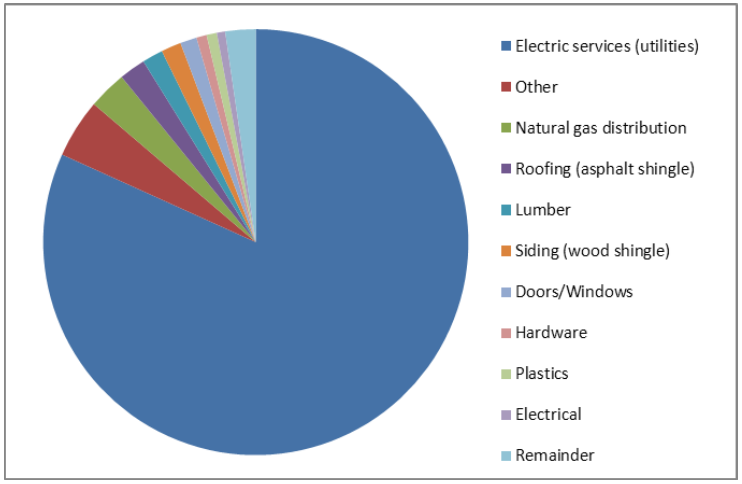
Eutrophication Potential (EP) – Input Contribution Analysis – Occupancy Phase

Rank	BEA Material/Product/Service Description	EP (kg PO4 eq.)	Contribution to Life Cycle EP
1	Electric services (utilities)	166.52	67.31%
2	Natural gas distribution	20.76	8.39%
3	Carpeting	12.02	4.86%
4	Other	11.37	4.60%
5	Roofing (asphalt shingle)	6.12	2.47%
6	Siding (wood shingle)	5.68	2.30%
7	Doors/Windows	4.65	1.88%
8	Plastics	4.23	1.71%
9	Lumber	4.17	1.69%
10	Petroleum refining	2.43	0.98%
	Total Accounted for in Top 10 M/P/S	237.95	96.18%
	Total Life Cycle EP impacts	247.40	100.00%
	Remainder	9.45	3.82%



Energy Consumption (EC) – Input Contribution Analysis – Occupancy Phase

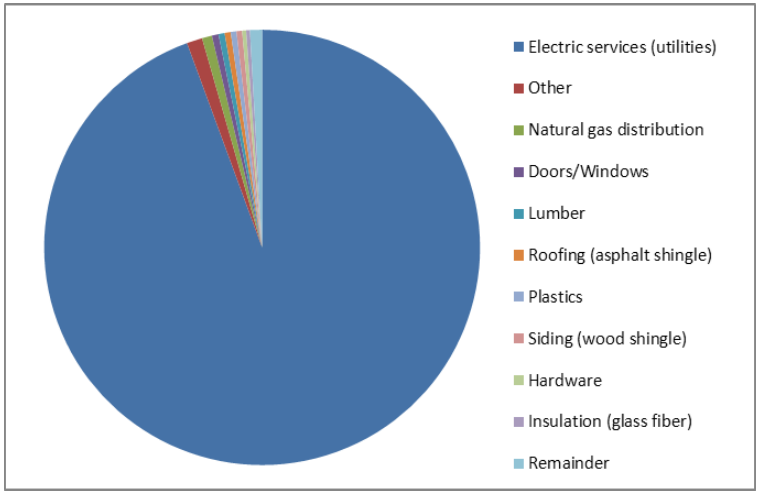
Rank	BEA Material/Product/Service Description	EC (mBTU)	Contribution to Life Cycle EC
1	Electric services (utilities)	11,266.92	81.74%
2	Other	616.77	4.47%
3	Natural gas distribution	400.95	2.91%
4	Roofing (asphalt shingle)	276.10	2.00%
5	Lumber	218.34	1.58%
6	Siding (wood shingle)	209.49	1.52%
7	Doors/Windows	173.88	1.26%
8	Hardware	107.92	0.78%
9	Plastics	107.82	0.78%
10	Electrical	87.46	0.63%
	Total Accounted for in Top 10 M/P/S	13,465.65	97.70%
	Total Life Cycle EC impacts	13,783.16	100.00%
	Remainder	317.51	2.30%



APPENDIX E3 (CONTINUED)

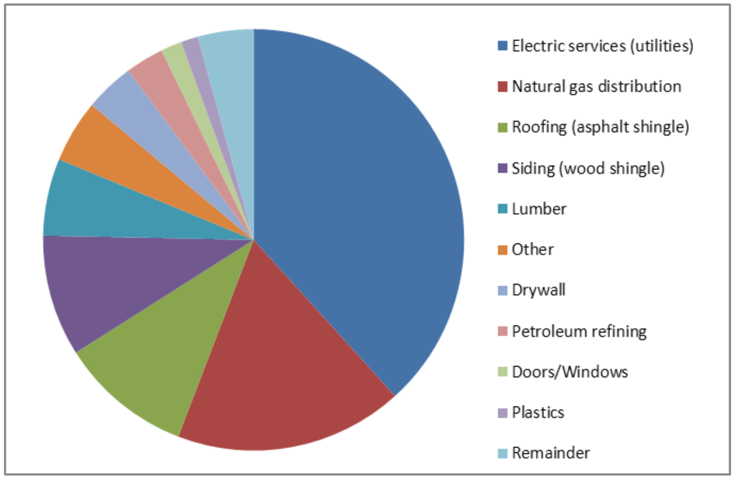
Water Consumption (WC) – Input Contribution Analysis – Occupancy Phase

Rank	BEA Material/Product/Service Description	WC (10^3 gal)	Contribution to Life Cycle WC
1	Electric services (utilities)	239,589.13	94.40%
2	Other	2,938.43	1.16%
3	Natural gas distribution	1,874.13	0.74%
4	Doors/Windows	1,259.02	0.50%
5	Lumber	1,153.52	0.45%
6	Roofing (asphalt shingle)	1,131.80	0.45%
7	Plastics	1,083.24	0.43%
8	Siding (wood shingle)	1,052.75	0.41%
9	Hardware	763.76	0.30%
10	Insulation (glass fiber)	703.53	0.28%
	Total Accounted for in Top 10 M/P/S	251,549.30	99.11%
	Total Life Cycle WC impacts	253,807.60	100.00%
	Remainder	2,258.30	0.89%



Material Input (MTL) – Input Contribution Analysis – Occupancy Phase

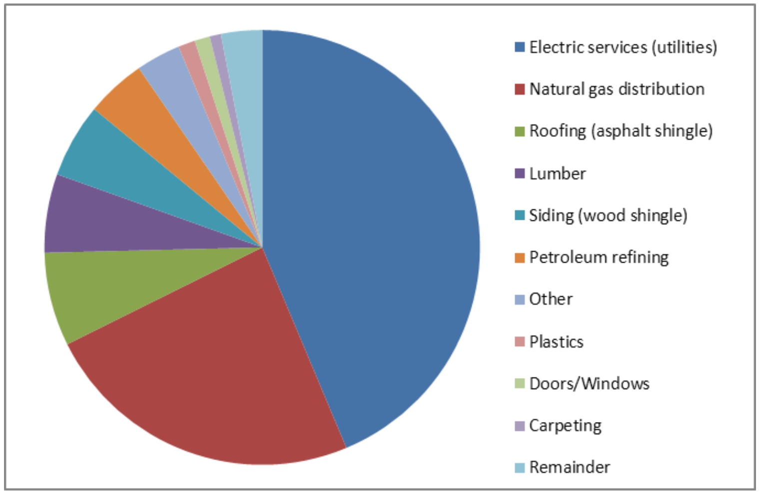
Rank	BEA Material/Product/Service Description	MTL (mton)	Contribution to Life Cycle MTL
1	Electric services (utilities)	401.85	38.28%
2	Natural gas distribution	184.19	17.55%
3	Roofing (asphalt shingle)	106.83	10.18%
4	Siding (wood shingle)	97.85	9.32%
5	Lumber	62.10	5.92%
6	Other	50.53	4.81%
7	Drywall	39.88	3.80%
8	Petroleum refining	30.89	2.94%
9	Doors/Windows	16.85	1.61%
10	Plastics	13.91	1.33%
	Total Accounted for in Top 10 M/P/S	1,004.87	95.73%
	Total Life Cycle MTL impacts	1,049.69	100.00%
	Remainder	44.82	4.27%



APPENDIX E3 (CONTINUED)

Waste (WST) – Input Contribution Analysis – Occupancy Phase

Rank	BEA Material/Product/Service Description	WST (mton)	Contribution to Life Cycle WST
1	Electric services (utilities)	272.15	43.68%
2	Natural gas distribution	149.31	23.97%
3	Roofing (asphalt shingle)	43.34	6.96%
4	Lumber	36.46	5.85%
5	Siding (wood shingle)	34.38	5.52%
6	Petroleum refining	27.69	4.44%
7	Other	20.58	3.30%
8	Plastics	7.84	1.26%
9	Doors/Windows	7.10	1.14%
10	Carpeting	5.21	0.84%
	Total Accounted for in Top 10 M/P/S	604.07	96.96%
	Total Life Cycle WST impacts	623.03	100.00%
	Remainder	18.96	3.04%



APPENDIX F - RATIONALE FOR SELECTING DIRECT INPUTS FOR SUPPLY CHAIN ANALYSIS

Material/Product/Service	Well-defined Matl/Prod	Rank: All Phases	Rank: Pre-Occ Only	Include?	Rationale
Asphalt paving mixtures and blocks (Pre-occupancy)	Yes	---	14	No	Relatively lower ranking
Brick and structural clay tile (Pre-occupancy)	Yes	18	1	Yes	High ranking pre-occ
Carpeting (Occupancy)/Carpets and Rugs (Pre-occupancy)	Yes	2/17	---/3	No	See 3.1.1
Cement, hydraulic (Pre-occupancy)	Yes	---	17	No	Relatively lower ranking
Converted paper products, n.e.c. (Pre-occupancy)	Yes	---	20	No	Relatively lower ranking
Cut stone and stone products (Pre-occupancy)	Yes	---	18	No	Relatively lower ranking
Dimension, crushed and broken stone (Pre-occupancy)	Yes	14	12	No	Relatively lower ranking
Direct construction (Construction)	No	3	---	No	Not well-defined matl/prod
Doors/Windows (Occupancy)	Yes	8	---	No	Relatively lower ranking
Electric services (utilities) (Occupancy)	No	1/---	---/19	No	Not well-defined matl/prod
Electrical (Occupancy)	Yes	19	---	No	Relatively lower ranking
Hardware (Occupancy)	Yes	15	---	No	Relatively lower ranking
Insulation (glass fiber) (Occupancy)/Mineral wool (Pre-occupancy)	Yes	7/10	---/4	Yes	High rank pre-occ, detailed OCA item
Lumber (Occupancy)	Yes	11	---	No	Relatively lower ranking
Millwork (Pre-occupancy)	Yes	---	15	No	Relatively lower ranking
Miscellaneous plastics products, n.e.c. (Pre-occupancy)	No	13	5	No	Not well-defined matl/prod
Motor vehicles and passenger car bodies (Pre-occupancy)	Yes	---	10	No	Relatively lower ranking
Natural gas distribution (Occupancy)	No	5	---	No	Not well-defined matl/prod
Other (Occupancy)	No	4	---	No	Not well-defined matl/prod
Paints and allied products (Pre-occupancy)	Yes	---	16	No	Relatively lower ranking
Plastics (Occupancy)	No	9	---	No	Not well-defined matl/prod
Ready-mixed concrete (Pre-occupancy)	Yes	---	2	Yes	High rank pre-occ, detailed OCA item
Reconstituted wood products (Pre-occupancy)	Yes	---	8	Yes	Detailed OCA item
Retail trade, except eating and drinking (Pre-occupancy)	No	---	6	No	Not well-defined matl/prod
Roofing (asphalt shingle) (Occupancy)	Yes	12	---	No	Relatively lower ranking
Sand and gravel (Pre-occupancy)	Yes	16	9	No	Relatively lower ranking
Sawmills and planing mills, general (Pre-occupancy)	Yes	20	11	No	Relatively lower ranking
Siding (wood shingle) (Occupancy)	Yes	6	---	Yes	High rank all phase
Trucking and courier services, except air (Pre-occupancy)	No	---	7	No	Not well-defined matl/prod
Wholesale trade (Pre-occupancy)	No	---	13	No	Not well-defined matl/prod

APPENDIX G – OUTPUT CONTRIBUTION ANALYSIS RESULTS

Appendix G1 – Pre-Occupancy-Phase Results by Impact Category

Appendix G2 – Vector Analysis Results, Output Contribution Basis, Pre-Occupancy Phase

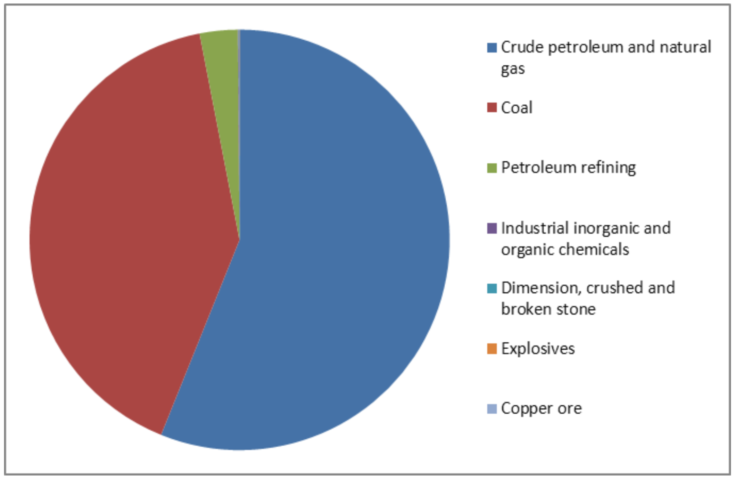
Appendix G3 – Occupancy-Phase Results by Impact Category

Appendix G4 – Vector Analysis Results, Output Contribution Basis, Occupancy Phase

APPENDIX G1 – PRE-OCCUPANCY-PHASE RESULTS BY IMPACT CATEGORY

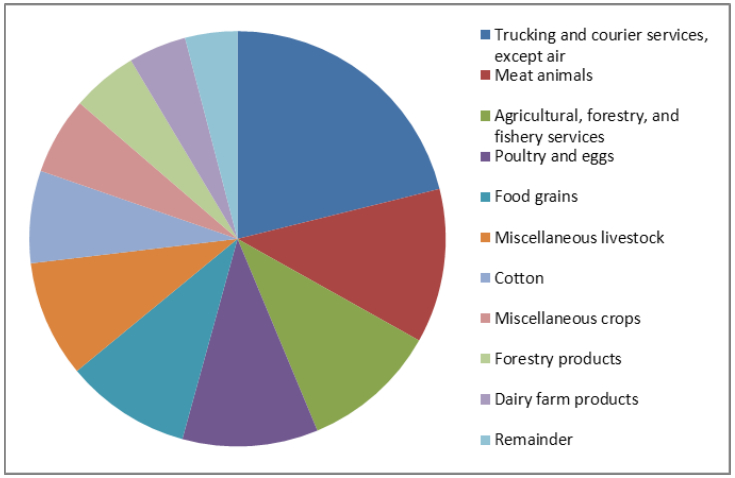
Abiotic Depletion Potential (ADP) – Output Contribution Analysis – Pre-Occupancy Phase

Rank	BEA Material/Product/Service Description	ADP (kg Sn eq.)	Contribution to Life Cycle ADP
1	Crude petroleum and natural gas	279.82	56.10%
2	Coal	203.72	40.84%
3	Petroleum refining	14.57	2.92%
4	Industrial inorganic and organic chemicals	0.38	0.08%
5	Dimension, crushed and broken stone	0.14	0.03%
6	Explosives	0.14	0.03%
7	Copper ore	0.00	0.00%
8	Iron and ferroalloy ores, and misc. metal ores...	0.00	0.00%
9	Nonferrous metal ores, except copper	0.00	0.00%
10	Nonmetallic mineral services and misc.	0.00	0.00%
	Total Accounted for in Top 10 M/P/S	498.78	100.00%
	Total Life Cycle ADP impacts	498.78	100.00%
	Remainder	0.00	0.00%



Land Use Competition (LUC) – Output Contribution Analysis – Pre-Occupancy Phase

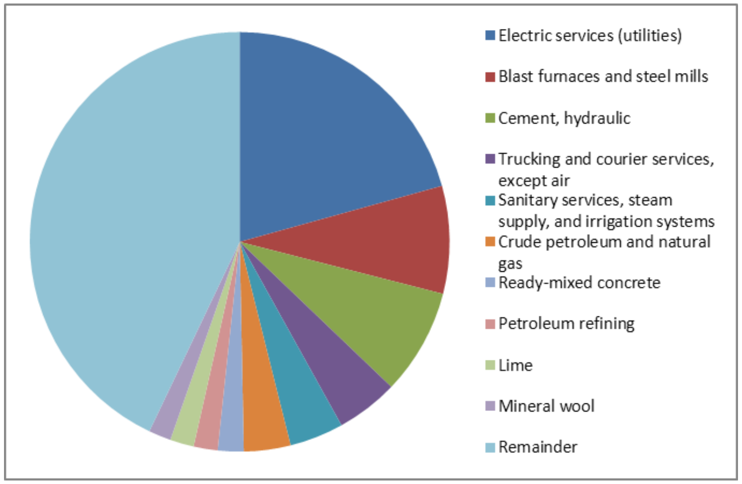
Rank	BEA Material/Product/Service Description	LUC (m2*yr)	Contribution to Life Cycle LUC
1	Trucking and courier services, except air	2,325.17	21.13%
2	Meat animals	1,320.90	12.01%
3	Agricultural, forestry, and fishery services	1,164.90	10.59%
4	Poultry and eggs	1,159.85	10.54%
5	Food grains	1,072.84	9.75%
6	Miscellaneous livestock	1,000.68	9.10%
7	Cotton	790.84	7.19%
8	Miscellaneous crops	662.71	6.02%
9	Forestry products	563.04	5.12%
10	Dairy farm products	494.43	4.49%
	Total Accounted for in Top 10 M/P/S	10,555.35	95.94%
	Total Life Cycle LUC impacts	11,002.07	100.00%
	Remainder	446.71	4.06%



APPENDIX G1 (CONTINUED)

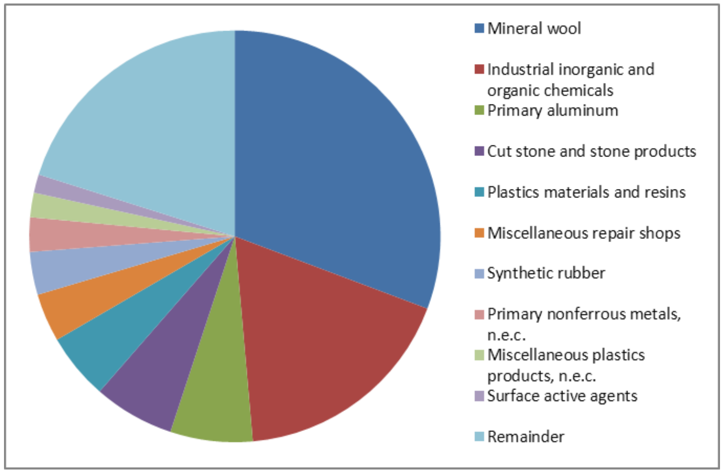
Global Warming Potential (GWP) – Output Contribution Analysis – Pre-Occupancy Phase

Rank	BEA Material/Product/Service Description	GWP (kg CO2 eq.)	Contribution to Life Cycle GWP
1	Electric services (utilities)	29,276.15	20.70%
2	Blast furnaces and steel mills	11,713.89	8.28%
3	Cement, hydraulic	11,540.82	8.16%
4	Trucking and courier services, except air	6,770.89	4.79%
5	Sanitary services, steam supply, and irrigation…	5,877.50	4.16%
6	Crude petroleum and natural gas	5,083.36	3.59%
7	Ready-mixed concrete	2,812.22	1.99%
8	Petroleum refining	2,619.91	1.85%
9	Lime	2,592.95	1.83%
10	Mineral wool	2,425.57	1.72%
	Total Accounted for in Top 10 M/P/S	80,713.26	57.08%
	Total Life Cycle GWP impacts	141,403.66	100.00%
	Remainder	60,690.40	42.92%



Stratospheric Ozone Depletion Potential (ODP) – Output Contribution Analysis – Pre-Occupancy Phase

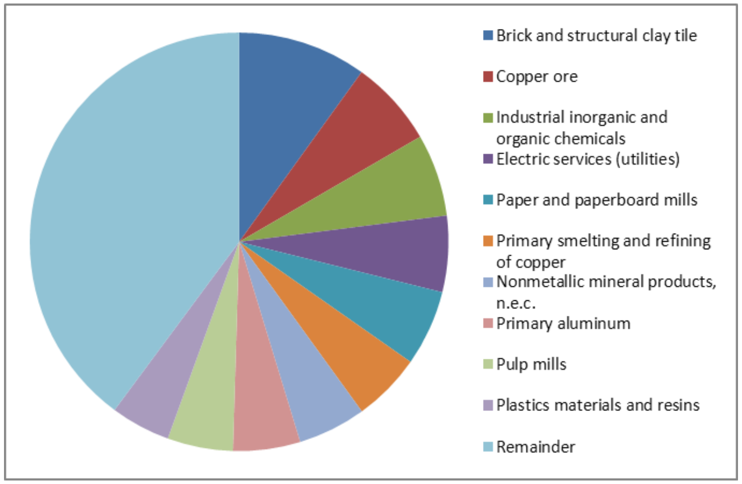
Rank	BEA Material/Product/Service Description	ODP (g CFC-11 eq.)	Contribution to Life Cycle ODP
1	Mineral wool	189.49	30.71%
2	Industrial inorganic and organic chemicals	110.37	17.89%
3	Primary aluminum	39.95	6.47%
4	Cut stone and stone products	39.16	6.35%
5	Plastics materials and resins	32.09	5.20%
6	Miscellaneous repair shops	23.43	3.80%
7	Synthetic rubber	20.79	3.37%
8	Primary nonferrous metals, n.e.c.	16.61	2.69%
9	Miscellaneous plastics products, n.e.c.	11.85	1.92%
10	Surface active agents	8.95	1.45%
	Total Accounted for in Top 10 M/P/S	492.69	79.86%
	Total Life Cycle ODP impacts	616.98	100.00%
	Remainder	124.28	20.14%



APPENDIX G1 (CONTINUED)

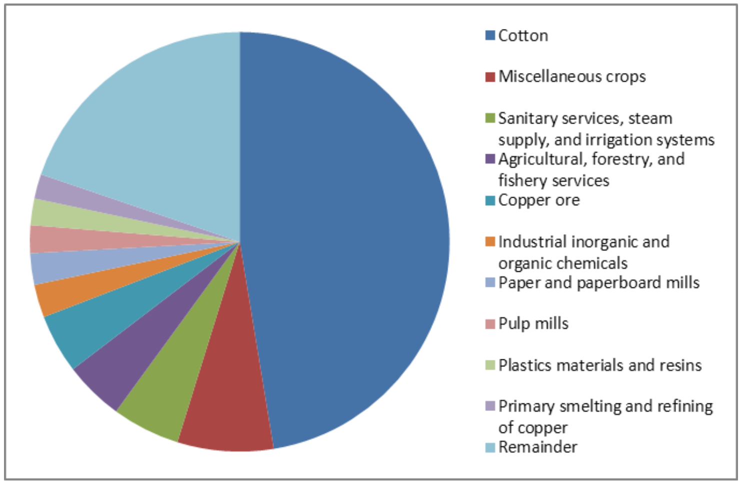
Human Toxicity Potential (HTP) – Output Contribution Analysis – Pre-Occupancy Phase

Rank	BEA Material/Product/Service Description	HTP (kg p-DCB eq.)	Contribution to Life Cycle HTP
1	Brick and structural clay tile	1,595.39	9.95%
2	Copper ore	1,071.49	6.68%
3	Industrial inorganic and organic chemicals	1,020.01	6.36%
4	Electric services (utilities)	943.79	5.88%
5	Paper and paperboard mills	938.76	5.85%
6	Primary smelting and refining of copper	850.48	5.30%
7	Nonmetallic mineral products, n.e.c.	842.73	5.25%
8	Primary aluminum	832.37	5.19%
9	Pulp mills	812.26	5.06%
10	Plastics materials and resins	738.91	4.61%
	Total Accounted for in Top 10 M/P/S	9,646.19	60.15%
	Total Life Cycle HTP impacts	16,037.52	100.00%
	Remainder	6,391.32	39.85%



Freshwater Aquatic Ecotoxicity Potential (FAETP) – Output Contribution Analysis – Pre-Occupancy Phase

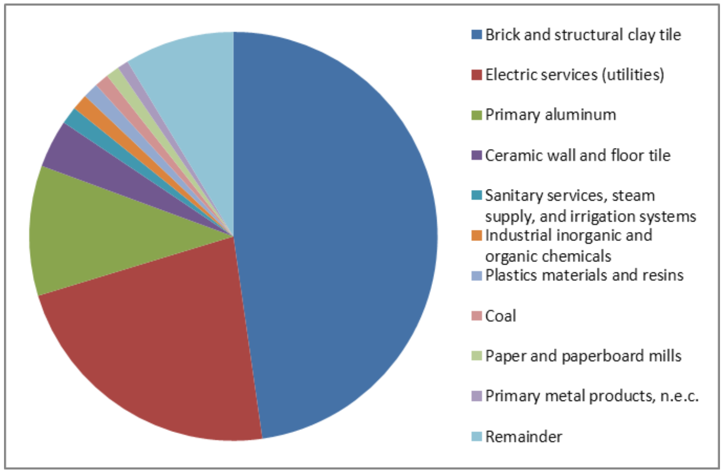
Rank	BEA Material/Product/Service Description	FAETP (kg p-DCB eq.)	Contribution to Life Cycle FAETP
1	Cotton	1,209.80	47.40%
2	Miscellaneous crops	188.73	7.40%
3	Sanitary services, steam supply, and irrigation…	133.35	5.22%
4	Agricultural, forestry, and fishery services	117.16	4.59%
5	Copper ore	116.09	4.55%
6	Industrial inorganic and organic chemicals	64.85	2.54%
7	Paper and paperboard mills	61.80	2.42%
8	Pulp mills	54.84	2.15%
9	Plastics materials and resins	52.11	2.04%
10	Primary smelting and refining of copper	48.45	1.90%
	Total Accounted for in Top 10 M/P/S	2,047.17	80.22%
	Total Life Cycle FAETP impacts	2,552.07	100.00%
	Remainder	504.91	19.78%



APPENDIX G1 (CONTINUED)

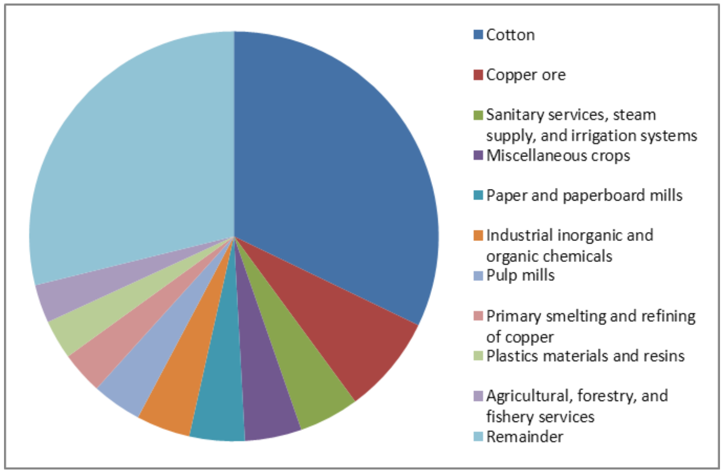
Marine Aquatic Ecotoxicity Potential (MAETP) – Output Contribution Analysis – Pre-Occupancy Phase

Rank	BEA Material/Product/Service Description	MAETP (mton p-DCB eq.)	Contribution to Life Cycle MAETP
1	Brick and structural clay tile	22,576.69	47.73%
2	Electric services (utilities)	10,677.90	22.57%
3	Primary aluminum	4,871.30	10.30%
4	Ceramic wall and floor tile	1,794.67	3.79%
5	Sanitary services, steam supply, and irrig…	656.37	1.39%
6	Industrial inorganic and organic chemicals	599.63	1.27%
7	Plastics materials and resins	573.53	1.21%
8	Coal	531.05	1.12%
9	Paper and paperboard mills	496.97	1.05%
10	Primary metal products, n.e.c.	417.85	0.88%
	Total Accounted for in Top 10 M/P/S	43,195.96	91.32%
	Total Life Cycle MAETP impacts	47,300.18	100.00%
	Remainder	4,104.21	8.68%



Terrestrial Ecotoxicity Potential (TETP) – Output Contribution Analysis – Pre-Occupancy Phase

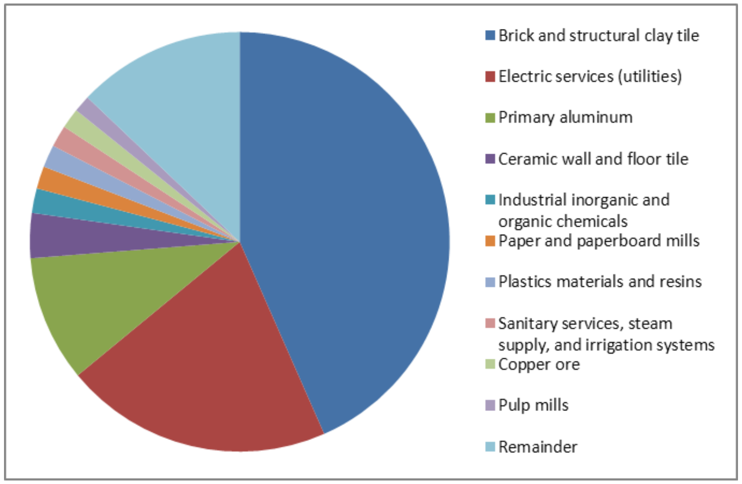
Rank	BEA Material/Product/Service Description	TETP (kg p-DCB eq.)	Contribution to Life Cycle TETP
1	Cotton	1,008.13	32.14%
2	Copper ore	243.79	7.77%
3	Sanitary services, steam supply, and irrig…	148.87	4.75%
4	Miscellaneous crops	140.82	4.49%
5	Paper and paperboard mills	136.95	4.37%
6	Industrial inorganic and organic chemicals	133.46	4.25%
7	Pulp mills	123.17	3.93%
8	Primary smelting and refining of copper	105.03	3.35%
9	Plastics materials and resins	97.08	3.09%
10	Agricultural, forestry, and fishery services	94.92	3.03%
	Total Accounted for in Top 10 M/P/S	2,232.22	71.16%
	Total Life Cycle TETP impacts	3,136.84	100.00%
	Remainder	904.63	28.84%



APPENDIX G1 (CONTINUED)

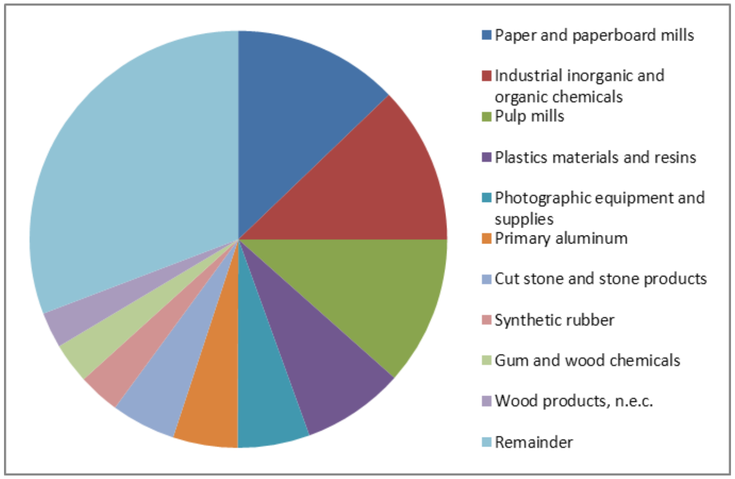
Freshwater Sediment Ecotoxicity Potential (FSETP) – Output Contribution Analysis – Pre-Occupancy Phase

Rank	BEA Material/Product/Service Description	FSETP (mton p-DCB eq.)	Contribution to Life Cycle FSETP
1	Brick and structural clay tile	7,432.71	43.40%
2	Electric services (utilities)	3,530.87	20.62%
3	Primary aluminum	1,665.83	9.73%
4	Ceramic wall and floor tile	591.91	3.46%
5	Industrial inorganic and organic chemicals	324.76	1.90%
6	Paper and paperboard mills	296.53	1.73%
7	Plastics materials and resins	296.08	1.73%
8	Sanitary services, steam supply, and irrig...	286.29	1.67%
9	Copper ore	265.66	1.55%
10	Pulp mills	221.41	1.29%
	Total Accounted for in Top 10 M/P/S	14,912.06	87.08%
	Total Life Cycle FSETP impacts	17,124.15	100.00%
	Remainder	2,212.09	12.92%



Marine Sediment Ecotoxicity Potential (MSETP) – Output Contribution Analysis – Pre-Occupancy Phase

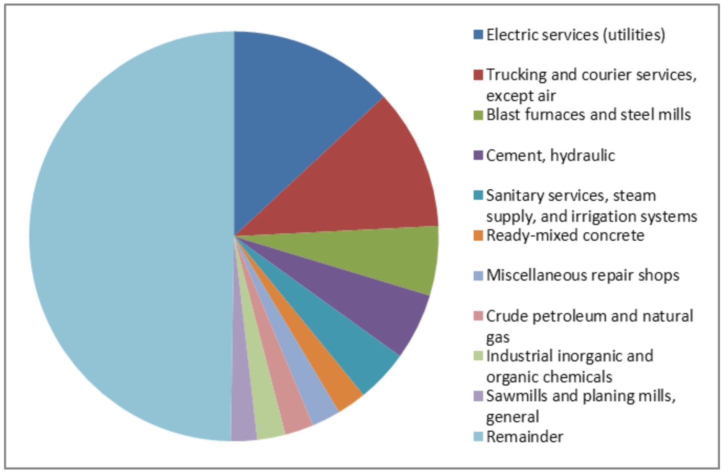
Rank	BEA Material/Product/Service Description	MSETP (kg p-DCB eq.)	Contribution to Life Cycle MSETP
1	Paper and paperboard mills	3,834.64	12.81%
2	Industrial inorganic and organic chemicals	3,652.88	12.21%
3	Pulp mills	3,453.02	11.54%
4	Plastics materials and resins	2,367.06	7.91%
5	Photographic equipment and supplies	1,672.66	5.59%
6	Primary aluminum	1,497.69	5.01%
7	Cut stone and stone products	1,493.28	4.99%
8	Synthetic rubber	967.06	3.23%
9	Gum and wood chemicals	939.48	3.14%
10	Wood products, n.e.c.	831.80	2.78%
	Total Accounted for in Top 10 M/P/S	20,709.57	69.21%
	Total Life Cycle MSETP impacts	29,923.75	100.00%
	Remainder	9,214.18	30.79%



APPENDIX G1 (CONTINUED)

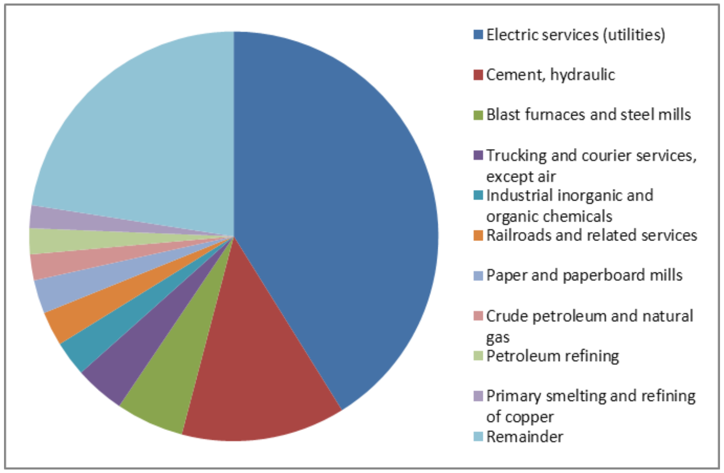
Photochemical Ozone Creation Potential (POCP) – Output Contribution Analysis – Pre-Occupancy Phase

Rank	BEA Material/Product/Service Description	POCP (kg C4H4 eq.)	Contribution to Life Cycle POCP
1	Electric services (utilities)	11.11	13.07%
2	Trucking and courier services, except air	9.44	11.12%
3	Blast furnaces and steel mills	4.66	5.49%
4	Cement, hydraulic	4.47	5.26%
5	Sanitary services, steam supply, and irrig...	3.53	4.15%
6	Ready-mixed concrete	1.96	2.31%
7	Miscellaneous repair shops	1.94	2.28%
8	Crude petroleum and natural gas	1.93	2.27%
9	Industrial inorganic and organic chemicals	1.89	2.22%
10	Sawmills and planing mills, general	1.76	2.07%
	Total Accounted for in Top 10 M/P/S	42.69	50.25%
	Total Life Cycle POCP impacts	84.96	100.00%
	Remainder	42.27	49.75%



Acidification Potential (AP) – Output Contribution Analysis – Pre-Occupancy Phase

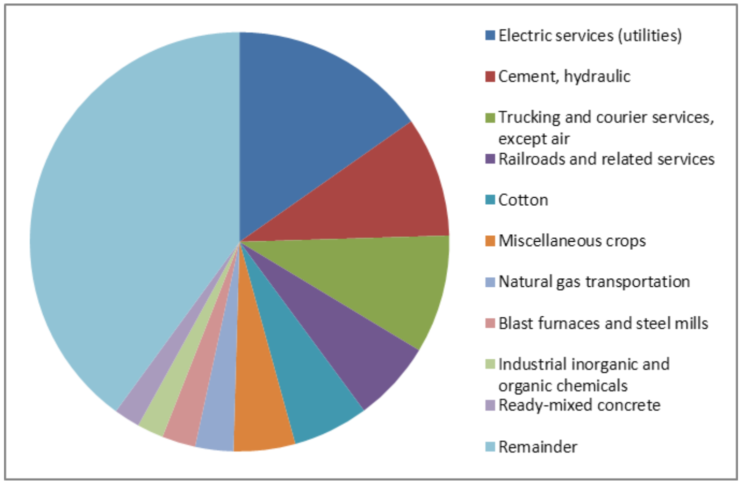
Rank	BEA Material/Product/Service Description	AP (kg SO2 eq.)	Contribution to Life Cycle AP
1	Electric services (utilities)	206.62	41.13%
2	Cement, hydraulic	65.14	12.97%
3	Blast furnaces and steel mills	26.93	5.36%
4	Trucking and courier services, except air	19.89	3.96%
5	Industrial inorganic and organic chemicals	13.93	2.77%
6	Railroads and related services	13.60	2.71%
7	Paper and paperboard mills	13.30	2.65%
8	Crude petroleum and natural gas	10.29	2.05%
9	Petroleum refining	10.25	2.04%
10	Primary smelting and refining of copper	9.08	1.81%
	Total Accounted for in Top 10 M/P/S	389.03	77.44%
	Total Life Cycle AP impacts	502.36	100.00%
	Remainder	113.33	22.56%



Appendix G1 (Continued)

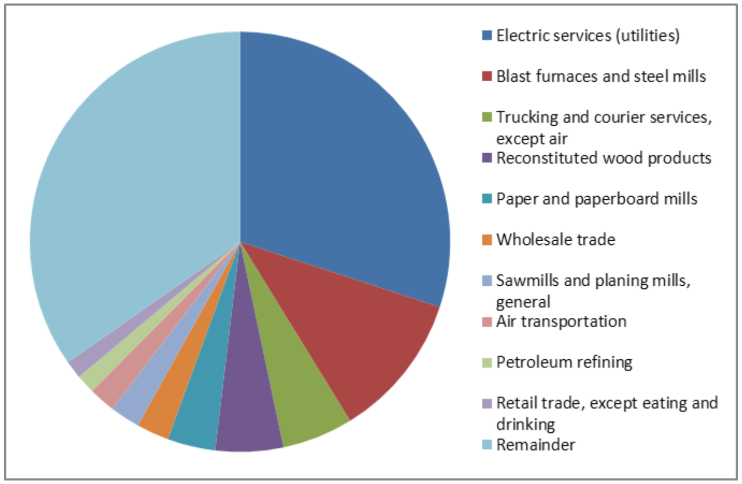
Eutrophication Potential (EP) – Output Contribution Analysis – Pre-Occupancy Phase

Rank	BEA Material/Product/Service Description	EP (kg PO4 eq.)	Contribution to Life Cycle EP
1	Electric services (utilities)	10.10	15.26%
2	Cement, hydraulic	6.14	9.27%
3	Trucking and courier services, except air	6.04	9.12%
4	Railroads and related services	4.13	6.24%
5	Cotton	3.86	5.83%
6	Miscellaneous crops	3.15	4.75%
7	Natural gas transportation	1.95	2.94%
8	Blast furnaces and steel mills	1.71	2.59%
9	Industrial inorganic and organic chemicals	1.35	2.04%
10	Ready-mixed concrete	1.33	2.01%
	Total Accounted for in Top 10 M/P/S	39.76	60.04%
	Total Life Cycle EP impacts	66.22	100.00%
	Remainder	26.47	39.96%



Energy Consumption (EC) – Output Contribution Analysis – Pre-Occupancy Phase

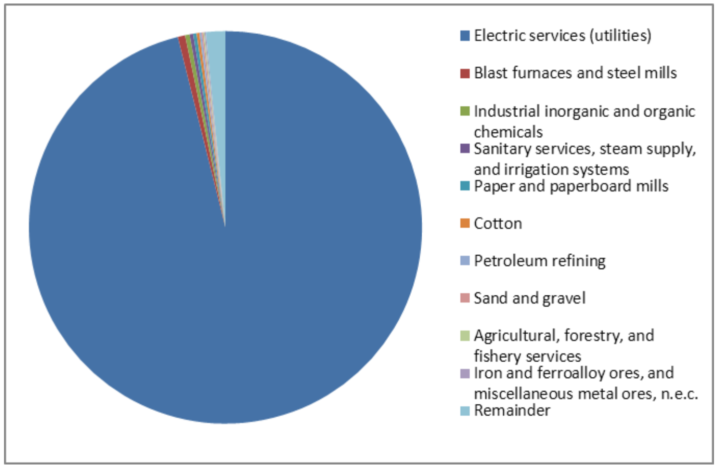
Rank	BEA Material/Product/Service Description	EC (mBTU)	Contribution to Life Cycle EC
1	Electric services (utilities)	365.21	30.03%
2	Blast furnaces and steel mills	136.15	11.19%
3	Trucking and courier services, except air	66.27	5.45%
4	Reconstituted wood products	63.53	5.22%
5	Paper and paperboard mills	44.86	3.69%
6	Wholesale trade	30.38	2.50%
7	Sawmills and planing mills, general	28.10	2.31%
8	Air transportation	24.78	2.04%
9	Petroleum refining	17.81	1.46%
10	Retail trade, except eating and drinking	16.89	1.39%
	Total Accounted for in Top 10 M/P/S	793.97	65.28%
	Total Life Cycle EC impacts	1,216.21	100.00%
	Remainder	422.24	34.72%



APPENDIX G1 (CONTINUED)

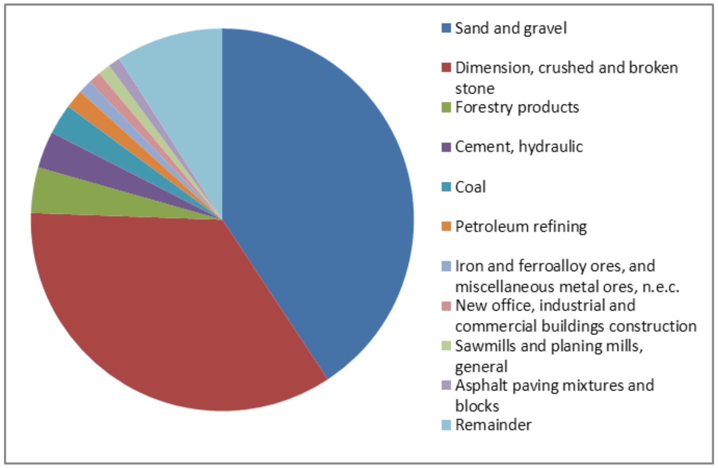
Water Consumption (WC) – Output Contribution Analysis – Pre-Occupancy Phase

Rank	BEA Material/Product/Service Description	WC (10^3 gal)	Contribution to Life Cycle WC
1	Electric services (utilities)	12,304.82	96.10%
2	Blast furnaces and steel mills	77.04	0.60%
3	Industrial inorganic and organic chemicals	47.59	0.37%
4	Sanitary services, steam supply, and irrig...	37.34	0.29%
5	Paper and paperboard mills	36.05	0.28%
6	Cotton	30.37	0.24%
7	Petroleum refining	22.14	0.17%
8	Sand and gravel	16.95	0.13%
9	Agricultural, forestry, and fishery services	13.33	0.10%
10	Iron and ferroalloy ores, and misc. metal...	12.94	0.10%
	Total Accounted for in Top 10 M/P/S	12,598.56	98.39%
	Total Life Cycle WC impacts	12,804.20	100.00%
	Remainder	205.64	1.61%



Material Input (MTL) – Output Contribution Analysis – Pre-Occupancy Phase

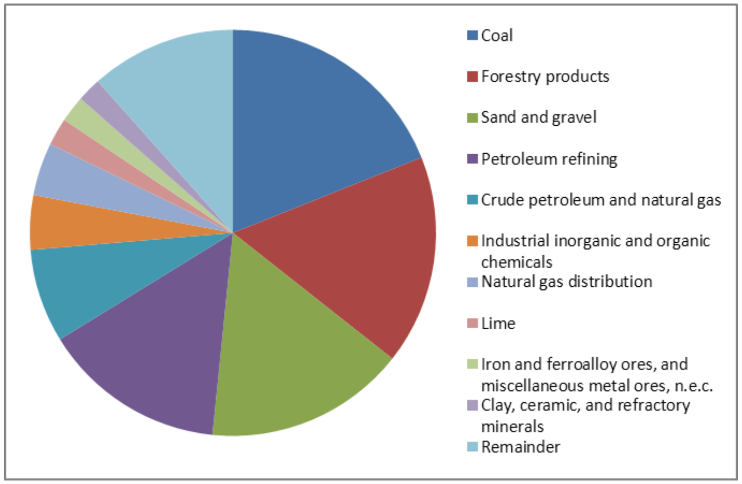
Rank	BEA Material/Product/Service Description	MTL (mton)	Contribution to Life Cycle MTL
1	Sand and gravel	1,086.83	40.73%
2	Dimension, crushed and broken stone	929.88	34.84%
3	Forestry products	102.95	3.86%
4	Cement, hydraulic	82.99	3.11%
5	Coal	68.52	2.57%
6	Petroleum refining	42.38	1.59%
7	Iron and ferroalloy ores, and misc. metal...	30.14	1.13%
8	New office, industrial and commercial bldg...	28.46	1.07%
9	Sawmills and planing mills, general	27.86	1.04%
10	Asphalt paving mixtures and blocks	26.99	1.01%
	Total Accounted for in Top 10 M/P/S	2,427.00	90.94%
	Total Life Cycle MTL impacts	2,668.70	100.00%
	Remainder	241.69	9.06%



APPENDIX G1 (CONTINUED)

Waste (WST) – Output Contribution Analysis – Pre-Occupancy Phase

Rank	BEA Material/Product/Service Description	WST (mton)	Contribution to Life Cycle WST
1	Coal	22.35	18.95%
2	Forestry products	19.67	16.68%
3	Sand and gravel	18.85	15.98%
4	Petroleum refining	17.22	14.60%
5	Crude petroleum and natural gas	8.79	7.45%
6	Industrial inorganic and organic chemicals	5.11	4.33%
7	Natural gas distribution	4.96	4.21%
8	Lime	2.59	2.19%
9	Iron and ferroalloy ores, and misc. metal…	2.48	2.10%
10	Clay, ceramic, and refractory minerals	2.25	1.91%
	Total Accounted for in Top 10 M/P/S	104.28	88.41%
	Total Life Cycle WST impacts	117.95	100.00%
	Remainder	13.67	11.59%



Appendix G2 – Vector Analysis Results, Output Contribution Basis, Pre-Occupancy Phase

<u>All Impacts</u>

Rank	Description	Number of Standard Deviations from the Mean																	
		ADP	LUC	GWP	ODP	HTP	FAETP	MAETP	TETP	FSETP	MSETP	POCP	AP	EP	EC	WC	MTL	WST	Vector Magnitude
1	Electric services (utilities)	-0.07	-0.14	17.22	-0.12	5.95	0.12	8.80	0.22	8.79	-0.18	13.48	19.74	13.86	18.94	21.17	-0.08	-0.14	45.35
2	Cotton	-0.07	4.44	-0.09	-0.13	-0.11	20.47	-0.09	19.33	-0.10	0.05	-0.17	-0.11	5.17	-0.13	0.00	-0.08	-0.11	28.97
3	Brick and structural clay tile	-0.07	-0.14	0.48	-0.13	10.21	-0.04	18.70	-0.09	18.62	-0.19	0.09	-0.06	-0.01	0.09	-0.05	-0.09	-0.14	28.30
4	Trucking and courier services, except air	-0.07	13.32	3.84	-0.12	0.05	-0.10	-0.09	-0.13	-0.10	-0.19	11.43	1.80	8.21	3.32	-0.03	-0.09	-0.14	20.11
5	Sand and gravel	-0.07	-0.14	0.45	-0.12	0.15	-0.10	-0.09	-0.13	-0.09	-0.19	-0.04	-0.09	-0.11	0.49	-0.02	15.96	9.64	18.66
6	Crude petroleum and natural gas	17.09	-0.14	2.84	-0.12	-0.11	-0.09	-0.09	-0.11	-0.09	-0.08	2.15	0.88	1.58	0.18	-0.03	0.25	4.42	18.10
7	Mineral wool	-0.07	-0.14	1.26	17.27	0.85	0.04	-0.07	0.22	-0.04	1.39	1.47	0.01	0.31	0.28	-0.04	-0.09	-0.14	17.46
8	Coal	12.42	-0.14	0.79	-0.13	0.49	0.19	0.35	0.32	0.38	-0.19	0.34	-0.10	-0.15	-0.07	-0.05	0.92	11.45	16.97
9	Industrial inorganic and organic chemicals	-0.04	-0.14	0.95	10.01	6.45	1.01	0.41	2.44	0.72	10.18	2.10	1.23	1.67	0.03	0.03	0.16	2.51	16.40
10	Dimension, crushed and broken stone	-0.06	-0.14	0.51	-0.13	-0.22	-0.10	-0.09	-0.13	-0.10	-0.19	0.10	-0.06	-0.01	0.49	-0.04	13.64	0.00	13.66

Rank	Description	Factor Influence (change in vector orientation, in degrees)																
		ADP	LUC	GWP	ODP	HTP	FAETP	MAETP	TETP	FSETP	MSETP	POCP	AP	EP	EC	WC	MTL	WST
1	Electric services (utilities)	0	0	22	0	8	0	11	0	11	0	17	26	18	25	28	0	0
2	Cotton	0	9	0	0	0	45	0	42	0	0	0	0	10	0	0	0	0
3	Brick and structural clay tile	0	0	1	0	21	0	41	0	41	0	0	0	0	0	0	0	0
4	Trucking and courier services, except air	0	41	11	0	0	0	0	0	0	-1	35	5	24	10	0	0	0
5	Sand and gravel	0	0	1	0	0	0	0	0	0	-1	0	0	0	2	0	59	31
6	Crude petroleum and natural gas	71	0	9	0	0	0	0	0	0	0	7	3	5	1	0	1	14
7	Mineral wool	0	0	4	81	3	0	0	1	0	5	5	0	1	1	0	0	0
8	Coal	47	0	3	0	2	1	1	1	1	-1	1	0	-1	0	0	3	42
9	Industrial inorganic and organic chemicals	0	0	3	38	23	4	1	9	3	38	7	4	6	0	0	1	9
10	Dimension, crushed and broken stone	0	-1	2	-1	-1	0	0	-1	0	-1	0	0	0	2	0	87	0

APPENDIX G2 (CONTINUED)

Natural Resources and Land Use Impact Grouping

		Number of Standard Deviations from the Mean							Factor Influence (change in vector orientation, in degrees)					
Rank	Description	ADP	LUC	EC	WC	MTL	WST	Vector Magnitude	ADP	LUC	EC	WC	MTL	WST
1	Electric services (utilities)	-0.07	-0.14	18.94	21.17	-0.08	-0.14	28.40	0	0	42	48	0	0
2	Sand and gravel	-0.07	-0.14	0.49	-0.02	15.96	9.64	18.65	0	0	2	0	59	31
3	Crude petroleum and natural gas	17.09	-0.14	0.18	-0.03	0.25	4.42	17.65	75	0	1	0	1	15
4	Coal	12.42	-0.14	-0.07	-0.05	0.92	11.45	16.92	47	0	0	0	3	43
5	Trucking and courier services, except air	-0.07	13.32	3.32	-0.03	-0.09	-0.14	13.73	0	76	14	0	0	-1
6	Dimension, crushed and broken stone	-0.06	-0.14	0.49	-0.04	13.64	0.00	13.65	0	-1	2	0	88	0
7	Forestry products	-0.07	3.12	0.01	-0.05	1.43	10.07	10.64	0	17	0	0	8	71
8	Petroleum refining	0.83	-0.14	0.79	-0.01	0.54	8.79	8.89	5	-1	5	0	3	82
9	Meat animals	-0.07	7.51	-0.14	-0.05	-0.09	-0.12	7.51	-1	88	-1	0	-1	-1
10	Blast furnaces and steel mills	-0.07	-0.14	6.97	0.08	-0.01	-0.14	6.98	-1	-1	88	1	0	-1

Toxicity Impact Grouping

		Number of Standard Deviations from the Mean							Factor Influence (change in vector orientation, in degrees)					
Rank	Description	HTP	FAETP	MAETP	TETP	FSETP	MSETP	Vector Magnitude	HTP	FAETP	MAETP	TETP	FSETP	MSETP
1	Brick and structural clay tile	10.21	-0.04	18.70	-0.09	18.62	-0.19	28.30	21	0	41	0	41	0
2	Cotton	-0.11	20.47	-0.09	19.33	-0.10	0.05	28.15	0	47	0	43	0	0
3	Electric services (utilities)	5.95	0.12	8.80	0.22	8.79	-0.18	13.79	26	0	40	1	40	-1
4	Paper and paperboard mills	5.91	0.95	0.33	2.51	0.65	10.70	12.54	28	4	1	12	3	59
5	Industrial inorganic and organic chemicals	6.45	1.01	0.41	2.44	0.72	10.18	12.37	31	5	2	11	3	55
6	Pulp mills	5.09	0.84	0.18	2.24	0.46	9.62	11.15	27	4	1	12	2	60
7	Primary aluminum	5.22	0.45	3.97	1.14	4.10	4.06	8.82	36	3	27	7	28	27
8	Copper ore	6.78	1.88	0.17	4.57	0.57	-0.16	8.42	54	13	1	33	4	-1
9	Plastics materials and resins	4.61	0.79	0.39	1.74	0.65	6.53	8.25	34	5	3	12	5	52
10	Primary smelting and refining of copper	5.34	0.73	0.02	1.89	0.18	-0.17	5.71	69	7	0	19	2	-2

APPENDIX G2 (CONTINUED)

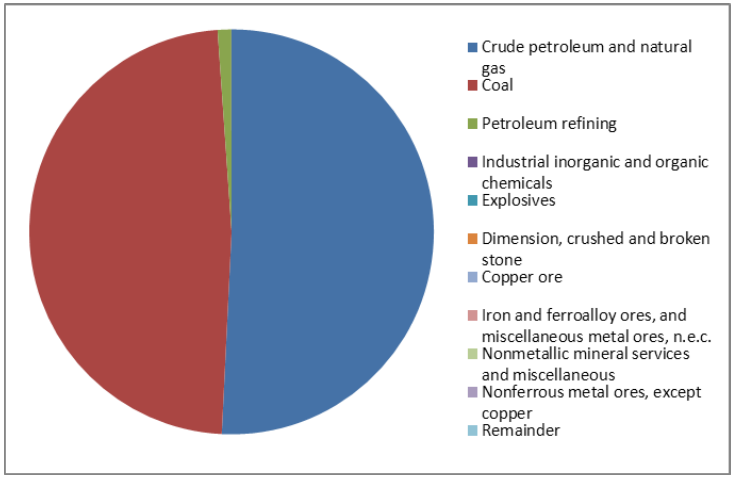
Pollution Impacts Grouping

		Number of Standard Deviations from the Mean						Factor Influence (change in vector orientation, in degrees)				
Rank	Description	GWP	ODP	POCP	AP	EP	Vector Magnitude	GWP	ODP	POCP	AP	EP
1	Electric services (utilities)	17.22	-0.12	13.48	19.74	13.86	32.56	32	0	24	37	25
2	Mineral wool	1.26	17.27	1.47	0.01	0.31	17.38	4	84	5	0	1
3	Trucking and courier services, except air	3.84	-0.12	11.43	1.80	8.21	14.70	15	0	51	7	34
4	Cement, hydraulic	6.68	-0.12	5.29	6.15	8.34	13.41	30	-1	23	27	38
5	Industrial inorganic and organic chemicals	0.95	10.01	2.10	1.23	1.67	10.48	5	73	12	7	9
6	Blast furnaces and steel mills	6.78	-0.11	5.52	2.48	2.18	9.35	46	-1	36	15	13
7	Railroads and related services	0.52	-0.13	1.09	1.20	5.55	5.80	5	-1	11	12	73
8	Sanitary services, steam supply, and irrigation…	3.31	-0.11	4.12	0.36	1.06	5.40	38	-1	50	4	11
9	Cotton	-0.09	-0.13	-0.17	-0.11	5.17	5.17	-1	-1	-2	-1	87
10	Miscellaneous crops	-0.17	-0.13	-0.22	-0.11	4.17	4.19	-2	-2	-3	-1	86

Appendix G3 – Occupancy-Phase Results by Impact Category

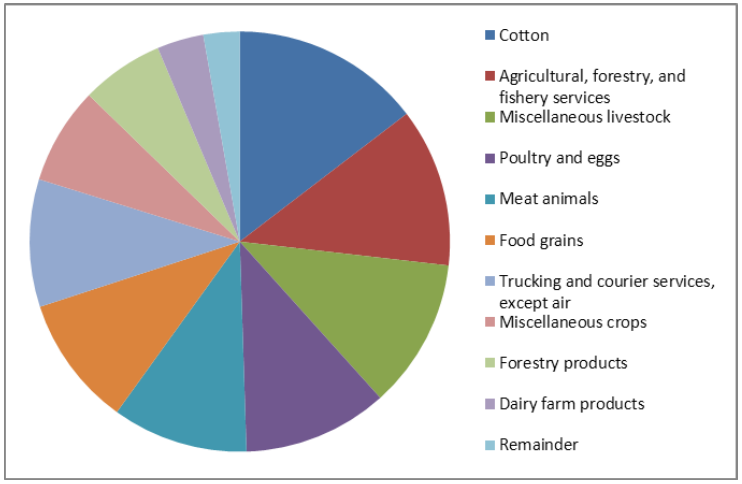
Abiotic Depletion Potential (ADP) – Output Contribution Analysis – Occupancy Phase

Rank	BEA Material/Product/Service Description	ADP (kg Sn eq.)	Contribution to Life Cycle ADP
1	Crude petroleum and natural gas	2,361.74	50.78%
2	Coal	2,238.20	48.12%
3	Petroleum refining	50.54	1.09%
4	Industrial inorganic and organic chemicals	0.65	0.01%
5	Explosives	0.21	0.00%
6	Dimension, crushed and broken stone	0.02	0.00%
7	Copper ore	0.00	0.00%
8	Iron and ferroalloy ores, and misc. metal...	0.00	0.00%
9	Nonmetallic mineral services and misc.	0.00	0.00%
10	Nonferrous metal ores, except copper	0.00	0.00%
	Total Accounted for in Top 10 M/P/S	4,651.36	100.00%
	Total Life Cycle ADP impacts	4,651.36	100.00%
	Remainder	0.00	0.00%



Land Use Competition (LUC) – Output Contribution Analysis – Occupancy Phase

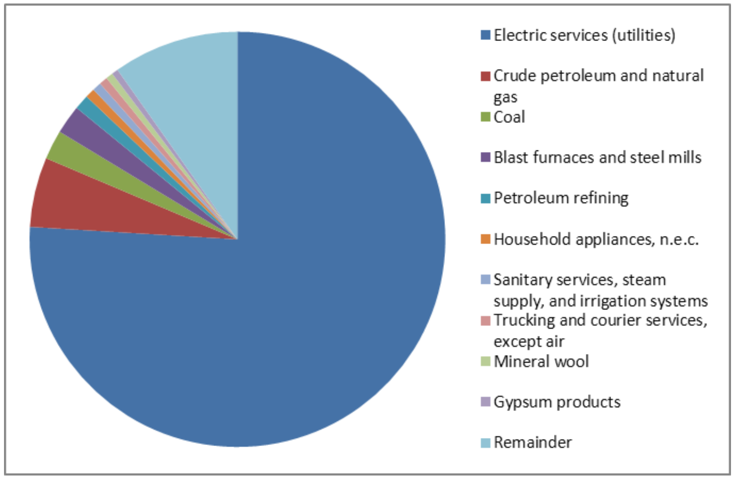
Rank	BEA Material/Product/Service Description	LUC (m2*yr)	Contribution to Life Cycle LUC
1	Cotton	3,591.56	14.60%
2	Agricultural, forestry, and fishery services	3,005.84	12.22%
3	Miscellaneous livestock	2,836.48	11.53%
4	Poultry and eggs	2,741.37	11.14%
5	Meat animals	2,570.39	10.45%
6	Food grains	2,469.93	10.04%
7	Trucking and courier services, except air	2,415.68	9.82%
8	Miscellaneous crops	1,838.66	7.47%
9	Forestry products	1,564.98	6.36%
10	Dairy farm products	881.72	3.58%
	Total Accounted for in Top 10 M/P/S	23,916.62	97.21%
	Total Life Cycle LUC impacts	24,601.79	100.00%
	Remainder	685.17	2.79%



APPENDIX G3 (CONTINUED)

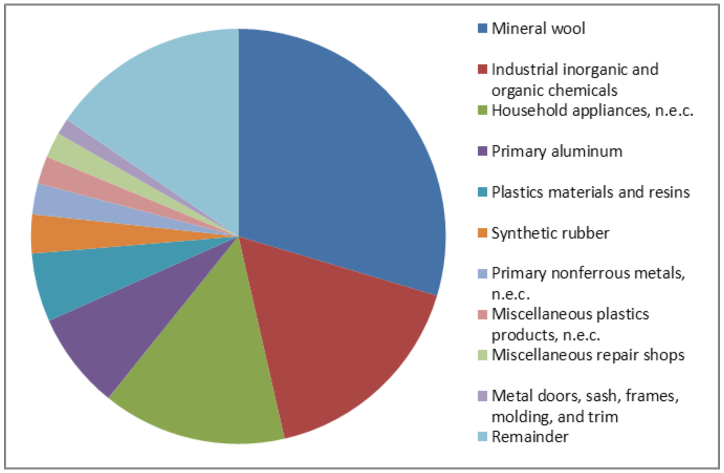
Global Warming Potential (GWP) – Output Contribution Analysis – Occupancy Phase

Rank	BEA Material/Product/Service Description	GWP (kg CO2 eq.)	Contribution to Life Cycle GWP
1	Electric services (utilities)	576,357.80	75.96%
2	Crude petroleum and natural gas	41,204.78	5.43%
3	Coal	17,305.55	2.28%
4	Blast furnaces and steel mills	17,086.43	2.25%
5	Petroleum refining	8,728.37	1.15%
6	Household appliances, n.e.c.	5,638.15	0.74%
7	Sanitary services, steam supply, and irrig...	5,207.66	0.69%
8	Trucking and courier services, except air	4,993.35	0.66%
9	Mineral wool	4,143.56	0.55%
10	Gypsum products	3,824.58	0.50%
	Total Accounted for in Top 10 M/P/S	684,490.23	90.21%
	Total Life Cycle GWP impacts	758,781.76	100.00%
	Remainder	74,291.53	9.79%



Stratospheric Ozone Depletion Potential (ODP) – Output Contribution Analysis – Occupancy Phase

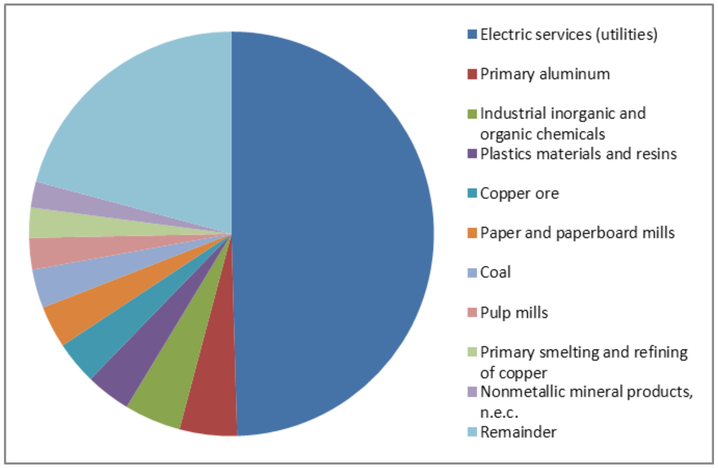
Rank	BEA Material/Product/Service Description	ODP (g CFC-11 eq.)	Contribution to Life Cycle ODP
1	Mineral wool	337.05	29.62%
2	Industrial inorganic and organic chemicals	191.25	16.80%
3	Household appliances, n.e.c.	163.55	14.37%
4	Primary aluminum	85.82	7.54%
5	Plastics materials and resins	60.82	5.34%
6	Synthetic rubber	34.42	3.02%
7	Primary nonferrous metals, n.e.c.	27.47	2.41%
8	Miscellaneous plastics products, n.e.c.	24.49	2.15%
9	Miscellaneous repair shops	22.57	1.98%
10	Metal doors, sash, frames, molding, and trim	14.36	1.26%
	Total Accounted for in Top 10 M/P/S	961.79	84.51%
	Total Life Cycle ODP impacts	1,138.08	100.00%
	Remainder	176.29	15.49%



APPENDIX G3 (CONTINUED)

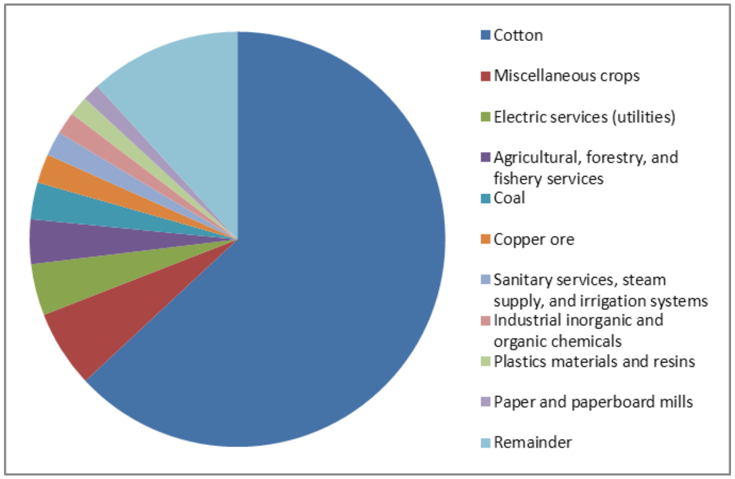
Human Toxicity Potential (HTP) – Output Contribution Analysis – Occupancy Phase

Rank	BEA Material/Product/Service Description	HTP (kg p-DCB eq.)	Contribution to Life Cycle HTP
1	Electric services (utilities)	19,183.45	49.55%
2	Primary aluminum	1,773.02	4.58%
3	Industrial inorganic and organic chemicals	1,752.57	4.53%
4	Plastics materials and resins	1,388.53	3.59%
5	Copper ore	1,333.96	3.45%
6	Paper and paperboard mills	1,302.82	3.37%
7	Coal	1,196.65	3.09%
8	Pulp mills	979.22	2.53%
9	Primary smelting and refining of copper	931.22	2.41%
10	Nonmetallic mineral products, n.e.c.	808.05	2.09%
	Total Accounted for in Top 10 M/P/S	30,649.50	79.17%
	Total Life Cycle HTP impacts	38,712.02	100.00%
	Remainder	8,062.52	20.83%



Freshwater Aquatic Ecotoxicity Potential (FAETP) – Output Contribution Analysis – Occupancy Phase

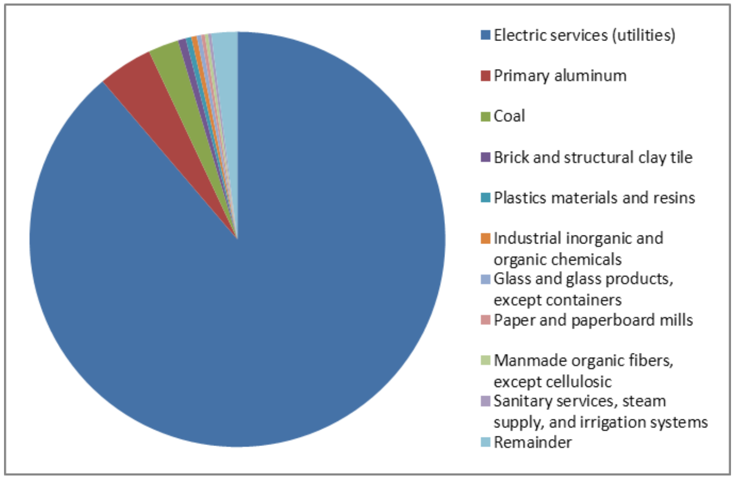
Rank	BEA Material/Product/Service Description	FAETP (kg p-DCB eq.)	Contribution to Life Cycle FAETP
1	Cotton	3,457.51	63.06%
2	Miscellaneous crops	329.51	6.01%
3	Electric services (utilities)	220.04	4.01%
4	Agricultural, forestry, and fishery services	190.24	3.47%
5	Coal	157.21	2.87%
6	Copper ore	124.09	2.26%
7	Sanitary services, steam supply, and irrig...	104.74	1.91%
8	Industrial inorganic and organic chemicals	95.68	1.75%
9	Plastics materials and resins	84.08	1.53%
10	Paper and paperboard mills	73.64	1.34%
	Total Accounted for in Top 10 M/P/S	4,836.77	88.21%
	Total Life Cycle FAETP impacts	5,482.93	100.00%
	Remainder	646.17	11.79%



APPENDIX G3 (CONTINUED)

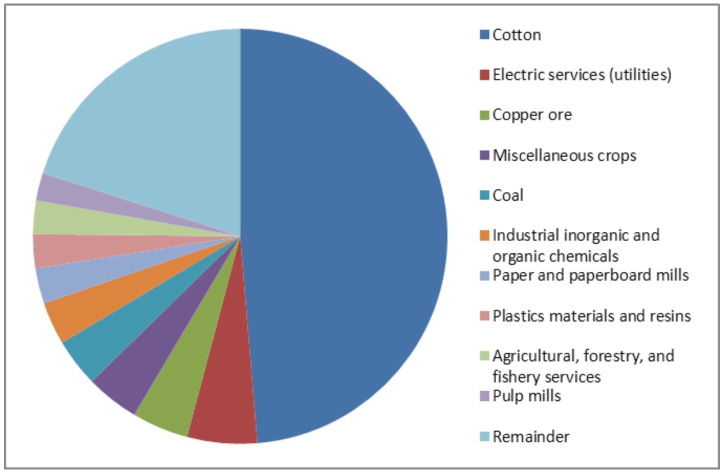
Marine Aquatic Ecotoxicity Potential (MAETP) – Output Contribution Analysis – Occupancy Phase

Rank	BEA Material/Product/Service Description	MAETP (mton p-DCB eq.)	Contribution to Life Cycle MAETP
1	Electric services (utilities)	218,884.87	88.76%
2	Primary aluminum	10,464.55	4.24%
3	Coal	5,834.30	2.37%
4	Brick and structural clay tile	1,516.88	0.62%
5	Plastics materials and resins	1,086.92	0.44%
6	Industrial inorganic and organic chemicals	1,039.04	0.42%
7	Glass and glass products, except containers	860.43	0.35%
8	Paper and paperboard mills	695.57	0.28%
9	Manmade organic fibers, except cellulosic	633.97	0.26%
10	Sanitary services, steam supply, and irrig...	605.55	0.25%
	Total Accounted for in Top 10 M/P/S	241,622.08	97.98%
	Total Life Cycle MAETP impacts	246,592.22	100.00%
	Remainder	4,970.13	2.02%



Terrestrial Ecotoxicity Potential (TETP) – Output Contribution Analysis – Occupancy Phase

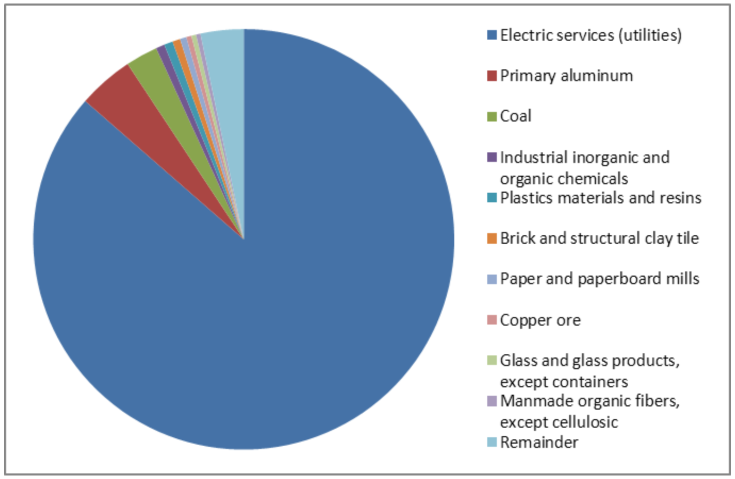
Rank	BEA Material/Product/Service Description	TETP (kg p-DCB eq.)	Contribution to Life Cycle TETP
1	Cotton	3,043.21	48.68%
2	Electric services (utilities)	341.28	5.46%
3	Copper ore	275.27	4.40%
4	Miscellaneous crops	259.69	4.15%
5	Coal	234.84	3.76%
6	Industrial inorganic and organic chemicals	207.98	3.33%
7	Paper and paperboard mills	172.38	2.76%
8	Plastics materials and resins	165.45	2.65%
9	Agricultural, forestry, and fishery services	162.80	2.60%
10	Pulp mills	134.67	2.15%
	Total Accounted for in Top 10 M/P/S	4,997.58	79.93%
	Total Life Cycle TETP impacts	6,252.11	100.00%
	Remainder	1,254.52	20.07%



APPENDIX G3 (CONTINUED)

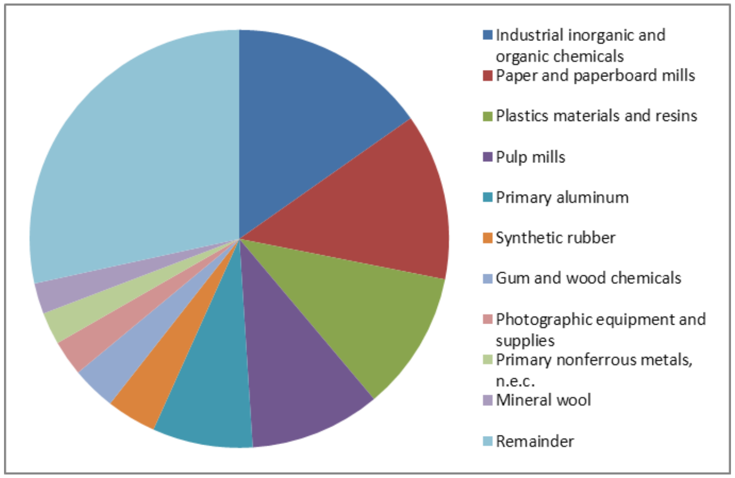
Freshwater Sediment Ecotoxicity Potential (FSETP) – Output Contribution Analysis – Occupancy Phase

Rank	BEA Material/Product/Service Description	FSETP (mton p-DCB eq.)	Contribution to Life Cycle FSETP
1	Electric services (utilities)	72,378.80	86.42%
2	Primary aluminum	3,578.54	4.27%
3	Coal	2,065.95	2.47%
4	Industrial inorganic and organic chemicals	562.75	0.67%
5	Plastics materials and resins	561.11	0.67%
6	Brick and structural clay tile	499.39	0.60%
7	Paper and paperboard mills	415.03	0.50%
8	Copper ore	333.55	0.40%
9	Glass and glass products, except containers	301.46	0.36%
10	Manmade organic fibers, except cellulosic	285.38	0.34%
	Total Accounted for in Top 10 M/P/S	80,981.97	96.70%
	Total Life Cycle FSETP impacts	83,747.98	100.00%
	Remainder	2,766.01	3.30%



Marine Sediment Ecotoxicity Potential (MSETP) – Output Contribution Analysis – Occupancy Phase

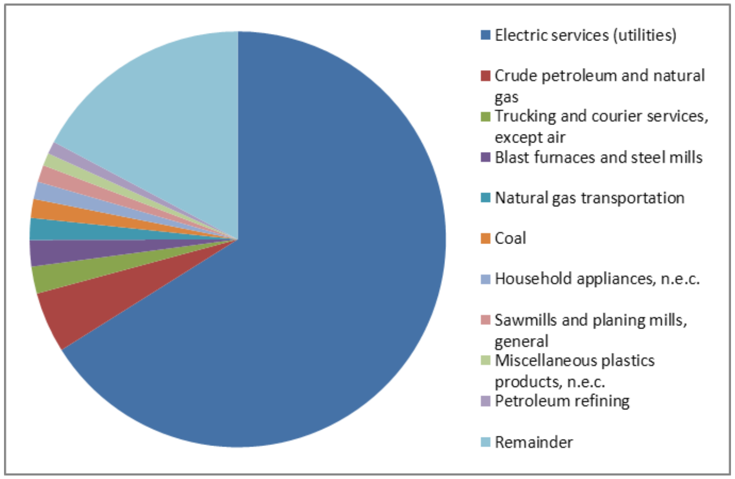
Rank	BEA Material/Product/Service Description	MSETP (kg p-DCB eq.)	Contribution to Life Cycle MSETP
1	Industrial inorganic and organic chemicals	6,328.72	15.21%
2	Paper and paperboard mills	5,366.14	12.90%
3	Plastics materials and resins	4,485.17	10.78%
4	Pulp mills	4,197.51	10.09%
5	Primary aluminum	3,216.81	7.73%
6	Synthetic rubber	1,600.71	3.85%
7	Gum and wood chemicals	1,413.42	3.40%
8	Photographic equipment and supplies	1,137.86	2.74%
9	Primary nonferrous metals, n.e.c.	1,036.62	2.49%
10	Mineral wool	990.39	2.38%
	Total Accounted for in Top 10 M/P/S	29,773.35	71.57%
	Total Life Cycle MSETP impacts	41,601.17	100.00%
	Remainder	11,827.82	28.43%



APPENDIX G3 (CONTINUED)

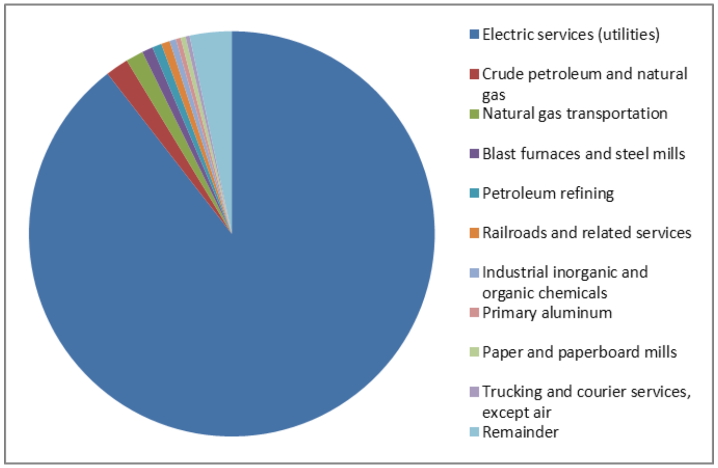
Photochemical Ozone Creation Potential (POCP) – Output Contribution Analysis – Occupancy Phase

Rank	BEA Material/Product/Service Description	POCP (kg C4H4 eq.)	Contribution to Life Cycle POCP
1	Electric services (utilities)	167.38	66.07%
2	Crude petroleum and natural gas	11.97	4.72%
3	Trucking and courier services, except air	5.33	2.10%
4	Blast furnaces and steel mills	5.20	2.05%
5	Natural gas transportation	4.31	1.70%
6	Coal	3.72	1.47%
7	Household appliances, n.e.c.	3.43	1.35%
8	Sawmills and planing mills, general	3.37	1.33%
9	Miscellaneous plastics products, n.e.c.	2.48	0.98%
10	Petroleum refining	2.47	0.97%
	Total Accounted for in Top 10 M/P/S	209.67	82.76%
	Total Life Cycle POCP impacts	253.35	100.00%
	Remainder	43.68	17.24%



Acidification Potential (AP) – Output Contribution Analysis – Occupancy Phase

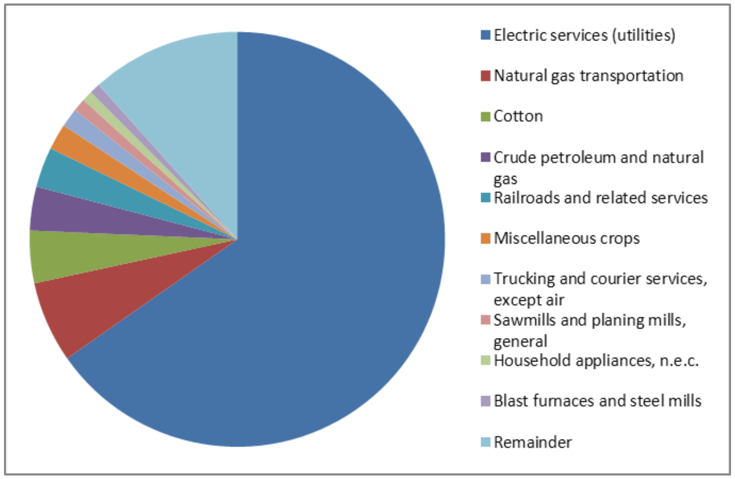
Rank	BEA Material/Product/Service Description	AP (kg SO2 eq.)	Contribution to Life Cycle AP
1	Electric services (utilities)	4,494.91	89.50%
2	Crude petroleum and natural gas	92.21	1.84%
3	Natural gas transportation	70.08	1.40%
4	Blast furnaces and steel mills	43.40	0.86%
5	Petroleum refining	37.73	0.75%
6	Railroads and related services	34.65	0.69%
7	Industrial inorganic and organic chemicals	25.62	0.51%
8	Primary aluminum	19.85	0.40%
9	Paper and paperboard mills	19.75	0.39%
10	Trucking and courier services, except air	16.21	0.32%
	Total Accounted for in Top 10 M/P/S	4,854.41	96.66%
	Total Life Cycle AP impacts	5,022.33	100.00%
	Remainder	167.92	3.34%



APPENDIX G3 (CONTINUED)

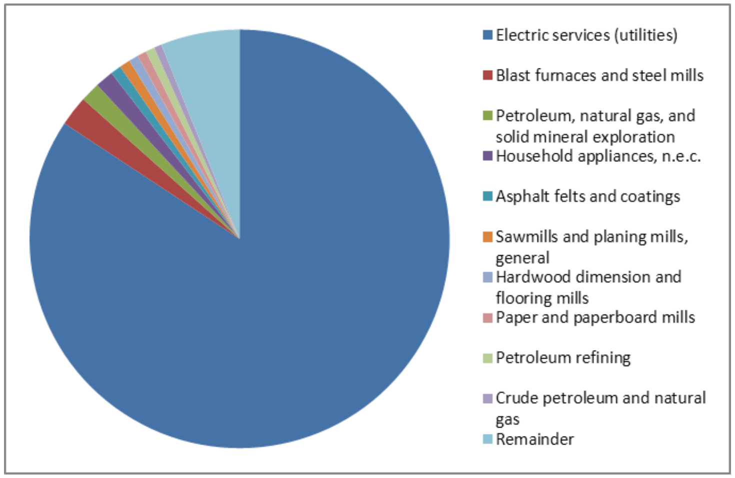
Eutrophication Potential (EP) – Output Contribution Analysis – Occupancy Phase

Rank	BEA Material/Product/Service Description	EP (kg PO4 eq.)	Contribution to Life Cycle EP
1	Electric services (utilities)	161.49	65.28%
2	Natural gas transportation	15.64	6.32%
3	Cotton	10.10	4.08%
4	Crude petroleum and natural gas	8.45	3.41%
5	Railroads and related services	7.74	3.13%
6	Miscellaneous crops	5.03	2.03%
7	Trucking and courier services, except air	3.62	1.46%
8	Sawmills and planing mills, general	2.49	1.01%
9	Household appliances, n.e.c.	2.04	0.83%
10	Blast furnaces and steel mills	2.03	0.82%
	Total Accounted for in Top 10 M/P/S	218.63	88.37%
	Total Life Cycle EP impacts	247.40	100.00%
	Remainder	28.78	11.63%



Energy Consumption (EC) – Output Contribution Analysis – Occupancy Phase

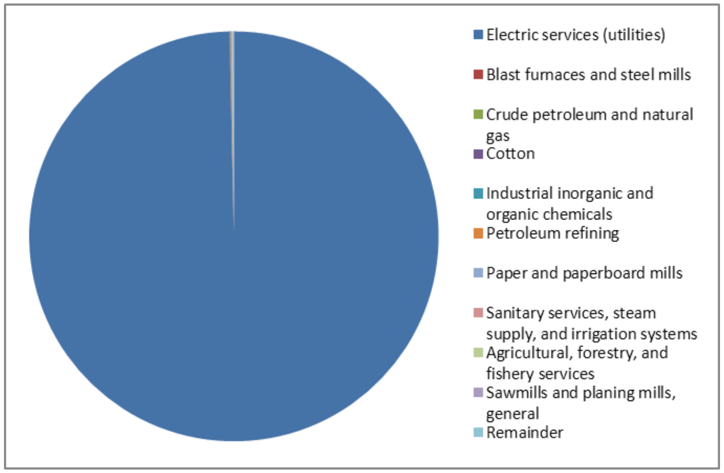
Rank	BEA Material/Product/Service Description	EC (mBTU)	Contribution to Life Cycle EC
1	Electric services (utilities)	11,618.99	84.30%
2	Blast furnaces and steel mills	320.93	2.33%
3	Petrol., natural gas, and solid min. explor...	208.46	1.51%
4	Household appliances, n.e.c.	194.97	1.41%
5	Asphalt felts and coatings	113.98	0.83%
6	Sawmills and planing mills, general	113.74	0.83%
7	Hardwood dimension and flooring mills	100.29	0.73%
8	Paper and paperboard mills	97.45	0.71%
9	Petroleum refining	95.89	0.70%
10	Crude petroleum and natural gas	80.24	0.58%
	Total Accounted for in Top 10 M/P/S	12,944.92	93.92%
	Total Life Cycle EC impacts	13,783.16	100.00%
	Remainder	838.23	6.08%



APPENDIX G3 (CONTINUED)

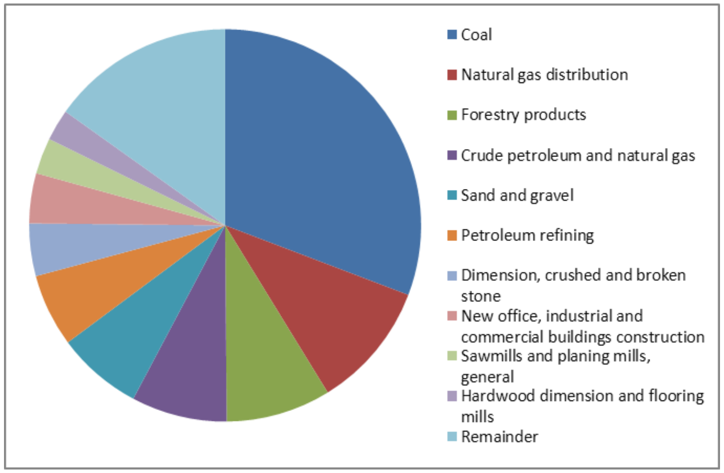
Water Consumption (WC) – Output Contribution Analysis – Occupancy Phase

Rank	BEA Material/Product/Service Description	WC (10^3 gal)	Contribution to Life Cycle WC
1	Electric services (utilities)	252,935.22	99.66%
2	Blast furnaces and steel mills	117.33	0.05%
3	Crude petroleum and natural gas	102.99	0.04%
4	Cotton	102.23	0.04%
5	Industrial inorganic and organic chemicals	82.69	0.03%
6	Petroleum refining	77.02	0.03%
7	Paper and paperboard mills	50.59	0.02%
8	Sanitary services, steam supply, and irrig...	34.54	0.01%
9	Agricultural, forestry, and fishery services	25.49	0.01%
10	Sawmills and planing mills, general	23.72	0.01%
	Total Accounted for in Top 10 M/P/S	253,551.82	99.90%
	Total Life Cycle WC impacts	253,807.60	100.00%
	Remainder	255.78	0.10%



Material Input (MTL) – Output Contribution Analysis – Occupancy Phase

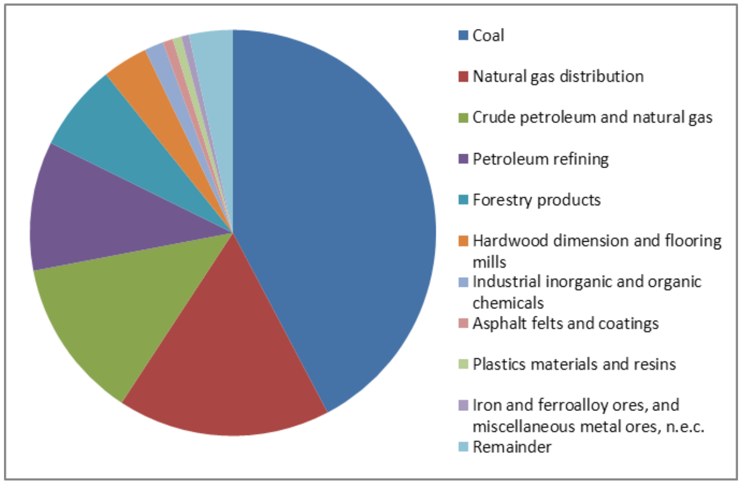
Rank	BEA Material/Product/Service Description	MTL (mton)	Contribution to Life Cycle MTL
1	Coal	322.92	30.76%
2	Natural gas distribution	109.85	10.47%
3	Forestry products	90.72	8.64%
4	Crude petroleum and natural gas	82.82	7.89%
5	Sand and gravel	74.19	7.07%
6	Petroleum refining	63.05	6.01%
7	Dimension, crushed and broken stone	45.46	4.33%
8	New office, industrial and commercial bldg	43.29	4.12%
9	Sawmills and planing mills, general	31.16	2.97%
10	Hardwood dimension and flooring mills	27.21	2.59%
	Total Accounted for in Top 10 M/P/S	890.69	84.85%
	Total Life Cycle MTL impacts	1,049.69	100.00%
	Remainder	159.01	15.15%



APPENDIX G3 (CONTINUED)

Waste (WST) – Output Contribution Analysis – Occupancy Phase

Rank	BEA Material/Product/Service Description	WST (mton)	Contribution to Life Cycle WST
1	Coal	263.43	42.28%
2	Natural gas distribution	105.58	16.95%
3	Crude petroleum and natural gas	79.62	12.78%
4	Petroleum refining	64.09	10.29%
5	Forestry products	43.36	6.96%
6	Hardwood dimension and flooring mills	22.54	3.62%
7	Industrial inorganic and organic chemicals	9.50	1.52%
8	Asphalt felts and coatings	5.06	0.81%
9	Plastics materials and resins	4.37	0.70%
10	Iron and ferroalloy ores, and misc. metal…	3.81	0.61%
	Total Accounted for in Top 10 M/P/S	601.36	96.52%
	Total Life Cycle WST impacts	623.03	100.00%
	Remainder	21.67	3.48%



APPENDIX G4 –VECTOR ANALYSIS RESULTS, OUTPUT CONTRIBUTION BASIS, OCCUPANCY PHASE

All Impacts

Rank	Description	Number of Standard Deviations from the Mean																	Vector Magnitude
		ADP	LUC	GWP	ODP	HTP	FAETP	MAETP	TETP	FSETP	MSETP	POCP	AP	EP	EC	WC	MTL	WST	
1	Electric services (utilities)	-0.07	-0.15	21.09	-0.10	20.70	1.26	21.13	2.23	21.13	-0.11	21.05	21.16	20.95	21.15	21.17	0.21	-0.10	63.23
2	Cotton	-0.07	9.57	-0.04	-0.12	-0.03	20.93	-0.05	20.60	-0.05	0.36	-0.06	-0.05	1.24	-0.05	-0.04	-0.11	-0.08	30.91
3	Coal	14.54	-0.15	0.57	-0.12	1.20	0.88	0.51	1.50	0.55	-0.15	0.40	-0.05	-0.03	-0.01	-0.05	17.78	18.24	29.42
4	Crude petroleum and natural gas	15.35	-0.15	1.45	-0.11	0.08	-0.05	-0.05	-0.03	-0.05	0.44	1.44	0.38	1.03	0.09	-0.04	4.46	5.44	17.05
5	Mineral wool	-0.07	-0.15	0.09	16.29	0.22	0.00	-0.05	0.11	-0.04	1.70	0.16	-0.04	0.00	-0.01	-0.05	-0.13	-0.10	16.38
6	Industrial inorganic and organic chemicals	-0.06	-0.15	0.06	9.19	1.81	0.51	0.05	1.32	0.11	11.81	0.23	0.07	0.17	-0.04	-0.04	0.58	0.56	15.16
7	Paper and paperboard mills	-0.07	-0.15	0.01	-0.09	1.32	0.37	0.01	1.08	0.07	9.99	0.10	0.04	0.07	0.12	-0.04	-0.11	-0.08	10.14
8	Natural gas distribution	-0.07	-0.15	-0.03	-0.12	-0.03	-0.06	-0.05	-0.04	-0.05	0.31	-0.01	-0.03	0.03	-0.02	-0.05	5.96	7.25	9.40
9	Plastics materials and resins	-0.07	-0.15	0.03	2.84	1.41	0.44	0.05	1.03	0.11	8.32	0.14	-0.01	0.03	-0.02	-0.05	0.11	0.21	8.98
10	Agricultural, forestry, and fishery services	-0.07	7.98	-0.05	-0.12	-0.08	1.08	-0.05	1.01	-0.05	-0.15	-0.05	-0.05	0.08	-0.05	-0.05	-0.09	-0.09	8.12

Rank	Description	Factor Influence (change in vector orientation, in degrees)																
		ADP	LUC	GWP	ODP	HTP	FAETP	MAETP	TETP	FSETP	MSETP	POCP	AP	EP	EC	WC	MTL	WST
1	Electric services (utilities)	0	0	19	0	19	1	20	2	20	0	19	20	19	20	20	0	0
2	Cotton	0	18	0	0	0	43	0	42	0	1	0	0	2	0	0	0	0
3	Coal	30	0	1	0	2	2	1	3	1	0	1	0	0	0	0	37	38
4	Crude petroleum and natural gas	64	0	5	0	0	0	0	0	0	1	5	1	3	0	0	15	19
5	Mineral wool	0	-1	0	84	1	0	0	0	0	6	1	0	0	0	0	0	0
6	Industrial inorganic and organic chemicals	0	-1	0	37	7	2	0	5	0	51	1	0	1	0	0	2	2
7	Paper and paperboard mills	0	-1	0	0	7	2	0	6	0	80	1	0	0	1	0	-1	0
8	Natural gas distribution	0	-1	0	-1	0	0	0	0	0	2	0	0	0	0	0	39	51
9	Plastics materials and resins	0	-1	0	18	9	3	0	7	1	68	1	0	0	0	0	1	1
10	Agricultural, forestry, and fishery services	0	79	0	-1	-1	8	0	7	0	-1	0	0	1	0	0	-1	-1

APPENDIX G4 (CONTINUED)

Natural Resources and Land Use Impact Grouping

Rank	Description	Number of Standard Deviations from the Mean						Vector Magnitude	Factor Influence (change in vector orientation, in degrees)					
		ADP	LUC	EC	WC	MTL	WST		ADP	LUC	EC	WC	MTL	WST
1	Electric services (utilities)	-0.07	-0.15	21.15	21.17	0.21	-0.10	29.92	0	0	45	45	0	0
2	Coal	14.54	-0.15	-0.01	-0.05	17.78	18.24	29.33	30	0	0	0	37	38
3	Crude petroleum and natural gas	15.35	-0.15	0.09	-0.04	4.46	5.44	16.88	65	-1	0	0	15	19
4	Cotton	-0.07	9.57	-0.05	-0.04	-0.11	-0.08	9.57	0	89	0	0	-1	-1
5	Natural gas distribution	-0.07	-0.15	-0.02	-0.05	5.96	7.25	9.39	0	-1	0	0	39	51
6	Agricultural, forestry, and fishery services	-0.07	7.98	-0.05	-0.05	-0.09	-0.09	7.98	0	89	0	0	-1	-1
7	Miscellaneous livestock	-0.07	7.52	-0.06	-0.05	-0.13	-0.10	7.53	-1	89	0	0	-1	-1
8	Poultry and eggs	-0.07	7.27	-0.06	-0.05	-0.13	-0.10	7.27	-1	89	0	0	-1	-1
9	Forestry products	-0.07	4.09	-0.04	-0.05	4.90	2.92	7.02	-1	36	0	0	44	25
10	Meat animals	-0.07	6.80	-0.06	-0.05	-0.12	-0.09	6.81	-1	88	0	0	-1	-1

Toxicity Impact Grouping

Rank	Description	Number of Standard Deviations from the Mean						Vector Magnitude	Factor Influence (change in vector orientation, in degrees)					
		HTP	FAETP	MAETP	TETP	FSETP	MSETP		HTP	FAETP	MAETP	TETP	FSETP	MSETP
1	Electric services (utilities)	20.70	1.26	21.13	2.23	21.13	-0.11	36.44	35	2	35	4	35	0
2	Cotton	-0.03	20.93	-0.05	20.60	-0.05	0.36	29.37	0	45	0	45	0	1
3	Industrial inorganic and organic chemicals	1.81	0.51	0.05	1.32	0.11	11.81	12.03	9	2	0	6	1	79
4	Paper and paperboard mills	1.32	0.37	0.01	1.08	0.07	9.99	10.14	7	2	0	6	0	80
5	Plastics materials and resins	1.41	0.44	0.05	1.03	0.11	8.32	8.51	10	3	0	7	1	78
6	Pulp mills	0.97	0.27	-0.02	0.82	0.02	7.77	7.88	7	2	0	6	0	81
7	Primary aluminum	1.83	0.28	0.96	0.77	0.99	5.92	6.40	17	3	9	7	9	68
8	Synthetic rubber	0.38	0.07	-0.04	0.26	-0.02	2.86	2.89	7	1	-1	5	0	81
9	Miscellaneous crops	-0.05	1.93	-0.05	1.67	-0.05	-0.15	2.56	-1	49	-1	41	-1	-3
10	Gum and wood chemicals	0.26	0.04	-0.04	0.20	-0.03	2.50	2.52	6	1	-1	5	-1	82

APPENDIX G4 (CONTINUED)

Pollution Impacts Grouping

		Number of Standard Deviations from the Mean						Factor Influence (change in vector orientation, in degrees)				
Rank	Description	GWP	ODP	POCP	AP	EP	Vector Magnitude	GWP	ODP	POCP	AP	EP
1	Electric services (utilities)	21.09	-0.10	21.05	21.16	20.95	42.12	30	0	30	30	30
2	Mineral wool	0.09	16.29	0.16	-0.04	0.00	16.29	0	89	1	0	0
3	Industrial inorganic and organic chemicals	0.06	9.19	0.23	0.07	0.17	9.19	0	88	1	0	1
4	Household appliances, n.e.c.	0.15	7.84	0.36	-0.01	0.19	7.85	1	87	3	0	1
5	Primary aluminum	-0.01	4.06	0.22	0.04	0.01	4.06	0	87	3	1	0
6	Plastics materials and resins	0.03	2.84	0.14	-0.01	0.03	2.84	1	87	3	0	1
7	Crude petroleum and natural gas	1.45	-0.11	1.44	0.38	1.03	2.32	39	-3	38	9	26
8	Natural gas transportation	-0.05	-0.12	0.47	0.28	1.96	2.04	-1	-3	13	8	74
9	Synthetic rubber	-0.05	1.55	-0.05	-0.05	-0.07	1.56	-2	86	-2	-2	-2
10	Cotton	-0.04	-0.12	-0.06	-0.05	1.24	1.25	-2	-6	-3	-2	83

APPENDIX H – REPORT ON LIFE CYCLE IMPACTS OF NEW COMMERCIAL BUILDING CONSTRUCTION

The following report was developed for EPA in July 2010 as a follow-on to the Sustainable Materials Management Relative Ranking Analysis to analyze the life cycle impacts associated with "new office, industrial and commercial building construction."

The methods used for analysis of *new office, industrial and commercial building construction* were consistent with those described herein for the analysis of life cycle impacts associated with single-family homes, with the following exceptions:

- The analysis of *new office, industrial and commercial building construction* did not include analyses of material input and waste impact categories;
- The analysis of *new office, industrial and commercial building construction* did not include analyses of the use and end-of-life life cycle phases of these types of buildings; and
- The analysis of *new office, industrial, and commercial building construction* was completed using CEDA 3.0, incorporating BEA 2002 input-output tables.

In addition, several terminological refinements have been incorporated into this more recent report on single-family homes to better communicate the concepts, methodologies, and results to a wider audience. Specifically, the reader is referred to the Glossary of Terms and Appendix B of this single-family homes report for more complete definitions of terms and impact categories.

Finally, the findings and conclusions presented in the *new office, industrial and commercial building construction report* in this appendix reflect the insights that can be gained and limitations of input and output contribution analyses (see Section 2 of the single-family homes report for a more detailed discussion). The findings and conclusions of the analysis of life cycle impacts associated with *new office, industrial and commercial building construction* have not been subject to more in-depth supply chain analyses, nor have they benefited from more in-depth peer review. More detailed analyses and peer review could offer additional insights and refinements to the findings and conclusions presented herein.

Contribution analysis for new commercial building construction

New office, industrial and commercial building construction

July, 2010

(Updated with editorial revisions November, 2011)

INTRODUCTION

The EPA report, *Sustainable Materials Management: The Road Ahead* (EPA, 2009) lays out EPA's vision for shifting our society's focus from managing wastes to managing materials by taking a broader life-cycle view of materials management. The report included an analysis of priority materials, products, and services whose consumption results in the largest environmental impacts, material use, waste, water use and energy use in our economy (the 2020 Vision Relative Ranking Analysis). The analysis utilized the Comprehensive Environmental Data Archive (CEDA) 3.0 for deriving direct, intermediate and final consumption-based impacts and a vector analysis for ranking materials, products, and services based on multiple criteria. CEDA 3.0 conducts input-output life-cycle impact analyses using U.S. Bureau of Economic Analysis (BEA) data and various environmental statistics including the Toxic Releases Inventory (TRI) and the U.S. Greenhouse Gas inventory (Suh, 2005).

Among the highest ranked materials, products, and services identified in the Sustainable Materials Management report was the "New office, industrial and commercial building construction" product category, referred to herein for simplicity as "new commercial building construction." From a final consumption perspective, new commercial building construction was ranked among the top 20 materials, products, and services when all impacts and resource use categories were considered. In addition, the 2020 Vision Relative Ranking analysis indicated that the impacts associated with new commercial building construction are widespread, ranking it among the top 20 materials, products and services based on 9 of 13 environmental impact and resource use categories.

In order to better understand this finding, a contribution analysis was conducted to identify direct inputs to and supply-chain processes associated with new office, industrial and commercial building construction that contribute most significantly to the environmental and resource consumption impacts.[1]

APPROACH

The contribution analysis considers the contribution of inputs to and supply chain processes associated with new office, industrial and commercial building construction in terms of the following 15 impact categories:

- Abiotic depletion
- Land use
- Global warming
- Ozone layer depletion
- Human toxicity
- Freshwater aquatic ecotoxicity
- Marine aquatic ecotoxicity
- Terrestrial ecotoxicity
- Freshwater sedimental ecotoxicity
- Marine sedimental ecotoxicity
- Photochemical oxidation
- Acidification

[1] For supplemental information, contact Alison Kinn, Office of Pollution Prevention and Toxics, U.S. EPA.

- Eutrophication
- Energy consumption
- Water consumption
- Acidification
- Eutrophication
- Energy consumption
- Water consumption

Three types of contribution analysis were performed for each of the 15 impact categories.

- Scope analysis
- Input contribution analysis
- Output contribution analysis

Each of these analyses provides a different perspective on the impacts associated with new office, industrial and commercial building construction, including impacts embodied in major inputs (e.g., raw materials and manufactured products) and impacts generated during the construction (e.g., emissions from construction equipment).

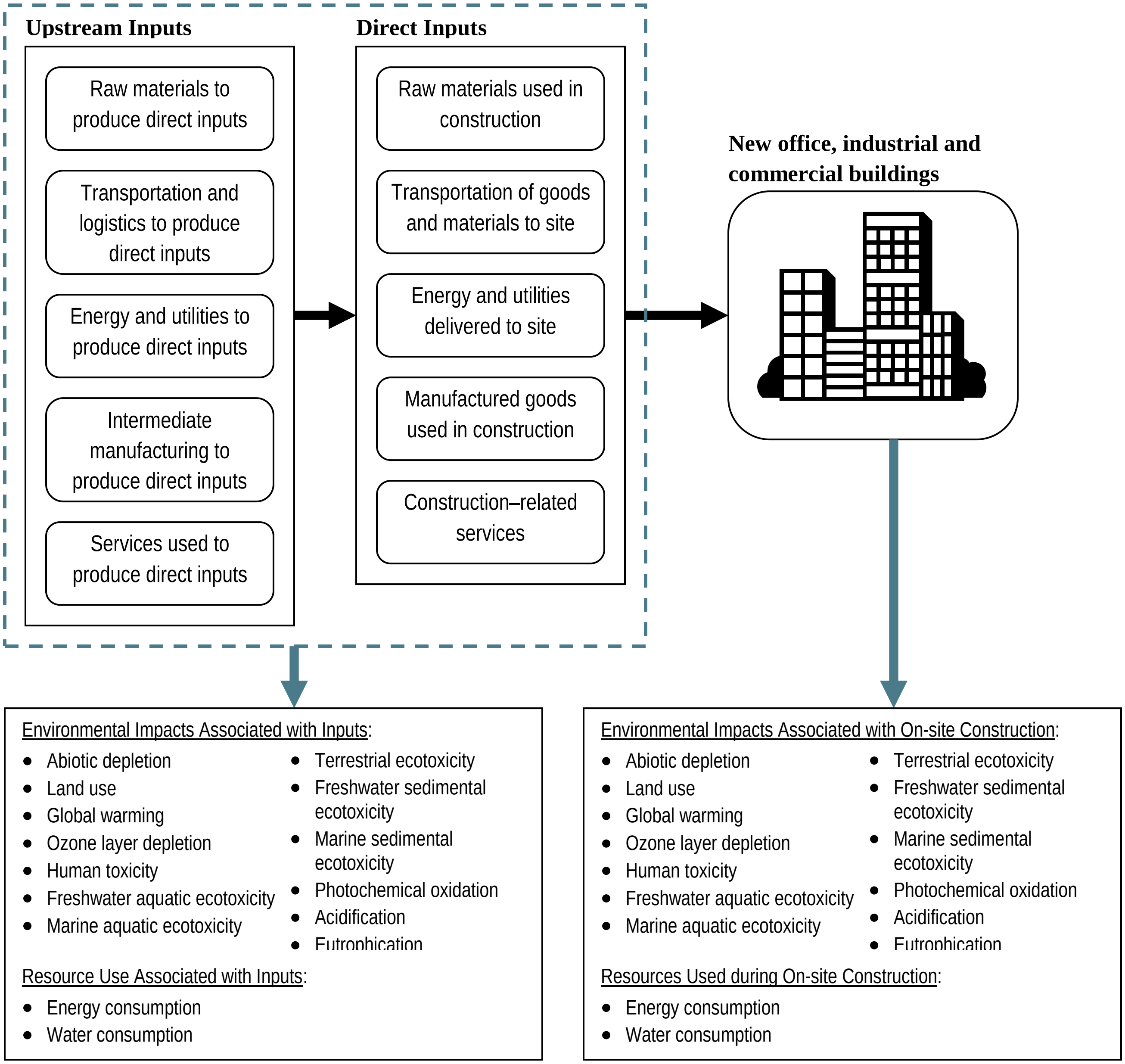
The scope analysis takes the broadest view, evaluating contributions to impact among impacts associated with on-site activities, impacts associated with the generation of electricity used in the construction, and all other impacts associated with inputs to the construction (e.g., from the extraction and delivery of raw materials, manufacture of products such as windows and doors or siding, etc.).

The input and output contribution analyses take a closer look at the direct inputs and supply chain processes contributing to the impacts associated with the construction of new office, industrial and commercial buildings. The input contribution analysis focuses on direct inputs to the new construction. The output contribution analysis allocates the impacts embodied in these direct inputs back through the supply chain.

Both types of analyses consider the impacts of inputs to the construction relative to direct on-site impacts. Both types of analyses are conducted first on an aggregated basis using categories such as “raw materials” and “manufactured products.” A more detailed analysis is then conducted to identify specific direct inputs and supply chain processes that contribute most significantly to the impacts associated with new office, industrial and commercial building construction.

Figure 1 provides a general overview of the approach used to conduct this contribution analysis. More detail regarding the approach is provided in Appendix A, and the results of the analyses are presented in Appendix B. A more detailed description of the methodologies used for contribution analysis is not within the scope of this report; interested readers are encouraged to consult the references cited in this report for further details.

Figure 1
Overview of Methodology for Contribution Analysis



Explanation of Contribution Analysis Methodology:

- The overall scope of the life-cycle analysis includes input and construction stages; it does not include the use stage and does not fully capture the end-of-life stage.
- The dotted line around inputs depicts the scope of the input stage of the life-cycle analysis.
- The aggregated contribution analyses (Appendix B, Tables B2 and B4) consider both input and construction stages; the detailed contribution analyses (Appendix B, Tables B3 and B5) address inputs only.
- Input contribution analysis accumulates life-cycle impacts at the level of "Direct Inputs," as shown above, plus direct emissions/consumption during construction.
- Output contribution analysis disaggregates life-cycle impacts to the level of "Upstream Inputs," as shown above, plus direct emissions/consumption during construction.

Results

Scope analysis

According to the scope analysis (Appendix B, Table B1 and associated figures), environmental impacts and energy/water use associated with inputs, other than electricity (i.e., Scope 3 impacts) dominate the overall life-cycle impacts associated with new office, industrial and commercial building construction. Most of the environmental impacts and energy and water consumption associated with new commercial building construction is embodied in the materials, products, and services and occurs prior to the actual construction.

Nonetheless, direct impacts by new commercial building construction activities (Scope 1 impacts) are reasonably significant in terms of global warming impacts, photochemical oxidation, acidification, eutrophication, and overall energy use. Direct global warming, photochemical oxidation, and acidification impacts as well as energy consumption are likely associated with on-site fossil fuel combustion during new commercial building construction activities (e.g., while operating construction equipment). Eutrophication impacts are likely associated with site run-off.

Input Contribution Analysis

According to the aggregated input contribution analysis (Appendix B, Table B2 and associated figures), impacts embodied in direct inputs used in new commercial building construction contribute most significantly to the total life-cycle impacts associated with this activity. While less significant, transportation and logistics (e.g., wholesale and retail trade) services associated with delivering materials and products to the job site contribute 5–12% in various impact categories. Other construction services (e.g., engineering, architectural, and surveying) also embodied from 5-12% of the overall impact in various impact categories.

The results of detailed input contribution analysis (Appendix B, Table B3) identify the ten direct inputs to residential construction that contribute most significantly within each impact category. The analysis identifies fabricated metal products in the list of the inputs contributing most significantly in all of the impact and resource use categories where new commercial building construction was ranked highly in the 2020 Vision analysis. Fabricated metal products ranked among the top ten inputs include:

- Prefabricated metal buildings and components
- Pipe, valves, and pipe fittings
- Fabricated structural metal
- Miscellaneous structural metal work
- Sheet metal work
- Metal doors, sash, frames, molding, and trim
- Non-ferrous wiredrawing and insulating

In addition, the category “motor vehicles and passenger car bodies” is identified as a significant contributor in several impact categories. This most likely reflects the use of light-duty vehicles in the construction trade. It may also reflect some cross-categorization in the BEA data with the “construction machinery and equipment” product category.

In addition to fabricated metal products, several non-metallic mineral products are identified as contributing significantly, particularly relative to some of the impact categories. Non-metallic mineral products ranked among the top ten inputs include:

- Brick and structural clay tile (human toxicity, marine aquatic ecotoxicity and freshwater sedimental ecotoxicity)
- Hydraulic cement and ready-mixed concrete (global warming, photochemical oxidation, acidification, and eutrophication)
- Cut stone and stone products (ozone layer depletion, human toxicity, and marine sedimental ecotoxicity)

Other inputs identified by the analysis as providing significant contributions include plastic products (ozone depletion, human toxicity, ecotoxicity categories), paints and allied products (ozone depletion, ecotoxicity categories), and carpets and rugs (ecotoxicity categories).

In general, the analysis showed that contributions to significant impacts were widely dispersed across direct inputs to new commercial building construction. In most cases, the top ten ranked materials, products, and services accounted for less than half of the overall impact associated with new commercial building construction, and the top ranked input typically accounted for less than 10% of the overall impact. The analysis identified two exceptions to this latter finding: brick and structural clay tile contributed 25% of the overall impact associated with marine aquatic ecotoxicity and 22% of the overall impact associated with freshwater sedimental ecotoxicity.

The results show the significance of fabricated metal products used in new commercial buildings and construction equipment from the standpoint of environmental impact. The results also emphasize the significance of basic building materials such as brick, structural clay tile, cement, ready-mixed concrete, cut stone and stone products as well as chemically-derived products such as plastics and paints and interior products such as carpets and rugs. In addition, service inputs such as engineering, architectural and surveying and transportation through retail and wholesale trade show significant contributions throughout the impact categories considered.

Output Contribution Analysis

Output contribution analysis allocates the impacts associated with direct inputs to the major processes involved in the supply chain associated with construction of new office, industrial, and commercial buildings. This analysis expands upon the information presented in the input analysis by identifying processes earlier in the supply chain that contribute most significantly to the overall impacts and resource use. Output contribution analysis, for example, can indicate impacts that are primarily associated with energy inputs or impacts associated with emissions resulting from the extraction of raw materials. In addition, output contribution analysis can highlight industries not identified in the input analysis, for example, where impacts are highly concentrated in early supply chain processes but are then allocated across a diverse range of final inputs.

The aggregated output contribution analysis (Appendix B, Table B4 and associated figures) shows that impacts associated with intermediate and final product manufacturing continue to dominate in terms of contribution to overall life-cycle impacts. However, the analysis also reveals the relatively greater importance of impacts generated during raw material extraction, impacts associated with energy and utility inputs, and transportation-related impacts as compared to input contribution analysis results.

For example, the raw material extraction phase dominates abiotic depletion. This result reflects the fact that the impacts associated with these earlier phases in the supply chain are embodied in direct inputs to commercial building construction mainly in the form of manufactured products (as measured in the input contribution analysis).

In addition to raw materials extraction and manufacturing, the use of energy and utilities contributes significantly to overall life-cycle impacts in fossil fuel combustion-related impact categories such as global warming, marine aquatic ecotoxicity, freshwater sedimental ecotoxicity, photochemical oxidation, and acidification. Use of energy and utilities dominates the water use category, as this category is defined in terms of "use" rather than "consumption" and, thus, the use of water for hydropower generally eclipses other uses.

The detailed output contribution analysis (Appendix B, Table B5) identifies the ten life-cycle processes that contribute most significantly to the life-cycle impacts associated with commercial building construction. Frequently appearing processes include:

- Metals and related processes, including iron and ferroalloy ores, copper ore, other non-ferrous metal ores, blast furnaces and steel mills, primary smelting and refining of copper, primary aluminum, and other primary non-ferrous metals
- Non-metallic minerals and related processes/products, including brick and structural clay tile, cut stone and stone products, glass and glass products, and ceramic wall and floor tile
- Industrial inorganic and organic chemicals and plastic materials and resins
- Paper and paperboard mills, pulp mills, and sawmills and planing mills
- Utilities, including electric services and sanitary services, steam supply, and irrigation
- Transportation-related processes

Among others, electric services (utilities) is not only one of the most frequent supply-chain process but also one of the largest contributors of impacts, ranked number 1 in 9 out of 15 impact categories.

The output analysis demonstrates how the demand for a complex product, such as new commercial buildings can contribute to certain environmental mechanisms through multiple supply chains and mechanisms. For example, the analysis consistently shows three process sectors – electric utilities, blast furnaces and steel mills, and hydraulic cement – as major contributors to global warming, photochemical oxidation, and acidification. Review of the output contribution analysis for energy consumption suggests that electric services and blast furnaces and steel mills contribute to these impacts via fossil fuel combustion to meet high energy needs. In contrast, the energy consumption results for hydraulic cement suggest that direct, non-combustion emissions from this industry are a significant source of the global warming, photochemical oxidation, and acidification impacts associated with new commercial building construction.

The output contribution analysis also highlights processes associated with inputs to new commercial building construction that were not consistently identified in the input contribution analysis, including wood products, glass, and ceramics. This finding emphasizes the value of examining impacts from multiple perspectives. For example, the 2020 Vision Relative Ranking Analysis ranked new commercial building construction among the top 20 materials, products, and services relative to marine sedimental ecotoxicity. The input contribution analysis does not identify forest products among the top ten contributors to these impacts. In contrast, the output perspective identifies paper and paperboard mills and pulp mills contributing 21% of the marine sedimental ecotoxicity impacts. This suggests that the impacts occur early in the supply chain and are then widely distributed among finished pulp and paper products used in new commercial building construction (e.g., reconstituted wood panels, construction papers).

Contribution Analysis by Impact/Use Category

The contribution analyses are further summarized in Appendix C, which compiles the results of each of the analyses for each of the environmental and resource use impact categories. By compiling the three perspectives by impact category, the tables offer further insights into the locus of impacts along the supply chain associated with new commercial building construction.

Review of the input and output contribution analysis results side-by-side suggests the following high-level supply chain patterns:

- Where the input contribution analysis indicates that metal products contribute most significantly to an impact, the output contribution analysis often highlights processes requiring high energy (electric services, blast furnaces and steel mills). This suggests that the use of fabricated metal products in new commercial building construction contributes significantly to the impacts of this sector due to the high energy associated with their supply chain, from extraction and primary processing through fabrication.

- Where primary building materials, such as brick and structural clay tile, stone and stone products, and cement and concrete, are identified as significant contributors to an impact, they are often identified as such from both input and output perspectives. This reflects the relatively minimal processing of these materials prior to their use in new commercial building construction. Impacts associated with extraction and early processing stages are not distributed among multiple inputs via the supply chain.

The diversity of the results of the input and output contribution analyses provides initial insights into the complexity of the relationship between new commercial building construction and its impact on the environment.

For example, the input contribution analysis suggests that fabricated metal products, non-metallic mineral products, and plastic products all contribute significantly to the human toxicity impacts associated with new commercial building construction. Review of the aggregate and detailed output contribution analyses suggests that a significant proportion of these impacts occur at the extraction stage and impacts occur through multiple environmental compartments (e.g., air emissions, water discharges). Review of the input and output contribution analyses relative to global warming impacts suggests a far less complex situation.

The complexity of the supply chain processes contributing to an environmental or resource use impact has implications for approaches for addressing these impacts, both in terms of the locus of action and the nature of the action. For example, in the case of brick and structural clay tile and its contribution to marine aquatic ecotoxicity, the analysis suggests the potential efficacy of policies focused narrowly on this one product area. Further, the close linkage between input and output contribution findings suggests that either end-product- or process-oriented policies could be effective. In contrast, the complexity of the impacts relative to human toxicity suggests that a more multi-faceted approach, involving, for example, multiple product standards and/or coordination among multiple environmental programs, would be needed to address this impact.

A more complete understanding of these supply chain interactions and their implications for policy action is beyond the scope of this study. Other, more detailed analyses, such a structural path analysis, could be used to further explore the findings suggested by the analyses described herein.

Summary and Discussion

In summary, the overall life-cycle impacts associated with new commercial building construction are characterized by significant amounts of on-site fossil fuel combustion; substantial use of energy-intensive inputs such as prefabricated metal building components, pipes, valves, pipe fittings, and construction equipment; transportation services (including retail/wholesale trade); and a complex array of products whose production involves significant amounts of toxic emissions (e.g., brick and structural clay tile, cut stone and stone products, plastic products, and wood products).

While many other products are manufactured using *either* energy intensive products *or* toxic emission-intensive products, commercial building construction incorporates *both* energy *and* toxic emission-intensive product inputs. The complex integration of materials, products, services, resources, and other inputs and their associated life-cycle impacts, combined with the direct impacts generated on-site, explains the relatively high ranking calculated for new commercial building construction in the Sustainable Materials Management Relative Ranking analysis.

Impacts embodied in direct inputs to new commercial building construction originate from significant life-cycle use of fossil fuel combustion-intensive products and services such as electric services, industrial inorganic and organic chemicals, ferrous and non-ferrous metals, and transportation and logistics. The use of these products and services in commercial building construction contributes not only to global warming and acidification but to other environmental impacts, as well. In addition, the complex mix of fabricated metal, non-metallic mineral, chemical, and forest product inputs used in commercial building construction contributes to air quality, human toxicity, and ecological toxicity impacts resulting from emissions via multiple environmental compartments.

As a point of comparison, the contribution analysis of new commercial building construction differs from the contribution analysis previously completed for new 1-unit residential building construction, primarily with regard to the environmental significance of fabricated metal products associated with building components and construction equipment. The analysis of new commercial building construction also stands out with regard to the lesser significance from an environmental standpoint of wood-based and plastic product inputs. On the other hand, both new residential and new commercial building construction share many common environmentally significant supply-chain processes including non-metallic mineral processes and materials (e.g., concrete, brick and structural clay tiles), electric services, and transportation-related processes.

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APPENDIX H-A

Methods for contribution analysis

Contribution analysis is used to gain insights regarding life-cycle assessment (LCA) results by identifying major "drivers" that shape the overall results. What is referred to here as "drivers" can include many things. For instance, drivers can be direct inputs to the main process in question such as "steel beams" to commercial building construction. A driver can also be a supply-chain process within the life cycle of a product such as "iron ore mining." While, iron ore may not be directly used in new commercial building construction, it is related to new commercial building construction through the supply chain by which iron ore is processed to form steel beams. In addition, a driver could be a particular substance that contributes substantial portion of a characterized result such as CO_2 for global warming.

In general, LCA studies often distinguish among the following classes of drivers:

- Direct inputs to a main process
- Supply-chain process
- Life cycle inventory item
- Life cycle impact category
- Life cycle stages

In addition, GHG accounts often distinguish "scopes". Scope 1 refers to on-site, direct emission from the main process in question, Scope 2 refers to emissions from electricity generation directly used by the main process, and Scope 3 refers to all other emissions from the supply-chain. Such a distinction helps us better understand the role of direct emissions and supply-chain induced emissions relative to total emissions.

The mode of computation and the level of aggregation used in LCA depend on the class of drivers selected and reflect different ways of slicing the total (Heijungs and Suh, 2002). Analysts often choose multiple classes of drivers to enable insights from multiple perspectives, which together help better understanding the whole picture.

In this report, we employed three classes of drivers for contribution analysis: (1) scopes, (2) direct inputs (input contribution analysis) and (3) life-cycle processes (output contribution analysis). The product considered in this study (new commercial building construction) involves at least 200 inputs and supply-chain processes, and, therefore, presentation of all of the contributions of all inputs and supply-chain processes would be impractical and difficult to interpret. Thus, direct inputs and life-cycle processes are shown in two different levels of aggregation for ease of presentation.

APPENDIX H-B – DETAILED CONTRIBUTION ANALYSIS RESULTS FOR COMMERCIAL BUILDING

H-B1. SCOPE ANALYSIS FOR NEW COMMERCIAL BUILDING CONSTRUCTION

This analysis shows where impacts take place in the entire life-cycle. Scope 1 impacts are the impacts associated with the operation of the production facility (on-site impact), Scope 2 impacts are the impacts associated with the direct electric utility supplier to the production facility, and Scope 3 impacts are the impacts associated with the rest of the supply-chain.

Table H-B1. Scope analysis for new commercial building construction

	Abiotic depletion	Land use increase of land competition	Global warming GWP100	Ozone layer depletion ODP steady state	Human toxicity HTP inf.	Freshwater aquatic ecotoxicity FAETP inf.	Marine aquatic ecotoxicity MAETP inf	Terrestrial ecotoxicity TETP inf
Scope 1	0%	0%	22%	0%	0%	0%	0%	0%
Scope 2	2%	0%	1%	0%	1%	0%	3%	0%
Scope 3	98%	100%	76%	100%	99%	100%	97%	100%
Total	100%	100%	100%	100%	100%	100%	100%	100%

	Freshwater sedimental ecotoxicity FSETP inf.	Marine sedimental ecotoxicity MSETP inf.	Photochemical oxidation (high NOx)	Acidification (incl. fate, average Europe total, A&B)	Eutrophication (fate not incl.)	Energy consumption (mBTU)	Water consumption (gallon)
Scope 1	0%	0%	20%	7%	15%	6%	0%
Scope 2	2%	0%	1%	3%	1%	2%	8%
Scope 3	98%	100%	79%	90%	84%	91%	92%
Total	100%	100%	100%	100%	100%	100%	100%

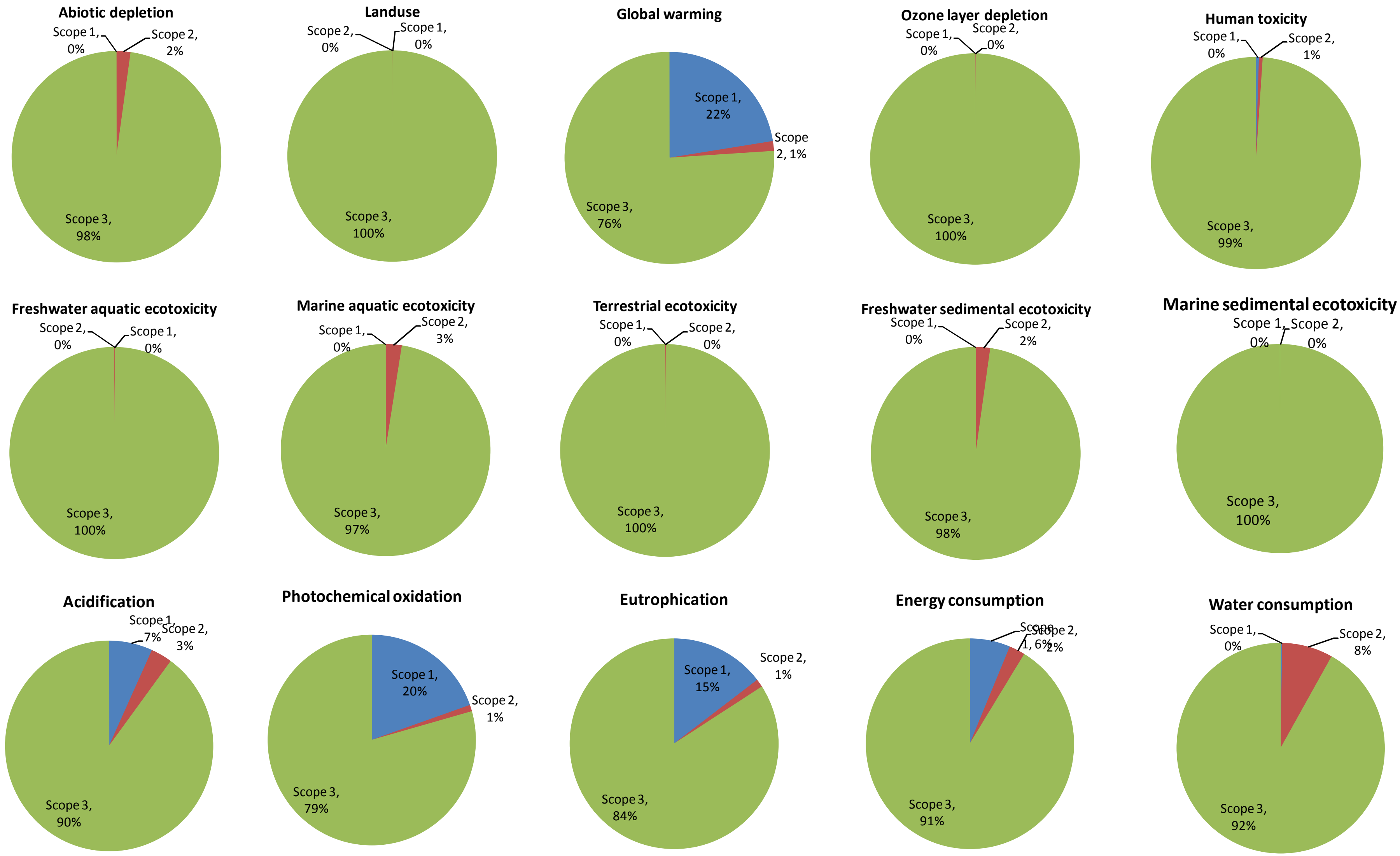

Figure H-B1. Pie charts for Scope Analysis (new commercial building construction)

H-B2. Total impact allocated over direct inputs and on-site operation (aggregated) for new commercial building construction

This analysis shows the relative importance of direct inputs to and on-site emission/use by new commercial building construction in terms of their contributions to each impact. A total of 205 direct inputs to new commercial building construction are aggregated into five categories: Raw material extraction, Transportation and logistics, Energy and utility, Manufacturing, and Service.

Table H-B2. Input contribution analysis for new commercial building construction

	Abiotic depletion	Land use	Global warming	Ozone layer depletion	Human toxicity	Freshwater aquatic ecotoxicity	Marine aquatic ecotoxicity	Terrestrial ecotoxicity
Raw material extraction	1%	20%	1%	0%	0%	11%	0%	7%
Transportation and logistics	10%	12%	7%	4%	5%	5%	5%	5%
Energy and utility	3%	0%	3%	0%	1%	2%	3%	2%
Manufacturing	79%	60%	61%	89%	88%	76%	86%	80%
Service	8%	9%	6%	6%	5%	6%	6%	6%
Direct emission/consumption	0%	0%	22%	0%	0%	0%	0%	0%
Total	100%	100%	100%	100%	100%	100%	100%	100%

	Freshwater sedimental ecotoxicity	Marine sedimental ecotoxicity	Photochemica l oxidation	Acidification	Eutrophication	Energy consumption	Water consumption
Raw material extraction	0%	1%	1%	0%	3%	1%	1%
Transportation and logistics	5%	6%	9%	9%	9%	11%	12%
Energy and utility	3%	0%	2%	4%	2%	3%	8%
Manufacturing	86%	85%	62%	72%	65%	71%	66%
Service	6%	7%	7%	8%	7%	8%	12%
Direct emission/consumption	0%	0%	20%	7%	15%	6%	0%
Total	100%	100%	100%	100%	100%	100%	100%

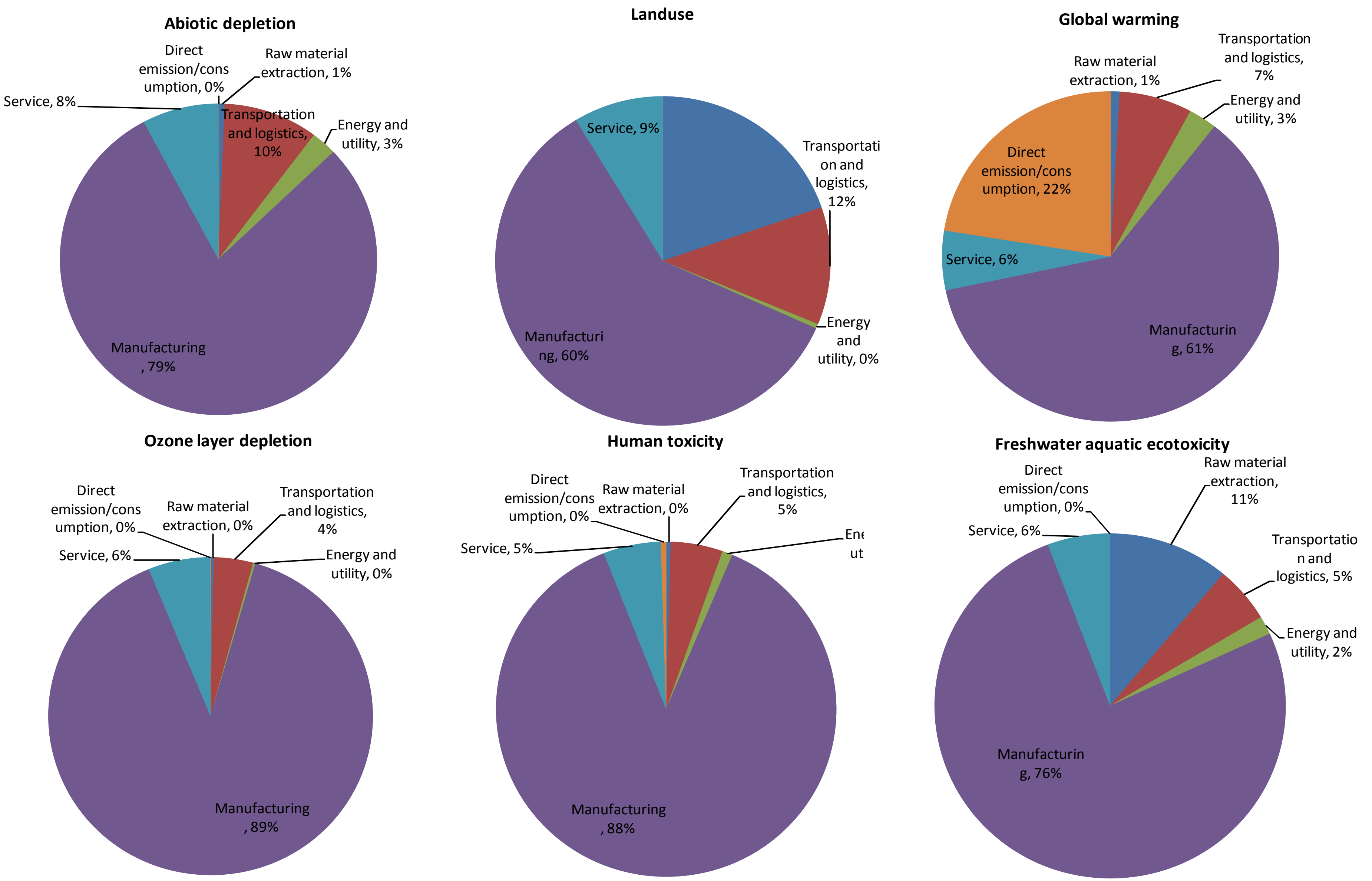

Figure H-B2a. Input contribution analysis for new commercial building construction

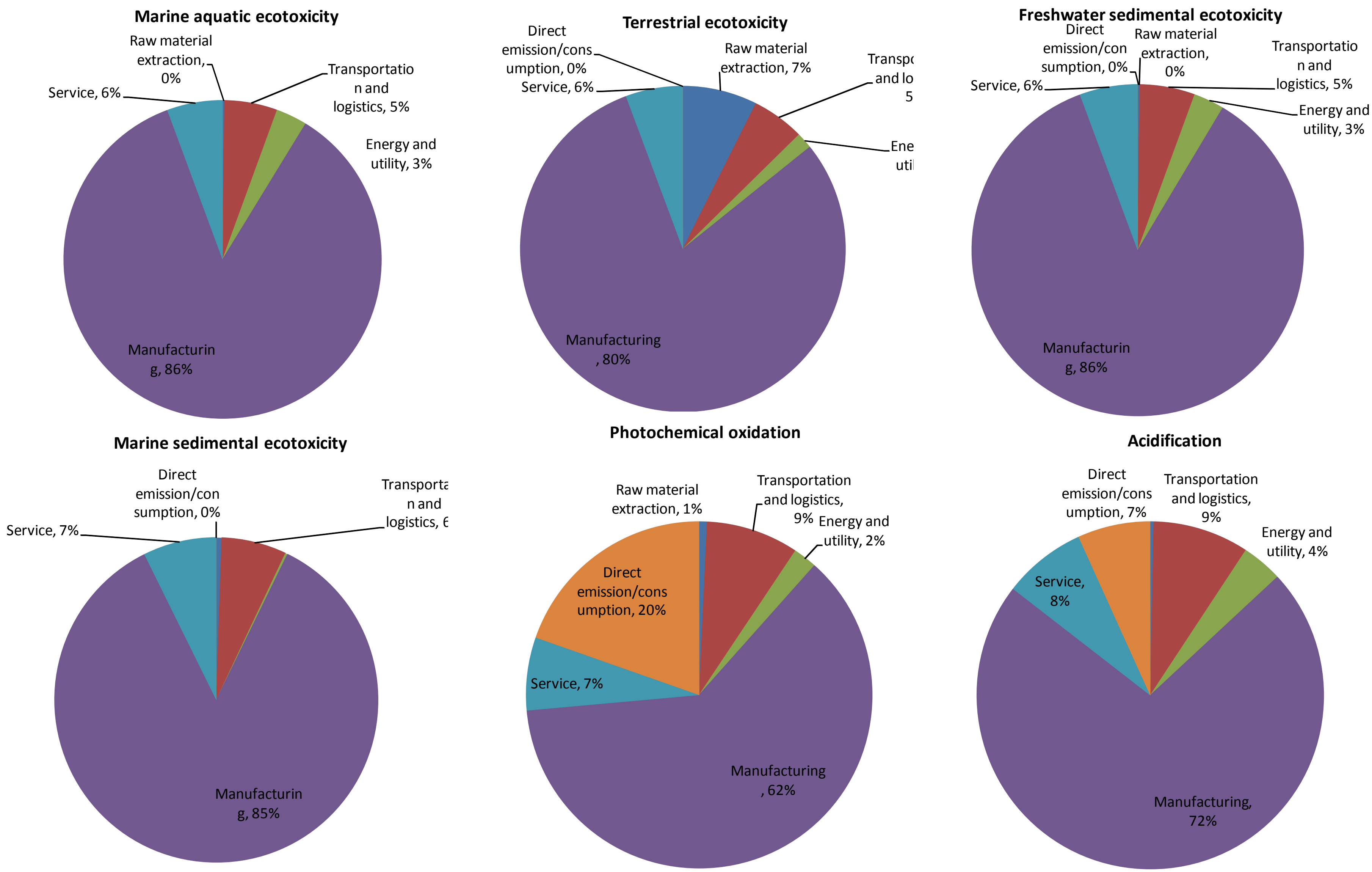

Figure H-B2b. Input contribution analysis for new commercial building construction

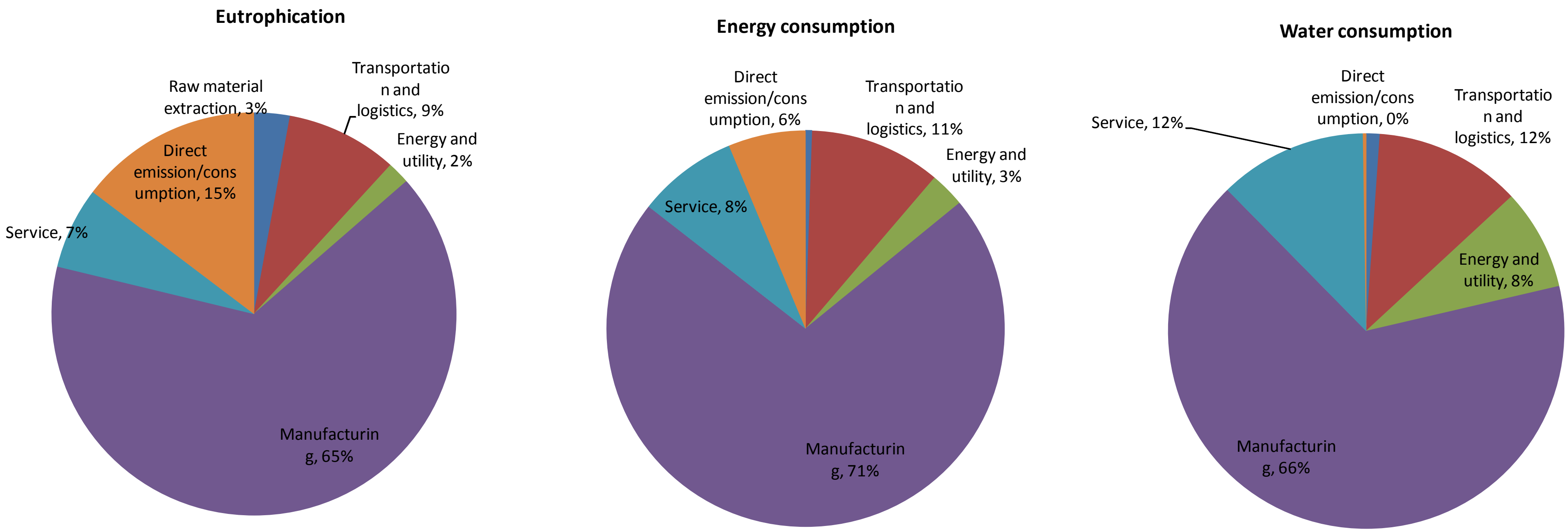

Figure H-B2c. Input contribution analysis for new commercial building construction

H-B3. Total supply-chain impact allocated over direct inputs (details for top 10 contributors)

This analysis shows the relative importance of direct inputs to new commercial building construction in terms of their contribution to each impact. A total of 205 direct inputs to new commercial building construction are distinguished in the analysis, and the 10 inputs contributing most significantly to the life cycle impact are identified for each impact category in this table.

Table H-B3. Input contribution analysis for new commercial building construction—detail for top 10 inputs

Rank	Abiotic depletion	Contribution	Land use	Contribution	Global warming	Contribution
1	Prefabricated metal buildings and components	5%	Feed grains	19%	Prefabricated metal buildings and components	5%
2	Engineering, architectural, and surveying	4%	Sawmills and planing mills, general	8%	Cement, hydraulic	4%
3	Motor vehicles and passenger car bodies	4%	Trucking and courier services, except air	6%	Ready-mixed concrete	4%
4	Fabricated structural metal	4%	Veneer and plywood	4%	Motor vehicles and passenger car bodies	4%
5	Retail trade, except eating and drinking	4%	Motor vehicles and passenger car bodies	4%	Engineering, architectural, and surveying	4%
6	Pipe, valves, and pipe fittings	3%	Millwork	3%	Fabricated structural metal	4%
7	Wholesale trade	3%	Engineering, architectural, and surveying	3%	Pipe, valves, and pipe fittings	3%
8	Miscellaneous structural metal work	3%	Wholesale trade	3%	Retail trade, except eating and drinking	3%
9	Sheet metal work	3%	Eating and drinking places	2%	Wholesale trade	3%
10	Petroleum refining	3%	Retail trade, except eating and drinking	2%	Miscellaneous structural metal work	3%
	The rest	64%	The rest	46%	The rest	63%
	Total	100%	Total	100%	Total	100%

Rank	Ozone layer depletion	Contribution	Human toxicity	Contribution	Freshwater aquatic ecotoxicity	Contribution
1	Cut stone and stone products	11%	Nonferrous wiredrawing and insulating	6%	Feed grains	11%
2	Pipe, valves, and pipe fittings	7%	Pipe, valves, and pipe fittings	5%	Carpets and rugs	8%
3	Misc. plastics products	5%	Brick and structural clay tile	4%	Motor vehicles bodies	6%
4	Metal doors, sash, frames, molding, and trim	5%	Prefabricated metal buildings and components	4%	Nonferrous wiredrawing and insulating	3%
5	Motor vehicles and passenger car bodies	4%	Motor vehicles and passenger car bodies	4%	Pipe, valves, and pipe fittings	3%
6	Paints and allied products	4%	Cut stone and stone products	4%	Miscellaneous plastics products, n.e.c.	3%
7	Prefabricated metal buildings and components	4%	Metal doors, sash, frames, molding, and trim	3%	Prefabricated metal buildings and components	2%
8	Sheet metal work	3%	Sheet metal work	3%	Wholesale trade	2%
9	Nonferrous wiredrawing and insulating	3%	Miscellaneous plastics products, n.e.c.	3%	Engineering, architectural, and surveying	2%
10	Lighting fixtures and equipment	3%	Engineering, architectural, and surveying	3%	Paints and allied products	2%
	The rest	53%	The rest	62%	The rest	56%
	Total	100%	Total	100%	Total	100%

Rank	Marine aquatic ecotoxicity	Contribution	Terrestrial ecotoxicity	Contribution	Freshwater sedimental ecotoxicity	Contribution
1	Brick and structural clay tile	25%	Feed grains	7%	Brick and structural clay tile	22%
2	Metal doors, sash, frames, molding, and trim	5%	Carpets and rugs	6%	Metal doors, sash, frames, molding, and trim	5%
3	Prefabricated metal buildings and components	4%	Motor vehicles and passenger car bodies	5%	Prefabricated metal buildings and components	4%
4	Motor vehicles and passenger car bodies	3%	Nonferrous wiredrawing and insulating	5%	Motor vehicles and passenger car bodies	3%
5	Sheet metal work	3%	Pipe, valves, & pipe fittings	4%	Sheet metal work	3%
6	Engineering, architectural, and surveying	3%	Prefabricated metal buildings and components	3%	Engineering, architectural, and surveying	3%
7	Retail trade, except restaur.	3%	Misc. plastics products	3%	Pipe, valves, and pipe fittings	3%
8	Pipe, valves, and pipe fittings	3%	Wholesale trade	2%	Nonferrous wiredrawing and insulating	3%
9	Electric services (utilities)	3%	Engineering, architectural, and surveying	2%	Retail trade, except eating and drinking	3%
10	Ceramic wall and floor tile	2%	Metal doors, sash, frames, molding, and trim	2%	Glass and glass products, except containers	2%
	The rest	47%	The rest	60%	The rest	50%
	Total	100%	Total	100%	Total	100%

Rank	Marine sedimental ecotoxicity	Contribution	Photochemical oxidation	Contribution	Acidification	Contribution
1	Cut stone and stone products	7%	Trucking and courier services, except air	5%	Cement, hydraulic	6%
2	Miscellaneous plastics products, n.e.c.	5%	Prefabricated metal buildings and components	4%	Engineering, architectural, and surveying	5%
3	Motor vehicles and passenger car bodies	4%	Motor vehicles and passenger car bodies	4%	Ready-mixed concrete	5%
4	Wholesale trade	4%	Engineering, architectural, and surveying	4%	Prefabricated metal buildings and components	4%
5	Engineering, architectural, and surveying	3%	Ready-mixed concrete	3%	Motor vehicles and passenger car bodies	4%
6	Paints and allied products	3%	Pipe, valves, and pipe fittings	3%	Retail trade, except eating and drinking	4%
7	Metal doors, sash, frames, molding, and trim	3%	Fabricated structural metal	3%	Electric services (utilities)	4%
8	Photographic equipment and supplies	3%	Wholesale trade	3%	Pipe, valves, and pipe fittings	3%
9	Prefabricated metal buildings and components	3%	Retail trade, except eating and drinking	3%	Wholesale trade	3%
10	Lighting fixtures and equipment	3%	Cement, hydraulic	3%	Fabricated structural metal	3%
	The rest	62%	The rest	65%	The rest	59%
	Total	100%	Total	100%	Total	100%

Rank	Eutrophication	Contribution	Energy consumption	Contribution	Water consumption	Contribution
1	Cement, hydraulic	5%	Prefabricated metal buildings and components	6%	Electric services (utilities)	8%
2	Ready-mixed concrete	4%	Engineering, architectural, and surveying	5%	Engineering, architectural, and surveying	8%
3	Motor vehicles and passenger car bodies	4%	Retail trade, except eating and drinking	4%	Retail trade, except eating and drinking	6%
4	Engineering, architectural, and surveying	4%	Fabricated structural metal	4%	Wholesale trade	4%
5	Trucking and courier services, except air	4%	Motor vehicles and passenger car bodies	4%	Motor vehicles and passenger car bodies	4%
6	Prefabricated metal buildings and components	4%	Wholesale trade	4%	Prefabricated metal buildings and components	4%
7	Feed grains	3%	Pipe, valves, and pipe fittings	4%	Pipe, valves, and pipe fittings	4%
8	Wholesale trade	3%	Miscellaneous structural metal work	3%	Fabricated structural metal	3%
9	Retail trade, except eating and drinking	3%	Sheet metal work	3%	Miscellaneous plastics products, n.e.c.	2%
10	Fabricated structural metal	3%	Electric services (utilities)	3%	Sheet metal work	2%
	The rest	64%	The rest	62%	The rest	55%
	Total	100%	Total	100%	Total	100%

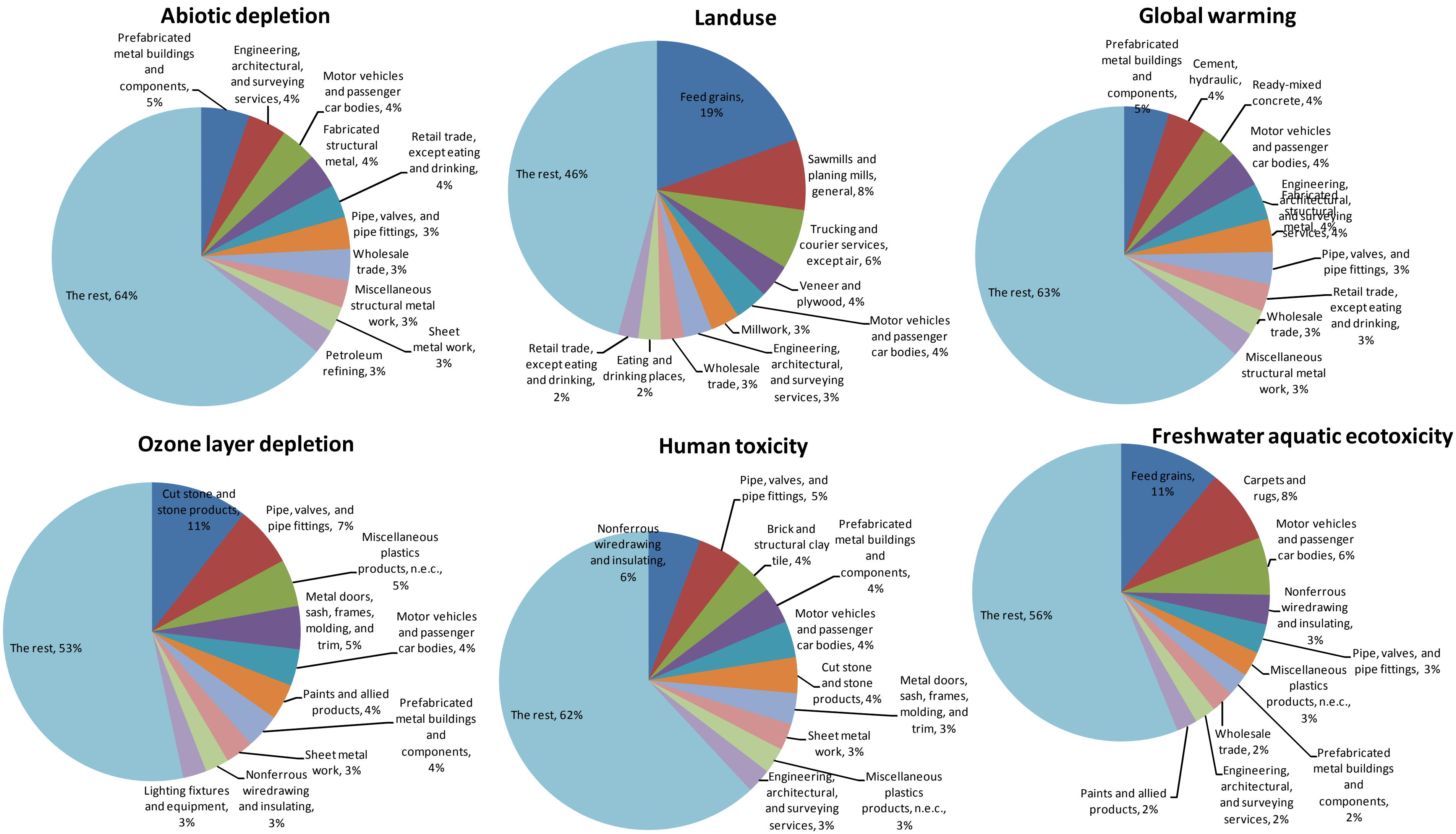

Figure H-B3a. Detailed input contribution analysis for new commercial building construction

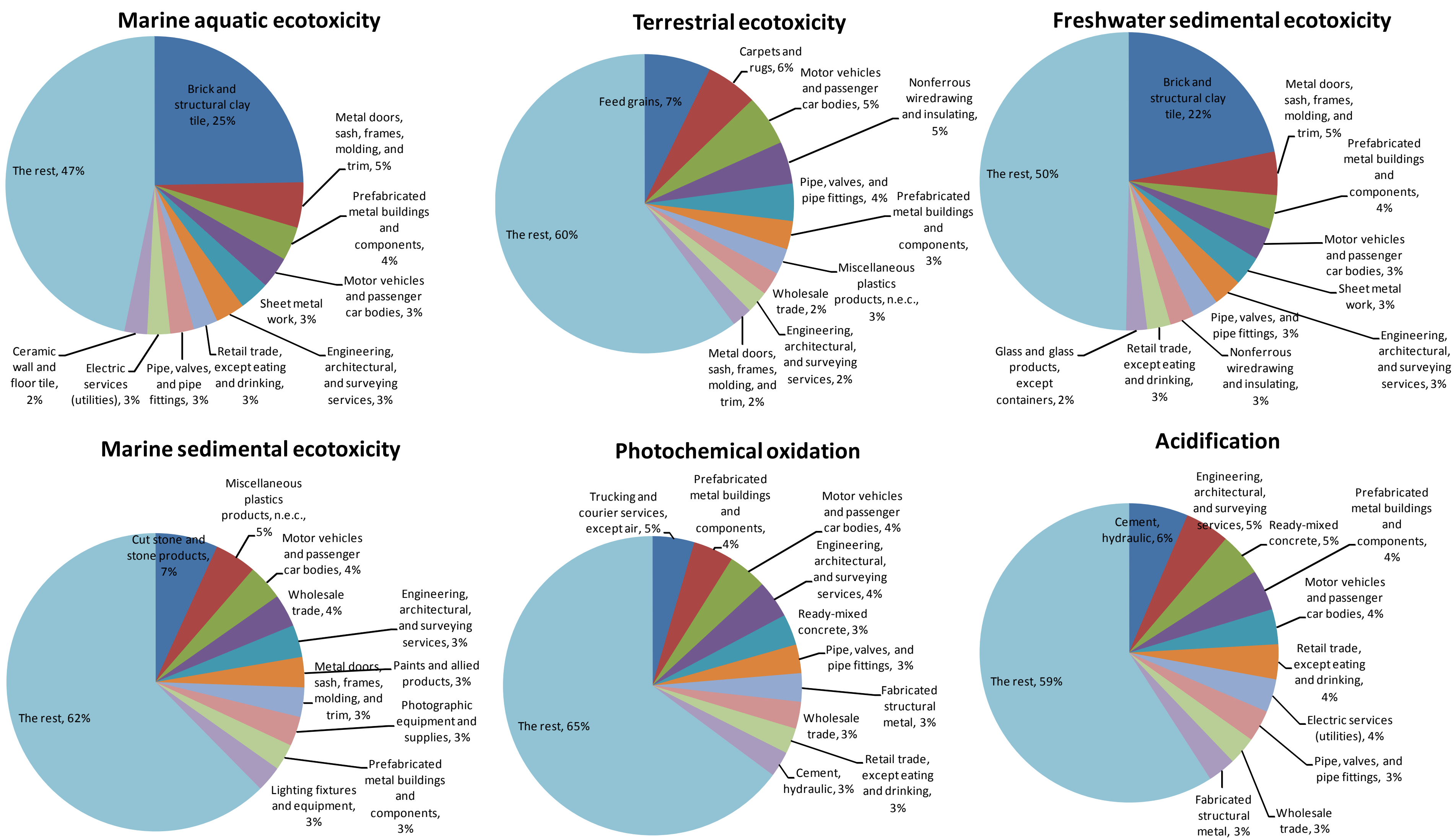

Figure H-B3b. Detailed input contribution analysis for new commercial building construction

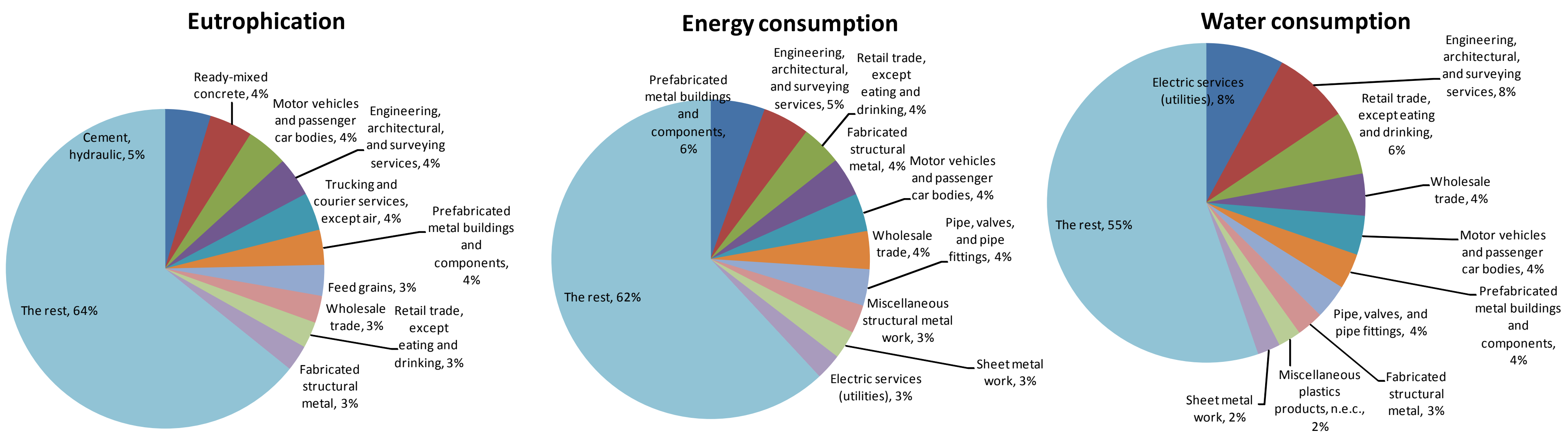

Figure H-B3c. Detailed input contribution analysis for new commercial building construction

H-B4. TOTAL IMPACT ALLOCATED OVER LIFE-CYCLE STAGES (AGGREGATED)

This analysis shows the relative importance of supply-chain processes and on-site emissions/use throughout the life-cycle of new commercial building construction in terms of their contribution to each impact. A total of 480 processes are directly or indirectly involved in the supply-chain of new commercial building construction, which are aggregated into five categories: Raw material extraction, Transportation and logistics, Energy and utility, Manufacturing, and Service.

Table H-B4. Output contribution analysis for new commercial building construction

	Abiotic depletion	Land use	Global warming	Ozone layer depletion	Human toxicity	Freshwater aquatic ecotoxicity	Marine aquatic ecotoxicity	Terrestrial ecotoxicity
Raw material extraction	98%	83%	5%	0%	16%	70%	4%	55%
Transportation and logistics	0%	17%	6%	0%	1%	0%	0%	0%
Energy and utility	0%	1%	20%	0%	7%	5%	31%	5%
Manufacturing	2%	0%	43%	92%	75%	23%	65%	38%
Service	0%	0%	2%	7%	1%	1%	0%	1%
Direct emission/consumption	0%	0%	22%	0%	0%	0%	0%	0%
Total	100%	100%	100%	100%	100%	100%	100%	100%

	Freshwater sedimental ecotoxicity	Marine sedimental ecotoxicity	Photochemica l oxidation	Acidification	Eutrophication	Energy consumption	Water consumption
Raw material extraction	6%	1%	4%	2%	16%	2%	2%
Transportation and logistics	0%	0%	11%	6%	14%	11%	0%
Energy and utility	28%	0%	15%	41%	17%	30%	95%
Manufacturing	66%	97%	45%	42%	36%	47%	2%
Service	1%	2%	5%	1%	3%	4%	0%
Direct emission/consumption	0%	0%	20%	7%	15%	6%	0%
Total	100%	100%	100%	100%	100%	100%	100%

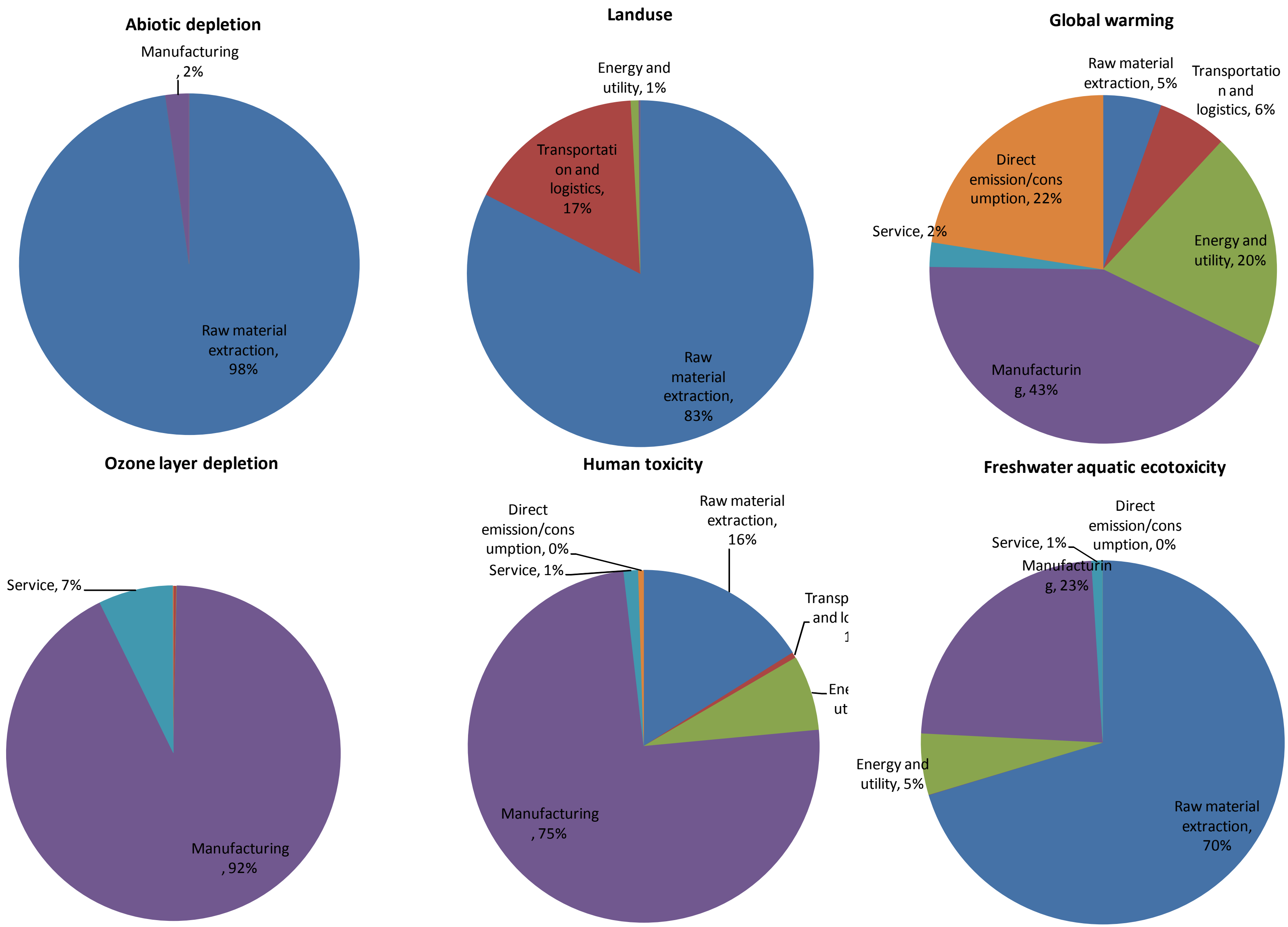

Figure H-B4a. Output contribution analysis for new commercial building construction

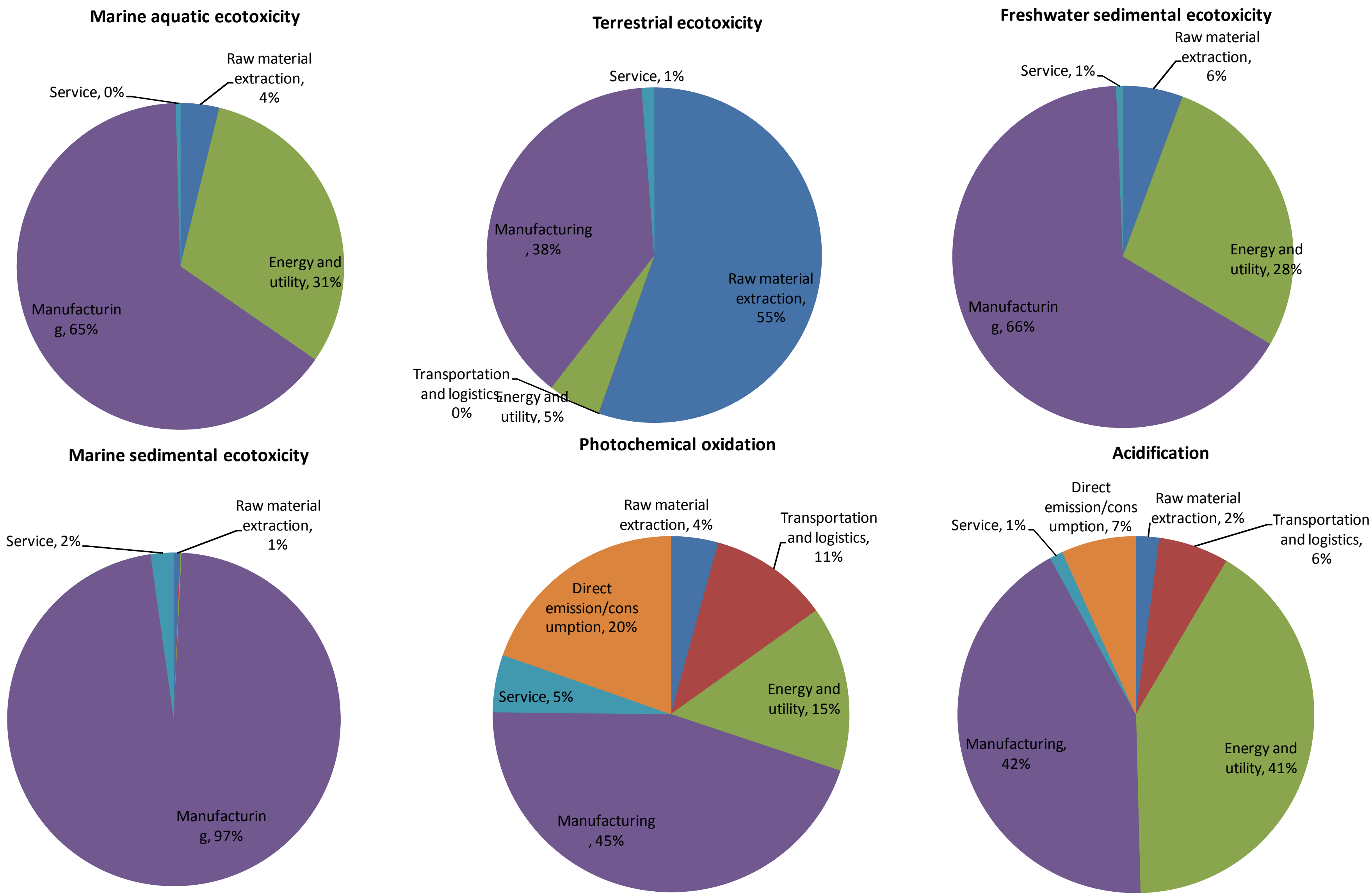

Figure H-B4b. Output contribution analysis for new commercial building construction

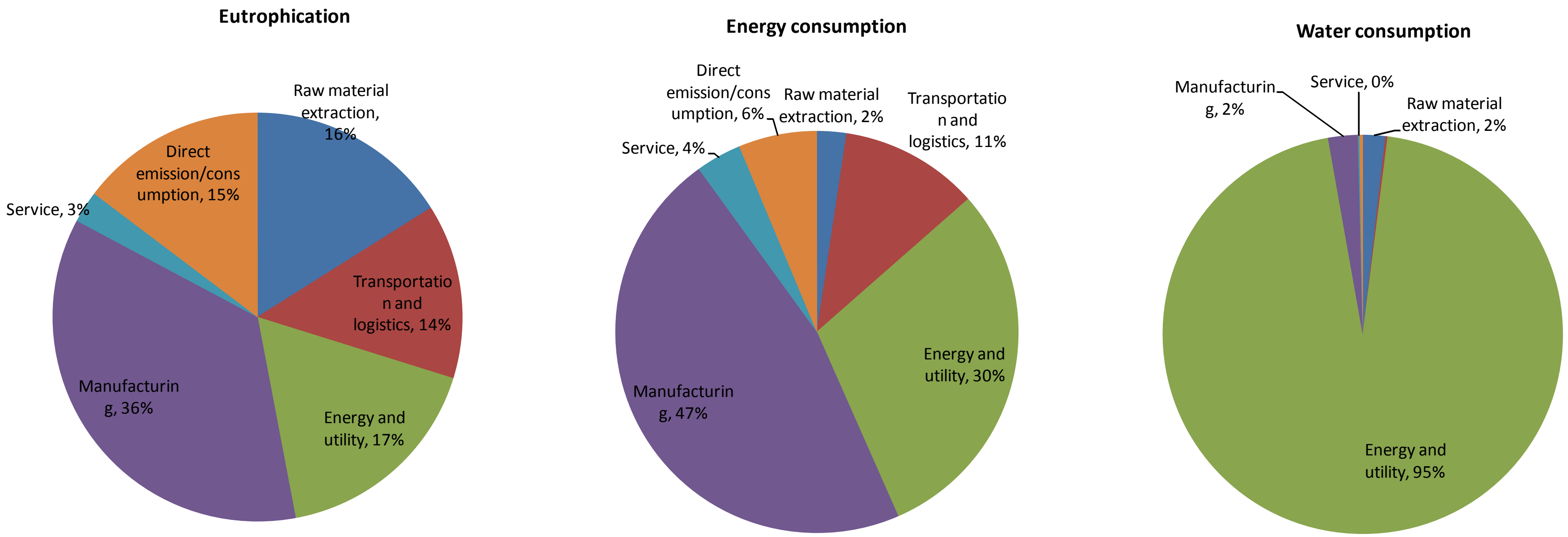

Figure H-B4c. Output contribution analysis for new commercial building construction

H-B5. Total impact allocated over life-cycle stages (detailed for top 10 contributors)

This analysis shows the relative importance of supply-chain processes and direct emissions/use throughout the life-cycle of new commercial building construction in terms of their contribution to each impact. A total of 480 processes are directly or indirectly involved in the supply-chain of new commercial building construction, and the top 10 processes contributing most significantly to overall impact are identified for each impact category in this table.

Table H-B5. Output contribution analysis for new commercial building construction—detailed for top 10 processes

Rank	Abiotic depletion	Contribution	Land use	Contribution	Global warming	Contribution
1	Crude petroleum and natural gas	49%	Feed grains	26%	Electric services (utilities)	21%
2	Coal	49%	Trucking and courier services, except air	15%	Blast furnaces and steel mills	15%
3	Petroleum refining	2%	Meat animals	10%	Cement, hydraulic	7%
4			Food grains	8%	Sanitary services, steam supply, and irrigation…	4%
5			Poultry and eggs	7%	Trucking and courier services, except air	4%
6			Agricultural, forestry, and fishery services	6%	Crude petroleum and natural gas	3%
7			Miscellaneous livestock	6%	Air transportation	2%
8			Cotton	5%	Coal	1%
9			Miscellaneous crops	5%	Petroleum refining	1%
10			Dairy farm products	4%	Lime	1%
	The rest	0%	The rest	6%	The rest	40%
	Total	100%	Total	100%	Total	100%

Rank	Ozone layer depletion	Contribution	Human toxicity	Contribution	Freshwater aquatic ecotoxicity	Contribution
1	Industrial inorganic and organic chemicals	20%	Copper ore	9%	Cotton	35%
2	Primary aluminum	13%	Primary aluminum	8%	Feed grains	15%
3	Cut stone and stone products	10%	Primary smelting and refining of copper	8%	Miscellaneous crops	6%
4	Plastics materials and resins	5%	Electric services (utilities)	6%	Copper ore	6%
5	Primary nonferrous metals, n.e.c.	5%	Industrial inorganic and organic chemicals	5%	Sanitary services, steam supply, and irrig…	5%
6	Miscellaneous repair shops	5%	Nonmetallic mineral products, n.e.c.	5%	Agricultural, forestry, and fishery services	3%
7	Pipe, valves, and pipe fittings	5%	Nonferrous metal ores, except copper	5%	Primary smelting and refining of copper	2%
8	Synthetic rubber	4%	Paper and paperboard mills	5%	Industrial inorganic and organic chemicals	2%
9	Scrap	2%	Brick and structural clay tile	4%	Nonferrous metal ores, except copper	2%
10	Miscellaneous plastics products, n.e.c.	2%	Pulp mills	4%	Paper and paperboard mills	2%
	The rest	28%	The rest	41%	The rest	22%
	Total	100%	Total	100%	Total	100%

Rank	Marine aquatic ecotoxicity	Contribution	Terrestrial ecotoxicity	Contribution	Freshwater sedimental ecotoxicity	Contribution
1	Electric services (utilities)	29%	Cotton	24%	Electric services (utilities)	26%
2	Brick and structural clay tile	27%	Copper ore	10%	Brick and structural clay tile	24%
3	Primary aluminum	20%	Feed grains	10%	Primary aluminum	18%
4	Glass and glass products, except containers	2%	Sanitary services, steam supply, and irrig…	5%	Copper ore	3%
5	Ceramic wall and floor tile	2%	Primary smelting and refining of copper	4%	Glass and glass products, except containers	2%
6	Sanitary services, steam supply, and irrig…	2%	Miscellaneous crops	4%	Sanitary services, steam supply, and irrig…	2%
7	Coal	2%	Paper and paperboard mills	3%	Ceramic wall and floor tile	2%
8	Industrial inorganic and organic chemicals	1%	Industrial inorganic and organic chemicals	3%	Industrial inorganic and organic chemicals	2%
9	Primary metal products, n.e.c.	1%	Nonferrous metal ores, except copper	3%	Paper and paperboard mills	2%
10	Plastics materials and resins	1%	Primary aluminum	3%	Plastics materials and resins	2%
	The rest	13%	The rest	31%	The rest	18%
	Total	100%	Total	100%	Total	100%

Rank	Marine sedimental ecotoxicity	Contribution	Photochemical oxidation	Contribution	Acidification	Contribution
1	Paper and paperboard mills	12%	Electric services (utilities)	14%	Electric services (utilities)	42%
2	Industrial inorganic and organic chemicals	11%	Trucking and courier services, except air	10%	Cement, hydraulic	10%
3	Pulp mills	9%	Blast furnaces and steel mills	10%	Blast furnaces and steel mills	9%
4	Primary aluminum	8%	Sanitary services, steam supply, and irrigation	4%	Trucking and courier services, except air	3%
5	Photographic equipment and supplies	7%	Cement, hydraulic	4%	Primary aluminum	3%
6	Cut stone and stone products	7%	Primary aluminum	3%	Primary smelting & refining of copper	3%
7	Plastics materials and resins	6%	Miscellaneous repair shops	2%	Industrial inorganic and organic chemicals	2%
8	Gum and wood chemicals	3%	Industrial inorganic and organic chemicals	2%	Railroads and related services	2%
9	Primary nonferrous metals, n.e.c.	3%	Crude petroleum and natural gas	2%	Paper and paperboard mills	2%
10	Synthetic rubber	3%	Clay refractories	2%	Crude petroleum and natural gas	2%
	The rest	30%	The rest	48%	The rest	21%
	Total	100%	Total	100%	Total	100%

Rank	Eutrophication	Contribution	Energy consumption	Contribution	Water consumption	Contribution
1	Electric services (utilities)	16%	Electric services (utilities)	31%	Electric services (utilities)	95%
2	Trucking and courier services, except air	8%	Blast furnaces and steel mills	20%	Feed grains	1%
3	Cement, hydraulic	8%	Trucking and courier services, except air	5%	Blast furnaces and steel mills	1%
4	Railroads and related services	5%	Paper and paperboard mills	3%	Industrial inorganic and organic chemicals	0%
5	Cotton	5%	Wholesale trade	3%	Sanitary services, steam supply, and irrig…	0%
6	Blast furnaces and steel mills	5%	Air transportation	2%	Paper and paperboard mills	0%
7	Miscellaneous crops	5%	Sawmills and planing mills, general	2%	Cotton	0%
8	Feed grains	4%	Retail trade, except eating and drinking	1%	Iron and ferroalloy ores, and misc. metal ores…	0%
9	Natural gas transportation	3%	Petroleum refining	1%	Petroleum refining	0%
10	Industrial inorganic and organic chemicals	2%	Cement, hydraulic	1%	Trucking and courier services, except air	0%
	The rest	41%	The rest	32%	The rest	1%
	Total	100%	Total	100%	Total	100%

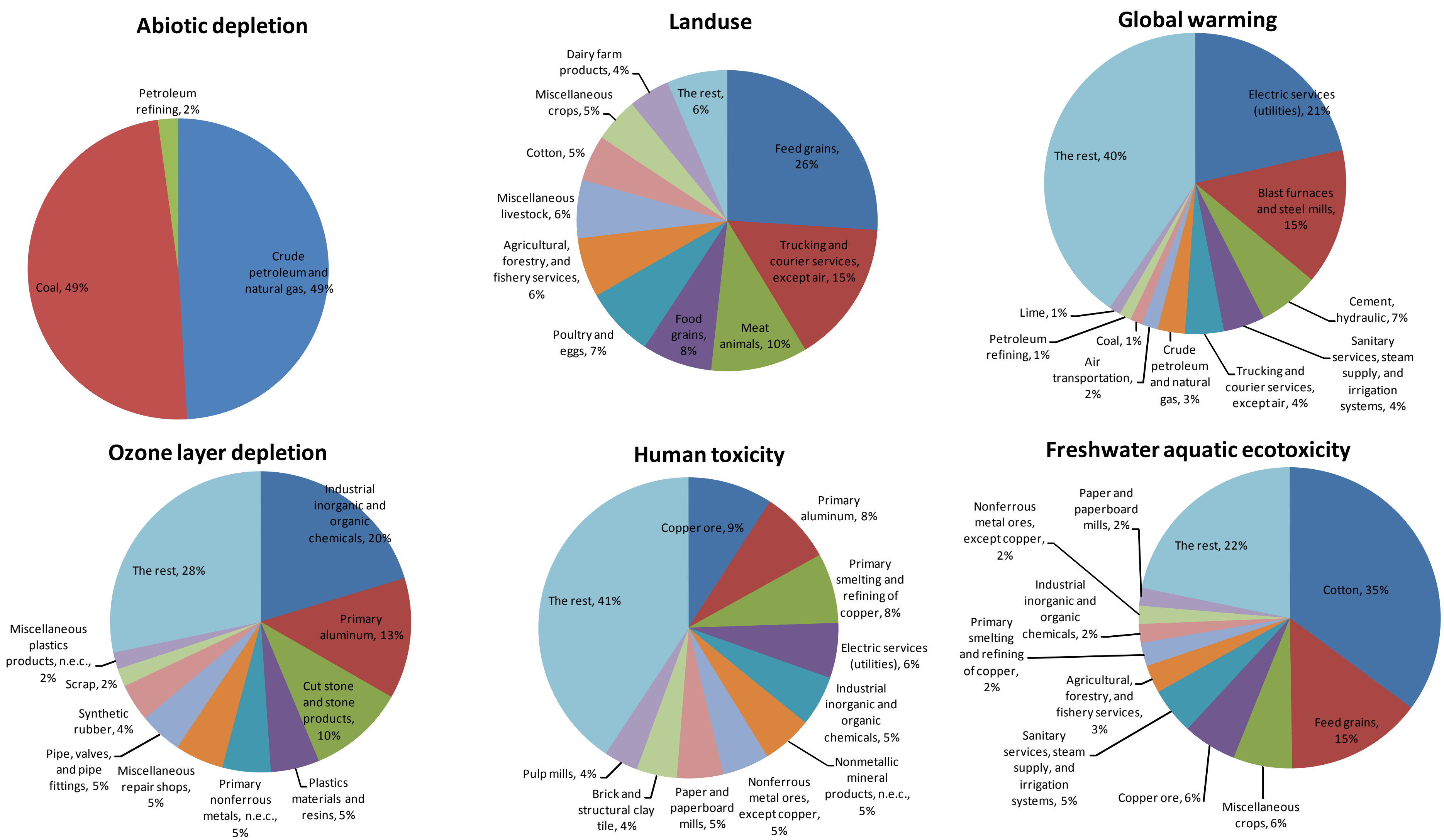

Figure H-B5a. Detailed output contribution analysis for new commercial building construction

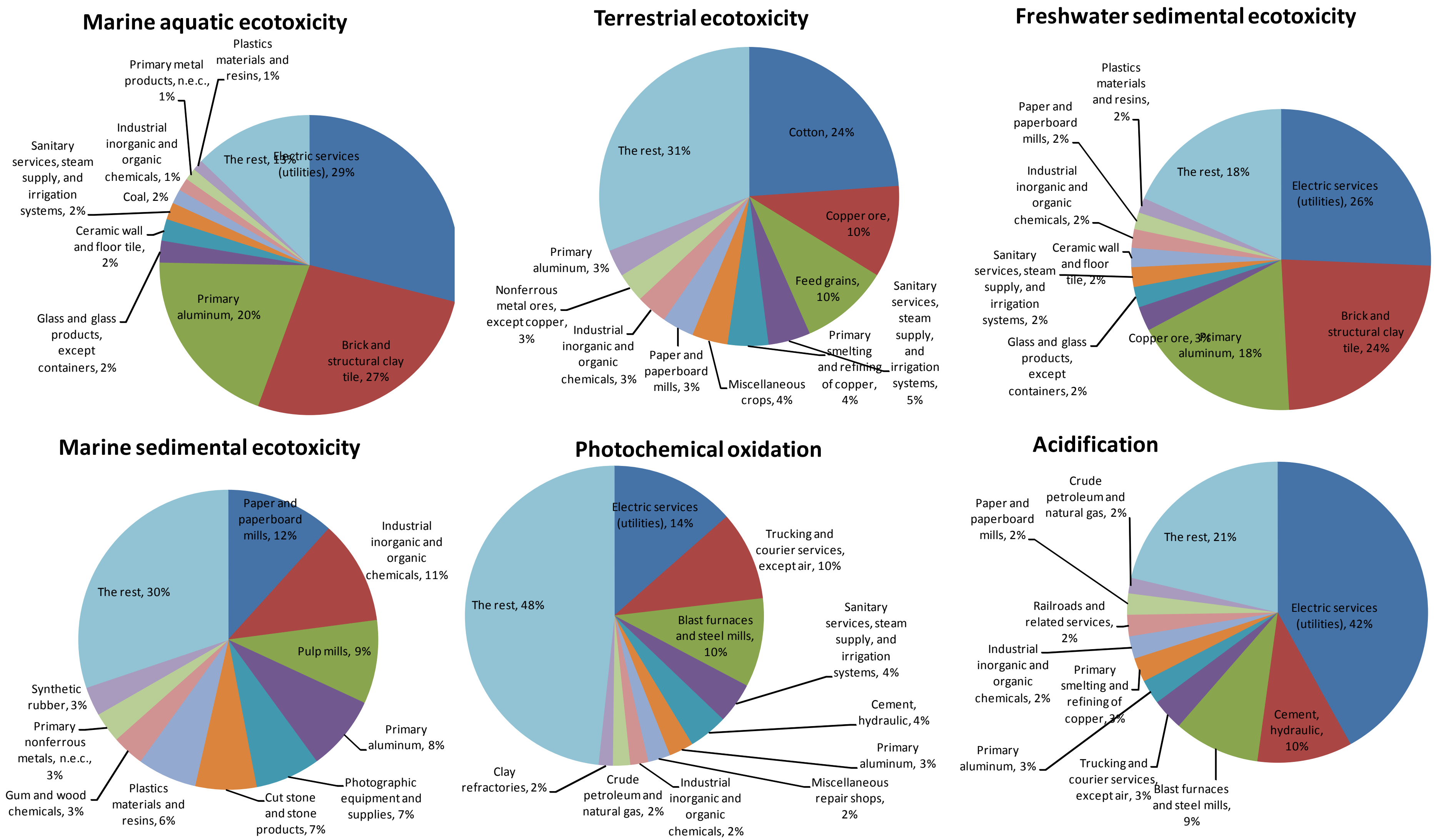

Figure H-B5b. Detailed output contribution analysis for new commercial building construction

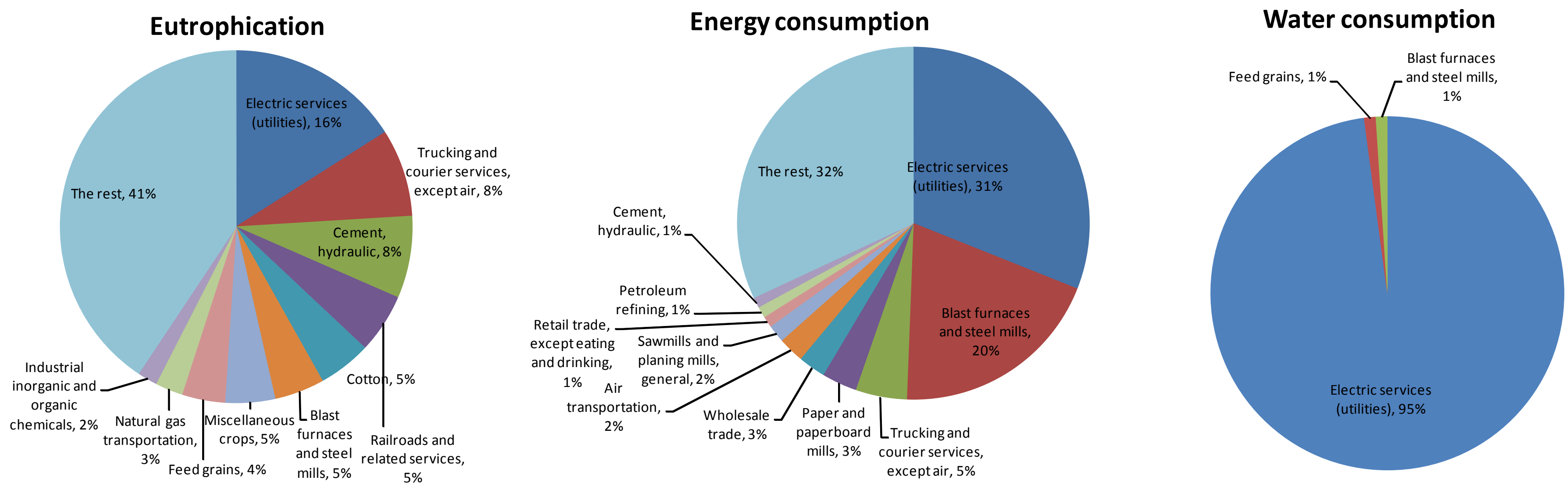

Figure H-B5c. Detailed output contribution analysis for new commercial building construction

APPENDIX H-C

CONTRIBUTION ANALYSIS RESULTS BY IMPACT CATEGORY

Table H-C1
Summary of Scope and Contribution Analyses
New Office, Industrial and Commercial Building Construction

Impact: Abiotic Depletion			
Rank in 2020 Vision Analysis relative to Abiotic Depletion (final consumption): 15			
Scope Analysis:			
• Scope 1 (contribution of on-site activities to Abiotic Depletion):			0%
• Scope 2 (contribution of electricity supplied to the site to Abiotic Depletion):			2%
• Scope 3 (contribution of all other inputs to Abiotic Depletion):			98%
Contribution Analyses			
Input Contribution Analysis		Output Contribution Analysis	
Aggregated Categories:		Aggregated Categories:	
Raw materials used in construction	1%	Raw materials used to produce direct inputs	98%
Transportation of goods and materials to site	10%	Transportation to produce direct inputs	0%
Energy and utilities delivered to site	3%	Energy and utilities used to produce direct inputs	0%
Manufactured goods used in construction	79%	Intermediate manufacturing	2%
Construction-related services	8%	Services used to produce direct inputs	0%
Direct impacts during construction	0%	Direct impacts during construction	0%
Top 10 contributing processes (and contribution):		Top 10 contributing processes (and contribution):	
Prefabricated metal buildings and components	5%	Crude petroleum and natural gas	49%
Engineering, architectural, and surveying	4%	Coal	49%
Motor vehicles and passenger car bodies	4%	Petroleum refining	2%
Fabricated structural metal	4%	The rest	0%
Retail trade, except eating and drinking	4%		
Pipe, valves, and pipe fittings	3%		
Wholesale trade	3%		
Miscellaneous structural metal work	3%		
Sheet metal work	3%		
Petroleum refining	3%		
The rest	64%		

Summary:

- Commercial building construction was ranked among the top 15 materials, products, and services contributing to Abiotic Depletion impacts in the 2020 Vision Relative Ranking Analysis.
- Almost all of the Abiotic depletion impacts associated with commercial building construction are embodied in the materials, products, and services, including transportation, employed in commercial building construction, rather than direct impacts during construction.
- From an input perspective, Abiotic Depletion impacts are widely distributed across inputs to commercial building construction, with fabricated metal products contributing most significantly to the impacts.
- From an output perspective, Abiotic Depletion impacts are concentrated in petroleum, natural gas, and coal sectors.

Table H-C2
Summary of Scope and Contribution Analyses
New Office, Industrial and Commercial Building Construction

Impact: Land Use (Increase of Land Competition)			
Rank in 2020 Vision Analysis relative to Land Use (final consumption): >20			
Scope Analysis:			
• Scope 1 (contribution of on-site activities to Land Use):			0%
• Scope 2 (contribution of electricity supplied to the site to Land Use):			0%
• Scope 3 (contribution of all other inputs to Land Use):			100%
Contribution Analyses			
Input Contribution Analysis		Output Contribution Analysis	
Aggregated Categories:		Aggregated Categories:	
Raw materials used in construction	20%	Raw materials used to produce direct inputs	83%
Transportation of goods and materials to site	12%	Transportation to produce direct inputs	17%
Energy and utilities delivered to site	0%	Energy and utilities used to produce direct inputs	1%
Manufactured goods used in construction	60%	Intermediate manufacturing	0%
Construction-related services	9%	Services used to produce direct inputs	0%
Direct impacts during construction	0%	Direct impacts during construction	0%
Top 10 contributing processes (and contribution):		Top 10 contributing processes (and contribution):	
Feed grains	19%	Feed grains	26%
Sawmills and planing mills, general	8%	Trucking and courier services, except air	15%
Trucking and courier services, except air	6%	Meat animals	10%
Veneer and plywood	4%	Food grains	8%
Motor vehicles and passenger car bodies	4%	Poultry and eggs	7%
Millwork	3%	Agricultural, forestry, and fishery services	6%
Engineering, architectural, and surveying	3%	Miscellaneous livestock	6%
Wholesale trade	3%	Cotton	5%
Eating and drinking places	2%	Miscellaneous crops	5%
Retail trade, except eating and drinking	2%	Dairy farm products	4%
The rest	46%	The rest	6%

Summary:

- Commercial building construction was not ranked among the top 20 materials, products, and services contributing to Land Use impacts in the 2020 Vision Relative Ranking Analysis.
- To the extent that commercial building construction contributes to competition for land, the contribution analyses suggest that the nature of the impacts are primarily associated with the use of land for agriculture and forestry.
- Impacts arise through the direct demand for raw materials and processed agricultural and forestry products in building construction and the use of these materials and products in the transportation industry supply chain.

Table H-C3
Summary of Scope and Contribution Analyses
New Office, Industrial and Commercial Building Construction

Impact: Global Warming (GWP 100)			
Rank in 2020 Vision Analysis relative to Global Warming (final consumption): 14			
Scope Analysis:			
• Scope 1 (contribution of on-site activities to Global Warming):			22%
• Scope 2 (contribution of electricity supplied to the site to Global Warming):			1%
• Scope 3 (contribution of all other inputs to Global Warming):			76%
Contribution Analyses			
Input Contribution Analysis		Output Contribution Analysis	
Aggregated Categories:		Aggregated Categories:	
Raw materials used in construction	1%	Raw materials used to produce direct inputs	5%
Transportation of goods and materials to site	7%	Transportation to produce direct inputs	6%
Energy and utilities delivered to site	3%	Energy and utilities used to produce direct inputs	20%
Manufactured goods used in construction	61%	Intermediate manufacturing	43%
Construction-related services	6%	Services used to produce direct inputs	2%
Direct impacts during construction	22%	Direct impacts during construction	22%
Top 10 contributing processes (and contribution):		Top 10 contributing processes (and contribution):	
Prefabricated metal buildings and components	5%	Electric services (utilities)	21%
Cement, hydraulic	4%	Blast furnaces and steel mills	15%
Ready-mixed concrete	4%	Cement, hydraulic	7%
Motor vehicles and passenger car bodies	4%	Sanitary services, steam supply, and irrigation systems	4%
Engineering, architectural, and surveying	4%	Trucking and courier services, except air	4%
Fabricated structural metal	4%	Crude petroleum and natural gas	3%
Pipe, valves, and pipe fittings	3%	Air transportation	2%
Retail trade, except eating and drinking	3%	Coal	1%
Wholesale trade	3%	Petroleum refining	1%
Miscellaneous structural metal work	3%	Lime	1%
The rest	63%	The rest	40%

Summary:

- Commercial building construction was ranked among the top 15 materials, products, and services contributing to Global Warming impacts in the 2020 Vision Relative Ranking Analysis.
- Global Warming impacts of commercial building construction primarily occur through two mechanisms: 1) during the production of manufactured goods used in construction; and 2) through direct emissions during on-site construction.
- From an input perspective, life-cycle Global Warming impacts are widely distributed across direct inputs to construction, with impacts concentrated in two areas: 1) fabricated metal products and 2) cement and concrete.
- Shifts from the input to output perspective indicate that the Global Warming impacts of manufactured goods used in commercial building construction include a significant contribution from embodied emissions associated with the energy used in their production (e.g., electricity, blast furnaces and steel mills).

Table H-C4
Summary of Scope and Contribution Analyses
New Office, Industrial and Commercial Building Construction

Impact: Ozone Layer Depletion (ODP Steady State)

Rank in 2020 Vision Analysis relative to Ozone Layer Depletion (final consumption): 9

Scope Analysis:

- Scope 1 (contribution of on-site activities to Ozone Layer Depletion): 0%
- Scope 2 (contribution of electricity supplied to the site to Ozone Layer Depletion): 0%
- Scope 3 (contribution of all other inputs to Ozone Layer Depletion): 100%

Contribution Analyses

Input Contribution Analysis		Output Contribution Analysis	
Aggregated Categories:		Aggregated Categories:	
Raw materials used in construction	0%	Raw materials used to produce direct inputs	0%
Transportation of goods and materials to site	4%	Transportation to produce direct inputs	0%
Energy and utilities delivered to site	0%	Energy and utilities used to produce direct inputs	0%
Manufactured goods used in construction	89%	Intermediate manufacturing	92%
Construction-related services	6%	Services used to produce direct inputs	7%
Direct impacts during construction	0%	Direct impacts during construction	0%
Top 10 contributing processes (and contribution):		Top 10 contributing processes (and contribution):	
Cut stone and stone products	11%	Industrial inorganic and organic chemicals	20%
Pipe, valves, and pipe fittings	7%	Primary aluminum	13%
Misc. plastics products	5%	Cut stone and stone products	10%
Metal doors, sash, frames, molding, and trim	5%	Plastics materials and resins	5%
Motor vehicles and passenger car bodies	4%	Primary nonferrous metals, n.e.c.	5%
Paints and allied products	4%	Miscellaneous repair shops	5%
Prefabricated metal buildings and components	4%	Pipe, valves, and pipe fittings	5%
Sheet metal work	3%	Synthetic rubber	4%
Nonferrous wiredrawing and insulating	3%	Scrap	2%
Lighting fixtures and equipment	3%	Miscellaneous plastics products, n.e.c.	2%
The rest	53%	The rest	28%

Summary:

- Commercial building construction was ranked among the top 10 materials, products, and services contributing to Ozone Layer Depletion impacts in the 2020 Vision Relative Ranking Analysis.
- Ozone Layer Depletion impacts of commercial building construction primarily result from the production of manufactured goods used in construction, with relatively significant contributions from transportation and construction-related services.
- From an input perspective, Ozone Depletion impacts are associated with a diverse range of direct inputs, with the most significant contributions from cut stone and stone products, fabricated metal products, and plastic products.
- The output analysis highlights the contributions of early supply chain processes, such as chemical manufacturing and primary metal processing, associated with the direct inputs identified in the input analysis.

Table H-C5
Summary of Scope and Contribution Analyses
New Office, Industrial and Commercial Building Construction

Impact: Human Toxicity (HTP_∞)			
Rank in 2020 Vision Analysis relative to Human Toxicity (final consumption): 13			
Scope Analysis:			
• Scope 1 (contribution of on-site activities to Human Toxicity):			0%
• Scope 2 (contribution of electricity supplied to the site to Human Toxicity):			1%
• Scope 3 (contribution of all other inputs to Human Toxicity):			99%
Contribution Analyses			
Input Contribution Analysis		Output Contribution Analysis	
Aggregated Categories:		Aggregated Categories:	
Raw materials used in construction	0%	Raw materials used to produce direct inputs	16%
Transportation of goods and materials to site	5%	Transportation to produce direct inputs	1%
Energy and utilities delivered to site	1%	Energy and utilities used to produce direct inputs	7%
Manufactured goods used in construction	88%	Intermediate manufacturing	75%
Construction-related services	5%	Services used to produce direct inputs	1%
Direct impacts during construction	0%	Direct impacts during construction	0%
Top 10 contributing processes (and contribution):		Top 10 contributing processes (and contribution):	
Nonferrous wiredrawing and insulating	6%	Copper ore	9%
Pipe, valves, and pipe fittings	5%	Primary aluminum	8%
Brick and structural clay tile	4%	Primary smelting and refining of copper	8%
Prefabricated metal buildings and components	4%	Electric services (utilities)	6%
Motor vehicles and passenger car bodies	4%	Industrial inorganic and organic chemicals	5%
Cut stone and stone products	4%	Nonmetallic mineral products, n.e.c.	5%
Metal doors, sash, frames, molding, and trim	3%	Nonferrous metal ores, except copper	5%
Sheet metal work	3%	Paper and paperboard mills	5%
Miscellaneous plastics products, n.e.c.	3%	Brick and structural clay tile	4%
Engineering, architectural, and surveying	3%	Pulp mills	4%
The rest	62%	The rest	41%

Summary:

- Commercial building construction was ranked among the top 15 materials, products, and services contributing to Human Toxicity impacts in the 2020 Vision Relative Ranking Analysis.
- Human Toxicity impacts of commercial building construction primarily result from the production of manufactured goods used in construction, with relatively significant contributions from transportation and construction-related services.
- From an input perspective, Human Toxicity impacts are associated with a diverse range of direct inputs, with the most significant contributions from fabricated metal products, stone, brick, and clay, and plastic products.
- The output analysis indicates diverse contributions from early supply chain processes with significant contributions from the mining and metal processing, chemical, minerals, and paper manufacturing sectors.

Table H-C6
Summary of Scope and Contribution Analyses
New Office, Industrial and Commercial Building Construction

<table>
<tr><th colspan="4">Impact: Freshwater Aquatic Ecotoxicity
(FAETP∞)</th></tr>
<tr><td colspan="4"><u>Rank in 2020 Vision Analysis relative to Freshwater Aquatic Ecotoxicity (final consumption)</u>: >20</td></tr>
<tr><td colspan="4"><u>Scope Analysis</u>:
• Scope 1 (contribution of on-site activities to Freshwater Aquatic Ecotoxicity): 0%
• Scope 2 (contribution of electricity supplied to the site to Freshwater Aquatic Ecotoxicity): 0%
• Scope 3 (contribution of all other inputs to Freshwater Aquatic Ecotoxicity): 100%</td></tr>
<tr><td colspan="4">Contribution Analyses</td></tr>
<tr><td colspan="2">Input Contribution Analysis</td><td colspan="2">Output Contribution Analysis</td></tr>
<tr><td colspan="2"><u>Aggregated Categories</u>:</td><td colspan="2"><u>Aggregated Categories</u>:</td></tr>
<tr><td>Raw materials used in construction</td><td>11%</td><td>Raw materials used to produce direct inputs</td><td>70%</td></tr>
<tr><td>Transportation of goods and materials to site</td><td>5%</td><td>Transportation to produce direct inputs</td><td>0%</td></tr>
<tr><td>Energy and utilities delivered to site</td><td>2%</td><td>Energy and utilities used to produce direct inputs</td><td>5%</td></tr>
<tr><td>Manufactured goods used in construction</td><td>76%</td><td>Intermediate manufacturing</td><td>23%</td></tr>
<tr><td>Construction-related services</td><td>6%</td><td>Services used to produce direct inputs</td><td>1%</td></tr>
<tr><td>Direct impacts during construction</td><td>0%</td><td>Direct impacts during construction</td><td>0%</td></tr>
<tr><td colspan="2"><u>Top 10 contributing processes (and contribution)</u>:</td><td colspan="2"><u>Top 10 contributing processes (and contribution)</u>:</td></tr>
<tr><td>Feed grains</td><td>11%</td><td>Cotton</td><td>35%</td></tr>
<tr><td>Carpets and rugs</td><td>8%</td><td>Feed grains</td><td>15%</td></tr>
<tr><td>Motor vehicles bodies</td><td>6%</td><td>Miscellaneous crops</td><td>6%</td></tr>
<tr><td>Nonferrous wiredrawing and insulating</td><td>3%</td><td>Copper ore</td><td>6%</td></tr>
<tr><td>Pipe, valves, and pipe fittings</td><td>3%</td><td>Sanitary services, steam supply, and irrigation systems</td><td>5%</td></tr>
<tr><td>Miscellaneous plastics products, n.e.c.</td><td>3%</td><td>Agricultural, forestry, and fishery services</td><td>3%</td></tr>
<tr><td>Prefabricated metal buildings and components</td><td>2%</td><td>Primary smelting and refining of copper</td><td>2%</td></tr>
<tr><td>Wholesale trade</td><td>2%</td><td>Industrial inorganic and organic chemicals</td><td>2%</td></tr>
<tr><td>Engineering, architectural, and surveying</td><td>2%</td><td>Nonferrous metal ores, except copper</td><td>2%</td></tr>
<tr><td>Paints and allied products</td><td>2%</td><td>Paper and paperboard mills</td><td>2%</td></tr>
<tr><td>The rest</td><td>56%</td><td>The rest</td><td>22%</td></tr>
<tr><td colspan="4">Summary:
• Commercial building construction was <u>not</u> ranked among the top 20 materials, products, and services contributing to Freshwater Aquatic Ecotoxicity impacts in the 2020 Vision Relative Ranking Analysis.
• To the extent that commercial building construction contributes to Freshwater Aquatic Toxicity, the contribution analyses suggest that the nature of the impacts are primarily associated with agricultural run-off and wastewater discharges from a variety of sectors.</td></tr>
</table>

Table H-C7
Summary of Scope and Contribution Analyses
New Office, Industrial and Commercial Building Construction

Impact: Marine Aquatic Ecotoxicity ($MAETP_{\infty}$)			
Rank in 2020 Vision Analysis relative to Marine Aquatic Ecotoxicity (final consumption): 10			
Scope Analysis:			
• Scope 1 (contribution of on-site activities to Marine Aquatic Ecotoxicity):			0%
• Scope 2 (contribution of electricity supplied to the site to Marine Aquatic Ecotoxicity):			3%
• Scope 3 (contribution of all other inputs to Marine Aquatic Ecotoxicity):			97%
Contribution Analyses			
Input Contribution Analysis		Output Contribution Analysis	
Aggregated Categories:		Aggregated Categories:	
Raw materials used in construction	0%	Raw materials used to produce direct inputs	4%
Transportation of goods and materials to site	5%	Transportation to produce direct inputs	0%
Energy and utilities delivered to site	3%	Energy and utilities used to produce direct inputs	31%
Manufactured goods used in construction	86%	Intermediate manufacturing	65%
Construction-related services	6%	Services used to produce direct inputs	0%
Direct impacts during construction	0%	Direct impacts during construction	0%
Top 10 contributing processes (and contribution):		Top 10 contributing processes (and contribution):	
Brick and structural clay tile	25%	Electric services (utilities)	29%
Metal doors, sash, frames, molding, and trim	5%	Brick and structural clay tile	27%
Prefabricated metal buildings and components	4%	Primary aluminum	20%
Motor vehicles and passenger car bodies	3%	Glass and glass products, except containers	2%
Sheet metal work	3%	Ceramic wall and floor tile	2%
Engineering, architectural, and surveying	3%	Sanitary services, steam supply, and irrigation systems	2%
Retail trade, except restaur.	3%	Coal	2%
Pipe, valves, and pipe fittings	3%	Industrial inorganic and organic chemicals	1%
Electric services (utilities)	3%	Primary metal products, n.e.c.	1%
Ceramic wall and floor tile	2%	Plastics materials and resins	1%
The rest	47%	The rest	13%

Summary:

- Commercial building construction was ranked among the top 10 materials, products, and services contributing to Marine Aquatic Ecotoxicity impacts in the 2020 Vision Relative Ranking Analysis.
- Marine Aquatic Ecotoxicity impacts of commercial building construction primarily result from the production of manufactured goods used in construction, with relatively significant contributions from upstream electricity generation, transportation and construction-related services.
- The input contribution analysis indicates that 25% of the Marine Aquatic Ecotoxicity impacts are embodied in brick and structural clay tile used in commercial building construction; fabricated metal products also show significant contributions.
- The output analysis again highlights the contribution of brick and structural clay tile and suggests that much of the embedded impacts associated with fabricated metal products are associated with aluminum processing.

Table H-C8
Summary of Scope and Contribution Analyses
New Office, Industrial and Commercial Building Construction

Impact: Terrestrial Ecotoxicity ($TETP_{\infty}$)			
Rank in 2020 Vision Analysis relative to Terrestrial Ecotoxicity (final consumption): >20			
Scope Analysis:			
• Scope 1 (contribution of on-site activities to Terrestrial Ecotoxicity):			0%
• Scope 2 (contribution of electricity supplied to the site to Terrestrial Ecotoxicity):			0%
• Scope 3 (contribution of all other inputs to Terrestrial Ecotoxicity):			100%
Contribution Analyses			
Input Contribution Analysis		Output Contribution Analysis	
Aggregated Categories:		Aggregated Categories:	
Raw materials used in construction	7%	Raw materials used to produce direct inputs	55%
Transportation of goods and materials to site	5%	Transportation to produce direct inputs	0%
Energy and utilities delivered to site	2%	Energy and utilities used to produce direct inputs	5%
Manufactured goods used in construction	80%	Intermediate manufacturing	38%
Construction-related services	6%	Services used to produce direct inputs	1%
Direct impacts during construction	0%	Direct impacts during construction	0%
Top 10 contributing processes (and contribution):		Top 10 contributing processes (and contribution):	
Feed grains	7%	Cotton	24%
Carpets and rugs	6%	Copper ore	10%
Motor vehicles and passenger car bodies	5%	Feed grains	10%
Nonferrous wiredrawing and insulating	5%	Sanitary services, steam supply, and irrigation systems	5%
Pipe, valves, & pipe fittings	4%	Primary smelting and refining of copper	4%
Prefabricated metal buildings and components	3%	Miscellaneous crops	4%
Misc. plastics products	3%	Paper and paperboard mills	3%
Wholesale trade	2%	Industrial inorganic and organic chemicals	3%
Engineering, architectural, and surveying	2%	Nonferrous metal ores, except copper	3%
Metal doors, sash, frames, molding, and trim	2%	Primary aluminum	3%
The rest	60%	The rest	31%
Summary: • Commercial building construction was not ranked among the top 20 materials, products, and services contributing to Terrestrial Ecotoxicity impacts in the 2020 Vision Relative Ranking Analysis. • To the extent that commercial building construction contributes to Terrestrial Ecotoxicity, the contribution analyses suggest that the nature of the impacts are primarily associated with agricultural run-off and wastewater discharges from a variety of sectors.			

Table H-C9
Summary of Scope and Contribution Analyses
New Office, Industrial and Commercial Building Construction

Impact: Freshwater Sedimental Ecotoxicity ($FSETP_\infty$)			
Rank in 2020 Vision Analysis relative to Freshwater Sedimental Ecotoxicity (final consumption): 10			
Scope Analysis:			
• Scope 1 (contribution of on-site activities to Freshwater Sedimental Ecotoxicity):			0%
• Scope 2 (contribution of electricity supplied to the site to Freshwater Sedimental Ecotoxicity):			2%
• Scope 3 (contribution of all other inputs to Freshwater Sedimental Ecotoxicity):			98%
Contribution Analyses			
Input Contribution Analysis		Output Contribution Analysis	
Aggregated Categories:		Aggregated Categories:	
Raw materials used in construction	0%	Raw materials used to produce direct inputs	6%
Transportation of goods and materials to site	5%	Transportation to produce direct inputs	0%
Energy and utilities delivered to site	3%	Energy and utilities used to produce direct inputs	28%
Manufactured goods used in construction	86%	Intermediate manufacturing	66%
Construction-related services	6%	Services used to produce direct inputs	1%
Direct impacts during construction	0%	Direct impacts during construction	0%
Top 10 contributing processes (and contribution):		Top 10 contributing processes (and contribution):	
Brick and structural clay tile	22%	Electric services (utilities)	26%
Metal doors, sash, frames, molding, and trim	5%	Brick and structural clay tile	24%
Prefabricated metal buildings and components	4%	Primary aluminum	18%
Motor vehicles and passenger car bodies	3%	Copper ore	3%
Sheet metal work	3%	Glass and glass products, except containers	2%
Engineering, architectural, and surveying	3%	Sanitary services, steam supply, and irrigation systems	2%
Pipe, valves, and pipe fittings	3%	Ceramic wall and floor tile	2%
Nonferrous wiredrawing and insulating	3%	Industrial inorganic and organic chemicals	2%
Retail trade, except eating and drinking	3%	Paper and paperboard mills	2%
Glass and glass products, except containers	2%	Plastics materials and resins	2%
The rest	50%	The rest	18%

Summary:

- Commercial building construction was ranked among the top 10 materials, products, and services contributing to Freshwater Sedimental Ecotoxicity impacts in the 2020 Vision Relative Ranking Analysis.
- Freshwater Sedimental Ecotoxicity impacts of commercial building construction primarily result from the production of manufactured goods used in construction, with relatively significant contributions from upstream electricity generation, transportation and construction-related services.
- The input contribution analysis indicates that 22% of the Freshwater Sedimental Ecotoxicity impacts are embodied in brick and structural clay tile; fabricated metal products also show significant contributions.
- The output analysis again highlights the contribution of brick and structural clay tile and suggests that much of the embedded impacts associated with fabricated metal products are associated with aluminum processing.

Table H-C10
Summary of Scope and Contribution Analyses
New Office, Industrial and Commercial Building Construction

Impact: Marine Sedimental Ecotoxicity
(MSETP∞)

Rank in 2020 Vision Analysis relative to Marine Sedimental Ecotoxicity (final consumption): 14

Scope Analysis:

- Scope 1 (contribution of on-site activities to Marine Sedimental Ecotoxicity): 0%
- Scope 2 (contribution of electricity supplied to the site to Marine Sedimental Ecotoxicity): 0%
- Scope 3 (contribution of all other inputs to Marine Sedimental Ecotoxicity): 100%

Contribution Analyses

Input Contribution Analysis		Output Contribution Analysis	
Aggregated Categories:		Aggregated Categories:	
Raw materials used in construction	1%	Raw materials used to produce direct inputs	1%
Transportation of goods and materials to site	6%	Transportation to produce direct inputs	0%
Energy and utilities delivered to site	0%	Energy and utilities used to produce direct inputs	0%
Manufactured goods used in construction	85%	Intermediate manufacturing	97%
Construction-related services	7%	Services used to produce direct inputs	2%
Direct impacts during construction	0%	Direct impacts during construction	0%
Top 10 contributing processes (and contribution):		Top 10 contributing processes (and contribution):	
Cut stone and stone products	7%	Paper and paperboard mills	12%
Miscellaneous plastics products, n.e.c.	5%	Industrial inorganic and organic chemicals	11%
Motor vehicles and passenger car bodies	4%	Pulp mills	9%
Wholesale trade	4%	Primary aluminum	8%
Engineering, architectural, and surveying	3%	Photographic equipment and supplies	7%
Paints and allied products	3%	Cut stone and stone products	7%
Metal doors, sash, frames, molding, and trim	3%	Plastics materials and resins	6%
Photographic equipment and supplies	3%	Gum and wood chemicals	3%
Prefabricated metal buildings and components	3%	Primary nonferrous metals, n.e.c.	3%
Lighting fixtures and equipment	3%	Synthetic rubber	3%
The rest	62%	The rest	30%

Summary:

- Commercial building construction was ranked among the top 15 materials, products, and services contributing to Marine Sedimental Ecotoxicity impacts in the 2020 Vision Relative Ranking Analysis.
- Marine Sedimental Ecotoxicity impacts of commercial building construction result from the production of manufactured goods used in construction, with relatively significant contributions from transportation and construction-related services.
- From an input perspective, Marine Sedimental Ecotoxicity impacts are associated with a diverse range of inputs, with the most significant contributions from cut stone and stone, plastic, paint, and fabricated metal products.
- The output analysis highlights the contributions of early supply chain processes associated with the direct inputs identified in the input analysis; it also highlights a concentration of impacts associated with paper/paperboard products that is not reflected in the input analysis, suggesting that these early supply chain impacts are widely distributed among direct inputs.

Table H-C11
Summary of Scope and Contribution Analyses
New Office, Industrial and Commercial Building Construction

Impact: Photochemical Oxidation (NOx)			
Rank in 2020 Vision Analysis relative to Photochemical Oxidation (final consumption): 15			
Scope Analysis:			
• Scope 1 (contribution of on-site activities to Photochemical Oxidation):			20%
• Scope 2 (contribution of electricity supplied to the site to Photochemical Oxidation):			1%
• Scope 3 (contribution of all other inputs to Photochemical Oxidation):			79%
Contribution Analyses			
Input Contribution Analysis		Output Contribution Analysis	
Aggregated Categories:		Aggregated Categories:	
Raw materials used in construction	1%	Raw materials used to produce direct inputs	4%
Transportation of goods and materials to site	9%	Transportation to produce direct inputs	11%
Energy and utilities delivered to site	2%	Energy and utilities used to produce direct inputs	15%
Manufactured goods used in construction	62%	Intermediate manufacturing	45%
Construction-related services	7%	Services used to produce direct inputs	5%
Direct impacts during construction	20%	Direct impacts during construction	20%
Top 10 contributing processes (and contribution):		Top 10 contributing processes (and contribution):	
Trucking and courier services, except air	5%	Electric services (utilities)	14%
Prefabricated metal buildings and components	4%	Trucking and courier services, except air	10%
Motor vehicles and passenger car bodies	4%	Blast furnaces and steel mills	10%
Engineering, architectural, and surveying	4%	Sanitary services, steam supply, and irrigation	4%
Ready-mixed concrete	3%	Cement, hydraulic	4%
Pipe, valves, and pipe fittings	3%	Primary aluminum	3%
Fabricated structural metal	3%	Miscellaneous repair shops	2%
Wholesale trade	3%	Industrial inorganic and organic chemicals	2%
Retail trade, except eating and drinking	3%	Crude petroleum and natural gas	2%
Cement, hydraulic	3%	Clay refractories	2%
The rest	65%	The rest	48%

Summary:

- Commercial building construction was ranked among the top 15 materials, products, and services contributing to Photochemical Oxidation impacts in the 2020 Vision Relative Ranking Analysis.
- Photochemical Oxidation impacts of commercial building construction primarily occur through two mechanisms: 1) during the production of manufactured goods used in construction; and 2) through direct emissions during on-site construction.
- From an input perspective, life-cycle Photochemical Oxidation impacts are widely distributed across direct inputs, including inputs associated with fabricated metal products, cement and concrete, and transportation and construction-related services.
- Shifts from the input to output perspective indicate that the Photochemical Oxidation impacts include significant contributions from embodied emissions associated with the energy used in manufacturing inputs and from transportation emissions.

Table H-C12
Summary of Scope and Contribution Analyses
New Office, Industrial and Commercial Building Construction

Impact: Acidification (including fate, average Europe total, A&B)			
Rank in 2020 Vision Analysis relative to Acidification (final consumption): 12			
Scope Analysis:			
• Scope 1 (contribution of on-site activities to Acidification):			7%
• Scope 2 (contribution of electricity supplied to the site to Acidification):			3%
• Scope 3 (contribution of all other inputs to Acidification):			90%
Contribution Analyses			
Input Contribution Analysis		Output Contribution Analysis	
Aggregated Categories:		Aggregated Categories:	
Raw materials used in construction	0%	Raw materials used to produce direct inputs	2%
Transportation of goods and materials to site	9%	Transportation to produce direct inputs	6%
Energy and utilities delivered to site	4%	Energy and utilities used to produce direct inputs	41%
Manufactured goods used in construction	72%	Intermediate manufacturing	42%
Construction-related services	8%	Services used to produce direct inputs	1%
Direct impacts during construction	7%	Direct impacts during construction	7%
Top 10 contributing processes (and contribution):		Top 10 contributing processes (and contribution):	
Cement, hydraulic	6%	Electric services (utilities)	42%
Engineering, architectural, and surveying	5%	Cement, hydraulic	10%
Ready-mixed concrete	5%	Blast furnaces and steel mills	9%
Prefabricated metal buildings and components	4%	Trucking and courier services, except air	3%
Motor vehicles and passenger car bodies	4%	Primary aluminum	3%
Retail trade, except eating and drinking	4%	Primary smelting & refining of copper	3%
Electric services (utilities)	4%	Industrial inorganic and organic chemicals	2%
Pipe, valves, and pipe fittings	3%	Railroads and related services	2%
Wholesale trade	3%	Paper and paperboard mills	2%
Fabricated structural metal	3%	Crude petroleum and natural gas	2%
The rest	59%	The rest	21%

Summary:

- Commercial building construction was ranked among the top 15 materials, products, and services contributing to Acidification impacts in the 2020 Vision Relative Ranking Analysis.
- Acidification impacts of commercial building construction primarily occur through two mechanisms: 1) during the production of manufactured goods used in construction; and 2) through direct emissions during on-site construction (e.g., from emissions from construction equipment).
- From an input perspective, life-cycle Acidification impacts are widely distributed across direct inputs, with concentrated contributions in two areas: 1) cement and concrete and 2) fabricated metal products.
- The output perspective indicates that the Acidification impacts include significant contributions from embodied emissions associated with the energy used in manufacturing inputs.

Table H-C13
Summary of Scope and Contribution Analyses
New Office, Industrial and Commercial Building Construction

Impact: Eutrophication (fate not included)			
Rank in 2020 Vision Analysis relative to Eutrophication (final consumption): >20			
Scope Analysis:			
• Scope 1 (contribution of on-site activities to Eutrophication):			15%
• Scope 2 (contribution of electricity supplied to the site to Eutrophication):			1%
• Scope 3 (contribution of all other inputs to Eutrophication):			84%
Contribution Analyses			
Input Contribution Analysis		Output Contribution Analysis	
Aggregated Categories:		Aggregated Categories:	
Raw materials used in construction	3%	Raw materials used to produce direct inputs	16%
Transportation of goods and materials to site	9%	Transportation to produce direct inputs	14%
Energy and utilities delivered to site	2%	Energy and utilities used to produce direct inputs	17%
Manufactured goods used in construction	65%	Intermediate manufacturing	36%
Construction-related services	7%	Services used to produce direct inputs	3%
Direct impacts during construction	15%	Direct impacts during construction	15%
Top 10 contributing processes (and contribution):		Top 10 contributing processes (and contribution):	
Cement, hydraulic	5%	Electric services (utilities)	16%
Ready-mixed concrete	4%	Trucking and courier services, except air	8%
Motor vehicles and passenger car bodies	4%	Cement, hydraulic	8%
Engineering, architectural, and surveying	4%	Railroads and related services	5%
Trucking and courier services, except air	4%	Cotton	5%
Prefabricated metal buildings and components	4%	Blast furnaces and steel mills	5%
Feed grains	3%	Miscellaneous crops	5%
Wholesale trade	3%	Feed grains	4%
Retail trade, except eating and drinking	3%	Natural gas transportation	3%
Fabricated structural metal	3%	Industrial inorganic and organic chemicals	2%
The rest	64%	The rest	41%

Summary:

- Commercial building construction was not ranked among the top 20 materials, products, and services contributing to Eutrophication impacts in the 2020 Vision Relative Ranking Analysis.
- To the extent that commercial building construction contributes to Eutrophication, the contribution analyses suggest that site activities directly impact eutrophication, likely from site run-off.
- Impacts embedded in inputs to commercial building construction are primarily associated with cement and concrete, fabricated metal products, transportation and construction services, and agricultural products.

Table H-C14
Summary of Scope and Contribution Analyses
New Office, Industrial and Commercial Building Construction

Impact: Energy Consumption (mBTU)			
Rank in 2020 Vision Analysis relative to Energy Consumption (final consumption): 13			
Scope Analysis:			
• Scope 1 (contribution of on-site activities to Energy Consumption):			6%
• Scope 2 (contribution of electricity supplied to the site to Energy Consumption):			2%
• Scope 3 (contribution of all other inputs to Energy Consumption):			91%
Contribution Analyses			
Input Contribution Analysis		Output Contribution Analysis	
Aggregated Categories:		Aggregated Categories:	
Raw materials used in construction	1%	Raw materials used to produce direct inputs	2%
Transportation of goods and materials to site	11%	Transportation to produce direct inputs	11%
Energy and utilities delivered to site	3%	Energy and utilities used to produce direct inputs	30%
Manufactured goods used in construction	71%	Intermediate manufacturing	47%
Construction-related services	8%	Services used to produce direct inputs	4%
Direct impacts during construction	6%	Direct impacts during construction	6%
Top 10 contributing processes (and contribution):		Top 10 contributing processes (and contribution):	
Prefabricated metal buildings and components	6%	Electric services (utilities)	31%
Engineering, architectural, and surveying	5%	Blast furnaces and steel mills	20%
Retail trade, except eating and drinking	4%	Trucking and courier services, except air	5%
Fabricated structural metal	4%	Paper and paperboard mills	3%
Motor vehicles and passenger car bodies	4%	Wholesale trade	3%
Wholesale trade	4%	Air transportation	2%
Pipe, valves, and pipe fittings	4%	Sawmills and planing mills, general	2%
Miscellaneous structural metal work	3%	Retail trade, except eating and drinking	1%
Sheet metal work	3%	Petroleum refining	1%
Electric services (utilities)	3%	Cement, hydraulic	1%
The rest	62%	The rest	32%

Summary:

- Commercial building construction was ranked among the top 15 materials, products, and services relative to Energy Consumption in the 2020 Vision Relative Ranking Analysis.
- Energy Consumption associated with commercial building construction is primarily related to the production of manufactured goods used in construction, though direct Energy Consumption during on-site construction is significant.
- From an input perspective, life-cycle Energy Consumption is widely distributed across direct inputs, with a concentration of contributions in the areas of fabricated metal products and transportation and construction-related services.
- The output analysis shows significant contributions from embodied energy used in manufacturing inputs (51% from electric services and blast furnaces and steel mills) it also highlights a concentration of energy consumption associated with wood products that is not reflected in the input analysis, suggesting that this consumption is widely distributed among direct inputs.

Table H-C15
Summary of Scope and Contribution Analyses
New Office, Industrial and Commercial Building Construction

Impact: Water Consumption (gallons)			
Rank in 2020 Vision Analysis relative to Water Consumption (final consumption): 14			
Scope Analysis:			
• Scope 1 (contribution of on-site activities to Water Consumption):			0%
• Scope 2 (contribution of electricity supplied to the site to Water Consumption):			8%
• Scope 3 (contribution of all other inputs to Water Consumption):			92%
Contribution Analyses			
Input Contribution Analysis		Output Contribution Analysis	
Aggregated Categories:		Aggregated Categories:	
Raw materials used in construction	1%	Raw materials used to produce direct inputs	2%
Transportation of goods and materials to site	12%	Transportation to produce direct inputs	0%
Energy and utilities delivered to site	8%	Energy and utilities used to produce direct inputs	95%
Manufactured goods used in construction	66%	Intermediate manufacturing	2%
Construction-related services	12%	Services used to produce direct inputs	0%
Direct impacts during construction	0%	Direct impacts during construction	0%
Top 10 contributing processes (and contribution):		Top 10 contributing processes (and contribution):	
Electric services (utilities)	8%	Electric services (utilities)	95%
Engineering, architectural, and surveying	8%	Feed grains	1%
Retail trade, except eating and drinking	6%	Blast furnaces and steel mills	1%
Wholesale trade	4%	Industrial inorganic and organic chemicals	0%
Motor vehicles and passenger car bodies	4%	Sanitary services, steam supply, and irrigation systems	0%
Prefabricated metal buildings and components	4%	Paper and paperboard mills	0%
Pipe, valves, and pipe fittings	4%	Cotton	0%
Fabricated structural metal	3%	Iron and ferroalloy ores, and miscellaneous metal ores, n.e.c.	0%
Miscellaneous plastics products, n.e.c.	2%	Petroleum refining	0%
Sheet metal work	2%	Trucking and courier services, except air	0%
The rest	55%	The rest	1%

Summary:

- Commercial building construction was ranked among the top 15 materials, products, and services relative to Water Consumption in the 2020 Vision Relative Ranking Analysis.
- Water Consumption associated with commercial building construction is related to the production of manufactured goods used in construction and transportation and construction services.
- The output contribution analysis indicates that 95% of the Water Consumption associated with commercial building construction is consumed in the generation of electricity used in manufacturing construction-related products and in providing transportation and construction services.

APPENDIX I – ENVIRONMENTAL JUSTICE AND EQUITY

I. Introduction

The link between affordability and Environmental Justice. The lack of housing opportunities in new construction markets places low-income households in polluted environments where land is cheap and environmental risks high. It also places them in older, existing structures where they are more likely to be exposed to toxic building materials, mold and allergens. If new, green, healthy homes are made affordable to low-income households, some of these injustices can be remedied.

In general, the cumulative upfront and running home-costs exceed the means of low-income households or exhaust their spending on health care and education. However, there are distinct opportunities to reduce these costs in green construction. For example, pursuing affordable, yet green materials and managing construction waste can improve the builder's bottom line and be an effective mechanism to lower the upfront costs for the owner; meanwhile, increasing energy efficiency can reduce the homeowner's operational costs. Taking advantage of such opportunities can attain the necessary balance between health and affordability to substantially benefit low-income households.

II. Reducing home costs

Taking a closer look, if developer profits are left out, upfront home costs will be comprised of construction costs, costs of land and technical services. It is possible to reduce each. For example, construction savings can be achieved through purchase of recycled and reused materials, construction waste management and use of low-skill labor. Costs of land and technical services can be offset through federal or local programs and grants, technical assistance and involvement of non-profits.[2] Further, more substantial savings can always be achieved by taking advantage of economies of scale and purchasing materials and labor in bulk, for several simultaneous low-income-home projects.

On the other hand, long-term housing costs will combine various costs of operating, maintaining and/or renovating homes. Savings on energy bills can be achieved if design and construction measures that optimize energy efficiency are combined with efficient lighting, appliances and mechanical systems that reduce energy consumption. Costs of regular maintenance can be reduced through purchases of recovered materials and construction waste management. Expenses on adaptation and remodeling can be minimized if homes are designed to feature multifunctional, adaptable, de-constructible spaces.

Recycled and Reused Materials

Reduce construction costs. As mentioned, the costs of construction and renovation can be reduced through purchase of recycled and reused building materials. The market for recovered materials primarily emerged from the growing awareness of the life cycle impacts of *new* building materials.

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[2] A number of case studies can be found at http://www.ncat.org/evergreen/evergreen_affordability_general.htm; Evergreen Affordability is the product of the Affordable Sustainability Technical Assistance for HOME (HomeASTA) project of the National Center for Appropriate Technology (NCAT), which was funded by the U.S. Department of Housing and Urban Development.

However, since recovered materials can function as financial assets to lower construction and renovation costs for low-income-home builders and home-owners, their value extends beyond just environmental protection. Pursuing affordable, sustainable materials can improve the builder's bottom line and be an effective mechanism to lower the upfront home or renovation costs for the owner.

Through virgin material extraction, manufacture into products, transportation and disposal, new building materials take their share in the overall resource depletion, pollution and landfill consumption. As consciousness of these impacts rises, jurisdictions are taking measures to tap into construction and demolition waste as a massive, sustainable source of building materials. Materials can be taken from waste streams, reprocessed and re-manufactured into recycled materials, or they can be cleaned up and/or refinished, adapted by cutting to size and reused. Different tools such as local regulatory measures, increases in disposal fees, education and green building are being used to drive the market toward building material recovery. As an example, certain jurisdictions are now requiring construction firms to perform waste stream audits. Materials that would in many cases just be disposed of, are identified and salvaged.[3] Such materials can become a source of low-cost building material.

The Building Material Reuse Association recently gathered industry representatives together at its 2011 convention, Decon '11 to speak about the value of deconstruction and material reuse. Participants included appraisers and reuse consultants and designers. One of the repeatedly mentioned benefits supported by industry examples was that deconstruction provided sustainable, low-cost building materials.[4] Along the same lines, the City of Seattle's Department of Planning and Development published that recycling or reusing salvaged building materials as well as minimizing materials and packaging, reduces material expenses.[5] Reduced material expenses translate into lower upfront housing costs as well as lower renovation/maintenance costs.

Differences in cost that exist between various recycled and reused materials reflect the value added through the recovery process. In limited cases, this difference can result in a higher cost for a recycled or reused material. However, even in these limited cases, funding may be available through the Low Income Housing Tax Credit program to offset this incremental cost. State and local governments provide funds based on how many points from their Qualified Allocation Plans the projects are able to meet. States allocate points for green building practices, and a number of them allocate points for recycled/reused materials.[6] In such a case, incorporating recovered materials may

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[3] Careers in Green Construction, Bureau of Labor Statistics, United States Department of Labor, http://www.bls.gov/green/construction/, Accessed on August 11, 2011.
[4] For more information and copies of presentation slides, please see http://www.bmra.org/about-bmra/newsupdates/323-decon-11-presentations-are-available .
[5] Department of Planning and Development, City of Seattle, June 2005: Construction Waste Management Guide for Architects, Designers, Developers, Facility Managers, Owners, Property Managers & Specification Writers, p.2.
http://www.seattle.gov/dpd/cms/groups/pan/@pan/@sustainablebldg/documents/web_informational/dpds_007173.pdf, August 11, 2011.
[6] Global Green USA, http://www.globalgreen.org/greenurbanism/affordablehousing/, Accessed August 15, 2011

help the project qualify for funding that would in turn help the project team afford more sustainable material choices for the needed applications.

Support job creation and community revitalization. Incorporating recycled and reused materials supports the recycling and reuse industry, which creates jobs.[7] According to The U.S. Recycling Economic Information Study, more than 56,000 recycling and reuse establishments in the United States employ approximately 1.1 million people.[8] Building materials recovery generally involves substantial activities around deconstruction, sorting, salvage, value adding, stocking, and resale. Therefore, the contribution of building material-recovery jobs to the overall recycling industry is significant.

Equally significant is the fact that recovered materials are typically sourced locally and that therefore, any associated economic activity should directly benefit local communities. These benefits range from creating local deconstruction, recovery, or resale jobs and providing low-cost materials for local residents, to creating tax revenues and revitalizing communities at large.

Reduce pollution associated with material disposal and new material production. Environmental Justice benefits can be achieved through pollution reduction that is enabled by material recovery. Material recovery diverts waste and intercepts the emissions associated with either the incineration or the material break-down in landfills. In addition, the recovered materials replace raw materials or finished products; thereby, the recovery intercepts the pollution associated with the extraction and processing of virgin materials and the manufacture of new products. [9] Even though the pollution reduction improves the environment for all, benefits are greatest for disadvantaged, low-income communities that are often in the closest proximity to waste and manufacturing facilities. These low-income households typically face cumulative pollution risks as various waste and manufacturing facilities are often grouped together.

Health and safety considerations. Although building material reuse and recovery affords needed economic, social and environmental benefits to society, concerns regarding human health and safety do exist. For example, with material reuse and recycling, potentially harmful materials that had historically circulated in the construction and maintenance of buildings (e.g. lead-based paint) could

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[7] The Tellus Institute in its report *More Jobs, Less Pollution: Growing the Recycling Economy in the U.S.*, compared two hypothetical 2030 waste management scenarios; the baseline scenario that was developed on continuing current practices to reach about 37-percent C&D waste diversion by 2030, and the Green Economy scenario reflecting 75-percent C&D diversion through significantly enhanced recycling and composting efforts. The Green Economy scenario generated more than twice the amount of jobs of the baseline scenario demonstrating that the recycling jobs gained through enhanced diversion outnumber any loss of jobs in C&D waste disposal. In addition, in its study *2008 Employment Trends in N.C.'S Recycling Industry*, the state of North Carolina looked at the recycling industry at large and found that job losses in waste disposal and virgin materials mining and manufacture that directly result from recycling program success, in North Carolina, were balanced or outweighed by job creation in the recycling sector.

[8] U.S. EPA: http://waste.supportportal.com/link/portal/23002/23023/Article/18602/If-there-is-plenty-of-landfill-space-then-why-should-I-recycle, Accessed August, 12, 2011.

[9] U.S. EPA, Is recycling worthwhile: http://waste.supportportal.com/ics/support/kbAnswer.asp?deptID=23023&task=knowledge&questionID=19159, Accessed August 12, 2011.

be reintroduced into the housing stock, if not properly managed. From an environmental justice perspective, of those materials, particular attention has been given to lead-based paint. Fighting childhood lead-based paint poisoning has become one of the Department of Housing and Urban Development (HUD)'s primary environmental justice initiatives.[10] Through this initiative, HUD provides public outreach and technical assistance and conducts technical studies to help protect children and their families from health and safety hazards in the home.[11]

The U.S EPA also works to promote safe reuse and has gathered useful information to communicate these issues.[12] For example, in its Pollution Prevention and Toxics website, the EPA specifically addresses the question of how reuse stores and their customers can manage the lead-based paint in older building materials. As a primary matter, the EPA notes that states may have laws or regulations addressing the management, handling or sale of materials containing lead-based paint, which would give very specific directions. Otherwise, the EPA recommends that reuse stores at a minimum label suspect items to indicate that they may contain lead, educate staff about lead hazards, and provide outreach materials to customers about lead-safe work practices. The EPA also lists useful resources.[13] While lead has taken center stage, health and safety concerns may revolve around other materials and products as well. Unsafe materials include asbestos, mercury, PCBs or arsenic.

It is also important to ensure that the chosen materials and products suit the application they are intended to fill. For example, unless properly treated, salvaged lumber may not be suitable for structural applications.[14] Using recovered materials because of their low-cost, but without due regard for functional suitability, could result in unsafe applications in affordable homes. Additionally, some products may not be sufficiently efficient to provide healthy indoor conditions or long-term cost-savings. For example, a single-pane window may be inexpensive and in usable condition, but meanwhile, it is energy-inefficient in certain climates and thus, not a good, affordable thermal solution for a home-owner in the long-run. However, such a window could still be used in interior applications, e.g. as a transom, where it could allow penetration of light into secondary spaces such as hallways. Using salvaged materials in certain applications might not meet the requirements of local building codes and it is most practical and protective for builders and home-owners to consult local building officials early.

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[10] U.S. Department of Housing and Urban Development, March 1995, Achieving Environmental Justice – a Departmental Strategy: http://www.hud.gov/offices/cpd/environment/library/subjects/justice/deptstrategy.cfm#b, Accessed August 15, 2011.

[11] U.S. Department of Housing and Urban Development, Healthy Homes and Lead Hazard Control, http://portal.hud.gov/hudportal/HUD?src=/program_offices/healthy_homes, Accessed August 15, 2011.

[12] U.S EPA, Pollution Prevention and Toxics, 2011: http://www.epa.gov/opptintr/, Accessed August 15,2011.

[13] U.S EPA, Pollution Prevention and Toxics, 2011, Frequent Questions, General Information about Lead, 2011: http://toxics.supportportal.com/link/portal/23002/23019/Article/32411/Building-material-reuse-stores-sometimes-accept-older-materials-which-have-been-coated-with-lead-based-paint-and-could-pose-a-lead-poisoning-hazard-In-particular-older-windows-and-doors-are-likely-to-, Accessed August 15, 2011.

[14] King County Department of Natural Resources and Parks, Solid Waste Division & City of Seattle Department of Planning and Development, 2006. {Green home remodel} salvage & reuse: http://your.kingcounty.gov/solidwaste/greenbuilding/documents/Green_home_remodel-salvage.pdf, Accessed August 15, 2011.

Therefore, builders and home-owners who purchase building products for reuse should select them judiciously in order to capitalize on their lower cost without jeopardizing the health and/or safety of home-occupants. In that respect, additional inquiries and/or inspections may be warranted around certain types of materials.

Durability and maintenance. Interest in using recovered materials in new construction is not uniformly present across the country. One common concern is that recycled or reused materials are inferior in quality and may not be as durable. This perception is limiting the development of needed infrastructure to increase the availability of these materials for affordable housing projects.

However, the U.S EPA has published that recycled materials contain similar chemical and physical properties as the virgin materials they replace, and when used according to appropriate environmental regulations engineering specifications, provide comparable—and in some cases, superior—performance at a lower cost.[15]

The Department of Planning & Development of the City of Seattle and the Department of Natural Resources and Parks of King County both advocate that salvaged materials cost less and last longer: their longevity is especially evident when building materials are salvaged from the structures of the periods that boasted construction of better quality.[16]

The USGBC consistently encourages the use of salvaged or reused building materials in single family home construction. The USGBC does not specifically recommend any additional operations and maintenance considerations pertaining to reused materials.[17] However, the USGBC does point out that the recycled-content materials may need different maintenance practices than conventional products. Homeowners should be made aware of any specific maintenance requirements in order to defer and minimize repairs. However, the USGBC's caution that recycled-content materials may require specific upkeep should not be interpreted to imply that these materials would not last long or perform as is expected. The performance requirements of building codes may on the outset determine the expected levels of maintenance and durability for the materials that are alternative to conventional. Accordingly, the recycled/reused product suppliers may warranty the product performance to ensure a customer base. Such warranties might sufficiently address any concerns for designers, builders and owners. In any case, designers, builders and developers must ensure that salvaged materials meet applicable building codes and laws.

Planning considerations. If the process to include reclaimed materials is to be successful, so that any benefits for low-income households could accrue, builders and homeowners should be aware that the

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[15] U.S. EPA, Office of Resource Conservation and Recovery, March 2009. Estimating 2003 *Building Related* Construction and Demolition Materials Amounts, p. 21.

[16] King County Department of Natural Resources and Parks, Solid Waste Division & City of Seattle Department of Planning and Development, 2006. {Green home remodel} salvage & reuse: http://your.kingcounty.gov/solidwaste/greenbuilding/documents/Green_home_remodel-salvage.pdf, Accessed August 15, 2011.

[17] U.S. Green Building Council, Green Building Design and Construction, LEED Reference Guide for the Design, Construction and Major Renovations of Commercial and Institutional Buildings Including Core and Shell and K-12 School Projects, 2009 Edition (Updated June 2010), p. 367 and 375.

construction process is not traditional and that additional planning steps are needed. Guidelines from industry practitioners and local governments and technical assistance are available to make this process more predictable. For example, considering that the material availability fluctuates, guidelines suggest that it is necessary to keep a flexible design and schedule. Flexibility will allow the designers/builders to investigate the market and capitalize on the safe, affordable materials as they become available. However, because the prospective materials will not all come at the same time, the designers/builders will need to provide spaces for their proper storage on-site. On the side of design though, reliance on random local materials that are available during construction will most likely result in unique structures and creative material patterns and applications[18] that could be aesthetically valuable in affordable housing.

Construction waste management

Savings on landfill fees. Another way to reduce construction and renovation costs and thereby the housing costs is through construction waste management. Already, in locations in which disposal fees are high, the clear opportunity for savings has facilitated the development of markets for material recovery as an alternative to disposal;[19] national trends suggest that such opportunities will become widespread. Tipping fees are increasing, regulations are excluding C&D materials from landfills, and the number of C&D landfills has declined 26% between 1990 and 2002.[20] In 2003, Connecticut was already running out of construction and demolition landfill capacity. Massachusetts was considering a full disposal ban on certain construction and demolition waste materials, such as asphalt, concrete, metal and wood.[21] These examples illustrate fairly well how C&D waste disposal options may grow fewer and more expensive in the future and support the idea that the savings from construction waste management if only through the avoidance of landfill fees may become significant.

Material efficiency. Further, through construction waste management and reclamation of material scraps, builders can use their primary materials more efficiently. In conventional building, builders may pay for materials at the initial purchase, for the landfill fees at the disposal of material scraps that are usable *and* again, at the unnecessary re-purchase.[22] Conversely, by managing construction waste, the builders will be able to fully capitalize on the scraps and wherever possible limit the expenditures to only initial purchases.

Resale. Third, the builders may sell the materials salvaged through construction waste management to create revenue; they may need to investigate the market to focus on materials and products with

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[18] Olivia Chen, Affordable Housing Made of Recycled Materials: http://inhabitat.com/low-income-housing-made-of-recycled-materials/, Accessed September 16, 2011.
[19] U.S. EPA, Office of Resource Conservation and Recovery, March 2009. Estimating 2003 *Building Related* Construction and Demolition Materials Amounts, p. 20.
[20] Tom Napier, Construction Waste Management, 2011: http://www.wbdg.org/resources/cwmgmt.php, Accessed August 17, 2011.
[21] Gruzen Samton LLP with City Green Inc. for NYC Department of Design & Construction, May 2003; Construction and Demolition Waste Manual: http://www.nyc.gov/html/ddc/downloads/pdf/waste.pdf, Accessed August 18, 2011.
[22] Adapted from NAHB Research Center, Residential Construction Waste: From Disposal to Management: http://www.toolbase.org/Best-Practices/Construction-Waste/residential-construction-waste, Accessed August 17, 2011.

higher resale values and be especially careful to protect materials from any damage that may render them undesirable. The changes in the construction demands and the limited stocking space may at times make the resale more difficult, but it should still be possible to get in-store credit.[23] The various reclamation outlets include used building materials retailers, online exchanges, classified ads and recycling companies.[24]

Incentive programs. Fourth, the builders may donate the materials salvaged through construction waste management and receive tax breaks. Further, various government incentive programs reward construction waste management efforts. For example, a number of states award a point toward Low Income Housing Tax Credit funding for projects that implement construction waste management;[25] construction waste management can help qualify for the funding.

In addition to local governments, non-profits may also provide grants or loans for green affordable housing. One example is Enterprise Community Partners who have developed the Green Communities criteria in collaboration with The Natural Resources Defense Council, American Institute of Architects, American Planning Association, etc, to support the funding of affordable projects decisions. The Green Communities criteria include two separate construction waste management requirements and one is mandatory to secure the funding.[26]

Savings on hauling fees. Finally, builders who reduce the waste through construction waste management also decrease the fees associated with its transportation to landfills. For example, by 2003, New York City had already run out of disposal facilities and had to export its waste. [27] As more landfills close and disposal options become fewer, average hauling distances will most likely increase[28] and raise the hauling fees. In comparison, salvaged materials are either reused on site or can be self-hauled to local outlets.

As illustrated, construction waste management can reduce material costs in different ways: by reducing disposal fees, initial material costs, by generating revenue through resale, through collecting tax breaks or qualifying for funding and reducing hauling fees. However, since some of the savings

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[23] King County Department of Natural Resources and Parks, Solid Waste Division & City of Seattle Department of Planning and Development, 2006; {Green home remodel} salvage & reuse: http://your.kingcounty.gov/solidwaste/greenbuilding/documents/Green_home_remodel-salvage.pdf, Accessed August 15, 2011.
[24] Ibid.
[25] Global Green USA, http://www.globalgreen.org/greenurbanism/affordablehousing/, Accessed August 15, 2011
[26] Enterprise Community Partners Inc, 2011 Enterprise Green Communities Criteria: http://www.greencommunitiesonline.org/tools/criteria/EGC2011Criteria_final.pdf, Accessed August 22, 2011
[27] Gruzen Samton LLP with City Green Inc. for NYC Department of Design & Construction, May 2003; Construction and Demolition Waste Manual: http://www.nyc.gov/html/ddc/downloads/pdf/waste.pdf, Accessed August 18, 2011.
[28] T.R. Napier, D.T. McKay, N.D. Mowry, 2007, A lifecycle perspective on recycling construction materials (The most sustainable materials may be the ones we already have), International conference on Sustainable Construction Materials and Technologies – Chun, Claisse, Naik & Ganijan (eds), Taylor & Francis Group, London, ISBN 978-0-415-44689-1

are contingent on market conditions, it may be necessary to first investigate the market to be able to find the path of most savings.

When builders are not looking to generate revenues from selling construction waste, or the temporary demand for particular materials is low and reuse businesses lack stocking space, the building materials can be saved for future reuse. In such cases, builders will still avoid landfill fees and cost savings can be transferred onto homeowners who would not have to repurchase the materials for the future maintenance. For example, NAHB recommends such a savings track in case of flooring sheets.[29]

Indirect Environmental Justice benefits. Because construction waste management and material recovery are inextricably linked, they provide some of the same Environmental Justice benefits. In brief, material salvaged through construction waste management serves as the source for the recycling and reuse industry, and thus, supports the sector and its addition of low-skill jobs. Construction waste management reduces the amount of waste sent to landfills and decreases potential sanitary and environmental pollution associated with the break-down that most affects the surrounding low-income households. Recovered materials replace virgin materials and intercept the new extraction and manufacture and the associated industrial pollution that again, most affects the surrounding low-income communities. In addition, the diversion of waste decreases the extent of needed landfill management efforts that typically drain public funds.[30] Reducing the landfill capping, closing and monitoring efforts allows that such public funds be used toward national and state programs that may directly benefit low-income households.

Planning considerations. The above examples note the ways in which construction waste management can bring savings. However, even though construction waste management can be a financially worthwhile undertaking and most residential construction waste is recyclable[31], the recovery opportunities may not exist or be obvious everywhere. The best way to explore their availability or develop new opportunities is to draft local and state solid waste officials, product manufacturers and recyclers and hold forums on existing opportunities or potential barriers and obstacles.[32]

Further, even with opportunities in place, any savings from construction waste management are contingent on timely planning. The key actions include finding salvage and recycle companies, identifying appropriate handling procedures and determining the best ways and time to haul the

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[29] NAHB Research Center, Residential Construction Waste: From Disposal to Management: http://www.toolbase.org/Best-Practices/Construction-Waste/residential-construction-waste, Accessed August 17, 2011.

[30] T.R. Napier, D.T. McKay, N.D. Mowry, 2007, A lifecycle perspective on recycling construction materials (The most sustainable materials may be the ones we already have), International conference on Sustainable Construction Materials and Technologies – Chun, Claisse, Naik & Ganijan (eds), Taylor & Francis Group, London, ISBN 978-0-415-44689-1

[31] NAHB Research Center, Residential Construction Waste: From Disposal to Management: http://www.toolbase.org/Best-Practices/Construction-Waste/residential-construction-waste, Accessed August 17, 2011.

[32] Ibid.

material. Reuse businesses may have limited space and might change the selection of materials they'll take, or processing facilities may only take sorted recyclable materials. Finding out such details early enables timely preparation and successful efforts. For example, specific handling procedures may introduce new on-site tasks such as materials sorting. Even if the separation is generally not very difficult since materials are mostly used one at a time, which reduces the time and effort spent sorting,[33] the added task may require some level of preparation.

Design measures

Size and spatial form. Other cost savings opportunities exist in the application of certain design decisions. For example, houses that are smaller all-around require less material input as well as fewer equipment and labor hours to construct. In addition, compact houses that are built "up" instead of "out" have smaller footprints that require less land and land preparation which translates into savings on land acquisition, as well as equipment use and labor effort. In turn, these reduced resources during construction reduce the upfront costs of a home. Design strategies that focus on reducing circulation paths, filling spaces under roofs, sharing spaces between different uses, using built-in furniture, etc, help achieve the needed spatial efficiency.

In addition, homeowners capitalize on using less energy to operate these smaller homes, and the houses that are developed vertically instead of horizontally increase land-use density; if accompanied by an appropriate mixing of land uses, the increased density allows homeowners to access various job opportunities and commercial services easily and thus, save on transportation costs. Reduced energy bills and transportation costs add up over life spans of homes.

Advanced Framing Techniques. Yet another distinct way to reduce construction and operational costs is to use advanced framing techniques. Builders eliminate unnecessary framing without compromising the homes' structural integrity and thus, use less material and labor in support of the same structural performance. The U.S. Department of Energy has maintained detailed information about advanced framing methods and has documented how fully implementing advanced framing techniques in 2000 could have resulted in materials cost savings of about $500 or $1000 (for a 1,200- and 2,400-square-foot house, respectively), and labor cost savings of between 3 and 5 %.[34] In addition, the reduced material input reduces the amount of waste that needs to be disposed of, which improves the builders' bottom line even further; the reductions in material purchasing and labor expenditures combine with the avoidance of landfill fees to create the full cost-savings amounts.

Savings to homeowners from implementing advanced framing techniques are accrued over the lifespan of the homes. By replacing the framing not needed to support the homes' structural integrity

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[33] M. U. Christiansen, 2007, An analysis of environmental and fiscal impacts or recycling during Kern Center construction, International conference on Sustainable Construction Materials and Technologies – Chun, Claisse, Naik & Ganijan (eds), Taylor & Francis Group, London, ISBN 978-0-415-44689-1

[34] U.S. Department of Energy, Energy Efficiency and Renewable Energy, Office of Building Technology, State and Community Programs, October 2000; Advanced Wall Framing: http://apps1.eere.energy.gov/buildings/publications/pdfs/building_america/26449.pdf, Accessed August 22, 2011.

with insulation materials, homebuilders are able to reduce the thermal bridging and increase the homes' energy efficiency. In fact, the U.S. Department of Energy has documented how fully implementing advanced framing techniques in 2000 could have resulted in annual heating and cooling cost savings of up to 5 %.[35]

Advanced Framing Techniques - Applicability considerations. However, even though advanced framing techniques have been proven effective, local codes might not allow them because of specific local conditions, e.g. wind or seismic potential.[36] The consulting of building officials may alert the builders to any code restrictions and help them find the advanced framing technique options that are the most suitable.

Open layouts. Similarly to how advanced framing techniques eliminate unnecessary framing, open layouts exclude unnecessary walls. For example, walls could be fully or partially removed between complementary spaces, such as dining and living rooms or corridors and day areas. Such open layouts reduce material input and simplify future reconfiguration and thus, reduce material and labor costs both initially and during future adaptations.

Reduced interior finishes. Eliminating interior finishes by relying on structural materials to double as finishes where possible, can serve as another effective method to reduce construction costs. For example, a stained or decorated concrete slab on grade can serve as a finished floor in kitchens or bathrooms and replace the tile. Again, this strategy reduces both the material and labor costs.

The strategies noted above begin to illustrate ways in which home design can reduce home costs in green construction. The list of strategies is not exhaustive.

Low Cost Professional Services, Technical Assistance and Labor

Green building design requires high-skill, specialized workforce that can streamline the design and construction processes to reach the "green" affordability objectives and avoid potential pitfalls. However, to limit the expense of green building professional services, a green building specialist can be hired as a consultant to just a traditional design firm. Alternatively, local professionals who bring to the table familiarity with the community and the site, connections to local manufacturers and suppliers, ability to find best deals on construction materials, a passion to learn about sustainability, willingness to tap into available technical resources but not necessarily the actual green building experience, may present the best value yet. Various collections of detailed case studies may provide additional guidance. For example, the U.S. Department of Housing and Urban Development has funded the National Center for Appropriate Technology (NCAT) to develop the Affordable Sustainability Technical Assistance for HOME (HomeASTA) project to help the recipients of HOME

[35] Ibid.
[36] Ibid.

grants build green affordable housing projects. Under the HomeAsta project, the NCAT produced Evergreen Affordability. The compiled case studies can be used as a resource.[37]

In contrast, many building construction trades can be learned through on-the-job training,[38] which raises an opportunity to employ a low-skill, low-cost workforce. For example, to build homes inexpensively, Habitat for Humanity recruits homeowner families to invest hundreds of hours of sweat equity. By involving future homeowners, Habitat for Humanity keeps the cost of labor down and manages to limit the funding needs and to sell the houses to the partner families at low cost.[39] Habitat for Humanity has used this building model to provide green affordable homes. In such a model, the non-profit developer uses the homeowners' sweat equity but meanwhile trains the families for free and equips them with sustainable building skills they may use for future jobs. In that respect, such affordable green construction building model provides additional environmental justice benefits.

Cost of Land

In order to keep properties affordable for low-income households, it is also important to acquire land at low cost. This is especially challenging when attempting to otherwise take advantage of economies of scale and acquire several adjacent properties for simultaneous low-income housing projects. However, building green gives access to a number of financial streams and incentives that can partially offset these costs, and at times, developers have relied on city donated land and land trusts as well.

Energy Efficiency

A yet another distinct way to reduce housing costs is to design homes with energy efficiency in mind. Energy efficiency features such as passive solar design, well-insulated and well-sealed shells, efficient HVAC equipment and appliances could combine with smaller sizes and advanced framing techniques to deliver long-term savings on energy bills. For illustrative purposes, compared to standard homes, Energy Star homes, which feature effective insulation, high-performance windows, tight construction and ducts, efficient equipment and appliances, use substantially less energy for home heating, cooling, and water heating and deliver $200 to $400 in annual savings on just these expenses.[40]

While some of the energy efficiency measures such as optimizing home-orientation or window size and positioning may not come at additional costs, others, such as increasing the amount of insulation

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[37] National center for Appropriate Technology for U.S. HUD, Evergreen Affordability, Tools for Building Sustainable Housing, 2004: http://www.ncat.org/evergreen/evergreen_affordability_general.htm, Accessed August 22, 2011.

[38] United States Department of Labor, Bureau of Labor Statistics, Green Jobs, Careers in Green Construction: http://www.bls.gov/green/construction/, Accessed August 22, 2011.

[39] Habitat for Humanity Fact Sheet, 2011: http://www.habitat.org/how/factsheet.aspx, Accessed September 16, 2011

[40] ENERGY STAR, Features & Benefits of ENERGY STAR Qualified New Homes: http://www.energystar.gov/index.cfm?c=new_homes.nh_features; Accessed September 19, 2011.

or including more-efficient windows, may. However, Habitat for Humanity Metro Denver partnered with the U.S Department of Energy's Building America Project and the National renewable Energy Laboratory to create affordable, energy-efficient demonstration homes which shows that energy efficiency features can be incorporated in cost-effective ways.[41]

III. Conclusion

An attempt to propose how to address the environmental risks of low-income families, led us to talk about affordability of green housing. Currently, low-income households face environmental risks because of the average quality and age of their housing. Our intent was to highlight the opportunities for cost savings in new green construction and underline that the health benefits of green homes can be extended to low-income groups to protect them from unnecessary environmental burdens.

In addition, some of the highlighted strategies resolve other Environmental Justice issues as well. For example, construction waste management and material recovery also support the recycling and reuse industry and its addition of low-skill jobs. The two strategies divert waste and decrease the potential sanitary and environmental pollution associated with material break-down and/or incineration that most affects the proximate low-income communities. Further, the waste diversion decreases the magnitude of landfill capping, closing and monitoring efforts and the amount of public funding going into it. The funding can then be streamed toward other efforts to further benefit low-income communities. In addition, the construction waste management and recovery also limit the unnecessary excavation and manufacturing and the pollution burdens and their effect on proximate communities that are typically low-income.

[41] Building America, U.S Department of Energy case studies: http://www.nrel.gov/docs/fy05osti/36102.pdf and http://www.nrel.gov/docs/fy08osti/42591.pdf, Accessed September 19, 2011.

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