

LIFE CYCLE IMPACTS OF MANUFACTURING REDWOOD DECKING IN NORTHERN CALIFORNIA

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Abstract. Awareness of the environmental footprint of building construction and use has led to increasing interest in green building. Defining a green building is an evolving process with life cycle inventory and life cycle impact assessment (LCIA) emerging as key tools in that evolution and definition process. This study used LCIA to determine the environmental footprint associated with manufacturing 38- × 138-mm redwood (*Sequoia sempervirens*) decking from sustainably managed northern California redwood forests. Primary survey data were collected from four redwood mills that represent 90% of redwood lumber production. The primary data were then weight-averaged on a per-unit basis of 1 m³ of planed redwood decking (380 oven-dry kg/m³) to calculate material flows and energy use. All of the raw material consumption and environmental outputs were assigned to dry planed redwood decking and none to coproducts. The gate-to-gate, cumulative energy consumption associated with manufacturing 1 m³ of planed redwood decking from 1.8 m³ of incoming logs was 1.36 GJ/m³ with 19% of the energy provided by burning wood residues. Emission data produced through modeling the production process found that the estimated biomass and fossil CO₂ emissions were 20.9 and 52.9 kg/m³, respectively. Based on the carbon content of redwood of 53%, a cubic meter of 38- × 138-mm redwood decking product stores 201 kg of carbon and if released

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into the atmosphere would emit 738 kg of CO₂. The amount of carbon stored in redwood decking is equivalent to about 10 times the total CO₂ emissions released during the manufacturing process. Low carbon emissions during the manufacturing process and carbon storage during the service life of a redwood deck are positive environmental attributes that should be considered when selecting a decking product.

Keywords: Redwood decking, life cycle assessment, greenhouse gases, manufacturing, environmental impacts.

INTRODUCTION

Buildings consume approximately 41% of all energy used in the US (USDOE 2012). Although much of that energy is used during building occupation, there is increased interest in decreasing the embodied energy, the amount of energy used in the production of a building material, as part of the overall goal of decreasing the environmental footprint of a building. Green construction practices have evolved substantially during the past 30 yr in an effort to decrease energy consumption, improve overall building performance, and move toward more sustainable practices. In practice, green building started as a series of prescriptions that experts thought were the most critical to move construction toward sustainability goals. Green building has now expanded to include life cycle analysis that provides insight on how to improve energy and material efficiency throughout the material production and building construction and operation while lowering overall environmental burdens throughout the building's entire life cycle.

Identifying building materials that possess positive environmental attributes is one result of the increased interest in green building practices. These practices may include using building materials with lower environmental impacts as well as reusing or reducing the use of building materials capable of performing the same function. The green building market for new nonresidential construction in 2013 was originally expected to triple to about \$96-140 billion from \$42 billion in 2008 (MHC 2010). However, a newer forecast made by McGraw Hill Construction (MHC 2012) indicates that the green building market in 2013 is expected to be \$98-106 billion, on the low end of the original forecast made in 2008.

This was most likely the result of the slow US economic recovery during this time. Despite the soft US economy, the percentage of new US residential and nonresidential construction being built green is forecasted to make up 45% of the market by the end of 2016 (MHC 2012). In addition, building codes and standards such as the International Green Construction Code (IgCC) are implementing performance-based decision-making based on scientific approaches including life cycle analysis (Bowyer et al 2012).

There are a number of green building certification systems in the US with the most well known being LEED, ICC-700 National Green Building Standard, Green Globes, IgCC, CA Green Construction Code (CalGreen), and ASHRAE 189.1 (Ritter et al 2011). These green building certification systems are based on a variety of parameters, and in recent years, there has been increasing interest in using life cycle inventory (LCI) and life cycle assessment (LCA) data as an objective scientific basis for quantifying the relative environmental benefit, or "greenness," of projects built using these certification systems. This trend represents a shift away from prescriptive-based toward performance-based certification systems. In anticipation of the adoption of such policies and their market implications, a number of industries have initiated efforts to develop LCI data for their products (Puettmann and Wilson 2005; Puettmann et al 2010a; FAL 2010, 2011). Whole building LCA tools, such as the ATHENA Impact Estimator for Buildings, are becoming a necessary part of determining a building's environmental impact and are increasingly becoming part of green building certification systems (ASMI 2014). Developing metrics to measure sustainability are part of the green building process.

LCA can be used to provide a measure of building sustainability. As part of an LCA, LCI measures the inputs and outputs of the energy, material, and waste associated with a product within a specified system boundary. LCI that measure from resource extraction through manufacturing, use, and disposal are called cradle-to-grave LCI. If only a subset of these steps is evaluated, the LCI may be called a cradle-to-gate, gate-to-gate, or gate-to-grave analysis. The goal of this study was to document a gate-to-gate LCA of redwood (*Sequoia sempervirens*) decking lumber from incoming logs to dry planed redwood decking in northern California. A companion study (Han et al 2014) examined the life cycle of upstream processes from the seedling through to harvest of redwood logs. In the companion study, Han et al (2014) discuss the sustainable forest harvesting practices conducted by the redwood industry by adhering to forest certification standards and to the California Forest Practice Rules, one of the most stringent forest harvesting regulations in the US. Sustainable harvesting is critical because it highlights the climate change mitigation value of long-lived wood products through their carbon storage capacity.

The LCA tracked all steps in the production of redwood decking from the logs in the log yard through the manufacturing process including sawing, drying, and planing. We evaluated the material flow, energy consumption, and emissions for the redwood decking manufacturing process on a per-unit basis (ie functional unit) of 1 m³. Primary data were collected by visiting the major redwood sawmills and administering a questionnaire. Peer-reviewed literature provided secondary data per Consortium for Research on Renewable Industrial Material (CORRIM) guidelines (CORRIM 2010). Wood mass balances were constructed with a spreadsheet algorithm using data from primary and secondary sources. From material and energy inputs and reported emissions, SimaPro 7 software (PRé Consultants, Amersfoort, The Netherlands) was used to model the estimates for raw material consumption and environmental outputs on a per-functional-unit basis (PRé Consultants 2014). The study used the

US LCI database for secondary LCI data inputs such as fuels and electricity (NREL 2014).

This study includes life cycle impact assessment (LCIA) impact categories of global warming potential (GWP) (kg CO₂-eq), acidification potential (AP) (kg SO₂-eq), respiratory effects (RE) (PM 2.5-eq), eutrophication potential (EP) (kg N-eq), ozone depletion potential (ODP) (kg CFC-11-eq), and smog potential (SP) (kg O₃-eq) (Bare 2011). Other impact measures included the cumulative (total) energy demand (primary energy) (MJ-eq), including both the biomass and fossil fuel contributions, which were calculated and reported directly from LCI flows. We also tracked fresh water consumption (in liters) and renewable and nonrenewable material resource consumption (nonfuel resources). Impact categories and other impact measures were reported per cubic meter of production.

Redwood decking is the primary product manufactured from redwood logs although fencing, siding, sashes, doors, blinds, and millwork are also made (Wiemann 2010). According to Binam (2013), 12 redwood mills produced 614,000 m³ of redwood lumber in 2010, which was about a 20% increase from 2009 (USDOC 2011; Binam 2013, 2014). Redwood decking production has declined substantially during the past several decades, with annual production volumes in 2012, 2001, 1994, and 1968 of 0.637, 1.33, 1.91, and 2.29 Mm³, respectively (Barrette et al 1970; USDOC 1995, 2006, 2011; Binam 2013, 2014). However, for 2009-2010, much of the increase in redwood decking production has been attributed to the increase in new residential single-family construction. Units of single-family residential construction on a seasonally adjusted annual rate increased about 20% from 358,000 in January 2009 to 429,000 in December 2010 (USDOC 2014). Redwood decking is used in both new residential construction and repair and remodeling of existing residential buildings. Regardless of the current housing market, which is expected to fully recover this year, increasing environmental concerns regarding the building industry will continue to define “green building” materials and practices.

METHODOLOGY

Scope

This study covered the processing of redwood logs arriving at the sawmill gate into redwood decking leaving the sawmill (ie gate to gate), following ISO (2006a, 2006b). LCA data from this stage of the redwood decking production process were used to facilitate a comparative LCA between redwood decking and other non-wood decking materials (Bergman et al 2013) and to develop a business-to-consumer environmental product declaration (an LCA-based ecolabel) (AWC 2014). To construct the full LCA, this LCA manufacturing stage was linked to the forest resource (Han et al 2014) through log transportation (upstream) and product transportation (downstream). Figure 1 shows the process flow for the gate-to-gate manufacturing of

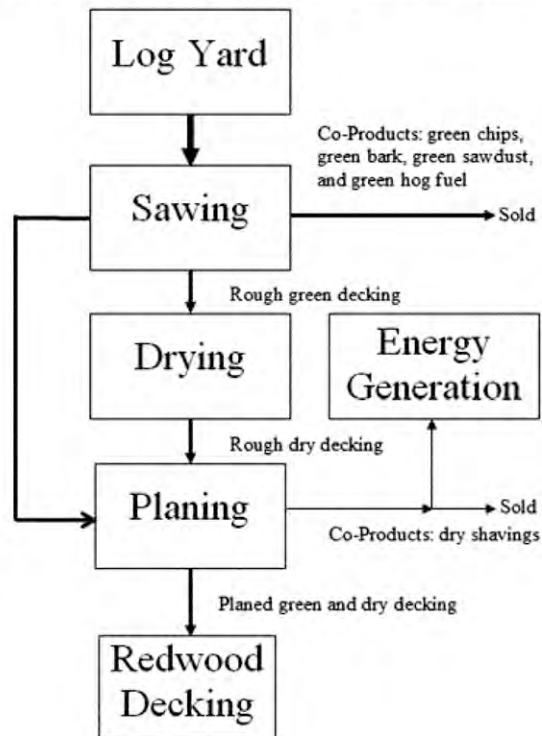
redwood decking. This LCA manufacturing stage provided a gate-to-gate analysis of the cumulative energy of manufacturing including resource (ie log) transportation.

In 2011, four redwood mills, representing 90% of redwood lumber production, were visited. The surveyed mills provided detailed annual production data for 2010 for their production facilities, including on-site energy consumption, electrical usage, log volumes, and decking production. The survey instrument administered at the redwood sawmills can be found in the Appendix of Bergman et al (2013).

Functional Unit

Specifying the system boundaries determined the unit processes to include in the LCA and

Inputs: Electricity, Diesel, Natural Gas, Steam, Propane, Gasoline



Outputs: Air emissions, Water emissions, Solid waste

Figure 1. Process flow for gate-to-gate manufacturing of redwood decking.

helped standardize the material flows, energy use, and emission data. This study selected a functional unit of 1 m³ of decking material 38 mm thick and no spacing between deck boards. One cubic meter of dry redwood decking equates to 26.3 m² at 38 mm thick. Results were reported per cubic meter of planed redwood decking. Based on US industry measurements, the following conversions were used for green and dry wood decking: 2.36 and 1.62 m³ per thousand board feet (bf), respectively. The different conversions were used because wood shrinks as it dries from its green state to its final dry state and is then planed (Bergman 2010).

System Boundary

Selection of the system boundary helps track the material and energy flows crossing the boundary precisely. To track flows tied to redwood decking production, two system boundaries were considered. One—the cumulative system boundary—is represented by the solid line shown in Fig 2 and includes both on- and off-site emissions from the materials and energy consumed within the redwood decking manufacturing process. Energy and material resources used for the generation and production of transportation and boiler fuels and grid electricity were included

within the cumulative system boundary and were considered off-site. Off-site emissions include emissions released during the production of grid electricity, during the transportation of logs to the mill, and during the production of the fuels consumed on-site for process energy and transportation. The on-site system boundary (represented by the dotted line shown in Fig 2) covered emissions occurring only at the mill from the four unit processes involved: log yard, sawing, drying, and planing. Energy consumption associated with log transportation was included as a separate upstream process. Ancillary material data such as lumber packaging, motor oil, paint, and hydraulic fluid were collected and were part of the analysis.

Data Quality

To ensure high-quality data, the original goal of this study was to survey a minimum of 50% of the redwood production capacity in the US. According to Binam (2013), 12 redwood mills produced 614,000 m³ of redwood lumber in 2010. The annual production of the four California redwood sawmills surveyed was 552,000 m³, representing approximately 90% of the total redwood lumber production in the US in 2010, which was well above the original goal.

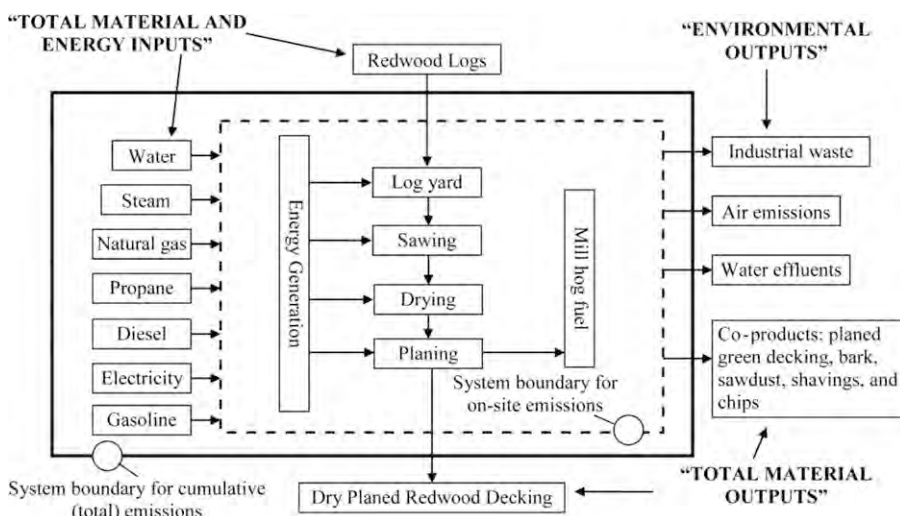


Figure 2. System boundaries for the redwood decking manufacturing process.

The weight-averaged annual production for the four redwood sawmills was 174,000 m³ with a range of 44,300–239,000 m³ of rough green redwood lumber. The weight-averaged log diameter was 27 cm, log length was 6.2 m, and kiln capacity was 2830 m³. One mill did no kiln-drying. Green chips comprised the greatest proportion of wood residue produced at 147 oven-dry (OD) kg/m³ planed dry redwood decking (Table 1).

The researchers collected process-specific (ie primary) annual data from each sawmill wherever possible. The primary data obtained from the four surveyed mills were weight-averaged (Milota 2004). Following CORRIM (2010) guidelines, a mass balance (from material input to material output for each sawmill), energy comparison with other wood products, and a sensitivity analysis were conducted to quantify uncertainty in data quality.

The method used for this study was consistent with the Mahalle and O'Connor (2009) LCA study for western red cedar (*Thuja plicata*) decking because of the large price differential (10 to 1) between western red cedar decking and coproducts. As is the case for western red cedar decking, redwood decking also has a large price differential relative to its coproducts. For this reason, all emissions (ie environmental outputs) as well as the energy and material consumed were assigned to the redwood decking and no environmental burdens were assigned to

the redwood residues, including green sawdust, chips, hog fuel, bark from sawing logs into rough green decking, and dry shavings from the planing process.

The LCI flows and environmental impacts of this no-allocation approach are similar to the revenue-allocation approach because the revenue of redwood decking far exceeds the revenue generated from the wood residues. In the revenue-allocation approach, the environmental burdens are assigned based on the revenue generated from the products and the coproducts (ie wood residues). The coproducts are made up of green and dry wood residues resulting from processing the redwood logs into redwood decking.

A sensitivity analysis was conducted that allocated LCI flows and environmental impacts on a mass basis to redwood decking and its associated wood residues. The analysis determined the difference between the no-allocation and mass-allocation approaches. The mass-allocation method is generally preferred for assigning environmental outputs because the final wood products have much greater mass than any of the coproducts generated during the manufacturing process (CORRIM 2010; Puettmann et al 2010a).

Manufacturing Process of Redwood Decking

Four main unit processes were identified in manufacturing redwood decking: log yard,

Table 1. Mass balance of redwood decking production.

Material (OD kg)	Sawing process		Boiler process	Dryer process		Planer process		All processes combined		
	In	Out	In	In	Out	In	Out	In	Out	Difference
Green logs (wood)	648	—	—	—	—	—	—	648	0	–648
Green logs (bark)	71	—	—	—	—	—	—	71	0	–71
Green chips	—	147	—	—	—	—	—	0	147	147
Green sawdust	—	68	—	—	—	—	—	0	68	68
Green bark	—	71	—	—	—	—	—	0	71	71
Green shaving	—	12	—	—	—	—	—	0	12	12
Green hog fuel	—	32	—	—	—	—	—	0	32	32
Rough green decking	—	388	—	388	—	—	—	388	388	0
Rough dry decking	—	—	—	—	388	388	—	388	388	0
Planed dry decking	—	—	—	—	—	—	380	0	380	380
Dry shavings	—	—	8	—	—	—	8	8	8	0
Sum	719	719	8	388	388	388	388	1503	1495	–8

sawing, drying, and planing. Energy generation is considered as an auxiliary process.

Log yard. Diesel logging trucks transported the redwood logs from the forest landing to the sawmill log yard. Log transport data were not included in the LCA results but were reported separately. The log yard operation therefore started with the logs already in the log yard, with inputs and outputs evaluated when moving the logs from the yard to the sawmill. On arrival at the log yard, logs were scaled using the Scribner short scale in thousand bf. In some seasons and for some mills, logs stored in the log yard were sprayed with a water sprinkler to prevent checking or splitting. Log stackers or front-end loaders were used to transport logs from the log yard to the sawmill. Inputs included logs with bark, electricity, water, fuel, and lubricants. Outputs included logs with bark and emissions from burning the fuels used by the log yard machines.

Sawing. Sawing began when the logs arrived at the debarker. In the sawing process, incoming redwood logs were sawn into 38- × 138-mm rough green decking. Sawing logs is typically a major source of electrical consumption for producing lumber products such as redwood decking (Puettmann and Wilson 2005; Puettmann et al 2010a). The rough green decking lumber was then tallied (to measure production volume) and, if necessary, stickered for drying. Outputs from the sawing process (less the bark) include rough green decking lumber (59.9%), wood chips (22.7%), sawdust (9.5%), hog fuel (5.0%), and shavings (1.9%). Hog fuel is comprised of a mixture of the wood residues. Two of the sawmills reported that they grind their wood residues into hog fuel, and another reported that they grind all wood residues together before measuring them. After grinding, all green wood residues left the system boundary with 71% trucked off-site for use in boilers that generate grid electricity, 25% sent to operations that ground them into mulch, and the remaining 4% was made into other wood products. In contrast, many sawmills burn their wood residues to

generate process energy for their kiln driers (Puettmann and Wilson 2005; Puettmann et al 2010a). Once sawing is complete, there are three processing options for the rough green decking lumber, including 1) planing on all four sides and selling as green planed decking (7.6%); 2) selling as-is as rough green lumber (28.4%); or 3) drying, planing, and selling as dry planed decking (64.0%).

Drying. Rough green decking is first air-dried to minimize kiln-drying (which is an energy-intensive process) (Denig et al 2000; Bergman 2010). Second-growth redwood has a high moisture content of about 127% dry basis (Isenberg et al 1980; Simpson 1991). Air-drying is typically done to bring that moisture content down to the FSP, which is about 30%. Drying redwood decking lowers the total mass of the lumber and decreases the volume of the boards after they dry below the FSP (although the mass of the wood per board remains constant). Sawmills account for wood shrinkage when sawing the logs into green lumber. Depending on customer demand, some redwood decking is kiln-dried before the FSP is reached. Of the original 100% rough green decking produced, 64% was dried. After air-drying, 57% of the incoming rough green decking was kiln-dried to 15-19% MC. Therefore, 36.5% ($= 64\% \times 57\%$) of total redwood decking was kiln-dried, whereas the remaining product, 27.5% ($43\% \times 64\%$), was just air-dried. Of the rough dry decking, 1.02% was shipped rough without being planed.

Planing. After drying, rough dry decking is usually planed on all four sides, which produces planer shavings, a dry wood residue. Inputs into the planing process include dry rough redwood decking, whereas outputs include dry planed redwood decking (98%) and dry planer shavings (2%). The dry planer shavings are used to fuel an on-site wood boiler that generates energy for the kiln dryer. Most redwood decking is sold as dry planed decking (62.4%), whereas the remaining 1.6% is sold as dry rough redwood decking. Dry planed redwood decking includes

both air-dried decking (25.9%) and kiln-dried decking (36.5%).

Auxiliary energy generation. The auxiliary energy process provided process (thermal) energy. Thermal energy used at the plant was provided by burning a mix of natural gas and dry wood residue generated from the planing process. Thermal energy was also produced in the form of steam and was used in the dry kilns. Another major source of energy was derived from off-site (grid) electricity, which released emissions off-site. Outputs from this upstream process included steam from the boilers, combustion gases from the drying process, solid waste (wood ash), and air emissions (eg CO₂, CO) from combustion.

Coproducts from the redwood decking production process included both materials that were sold off-site and wood residues that were burned on-site for energy generation. In this study, byproducts are also referred to as coproducts because all wood residuals whether used on-site or sold off-site had further use and were not landfilled. In this study, when referring to logs, lumber, and coproducts, the term green was used in the context of freshly cut materials.

Project Assumptions

Higher heating values. This study converted fuel from its volume or mass basis to its energy value. Higher heating values (HHV) is the preferred method in the US to calculate energy values (EIA 2014). HHV represents the (gross) energy content of a fuel with the combustion products at 25°C with all water vapor brought to liquid form.

Log conversion factor. Log volume is measured using the Scribner log scale, which reports volume in thousand bf. This volume was converted to cubic meters using a log conversion factor of 5.37 m³/thousand bf (Fonseca 2005), and that solid wood measure combined with average specific gravity was used to determine the mass balance.

Project Limitations

Omissions of life cycle stages, processes, and input or output flows. Human labor and the manufacturing LCA of the machinery and infrastructure were outside the system boundaries and therefore were not modeled in this analysis.

Cutoff rules. All materials used in the logging and manufacturing process were tracked. According to the North American product category rule, if the mass/energy of a flow is less 1% of the cumulative mass/energy of the model flow, it may be excluded provided its environmental relevance is minor. This analysis included all energy and mass flows for primary data (FPInnovations 2011).

RESULTS AND DISCUSSION

Detailed primary data on mass flow, energy consumption, and fuel types were obtained from the redwood mill surveys and collated with upstream process data for grid electricity and other inputs included in the SimaPro and databases to produce LCI and LCIA data for redwood decking. We used SimaPro 7 to model the weight-averaged survey data to estimate non-wood raw material use and emission data on a 1-m³ unit basis. With SimaPro 7, the life cycle data were compiled into impact measures using the Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI) (Bare 2011) impact estimation method.

Product Yields

Mass balance. The results of a mass balance analysis that was used to confirm the data quality obtained from surveys and site visits of the redwood sawmills are summarized in Table 1. In performing the mass balance for redwood decking, all unit processes located within the site system boundary were considered. With a weight-averaged approach for the four surveyed mills, 648 OD kg (1.8 m³) of incoming redwood logs, with a green density (127% MC) of 803 kg/m³, produced 1.0 m³ (380 OD kg) of planed

redwood decking. The sawing process yielded 388 kg of rough green decking. No loss of wood material occurred during the drying process. Planing the rough lumber into surfaced decking decreased the 388 OD kg of rough dry decking to 380 OD kg of planed dry redwood decking (a 2% decrease in mass). All 8 OD kg of dry shavings produced on-site were burned to produce thermal process energy in the on-site boiler. Overall, an average redwood log was decreased to 58.6% (380 of 648) of its original mass during its conversion to planed dry redwood decking. The hog fuel listed as 32 OD kg/m³ is a mixture of wood residues generated from the sawing process and was not used on-site.

Carbon storage. Redwood decking stores carbon during its service life. The carbon content for redwood has been estimated at 53% of OD mass (Jones and O’Hara 2012). When this carbon content factor of 0.53 and the molecular weight ratio of CO₂ (44 g/mole) and carbon (12 g/mole) are used to calculate, the carbon stored in 1 m³ (380 OD kg) of redwood decking if released into the atmosphere would produce 738 kg of CO₂.

Electrical Grid Composition

Table 2 shows the composite grid used in SimaPro 7 to model the environmental effects from using grid electricity. For redwood deck-

Table 2. Composite electrical grid data for producing redwood decking in northern California.

Energy resources	CAMX 2008 ^a (%)	NWPP 2008 ^b (%)	Composite (%)
Natural gas	59.0	12.8	35.9
Hydro	11.8	42.3	27.0
Coal	1.1	37.6	19.3
Uranium	16.1	3.0	9.5
Geothermal	4.5	0.5	2.5
Wind	2.6	2.4	2.5
Biomass	1.5	0.5	1.0
Crude oil	0.8	0.1	0.5
Solar	0.3	0.0	0.2
Energy, unspecified	2.3	0.8	1.6
Total	100	100	100

^a CAMX 2008: electrical grid covering lower northern California (50%).
^b NWPP 2008: electrical grid covering upper northern California (50%).

ing produced in northern California, the composite electrical grid is comprised of the CAMX 2008 (50%) and the NWPP 2008 (50%) regional grids (EPA 2012). The CAMX 2008 and NWPP 2008 grids provide power to lower and upper northern California, respectively. Natural gas (35.9%), hydro (27.0%), and coal (19.3%) are the three main contributors to the composite electrical grid.

Energy Consumption

Overall. Redwood decking production requires both electrical and thermal energy inputs for processing logs into decking. Electrical energy was required for the log yard operations, sawing, drying, and planing unit processes. Electricity for the sawmills was obtained off-site from the combined NWPP/CAMX power grids (50/50) as shown in Table 2. Thermal energy was only used during the drying process. The mill surveys reported that most thermal energy was produced on-site, although one mill used waste steam from a nearby wood-fired power plant. Primary energy was not included in the electricity values in Table 3. Primary energy is energy embodied in natural resources such as biomass and fossil

Table 3. Material and energy consumed on-site to produce 1 m³ of dry planed redwood decking (SimaPro 7 input values).

Fuel type	Amount per m ³	SI units
Fossil fuel		
Natural gas	0.375	m ³
Electricity		
Grid (eGrid)	91	kWh
On-site transportation fuel		
Off-road diesel	2.43	L
Gasoline	0.36	L
Propane	0.10	L
Renewable fuel ^a		
Wood fuel ^b	9.91	kg
Water use ^c		
Surface water	187	L
Ground water	22	L

^a Values given in oven-dry mass.
^b Wood fuel includes wood burned off-site and the resultant steam piped to the mills for process energy.
^c These are the gross values: 86% of water is recycled and returned to storage ponds for reuse.

fuels before conversion into useful energy. Table 3 shows the SimaPro 7 input values derived from a weighted average of the sawmill survey data.

Survey results showed that 221 MJ of process energy was consumed per cubic meter of redwood decking produced. Total electrical consumption was 91 kWh/m³ of final product. For the log yard operations, sawing, drying, and planing, the consumption of the grid electrical energy was 1.1, 67.7, 10.7, and 20.5% of the total, respectively. Based on this breakdown, the four unit processes used 1.0, 61.9, 9.8, and 18.7 kWh of grid electricity per cubic meter of redwood decking produced. The major sources of process energy were derived from the wood fuel generated on-site during the planing process (76.0%), from piped-in steam produced from burning wood biomass off-site (17.6%), and from natural gas (6.5%).

Electricity comparison. Electricity consumption of 91 kWh per cubic meter of redwood decking produced is similar to the value of 99 kWh/m³ found for manufacturing northeast and north-central (NE/NC) US softwood lumber (Bergman and Bowe 2010) and approximately 33% lower than the published value for western red cedar decking (118 kWh/m³) (Mahalle and O'Connor 2009). None of these values included primary energy resources. Table 4 summarizes the ancillary material consumed during the decking manufacturing process as well as amounts of these materials used.

Cumulative energy. Table 5 shows the cumulative energy consumption for a cubic meter of

Table 5. Cumulative energy consumed during production of planed (surfaced) redwood decking using cumulative gate-to-gate life cycle inventory values.^a

Fuel ^b	kg/m ³	MJ/m ³	Percent
Wood fuel/wood waste	11.1	232	17.3
Coal ^c	11.5	302	22.5
Natural gas ^c	8.35	454	33.9
Crude oil ^c	3.27	149	11.1
Hydro	0	85	6.3
Uranium ^c	0.000285	109	8.1
Energy, unspecified	0	9	0.7
Total	—	1340	100

^a Includes fuel used for electricity production (unallocated).

^b Values are unallocated and cumulative and based on higher heating values.

^c Materials as they exist in nature and have neither emissions nor energy consumption associated with them.

planed dry redwood decking. Cumulative energy values were determined using the HHV shown in Table 6. Cumulative energy consumption for manufacturing redwood decking was 1.34 GJ/m³ with wood fuel comprising about 18.8% of the total energy input. Natural gas (33.9%) and coal (22.5%) were the two largest energy resources consumed during the manufacturing process, largely because of their preponderance (35.9 and 19.3%, respectively) of regional electricity grid production (Table 2). As shown in Table 5, coal consumption increased as a percentage compared with natural gas. This increase in coal percentage occurred despite the natural gas consumed at the mills because coal is only about 50% as efficient when burned to generate grid electricity. Because coal is only 50% as efficient as natural gas when generating grid electricity, twice as much coal is needed as natural gas on a per-kilowatt basis.

Table 6. Higher heating values (HHV) used to calculate energy values from raw material resources.

Fuel	HHV (MJ/kg)
Wood fuel/wood waste ^{a,b}	20.9
Coal ^a	26.2
Natural gas ^a	54.4
Crude oil ^a	45.5
Diesel ^a	44.0
Gasoline ^a	48.4
Uranium ^c	381,000

^a As per Consortium for Research on Renewable Industrial Materials (CORRIM) guidelines.

^b Oven-dry basis.

^c Todrewas and Kazimi (1995).

Table 4. List of ancillary materials consumed during manufacturing.

Ancillary materials	kg/m ³
Hydraulic fluid	2.41E-01
Motor oil	6.63E-02
Grease	0.00E+00
Cardboard	1.21E-04
Plastic strapping	6.36E-02
Paint	2.12E-03
Potable water	1.81E+00
Replacement stickers	3.40E+00

Kiln-drying lumber products is energy-intensive with the primary boiler fuel being derived from the wood residue generated on-site (Puettmann and Wilson 2005; Puettmann et al 2010a). Low wood fuel consumption, as reported for redwood decking, indicates that little kiln-drying occurs and when it does occur, the energy input is decreased because of the initial air-drying of the decking lumber. Only 9.91 OD kg of wood fuel per cubic meter of redwood decking produced was burned for thermal energy used on-site. Additional wood fuel amounting to 1.15 OD kg/m³ was consumed to kiln-dry the wood stickers that are used as spacers when stacking the redwood decking for drying. Redwood decking is not the only wood product to have a low energy consumption profile. Douglas-fir (*Pseudotsuga menziesii*) used for structural lumber is usually not kiln-dried. Thus, the energy profile for green Douglas-fir looks similar to that of redwood decking (Milota et al 2005; Puettmann and Wilson 2005).

Energy comparison. Most wood products consume more energy per cubic meter of final product during the manufacturing process than does redwood decking. In the Pacific Northwest (PNW) of the US, the cumulative allocated energy consumption for manufacturing 1 m³ of planed dry softwood lumber is 3.364 GJ/m³ of which 47% comes from wood fuel (Milota et al 2005). The values listed in Milota et al (2005) and Puettmann et al (2010b) use mass allocation to estimate energy consumption. This study allocates all primary energy to the redwood decking and none to the residues. Primary energy is defined as the energy embodied in the original resources such as natural gas and coal found in the earth before conversion. However, the cumulative energy used to manufacture redwood decking is 1.34 GJ/m³, which is only 40% of the energy used to produce softwood lumber in the PNW (Milota et al 2005). The low cumulative energy for redwood decking can be attributed largely to the minimal use of kiln-drying, which is the most energy-intensive part of producing dry lumber. Assigning primary energy consumption and environmental outputs to both the

primary product and its associated wood residues (ie mass allocation) would further decrease the energy values for redwood lumber.

Mass-allocation approach. As indicated in Table 7, allocating by mass to both the product and wood residues lowers the cumulative energy consumption substantially. Cumulative energy dropped to 0.951 GJ/m³ from 1.34 GJ/m³, about a 29% decrease. This decrease was largely driven by allocating electrical consumption between rough green decking and the wood residues generated during the sawing process. Rough green decking made up about 54% of the incoming log (including bark) with the remaining log converted into chips, sawdust, shavings, bark, and hog fuel. This mass allocation decreased coal consumption from 11.5 to 7.7 kg/m³. Hydro and nuclear power use decreased similarly. Coal, hydro, and uranium were only consumed to generate grid electricity, unlike wood fuel and natural gas, which were used on-site for boiler fuel.

Fresh Water Consumption

Fresh water was used primarily for spraying the logs in the log yard and for cooling the saw, with most of the water being recycled back into holding ponds for reuse. Three of the four surveyed redwood mills reported that they sprinkle their logs with water to maintain freshness and to prevent the logs from checking and splitting in the hot summer sun. Fresh water consumption

Table 7. Cumulative energy consumed during production of planed (surfaced) redwood decking using cumulative, mass-allocated gate-to-gate life cycle inventory values.^a

Fuel ^b	kg/m ³	MJ/m ³	Percent
Wood fuel/wood waste	10.3	216	22.7
Coal ^c	7.7	201	21.1
Natural gas ^c	5.66	308	32.4
Crude oil ^c	1.99	90	9.5
Hydro	0	57	6.0
Uranium ^c	0.000190	73	7.6
Energy, unspecified	0	6	0.6
Total	—	951	100

^a Includes fuel used for electricity production (allocated).
^b Values are allocated and cumulative and based on higher heating values (Table 6).
^c Materials as they exist in nature and have neither emissions nor energy consumption associated with them.

rates were based on responses obtained from all four sawmills. Surface and ground water consumption were found to average 187 and 22 L/m³ of planed dry redwood decking with 86% of the water being recycled (Table 3).

Resource Transportation

Redwood logs are transported from the forest with diesel-powered logging trucks. Logging trucks collect the redwood logs (127% MC) at the forest landing and transport the logs an average of 54 km to the sawmill log yard. No other material transported to the mill was reported to be more than 1% of the mass of the incoming logs. Therefore, resource transport was determined to include only log transport for the purposes of

any calculations. Energy impacts for the resource transport module have been reported separately. The cumulative energy consumption during the log transport phase was calculated to be 111 MJ/m³, and this value must be added to the combination of forest management activities and lumber production to calculate the cradle-to-gate cumulative energy.

Environmental Emission Profile

Gate-to-gate. Table 8 lists the cumulative environmental outputs generated during the production of 1 m³ of redwood decking for the on-site (mill only) and base-case (no-allocation) system boundaries (Fig 2) along with the cumulative outputs using a mass-allocation approach.

Table 8. Environmental outputs for manufacturing one cubic meter of dry planed redwood decking.

Substance	On-site ^a (kg/m ³)	Cumulative ^b (kg/m ³)	Cumulative ^c (kg/m ³)
Water effluents			
BOD5 (biological oxygen demand)	1.41E-01	2.09E-01	1.91E-01
Chloride	0.00	1.74	1.15
COD (chemical oxygen demand)	5.64E-04	2.17E-02	1.42E-02
DOC (dissolved organic carbon)	0.00E+00	2.16E-03	1.39E-03
Oils, unspecified	1.65E-06	3.10E-03	2.01E-03
Suspended solids, unspecified	8.15E-05	5.15E-02	3.28E-02
Industrial waste ^d			
Waste in inert landfill	0.267	0.267	0.261
Waste to recycling	0.222	0.222	0.217
Solid waste ^e	0.081	0.111	0.103
Air emissions			
Acetaldehyde	9.30E-05	1.19E-04	9.84E-05
Acrolein	2.94E-04	4.05E-04	3.76E-04
Benzene	3.44E-04	4.95E-04	4.38E-04
Carbon monoxide	0.122	0.196	0.143
Carbon dioxide, biogenic	14.1	20.9	19.1
Carbon dioxide, fossil	7.6	52.9	34.9
Formaldehyde	3.70E-04	5.08E-04	4.51E-04
Mercury	2.55E-07	8.28E-07	6.45E-07
Methane	0.002	0.171	0.115
Nitrous oxide	2.08E-05	5.36E-04	3.57E-04
Nonmethane VOC, ^f unspecified origin	0.00E+00	1.10E-02	6.87E-03
Particulates, >2.5 and <10 µm	4.01E-02	5.64E-02	5.05E-02
Particulates, unspecified	0.00E+00	1.54E-02	1.01E-02
Phenol	0.00E+00	3.79E-07	2.02E-07
Sulfur dioxide	0.00E+00	0.352	0.237
VOC	4.29E-02	5.13E-02	4.61E-02

^a Environmental outputs released on-site from fuel burned on-site (no allocation).

^b All environmental outputs assigned to the final product, dry planed redwood decking (no allocation).

^c Environmental outputs assigned to the final product by mass allocation.

^d Includes solid materials not incorporated into the product or coproducts but left the system boundary.

^e Solid waste was boiler ash from burning wood. Wood ash is typically used as soil amendment or is landfilled.

^f VOC, volatile organic compound.

For the base-case cumulative system boundary, biogenic CO₂ and fossil CO₂ emissions were 20.9 and 52.9 kg/m³, respectively. Fossil CO₂ for the base-case cumulative case was about seven times (52.9/7.6) the fossil CO₂ emitted on-site because the only sources of on-site fossil CO₂ came from the equipment used at the mill facility (eg front-end loaders and forklifts). Also, mercury emissions to the air dropped by a factor of 86 (0.171/0.002) because coal grid electricity, the primary source of mercury emissions, occurred outside of the mill.

Coal power plants are major emitters of mercury in the US (Pirrone et al 2010). The amount of sulfur dioxide emitted is similar to mercury, because its emissions correlate to coal power production. Biogenic (biomass-based) CO₂ emitted from mill operations is about 67% of the cumulative total with the remaining 33% coming from wood fuel that is burned off-site to provide thermal energy for the dry stickers that were used as spacers between the decking during the drying process and from steam produced from wood fuel that was piped into the sawmill from outside the system boundary. The allocation of biogenic CO₂ emissions was approximately equal between the stickers and the piped

steam, mainly because kiln-drying the stickers requires substantial amounts of energy. Solid waste (wood boiler ash), such as biogenic CO₂, is generated during the consumption of wood fuel during the manufacture of redwood decking.

There is only a slight variation in biogenic CO₂ emissions between the no-allocation and mass-allocation approaches. This slight variation occurs because most biogenic CO₂ is released during the drying process from burning wood fuel on-site for steam production (ie thermal energy), which happens after the log breakdown into decking and its associated green wood residues.

Unit processes. Table 9 portrays the air emission profiles for each unit process. Air emissions, especially carbon emissions, are of primary importance to many “green building” stakeholders because carbon emissions are tied to energy consumption and global warming. Therefore, decreasing energy consumption during the manufacture of building materials would aid in decreasing the overall environmental impact of the building. As expected, the kiln-drying process released the most biogenic CO₂ emissions, 17.6 kg/m³ of the total 20.9 kg/m³. This can be attributed to the fact that wood fuel was burned

Table 9. Air emission profile by individual unit processes per cubic meter of dry planed redwood decking using cumulative gate-to-gate life cycle inventory values.^a

Substances	Log yard (kg/m ³)	Sawing (kg/m ³)	Drying (kg/m ³)	Planing (kg/m ³)	Total (kg/m ³)
Acetaldehyde	2.60E-05	1.37E-05	7.63E-05	2.67E-06	1.19E-04
Acrolein	3.16E-06	4.26E-05	3.59E-04	5.90E-07	4.05E-04
Benzene	3.28E-05	6.97E-05	3.82E-04	1.01E-05	4.95E-04
Carbon monoxide	0.071	0.038	0.065	0.021	0.196
Carbon dioxide, biogenic	0.0	3.0	17.6	0.3	20.9
Carbon dioxide, fossil	6.7	30.7	5.9	9.5	52.9
Formaldehyde	4.05E-05	6.06E-05	3.99E-04	7.24E-06	5.08E-04
Mercury	1.16E-08	3.56E-07	3.65E-07	9.58E-08	8.28E-07
Methane	0.011	0.105	0.023	0.032	0.171
Nitrous oxide	2.02E-05	3.51E-04	5.63E-05	1.09E-04	5.36E-04
Nonmethane VOC, ^b unspecified	4.57E-03	4.01E-03	7.64E-04	1.63E-03	1.10E-02
Particulates, >2.5 and <10 µm	3.35E-03	7.04E-03	4.53E-02	7.12E-04	5.64E-02
Particulates, unspecified	7.52E-04	1.03E-02	1.52E-03	2.89E-03	1.54E-02
Phenol	1.86E-10	3.75E-07	1.17E-09	2.27E-09	3.79E-07
Sulfur dioxide	0.007	0.231	0.043	0.070	0.352
VOC	3.28E-03	6.00E-03	1.31E-03	1.93E-03	1.25E-02

^a Includes fuel used for electricity production (unallocated).

^b VOC, volatile organic compound.

in the boilers to supply heat for kiln-drying the redwood decking. In addition, the sawing process consumed the most electricity and generated the most fossil CO₂ emissions, 30.7 kg/m³ of the total 52.9 kg/m³. Other emissions, including methane, mercury, and sulfur dioxide, are linked to grid electricity consumption because coal burning makes up 22.1% of the composite grid (Table 2). Sawing released some biogenic CO₂ (3.0 kg/m³) because the wood energy consumed during production of the stickers that are used to space the decking during drying was allocated to the sawing process. In this study, the redwood decking was considered to be stickered before going to the drying process (both air-drying and kiln-drying).

An air emission comparison shows that redwood decking generates less greenhouse gas (GHG) emissions than most other US softwood products. For example, Puettmann et al (2010b) reported fossil and biogenic CO₂ emissions for Inland West softwood lumber of 71.7 and 116 kg/m³, respectively. In addition, Bergman and Bowe (2010) reported fossil and biogenic CO₂ emissions for NE/NC softwood lumber of 65.1 and 187 kg/m³, respectively. The NE/NC included log production emissions, whereas the Inland West estimates did not. Regardless, the reported values show the higher impacts of the drying process if the wood product is mostly kiln-dried instead of air-dried.

The distinction among sources of CO₂ emissions is made because GWP is reported in kg CO₂ equivalents using the default TRACI impact assessment method (Bare 2011; Brandão and Levasseur 2011). This default method does not

count the CO₂ emissions released during the combustion of woody biomass during production. Other emissions associated with wood combustion such as methane or nitrogen oxides, however, do contribute to and are included in the GWP impact category. This approach to reporting the impacts of biogenic CO₂ is consistent with the Intergovernmental Panel for Climate Change (IPCC 2006) inventory reporting framework in that there is no assumption that biomass combustion is carbon-neutral but that net carbon emissions from biomass combustion are accounted for under the Land Use Change and Forestry Sector and are therefore ignored in energy emissions reporting for the product LCA to prevent double counting.

Impact Categories and Impact Measures

With the LCI flows from the individual unit processes for the no-allocation approach, six environmental impact categories were estimated using TRACI 2.1 (PRé Consultants 2014). Tables 10 and 11 show that GWP, AP, and RE were highest for the sawing process whereas ODP and EP were highest for the drying process. Most fossil CO₂ was generated during the sawing process from burning coal and natural gas for grid electricity, which translated into a higher GWP. AP followed GWP because of the fossil fuel usage for electricity. High RE impacts can be attributed to refining natural gas. For the drying process, burning wood for thermal energy and refining diesel for fuel contributed the most to ODP, whereas burning diesel and use of coal for electricity production on the grid contributed the most to EP. In addition, the log yard

Table 10. Environmental impacts by individual unit processes by values per cubic meter of dry planed redwood decking using cumulative gate-to-gate LCI values.^a

Impact categories	Unit	Log yard	Sawing	Drying	Planing	Total
Ozone depletion potential	kg CFC-11 eq	5.78E-08	5.78E-07	2.97E-06	7.97E-08	3.69E-06
Global warming potential	kg CO ₂ eq	6.99	33.5	6.49	10.4	57.4
Smog potential	kg O ₃ eq	2.80	2.04	1.01	0.76	6.61
Acidification potential	kg SO ₂ eq	0.086	0.286	0.072	0.090	0.534
Eutrophication potential	kg N eq	0.0055	0.006	0.0107	0.0017	0.0234
Respiratory effects	kg PM2.5 eq	0.0021	0.0165	0.0133	0.0047	0.0365

^a Includes fuel used for electricity production (unallocated).

Table 11. Environmental impacts by individual unit processes by percentage per cubic meter of dry planed redwood decking using cumulative gate-to-gate life cycle inventory values.^a

Impact categories	Log yard (%)	Sawing (%)	Drying (%)	Planing (%)	Total (%)
Ozone depletion potential	1.6	15.7	80.6	2.2	100
Global warming potential	12.2	58.4	11.3	18.1	100
Smog depletion potential	42.4	30.8	15.3	11.4	100
Acidification potential	16.2	53.5	13.5	16.9	100
Eutrophication potential	23.3	23.9	45.6	7.1	100
Respiratory effects	5.7	45.1	36.4	12.9	100

^a Includes fuel used for electricity production (unallocated).

process contributed the most to SP because consumption of diesel burned in log yard equipment is greater than in any other unit process. Mass-allocation impacts were not shown but were lower, as expected (about 38.4% less than the no-allocation impacts on average for the six environmental impact categories).

Carbon Balance

The carbon balance associated with the production of redwood decking was calculated by estimating the amount of carbon found in wood and bark using a carbon content of 53% and allocating it to the wood material uses shown in Table 1. Table 12 shows the carbon balance for 1 m³ of dry planed redwood decking and all coproducts. Seventy-one percent of redwood sawmill residue is used for generating electricity in off-site wood power plants to supply power to the electrical grid. If the wood residue was not available, nonrenewable resources (eg coal and natural gas) would be required to make up the difference. Additional carbon benefits accrued from using the wood residue to offset power production, but this energy impact was not considered in the

analysis. Nearly 53% of the carbon contained in the redwood logs (including the bark) remains stored in the redwood decking. The carbon stored in the final product (201 kg) outweighed all wood residue generated and is a long-term carbon benefit because the carbon is sequestered within the product for as long as it remains in service. The amount of carbon stored in redwood decking if emitted into the atmosphere as CO₂ would be approximately 10 times the total CO₂ emissions released during its manufacturing.

CONCLUSIONS

Wood products store carbon while in service. The amount of carbon stored in redwood decking if emitted into the atmosphere as CO₂ is approximately 10 times greater than the total CO₂ emissions released during manufacturing. Low carbon manufacturing emissions and the carbon storage inherent in redwood decking during its service life are positive environmental attributes that should be strongly considered when selecting a decking product.

During the entire life cycle of wood products, the manufacturing stage typically consumes the

Table 12. Carbon balance of redwood decking in the manufacturing stage.

Carbon flows per cubic meter of dry planed redwood decking made	kg CO ₂ -eq/m ³	Percentage (%)
Carbon stored in incoming log (carbon uptake)	−1260	−90.1
Carbon stored in incoming bark (carbon uptake)	−138	−9.9
Mill residue combusted on-site for on-site thermal energy	16	1.1
Mill residue leaving site and combusted for electricity (71%)	457	32.7
Mill residue leaving site and decayed as soil amendment/mulch (25%)	161	11.5
Mill residue leaving site and made into new wood product (4%)	26	1.8
Carbon stored in final product	738	52.8
Balance	0	0

most energy and releases the highest GHG emissions because of the electricity used for sawing and the energy-intensive nature of the kiln-drying process. The release of GHG emissions is especially high when fossil fuels are consumed to generate steam (ie thermal energy) for the dry kilns. Wood product manufacturing in general typically consumes far more fossil and wood fuel than was reported for redwood decking per functional unit of 1 m³. This disparity between products arises because most wood manufacturing facilities, including those processing hardwoods, kiln-dry their lumber while it is still green. Air-drying redwood decking prior to kiln-drying dramatically lowers energy consumption during the manufacturing process and thus substantially lowers GHG emissions.

Air-drying also affects variation in results between LCA allocation methods. The difference between no-allocation and mass-allocation methods has only a small impact on biogenic CO₂ emissions because most coproducts (ie wood residues) were removed during the sawing process, at which point almost 70% of the energy has already been expended. However, biogenic CO₂ is just one of many environmental outputs that need to be considered.

Overall, the selection of the allocation approach does affect most of the environmental outputs assigned to the final product. Mass allocation for wood products results in lower environmental burdens being assigned to the final products than a no-allocation approach. This occurs for redwood decking because although it makes up about 53% of the volume of the incoming log, the final product carries the entire environmental burden in a no-allocation approach. Therefore, conducting both a mass- and no-allocation approach would show the differences if any in the environmental outputs.

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