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# Life-Cycle Energy and GHG Emissions for New and Recovered Softwood Framing Lumber and Hardwood Flooring Considering End-of-Life Scenarios

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## Abstract

Within the green building fields is a growing movement to recover and reuse building materials in lieu of demolition and land fill disposal. However, they lack life-cycle data to help quantify environmental impacts. This study quantifies the primary energy and greenhouse gas (GHG) emissions released from the production of wood recovered from an old house and from new wood harvested from the forest and produced in a sawmill with both products ending up installed in a new house. In addition, the study quantifies the primary energy and GHG emissions released if the recovered wood is not reused but instead is either burned to replace coal or natural gas to generate electricity, landfilled with or without landfill gas capture equipment, ground into mulch, or some combination.

Keywords: energy, carbon emissions, reuse, softwood framing lumber, hardwood flooring, life-cycle, life-cycle inventory, LCI, end-of-life, EOL

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## Conversion Table

| English unit               | Conversion factor | SI unit                  |
|----------------------------|-------------------|--------------------------|
| board feet                 | 0.0023597         | m <sup>3</sup> (nominal) |
| mile (m)                   | 1.6093            | kilometer (km)           |
| British thermal unit (Btu) | 0.00105506        | megajoule (MJ)           |

# Life-Cycle Energy and GHG Emissions for New and Recovered Softwood Framing Lumber and Hardwood Flooring Considering End-of-Life Scenarios

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## Executive Summary

Within the green building and sustainable construction fields is a growing movement to recover and reuse building materials in lieu of demolition and landfill disposal. Building materials reuse has several benefits including reducing carbon footprint, conserving resources, extending landfill life, and minimizing pollution. Additionally, recovering building materials for reuse in construction typically provides greater economic benefits than any alternative use. Building professionals including architects, materials specifiers, and contractors are more interested in mitigating the environmental impact of the buildings they create. However, they lack life-cycle data that will help quantify the environmental impact of the building materials they specify as well as the project's overall impact, including contribution to global climate change.

The goal of this study was to use life-cycle assessment (LCA) to quantify greenhouse gas (GHG) emissions and primary energy use of new and reused wood products with additional information on end-of-life (EOL) options. At the end, we compare the impact on GHG emissions for two alternatives: reusing old wood in recovered products or discarding old wood with the attendant end-of-life emissions and making new products. We use existing life-cycle inventory (LCI) data and develop new LCI data from reusing two recovered wood products, softwood framing lumber and solid-strip hardwood flooring, production of new wood products, and disposal of old wood products. Life-cycle stages for new products include harvesting (i.e., resource extraction or deconstruction), resource transportation, primary product production, and product transportation. For reusing recovered wood, the environmental burdens associated with

recovery include decay of waste wood generated, transportation, production, and product transportation. For disposal of old wood, the EOL burdens include demolition, waste transport, and processing of waste wood whether burning it to replace fossil fuels for generation of electricity, mulching it, or landfilling it.

This study involved two parts. The first developed life-cycle data for the two recovered wood products and compared these data with life-cycle data for their new wood product counterparts. LCI data for new products are from forest cradle to installation in a new building. LCI data for recovered products includes the deconstruction process through to installation in a new building. The second part estimates emissions for various EOL scenarios when old wood is discarded from old structures (i.e., burning to generate electricity, grinding for mulch, landfilling without methane capture, and other disposal options for wood removed from old buildings). The second part also compared GHG emissions for cases where old wood is reused for products to cases in which old wood is discarded to various EOL dispositions and new products are produced.

The LCI for recovered wood excluded the environmental impacts associated with the previous product production of those products. The processes that were excluded from the initial product system include raw material extraction, resource transportation, product manufacturing, product transportation, construction, and use. The focus of this analysis was on comparing impacts of making new products compared with making recovered wood products.

The study methodology followed ISO 14040 and 14044 guidelines. The present study used allocated emissions using

an economic screen and mass allocation to assign emissions to wood products and waste co-products. Emissions were allocated on the basis of mass to primary products and co-products if they each had some economic value (as is the case for new products). If the waste has no economic value, then all emissions are assigned to the primary products (as is the case for recovered/reused products). Primary (annual production) data for reused products were collected on the residential sector from 13 deconstruction companies spread across the United States in 2009. Using production weight-averaged survey data, our study estimated emissions per functional unit, which was 1 m<sup>3</sup> of final product at the construction site where the reused product was installed.

Evaluation of the emissions associated with discarding old wood products used a base case EOL scenario and five alternate scenarios. The base case approximates current practice and was comprised of burning the wood for energy to replace coal power (30%), grinding for mulch (10%), and disposal in a construction and demolition landfill (C&D) without methane capture (60%). In landfills, wood breaks down anaerobically into biogenic methane and biogenic carbon dioxide. C&D landfills, unlike municipal solid waste (MSW) landfills, typically do not have methane capture technology installed. Biogenic methane, a potent GHG if captured from landfills, avoids the necessity of producing natural gas, although not all biogenic CH<sub>4</sub> that is generated can be captured. In the present study, the captured landfill methane was burned to generate electricity to replace natural gas. The Global Warming Potential (GWP) for EOL GHG emissions was calculated using the International Panel on Climate Change (IPCC) 2007 100-year time horizon.

LCI data for recovered wood products includes cumulative cradle-to-gate energy use and emissions obtained from the survey of demolition/reuse businesses and from the U.S. LCI Database. Fossil energy used to recover softwood framing lumber and hardwood flooring was 418 and 859 MJ/m<sup>3</sup>, respectively. Crude oil was the largest energy component due mostly to resource and product transportation with values of 178 and 437 MJ/m<sup>3</sup>, respectively. No biomass energy was used to make recovered products.

### **Comparison of Processes to Make New Wood Products and Recovered Products**

Fossil and biomass energy used to make new softwood framing lumber and hardwood flooring was 6,440 and 7,750 MJ/m<sup>3</sup>, about 15 and 9 times, respectively, the amount used to make recovered wood products. One-half or more of the energy used to make new softwood framing lumber and hardwood flooring was from biomass: 4,360 and 3,880 MJ/m<sup>3</sup>, respectively.

Of the life cycle stages examined for both new and recovered wood products, the highest energy consumed was associated with new wood product production. Most energy for new wood products came from burning of on-site biomass

(i.e., mill residues) to generate thermal energy. Burning biomass such as mill residues emits biogenic CO<sub>2</sub>.

Fossil CO<sub>2</sub> emitted for new framing lumber and new hardwood flooring were about four times greater than for recovered softwood framing lumber (109 vs 23.9 kg/m<sup>3</sup>) and recovered hardwood flooring (228 vs 49.7 kg/m<sup>3</sup>). Primary drivers for the higher fossil CO<sub>2</sub> emissions for new products were from new wood product production and transportation. New wood products typically travel much further to their markets, urban centers, than recovered wood products. Recovered wood products are primarily produced in urban centers and have low transportation environmental burdens. When biogenic CO<sub>2</sub> emissions are added to fossil emissions, the total new products' CO<sub>2</sub> emissions were 8 to 10 times the emissions for the recovered products.

When estimating GWP, it is standard protocol not to include biogenic CO<sub>2</sub> emissions, as they are assumed to be recovered by forest carbon sequestration over time. GWP without biogenic CO<sub>2</sub> emissions is lower for recovered wood products than for the new wood products. GWP without biogenic CO<sub>2</sub> emissions is also lower for recovered products if disposal of wood waste during deconstruction is not considered.

### **Energy and Emissions for Discarded Old Wood Products at Their End-of-Life**

EOL scenarios for old wood products can result in large negative energy use and fossil CO<sub>2</sub> emissions if discarded wood is used to displace coal or natural gas in producing electric power. In the base case EOL scenario, where 30% of the discarded wood replaces coal power, the displaced coal energy consumption was -2,300 and -2,920 MJ/m<sup>3</sup> for the discarded softwood framing lumber and hardwood flooring, respectively. To put this into perspective, this negative energy amount would offset 53% (2,300/4,360) and 75% (2,920/3,880) of biomass energy consumed to make the new softwood framing lumber and hardwood flooring.

Five other EOL scenarios that examined various alternatives included 1) burning wood as a replacement for natural gas to generate electricity, 2) turning 100% wood waste into mulch, 3) disposing 100% to construction, and 4) demolition landfills with or 5) without methane capture and energy recovery into electricity. When 100% of wood replaces natural gas to generate electricity, energy use and GWP were also negative but less negative than when offsetting coal. All other EOL scenarios result in positive energy and GWP values.

For the base case EOL scenario (approximate current practice) where we assumed making new products would require discard of old wood to the current mix of proportions to energy, landfills, and mulch, the reuse of both softwood lumber and hardwood flooring produces less GWP than making new products. The GWP benefit is greatest for reusing hardwood flooring instead of making of new flooring.

This is true for GWP estimates that either exclude or include biogenic CO<sub>2</sub> emission. However, if we consider GWP that excludes biogenic CO<sub>2</sub> emissions (standard LCA practice), reuse could be notably worse (higher GWP) than new wood if all old wood could be burned to offset coal or natural gas in making electric power. Reuse could be slightly worse than new for softwood lumber if all old wood could be used as mulch (unlikely if wood is contaminated). So a key point is that if wood cannot be reused for products, the next best step is to keep it out of landfills and use it for either energy (top priority) or mulch (lower priority). There is a greater benefit from keeping hardwood out of landfills than keeping softwood out of landfills.

## Introduction

The role of carbon emissions on global climate and the projected negative impact on ecosystem sustainability and the general health of our planet have never been more elevated in the public's consciousness. This awareness is particularly evident in the building construction field where *green building* concepts are becoming more prevalent. Green building is defined as the practice of increasing the efficiency with which buildings use resources—energy, water, and materials—while reducing building impacts on human health and the environment. This is done through better siting, design, material selection, construction, operation, maintenance, and removal throughout the complete building life cycle. Building professionals, including architects, materials specifiers, and contractors, are more interested in mitigating the environmental impact of the buildings they create. However, they lack life-cycle data that will help quantify the environmental impact of the building materials they specify and a given project's contribution to global climate change.

Within the green building and sustainable construction fields is a growing movement to recover and reuse building materials in lieu of demolition and landfill disposal. Building materials reuse has several benefits including reducing carbon footprint, conserving resources, extending landfill life, and minimizing pollution (Smith and others 2001, Falk 2002, Ericksson and others 2005, Heilmann and Winkler 2005, Olofsson and others 2005, Thorneloe and others 2007). In spite of these benefits, there is currently no easy way for building professionals to quantify the environmental impact of incorporating reused building materials in new building or remodeling construction.

The goal of this study was to use life-cycle analysis to quantify greenhouse gas (GHG) emissions and primary energy use of new and reused wood products with additional information on end-of-life (EOL) options or scenarios. Incorporating existing and developed life-cycle inventory (LCI) data, the environmental consequences of reusing two recovered wood products—softwood framing lumber and solid-strip hardwood flooring—relative to the virgin counterparts were evaluated. A study by Bergman and

others (2010) developed cradle-to-gate LCI data for these two recovered wood products and compared these data with corresponding cradle-to-gate LCI data of their new wood product counterparts (Puettmann and Wilson 2005, Puettmann and others 2010). These studies found that the new wood products consumed more energy and emitted more GHGs than did the recovered wood products; however, those results considered neither product transportation for the new wood from the manufacturing facility to the construction site nor transportation of the recovered wood from the resale facility to the construction site.

The results presented here include new wood product transportation to the construction site. In addition, various EOL scenarios (i.e., burning for energy, grinding for mulch, and other disposal options) for the two wood products removed from old buildings were studied to evaluate the impact on global warming potential (GWP).

## Background

The recovery and reuse of building materials from wood-framed building removal is becoming more widely recognized as a positive environmental alternative to demolition and landfilling. Using “deconstruction,” or dismantlement, a building can be selectively dismantled and usable materials recovered for reuse in construction (Falk 2002, Falk and Guy 2007, Kibert 2003). This deconstruction and reuse strategy is consistent with resource conservation efforts, waste reduction, and green building certification programs. Examples of such programs are United States Green Building Council's (USGBC) Leadership in Energy and Environmental Design (LEED), and the Green Globe Green Building Initiative (GBI).

Using conventional demolition, the wood-framed building is cleared from the site by the most expedient means possible, typically using a “track-hoe” or other heavy machinery to reduce the building to the smallest pieces possible for easy loading and transport to a construction and demolition (C&D) landfill. This process is by its nature destructive to the building materials and typically results in nearly all of the building ending up as unusable for reuse in new construction.

As for deconstruction, two approaches are typically used in salvaging building materials. At its simplest level, a non-structural approach is taken (also known as “soft-stripping”) and focuses on the recovery of easier to remove components, such as finish flooring, wall finishes, doors, windows, and other finish materials. A more involved approach, often called “full deconstruction,” involves the dismantling of the structural components of a building. As a result, it is more time intensive. The material recovered typically includes roof, wall, and floor framing, sheathing, and other building frame components. Unusable wood material goes typically to a local C&D landfill.

## Construction and Demolition Waste Management

In 2003 (latest figures), the United States produced about 164 million metric tons of C&D waste from building-related activities (EPA 2009a, 2012a). Of this, about 69 million metric tons comes from residential construction (primarily wood framed). Because wood contributes between 25% and 40% of a C&D landfill (EPA 1995, NWMOA 2009, Falk and McKeever 2012), potentially a significant amount of reusable wood building materials can be diverted and reused. Better materials management strategies for C&D waste would result in conservation of natural resources, reduced landfill requirements and associated pollution, and GHG emissions that result from such facilities. In the United States, landfills are the third largest source of methane behind intestinal fermentation and natural gas systems (EPA 2011).

Three recent events illustrate the importance of the need for such strategies:

- 1) The USEPA has declared carbon dioxide and other GHG emissions as air pollutants (EPA 2009b).
- 2) A requirement for 50% C&D waste diversion by 2015 for Federal agencies (Executive Order (EO) 13514, Federal Leadership in Environmental, Energy, and Economic Performance).
- 3) A requirement for Federal agencies to set goals in the areas of energy efficiency, acquisition, renewable energy, toxics reductions, recycling, sustainable buildings, electronics managements, fleets, and water conservation (EO 13423 Strengthening Federal Environmental, Energy, and Transportation Management).

Not surprisingly, many studies indicate that increasing the reuse and recycling of C&D materials results in corresponding lower levels of landfilling. Additionally, this utilization lowers the need for new product production, lowering overall energy consumption and environmental impact (Blengini 2009, Smith and others 2001, Eriksson and others 2005, Heilmann and Winkler 2005, Sunberg and others 2004, Thorneloe and others 2007).

Reusing, or otherwise diverting, building materials fated for landfills can help reduce energy use and mitigate GHG

emissions (e.g., biogenic methane) released from landfills (EPA 2011). Thorneloe and others (2007) indicates that for a typical U.S. landfill accumulating 437,000 tonnes/y with a recycling rate of 40% saved almost 8.44 million GJ (8,000 trillion ( $10^{12}$ ) Btu (TBTU)) of energy compared to a recycling rate of 30%, which saved about 2.11 million GJ (2,000 TBTU) of energy. This effect seems counter-intuitive. Nevertheless, improving the recycling rate affects materials that may be more difficult to remove but require more energy to produce as new. As a result, higher recycling rates create higher energy savings per percentage increase.

Recycling and reuse have different environmental impacts depending on types of materials recycled and reused, transportation distances, and the remanufacturing processes (Thorneloe and others 2007). Life-cycle research can play an important role by examining various scenarios for their environmental trade-offs (Borghi and others 2009).

## Life-Cycle Assessment

Life-cycle assessment (LCA) is comprised of four stages (phases) as defined by the International Organization for Standardization (ISO). These are 1) goal and scope definition, 2) inventory analysis, 3) impact assessment, and 4) interpretation (Fig. 1). A LCA study includes all stages but a LCI study does not include stage 3, the impact assessment (SAIC 2006, ISO 2006a,b).

LCA is a well-established method for evaluating the environmental impacts of processes and products. Among other attributes of environmental performance, LCA quantifies the carbon impact of products. Performing a unit process based LCA of a product is a detailed, data-intensive process. A LCA is composed of life-cycle stages. Life-cycle stages for building products include resource extraction, transportation, product manufacturing, construction, use, and final disposition (i.e., EOL) (Fig. 2).

Each life-cycle stage is evaluated by conducting LCIs. LCIs quantify the material and energy inputs as well as the environmental burdens within carefully defined system boundaries for a given product, process, or service in relation to a functional unit (ISO 2006a,b). LCIs track all the inputs and outputs including emissions of a single life-cycle stage such as harvesting or product manufacturing across the system boundary (ISO 2006a). While LCAs have typically been

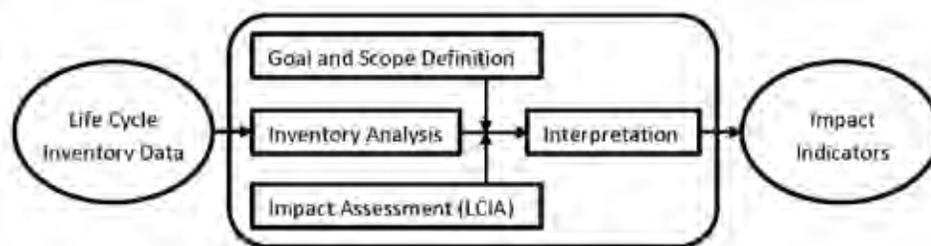
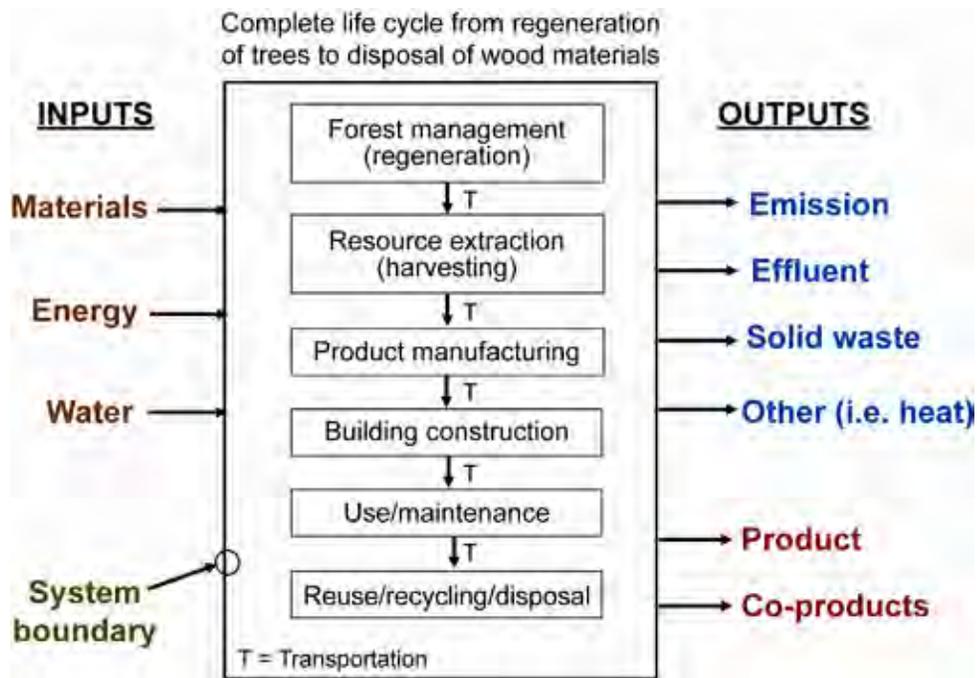


Figure 1. Life-cycle assessment phases.



**Figure 2. Complete life-cycle from regeneration of trees to disposal of wood materials (based on Fava and others (1994)).**

used to evaluate the environmental impact of producing virgin materials, they can also be used to evaluate the environmental impacts of reusing recovered materials. For example, a study by Blengini (2009) indicated that the total energy and GHG emissions associated with the reuse of recovered building materials from a residential building shell located in Italy are 29% and 18%, respectively, of the environmental burdens of similar virgin materials.

### Environmental Assessment Tools

Research on assessing the environmental impact of final product disposition for wood products draws on and must integrate diverse literature, available U.S. LCI data for virgin wood products, and analysis of various disposal scenarios.

For LCA practitioners, obtaining transparent and consistent U.S. LCI datasets on wood products was difficult until the mid-2000s. As part of an on-going effort, the National Renewable Energy Laboratory (NREL) working with LCA experts manages a publically available LCI database called the U.S. LCI Database. To aid in populating the U.S. LCI Database, the Consortium for Research on Renewable Industrial Materials (CORRIM) is developing critically reviewed LCI datasets on forestry and forest products for the U.S. LCI database (CORRIM 2010, USDA 2013).

In the various geographical regions of the United States, CORRIM has constructed cradle-to-gate LCI data based on individual gate-to-gate LCIs for many new wood products (Puettmann and Wilson 2005, Puettmann and others 2010).

The U.S. LCI Database has become a repository of many wood building materials. Other environmental tools, such as the U.S. Environmental Protection Agency's (EPA) Waste Reduction Model (WARM) are available to evaluate materials for their carbon emissions and energy use.

Initial work on broad categories of waste disposal, including dimensional lumber, are being evaluated through WARM that was developed using a streamlined LCA approach (EPA 2012b). WARM's streamlined LCA is limited to an inventory of GHG emissions, carbon sinks, and energy impacts. The model does not evaluate human health impacts or air, water, or other environmental burdens that do not have a direct impact on climate change. In addition, WARM simplifies the determination of emissions from life-cycle stages that occur before a material reaches its end-of-life (EPA 2010). WARM calculates GHG emissions and energy benefits of baseline and alternative waste management practices. Another LCA tool for building products, the ATHENA Impact Estimator (IE, Athena 2012), includes evaluation of several LCA impact categories including primary energy consumption, air pollution index, water pollution index, and GWP.

Napier and others (2007) used both the WARM and ATHENA IE tools in a study to evaluate the GHG impact of recovering wood products from deconstructed military facilities. Results were limited to the effects of diverting materials from landfills and did not include end-of-life effects. Results indicated that 15,000 tonnes of recovered dimensional lumber that was reused instead of being landfilled

reduced carbon emissions by 3,257 tonnes of CO<sub>2</sub> equivalents and reduces energy use by approximately 8,750 GJ. As for the ATEHNA IE, results did indicate significant reduction for all six impact categories when recovering framing lumber for reuse. These results suggested that a comparative assessment of the environmental impacts of substituting recovered wood for new wood building material in construction could be made. This could include not only GHG effects of the manufacturing process and transportation but EOL effects as well.

## Methodology

The first step in this study was to develop cradle-to-gate unit process life-cycle data for the two recovered wood products and compare these data with cradle-to-gate life-cycle data of their new wood product counterparts. No burdens of the previous life for the recovered wood products were assigned. For recovered wood, the old building from which the lumber was recovered was the cradle, whereas the forest was the cradle for new wood products. Therefore, the location from where the wood products are extracted is a critical distinction between products because the old building from which reused wood was removed was once built with new wood harvested from forests. To further emphasize that the LCI data developed was modular in nature, this study assigned impacts to each product as they happened, not for any future impacts. The gate is defined as the installation at the construction site for both new wood and recovered wood. For recovered wood products, a transportation distance of 25 miles was assumed between the deconstruction site and the resale facility. For new wood products, data from the United States Department of Transportation (USDOT) were used to calculate an average transportation distance from a manufacturing facility to a local wholesale facility. For both new products, the transportation from the sale facility to the construction site was assumed to be 24 km (15 miles).

The second part of this study evaluated various EOL scenarios of old wood products discarded from old buildings (i.e., burning to generate electricity, grinding for mulch, and other disposal options) and their environmental impacts.

Emission profiles per functional unit of products were estimated using SimaPro 7 modeling software. Input data averages from the survey of demolition and recovery businesses were production weighted and additional secondary data used from U.S. LCI Database (PRé Consultants 2013, USDA 2013). The modeling software provided a list of raw materials consumed during the cradle-to-gate production (i.e., LCI flows) that was used to calculate cumulative (primary) energy consumption. The study estimated the GWP in kg CO<sub>2</sub> equivalent using the IPCC 2007 100-year Method (PRé Consultants 2013, IPCC 2007). Calculating values for GWP typically does not include biogenic CO<sub>2</sub> emissions, as they are part of the natural carbon cycle and thus are

excluded as standard LCA practice. However, new wood production burns wood waste (i.e., mill residue), a byproduct of making new wood products, thus emitting biogenic CO<sub>2</sub>. Therefore, GWP with and without biogenic CO<sub>2</sub> was calculated to provide insight on overall CO<sub>2</sub> emissions in relation to new and recovered wood products.

## Part 1—Cradle-to-Gate LCIs

### New Softwood Framing Lumber and Hardwood Flooring

An analysis of the energy consumption and associated emissions of new wood products was made by using the LCA framework from cradle-to-gate and existing information from the U.S. LCI Database and other resources. The two products were evaluated for their environmental impact from harvesting through manufacturing to product transportation to the construction site.

Figure 3 highlights the system boundaries for a cradle-to-gate LCI for new framing lumber and hardwood flooring, respectively. Within each system boundary, the individual unit processes were identified for greater transparency and identifying environmental “hot spots.” Unit processes for producing softwood framing lumber include log yard, sawing, drying, and planing operations (Milota and others 2005, Bergman and Bowe 2010).

Assumptions of this analysis include that new wood material transport from the manufacturing site to a wholesale location occurs by rail and truck. Because wood products production is regionally located in the United States, and new lumber must be transported long distances to local markets, an average distance of travel from manufacturer to wholesaler based on data from USDOT (2010) for softwood framing lumber (NAICS 321) and hardwood flooring (NAICS 337) was calculated. Table 1 shows transportation data for moving the new product from the manufacturing site to wholesaler to the construction site. For product transportation, we assumed a distance of 24 km (15 miles) from wholesaler to construction site for the new lumber and the same distance for moving the recovered wood products from the resale facility to the construction site.

### Recovered Softwood Framing Lumber and Hardwood Flooring

An analysis analogous to the new wood products was performed for the recovered products, however, because LCI information did not exist for the recovery process, a survey of the deconstruction industry was performed to collect necessary primary data (Appendix 1—Survey Instrument). The resultant survey data were weight-averaged before entering into the LCA modeling software for estimating the emission profile and raw material usage for the recovered material deconstruction process.

Figure 4 shows system boundaries for recovered softwood framing lumber and hardwood flooring cradle-to-gate LCI.

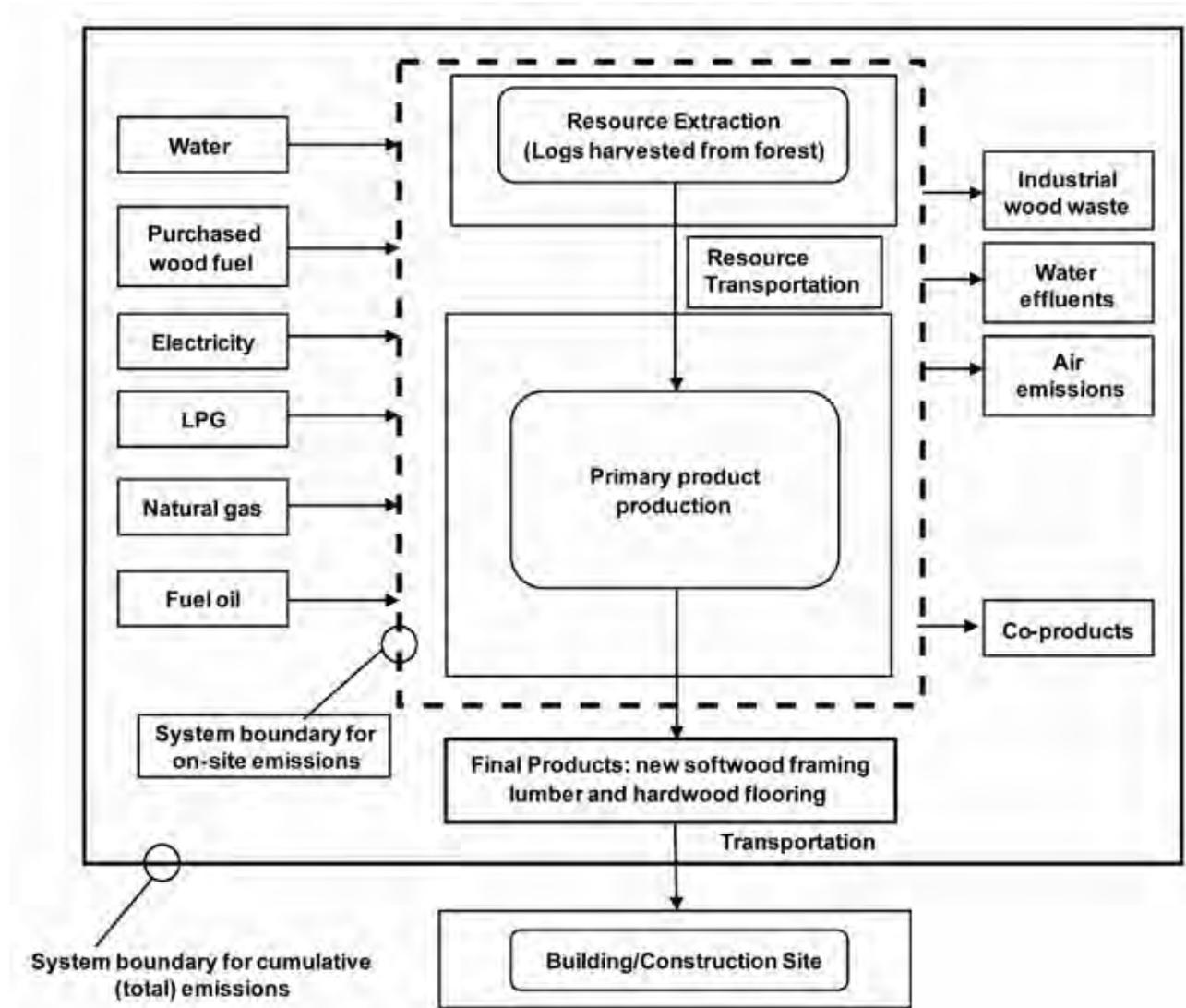


Figure 3. Cradle-to-gate system boundaries for new softwood framing lumber and hardwood flooring.

The process begins with extraction of the installed material (the raw material) from a building (i.e., the cradle), and includes transportation of the recovered material to storage and processing if necessary (product refurbishing) as well as transportation of the final product to the construction site (i.e., the gate). This cradle-to-gate analysis included everything within the “system boundary” that covers raw material extraction and product manufacturing (refurbishing) with the associated transportation up to but not including the use phase. Unit processes upstream of extraction such as storage of the recovered material were included in this analysis and the storage LCI data were the same for storing new material.

For recovered wood, survey data provided the basis for transporting the material from storage facility to construction site along with secondary sources (see Table 11 for new wood products) and expert opinion assuming recovered material reused locally. Surveying 13 U.S. building

deconstruction companies that regularly recover lumber and wood flooring provided the primary (2009 annual production) data. LCA modeling software using weight-averaged production data along with secondary data from the U.S. LCI Database estimated emissions and raw material usage. Survey data included information as a basis for calculating materials transportation from extraction (deconstruction site) to resale location. The distance from resale location to construction site was assumed to be the same as for new wood products. In addition, because the deconstruction process generated wood waste, estimated material lost were 17% and 11% for softwood framing lumber and hardwood flooring, respectively. The deconstruction wood waste (i.e., unusable wood) was transported to a C&D landfill with no methane capture.

Many laboratory and field studies have focused on decomposition of wood (i.e., biomass) disposed in a landfill.

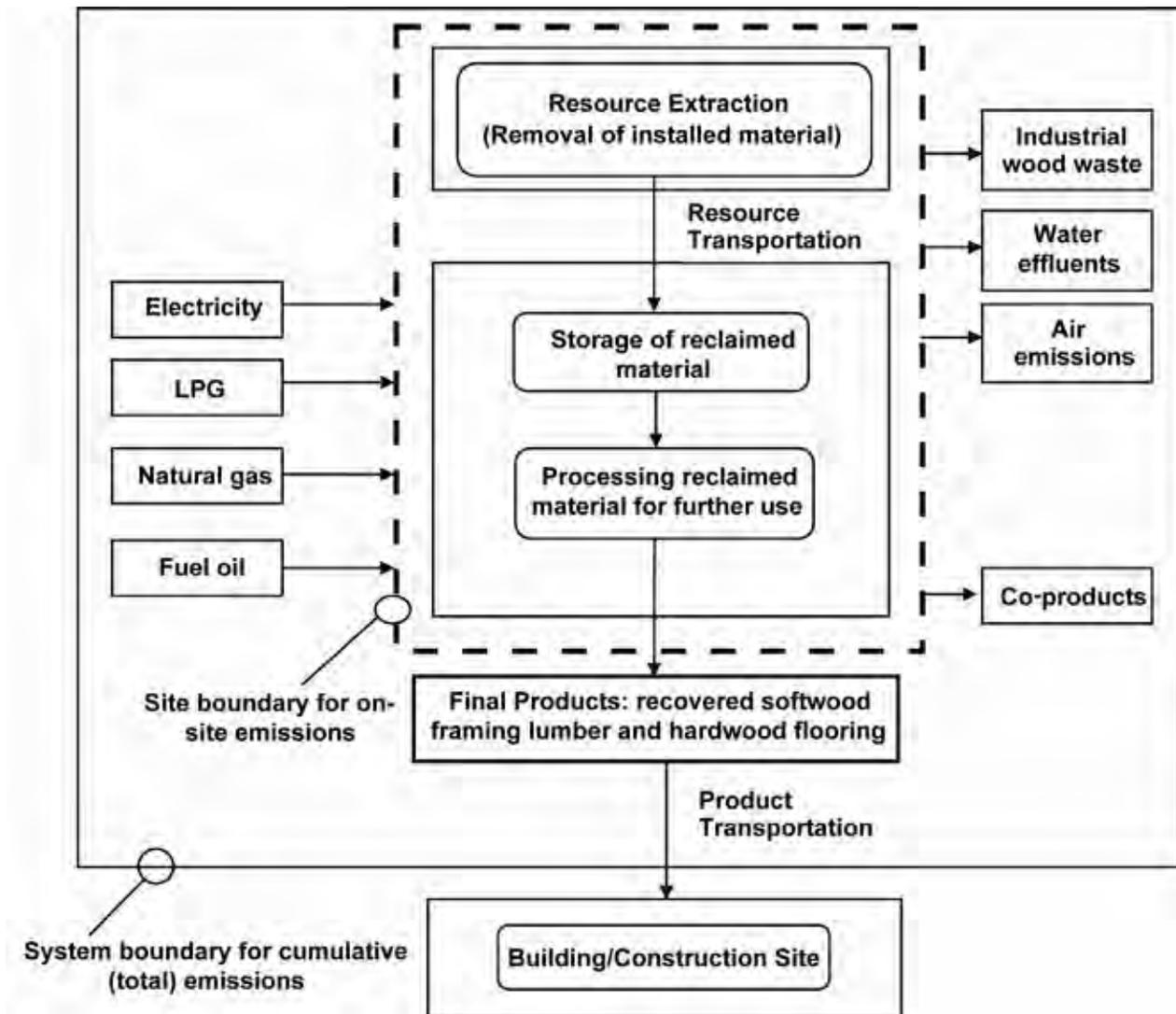


Figure 4. System boundaries for recovered framing lumber and hardwood flooring.

The question pertains to what percentage of wood actually breaks down to generate biogenic  $\text{CO}_2$  and biogenic  $\text{CH}_4$ . The IPCC (2006) recommends a carbon loss for wood products of 0.5 in a landfill. Wang and others (2011) reported a range of 0%–19.9% wood decomposition for a laboratory study conducted on solid wood and engineered wood products. An Australian study (Ximenes and others 2008) indicated that after 46 years, hardwoods and softwoods under different waste management schemes lose on average about 18% and 17%, respectively, of their original carbon content. A study by Skog (2008) states an average 23% carbon loss for wood products disposed of in the landfill and is the basis for this study. A portion (23%) of this waste wood was assumed to decompose anaerobically (in the absence of oxygen) and be released as landfill gas in the LCI analysis whereas the remaining wood remained in the landfill as is. This study assumed that both types of landfills examined

(MSW and C&D) passed through the four typical phases of a landfill over time but spent the vast majority of time in phase IV where biogenic methane and biogenic carbon dioxide are produced. Anaerobic conditions prevent the full decomposition of wood, unlike aerobic conditions. Wood material completely breaks down in aerobic conditions such as the forest floor and generates biogenic carbon dioxide and water as a result (ATSDR 2001, Staley and Barlaz 2009)). Future work will evaluate this phenomenon. In addition, we assumed that landfills captured the biogenic methane during decomposition and avoided natural gas production on 1:1 energy basis and was used to generate electricity. Biogenic methane is a GHG included in calculating GWP because it is human-made.

**Deconstruction (extraction of recovered materials)**—This unit process begins with installed softwood framing lumber (structural deconstruction) and installed hardwood flooring

**Table 1. New wood product transportation data**

| Transportation                                   | Wood products <sup>a</sup>      |                     |                                 |                     |
|--|---------------------------------|---------------------|---------------------------------|---------------------|
|  | Softwood framing<br>lumber      |                     | Hardwood flooring               |                     |
|  | tkm/m <sup>3</sup> <sup>b</sup> | tm/Mbf <sup>c</sup> | tkm/m <sup>3</sup> <sup>b</sup> | tm/Mbf <sup>c</sup> |
| Gate to wholesaler, by diesel truck              | 233                             | 258                 | 813                             | 1,314               |
| Gate to wholesaler, by rail                      | 96                              | 107                 | 4                               | 6                   |
| Wholesaler to construction site, by diesel truck | 14                              | 16                  | 17                              | 26                  |

<sup>a</sup>Softwood framing lumber and solid strip hardwood flooring are 1.63 and 2.36 m<sup>3</sup>/thousand board feet (Mbf), respectively.

<sup>b</sup>tkm/m<sup>3</sup> is tonne-kilometer per cubic meter of wood.

<sup>c</sup>tm/Mbf is ton-mile per thousand board feet of wood.



**Figure 5. Hardwood flooring boards being removed during deconstruction.**

(non-structural deconstruction) and includes the following operations:

Recovered softwood framing lumber unit processes

- Transporting workers to the deconstruction site.
- Transporting forklifts, bobcats, or other energy-consuming equipment to the jobsite.
- Removing surface materials such as roofing, drywall, subflooring, and insulation that would interfere with removal of framing lumber, either by hand or with machinery.
- Removing actual framing.
- Denailing framing, either by hand or pneumatic tool (i.e., denailer).
- Loading framing onto trucks, either by hand or with equipment.
- Transporting framing to a storage facility (i.e., resale facility).
- Unloading and storing the material until sold.

Recovered solid-strip hardwood flooring unit processes

- Transporting workers to the deconstruction site.
- Removing any furniture or other materials such as moulding that would interfere with the removal of the flooring.
- Sawing floor to ease removal.
- Removing the wood flooring board by board (Fig. 5)
- Denailing the flooring, either by hand or pneumatic tool (i.e., denailer).
- Loading the wood flooring onto trucks, either by hand or with equipment.
- Transporting the wood flooring to a retail facility.
- Unloading and storing the material until sold

Inputs include transportation fuel for worker vehicles and for material, fuel to run generators providing on-site electricity and/or grid electricity for tools to remove framing lumber and flooring, and fuel to run heavy equipment used for structural deconstruction and unloading material at storage facility. Outputs include recovered softwood framing lumber and recovered hardwood flooring. Emissions include solid (wood) waste produced during the removal process, air emissions from grid electricity, on-site generators, and other equipment, and non-wood waste such as nails and drywall. Solid waste was transported to a C&D landfill.

## Part 2—End-of-Life Scenarios

Various EOL strategies were also evaluated to assign the environmental burdens for cases where wood is not reused. EOL scenarios included burning wood for electric power production (decreases fossil emissions), grinding for mulch, and landfilling (without or with methane capture for energy production). A base-case scenario assumed that 30% of the wood not reused would be burned to replace coal to generate electricity, 10% would be ground for mulch, and the remaining 60% would be disposed of in a C&D landfill without methane capture. Additional scenarios were evaluated that extend the work done by Bergman and others (2012) and Winistorfor and others (2005).

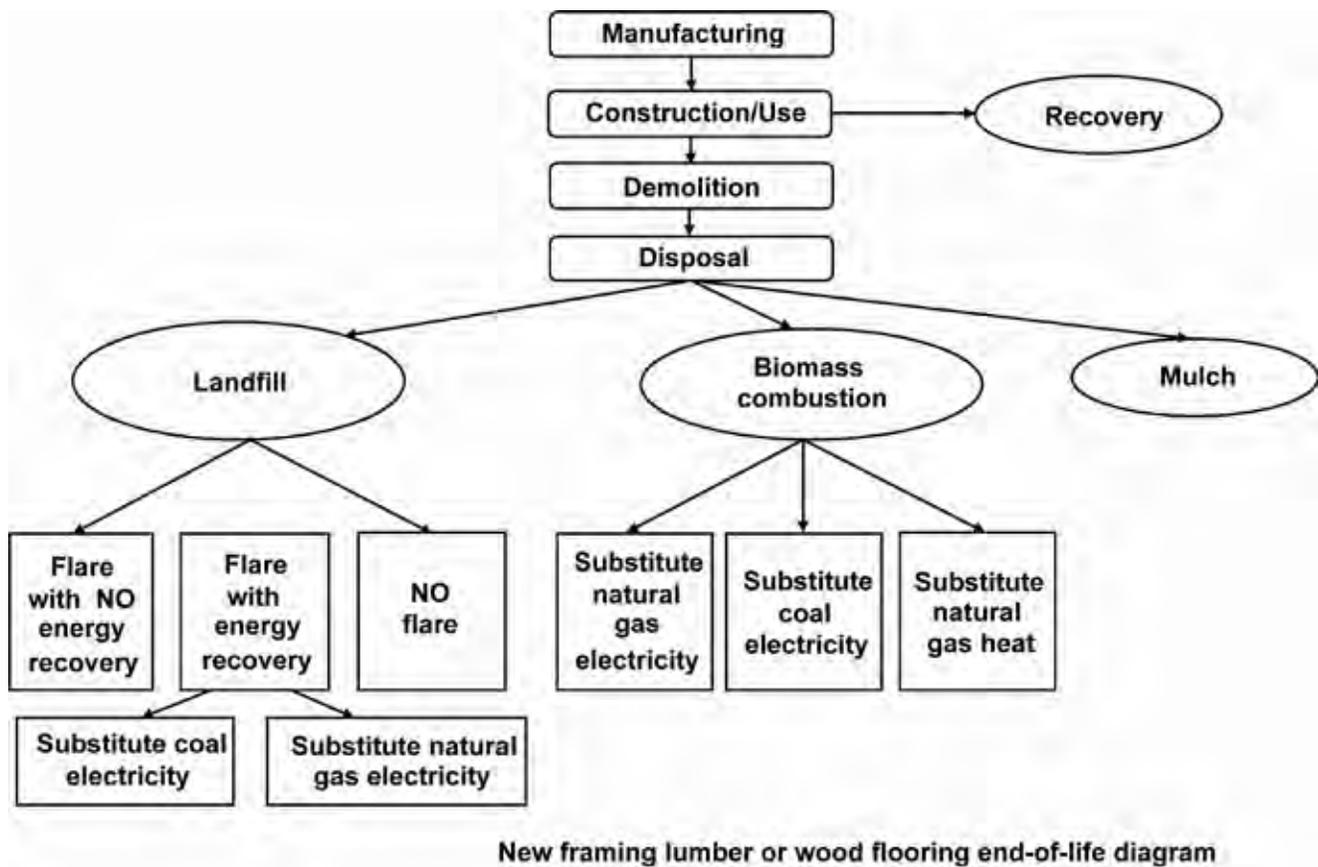


Figure 6. End-of-life disposal options for recovered wood materials.

Figure 6 indicates expected EOL scenarios for wood materials (Bergman and others 2012). Equations that estimate landfill emissions of biogenic  $\text{CH}_4$  and biogenic  $\text{CO}_2$  from anaerobic decomposition of wood are provided in Appendix 2—Landfill Equations.

The base case was comprised of burning the wood for coal power substitution (30%), grinding the wood into mulch (10%), and landfilling the wood without methane capture (60%). This distribution of wood to energy and landfills is in line with recent U.S. practices (Salazar and Meil 2009, Kaplan and others 2009, EPA 2011). Roughly 30% of C&D wood is burned for energy recovery: 11.2 million tons out of 39.4 million tons (EPA 2009c, EPA 2012b). C&D landfills contain much more wood than a MSW landfill on a volume basis (25% to 40% vs 6%), according to the EPA (2011). In addition, methane is not captured in C&D landfills. In alternate scenarios, we considered biogenic methane captured from C&D landfills and burning it to generate electricity to replace natural gas. Table 2 shows the base case scenario and the five alternatives scenarios.

#### Analysis Considerations

**Reuse**—This study evaluated the direct effects of reusing recovered wood products. Sathre and Gustavsson (2006)

conducted a somewhat broader study that evaluated energy and carbon from a series of cascading uses where cascading wood is the sequential use (i.e., reuse) for different purposes and assumed that wood quality declines over time. In the present study, no decline in wood quality was assumed.

This study also assumed that the lumber and flooring were used in the same application for which they were originally manufactured. We assume reused wood will be graded and this tends to assure that its performance will be the same as virgin wood that could have been used instead.

We assumed that carbon storage in recovered wood is the same as carbon stored in virgin wood. The benefits of reusing recovered wood relative to use of virgin wood include avoiding the environmental burdens associated with production of virgin wood and avoiding the generation of biogenic methane from the decay of discarded wood in landfills (Salazar and Meil 2009).

**Forest Carbon Sequestration**—We assumed that the use of wood harvested on a sustainable basis does not alter the carbon storage of forests in the long run. The USFS Forest Inventory Analysis indicates that forest area in the United States has been relatively constant since 1910 (USFS 2011, Oswald and others 2009, Smith and others 2009). According to the International Panel on Climate Change (IPCC) GWP

**Table 2. End-of-life scenarios by type and percentage**

| End-of-life scenarios                     | Base case (%) | Alt#1 (%) | Alt#2 (%) | Alt#3 (%) | Alt#4 (%) | Alt#5 (%) |
|---|---------------|-----------|-----------|-----------|-----------|-----------|
| Wood burned (substitute coal power)       | 30            | 100       | 0         | 0         | 0         | 0         |
| Wood mulched                              | 10            | 0         | 100       | 0         | 0         | 0         |
| C&D landfill (no CH <sub>4</sub> capture) | 60            | 0         | 0         | 100       | 0         | 0         |
| Wood burned (substitute gas power)        | 0             | 0         | 0         | 0         | 100       | 0         |
| C&D landfill (CH <sub>4</sub> capture)    | 0             | 0         | 0         | 0         | 0         | 100       |

method found in SimaPro 7.3 (PRé Consultants 2013, IPCC 2007), the characterization factor for biogenic CO<sub>2</sub> emissions was not assigned a value in the calculation for GWP. This approach also follows the ISO 14067 standard (ISO 2012). In addition, the issue of how to properly account for the carbon in harvested wood products has not been developed in a consensus-based standard. Therefore, the system boundary assumed for this study starts at the harvesting of the tree and extends to the time where new or reused material would be placed in a new use. This temporal end-point is assumed to include all EOL emissions for wood that is discarded when it is not reused.

**Data Collection and Treatment**—Building material recovery and reuse data were collected for the United States only. Primary data of deconstruction companies were collected across the entire United States. Primary mill data for deconstruction and reuse businesses were production-weight-averaged as required by CORRIM research guidelines to maintain confidentiality of surveyed facilities (CORRIM 2010). The following tasks are part of a standard LCA research protocol.

**Validation of Data**—The reused wood materials considered in this study were tracked through the entire process to ensure validation of raw and LCI data. No physical changes occurred in the softwood framing lumber and hardwood flooring recovered for reuse in new construction.

**Data Quality Statement**—Primary data quality was high because of expert knowledge and complete responses obtained from the extensive and comprehensive survey of industry (Appendix 1—Survey Instrument). Annual production data were collected for the years 2008 and 2009 from deconstruction facilities across the United States that used average technologies and produced 362 m<sup>3</sup> (230,000 bf) of recovered softwood framing and 25.4 thousand m<sup>2</sup> (273 thousand ft<sup>2</sup>) of recovered hardwood flooring. Statistics for total production of recovered softwood framing and hardwood flooring for the same time period were not available at the time of completion of this study.

**Aggregation**—Primary data on environmental burdens per unit of reused wood were weighted as in previous CORRIM reports (Milota and others 2004) using

$$\bar{P}_{\text{weighted}} = \frac{\sum_{i=1}^n P_i x_i}{\sum_{i=1}^n x_i}$$

where  $\bar{P}_{\text{weighted}}$  is the weighted average of the survey values reported by the mills,  $P_i$  is the reported mill value, and  $x_i$  is the ratio of the mill's production to total production for all surveyed facilities.

**Modeling Procedure Including Allocation**—The weighted-average primary data on environmental burdens was estimated per functional unit using SimaPro LCA software (PRé Consultants 2013). A wood mass balance and energy consumption verification for the necessary unit processes were performed and the weighted-average data were linked together into SimaPro for each unit process. Secondary data found in the U.S. LCI Database within SimaPro software provided additional life-cycle data. The additional life-cycle data includes generation and delivery of electricity and fossil fuel use and emissions. LCI outputs from SimaPro included raw material consumption, solid waste, and emission to air, water, and land. The mass allocation method was used to allocate environmental burdens to the primary product and co-products.

The mass allocation method was chosen because the highest volume product had the highest economic value. Emissions were allocated based on mass to primary products and co-products if they each had some economic value (as is the case for new products). If the waste has no economic value, then all emissions are assigned to the primary products (as is the case for recovered/reused products). The cradle-to-gate LCI data for recovered hardwood flooring and softwood framing lumber were developed using a functional unit of 1 m<sup>3</sup>, the same functional unit as new wood products.

**Elementary Flows**—Nearly all individual wood products flow through the system without changing shape. Softwood framing lumber and hardwood flooring that suffered physical damage during deconstruction were not reused and were sent as waste wood to a C&D landfill with no methane capture.

**Assumptions**—Assumptions and limitations associated with making the LCI estimates are provided in Appendix 3—Assumptions and Limitations.

**Table 3. Cradle-to-gate cumulative energy requirements by fuel source allocated to 1 m<sup>3</sup> new wood products<sup>a</sup>**

|             | Softwood framing lumber |     | Hardwood flooring |     |
|-------------|-------------------------|-----|-------------------|-----|
|             | MJ/m <sup>3</sup>       | %   | MJ/m <sup>3</sup> | %   |
| Coal        | 462                     | 7   | 816               | 11  |
| Crude oil   | 826                     | 13  | 1,980             | 26  |
| Natural gas | 592                     | 9   | 790               | 10  |
| Uranium     | 160                     | 2   | 270               | 3   |
| Biomass     | 4,360                   | 68  | 3,880             | 50  |
| Hydropower  | 37                      | 1   | 12                | 0   |
| Total       | 6,440                   | 100 | 7,750             | 100 |

<sup>a</sup>Energy values were determined using their higher heating values in MJ/kg: 54.4 for natural gas, and 20.9 for oven-dried wood, 26.2 for coal, 45.5 for crude oil, and 381,000 for uranium.

## Results and Discussion

### Part 1—Cradle-to-Gate LCIs

LCI data for cumulative cradle-to-gate materials use, energy use, and emissions per cubic meter of newly made softwood framing lumber and hardwood flooring were generated using SimaPro modeling. Additional data were obtained on energy and emissions per cubic meter for product transportation to the construction site from literature. LCI data were estimated using primary data from surveys and secondary data found in the U.S. LCI Database and literature. The surveyed facilities provided detailed data on mass flow, and energy consumption and emissions by type of fuel. Data from surveys were weighted by facility production and were input into SimaPro 7 to estimate average non-wood raw material use and emissions. Input data collected by survey are listed in Appendix 4—SimaPro Inputs. The total energy to produce 1-m<sup>3</sup> framing lumber and hardwood flooring from new wood materials was 6,440 and 7,750 MJ/m<sup>3</sup>, respectively (Table 3). Based on information obtained, at least 50% of the energy used to make new wood products came from woody biomass.

Table 4 shows the major GHG emitted in making new softwood framing lumber and hardwood flooring. Emissions

were consistently greater per cubic meter to make hardwood flooring because of its higher density and greater energy requirements in product production (principally drying) than softwood framing lumber. Production of hardwood lumber emits about twice as much fossil CO<sub>2</sub> (228 kg/m<sup>3</sup>) as does the production of softwood framing lumber (109 kg/m<sup>3</sup>). Appendix 5—LCI Flows shows detailed LCI results for newly made and recovered softwood lumber and hardwood lumber including raw materials used, solid waste generated, and emissions to air, water, and soil.

Table 5 shows cradle-to-gate LCI energy use data for recovered softwood framing lumber and hardwood flooring per cubic meter of recovered wood and includes energy for product transportation to the construction site. Recovered softwood framing lumber and hardwood flooring consume 418 and 859 MJ/m<sup>3</sup> of energy, respectively. Included in the energy allocated to the recovered wood are those from wood lost during deconstruction process (i.e., waste wood) that was sent a C&D landfill with no methane capture. Crude oil was the largest energy component because of resource (i.e., raw material) and product transportation with values of 178 and 437 MJ/m<sup>3</sup>, respectively. Coal consumption was next at 145 and 235 MJ/m<sup>3</sup>. However, more energy was consumed during hardwood flooring recovery because the flooring was primarily stored in a closed, natural gas-heated building. No biomass was burned for energy in recovering old wood products for reuse.

Table 6 shows cradle-to-gate major GHG emissions for recovered softwood framing lumber and hardwood flooring. Recovered hardwood flooring production emitted more fossil CO<sub>2</sub> than recovered softwood framing lumber did. This was due to the higher wood density for hardwood versus softwood and because hardwood flooring was stored inside heated closed buildings unlike softwood framing lumber, which was stored covered outside. In addition, more biogenic CO<sub>2</sub> was emitted for softwood framing lumber (24.8 kg/m<sup>3</sup>) than hardwood flooring (19.2 kg/m<sup>3</sup>) because more lumber was lost during the recovery process for softwood framing lumber than flooring. Therefore, a higher percentage of removed softwood framing lumber later

**Table 4. Cradle-to-gate major GHG emissions allocated to 1 m<sup>3</sup> new wood products**

|                          | Quantity emitted (kg/m <sup>3</sup> ) |                         |
|--------------------------|---------------------------------------|-------------------------|
|                          | Softwood framing lumber               | Hardwood flooring       |
| Carbon dioxide, fossil   | 109                                   | 228                     |
| Methane, fossil          | 0.303                                 | 0.459                   |
| Methane, biogenic        | 0                                     | 0                       |
| Nitrous oxide            | 3.32 × 10 <sup>-3</sup>               | 2.87 × 10 <sup>-3</sup> |
| Carbon dioxide, biogenic | 365                                   | 390                     |

**Table 5. Cradle-to-gate cumulative energy requirements by fuel source allocated to 1 m<sup>3</sup> recovered wood products<sup>a</sup>**

|             | Softwood framing lumber |     | Hardwood flooring |     |
|-------------|-------------------------|-----|-------------------|-----|
|             | MJ/m <sup>3</sup>       | %   | MJ/m <sup>3</sup> | %   |
| Coal        | 145                     | 35  | 235               | 27  |
| Crude oil   | 178                     | 43  | 437               | 51  |
| Natural gas | 47                      | 11  | 109               | 13  |
| Uranium     | 43                      | 10  | 70                | 8   |
| Biomass     | 0                       | 0   | 0                 | 0   |
| Hydropower  | 5                       | 1   | 8                 | 1   |
| Total       | 418                     | 100 | 859               | 100 |

<sup>a</sup>Energy values were determined using their higher heating values in MJ/kg: 54.4 for natural gas and 20.9 for oven-dried wood, 26.2 for coal, 45.5 for crude oil, and 381,000 for uranium.

**Table 6. Cradle-to-gate major GHG emissions allocated to 1 m<sup>3</sup> recovered wood products**

|                          | Quantity emitted (kg/m <sup>3</sup> ) |                       |
|--------------------------|---------------------------------------|-----------------------|
|                          | Softwood framing lumber               | Hardwood flooring     |
| Carbon dioxide, fossil   | 23.9                                  | 49.7                  |
| Methane, fossil          | $4.73 \times 10^{-3}$                 | $9.94 \times 10^{-3}$ |
| Methane, biogenic        | 7.31                                  | 5.59                  |
| Nitrous oxide            | $3.32 \times 10^{-3}$                 | $7.99 \times 10^{-3}$ |
| Carbon dioxide, biogenic | 24.8                                  | 19.2                  |

decomposed in a landfill. Biogenic methane has a much greater impact on climate change than carbon dioxide, 22 to 1 when calculating GWP (non-biogenic methane has a GWP characterization factor of 25 for the IPCC 2007 100-year time horizon) (PRé Consultants 2013, IPCC 2007). Bergman and others (2010) provided LCI data for recovered framing lumber and hardwood flooring without considering disposal of the unusable wood from deconstruction. Total methane production was 0.3 kg/m<sup>3</sup> for both recovered wood products when the analysis did not include biogenic methane emissions generated after landfilling of unusable wood. Biogenic methane emissions from the decomposition of wood lost increased total methane emitted by a factor of 24 (7.31/0.3) and 19 (5.59/0.3), respectively, a huge increase in GWP. Survey results estimated wood lost during removal at 17% and 11% for recovered framing lumber and wood flooring, respectively. Wood decomposition in landfills was the source for all the biogenic CO<sub>2</sub> and biogenic CH<sub>4</sub> emitted in production of recovered wood products.

Tables 7 and 8 show that cradle-to-gate GWP including and excluding biogenic CO<sub>2</sub> for products and recovered products. For new products, GWP with biogenic CO<sub>2</sub> emissions included was two to four times greater than when biogenic CO<sub>2</sub> emissions were excluded. For recovered wood

products, GWP was marginally greater when biogenic CO<sub>2</sub> emissions were included. Biogenic CO<sub>2</sub> emitted came from the decomposition in the landfilled wood lost during the recovery process for recovered wood products.

GWP for new products is substantially higher when biogenic CO<sub>2</sub> is included because production includes burning on-site biomass (i.e., mill residues) to provide thermal energy for drying wood. Considerably lower GWPs were indicated when biogenic CO<sub>2</sub> emissions were not considered (standard LCA practice).

Tables 7 and 8 show cumulative energy requirements for the new framing lumber and flooring were 15 and 9.0 times greater, respectively, than for the equivalent recovered wood products. The GWP ratio between new and recovered products is much lower because it includes, for recovered products, the landfill methane emissions generated from wood lost during the recovery.

When GWP excludes biogenic CO<sub>2</sub> emissions (standard LCA practice), then GWP for new hardwood flooring is greater than for recovered flooring (ratio is 1.4). However, GWP is less for new softwood lumber than for recovered softwood lumber (ratio is 0.6). GWP that includes biogenic CO<sub>2</sub> emissions is greater for new products than for recovered products by factors of 2.3 and 3.2 for softwood lumber and hardwood flooring, respectively. The doubling or more of GWP when including biogenic CO<sub>2</sub> indicates the importance of what emissions are included for wood products production.

## Part 2—End-of-Life Scenarios

The second part of this study examined various EOL scenarios for the case where wood is not recovered and estimated the associated cumulative energy use and GHG emissions. This portion of the study is intended to answer the question, “If recovered wood were not reused in construction and had a different fate (e.g., burned to generate electricity, ground for mulch, or landfilled), what would the impact be on environmental burdens?” In addition, we answer the question, “When are GHG emissions less for reuse of old wood compared to discard of old wood under several EOL scenarios and associated production of new products?”

The base case EOL scenario assumes a mix of dispositions for discarded wood: burning wood for energy to replace coal power (30%), grinding for mulch with open air decay (10%), and disposal in a C&D landfill without methane capture (60%). All EOL analyses used data from the U.S. LCI Database. There are five alternate scenarios.

Table 9 shows that for the base case (current U.S. practice) cumulative EOL energy is negative because of decreased coal burning with increased wood burning. Wood burning allows for coal energy decreases of –2,300 and –2,920 MJ/m<sup>3</sup> of softwood framing lumber and hardwood flooring, respectively. To put this into perspective,

**Table 7. Summary environmental impact measures for producing softwood framing lumber**

| Environmental impact measures  | (1)                   | (2)                         | Ratio<br>(1)/(2) |
|--|-----------------------|-----------------------------|------------------|
|  | New framing<br>lumber | Recovered<br>framing lumber |                  |
| Cumulative energy (MJ/m <sup>3</sup> )   | 6440                  | 418                         | 15               |
| CO <sub>2</sub> total (kg/m <sup>3</sup> )   | 474                   | 48.9                        | 9.7              |
| CO <sub>2</sub> less biogenic (kg/m <sup>3</sup> )   | 109                   | 24.8                        | 4.4              |
| GWP including biogenic CO <sub>2</sub><br>(kg CO <sub>2</sub> -e/m <sup>3</sup> ) <sup>a</sup> | 483                   | 211                         | 2.3              |
| GWP less biogenic CO <sub>2</sub><br>(kg CO <sub>2</sub> -e/m <sup>3</sup> )                   | 118                   | 186                         | 0.6              |

<sup>a</sup>Global warming potential (GWP) when biogenic CO<sub>2</sub> is given a characterization factor of 1.

**Table 8. Summary environmental impact measures for producing hardwood flooring**

| Environmental impact measures  | (1)                         | (2)                               | Ratio<br>(1)/(2) |
|--|-----------------------------|-----------------------------------|------------------|
|  | New<br>hardwood<br>flooring | Recovered<br>hardwood<br>flooring |                  |
| Cumulative energy (MJ/m <sup>3</sup> )   | 7,750                       | 859                               | 9.0              |
| CO <sub>2</sub> total (kg/m <sup>3</sup> )   | 618                         | 79.4                              | 7.8              |
| CO <sub>2</sub> less biogenic CO <sub>2</sub> (kg/m <sup>3</sup> )                             | 228                         | 48.7                              | 4.7              |
| GWP including biogenic CO <sub>2</sub><br>(kg CO <sub>2</sub> -e/m <sup>3</sup> ) <sup>a</sup> | 630                         | 195                               | 3.2              |
| GWP less biogenic CO <sub>2</sub><br>(kg CO <sub>2</sub> -e/m <sup>3</sup> )                   | 240                         | 175                               | 1.4              |

<sup>a</sup>Global warming potential (GWP) when biogenic CO<sub>2</sub> is given a characterization factor of 1.

53% (2,300/4,360) and 75% (2,920/3880) of the biomass energy used in making new softwood framing lumber and hardwood flooring is displaced by burning the old wood at EOL to avoid coal power production. Wood burned for energy recovery at EOL has a considerable effect, although only 30% of the old wood is burned to replace coal.

Table 10 shows that for the base case, some major GHG emissions were positive overall. Positive GHG emissions occurred even though cumulative energy at EOL was negative (Table 9). Negative fossil CO<sub>2</sub> emissions correspond to negative energy consumption and result from the discarded wood being burned to displace coal to generate electricity. As a result, fossil CO<sub>2</sub> values were –156 kg/m<sup>3</sup> for softwood framing lumber and –193 kg/m<sup>3</sup> for hardwood flooring. However, some positive GHG emissions occurred because of the release of biogenic CO<sub>2</sub> and biogenic methane from wood burning and degradation. Wood degradation occurs from two sources: the spreading of mulch and the landfilling of the discarded wood. Biogenic CO<sub>2</sub> generated from burning wood, mulch, and landfills was large for softwood framing lumber (317 kg/m<sup>3</sup>) and hardwood flooring (402 kg/m<sup>3</sup>). Biogenic methane emissions from landfills were 21.5 and 27.2 kg for softwood framing lumber and hardwood flooring, respectively. The discarded wood burned to replace coal to generate electricity substantially offsets fossil CO<sub>2</sub> emissions but adds to biogenic CO<sub>2</sub> emissions.

**Table 9. Cumulative end-of-life energy consumption by fuel source allocated to 1 m<sup>3</sup> wood products (base-case scenario<sup>a,b</sup>)**

|             | Softwood framing<br>lumber |     | Hardwood flooring |     |
|-------------|----------------------------|-----|-------------------|-----|
|             | MJ/m <sup>3</sup>          | %   | MJ/m <sup>3</sup> | %   |
| Coal        | –2,300                     | 106 | –2,920            | 110 |
| Crude oil   | 65                         | –3  | 173               | –7  |
| Natural gas | 31                         | –1  | 41                | –2  |
| Uranium     | 32                         | –1  | 38                | –1  |
| Biomass     | 0                          | 0   | 0                 | 0   |
| Hydropower  | 5                          | 0   | 7                 | 0   |
| Total       | –2,170                     | 100 | –2,660            | 100 |

<sup>a</sup>30% of wood waste from old structures goes to replace coal to generate electricity, 10% gets ground into mulch, and the remaining 60% transported to a construction and demolition landfill with no methane capture.

<sup>b</sup>Energy values were determined using their higher heating values in MJ/kg: 54.4 for natural gas and 20.9 for oven-dried wood, 26.2 for coal, 45.5 for crude oil and 381,000 for uranium.

Tables 11 and 12 show cumulative energy use and GWP for the base case and five alternative EOL scenarios. GWP<sub>1</sub> excludes biogenic CO<sub>2</sub>, the method consistent with TRACI 2 Method (PRé Consultants 2013, Bare 2011). GWP<sub>2</sub> includes biogenic CO<sub>2</sub>. Alternative scenario #1 (burn all the wood to replace coal to generate electricity) had the lowest levels of GWP<sub>1</sub> and GWP<sub>2</sub> across all the scenarios. Softwood framing

**Table 10. Major GHG emissions for the end-of-life (base-case scenario<sup>a</sup>)**

| GHG                      | Quantity emitted<br>(kg/m <sup>3</sup> ) |                       |
|--------------------------|--|-----------------------|
|                          | Softwood framing<br>lumber               | Hardwood<br>flooring  |
| Carbon dioxide, fossil   | -156                                     | -193                  |
| Methane, fossil          | -0.286                                   | -0.353                |
| Methane, biogenic        | 21.5                                     | 27.2                  |
| Nitrous oxide            | $1.78 \times 10^{-3}$                    | $2.40 \times 10^{-3}$ |
| Carbon dioxide, biogenic | 317                                      | 402                   |

<sup>a</sup>30% of wood waste from old structures goes to replace coal to generate electricity, 10% gets ground into mulch, and the remaining 60% is transported to a construction and demolition landfill with no methane capture.

**Table 11. Cumulative energy and GWP for the various end-of-life scenarios<sup>a</sup> for softwood framing lumber**

| Environmental impacts  | Base case | Alt#1  | Alt#2 | Alt#3 | Alt#4  | Alt#5  | Reuse | New   |
|--|-----------|--------|-------|-------|--------|--------|-------|-------|
| Cumulative energy (MJ/m <sup>3</sup> )                               | -2,160    | -8,100 | 471   | 329   | -7,300 | -1,420 | 418   | 6,440 |
| GWP <sub>1</sub> (kgCO <sub>2</sub> -e/m <sup>3</sup> ) <sup>g</sup> | 310       | -592   | 28    | 808   | -379   | 199    | 186   | 118   |
| GWP <sub>2</sub> (kgCO <sub>2</sub> -e/m <sup>3</sup> ) <sup>h</sup> | 627       | -93    | 980   | 928   | 120    | 394    | 211   | 483   |

<sup>a</sup>Base case: 60% of wood waste into landfill with no methane capture/30% burned to replace coal power/10% ground into mulch; Alt#1: 100% wood waste burned to replace coal power; Alt#2: 100% wood waste ground into mulch; Alt#3: 100% wood waste into landfill with no methane capture; Alt#4: 100% wood waste burned to replace natural gas power; Alt#5: 100% wood waste into landfill with methane capture; Global warming potential (GWP) with biogenic CO<sub>2</sub> having a characterization factor of 1.

**Table 12. Cumulative energy and GWP for the various end-of-life scenarios<sup>a</sup> for hardwood flooring**

| Environmental impacts  | Base case | Alt#1   | Alt#2 | Alt#3 | Alt#4  | Alt#5  | Reuse | New   |
|--|-----------|---------|-------|-------|--------|--------|-------|-------|
| Cumulative energy (MJ/m <sup>3</sup> )                               | -2660     | -10,100 | 676   | 497   | -9,200 | -1,720 | 859   | 7,750 |
| GWP <sub>1</sub> (kgCO <sub>2</sub> -e/m <sup>3</sup> ) <sup>g</sup> | 397       | -744    | 40    | 1030  | -475   | 257    | 175   | 240   |
| GWP <sub>2</sub> (kgCO <sub>2</sub> -e/m <sup>3</sup> ) <sup>h</sup> | 799       | -113    | 1,250 | 1180  | 156    | 504    | 195   | 630   |

<sup>a</sup>Base case: 60% of wood waste into landfill with no methane capture/ 30% burned to replace coal power/ 10% ground into mulch; Alt#1: 100% wood waste burned to replace coal power; Alt#2: 100% wood waste ground into mulch; Alt#3: 100% wood waste into landfill with no methane capture; Alt#4: 100% wood waste burned to replace natural gas power; Alt#5: 100% wood waste into landfill with methane capture; Global warming potential (GWP) with biogenic CO<sub>2</sub> having a characterization factor of 1.

lumber and hardwood flooring had GWP<sub>1</sub> values of -592 and -744 kg/m<sup>3</sup>, respectively. GWP<sub>2</sub> values were -93 and -113 kg/m<sup>3</sup>, respectively.

Cumulative energy was negative and lowest for alternative scenario 1. Scenario 4 (burn wood to replace natural gas to generate electricity) followed closely behind the first alternative with values of -7,300 and -9,200 MJ/m<sup>3</sup> for softwood framing lumber and hardwood flooring, respectively. Scenario 5 was next lowest but significantly behind. In Scenario 5, all wood goes to landfills and a small part is emitted as biogenic methane (i.e., landfill gas). Seventy-five % of the biogenic methane generated in the landfill was captured and burned to generate electricity to replace natural gas. Burning landfill methane generates biogenic CO<sub>2</sub>. The remaining 25% was considered fugitive emissions and was emitted to the atmosphere. These results are consistent with Kaplan and others (2009) who found burning wood for energy provides substantially lower (negative) GHG emissions than landfilling and burning the captured landfill meth-

ane for energy. When landfill methane is not burned as in Scenario 3, GHG emissions are much higher. For softwood lumber, the effect of not burning landfill methane for energy when all wood is landfilled was to increase GWP<sub>1</sub> by a factor of four, from 199 to 808 kg CO<sub>2</sub>-equivalents/m<sup>3</sup>. The effect was similar for hardwood flooring. Thus, methane capture is critical for wood products when stored in a landfill to lower their impact on climate change.

Tables 13 and 14 compare GWP for cases where 1) old wood products are discarded (six EOL cases) and new products are made or 2) old wood is reused to make products. For the base case EOL scenario where we assume making new products would require discard of old wood to the current mix of proportions to energy, landfills, and mulch, then the reuse of both softwood lumber and hardwood flooring produces less GWP than making new products. The benefit is greatest for reuse of hardwood flooring (1,429/195 vs 1,110/211). This is true for GWP estimates that either include or exclude biogenic CO<sub>2</sub> emission. However, if we

**Table 13. Scenarios<sup>a</sup> of GWP comparison of new softwood framing lumber plus the various end-of-life scenarios to recovered softwood framing lumber**

| Environmental impacts  | Base case <sup>a</sup> | Alt#1 <sup>b</sup> | Alt#2 <sup>c</sup> | Alt#3 <sup>d</sup> | Alt#4 <sup>e</sup> | Alt#5 <sup>f</sup> | Reuse |
|--|------------------------|--------------------|--------------------|--------------------|--------------------|--------------------|-------|
| GWP <sub>1</sub> (kgCO <sub>2</sub> -e/m <sup>3</sup> ) <sup>g</sup> | 427                    | -474               | 146                | 926                | -262               | 317                | 186   |
| GWP <sub>2</sub> (kgCO <sub>2</sub> -e/m <sup>3</sup> ) <sup>h</sup> | 1,110                  | 390                | 1,463              | 1,411              | 603                | 877                | 211   |

<sup>a</sup>Base case: 60% of wood waste into landfill with no methane capture/ 30% burned to replace coal power/ 10% ground into mulch; Alt#1: 100% wood waste burned to replace coal power; Alt#2: 100% wood waste ground into mulch; Alt#3: 100% wood waste into landfill with no methane capture; Alt#4: 100% wood waste burned to replace natural gas power; Alt#5: 100% wood waste into landfill with methane capture; Global warming potential (GWP) with biogenic CO<sub>2</sub> having a characterization factor of 1.

**Table 14. GWP comparison of new hardwood flooring plus the various EOL scenarios<sup>a</sup> to recovered hardwood flooring**

| Environmental impacts                                   | Base case | Alt#1 | Alt#2 | Alt#3 | Alt#4 | Alt#5 | Reuse |
|---|-----------|-------|-------|-------|-------|-------|-------|
| GWP <sub>1</sub> (kgCO <sub>2</sub> -e/m <sup>3</sup> ) | 637       | -504  | 280   | 1,270 | -235  | 497   | 175   |
| GWP <sub>2</sub> (kgCO <sub>2</sub> -e/m <sup>3</sup> ) | 1,429     | 518   | 1,880 | 1,810 | 787   | 1,134 | 195   |

<sup>a</sup>Global warming potential (GWP) with biogenic CO<sub>2</sub> having a characterization factor of 1; Base case: 60% of wood waste into landfill with no methane capture/30% burned to replace coal power/10% ground into mulch; Alt#1: 100% wood waste burned to replace coal power; Alt#2: 100% wood waste ground into mulch; Alt#3: 100% wood waste into landfill with no methane capture; Alt#4: 100% wood waste burned to replace natural gas power; Alt#5: 100% wood waste into landfill with methane capture.

consider GWP that excludes biogenic CO<sub>2</sub> emissions (standard LCA practice) reuse could be notably worse (higher GWP) than new wood if all old wood could be burned to offset coal or natural gas in making electric power. Reuse could be slightly worse than new for softwood lumber if all old wood could be used as mulch (unlikely if wood is contaminated (186/146)). So a key point is that if wood cannot be reused for products the next best step is to keep it out of landfills and use it for either energy (top priority) or mulch (lower priority). There is a greater benefit from keeping hardwood out of landfills than keeping softwood out of landfills.

## Conclusion

Recovering softwood framing lumber and hardwood flooring for reuse instead of making new products displaces a considerable amount of production energy use and avoids some GHG emissions, particularly biogenic CO<sub>2</sub>. Reusing wood products for construction does not use biomass energy during its production, unlike new wood products. Including biogenic CO<sub>2</sub> from burning biomass for energy adds considerably to the estimate of GWP for new wood products. Adding biogenic CO<sub>2</sub> results in substantially higher GWP for new wood products because over 50% of its primary energy is from mill residues (i.e., wood). However, if biogenic CO<sub>2</sub> is not included, then the GWP values for new products are lower and reuse of wood does not avoid as much GWP as new product production.

GWP values change considerably for the different cases of discarding old wood (i.e., C&D waste). Standard GWP protocol excludes biogenic CO<sub>2</sub> emissions whether generated from burning wood, decaying mulch, decomposing wood in landfills, or burning landfill methane. Biogenic CO<sub>2</sub>

emissions are assumed to be balanced out by the carbon sequestration from trees over time as part of the natural carbon cycle. Standard U.S. waste disposal practice includes burning wood for energy to replace coal power (30%), grinding for mulch with open air decay (10%), and disposal in a C&D landfill without methane capture (60%). Therefore, the following hierarchy in this study shows the lowest to the highest GWP values for the six EOL scenarios investigated: 1) burning wood to generate electricity to replace coal, 2) burning wood to generate electricity to replace natural gas, 3) grinding wood into mulch, 4) installing methane capture equipment to capture most of the landfill methane and burning it to generate electricity to replace natural gas, 5) current U.S. practice, and 6) storing the wood in a landfill without methane capture. The two cases of burning old wood to replace fossil fuels have greater GHG benefits than the two cases of landfilling the discarded old wood with or without methane capture with mulching the old wood falling in between.

A downside to using C&D waste in energy generation to offset coal or natural gas emissions is that C&D waste typically contains contaminants unless the material is separated at the demolition or deconstruction site. Therefore, burning C&D waste can result in other air emissions and unknown materials that may require additional handling and associated energy consumption in the process than that already noted.

Greater environmental benefits tend to occur by keeping hardwoods out of landfills than keeping softwoods out of landfills. This is because hardwood flooring is produced from a dense wood species, and if kept out of landfills, could generate more energy per unit weight of wood than softwoods. Alternately, hardwoods that are kept out of

landfills and are then reused will avoid production of new hardwood flooring, which requires more energy for drying to a lower moisture content to improve dimensional stability and to avoid degrade than softwood framing lumber does. This translates to greater environmental benefits of keeping hardwoods out of landfills and reusing for flooring or using it for energy than can be realized by recovery of softwood species for reuse.

Product transportation can be a critical component of the cradle-to-gate LCI. For new products, transportation often requires long distances. For example, new wood flooring is primarily produced in the eastern United States. Therefore, transportation by both truck and rail is typically required to deliver products to wholesale locations on the West Coast. For reused wood products, transport distance can be shorter because wood is recovered in large urban centers and can be reused locally.

## References

- Athena. 2012. Athena Impact Estimator for Buildings. Ottawa, Ontario: Athena Sustainable Materials Institute. <http://www.athenasmi.org/our-software-data/impact-estimator/> (Accessed March 5, 2013).
- ATSDR. 2001. Landfill gas primer—an overview for environmental health professionals. Chapter 2: Landfill gas basics. Agency for Toxic Substances & Disease Registry (ATSDR). [http://www.atsdr.cdc.gov/HAC/landfill/PDFs/Landfill\\_2001\\_ch2mod.pdf](http://www.atsdr.cdc.gov/HAC/landfill/PDFs/Landfill_2001_ch2mod.pdf) (Accessed March 5, 2013)
- Bare, J.C. 2011. TRACI 2.0: the tool for the reduction and assessment of chemical and other environmental impacts 2.0. Clean Technologies and Environmental Policy. 13: 687–696.
- Bergman, R.D.; Bowe, S.A. 2010. Environmental impact of manufacturing softwood lumber in northeastern and north central United States. Wood and Fiber Science. 42(CORRIM Special Issue): 67–78.
- Bergman, R.D.; Gu, H.; Falk R.H.; Napier, T.R. 2010. Using reclaimed lumber and flooring in construction: measuring environmental impact using life-cycle inventory analysis. Society of Wood Science and Technology 53rd International Convention. Geneva, Switzerland. October 11–15, 2010. WS-11. 1–11.
- Bergman, Richard D.; Gu, Hongmei; Napier, Thomas R.; Salazar, James; and Falk, Robert H. 2012. Life cycle primary energy and carbon analysis of recovering softwood framing lumber and hardwood flooring for reuse. In: Proceedings, Instruments for Green Futures Markets, American Center for Life Cycle Assessment XI Conference. October 4–6, 2011. Vashon, WA: 44–51.
- Blengini, G.A. 2009. Life-cycle of buildings, demolition and recycling potential: a case study in Turin, Italy. Building and Environment. (44): 319–330.
- Borghi, A.D.; Gallo, M.; Borghi, M.D. 2009. A survey of life-cycle approaches in waste management. International Journal of Life Cycle Assessment. (14): 597–610.
- CORRIM. 2010. Research guidelines for life-cycle inventories. Consortium for Research on Renewable Industrial Materials (CORRIM), Inc., University of Washington, Seattle, WA. Updated 2010. 47 p.
- EIA. 2013. Independent statistics and analysis: Glossary (H). United States Energy Information Association. <http://www.eia.gov/tools/glossary/index.cfm?id=H> (Accessed March 5, 2013).
- EPA. 1995. Construction and demolition waste landfills. ICF Incorporated, Contract No. 68-W3-0008, February 1995. 39 p. <http://www.epa.gov/osw/hazard/generation/sqg/const/cdrpt.pdf> (Accessed March 5, 2013).
- EPA. 2009a. Estimating 2003: building-related construction and demolition material amounts. Washington, D.C.: United States Environmental Protection Agency. 60 p. <http://www.epa.gov/osw/conserv/imr/cdm/pubs/cd-meas.pdf> (Accessed March 5, 2013).
- EPA. 2009b. 40 CFR Chapter I: endangerment and cause or contribute findings for greenhouse gases under Section 202(a) of the Clean Air Act; Final Rule. Federal Register Docket ID No. EPA-HQ-OAR-2009-0171. Washington, D.C.: United States Environmental Protection Agency. 52 p.
- EPA. 2009c. Combustor survey database in support of the 2009 proposal of the Commercial and Industrial Solid Waste Incinerator (CISWI) standards and the Industrial Boilers Maximum Achievable Control Technology (MACT) standards, April 2009. Washington, D.C.: U.S. Environmental Protection Agency.
- EPA. 2010. WARM background and overview. <http://epa.gov/climatechange/wycd/waste/downloads/background-and-overview10-28-10.pdf> (Accessed March 5, 2013). Washington, D.C.: U.S. Environmental Protection Agency. 25 p.
- EPA. 2011. Inventory of U.S. greenhouse gas emissions and sinks: 1990–2009, EPA-430-R-11-005. <http://www.epa.gov/climatechange/Downloads/ghgemissions/US-GHG-Inventory-2011.pdf> (Accessed March 13, 2013) 470 p.
- EPA. 2012a. Materials characterization paper in support of the final rulemaking – identification of nonhazardous secondary materials that are solid waste construction and demolition materials—building-related C&D materials. Washington, D.C.: U.S. Environmental Protection Agency. 15 p. <http://www.regulations.gov/#!documentDetail;D=EPA-HQ-RCRA-2008-0329-1811> (Accessed March 5, 2013).
- EPA. 2012b. Waste reduction model. Updated February 2012. Washington, D.C.: U.S. Environmental Protection Agency. [http://www.epa.gov/climatechange/wycd/waste/calculators/Warm\\_home.html](http://www.epa.gov/climatechange/wycd/waste/calculators/Warm_home.html) (Accessed March 5, 2013).

- Eriksson O.; Reich, C.M.; Frostell B.; Björklund, A.; Assefa, G.; Sundqvist, J.-O.; Granath, J.; Baky, A.; Thyselius, L. 2005. Municipal solid waste management from a system perspective. *Journal of Cleaner Production*. 13(3): 241–252.
- Falk, R.H. 2002. Wood-framed building deconstruction: a source of lumber for construction? *Forest Products Journal*. 52(3): 8–15.
- Falk, R.H.; Guy B. 2007. *Unbuilding: salvaging the architectural treasures of unwanted houses*. Newtown, CT: The Taunton Press Inc. 248 p.
- Falk, R.H.; McKeever. 2012. Generation and recovery of solid wood waste. *BioCycle*. August 2012: 30–32.
- Fava J.; Jensen A.; Lindfors L.; Pomper, S., De Smet, B., Warren J, Vigon B. 1994. Life-cycle assessment data quality: a conceptual framework. Society for Environmental Toxicology and Chemistry (SETAC) and SETAC Foundation for Environmental Education. 179 p.
- Heilmann, A.; Winkler, J. 2005. Influence of the source separation efficiency of recyclable materials on the environmental performance of municipal waste management systems. *Proceedings Sardinia 2005, Tenth International Waste Management and Landfill Symposium*; S. Margherita di Pula, Cagliari, 3–7 October 2005.
- Hubbard, S.S.; Bove S.A. 2010. A gate-to-gate life-cycle inventory of solid strip hardwood flooring in the eastern U.S. *Wood and Fiber Science*. 42(CORRIM Special Issue): 79–89.
- ISO. 2006a. Environmental management—life-cycle assessment—principles and framework. ISO 14040. Geneva, Switzerland: International Organization for Standardization. 20 p.
- ISO. 2006b. Environmental management—life-cycle assessment—requirements and guidelines. ISO 14044. Geneva, Switzerland: International Organization for Standardization. 46 p.
- ISO. 2012. ISO 14067 Carbon footprint of products (draft). ISO 14067. Geneva, Switzerland: International Organization for Standardization. 52 pp.
- IPCC. 2006. 2006 IPCC guidelines for national greenhouse gas inventories. Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds). Published: Institute for Global Environmental Strategies, Japan. Geneva, Switzerland: Intergovernmental Panel on Climate Change (IPCC).
- IPCC. 2007. *Climate change 2007: The physical science basis*. In: Solomon S., Qin D., Manning M., Chen Z., Marquis M., Averyt K.B., Tignor M., Miller H.L. (eds.). *Contribution of working group to the fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC)*, Cambridge, United Kingdom: Cambridge University Press. 996 p.
- Kaplan, P.O.; DeCarolis, J.; Thorneloe, S. 2009. Is it better to burn or bury waste for clean electricity generation? *Environmental Science and Technology*. 43(6): 1711–1717.
- Kibert, C.J. 2003. Deconstruction: the start of a sustainable materials strategy for the built environment. *UNEP Industry and Environment*. 26(2–3): 84–88.
- Milota, M.R.; West, C.D.; Harley, I.D. 2004. Softwood lumber—Southeast Region. In *CORRIM Phase I Final Report Module B. Life-cycle environmental performance of renewable building materials in the context of residential construction*. Seattle, WA: University of Washington. 75 p.
- Milota, M.R.; West, C.D.; Hartley, I.D. 2005. Gate-to-gate life inventory of softwood lumber production. *Wood and Fiber Science*. 37: 47–57.
- Napier, T.R.; McKay D.T.; Mowry N.D. 2007. A life-cycle perspective on recycling construction materials (The most sustainable materials may be the ones we already have). In: Y.M. Chun, P. Claisse, T.R. Naik, E. Ganjian, eds. *Proceedings of the International Conference: Sustainable construction materials and technologies*, 11–13 June 2007 Coventry. London: Taylor and Francis. ISBN 13: 978-0-415-44689-1: 563–573.
- NWMOA. 2009. *Construction & demolition waste management in the northeast in 2006. A report of the Northeast Waste Management Officials Association (NWMOA)*, June 30, 2009. 65 p. <http://www.newmoa.org/solidwaste/CDReport2006DataFinalJune302009.pdf> (Accessed March 5, 2013).
- Ogden, C.L.; Fryar, C.D.; Carroll, M.D.; Flegal, K.M. 2004. Mean body weight, height, and body mass index, United States. *Advance Data No. 347*, October 27, 2004. Hyattsville, Maryland: National Center for Health Statistics. 18 p.
- Olofsson, M.; Sunberg, J.; Sahlin, J. 2005. Evaluating waste incineration as treatment and energy recovery method from an environmental point of view. *ASME Conference Proceedings*, 2005, 175 (2005), DOI:10.1115/NAWTEC13-3168. May 23–25, 2005. Orlando, Florida. 175–192.
- Oswalt S.N., Thompson M., Smith W.B. 2009. *U.S. forest resource facts and historical trends (metric unit brochure)*. FS-901M. Revised September 2009. 60 p. <http://fia.fs.fed.us/library/brochures/docs/Forest%20Facts%201952-2007%20English.pdf>. (Accessed March 5, 2013).
- PRé Consultants. 2013. *SimaPro 7 Life-Cycle assessment software package, Version 7. Plotter 12, 3821 BB Amersfoort, The Netherlands*. <http://www.pre.nl>. (Accessed March 5, 2013).

- Puettmann, M.E.; Wilson, J.B. 2005. Life-cycle analysis of wood products: cradle-to-grave LCI of residential wood building materials. *Wood and Fiber Science*. (37): 18–29.
- Puettmann, M.; Bergman, R.; Hubbard, S.; Johnson, L.; Lippke, B.; Oneil, E.; Wagne, F.G. . 2010. Cradle-to-gate life-cycle inventories of U.S. wood products production – CORRIM Phase I and Phase II Products. *Wood and Fiber Science*. 42(CORRIM Special Issue): 15–28.
- SAIC. 2006. Life-cycle assessment: Code and practices. Scientific Applications International Corporation (SAIC). EPA/600/R-06/060 May 2006. 80 p.
- Salazar, J.; Meil, J. 2009. Prospects for carbon-neutral housing – the influence of greater wood use on the carbon-footprint of a single-family residence. *Journal of Cleaner Production*. 17 (17): 1563–1571.
- Sathre, R.; Gustausson L. 2006. Energy and carbon balances of wood cascade chains. *Resource, Conservation and Recycling* 47(4): 332–355.
- Skog, Kenneth E. 2008. Sequestration of carbon in harvested wood products for the United States. *Forest Products Journal*. 58(6): 56–72.
- Smith, A.; Brown, K.; Ogilvie, S.; Rushton, K.; Bates, J. 2001. Waste management options and climate change. Final report to the European Commission, DG Environment. 205 p. [http://ec.europa.eu/environment/waste/studies/pdf/climate\\_change.pdf](http://ec.europa.eu/environment/waste/studies/pdf/climate_change.pdf) (Accessed March 5, 2013).
- Smith, B.W.; Miles, P.D.; Perry, C.H.; Pugh, S.A. 2009. *Forest Resources of the United States, 2007*. Gen. Tech. Rep. WO-78. Washington, D.C.: U.S. Department of Agriculture, Forest Service, Washington Office. 336 pp.
- Staley B.F.; Barlaz M.A. 2009. Composition of municipal solid waste in the United States and implications for carbon sequestration and methane yield. *Journal of Environmental Engineering*. 135(10): 901–909.
- Sunberg, J.; Olofsson, M.; Sahlin, J. 2004. Evaluating waste incineration as treatment and energy recovery method from an environmental point of view. Final version 2004-05-13. Profu. Stockholm, Sweden. 81 p.
- Thorneloe, S.A.; Weitz, K.A.; Jambeck, J. 2007. Application of the U.S. decision support tool for materials and waste management. *Waste Management*. 27(2007): 1006–1020.
- USDA. 2013. Life-cycle inventory database project. Washington, D.C.: United Department of Agriculture. <https://www.lcacommons.gov/nrel> (Accessed March 5, 2013).
- USFS. 2011. National report on sustainable forests—2010. United States Department of Agriculture, Forest Service, FS-979, June 2011. 214 p.
- USDOT. 2010. Bureau of Transportation Statistics and U.S. Census Bureau, 2007 Economic Census. Transportation. 2007 Commodity flow survey. United States Department of Transportation (USDOT). 68 pp. <http://www.census.gov/prod/2010pubs/ec07tcf-ex.pdf> (Accessed March 5, 2013).
- Wang, X.; Padgett, J.M.; De la Cruz, F.B; Barlaz, M.A. 2011. Wood biodegradation in laboratory-scale landfills. *Environmental Science and Technolpgy*. 45(16): 6864–6871.
- Winistorfer, P.; Chen, Z.; Lippke, B.; Stevens, N. 2005. Energy consumption and greenhouse gas emissions related to use, maintenance, and disposal of a residential structure. *Wood and Fiber Science*. 37(CORRIM Special Issue): 128–139.
- Ximenes, F.A.; Gardner, W.D.; Cowie, A.L. 2008. The decomposition of wood products in landfills in Sydney, Australia. *Waste Management*. 28 (11): 2344–2354.

## Appendix 1—Survey Instrument

### Survey Instrument for Deconstruction Facility Operators and Managers

This questionnaire is comprised of two parts: 1. wood flooring and; 2. framing lumber. Some questions pertain to companies or individuals who do deconstruction/demolishing whereas some questions pertain to transportation to and around a resale facility. We are looking to evaluate your most current practices.

#### Part I—Wood Flooring

For this project, we are limiting our analysis to solid wood flooring, including tongue and groove (T&G) and plank flooring. We are not interested at this time in laminated (or engineered) wood flooring. The goal of this section is to determine all the energy inputs to remove, store, and sell the flooring. We are assuming that the following represents a typical sequence of flooring removal.

1. Transportation of workers to job-site.
2. Removal of any furniture or other materials such as molding that would interfere with removal of the flooring.
3. Removal flooring board by board.
4. Denailing of flooring either by hand or nail kicker.
5. Loading of flooring onto truck either by hand or with equipment.
6. Transport the flooring to storage facility
7. Unload the wood flooring either by hand or equipment.
8. Store the wood flooring in a facility until sold
9. Electricity and fuel used to keep facility lighted and heated.
10. Selling of wood flooring to customers

#### Part I—Wood Flooring (Soft-Strip)

1. What is the typical distance your crew travels to a job-site to remove flooring? \_\_\_\_\_ miles
2. How many days do you typically stay on a deconstruction job to remove wood flooring? \_\_\_\_\_ days
3. How many hours per day spent removing flooring? \_\_\_\_\_ hours
4. How many miles are driven per day while at the jobsite? That is, driving to lunch, to the hardware store, picking up equipment, back and forth from office, etc. \_\_\_\_\_ miles

5. Does your crew typically travel individually or as a group to the jobsite? Circle one: individual, group.
6. If a group, how many typically ride in each vehicle? \_\_\_\_\_ persons
7. Estimate how many square feet of flooring each person can remove in an hour? \_\_\_\_\_ sq.ft/hr/person
8. How many total sites (jobs) for wood floor removal are completed on annual basis?
9. List tools used to remove flooring?

If no tools use fuel or electricity, go to question 11, otherwise continue with question 10.

10. What tools do you use that require fuel or electricity, such as a Nail Kicker, electric saw/etc. in the flooring removal and denailing process?

What do you typically use for a power source? Circle one: electrical outlet onsite or a jobsite generator

If you use a jobsite generator, what fuel does the generator use and how much fuel does it use per hour of operation?

\_\_\_\_\_ gallons per hour gasoline  
 \_\_\_\_\_ gallons per hour fuel oil  
 \_\_\_\_\_ gallons per hour propane

11. Estimate how many square feet of flooring each person can denail and trim in an hour using the Nail Kicker or other electrical tools? \_\_\_\_\_ sq.ft./hr/person
12. If you use plug-in electricity for your tools, do you know how many Kw/hrs are used per square foot of flooring removed?  
 \_\_\_\_\_ kw-hr/sq.ft. flooring
13. On average, how much flooring do you recover per site? \_\_\_\_\_ sq.ft.
14. Estimate how much flooring you lose in the removal and trimming process? 5, 10, 25, 50%? \_\_\_\_\_ %
15. What percentage of recovered flooring is hardwood or softwood? \_\_\_\_\_ % hardwood \_\_\_\_\_ % softwood
16. Estimate how much flooring you recovered in the last year? Please give your answer in square feet.
17. What is the average distance you must move the recovered flooring to your resale facility? \_\_\_\_\_ miles
18. Average number of trips to move the recovered flooring to resale facility per job? \_\_\_\_\_
19. Please indicate what type of truck is used? Circle one: pickup truck, box truck, semi, etc.

20. Estimate what percentage of the load (by weight) is flooring for a typical job? \_\_\_\_\_%
21. What type of fuel is used? Circle one: diesel or gas
22. We are trying to determine the energy costs associated with storing and selling the wood flooring you recover. Can you estimate the holding costs (e.g., heating, lighting in BTU's/KWH's) associated with the retailing or wholesaling of wood flooring in your store?
- a. Store size \_\_\_\_\_ sq. ft.
  - b. Typically, how much wood flooring is stored at one time? \_\_\_\_\_ sq. ft.
  - c. What would you estimate the percentage of wood flooring (by weight) is in your store compared to overall inventory \_\_\_\_\_%
  - d. Typically, how long is flooring stored before selling? \_\_\_\_\_ days or weeks or months
  - e. Annual fuel consumption to heat store  
\_\_\_\_\_ gallons heating oil  
\_\_\_\_\_ gallons propane  
\_\_\_\_\_ 1000 cubic feet natural gas  
\_\_\_\_\_ Kw-hr electricity
  - f. Annual electrical consumption for store (please provide at least two of the following items)  
\_\_\_\_\_ kilowatt-hours  
\_\_\_\_\_ cents/Kw-hr  
\_\_\_\_\_ monthly electric bill
23. If you use equipment such as a forklift to move flooring around the facility, please list what type of equipment?
24. If the equipment uses fuel, what type of fuel? Circle one: gas, diesel, LP, or electric
25. Estimate how much fuel (or electricity) is used per year to move wood flooring around the facility and for loading onto a customer's vehicle? \_\_\_\_\_ gallons fuel / \_\_\_\_\_ kw-hr
26. If you sell, average selling price of wood flooring? \_\_\_\_\_ \$/sq.ft

## Part II—Framing Lumber

Framing lumber is the structural support of a building, not the sheathing, trim, or other wood. In a house, it is usually 2 × 4s, 2 × 6s, 2 × 8s, and 2 × 10s. Once again, we are looking to see what energy goes into removing, transporting, and selling the framing lumber. However, if other re-useable material is also removed when removing the framing lumber, please indicate that. We expect that heavier equipment might be used. We are assuming that the following represents a typical sequence of framing removal.

1. Transportation of workers to jobsite.
2. Transportation of forklift, bobcat, or other energy using equipment to jobsite.
3. Removal of surface materials such as roofing, drywall, subfloors, and insulation that would interfere with the removal of the framing lumber
4. Removal of actual framing.
5. Denailing of framing either by hand or nail kicker.
6. Loading of framing onto truck either by hand or with equipment.
7. Transport the framing to storage facility
8. Unload the wood framing either by hand or equipment.
9. Store the wood framing in a facility until sold
10. Electricity and fuel used to keep facility lighted and heated.
11. Selling of framing lumber to customer

### Part II—Framing Lumber (Full Deconstruction)

What is the typical distance your crew travels to a jobsite to remove framing? \_\_\_\_\_ miles.

1. How many miles are driven per day while at the jobsite? That is, driving to lunch, to the hardware store, picking up equipment, back and forth from office, etc. \_\_\_\_\_ miles
2. Does your crew typically travel individually or as a group to the jobsite? Circle one: individual, group.
3. If a group, how many typically ride in each vehicle? \_\_\_\_\_ persons
4. How many days do you typically stay on a deconstruction job to remove framing? \_\_\_\_\_ days
5. How many hours per day spent removing framing? \_\_\_\_\_ hours

6. Estimate how many linear feet or board feet of framing each person can remove in an hour?  
\_\_\_\_\_ linear ft/hr/person or board ft/hr/person

7. How many total sites (jobs) for framing removal are completed on annual basis?

8. List tools used to remove flooring.

If no tools use fuel or electricity, go to question 11, otherwise continue with question 10.

9. What tools do you use that require fuel or electricity, such as a power saw/etc. in the framing removal and denailing process?

What do you typically use for a power source? Circle one: electrical outlet onsite or a jobsite generator

If you use a jobsite generator, what fuel does the generator use and how much fuel does it use per hour of operation?

\_\_\_\_\_ gallons per hour gasoline  
 \_\_\_\_\_ gallons per hour fuel oil  
 \_\_\_\_\_ gallons per hour propane

10. Please estimate how many lineal feet, board ft. or tons of framing each person can denail and trim in an hour using the Nail Kicker or other electrical tools?

11. If you use plug-in electricity for your tools, do you know how many Kw/hrs are used per square foot of framing removed?

12. On average, how much framing do you recover per site? \_\_\_\_\_ board feet or lineal feet or tons

Can you estimate how much framing you loose in the removal and trimming process? 10% 25% 50%

13. Do you use heavy equipment to recover and move framing, such as a telescoping forklift, Bob Cat, boom lift, or other equipment? If so, please indicate how many total hours you typically use each machine on each job and how much fuel it burns per hour.

| Machine Type | Hours used | Fuel type | Fuel use per hour |
|--------------|------------|-----------|-------------------|
| Forklift     |            |           |                   |
| Bobcat       |            |           |                   |
|              |            |           |                   |
|              |            |           |                   |
|              |            |           |                   |

14. Can you estimate how much framing you recovered in the last year? Please give your answer in either board feet, lbs (tons), or lineal feet of each size.
15. What is the average distance you must move the recovered framing to your resale facility? \_\_\_\_\_ miles
16. Average number of trips to move the framing lumber to resale facility per job? \_\_\_\_\_
17. Please indicate what type of truck is used? Circle one: pickup truck, box truck, semi, etc.
18. Estimate what percentage of the load (by weight) is framing for a typical job? \_\_\_\_\_%
19. What type of fuel is used in the truck? Circle one: diesel or gas
20. We are trying to determine the energy costs associated with storing and selling the wood framing you recover. Can you estimate the holding costs (e.g., heating, lighting in BTU's/KWH's) associated with the retailing or wholesaling of wood framing in your store?
  - a. Store size \_\_\_\_\_ sq. ft.
  - b. Typically, how much wood framing is stored at one time? \_\_\_\_\_ sq. ft.
  - c. Estimate the percentage of wood framing (by weight) is in your store compared to overall inventory \_\_\_\_\_%
  - d. Typically, how long is framing stored before selling? \_\_\_\_\_ days or weeks or months
  - e. Annual fuel consumption to heat store
    - \_\_\_\_\_ gallons heating oil
    - \_\_\_\_\_ gallons propane
    - \_\_\_\_\_ 1000 cubic feet natural gas
    - \_\_\_\_\_ kw-hr electricity
  - f. Annual electrical consumption for store (please provide at least two of the following items)
    - \_\_\_\_\_ kilowatt-hours
    - \_\_\_\_\_ cents/kw-hr
    - \_\_\_\_\_ monthly electric bill
21. If you use equipment such as a forklift to move flooring around the facility, please list what type of equipment?
22. If the equipment uses fuel, what type of fuel? Circle one: gas, diesel, LP, or electric

23. Estimate how much fuel (or electricity) is used per year to move wood flooring around the facility and for loading onto a customer's vehicle? \_\_\_\_\_ gallons fuel / \_\_\_\_\_ kw-hr
24. If you sell framing lumber, average selling price of material broken down by size if possible?

| Size        | Price (\$ per bf) |
|-------------|-------------------|
| 2x4's       |                   |
| 2x6's       |                   |
| 2x8's       |                   |
| 2x10's      |                   |
| 2x12's      |                   |
| 3x3's       |                   |
| 3x4's       |                   |
| 4x4's       |                   |
| 6x6's       |                   |
| Other _____ |                   |

If you have more to add please make as many additional comments as necessary. We appreciate your time to help out on this important research project. Also, please call Rick Bergman (608) 231-9477 or email at [rbergman@fs.fed.us](mailto:rbergman@fs.fed.us) if you have any questions.

Please send the complete questionnaire to:

Rick Bergman  
 Mail: Forest Products Laboratory  
 One Gifford Pinchot Dr.  
 Madison, WI 53704  
 Fax: (608) 231-9508 (fax)  
 Email: [rbergman@wisc.edu](mailto:rbergman@wisc.edu)

## Appendix 2—Landfill Gas (LFG) Equations

Equation 1: Where  $\text{GHG}_{\text{DE}}$  is GHGs directly emitted to atmosphere (kg CO<sub>2</sub>-eq):

$$\text{GHG}_{\text{DE}} = (W_{\text{kg}})(C)(C_{\text{CO}_2})(D)(1 - \text{LFG}_C)\left(\frac{44}{12}\right) + (W_{\text{kg}})(C)(C_{\text{CH}_4})(D)(1 - \text{LFG}_C)\left(\text{GWP}_{\text{CH}_4} \cdot \frac{16}{12}\right)$$

Equation 2: Where  $\text{GHG}_{\text{LFGR}}$  is GHG emitted from LFG energy recovery (kg CO<sub>2</sub>-eq):

$$\text{GHG}_{\text{LFGR}} = (W_{\text{kg}})(C)(D)(\text{LFG}_C)(\text{LFG}_R)\left(\frac{44}{12}\right)$$

Equation 3: Where  $\text{GHG}_{\text{LFGF}}$  is GHG emitted from LFG flaring (kg CO<sub>2</sub>-eq):

$$\text{GHG}_{\text{LFGF}} = (W_{\text{kg}})(C)(D)(\text{LFG}_C)(1 - \text{LFG}_R)\left(\frac{44}{12}\right)$$

Equation 4:  $\text{EO}_{\text{LFGR}}$  is the energy offset by LFG recovery (MJ/kg):

$$\text{EO}_{\text{LFGR}} = (\text{LFG}_{\text{HHV}})(W_{\text{kg}})(C)(D)(\text{LFG}_C)(\text{LFG}_R)\left[\left(\frac{44}{12}\right)(C_{\text{CO}_2}) + \left(\frac{16}{12}\right)(C_{\text{CH}_4})\right]$$

|                            |   |
|----------------------------|---|
| $W_{\text{kg}}$            | wood mass (kg)  |
| $C$                        | carbon content of wood = 50%  |
| $D$                        | decomposition of wood in landfill = 23% (Skog 2008)                           |
| $C_{\text{CO}_2}$          | carbon content of wood converted to CO <sub>2</sub> at landfill surface = 55% |
| $C_{\text{CH}_4}$          | carbon content of wood converted to CH <sub>4</sub> at landfill surface = 45% |
| $\text{GWP}_{\text{CH}_4}$ | global warming potential of CH <sub>4</sub> = 25                              |
| $\text{LFG}_C$             | landfill gas capture efficiency = 75%   |
| $\text{LFG}_R$             | landfill gas energy recovery efficiency = 70%                                 |
| $\text{LFG}_{\text{HHV}}$  | landfill gas higher heating value = 15.8 MJ/kg                                |

## Appendix 3—Assumptions and Limitations

- The oven-dried (OD) density of solid-strip hardwood flooring was assumed to be 657 kg/m<sup>3</sup> based on several hardwood species including hard maple, oak, cherry, ash, and beech (Hubbard and Bowe 2010).
- Based calculation for the OD density of recovered framing lumber on a Southeast (SE) and Pacific Northwest (PNW) softwood lumber study done by Milota and others (2005). Milota and others reported 774 OD kg wood per 1.623 m<sup>3</sup> planed dry western lumber and 883 OD kg per 1.623 m<sup>3</sup> planed dry southwestern lumber. In addition, Milota and others reported approximately 21 million cubic meters annual lumber production in the PNW for Douglas fir and western hemlock and 36 million cubic meters in southern pine dimension lumber. Density value for recovered framing lumber estimated using weighted-averages as following:  $(774/1.623) \times (21/(21+36)) + (883/1.623) \times (36/(21+36)) = 519 \text{ kg/m}^3$
- Based calculation for onsite electricity use during the reclaiming process on the assumption that the on-site grid electricity has the same value as the electricity per volume reclaimed material produced from on-site generators. During a physical visit to a demolition site (7/7/2009 in Madison, WI), data collected included time and power of the generator powered by gasoline. Using run-time data, results estimated the electricity used from the grid per volume of material recovered. Results estimated 20.09 kWh/Msf of flooring and 27.08 kWh/Mbf of framing lumber recovered. Although removal of other materials such as wood doors, cast iron sink, etc. occurred during deconstruction, the study assigned all of the material and energy inputs to the old wood products.
- HHV represents the energy content of a fuel with the combustion products such as water vapor brought to 25° C (77° F), whereas lower heating value (LHV) ignores the energy produced by the combustion of hydrogen in fuel. HHV is the preferred method in the United States (EIA 2013).
- For transportation of workers and materials to/from the demolition site, survey results indicated transportation of five men during each building deconstruction daily with an average weight 86 kg per worker (Ogden and others 2004).
- During deconstruction, survey results estimated weighted average of 17% and 11% material loss for softwood framing lumber and solid-strip hardwood flooring, respectively.
- During the transportation, assumed the recovered materials had 8% MC to account for the water weight.
- U.S. LCI Database typically provided LCI data for materials and energy including electricity (USDA 2012).
- The study modified a sanitary landfill process in the U.S. Ecoinvent database to alter waste and emissions to waste treatment based on U.S. specific data, named specific for our project: Disposal, wood untreated, 20% water, to sanitary landfill/CH with U.S. electricity U – USLCI. To create a U.S.-specific process, removed all processes associated with burning of sludge from wastewater treatment of short-term leachate.
- Assumed 1kg of disposal wood produce 0.314 of LFG, and 45% of it was methane at the surface on a molar basis and the rest was CO<sub>2</sub>. On a mass basis, the landfill emits 0.072 kg CH<sub>4</sub>/kg and 0.242 kg CO<sub>2</sub>/kg. In addition, assumed approximately 75% of methane captured leaving the landfill and the remainder emitted directly to the atmosphere. Of the LFG, collected, assumed 30% flared (without energy recovery) and 70% burned for energy recovery (Salazar and Meil 2009).
- Assumed landfill methane has the same characteristics as natural gas.
- Survey questionnaire collected primary data on an annual basis across the United States for 2009.
- Collected primary mill data through a critically reviewed questionnaire in accordance with ISO 14040 and 14044 standards (2006a,b). Missing values were not weighted-average for a particular process in accordance with ISO standards.
- Background information<sup>1</sup>: recycled maple floor can be sold for \$1.50/ft<sup>2</sup>, Oak floor for \$1.00/ft<sup>2</sup>, Birch for \$1.25/ft<sup>2</sup>, and Douglas-fir for \$1.25/ft<sup>2</sup>.
- Ideal reclaimed material cost is 50–75% of virgin materials.
- Size of the deconstruction industry is unknown.
- Changed wood conversion to electricity process in U.S. LCI Database because less electricity was produced from wood from steam turbine (standard U.S. practice) than gasification systems provided in the dataset. Estimations provided by actual wood power plants lowered the value from 2.17 to 1.14 kWh/kg OD wood, a more conservative but realistic value. Calculation assuming HHV of 20.9 MJ/kg OD wood and 20% conversion of wood to electricity confirmed the value of 1.14 kWh/OD kg wood.
- Assumed energy use to store the virgin and recover wood material the same on a per unit basis.
- The study derived new framing lumber and new wood flooring transportation data from USDOT (2010).

<sup>1</sup> Frank Bryne, Madison Restore, July 20, 2009

Assumed transportation data on Wood product manufacturing (NAICS code 321) estimated virgin wood framing and Furniture and related product manufacturing (NAICS code 337) estimated new solid-strip hardwood flooring.

- Future work will examine regional effects because insufficient data were available.

## Appendix 4— SimaPro Inputs

Recovered wood framing lumber

### Composite Recovered Softwood Framing Lumber for the United States

#### Removal

| <b>Output</b>  | Amount | Unit |     |
|--|--------|------|-----|
| Recovered softwood framing lumber, at deconstruction site                                  | 519    | kg   | 83% |
| Disposal, wood untreated, 20% water, to sanitary lanfilled/CH with US electricity - US LCI | 106    | kg   | 17% |

#### **Input**

|   |      |       |           |
|---|------|-------|-----------|
| Installed softwood framing lumber, at deconstruction site | 625  | kg    |           |
| Transport, Single unit truck, gasoline powered/US         | 0.62 | tkm   | materials |
| Transport, Single unit truck, diesel powered/US           | 0.51 | tkm   | materials |
| Gasoline, combusted in equipment/US                       | 1.53 | liter |           |
| Electricity, at grid, US/US                               | 14.3 | kWh   |           |

#### Storage

| <b>Output</b>  | Amount | Unit |  |
|--|--------|------|--|
| Recovered softwood framing lumber, at storage facility | 519    | kg   |  |

#### **Input**

|  |         |                |                      |
|--|---------|----------------|----------------------|
| Recovered framing lumber, at deconstruction site     | 519     | kg             |                      |
| Transport, combination truck, gasoline powered/US    | 0.67    | tkm            | to storage facility  |
| Transport, combination truck, diesel powered/US      | 0.55    | tkm            | to storage facility  |
| Electricity, at grid, US/US                          | 2.86    | kWh            | lighting             |
| Residual fuel oil, combusted in industrial boiler/US | 0.22    | liter          | heating              |
| Natural gas, combusted in industrial boiler/US       | 9.0E-05 | m <sup>3</sup> | heating              |
| Gasoline, combusted in equipment/US                  | 1.44    | liter          | transporting on-site |

#### Product Transportation

| <b>Output</b>   | Amount | Unit |  |
|---|--------|------|--|
| Recovered softwood framing lumber, at construction site | 519    | kg   |  |

#### **Input**

|   |      |     |                      |
|---|------|-----|----------------------|
| Recovered framing lumber, at storage facility   | 519  | kg  |                      |
| Transport, single unit truck, diesel powered/US | 12.5 | tkm | to construction site |

## New wood framing LCI Inputs

**Composite Softwood Framing Lumber Mill for the United States**

| <b>Output</b>  | Amount | Unit |
|--|--------|------|
| Surfaced dried lumber, at planer mill, US AVG, at mill | 519    | kg   |

| <b>Input</b>  |     |    |       |
|---|-----|----|-------|
| Surfaced dried lumber, at planer mill, US SE/kg/US - Modified | 328 | kg | 63.2% |
| Surfaced dried lumber, at planer mill, US SE/kg/US - Modified | 191 | kg | 36.8% |

**Storage**

| <b>Output</b>  | Amount | Unit |
|--|--------|------|
| Surfaced dried lumber, at planer mill, US AVG, at storage facility | 519    | kg   |

| <b>Input</b>   |         |                |                      |
|--|---------|----------------|----------------------|
| Surfaced dried lumber, at planer mill, US AVG, at mill | 519     | kg             |                      |
| Transport, single unit truck, diesel powered/US        | 233     | tkm            | to storage facility  |
| Transport, train, diesel powered/US                    | 96      | tkm            | to storage facility  |
| Electricity, at grid, US/US                            | 2.86    | kWh            | lighting             |
| Residual fuel oil, combusted in industrial boiler/US   | 0.22    | liter          | heating              |
| Natural gas, combusted in industrial boiler/US         | 9.0E-05 | m <sup>3</sup> | heating              |
| Gasoline, combusted in equipment/US                    | 1.44    | liter          | transporting on-site |

**Product Transportation**

| <b>Output</b>   | Amount | Unit |
|---|--------|------|
| Surfaced dried lumber, at planer mill, US AVG, at construction site | 519    | kg   |

| <b>Input</b>   |     |     |                      |
|--|-----|-----|----------------------|
| Surfaced dried lumber, at planer mill, US AVG, at storage facility | 519 | kg  |                      |
| Transport, combination truck, diesel powered/US                    | 14  | tkm | to construction site |

## Recovered solid strip wood flooring

**Composite Recovered Hardwood Flooring the United States****Removal**

| <b>Output</b>   | Amount | Unit |     |
|---|--------|------|-----|
| Recovered hardwood flooring, at deconstruction site                                       | 657    | kg   | 89% |
| Disposal, wood untreated, 20% water, to sanitary lanfilled/CH with US electricty - US LCI | 81     | kg   | 11% |

**Input**

|   |      |       |           |
|---|------|-------|-----------|
| Installed hardwood flooring, at deconstruction site | 738  | kg    |           |
| Transport, Single unit truck, gasoline powered/US   | 2.86 | tkm   | materials |
| Transport, Single unit truck, diesel powered/US     | 3.84 | tkm   | materials |
| Gasoline, combusted in equipment/US                 | 4.57 | liter |           |
| Electricity, at grid, US/US                         | 18.6 | kWh   |           |

**Storage**

| <b>Output</b>                                    | Amount | Unit |  |
|--|--------|------|--|
| Recovered hardwood flooring, at storage facility | 657    | kg   |  |

**Input**

|  |       |                |                      |
|--|-------|----------------|----------------------|
| Recovered hardwood flooring, at deconstruction site        | 657   | kg             |                      |
| Transport, combination truck, gasoline powered/US          | 2.86  | tkm            | to storage facility  |
| Transport, combination truck, diesel powered/US            | 3.84  | tkm            | to storage facility  |
| Electricity, at grid, US/US                                | 1.17  | kWh            | heating              |
| Residual fuel oil, combusted in industrial boiler/US       | 1.12  | liter          | heating              |
| Natural gas, combusted in industrial boiler/US             | 0.659 | m <sup>3</sup> | heating              |
| Liquefied petroleum gas, combusted in industrial boiler/US | 0.831 | liter          | heating              |
| Electricity, at grid, US/US                                | 7.55  | kWh            | lighting             |
| Electricity, at grid, US/US                                | 0.558 | kWh            | transporting on-site |
| Gasoline, combusted in equipment/US                        | 2.47  | liter          | transporting on-site |

**Product Transportation**

| <b>Output</b>                                     | Amount | Unit |  |
|---|--------|------|--|
| Recovered hardwood flooring, at construction site | 657    | kg   |  |

**Input**

|  |     |     |                      |
|--|-----|-----|----------------------|
| Recovered hardwood flooring, at storage facility | 657 | kg  |                      |
| Transport, single unit truck, diesel powered/US  | 17  | tkm | to construction site |

New solid strip hardwood flooring

### US Solid Strip Hardwood Flooring Composite

#### Storage

| <b>Output</b>   | Amount | Unit           |                      |
|---|--------|----------------|----------------------|
| Solid strip and plank flooring, hardwood, US NE-NC, at storage facility | 657    | kg             |                      |
| <b>Input</b>  |        |                |                      |
| Solid strip and plank flooring, hardwood, US NE-NC, at mill             | 657    | kg             |                      |
| Transport, combination truck, diesel powered/US                         | 813    | tkm            | to storage facility  |
| Transport, train, diesel powered/US                                     | 4      | tkm            | to storage facility  |
| Electricity, at grid, US/US   | 1.17   | kWh            | heating              |
| Residual fuel oil, combusted in industrial boiler/US                    | 1.12   | liter          | heating              |
| Natural gas, combusted in industrial boiler/US                          | 0.659  | m <sup>3</sup> | heating              |
| Liquefied petroleum gas, combusted in industrial boiler/US              | 0.831  | liter          | heating              |
| Electricity, at grid, US/US   | 7.55   | kWh            | lighting             |
| Electricity, at grid, US/US   | 0.558  | kWh            | transporting on-site |
| Gasoline, combusted in equipment/US                                     | 2.47   | liter          | transporting on-site |

#### Product Transportation

| <b>Output</b>  | Amount | Unit |                      |
|--|--------|------|----------------------|
| Solid strip and plank flooring, hardwood, US NE-NC, at construction site | 657    | kg   |                      |
| <b>Input</b>   |        |      |                      |
| Solid strip and plank flooring, hardwood, US NE-NC, at storage facility  | 657    | kg   |                      |
| Transport, combination truck, diesel powered/US                          | 17     | tkm  | to construction site |

# Appendix 5—LCI Flows

| No | Substance  | Compartment | Unit | Reclaimed flooring, no EOL, at construction site | Solid strip and plank flooring, hardwood, US NE-NC, at construction site | Reclaimed framing lumber, no EOL, at construction site | Surfaced dried lumber, at planer mill, US AVG, at construction site |
|----|--|-------------|------|--|--|--|---|
| 1  | Carbon dioxide, in air   | Raw         | kg   | 0.394989242                                      | 1115.391423  | 0.243722696  | 2461.63328  |
| 2  | Coal, 26.4 MJ per kg, in ground                                      | Raw         | kg   | 8.900009534                                      | 30.9100888   | 5.491160187  | 17.49535827   |
| 3  | Energy, from hydro power   | Raw         | MJ   | 7.716753336                                      | 11.60133582  | 4.861951228  | 37.02101266   |
| 4  | Gas, natural, 46.8 MJ per kg, in ground                              | Raw         | kg   | 0.003127892                                      | 0.586299379 x  |  | 0.655641422   |
| 5  | Gas, natural, in ground  | Raw         | m3   | 2.254683069                                      | 17.52841005  | 0.974065359  | 12.73090649   |
| 6  | Iron ore, in ground  | Raw         | kg   | x  | 0.000210417 x  |  | x   |
| 7  | Limestone, in ground   | Raw         | kg   | 4.40529E-05                                      | 21.40715507 x  |  | 24.06784967   |
| 8  | Nickel   | Raw         | m3   | 0.545879263                                      | 2.002789587  | 0.224457368  | 1.66269518  |
| 9  | Occupation, forest, intensive, normal                                | Raw         | m2a  | x  | 2400.896794 x  |  | x   |
| 10 | Oil, crude, 42 MJ per kg, in ground                                  | Raw         | kg   | 0.044943599                                      | 2.676549027 x  |  | 2.958685658   |
| 11 | Oil, crude, in ground  | Raw         | kg   | 9.555540097                                      | 41.13096704  | 3.910362129  | 15.43115058   |
| 12 | Oxygen, in air   | Raw         | kg   | x  | 1.50374E-05 x  |  | x   |
| 13 | Uranium oxide, 332 GJ per kg, in ore                                 | Raw         | kg   | 0.000211681                                      | 0.000751922  | 0.000130615  | 0.000412281   |
| 14 | Uranium, 2291 GJ per kg, in ground                                   | Raw         | kg   | 3.10718E-09                                      | 8.86132E-06 x  |  | 9.95911E-06   |
| 15 | Water, process, well, in ground                                      | Raw         | kg   | x  | 2.959882421 x  |  | x   |
| 16 | Water, unspecified natural origin/m3                                 | Raw         | m3   | x  | x  |  | 0.190482081   |
| 17 | Water, well, in ground   | Raw         | m3   | x  | 0.106907415 x  |  | x   |
| 18 | Wood and wood waste, 20.9 MJ per kg, ovenry basis                    | Raw         | kg   | x  | 185.6510361 x  |  | 208.7263515   |
| 19 | Wood and wood waste, 9.5 MJ per kg                                   | Raw         | kg   | 3.21075E-05                                      | 3.21355E-05 x  |  | x   |
| 20 | Wood, soft, US SE, standing/m3                                       | Raw         | m3   | x  | x  |  | 1.056604878   |
| 21 | 2-Chloroacetophenone   | Air         | kg   | 1.3151E-11                                       | 4.56847E-11  | 8.11462E-12  | 4.64181E-11   |
| 22 | 5-methyl Chrysene  | Air         | kg   | 8.57664E-11                                      | 2.9567E-10   | 5.2921E-11   | 1.66486E-10   |
| 23 | Acenaphthene   | Air         | kg   | 1.98817E-09                                      | 6.85399E-09  | 1.22677E-09  | 3.85934E-09   |
| 24 | Acenaphthylene   | Air         | kg   | 9.74621E-10                                      | 3.3599E-09   | 6.01376E-10  | 1.89189E-09   |
| 25 | Acetaldehyde   | Air         | kg   | 8.23735E-05                                      | 0.000728841  | 3.57812E-05  | 0.001719876   |
| 26 | Acetophenone   | Air         | kg   | 2.81806E-11                                      | 9.78959E-11  | 1.73885E-11  | 9.94673E-11   |
| 27 | Acrolein   | Air         | kg   | 1.10648E-05                                      | 0.000516431  | 5.01271E-06  | 0.007478123   |
| 28 | Aldehydes, unspecified   | Air         | kg   | 0.000394706                                      | 0.001686594  | 0.000161184  | 0.000634206   |
| 29 | Ammonia  | Air         | kg   | 0.000214002                                      | 0.000904373  | 9.15732E-05  | 0.000652492   |
| 30 | Ammonium chloride  | Air         | kg   | 1.12352E-05                                      | 3.99092E-05  | 6.93253E-06  | 2.18823E-05   |
| 31 | Anthracene   | Air         | kg   | 8.18683E-10                                      | 2.82232E-09  | 5.05157E-10  | 1.58919E-09   |
| 32 | Antimony   | Air         | kg   | 7.03936E-08                                      | 1.22941E-06  | 4.32991E-08  | 1.48881E-05   |
| 33 | Arsenic  | Air         | kg   | 1.86538E-06                                      | 2.41679E-05  | 1.06711E-06  | 4.44422E-05   |
| 34 | Barium   | Air         | kg   | x  | 0.000763005 x  |  | x   |
| 35 | Benzene  | Air         | kg   | 0.000105582                                      | 0.001295539  | 4.68139E-05  | 0.007918452   |
| 36 | Benzene, chloro-   | Air         | kg   | 4.13316E-11                                      | 1.43581E-10  | 2.55031E-11  | 1.45885E-10   |
| 37 | Benzene, ethyl-  | Air         | kg   | 1.76599E-10                                      | 6.93994E-10  | 1.08968E-10  | 6.23329E-10   |
| 38 | Benzo(a)anthracene   | Air         | kg   | 3.11875E-10                                      | 1.07515E-09  | 1.92439E-10  | 6.05396E-10   |
| 39 | Benzo(a)pyrene   | Air         | kg   | 1.48143E-10                                      | 5.10706E-10  | 9.14095E-11  | 2.87568E-10   |
| 40 | Benzo(b,j,k)fluoranthene   | Air         | kg   | 4.28832E-10                                      | 1.47835E-09  | 2.64605E-10  | 8.32428E-10   |
| 41 | Benzo(g,h,i)perylene   | Air         | kg   | 1.0526E-10                                       | 3.62872E-10  | 6.49492E-11  | 2.04326E-10   |
| 42 | Benzyl chloride  | Air         | kg   | 1.3151E-09                                       | 4.56847E-09  | 8.11462E-10  | 4.64181E-09   |
| 43 | Beryllium  | Air         | kg   | 9.21059E-08                                      | 5.22874E-07  | 5.48416E-08  | 2.2649E-06  |
| 44 | Biphenyl   | Air         | kg   | 6.62746E-09                                      | 2.28474E-08  | 4.08938E-09  | 1.28649E-08   |
| 45 | Bromoform  | Air         | kg   | 7.32697E-11                                      | 2.54529E-10  | 4.521E-11  | 2.58615E-10   |
| 46 | BTEX (Benzene, Toluene, Ethylbenzene, and Xylene), unspecified ratio | Air         | kg   | 0.000689952                                      | 0.004811743  | 0.00029527   | 0.003546035   |
| 47 | Butadiene  | Air         | kg   | 4.19929E-06                                      | 5.34675E-06  | 1.82407E-06  | 2.17232E-06   |
| 48 | Cadmium  | Air         | kg   | 3.27987E-07                                      | 1.76423E-06  | 1.68075E-07  | 8.36955E-06   |
| 49 | Carbon dioxide   | Air         | kg   | x  | x  | x  | 0.387940417   |
| 50 | Carbon dioxide, biogenic   | Air         | kg   | 19.18702515                                      | 389.9056033  | 24.8357227   | 365.0154064   |
| 51 | Carbon dioxide, fossil   | Air         | kg   | 49.67036669                                      | 227.9076378  | 32.92201678  | 108.5247301   |
| 52 | Carbon disulfide   | Air         | kg   | 2.44232E-10                                      | 8.8431E-10   | 1.507E-10  | 8.6205E-10  |
| 53 | Carbon monoxide  | Air         | kg   | 0.027648663                                      | 2.498400905  | 2.24647E-05  | 1.162003941   |
| 54 | Carbon monoxide, fossil  | Air         | kg   | 1.115974063                                      | 1.180377546  | 0.463712491  | 0.525031041   |
| 55 | Chloride   | Air         | kg   | 3.02705E-10                                      | 1.05355E-09  | 1.8678E-10   | 6.78568E-10   |
| 56 | Chlorine   | Air         | kg   | 8.97629E-09                                      | 0.001451336 x  |  | 0.001475193   |
| 57 | Chloroform   | Air         | kg   | 1.10844E-10                                      | 3.85057E-10  | 6.83947E-11  | 3.91238E-10   |
| 58 | Chromium   | Air         | kg   | 1.2409E-06                                       | 1.49109E-05  | 7.01312E-07  | 4.16248E-05   |
| 59 | Chromium VI  | Air         | kg   | 3.07975E-07                                      | 1.06171E-06  | 1.90032E-07  | 5.97826E-07   |
| 60 | Chrysene   | Air         | kg   | 3.89852E-10                                      | 1.34397E-09  | 2.40553E-10  | 7.56762E-10   |
| 61 | Cobalt   | Air         | kg   | 1.5441E-06                                       | 4.31635E-06  | 5.78788E-07  | 1.36177E-05   |
| 62 | Copper   | Air         | kg   | 8.76266E-09                                      | 1.7934E-07   | 5.10678E-09  | 9.22764E-08   |
| 63 | Cumene   | Air         | kg   | 9.95716E-12                                      | 3.45899E-11  | 6.14393E-12  | 3.51451E-11   |
| 64 | Cyanide  | Air         | kg   | 4.69677E-09                                      | 1.6316E-08   | 2.89808E-09  | 1.65779E-08   |
| 65 | Dinitrogen monoxide  | Air         | kg   | 0.000798902                                      | 0.002866567  | 0.000326802  | 0.003324541   |
| 66 | Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-                                | Air         | kg   | 5.80321E-12                                      | 2.08718E-07  | 2.64976E-12  | 3.11841E-06   |
| 67 | Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin             | Air         | kg   | 1.51906E-16                                      | 1.51906E-16 x  |  | x   |
| 68 | Ethane, 1,1,1-trichloro-, HCFC-140                                   | Air         | kg   | 9.33979E-10                                      | 3.98902E-09  | 3.90016E-10  | 1.58022E-09   |
| 69 | Ethane, 1,2-dibromo-   | Air         | kg   | 2.25445E-12                                      | 7.83167E-12  | 1.39108E-12  | 7.95739E-12   |
| 70 | Ethane, 1,2-dichloro-  | Air         | kg   | 7.51484E-11                                      | 2.61056E-10  | 4.63693E-11  | 2.65246E-10   |
| 71 | Ethane, chloro-  | Air         | kg   | 7.89058E-11                                      | 2.74108E-10  | 4.86877E-11  | 2.78509E-10   |
| 72 | Ethene, tetrachloro-   | Air         | kg   | 1.82195E-07                                      | 6.20452E-07  | 1.08039E-07  | 3.42634E-07   |
| 73 | Ethene, trichloro-   | Air         | kg   | 2.62384E-11                                      | 2.71274E-11 x  |  | x   |
| 74 | Fluoranthene   | Air         | kg   | 2.76794E-09                                      | 9.54217E-09  | 1.70792E-09  | 5.373E-09   |
| 75 | Fluorene   | Air         | kg   | 3.54755E-09                                      | 1.22298E-08  | 2.18897E-09  | 6.88633E-09   |
| 76 | Fluoride   | Air         | kg   | 3.34582E-07                                      | 1.18848E-06  | 2.06449E-07  | 5.167E-06   |
| 77 | Formaldehyde   | Air         | kg   | 0.000167358                                      | 0.001923641  | 5.88787E-05  | 0.008319854   |
| 78 | Furan  | Air         | kg   | 1.77491E-11                                      | 6.31152E-11  | 1.09518E-11  | 3.61766E-11   |
| 79 | Heat, waste  | Air         | MJ   | 0.39771 x  |  | 0.52046 x  |   |
| 80 | Hexane   | Air         | kg   | 1.25874E-10                                      | 4.37268E-10  | 7.76685E-11  | 4.44287E-10   |
| 81 | Hydrazine, methyl-   | Air         | kg   | 3.19381E-10                                      | 1.10949E-09  | 1.97069E-10  | 1.1273E-09  |
| 82 | Hydrocarbons, unspecified  | Air         | kg   | 6.48455E-05                                      | 0.000230341  | 4.0012E-05   | 0.000126297   |
| 83 | Hydrogen chloride  | Air         | kg   | 0.004818197                                      | 0.018896858  | 0.002929338  | 0.044715943   |
| 84 | Hydrogen fluoride  | Air         | kg   | 0.000584709                                      | 0.002015663  | 0.000360775  | 0.001134831   |
| 85 | Hydrogen sulfide   | Air         | kg   | 9.78444E-12                                      | 3.40544E-11  | 6.03736E-12  | 2.19336E-11   |
| 86 | Indeno(1,2,3-cd)pyrene   | Air         | kg   | 2.37814E-10                                      | 8.19838E-10  | 1.4674E-10   | 4.61634E-10   |
| 87 | Iron   | Air         | kg   | x  | 0.000763005 x  |  | x   |
| 88 | Isophorone   | Air         | kg   | 1.08965E-09                                      | 3.78531E-09  | 6.72354E-10  | 3.84607E-09   |
| 89 | Isoprene   | Air         | kg   | 0.009921691                                      | 0.034532074  | 0.006122043  | 0.022241254   |
| 90 | Kerosene   | Air         | kg   | 5.38147E-06                                      | 1.91142E-05  | 3.32018E-06  | 1.048E-05   |
| 91 | Lead   | Air         | kg   | 1.98363E-06                                      | 0.00022075   | 1.12535E-06  | 9.32676E-05   |
| 92 | Magnesium  | Air         | kg   | 4.28832E-05                                      | 0.000147835  | 2.64605E-05  | 8.32428E-05   |
| 93 | Manganese  | Air         | kg   | 2.50896E-06                                      | 0.001768589  | 1.35847E-06  | 0.002991965   |
| 94 | Mercaptans, unspecified  | Air         | kg   | 3.81527E-07                                      | 1.35651E-06  | 2.35416E-07  | 1.41564E-06   |
| 95 | Mercury  | Air         | kg   | 3.63339E-07                                      | 1.76988E-06  | 2.14805E-07  | 7.28671E-06   |
| 96 | Metals, unspecified  | Air         | kg   | 1.45013E-08                                      | 0.005345182  | 6.92614E-13  | 0.079867914   |
| 97 | Methane  | Air         | kg   | 0.08692436                                       | 0.421212633  | 0.041932457  | 0.278714432   |
| 98 | Methane, biogenic  | Air         | kg   | 5.589 x  |  | 7.314 x  |   |
| 99 | Methane, bromo-, Halon 1001  | Air         | kg   | 3.00594E-10                                      | 1.04422E-09  | 1.85477E-10  | 1.06098E-09   |

|   |       |    |             |             |             |             |
|---|-------|----|-------------|-------------|-------------|-------------|
| 100 Methane, dichloro-, HCC-30  | Air   | kg | 2.09877E-06 | 4.28123E-05 | 9.94679E-07 | 0.000544782 |
| 101 Methane, dichlorodifluoro-, CFC-12                                | Air   | kg | 1.10892E-09 | 4.77325E-09 | 4.53798E-10 | 1.79079E-09 |
| 102 Methane, fossil   | Air   | kg | 0.01250587  | 0.03732056  | 0.005374387 | 0.024599024 |
| 103 Methane, monochloro-, R-40  | Air   | kg | 9.95716E-10 | 3.45899E-09 | 6.14393E-10 | 3.51451E-09 |
| 104 Methane, tetrachloro-, CFC-10                                     | Air   | kg | 2.21369E-10 | 5.6243E-06  | 4.53798E-11 | 8.40302E-05 |
| 105 Methanol  | Air   | kg | x           | x           | x           | 0.000199253 |
| 106 Methyl ethyl ketone   | Air   | kg | 7.32697E-10 | 2.54529E-09 | 4.521E-10   | 2.58615E-09 |
| 107 Methyl methacrylate   | Air   | kg | 3.75742E-11 | 1.30528E-10 | 2.31846E-11 | 1.32623E-10 |
| 108 N-Nitrosodimethylamine  | Air   | kg | 5.80007E-12 | 5.99872E-12 | x           | x           |
| 109 Naphthalene   | Air   | kg | 2.9319E-07  | 0.000429068 | 1.05857E-07 | 0.000181492 |
| 110 Nickel  | Air   | kg | 1.73382E-05 | 0.000135687 | 5.44088E-06 | 7.41356E-05 |
| 111 Nitrogen oxides   | Air   | kg | 0.363888569 | 1.746210706 | 0.170237861 | 1.193315102 |
| 112 Nitrogen, total   | Air   | kg | x           | x           | x           | 8.76702E-05 |
| 113 NMVOC, non-methane volatile organic compounds, unspecified origin | Air   | kg | 0.020800881 | 0.084952299 | 0.008191468 | 0.033816433 |
| 114 Organic acids   | Air   | kg | 4.12865E-08 | 1.46656E-07 | 2.54753E-08 | 8.04118E-08 |
| 115 Organic substances, unspecified                                   | Air   | kg | 2.6016E-05  | 0.028871248 | 1.49451E-05 | 4.70208E-05 |
| 116 PAH, polycyclic aromatic hydrocarbons                             | Air   | kg | 1.80433E-05 | 2.29731E-05 | 7.83758E-06 | 1.16535E-05 |
| 117 Particulates, < 10 um   | Air   | kg | 4.46743E-05 | 0.0332225   | x           | x           |
| 118 Particulates, > 2.5 um, and < 10um                                | Air   | kg | 0.004557214 | 0.091028294 | 0.002277674 | 0.947526756 |
| 119 Particulates, unspecified   | Air   | kg | 0.01519143  | 0.874807804 | 0.008906701 | 0.343247833 |
| 120 Phenanthrene  | Air   | kg | 1.0526E-08  | 3.62872E-08 | 6.49492E-09 | 2.04326E-08 |
| 121 Phenol  | Air   | kg | 7.20543E-10 | 0.006936408 | 1.85477E-11 | 2.06475E-05 |
| 122 Phenols, unspecified  | Air   | kg | 7.91815E-07 | 8.6026E-06  | 2.62337E-07 | 9.61544E-05 |
| 123 Phosphate   | Air   | kg | x           | x           | x           | 2.00047E-06 |
| 124 Phthalate, dioctyl-   | Air   | kg | 1.37146E-10 | 4.76427E-10 | 8.46239E-11 | 4.84074E-10 |
| 125 Potassium   | Air   | kg | x           | 0.135259945 | x           | x           |
| 126 Propanal  | Air   | kg | 7.1391E-10  | 2.48003E-09 | 4.40508E-10 | 2.51984E-09 |
| 127 Propene   | Air   | kg | 0.000277089 | 0.000352801 | 0.000120361 | 0.000178965 |
| 128 Propylene oxide   | Air   | kg | x           | 7.29658E-11 | x           | x           |
| 129 Pyrene  | Air   | kg | 1.2865E-09  | 4.43505E-09 | 7.93815E-10 | 2.49728E-09 |
| 130 Radioactive species, unspecified                                  | Air   | Bq | 220696.1287 | 760660.4401 | 136098.3141 | 428047.3597 |
| 131 Radionuclides (Including Radon)                                   | Air   | kg | 0.000300902 | 0.001068848 | 0.000185667 | 0.000586052 |
| 132 Selenium  | Air   | kg | 5.22194E-06 | 1.85198E-05 | 3.17861E-06 | 1.53823E-05 |
| 133 Sodium  | Air   | kg | x           | 0.003121383 | x           | x           |
| 134 Styrene   | Air   | kg | 4.69677E-11 | 1.6316E-10  | 2.89808E-11 | 1.65779E-10 |
| 135 Sulfur dioxide  | Air   | kg | 0.163796405 | 0.743235329 | 0.09183665  | 0.481662491 |
| 136 Sulfur oxides   | Air   | kg | 0.040618974 | 0.172844458 | 0.016847482 | 0.108597679 |
| 137 Sulfuric acid, dimethyl ester                                     | Air   | kg | 9.01781E-11 | 3.13267E-10 | 5.56431E-11 | 3.18295E-10 |
| 138 t-Butyl methyl ether  | Air   | kg | 6.57548E-11 | 2.28424E-10 | 4.05731E-11 | 2.3209E-10  |
| 139 Tar   | Air   | kg | 3.4046E-10  | 1.18496E-09 | 2.10076E-10 | 7.63202E-10 |
| 140 TOC, Total Organic Carbon   | Air   | kg | x           | 0.000511133 | x           | 0.007637393 |
| 141 Toluene   | Air   | kg | 4.39265E-05 | 5.59305E-05 | 1.90807E-05 | 2.83724E-05 |
| 142 Toluene, 2,4-dinitro-   | Air   | kg | 5.26039E-13 | 1.82739E-12 | 3.24585E-13 | 1.85672E-12 |
| 143 Vinyl acetate   | Air   | kg | 1.42782E-11 | 4.96006E-11 | 8.81016E-12 | 5.03968E-11 |
| 144 VOC, volatile organic compounds                                   | Air   | kg | 0.026182848 | 1.231171265 | 0.011134295 | 0.376528589 |
| 145 Xylene  | Air   | kg | 3.06087E-05 | 3.8973E-05  | 1.32957E-05 | 1.9798E-05  |
| 146 Zinc  | Air   | kg | 5.84177E-09 | 0.000763124 | 3.40452E-09 | 1.6771E-06  |
| 147 2-Hexanone  | Water | kg | 2.79726E-07 | 1.35871E-06 | 1.15556E-07 | 6.55918E-07 |
| 148 4-Methyl-2-pentanone  | Water | kg | 1.80037E-07 | 8.74494E-07 | 7.4374E-08  | 4.22162E-07 |
| 149 Acetone   | Water | kg | 4.28395E-07 | 2.08085E-06 | 1.76972E-07 | 1.00453E-06 |
| 150 Acidity, unspecified  | Water | kg | 4.90244E-11 | 4.90365E-11 | x           | x           |
| 151 Acids, unspecified  | Water | kg | 6.35839E-09 | 2.21301E-08 | 3.92336E-09 | 1.42535E-08 |
| 152 Aluminium   | Water | kg | 0.003297335 | 0.014562978 | 0.001370755 | 0.00693024  |
| 153 Ammonia   | Water | kg | 0.000762179 | 0.003568032 | 0.000315077 | 0.001619134 |
| 154 Ammonia, as N   | Water | kg | 3.19325E-09 | 1.1114E-08  | 1.97035E-09 | 7.15824E-09 |
| 155 Ammonium, ion   | Water | kg | 2.40216E-06 | 6.61583E-06 | 1.48222E-06 | 4.67857E-06 |
| 156 Antimony  | Water | kg | 2.0029E-06  | 8.8875E-06  | 8.21503E-07 | 3.58594E-06 |
| 157 Arsenic, ion  | Water | kg | 1.14315E-05 | 5.4387E-05  | 4.73003E-06 | 2.91491E-05 |
| 158 Barium  | Water | kg | 0.044225109 | 0.197105639 | 0.018145317 | 0.080320868 |
| 159 Benzene   | Water | kg | 7.1867E-05  | 0.000349073 | 2.96886E-05 | 0.00016852  |
| 160 Benzene, 1-methyl-4-(1-methylethyl)-                              | Water | kg | 4.28095E-09 | 2.07939E-08 | 1.76848E-09 | 1.00383E-08 |
| 161 Benzene, ethyl-   | Water | kg | 4.04269E-06 | 1.96368E-05 | 1.67005E-06 | 9.47963E-06 |
| 162 Benzene, pentamethyl-   | Water | kg | 3.21075E-09 | 1.55956E-08 | 1.32638E-09 | 7.52878E-09 |
| 163 Benzenes, alkylated, unspecified                                  | Water | kg | 1.75686E-06 | 7.79511E-06 | 7.20586E-07 | 3.14457E-06 |
| 164 Benzo(a)pyrene  | Water | kg | x           | 8.71687E-10 | x           | x           |
| 165 Benzoic acid  | Water | kg | 4.3458E-05  | 0.00021109  | 1.79527E-05 | 0.000101904 |
| 166 Beryllium   | Water | kg | 6.15994E-07 | 2.88877E-06 | 2.53745E-07 | 1.30804E-06 |
| 167 Biphenyl  | Water | kg | 1.13749E-07 | 5.04701E-07 | 4.66549E-08 | 2.03599E-07 |
| 168 BOD5, Biological Oxygen Demand                                    | Water | kg | 0.007774409 | 0.28058594  | 0.003210139 | 3.648924516 |
| 169 Boron   | Water | kg | 0.000134624 | 0.000653275 | 5.55454E-05 | 0.000315288 |
| 170 Bromide   | Water | kg | 0.00917871  | 0.044585209 | 0.003791775 | 0.021524725 |
| 171 Cadmium, ion  | Water | kg | 1.717E-06   | 8.10037E-06 | 7.12535E-07 | 5.0297E-06  |
| 172 Calcium, ion  | Water | kg | 0.137634332 | 0.668566023 | 0.056857903 | 0.322781263 |
| 173 Chloride  | Water | kg | 1.547287631 | 7.515803026 | 0.639192781 | 3.628429016 |
| 174 Chromate  | Water | kg | 5.73102E-10 | 5.73873E-10 | x           | x           |
| 175 Chromium  | Water | kg | 8.12708E-05 | 0.000349797 | 3.32549E-05 | 0.000136857 |
| 176 Chromium VI   | Water | kg | 3.41926E-07 | 1.47179E-06 | 1.39924E-07 | 5.52173E-07 |
| 177 Chromium, ion   | Water | kg | 9.76081E-06 | 5.40097E-05 | 4.07854E-06 | 3.15997E-05 |
| 178 Cobalt  | Water | kg | 9.49108E-07 | 4.61012E-06 | 3.92081E-07 | 2.22555E-06 |
| 179 COD, Chemical Oxygen Demand                                       | Water | kg | 0.014454992 | 0.069017324 | 0.00596115  | 0.032331671 |
| 180 Copper, ion   | Water | kg | 1.33145E-05 | 5.88711E-05 | 5.925E-06   | 2.92382E-05 |
| 181 Cyanide   | Water | kg | 3.12277E-09 | 1.14769E-07 | 1.28952E-09 | 7.29457E-09 |
| 182 Decane  | Water | kg | 1.24877E-06 | 6.06568E-06 | 5.15874E-07 | 2.92821E-06 |
| 183 Detergent, oil  | Water | kg | 3.71296E-05 | 0.00018343  | 1.536E-05   | 9.113E-05   |
| 184 Dibenzofuran  | Water | kg | 8.14577E-09 | 3.95668E-08 | 3.36505E-09 | 1.91009E-08 |
| 185 Dibenzothiophene  | Water | kg | 6.95088E-09 | 3.36151E-08 | 2.8704E-09  | 1.61042E-08 |
| 186 DOC, Dissolved Organic Carbon                                     | Water | kg | 1.95244E-11 | 6.79539E-11 | 1.20473E-11 | 4.37674E-11 |
| 187 Docosane  | Water | kg | 4.58418E-08 | 2.22669E-07 | 1.89375E-08 | 1.07494E-07 |
| 188 Dodecane  | Water | kg | 2.36933E-06 | 1.15086E-05 | 9.78782E-07 | 5.55581E-06 |
| 189 Eicosane  | Water | kg | 6.52339E-07 | 3.16862E-06 | 2.69484E-07 | 1.52966E-06 |
| 190 Fluorene, 1-methyl-   | Water | kg | 4.87556E-09 | 2.36821E-08 | 2.01412E-09 | 1.14326E-08 |
| 191 Fluorenes, alkylated, unspecified                                 | Water | kg | 1.01814E-07 | 4.51746E-07 | 4.17597E-08 | 1.82236E-07 |
| 192 Fluoride  | Water | kg | 3.9076E-05  | 0.000138827 | 2.41098E-05 | 0.011203709 |
| 193 Fluorine  | Water | kg | 5.07316E-08 | 2.26643E-07 | 2.08187E-08 | 9.28492E-08 |
| 194 Hexadecane  | Water | kg | 2.58613E-06 | 1.25616E-05 | 1.06834E-06 | 6.06415E-06 |
| 195 Hexanoic acid   | Water | kg | 8.99973E-06 | 4.37146E-05 | 3.71783E-06 | 2.11033E-05 |
| 196 Hydrocarbons, unspecified   | Water | kg | 2.44297E-11 | 8.50267E-11 | 1.5074E-11  | 5.47636E-11 |
| 197 Iron  | Water | kg | 0.006751376 | 0.030279538 | 0.002814926 | 0.012788917 |
| 198 Lead  | Water | kg | 2.31121E-05 | 0.000106797 | 9.57503E-06 | 4.92358E-05 |
| 199 Lead-210/kg   | Water | kg | 4.45123E-15 | 2.1621E-14  | 1.83882E-15 | 1.04376E-14 |
| 200 Lithium, ion  | Water | kg | 0.009561175 | 0.066582562 | 0.004091097 | 0.049011523 |
| 201 m-Xylene  | Water | kg | 1.29796E-06 | 6.30462E-06 | 5.36193E-07 | 3.04359E-06 |
| 202 Magnesium   | Water | kg | 0.026906192 | 0.13069937  | 0.01111512  | 0.06310174  |
| 203 Manganese   | Water | kg | 0.000111269 | 0.000451528 | 5.98552E-05 | 0.000237695 |
| 204 Mercury   | Water | kg | 3.82188E-08 | 1.66821E-07 | 1.63188E-08 | 1.2516E-07  |

Life-Cycle Energy and GHG Emissions for New and Recovered Softwood Framing Lumber and Hardwood Flooring Considering End-of-Life Scenarios

|  |          |      |             |              |             |             |
|--|----------|------|-------------|--------------|-------------|-------------|
| 205 Metallic ions, unspecified                 | Water    | kg   | 1.03602E-06 | 1.03702E-06  | 1.84046E-10 | 6.68634E-10 |
| 206 Methane, monochloro-, R-40                 | Water    | kg   | 1.72433E-09 | 8.37564E-09  | 7.1233E-10  | 4.04336E-09 |
| 207 Methyl ethyl ketone                        | Water    | kg   | 3.44855E-09 | 1.67507E-08  | 1.42461E-09 | 8.08642E-09 |
| 208 Molybdenum                                 | Water    | kg   | 9.84803E-07 | 4.7835E-06   | 4.06826E-07 | 2.30924E-06 |
| 209 n-Hexacosane                               | Water    | kg   | 2.85994E-08 | 1.38916E-07  | 1.18146E-08 | 6.70621E-08 |
| 210 Naphthalene                                | Water    | kg   | 7.80116E-07 | 3.78142E-06  | 3.22261E-07 | 1.82772E-06 |
| 211 Naphthalene, 2-methyl-                     | Water    | kg   | 6.78563E-07 | 3.29599E-06  | 2.80317E-07 | 1.59115E-06 |
| 212 Naphthalenes, alkylated, unspecified       | Water    | kg   | 2.87887E-08 | 1.27734E-07  | 1.18078E-08 | 5.15285E-08 |
| 213 Nickel                                     | Water    | kg   | 1.08905E-05 | 5.10226E-05  | 4.48575E-06 | 2.49356E-05 |
| 214 Nickel, ion                                | Water    | kg   | x           | 2.31632E-10  | x           | x           |
| 215 Nitrate                                    | Water    | kg   | 2.3E-10     | 2.44338E-10  | 1.32066E-12 | 4.79792E-12 |
| 216 Nitrate compounds                          | Water    | kg   | 8.61713E-11 | 2.99916E-10  | 5.31708E-11 | 1.93168E-10 |
| 217 Nitric acid                                | Water    | kg   | 1.93286E-07 | 6.72724E-07  | 1.19264E-07 | 4.33285E-07 |
| 218 Nitrogen, total                            | Water    | kg   | 5.97993E-06 | 2.13503E-05  | 3.68984E-06 | 1.16468E-05 |
| 219 o-Cresol                                   | Water    | kg   | 1.23239E-06 | 5.98613E-06  | 5.09107E-07 | 2.88982E-06 |
| 220 Octadecane                                 | Water    | kg   | 6.38901E-07 | 3.10335E-06  | 2.63933E-07 | 1.49815E-06 |
| 221 Oils, unspecified                          | Water    | kg   | 0.000981118 | 0.004650683  | 0.00040586  | 0.00218248  |
| 222 Organic substances, unspecified            | Water    | kg   | 4.97148E-07 | 4.99635E-07  | x           | x           |
| 223 p-Cresol                                   | Water    | kg   | 1.32966E-06 | 6.4586E-06   | 5.49288E-07 | 3.11793E-06 |
| 224 Phenanthrene                               | Water    | kg   | 1.0827E-08  | 4.96386E-08  | 4.45198E-09 | 2.14911E-08 |
| 225 Phenanthrenes, alkylated, unspecified      | Water    | kg   | 1.1937E-08  | 5.29639E-08  | 4.89601E-09 | 2.13658E-08 |
| 226 Phenol                                     | Water    | kg   | 1.51356E-05 | 6.51386E-05  | 6.19249E-06 | 2.44369E-05 |
| 227 Phenol, 2,4-dimethyl-                      | Water    | kg   | 1.19997E-06 | 5.82865E-06  | 4.95714E-07 | 2.8138E-06  |
| 228 Phenols, unspecified                       | Water    | kg   | 6.09505E-06 | 3.68337E-05  | 2.56861E-06 | 2.3834E-05  |
| 229 Phosphate                                  | Water    | kg   | 2.07145E-08 | 1.96866E-08  | x           | 0.008376962 |
| 230 Phosphorus                                 | Water    | kg   | x           | 2.19489E-09  | x           | x           |
| 231 Radioactive species, Nuclides, unspecified | Water    | Bq   | 348.9136622 | 1239.39443   | 215.292391  | 679.5631383 |
| 232 Radium-226/kg                              | Water    | kg   | 1.54861E-12 | 7.52204E-12  | 6.39736E-13 | 3.63126E-12 |
| 233 Radium-228/kg                              | Water    | kg   | 7.92139E-15 | 3.84767E-14  | 3.27236E-15 | 1.85748E-14 |
| 234 Selenium                                   | Water    | kg   | 1.22962E-06 | 4.71283E-06  | 6.78303E-07 | 2.33496E-06 |
| 235 Silver                                     | Water    | kg   | 8.99456E-05 | 0.000436795  | 3.71562E-05 | 0.000210781 |
| 236 Sodium, ion                                | Water    | kg   | 0.436307313 | 2.11937221   | 0.180242611 | 1.023216853 |
| 237 Solids, inorganic                          | Water    | kg   | 4.91424E-10 | 1.71038E-09  | 3.03226E-10 | 1.10161E-09 |
| 238 Solved solids                              | Water    | kg   | 1.908660079 | 9.270560665  | 0.788398128 | 4.47564447  |
| 239 Strontium                                  | Water    | kg   | 0.002335453 | 0.011344004  | 0.000964786 | 0.005476322 |
| 240 Sulfate                                    | Water    | kg   | 0.007997099 | 0.03248363   | 0.004294245 | 0.016827245 |
| 241 Sulfide                                    | Water    | kg   | 1.75587E-06 | 7.8514E-06   | 7.18554E-07 | 2.83556E-06 |
| 242 Sulfur                                     | Water    | kg   | 0.000113501 | 0.000551312  | 4.6888E-05  | 0.000266148 |
| 243 Sulfuric acid                              | Water    | kg   | 4.07386E-08 | 4.13776E-08  | x           | x           |
| 244 Suspended solids, unspecified              | Water    | kg   | 0.1001116   | 0.445249952  | 0.041257201 | 0.181847715 |
| 245 Tar  | Water    | kg   | 4.87021E-12 | 1.69506E-11  | 3.00509E-12 | 1.09174E-11 |
| 246 Tetradecane                                | Water    | kg   | 1.03839E-06 | 5.04377E-06  | 4.28962E-07 | 2.43489E-06 |
| 247 Thallium                                   | Water    | kg   | 4.221E-07   | 1.87317E-06  | 1.73129E-07 | 7.55954E-07 |
| 248 Tin  | Water    | kg   | 8.61387E-06 | 3.98856E-05  | 3.54331E-06 | 1.73537E-05 |
| 249 Titanium, ion                              | Water    | kg   | 3.07602E-05 | 0.000136499  | 1.26166E-05 | 5.50799E-05 |
| 250 Toluene                                    | Water    | kg   | 6.78984E-05 | 0.000329804  | 2.80491E-05 | 0.000159214 |
| 251 Vanadium                                   | Water    | kg   | 1.1633E-06  | 5.65052E-06  | 4.80564E-07 | 2.7278E-06  |
| 252 Water                                      | Water    | kg   | x           | 0.006119306  | x           | x           |
| 253 Xylene                                     | Water    | kg   | 3.62544E-05 | 0.000175529  | 1.49728E-05 | 8.42605E-05 |
| 254 Yttrium                                    | Water    | kg   | 2.88705E-07 | 1.40232E-06  | 1.19265E-07 | 6.76972E-07 |
| 255 Zinc                                       | Water    | kg   | 7.8296E-05  | 0.000345884  | 3.29023E-05 | 0.000143119 |
| 256 Zinc, ion                                  | Water    | kg   | 3.79766E-09 | -6.34299E-09 | x           | x           |
| 257 Waste, solid                               | Waste    | kg   | 0.000780247 | 0.000780247  | x           | x           |
| 258 Bark                                       | Soil     | kg   | x           | x            | x           | 4.836418555 |
| 259 Cost, Total                                | Non mat. | \$US | x           | 6.236109334  | x           | x           |