Assessment of Carbon Footprinting in the Wood Industry

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Abstract The management of natural resources is a subject that often arises when sustainable development is considered. Wood is a renewable, biological raw material used in numerous applications and is therefore growing in importance for sustainable development efforts. This chapter presents the applicability of carbon footprinting in the wood industry by comparing the carbon footprint of 14 primary wood products: air-dried and kiln-dried softwood and hardwood sawn timber, hard fiberboard, glued laminated timber for indoor and outdoor use, medium-density fiber board, oriented strand board, particleboard for indoor and outdoor use, plywood for indoor and outdoor use, and wood pellets. Furthermore, the use of timber products for the purposes of carbon storage and the effect of allocation methods on carbon footprinting are discussed. Additionally, the European policy strategies and actions directly impacting the forest products industry are discussed in relation to primary wood products. Also, wood as a building material and its placement in green building programs are considered.

Keywords Allocation · Carbon footprint · Carbon storage · Primary wood products · Sawn wood · Wood composites

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1 Introduction

The European forest-based sector makes important contributions to Europe's sustainable, knowledge-based society by securing a renewable material supply and providing low-environmental-impact energy solutions. Wood use as a multifunctional material is expected to increase significantly in carbon-negative housing and furnishings, weight-efficient packaging and transportation, and heat and energy production, as well as being a raw material source for chemical production. Despite remarkable self-renewing capabilities, forests and their products cannot adequately provide enough raw materials for the growing global resource demands without significant improvements to resource utilization efficiency. The extension of material lifetimes by reasonable reuse and recycling loops has been identified as one of the most effective strategies for reducing pressure on resources. Furthermore, the European Union has set a goal of becoming a recycling society. The latest waste directive from 2008 (Directive 2008) contains an article requiring expanded reuse and recycling of materials, in addition to products. Amongst other things, it requires member countries to proceed with actions necessary to expand material and product recycling. To fulfill these requirements, simple recycling should be included in product design.

In the wood products sector, the waste hierarchy is presently underdeveloped and largely ignores the preferred option of maximizing the carbon storage potential of wooden materials. Reuse in solid form, with subsequent cycling of reclaimed wood in as many steps of material cascades as possible, is the best way to achieve the maximum carbon storage potential. Furthermore, the maintenance of natural resources is a subject that often appears when sustainable development is considered. In addition, as the world population increases and more nations develop economically, the strain on resources will continue to increase. As economic development and environmental pressures are linked, conserving both energy and resources has become paramount (Hill 2011).

In engineering, sustainable design is a design ideology that harbors the notion of sustainable human and societal development. However, every individual will approach the issue of sustainability in a different manner depending upon various factors, such as sustainability goals, background, awareness, and economic conditions. Resource sustainability can be defined as the development of opportunities for future generations to gain value from natural resources. One of the key aspects affecting efforts to become a sustainable society is construction. Sustainable construction principles are derived from ecological goals, which ideally produce buildings with no environmental impacts, a closed material loop, and full integration into the landscape after the service life of the structure is over. "Green buildings" represent the current efforts to achieve the sustainable construction ideal. According to the U.S. Environmental Protection Agency (EPA), Green Building is the "practice of creating structures and using processes that are environmentally responsible and resource-efficient throughout a building's life-cycle from siting to design, construction, operation, maintenance, renovation, and deconstruction." *Green building* is an ever-evolving, dynamic, and imprecise term; as technology evolves and new materials are developed, sustainability targets and the standards for what defines a green building also evolve. Furthermore, the role of life cycle assessment (LCA) in assessing the sustainability claims of green buildings and building materials is being introduced worldwide.

In this chapter, wood as building material, including the European Policy strategies and actions directly impacting the forest products industry, are discussed in relation to primary wood products. In total, 14 primary wood products are presented and their carbon footprints compared. Furthermore, the use of timber products for the purposes of carbon storage and allocation methods on carbon footprinting are discussed.

1.1 Wood as a Building Material

Wood is the most important renewable material resource. The utilization of wood in all aspects of human existence appears to be the most effective way to optimize the use of resources and to reduce the environmental impact associated with mankind's activities. Wood as a renewable biological raw material, used in numerous applications, is therefore gaining in importance.

Wood is the material of choice in many countries for residential and light commercial construction. In the United States, 90 % of the residential buildings are of wood-frame construction. Japan is not far behind. Wood use for construction, furniture, and other products aligns well with criteria for green building materials. Wood is a renewable resource, manufactured in nature using a large quantity of solar energy. Hence, no fossil fuels are required for the 'manufacturing' of wood. However, subsequently, processing of the wood will require an energy input that is often derived from fossil resources.

When waste wood is burned, it provides an independent source of energy. Energy from waste wood is converted solar energy (this is the embedded energy content), which has been stored in the wood since harvesting. Furthermore, the embodied energy associated with wood products is invariably lower when compared to other building materials, although this depends upon the number of subsequent processing steps for the wood product. For example, particleboard has a higher embodied energy than solid wood. At the end of the life of a wood product, it is possible to incinerate and use the embedded (i.e. trapped solar) energy, which is usually greater than the embodied energy. Consequently, when the carbon footprint of wood is calculated, the result is often a net benefit in that the atmospheric carbon stored is greater than that released to the atmosphere due to subsequent processing. Wood can be recycled, but not in the extensive manner of materials such as metals and glass. In most situations, the wood is downcycled to lower performance products. The production of wood is generally nonpolluting at all stages, although there have been instances in the past with polluted sites from chemical preservation processes (Buchanan 2006, 2010).

Another reason for building with wood is to increase the pool of carbon stored in wood and wood products. This is very important from a climate change standpoint. Green building programs often do not give proper credit to wood and its low embodied energy/carbon storage potential (Bowyer 2008). As a result, architects, builders, and contractors often overlook wood products. Within the green building sector, the wood industry must innovate and try to improve their market by creating a demand for new structural products.

Sustainability is increasingly becoming a key consideration of building practitioners, policy makers, and industry because the world has the aspiration of moving towards zero-energy construction. When buildings have net-zero energy consumption, the contribution of embodied energy and the associated greenhouse gas emissions become important. A zero-energy house can be built with different materials and construction methods that create different cumulative carbon footprints. Wood products can have a very low or negative carbon footprint. Therefore, the utilization of wood—the most important renewable material—in all aspects of human life appears to be the most effective way to optimize the use of resources and to reduce the environmental impact associated with mankind's activities.

Typically, the use of wood products results in lower greenhouse gas (GHG) emissions into the atmosphere than competing products and thus a lower overall environmental impact. However, to achieve sustainable development, certain criteria within a framework of economic, environmental, and social systems must be followed. It is important to note that only if wood is used effectively—through the whole value chain, from forest management and multiple use of forest resources through new wood and fiber-based materials, new processing technologies, and new end-use concepts, such as in the area of construction—can this lead to truly sustainable development. Therefore, research, development, and innovation related to "green" buildings should be informed through LCA analysis in all product stages, from primary processing, to use, through to disposal. Furthermore, research and development efforts should integrate knowledge and experience from various disciplines, engaging scientists from areas such as engineering, material science, forestry, environmental science, architecture, marketing, and business. These activities should be oriented towards new product development from renewable materials and utilization of the entire wood value chain, engineering solutions, and the cradle-to-cradle concept.

1.2 European Policy and Primary Wood Products

European policy is affecting and, indeed, directing current research, development, and marketing in the EU. Many policy strategies and actions directly affect the forest products industry. The main policies with direct impacts on the forest-based sector are the EU Sustainable Development Strategy (SDS, European Commission 2009), which was published in 2006 and reviewed in 2009; the EU Roadmap 2050 (European Commission 2011); and the recycling society directive (Directive 2008/

98/EC, European Parliament Council 2008). Additionally, with the support of the EU Commission, industry stakeholders created the Forest-based Sector Technology Platform (FTP). This group produced FTP Vision 2030 (Forest-based Sector Technology Platform 2013a, b), which is a strategy guide for the forest-based sector to help achieve the EU's goals of sustainable, inclusive growth.

1.2.1 Sustainable Development Strategy

The Sustainable Development Strategy (SDS) sets out a single, coherent strategy on how the EU will more effectively live up to its long-standing commitment to meet the challenges of sustainable development. It recognizes the need to gradually change the current unsustainable consumption and production patterns and move towards a more integrated approach to policy-making. It reaffirms the need for global solidarity and recognizes the importance of strengthening our work with partners outside the EU, including rapidly developing countries, which are expected to significantly impact global sustainable development. The overall intent of the SDS is to identify and develop actions to enable the EU to achieve continuous long-term improvement of quality of life. Specifically, the SDS calls for the creation of sustainable communities that are able to manage and use resources efficiently, tap the ecological and social innovation potential of the economy, and ultimately enjoy prosperity, environmental protection, and social cohesion.

1.2.2 Roadmap 2050

The Roadmap 2050 project mission is to provide a practical, independent, and objective analysis of pathways to achieve a low-carbon economy in Europe, which promotes energy security as well as the environmental and economic goals of the European Union. The Roadmap 2050 project is an initiative of the European Climate Foundation (ECF) and has been developed by a consortium of experts funded by the ECF. Roadmap 2050 breaks new ground by outlining plausible ways to achieve an 80 % reduction in greenhouse gas emissions from a broad European perspective, based on the best available facts elicited from industry members and academia; it was developed by a team of recognized experts rigorously applying established industry standards. Roadmap 2050 determines five priorities that must be established between 2010 and 2015 in order for Europe to progress towards implementation of an 80 % reduction target for greenhouse gas emissions by 2050:

(1) Energy efficiency (through aggressive energy-efficiency measures in buildings, industry, transport, power generation, agriculture, etc.)
(2) Low-carbon technology (development and deployment of offshore wind, biomass, electric vehicles, fuel cells, integrated heat pump and thermal storage systems, and networked high-voltage/direct-current technologies, including adoption of common standards, etc.)

(3) Advanced electricity grids and integrated market operation (i.e., an increase in regional integration and interconnection of electricity markets; effective transmission and distribution regulation, the development of regionally integrated approaches to planning and operation of grids and markets)
(4) Fuel shift in transport and buildings (fossil fuels are replaced in the building and transport sectors by decarbonized electricity and low CO_2 fuels, such as second-generation biofuels)
(5) Markets (a massive and sustained mobilization of investment into commercial low-carbon technologies)

1.2.3 European Recycling Society

The waste directive from 2008 (Directive 2008/98/EC) contains an article for the reuse and recycling of all consumer and industrial materials. Among other things, it requires member countries to proceed with the actions necessary to recycle materials as well as products. To fulfill these requirements, products should be developed with simple recycling as a product feature. In the wood products sector, the waste hierarchy is presently underdeveloped and largely ignores the EU's preferred option of maximizing the carbon storage potential of wooden materials by their reuse in solid form, with subsequent down-cycling of reclaimed wood in as many steps of a material cascade as possible (Leek 2010). At present in Europe, recovered wood volumes total approximately 55.4 million m^3. One third of this volume is burned for energy production, and one third is down-cycled and used for the production of particleboard, thus losing the favorable material properties of solid wood. The remaining (and largest) fraction of waste wood (20.4 million m^3) is not used at all at the moment in the EU27 and is landfilled (Leek 2010). However, this ignores the environmentally preferred option to maintain wood materials at a maximum quality level by reuse in solid form, therefore extending the carbon storage duration. This shortfall presents an opportunity for the forest-based sector to become a leader in achieving the European Commission's ambitious target of reduced CO_2 emissions with innovative production technologies, reduced energy consumption, increased wood product recycling, and the reuse and refining of side streams (e.g., manufacturing byproducts, such as sawdust as planer shavings).

1.2.4 Forest-based Sector Technology Platform

The FTP Vision 2030 supports the EU's Europe 2020 strategy for smart, sustainable and inclusive growth and identifies themes to address the 'grand societal challenges', as described by the European Commission, and drive towards the development of a bio-based society.

FTP Vision 2030 targets are grouped under four strategic themes that are essential for building a new forest-based sector in Europe by 2030. One of the themes, 'The forest-based sector in a bio-based society', is cross-cutting. The other three respond to a specific set of vision targets. These three strategic themes and specific vision targets are responsible management of forest resources, creating industrial leadership, and fulfilling consumer needs.

The European forest-based sector is directly affected by climate change, competition for wood resources, changing consumer demands, increasing competition, and the growing complexity of manufacturing processes. Traditional forest-based industries have used non-food renewable natural resources in a sustainable and responsible way; this growing and evolving sector now has great potential as a leader for a sustainable European bioeconomy in the future. The EU and the European forest-based sector can together contribute to achieving FTP Vision 2030 by implementing the revised Strategic Research and Innovation Agenda 2020 (SRA, Forest-based sector Technology Platform 2013a, b).

The SRA identifies strategic cross-sector alliances with other industries, investors, and public institutions as a vital role in the process. Open innovation concepts and methods that reach beyond the sector's usual technology providers, especially in the key area of enabling technologies (e.g., information and communication technologies, electronics, nanotechnology, sensor technologies and monitoring systems, advanced materials and manufacturing systems, industrial biotechnology) must be established to maintain the sector's competitive edge and accelerate development towards a bio-based society.

2 Primary Wood Products

Primary wood products are those produced directly from forest trees, including pulp, lumber, and wood composites. Wood composites are a family of materials that contain wood either in whole or fiber form as the basic constituent (Bodig and Jayne 1982). A binding adhesive of either natural or synthetic origin interconnects the wood or fiber elements. Composites are normally thought of as two-phase systems (i.e., particles interconnected by a binder); wood composites, however, are multiphase systems including moisture, voids, and additives. Furthermore, Berglund and Rowell (2005) defined a composite as two or more elements held together by a matrix. By this definition, what we call "solid wood" is also a composite. Solid wood is a three-dimensional composite composed of cellulose and hemicelluloses (with smaller amounts of inorganics and extractives), which are held together by a lignin matrix. The advantages of developing wood composites are to use smaller trees, to use waste wood from other processing, to remove defects, to create more uniform components, to develop composites that are stronger than the original solid wood, and to be able to make composites of different shapes.

Sawn softwood timber is most commonly used directly in structural applications or as a component of engineered products (e.g., glulams). Planed (also surfaced or dressed) timber has been machined to have a smooth, uniform surface and ensures proper sizing. Air-dried timber has been dried without mechanical aid, whereas kiln-dried timber has been dried with mechanical aid, often using co-generated electricity or natural gas as an energy source to provide heat and maintain regular air flow.

Conventional wood composites fall into five main categories based on the physical configuration of the wood: plywood, oriented strand board, particleboard, hardboard, and fiber board (Youngquist 1999). The performance of composites can be tailored to the end-use application of a product by optimally arranging the physical configuration of the wood, adjusting the density, varying the resin type and amount, and incorporating additives to increase water or fire resistance or to resist specific environmental conditions.

Because wood composites cover a wide field, it is hard to precisely define the term. Below, the description of various primary wood-based products, with accompanying carbon footprints presented in the following chapter, is summarized and simplified from Suchsland (2004) and descriptions given by Forest Products Laboratory (2010).

Hard fiberboard (also known as hardboard or high-density fiberboard [HDF]) is most often used for indoor, nonstructural applications, such as in furniture. This product is made by breaking wood (most often residues from other manufacturing processes) down to small fibers, then mixing the fibers with resin and wax to form mats that are compressed with pressure and heat. Hard fiberboard is very dense, typically more than 800 kg m^{-3}.

Glued laminated timbers are structural composite beams used to support large loads in building construction. Sawn timber, selected for stress-related mechanical properties, are glued and arranged in layers (with the high-grade timber in the outer layers and low-grade timber in the inner layers) with the grain direction parallel to the length of the timber. The size of the resulting glued laminated timbers may vary greatly, allowing the beams to be used as needed for a specific application. Glued laminated timbers for indoor use may use adhesives that are less resistant to the effects of the outdoor environment (e.g., relative humidity and temperature), while glued laminated timbers for outdoor use must use adhesives that are more resistant to changes in the outdoor environment.

Medium density fiberboard (MDF) is most often used for indoor, nonstructural applications, such as in furniture. This product is made by breaking wood (most often residues from other manufacturing processes) down to small fibers, then mixing the fibers with resin and wax to form mats that are compressed with pressure and heat. MDF density varies between 600 and 800 kg m^{-3}.

Oriented strand board (OSB) is a structural panel product most often used for roof, wall, and floor sheathing in construction. The product is made of usually made of three or more layers with strands in each layer oriented in alternating directions (i.e., parallel to the length of the panel or perpendicular to it). Water-resistant adhesives are used for OSB. The strands in the outer layer are oriented with the grain direction parallel to the length of the panel. The strands used are typically about three times longer than they are wide.

Particleboard is constructed by reducing wood product manufacturing residues (e.g., planer shavings, sawdust) and recycled wood products to small particles. Particle sizes often vary across the thickness of the board, with smaller particles in the outer layers and larger particles in the core layer. Particleboard is most commonly used for indoor uses, such as furniture, and has a density range of approximately 600–800 kg m^{-3}.

Plywood is made from thin layers of wood, which has been peeled from a log on a rotary lathe. These thin veneers are then combined in three or more (usually an odd number) of layers in alternating grain directions. The outer layers are aligned with the grain direction parallel to the length of the panel. Plywood for indoor applications may use an adhesive that is less water-resistant than plywood for outdoor use. In indoor applications, plywood is often used in furniture. Plywood for outdoor applications must use a water-resistant adhesive. Sheathing is the most common use of plywood in exterior applications.

Wood pellets are made by compressing wood residues from other manufacturing processes. Wood pellets are primarily used for industrial, commercial, and residential heating systems.

Wood-based composites have long been used as both decorative and structural components in the human environment. These materials extract the best properties of wood (and eliminate or minimize the defects) and combine them with other materials (adhesives, plastics, etc.) to create a wide variety of new products that meet market demands. In Europe, the most commonly produced wood based panels are particleboard and MDF. However, OSB, traditional plywood, insulation board, and hardboard are also important products. Other more recent products include laminated veneer lumber (LVL), light MDF (LDF), HDF, and cross-laminated timber (CLT). In the past years, technological innovations have advanced the field of wood-based panels. Most notably, hot pressing and the consequent viability of thermosetting resins have improved composites produced from particles and strands (particleboard, OSB), fibers (MDF, HDF) and veneers (plywood, LVL).

In spite of stronger regulations, the production of wood-based panels has recently experienced a dramatic, worldwide growth period. Europe and China each control more than 30 % of the worldwide capacity for wood-based panel production (Barbu and van Riet 2008). In Eastern Europe, new production is increasing, particularly in CIS and Turkey. In Western Europe, Germany is the main wood-based panel producer (25 %), followed by France and Poland (10 % each), then Italy and Spain (8 % each). Turkey has dramatically increased production and is now approaching Germany's capacity. Russia surpassed German production in 2011, but Germany may have latent capacity remaining from constricted production during the economic downturn (Forest-based Sector Technology Platform 2013a, b). Total European production was approximately 71 million m^3 in 2012, an increase of 14 % from 2002 (62 million m^3), but a decrease of 14 % from peak production in 2007 (81 million m^3) (Forest-based Sector Technology Platform 2013a, b). In Table 1, the European wood-based panel (excluding insulation boards), sawnwood, glulam, and wood pellets productions for 2012 are shown.

Table 1 European wood-based panel (WBP), sawnwood, glulam, and wood pellets production for 2012 (FAO 2013)

Product	Quantity (m^3)
Hardboard	4,408,653
MDF	11,852,683
Particleboard	45,243,727
Plywood[a]	3,204,944
OSB_a	3,917,153
Total WBP	68,627,160
Sawn hardwood	13,533,427
Sawn softwood	126,751,739
Total sawnwood	140,285,166
Glulam[b]	4,800,000
Wood pellets[c]	9,262,990

[a] These numbers are from FAOStat, which combines plywood and OSB into one category. It was estimated OSB was 55 % of the total, and traditional plywood was the remaining 45 %
[b] Glulam estimate derived from graph 12.3.1 in the report for 2010: http://www.unece.org/fileadmin/DAM/timber/docs/tc-sessions/tc-65/md/presentations/19Dory.pdf
[c] Wood pellet quantity estimated from the report (2010 value): http://www.bioenergytrade.org/downloads/t40-global-wood-pellet-market-study_final.pdf (executive summary, Fig. 1.5, p. 8)

2.1 Environmental Impact of Primary Wood Products

With regard to greenhouse gas emissions, wood is a better alternative than other materials. Werner and Richter (2007) reviewed the results of approximately 20 years of international research on the environmental impact of the life cycle of wood products used in the building sector compared to functionally equivalent products from other materials. The study concluded that fossil fuel consumption, potential contributions to the greenhouse effect, and quantities of solid waste tend to be minor for wood products compared to competing products. Impregnated wood products tend to be more critical than comparative products with respect to toxicological effects and/or photo-generated smog depending on the type of preservative. Although composite wood products such as particle board or fiberboard make use of a larger share of the wood of a tree compared to products out of solid wood, there is a high consumption of fossil energy associated with the production of fibers and particles/chips as well as with the production of glues, resins, etc. Furthermore, wood is causing less emissions of SO_2 and generates less waste compared to the alternative materials (Petersen and Solberg 2005). However, treated wood, adhesively bonded wood, and coated wood might have toxicological impacts on human health and ecosystems.

Richter (2001) provided a comparison of environmental assessment data of different wood adhesives. The interventions increase from the polymerization adhesives to the polycondensation types. Within the polycondensation resins, the energy demand and emissions of substances increase with increasing percentage of aromatic compounds in the resin formulations. Limited LCA data have been published so far for resins based on renewable resources or components (e.g. tannins, lignins, proteins). A study of the use of a lignin-based phenolic adhesive in combination with a laccase initiating system has been conducted by Gonzalez-Garcia et al. (2011). This concluded that there was a significant impact associated with the enzyme production.

Incineration of wood products at the end of life provides various environmental benefits. The use of woody biomass as feedstock for biofuels production avoids the food versus fuel debate, which makes it more attractive from the environmental perspective (Wang 2005). However, Rivela et al. (2006a, b) applied a multicriterial approach in order to define the most adequate use of wood wastes. Based on environmental, economical, and social considerations, the study concluded that the use of forest residues in particleboard manufacture is more sustainable than their use as fuel. Cascading through several life cycles prior to incineration is a better option.

In a sensitivity analysis of an LCA of MDF manufacture, it was found that the final transport of product and the electricity generation profile had a significant influence upon the results (Rivela et al. 2007). A study of MDF production in a Brazilian context showed that the use of heavy fuel in the manufacturing process (including forestry operations) was the hotspot in all impact categories except ecotoxicity (Silva et al. 2013). Benetto et al. (2009) conducted an LCA of OSB production with emphasis on evaluating the environmental impact associated with a new wood drying process that had reduced emissions of volatile organic compounds. The study concluded that the environmental gains resulting from the new drying process were largely negated by changes required in the adhesive formulation. This shows the need to consider the whole process when considering the environmental impact of production and not focusing on making improvements of one part of the production. The combination of an OSB production plant with a biorefinery for the production of acetic acid and methanol has been studied from an LCA perspective recently (Earles et al. 2011). Significant reductions in human toxicity potential and freshwater ecotoxicity potential were recorded for the combined plant compared to a conventional OSB production process.

However, a renewable origin does not necessarily equate to environmental friendliness or sustainable use (Lindholm et al. 2010). Hall and Scrase (1998) provided a literature review concerning greenhouse gas and energy balances of bioenergy. The LCA study revealed that results may differ due to the type and management of raw materials, conversion technologies, end-use technologies, system boundaries, and reference energy systems with which the bioenergy chain is compared. A comprehensive sustainability assessment of biofuels is urgently needed to assess the economic, social, and environmental impacts of biofuel production and consumption (Halog 2009). Lindholm et al. (2010) modeled and calculated the environmental performance from an LCA prospective of different procurement chains of forest energy in Sweden. One of the conclusions of the study was that uncertainties and use of specific local factors for indirect effects (e.g., land-use change and nitrogen-based soil emissions) may give rise to wide ranges of final results.

Cherubini and Strømman (2011) performed a review of the recent bioenergy LCA literature. They concluded that most LCAs found a significant net reduction in greenhouse gas emissions and fossil energy consumption when bioenergy replaces fossil energy. Cherubini et al. (2009) explained the determination of energy balance and greenhouse gas emissions from bioenergy. The initial use of biomass for products followed by use for energy, known as cascading, can further enhance greenhouse gas savings, given what will be increasingly scarce resources of biomass. It has been shown that the environmental footprint associated with particleboard production can be reduced by using increasing amounts of recycled wood (Saravia-Cortez et al. 2013).

The number of LCA studies of wood-based composites is relatively limited, geographically distributed, and uses of a variety of databases and impact assessment protocols. A comparison between different production processes is not possible given the availability of information. Thus, a comparison of different production methods using common calculation rules is clearly required.

3 Carbon Footprint of Primary Wood Products

Following the common LCA methodology (ISO 14044, 2006), the scope and goal of the study was to compare the environmental impact of different primary wood products. The carbon footprint was chosen as indicator of environmental impact. Carbon footprinting summarizes the amount of GHG emissions caused by a particular activity or entity; it is also referred to as global warming potential (GWP). It is measured in tons (or kilograms) of carbon dioxide equivalent (CO_2e).

The comparison included 14 primary wood products: air-dried and kiln-dried softwood and hardwood sawn timber, hard fiberboard, glued laminated timber for indoor and outdoor use, medium-density fiber board, oriented strand board, particleboard for indoor and outdoor use, plywood for indoor and outdoor use, and wood pellets. The environmental impact of primary wood products was analyzed by the cradle-to-gate method, an assessment of a partial product life cycle that extends from manufacture ('cradle') to the factory gate (i.e., before it is transported to the consumer). Because the use phase and disposal phase of a product is highly dependent on the user and consequently the assumption of the product life cycle, the performance in use and life span are needed; the use phase and disposal phase of the product were omitted.

The environmental burdens associated with each primary wood product were considered from raw material acquisition through the manufacture/processing stages, accounting for the production and use of fuels, electricity, and heat, as well as the impact of transportation and distribution for all stages of the product supply chain. The functional unit for the calculation was 1 m^3. Data of energy inputs, raw materials, products, co-products, waste, and releases to air, water, and soil and the

Table 2 Life cycle inventory for carbon footprint calculations: 1 m^3 of sawn timber, hardwood, raw, kiln dried, $u = 10$ %, at plant/RER U (Ecoinvent 2.0)

	Quantity	Unit
Materials/fuels		
Electricity, medium voltage, production UCTE, at grid/UCTE U	33	kWh
Hardwood, allocation correction, 1/RER U	−0.136	m^3
Sawn timber, hardwood, raw, plant-debarked, $u = 70$ %, at plant/RER U	1.14	m^3
Technical wood drying, infrastructure/RER/I U	0.0000609	p
Wood chips, from industry, hardwood, burned in furnace 300 kW/CH U	1300	MJ
Emissions to air		
Heat, waste	119	MJ

Table 3 Life cycle inventory for carbon footprint calculations: 1 m^3 of sawn timber, hardwood, raw, air dried, $u = 20$ %, at plant/RER U (Ecoinvent 2.0)

	Quantity	Unit
Resources		
Occupation, industrial area, vegetation (land)	0.85	m^2a
Transformation, from unknown (land)	0.0085	m^2
Transformation, to industrial area, vegetation (land)	0.0085	m^2
Materials/fuels		
Hardwood, allocation correction, 1/RER U	−0.136	m^3
Sawn timber, hardwood, raw, plant-debarked, $u = 70$ %, at plant/RER U	1.14	m^3

upstream life cycle impacts of input materials were not specifically analyzed for this project. Instead, sound secondary life cycle data were sourced from the Ecoinvent database 2.0 (2010). In Tables 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, the life cycle inventory (LCI) of input/output data for the carbon footprint calculations for selected 14 primary wood products are given. The data collected were modeled in SimaPro (2009).

Carbon footprints were calculated with the methodology detailed in IPCC 2001 GWP 100a V1.02 (Climate Change 2001). IPCC 2007 contains the climate change factors of IPCC with a timeframe of 100 years. IPCC characterization accounts for the direct global warming potential of air emissions (excluding CH_4). They do not include indirect formation of dinitrogen monoxide from nitrogen emissions; do not account for radiative forcing due to emissions of NOx, water, sulfate, etc., in the lower stratosphere and upper troposphere; do not consider the range of indirect effects given by the IPCC; and do not include indirect effects of CO emissions. Embodied emissions do not include any offset for carbon stored in the timber materials.

In Table 16 and Fig. 1, the carbon footprints of selected primary wood products are presented. The products with the lowest carbon footprints are air-dried sawn timber, followed closely by kiln-dried sawn timber. This is unsurprising because these products are processed less than wood-based composites and require no adhesives. Wood-based composite production requires additional energy inputs to process raw materials, manufacturing byproducts, and recycled wood into the

Table 4 Life cycle inventory for carbon footprint calculations: 1 m^3 of sawn timber, softwood, raw, air dried, u = 20 %, at plant/RER U (Ecoinvent 2.0)

	Quantity	Unit
Resources		
Occupation, industrial area, vegetation (land)	0.749	m^2a
Transformation, from unknown (land)	0.00749	m^2
Transformation, to industrial area, vegetation (land)	0.00749	m^2
Materials/fuels		
Sawn timber, softwood, raw, forest-debarked, $u = 70$ %, at plant/RER U	1.1	m^3
Softwood, allocation correction, 1/RER U	−0.099	m^3

Table 5 Life cycle inventory for carbon footprint calculations: 1 m^3 of sawn timber, softwood, planed, air dried, at plant/RER U (Ecoinvent 2.0)

	Quantity	Unit
Materials/fuels		
Electricity, medium voltage, production UCTE, at grid/UCTE U	30.789	kWh
Planing mill/RER/I U	0.000000792	P
Sawn timber, softwood, raw, air dried, $u = 20$ %, at plant/RER U	1.1385	m^3
Softwood, allocation correction, 1/RER U	−0.138	m^3
Emissions to air		
Heat, waste	110.88	MJ

Table 6 Life cycle inventory for carbon footprint calculations: 1 m^3 of fiberboard hard, at plant/RER U (Ecoinvent 2.0)

	Quantity	Unit
Resources		
Water, cooling, unspecified natural origin/m^3 (in water)	0.18	m^3
Materials/fuels		
Aluminum sulfate, powder, at plant/RER U	0.9	Kg
Sodium hydroxide, 50 % in H2O, production mix, at plant/RER U	0.1	Kg
Paraffin, at plant/RER U	4.14	Kg
Electricity, medium voltage, production UCTE, at grid/UCTE U	408	kWh
Natural gas, burned in industrial furnace >100 kW/RER U	4140	MJ
Phenolic resin, at plant/RER U	9	Kg
Transport, lorry >16t, fleet average/RER U	99.5	Tkm
Transport, freight, rail/RER U	205	tkm
Industrial residue wood, mix, hardwood, $u = 40$ %, at plant/RER U	0.418	m^3
Industrial residue wood, mix, softwood, $u = 40$ %, at plant/RER U	1.25	m^3
Industrial wood, hardwood, under bark, $u = 80$ %, at forest road/RER U	0.16	m^3
Industrial wood, softwood, under bark, $u = 140$ %, at forest road/RER U	0.489	m^3
Wooden board manufacturing plant, organic bonded boards/RER/I U	3.33E-08	p
Emissions to air		
Heat, waste	1470	MJ
Waste to treatment		
Treatment, fiberboard production effluent, to wastewater treatment, class 3/CH U	0.799	m^3

Table 7 Life cycle inventory for carbon footprint calculations: 1 m^3 of glued laminated timber, indoor use, at plant/RER U (Ecoinvent 2.0)

	Quantity	Unit
Materials/fuels		
Diesel, burned in building machine/GLO U	33.6	MJ
Electricity, medium voltage, production UCTE, at grid/UCTE U	129	kWh
Heat, light fuel oil, at industrial furnace 1 MW/RER U	23	MJ
Sawn timber, softwood, raw, air dried, u = 20 %, at plant/RER U	1.37	m^3
Softwood, allocation correction, 1/RER U	−0.0522	m^3
Transport, freight, rail/RER U	81.2	tkm
Transport, lorry >16t, fleet average/RER U	38.2	tkm
Urea formaldehyde resin, at plant/RER U	12	kg
Wood chips, from industry, softwood, burned in furnace 300 kW/CH U	2680	MJ
Wood chips, softwood, from industry, u = 40 %, at plant/RER U	−0.84751	m^3
Wooden board manufacturing plant, organic bonded boards/RER/I U	3.33E-08	p
Emissions to air		
Formaldehyde	0.012	Kg
Heat, waste	463	MJ
Waste to treatment		
Disposal, polyurethane, 0.2 % water, to municipal incineration/CH U	0.974	Kg

Table 8 Life cycle inventory for carbon footprint calculations: 1 m^3 of glued laminated timber, outdoor use, at plant/RER U (Ecoinvent 2.0)

	Quantity	Unit
Materials/fuels		
Diesel, burned in building machine/GLO U	33.6	MJ
Electricity, medium voltage, production UCTE, at grid/UCTE U	129	kWh
Heat, light fuel oil, at industrial furnace 1 MW/RER U	23	MJ
Melamine formaldehyde resin, at plant/RER U	12	Kg
Sawn timber, softwood, raw, air dried, u = 20 %, at plant/RER U	1.37	m^3
Softwood, allocation correction, 1/RER U	−0.0553	m^3
Transport, freight, rail/RER U	81.2	tkm
Transport, lorry >16t, fleet average/RER U	38.2	tkm
Wood chips, from industry, softwood, burned in furnace 300 kW/CH U	2660	MJ
Wood chips, softwood, from industry, u = 40 %, at plant/RER U	−0.84056	m^3
Wooden board manufacturing plant, organic bonded boards/RER/I U	3.33E-08	p
Emissions to air		
Formaldehyde	0.012	Kg
Heat, waste	463	MJ

desired form, as well as adhesives and other additives to form the composite matrices, which considerably increases the carbon footprint of these wood products. The highest carbon footprint among the compared products was plywood for outdoor use, followed by hard fiberboard and plywood for indoor use.

In Figs. 2, 3, 4, 5, 6, 7, the emission contributions from different sources to the carbon footprints of 14 primary wood products are presented. The largest

Table 9 Life cycle inventory for carbon footprint calculations: 1 m^3 of medium-density fiber-board, at plant/RER U (Ecoinvent 2.0)

	Quantity	Unit
Resources		
Water, cooling, unspecified natural origin/m^3 (in water)	0.18	m^3
Materials/fuels		
Aluminum sulfate, powder, at plant/RER U	4.36	Kg
Paraffin, at plant/RER U	22.8	Kg
Electricity, medium voltage, production UCTE, at grid/UCTE U	355	kWh
Natural gas, burned in industrial furnace >100 kW/RER U	1670	MJ
Urea formaldehyde resin, at plant/RER U	49.6	kg
Transport, lorry >16t, fleet average/RER U	85.6	tkm
Transport, freight, rail/RER U	202	tkm
Wood chips, softwood, from industry, $u = 40$ %, at plant/RER U	−0.87564	m^3
Wood chips, from industry, softwood, burned in furnace 300 kW/CH U	2770	MJ
Industrial residue wood, mix, hardwood, $u = 40$ %, at plant/RER U	0.333	m^3
Industrial residue wood, mix, softwood, $u = 40$ %, at plant/RER U	0.998	m^3
Industrial wood, hardwood, under bark, $u = 80$ %, at forest road/RER U	0.127	m^3
Industrial wood, softwood, under bark, $u = 140$ %, at forest road/RER U	0.388	m^3
Wooden board manufacturing plant, organic bonded boards/RER/I U	3.33E-08	p
Emissions to air		
Formaldehyde	0.00927	kg
Heat, waste	1280	MJ

Table 10 Life cycle inventory for carbon footprint calculations: 1 m^3 of oriented strand board, at plant/RER U (Ecoinvent 2.0)

	Quantity	Unit
Materials/fuels		
Paraffin, at plant/RER U	5.3	kg
Diesel, burned in building machine/GLO U	15	MJ
Electricity, medium voltage, production UCTE, at grid/UCTE U	130	kWh
Natural gas, burned in industrial furnace >100 kW/RER U	203	MJ
Phenolic resin, at plant/RER U	44.7	kg
Transport, lorry >16t, fleet average/RER U	78.7	tkm
Transport, freight, rail/RER U	177	tkm
Wood chips, softwood, from industry, $u = 40$ %, at plant/RER U	−0.948	m3
Wood chips, from industry, softwood, burned in furnace 300 kW/CH U	3000	MJ
Industrial wood, softwood, under bark, $u = 140$ %, at forest road/RER U	1.19	m^3
Residual wood, softwood, under bark, air dried, $u = 20$ %, at forest road/RER U	0.115	m^3
Wooden board manufacturing plant, organic bonded boards/RER/I U	3.33E-08	p
Emissions to air		
Formaldehyde	0.00263	kg
Heat, waste	468	MJ

Table 11 Life cycle inventory for carbon footprint calculations: 1 m^3 of particle board, indoor use, at plant/RER U (Ecoinvent 2.0)

	Quantity	Unit
Resources		
Water, cooling, unspecified natural origin/m^3 (in water)	0.304	m^3
Materials/fuels		
Ammonia, liquid, at regional storehouse/RER U	0.64	kg
Hydrochloric acid, 30 % in H_2O, at plant/RER U	1.36	kg
Paraffin, at plant/RER U	11	kg
Electricity, medium voltage, production UCTE, at grid/UCTE U	104	kWh
Natural gas, burned in industrial furnace >100 kW/RER U	154	MJ
Heat, heavy fuel oil, at industrial furnace 1 MW/RER U	86	MJ
Heat, light fuel oil, at industrial furnace 1 MW/RER U	86	MJ
Urea formaldehyde resin, at plant/RER U	51	kg
Transport, lorry >16t, fleet average/RER U	63.3	tkm
Transport, freight, rail/RER U	152	tkm
Wood chips, softwood, from industry, u = 40 %, at plant/RER U	−0.34653	m^3
Wood chips, from industry, softwood, burned in furnace 300 kW/CH U	1100	MJ
Industrial residue wood, mix, hardwood, u = 40 %, at plant/RER U	0.217	m^3
Industrial residue wood, mix, softwood, u = 40 %, at plant/RER U	0.823	m^3
Industrial wood, hardwood, under bark, u = 80 %, at forest road/RER U	0.128	m^3
Industrial wood, softwood, under bark, u = 140 %, at forest road/RER U	0.215	m^3
Wooden board manufacturing plant, organic bonded boards/RER/I U	3.33E-08	p
Emissions to air		
Formaldehyde	0.003	kg
Heat, waste	375	MJ
Nonmethane volatile organic compounds, unspecified origin	0.166	kg
Particulates, <2.5 μm	0.0039	kg
Particulates, >10 μm	0.039	kg
Particulates, >2.5 μm, and <10 μm	0.0351	kg
Waste to treatment		
Treatment, particle board production effluent, to wastewater treatment, class 3/CH U	0.036	m^3

emissions source for both air-dried and kiln-dried sawn softwood timber is raw material processing, which includes harvesting (32.3 kg CO_2e), sawing (20.7 kg CO_2e), and the sawmill facility allocation (4 kg CO_2e). The increased raw material processing emissions for kiln-dried sawn softwood timber is due to the energy required for the drying process (18.7 kg CO_2e) (Figs. 2a, b). Manufacturing 1 m^3 of hardwood sawn timber results in a lower carbon footprint than softwood sawn timber. However, the raw material processing still accounts for the greatest contribution to the carbon footprint of air-dried hardwood sawn wood (Fig. 2c). As with softwood sawn timber, the kiln-drying process causes a significant increase in emissions (Fig. 2d).

In glued laminated timber, also known as glulam, emissions derive predominantly from timber harvest and initial lumber production of the softwood but also from the energy and adhesives required to bond the lumber (Fig. 3). Urea

Table 12 Life cycle inventory for carbon footprint calculations: 1 m^3 of particle board, outdoor use, at plant/RER U (Ecoinvent 2.0)

	Quantity	Unit
Resources		
Water, cooling, unspecified natural origin/m^3 (in water)	0.304	m^3
Materials/fuels		
Ammonia, liquid, at regional storehouse/RER U	0.64	Kg
Hydrochloric acid, 30 % in H_2O, at plant/RER U	1.36	Kg
Paraffin, at plant/RER U	11	Kg
Electricity, medium voltage, production UCTE, at grid/UCTE U	104	kWh
Natural gas, burned in industrial furnace >100 kW/RER U	154	MJ
Heavy fuel oil, burned in industrial furnace 1 MW, non-modulating/RER U	86	MJ
Light fuel oil, burned in industrial furnace 1 MW, non-modulating/RER U	86	MJ
Phenolic resin, at plant/RER U	51	Kg
Transport, lorry >16t, fleet average/RER U	63.3	Tkm
Transport, freight, rail/RER U	152	Tkm
Wood chips, softwood, from industry, u = 40 %, at plant/RER U	0.34653	m^3
Wood chips, from industry, softwood, burned in furnace 300 kW/CH U	1100	MJ
Industrial residue wood, mix, hardwood, u = 40 %, at plant/RER U	0.217	m^3
Industrial residue wood, mix, softwood, u = 40 %, at plant/RER U	0.823	m^3
Industrial wood, hardwood, under bark, u = 80 %, at forest road/RER U	0.128	m^3
Industrial wood, softwood, under bark, u = 140 %, at forest road/RER U	0.215	m^3
Wooden board manufacturing plant, organic bonded boards/RER/I U	3.33E-08	P
Emissions to air		
Formaldehyde	0.003	Kg
Heat, waste	375	MJ
Nonmethane volatile organic compounds, unspecified origin	0.166	Kg
Particulates, <2.5 µm	0.0039	Kg
Particulates, >10 µm	0.039	Kg
Particulates, >2.5 µm, and <10 µm	0.0351	Kg
Waste to treatment		
Treatment, particle board production effluent, to wastewater treatment, class 3/CH U	0.19	m^3

formaldehyde (UF) is the adhesive used for glued laminated timer for indoor use, which contributes 34.2 kg CO_2e (17 %) to the total carbon footprint of 1 m^3 of glued laminated timber (Fig. 3a). Melamine formaldehyde (MF) adhesive is used outdoor glued laminated timber. The MF adhesive has higher environmental impact then UF adhesive, which results in a higher carbon footprint of glued laminated timber for outdoor use (Fig. 3b). The MF adhesive contributes 55.2 kg CO_2e (24.8 %) to the carbon footprint of 1 m^3 of glued laminated timber for outdoor use.

For fiber composites (MDF and HDF), the extra energy required to convert the raw material to fibers, in addition to the energy required to apply pressure and heat to the products, is responsible for the bulk of the emissions from these products (Fig. 4a and b). However, the use of UF resin in MDF contributes significantly (28.5%) to the total carbon footprint of 1 m^3 of MDF board as well, despite

Table 13 Life cycle inventory for carbon footprint calculations: 1 m^3 of plywood, indoor use, at plant/RER U (Ecoinvent 2.0)

	Quantity	Unit
Resources		
Water, cooling, unspecified natural origin/m^3 (in water)	1.84	m^3
Materials/fuels		
Diesel, burned in building machine/GLO U	3.2	MJ
Electricity, medium voltage, production UCTE, at grid/UCTE U	306	kWh
Hardwood, allocation correction, 1/RER U	−1.32	m^3
Round wood, hardwood, under bark, $u = 70$ %, at forest road/RER U	2.7	m^3
Transport, freight, rail/RER U	348	tkm
Transport, lorry >16t, fleet average/RER U	157	tkm
Urea formaldehyde resin, at plant/RER U	83.2	kg
Wood chips, from industry, hardwood, burned in furnace 50 kW/CH U	8110	MJ
Wood chips, hardwood, from industry, $u = 40$ %, at plant/RER U	−1.9297	m^3
Wooden board manufacturing plant, organic bonded boards/RER/I U	3.33E-08	p
Emissions to air		
Formaldehyde	0.0832	kg
Heat, waste	1100	MJ
Waste to treatment		
Treatment, plywood production effluent, to wastewater treatment, class 3/CH U	1.84	m^3

Table 14 Life cycle inventory for carbon footprint calculations: 1 m^3 of plywood, outdoor use, at plant/RER U (Ecoinvent 2.0)

	Quantity	Unit
Resources		
Water, cooling, unspecified natural origin/m3 (in water)	1.84	m^3
Materials/fuels		
Diesel, burned in building machine/GLO U	3.2	MJ
Electricity, medium voltage, production UCTE, at grid/UCTE U	306	kWh
Hardwood, allocation correction, 1/RER U	−1.32	m^3
Melamine formaldehyde resin, at plant/RER U	83.2	Kg
Round wood, hardwood, under bark, $u = 70$ %, at forest road/RER U	2.7	m^3
Transport, freight, rail/RER U	348	Tkm
Transport, lorry >16t, fleet average/RER U	157	Tkm
Wood chips, from industry, hardwood, burned in furnace 50 kW/CH U	8110	MJ
Wood chips, hardwood, from industry, $u = 40$ %, at plant/RER U	−1.9297	m^3
Wooden board manufacturing plant, organic bonded boards/RER/I U	3.33E-08	P
Emissions to air		
Formaldehyde	0.0832	Kg
Heat, waste	1100	MJ
Waste to treatment		
Treatment, plywood production effluent, to wastewater treatment, class 3/CH U	1.84	m^3

Table 15 Life cycle inventory for carbon footprint calculations: 1 m^3 of wood pellets, $u = 10$ %, at storehouse/RER U (Ecoinvent 2.0)

	Quantity	Unit
Materials/fuels		
Electricity, medium voltage, production UCTE, at grid/UCTE U	164	kWh
Industrial residue wood, from planing, hard, air/kiln dried, $u = 10$ %, at plant/RER U	0.36	m^3
Industrial residue wood, from planing, softwood, kiln dried, $u = 10$ %, at plant/RER U	0.925	m^3
Transport, freight, rail/RER U	71.5	Tkm
Transport, lorry >16t, fleet average/RER U	35.8	Tkm
Wood pellet manufacturing, infrastructure/RER/I U	0.00000001	P
Emissions to air		
Heat, waste	591	MJ

Table 16 Carbon footprint of 1 m^3 of selected primary wood products from Ecoinvent 2.0 (2010)

Primary wood product	Carbon footprint ($kg\ CO_2e$)
Sawn timber, hardwood, raw, air dried, $u = 20$ %, at plant/RER U	57
Sawn timber, hardwood, raw, kiln dried, $u = 10$ %, at plant/RER U	79
Sawn timber, softwood, planed, air dried, at plant/RER U	85
Wood pellets, $u = 10$ %, at storehouse/RER U	103
Sawn timber, softwood, planed, kiln dried, at plant/RER U	104
Glued laminated timber, indoor use, at plant/RER U	204
Glued laminated timber, outdoor use, at plant/RER U	222
Particle board, indoor use, at plant/RER U	262
Oriented strand board, at plant/RER U	310
Particle board, outdoor use, at plant/RER U	329
Medium-density fiberboard, at plant/RER U	495
Plywood, indoor use, at plant/RER U	497
Fiberboard hard, at plant/RER U	581
Plywood, outdoor use, at plant/RER U	643

comprising only 10–20 % of the finished product. Paraffin, which is a hydrophobic agent that is present in small amounts (less than 1 %) in fiberboard, contributes 3.8 % of the total carbon footprint of 1 m^3 of MDF board. Compared to MDF, the carbon footprint of HDF board is higher due to higher energy consumption of the process (Fig. 4b).

In particle board and OSB, the main emission sources are adhesives (Fig. 5). Although the UF adhesive that is used in particle board for indoor applications only comprises approximately 6–9 % of the final product, it contributes 55.3 % to the total carbon footprint of 1 m^3 of particle board for indoor applications (Fig. 5a). Phenol formaldehyde (PF) adhesive is used for outdoor particleboard, which increases the share of carbon footprint attributed to the adhesive to 64.5 %

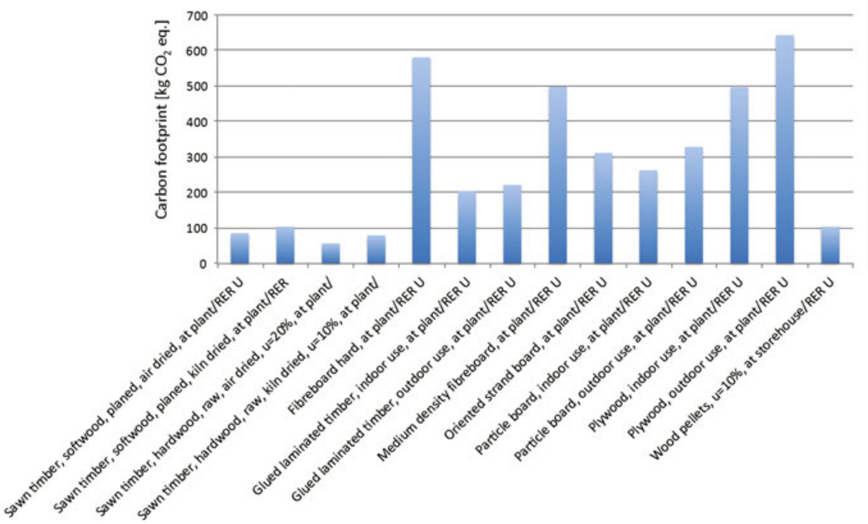

Fig. 1 Carbon footprint of selected primary wood products from Ecoinvent 2.0 (2010)

(Fig. 5b). PF adhesive is also used in OSB and accounts for 2–4 % of the product content, but contributes 59.6 % of the total carbon footprint (Fig. 5c). The marginally lower carbon footprint of OSB compared to particle board for outdoor applications is mainly a consequence of the lower adhesive content in OSB.

In plywood production, the main emission sources are the adhesives (Fig. 6). The UF adhesive in the plywood for indoor use contributes 47.7 % to total carbon footprint (Fig. 6a), whereas MF adhesive contributes 59.6 % to the total carbon footprint of plywood for outdoor use (Fig. 6b). The higher environmental impact of MF adhesive is the cause of the larger carbon footprint for outdoor plywood than for indoor plywood.

The main emission source during the production of wood pellets is the energy used during manufacturing, which includes compression (Fig. 7). Emissions are almost entirely from the energy demand during manufacturing because wood pellets are made mostly from manufacturing residues and contain no adhesives.

3.1 Carbon Storage

Trees capture atmospheric carbon dioxide via photosynthesis, and a proportion of this sequestered carbon is stored in the above-ground woody biomass. Wood is composed of three main biopolymers (cellulose, hemicellulose, and lignin). In a first approximation, the elementary composition can be assigned a stoichiometric ratio of CH_2O. This means that atmospheric carbon comprises a minimum of 40 % of the dry wood mass (increasing somewhat with increasing lignin content). Each

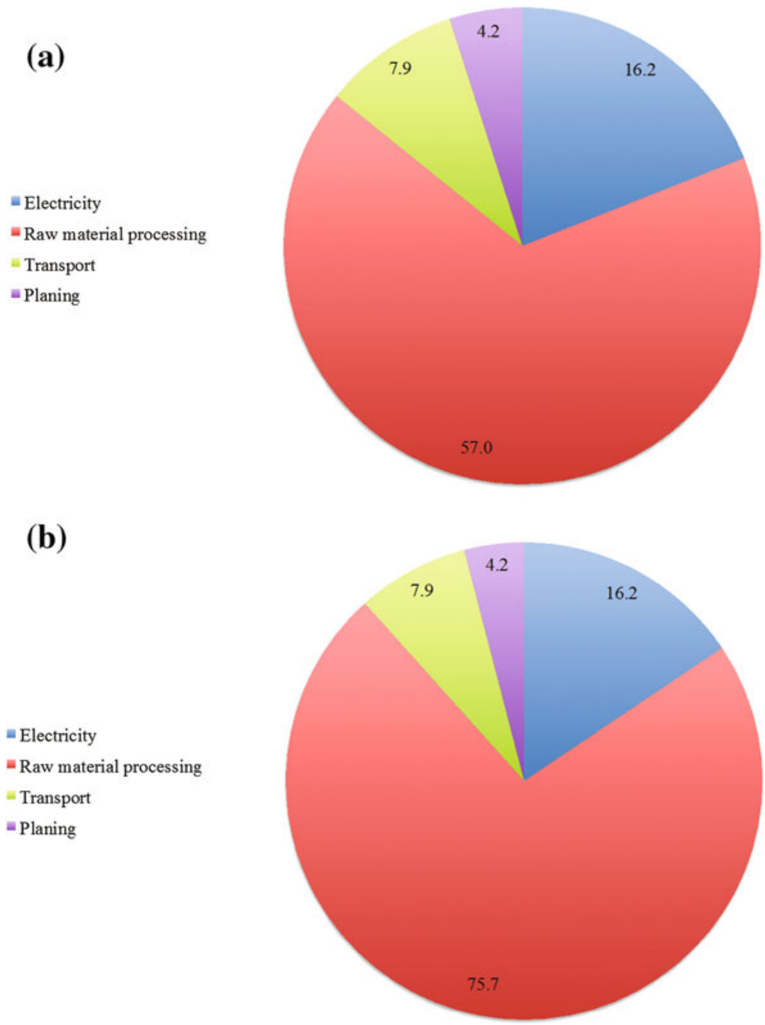

Fig. 2 Carbon footprint emission sources for 1 m^3 of sawn timber. **a** Air-dried softwood; **b** Kiln-dried softwood; **c** Air-dried hardwood; **d** Kiln-dried hardwood

ton of dry wood therefore equates to the removal of approximately 1.5 tons of atmospheric carbon dioxide (the ratio of the molecular weight of CO_2 compared to CH_2O: 44/30). The net benefit of this ability to store atmospheric carbon depends upon the length of time before the material is subsequently oxidized and the carbon released back to the atmosphere. In all situations where carbon flows and stocks are considered, it is essential that a distinction is made between biogenic and fossil carbon sources. Even with biogenic carbon, it is also important to differentiate between carbon that is held in long-term storage (such as old-growth forest) and that derived from newer managed or plantation forests.

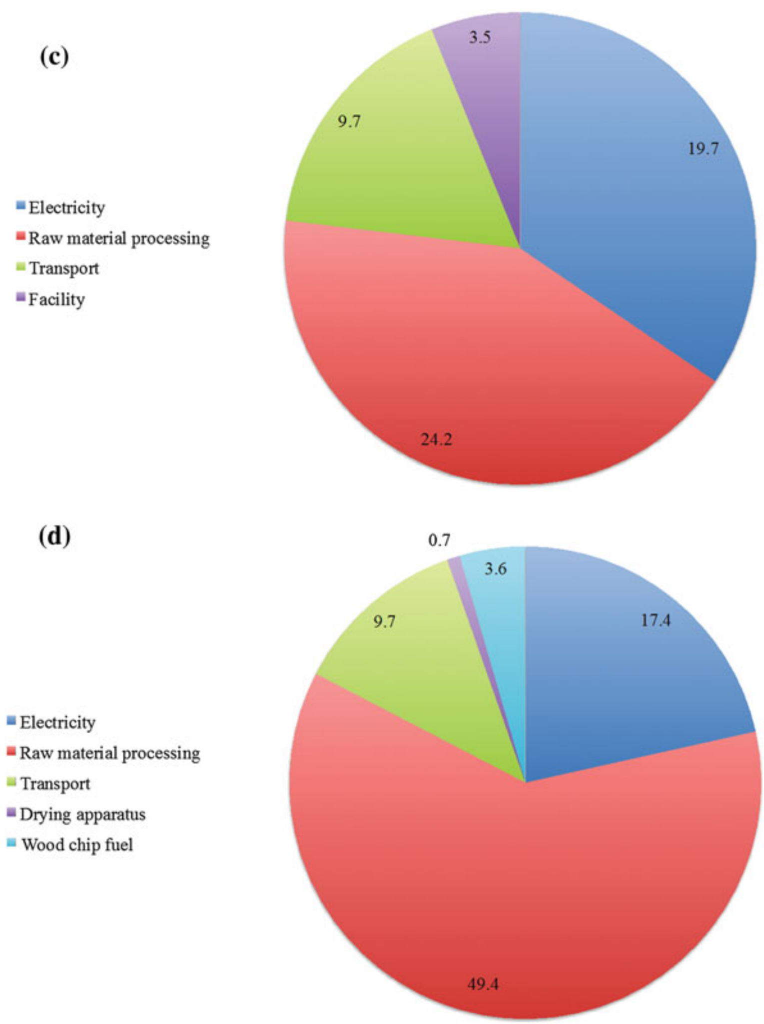

Fig. 2 continued

In Fig. 8, different scenarios for biogenic carbon storage and release are considered. In Fig. 8a, old-growth forest is burnt and the land is cleared for alternative use. The result is a release to the atmosphere of fossil carbon in the form of carbon dioxide (carbon stored in old-growth forest is treated the same as subterranean fossil carbon), which is shown as positive on the plot. This carbon content was previously held in long-term (historical) storage. Therefore, although technically this is biogenic carbon, it represents carbon that would have been in storage; prior to the industrial revolution, it was part of the natural biogenic cycle and can be considered equivalent to fossil carbon. The concentration of this 'fossil' carbon in

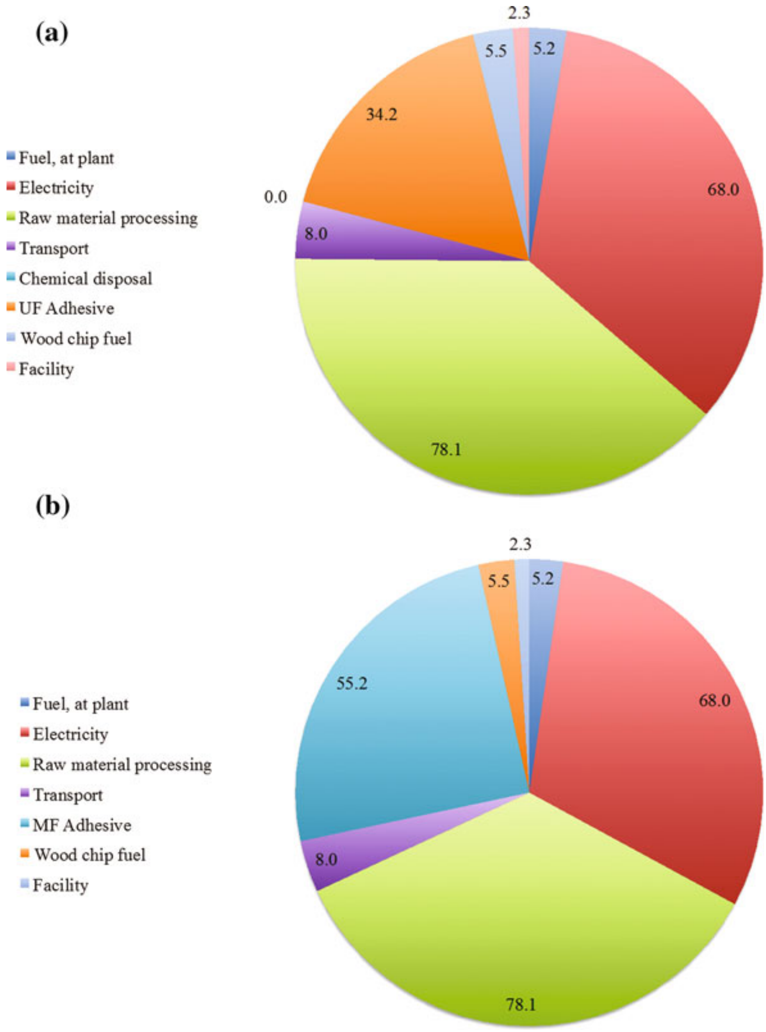

Fig. 3 Carbon footprint emission sources for 1 m^3 of glued laminated timber for indoor use (**a**) and glued laminated timber for outdoor use (**b**)

the atmosphere gradually decreases after the release (the Bern cycle) as it is removed by sequestration in oceanic and terrestrial sinks.

In Fig. 8b, a scenario is shown where a new forest plantation is established and the trees are allowed to grow for 50 years before harvesting and restocking. Carbon is removed from the atmosphere as the atmospheric carbon dioxide is photosynthetically bound in the biomass. The overall result is a benefit (shown as negative carbon) because atmospheric carbon dioxide has been sequestered. If the forest biomass is subsequently burnt with energy recovery after 50 years, then the

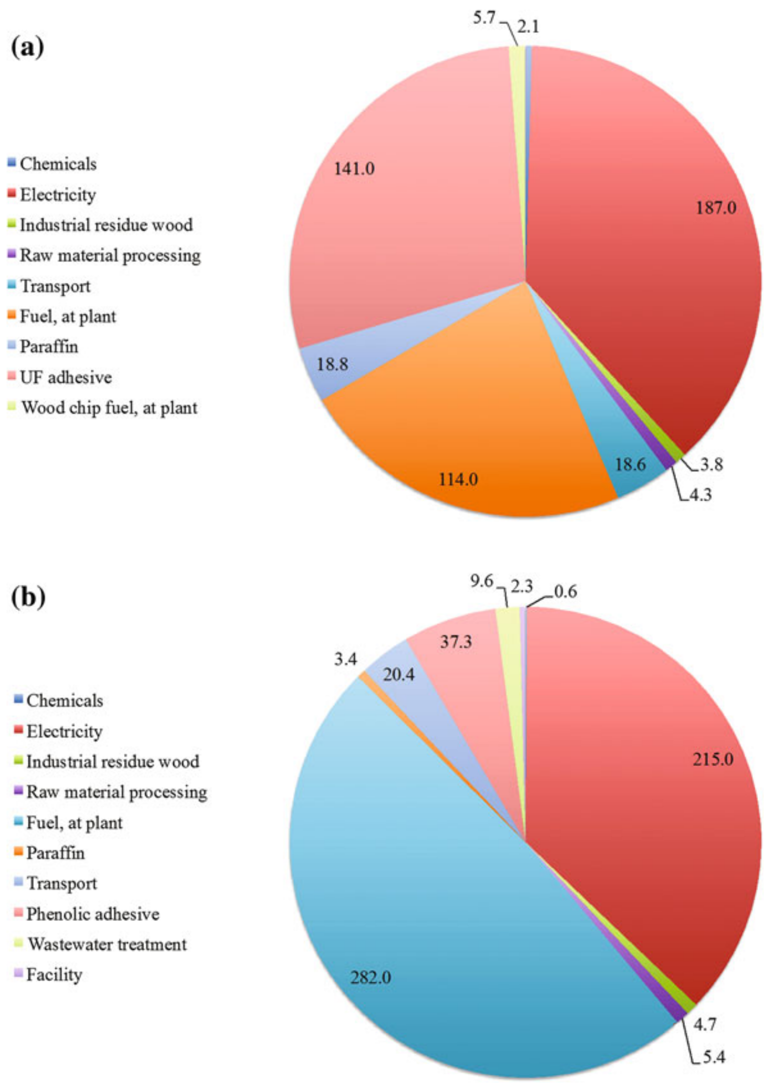

Fig. 4 Carbon footprint emission sources for 1 m^3 of medium-density fiberboard (**a**) and hard fiberboard (**b**)

above-ground biomass is oxidized and the accumulated atmospheric carbon is lost. The overall result is nonetheless still a benefit in terms of carbon sequestration. This is because there has been removal of atmospheric carbon dioxide during the 100-year period of consideration. When the aboveground biomass is subsequently burnt, this results in the return of atmospheric carbon dioxide. This only applies because new forest was created. However, the burning of virgin woody biomass cannot seriously be considered an effective mitigation strategy. Far better is one in

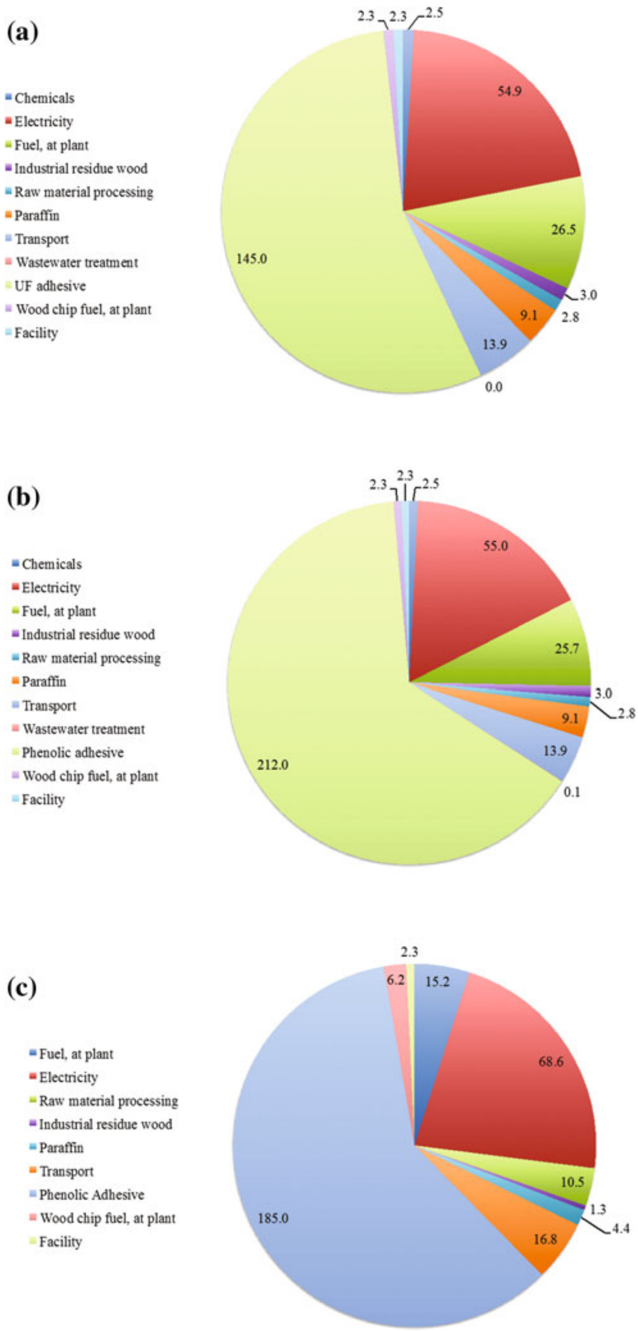

Fig. 5 Carbon footprint of emission sources and their contribution to the total carbon footprint of 1 m^3 of particle board for indoor use (**a**), particle board for outdoor use (**b**), and oriented strand board (**c**)

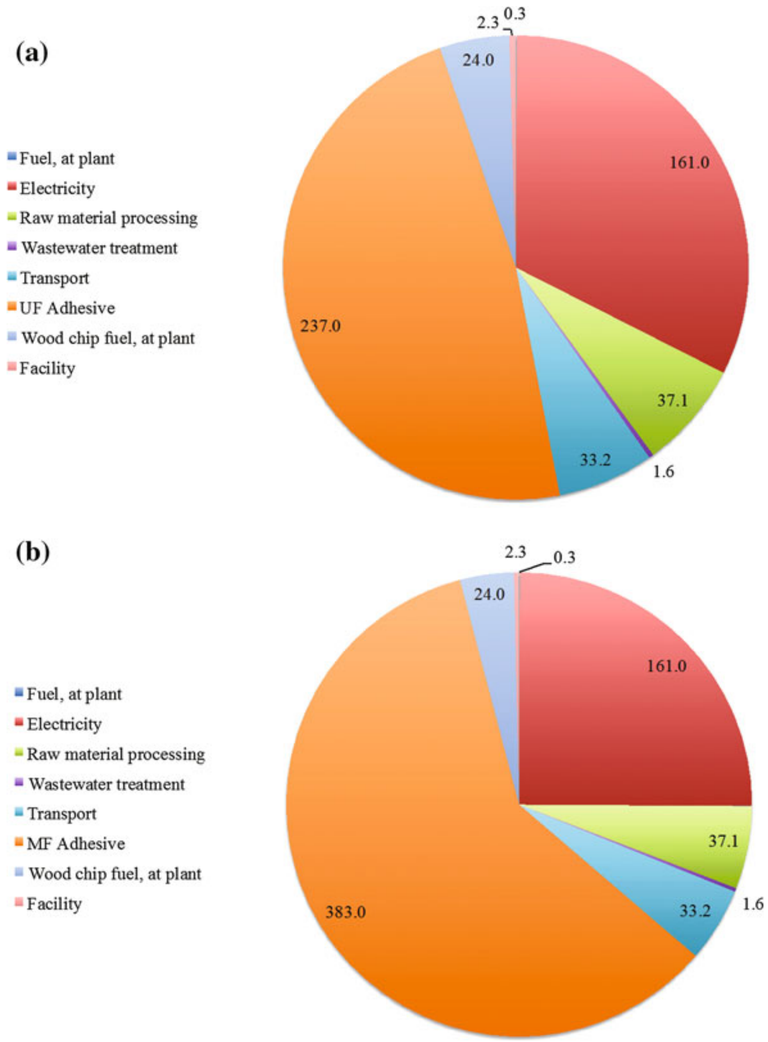

Fig. 6 Carbon footprint emission sources for 1 m^3 of plywood for indoor use (**a**) and plywood for outdoor use (**b**)

which the calorific value of the biomass is utilized and substituted for a fossil fuel alternative. The benefit then arises not only from the storage of atmospheric carbon in the growing biomass, but additionally from the avoided emission of the fossil carbon.

In Fig. 8c, the biogenic carbon embedded in the plantation forest is stored in timber products for 50 years, before it is used to generate energy. In this way, three benefits are realized. During the growth phase of the forest, carbon dioxide is sequestered due to the incremental growth of the trees. After harvesting, the carbon

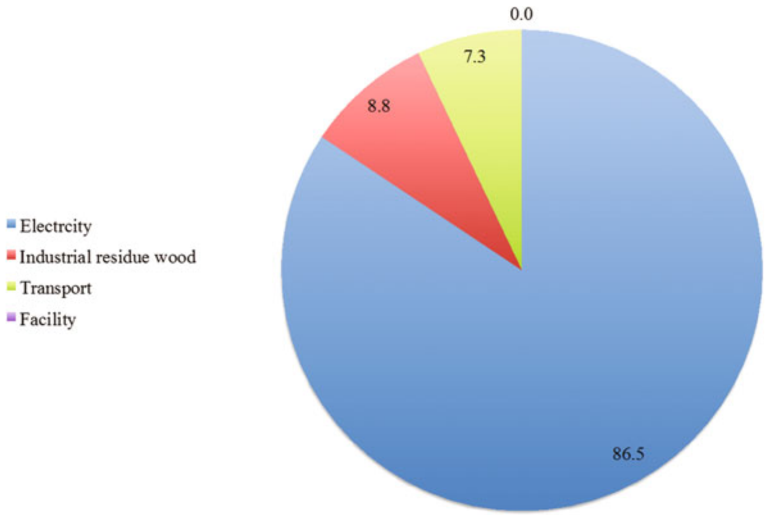

Fig. 7 Carbon footprint emission sources for 1 m^3 of wood pellets

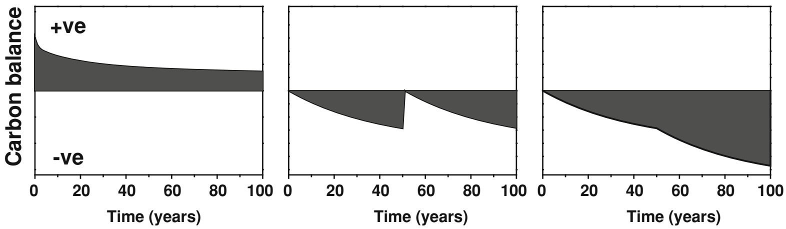

Fig. 8 Effect on carbon balance of burning old growth forest (**a**), burning plantation forest with a 50-year rotation (**b**), and using timber in long-life products (**c**)

continues to be stored in the timber products. It is only at the end of the life that this stored carbon is released into the atmosphere. Once again, if the wood is burnt with energy recovery, then there is also the benefit of the avoided emission of the fossil carbon. An even better option is to cascade the wood material down the product value chain through several life cycles before final incineration with energy recovery.

Although the storage of biogenic carbon clearly has benefits, it is necessary to consider an appropriate framework for reporting this. There has been some attempt to deal with the evaluation of biogenic carbon storage in long-life products in national standards. In the United Kingdom, this issue was dealt with in Publically Available Specification (PAS) 2050 (2011), which considers a 100-year assessment period following IPCC guidelines. Annex C of PAS 2050 (2011) describes the methodology to be used for calculating the storage of carbon in products. Two methods for calculating the weighted average of the effect of carbon storage in a product are given, although for a product with a life less than 2 years, no carbon storage benefit can be assigned. For products with a life of 2–25 years, a weighting factor is calculated, with a different weighting factor for other storage scenarios. This can only be applied to the storage of biogenic carbon, which is assigned a negative CO_2 value. However, this cannot be applied if the biogenic carbon is derived from old growth or native forests, where land use change has occurred. Emissions of biogenic carbon are not considered, because the origin of biogenic carbon is atmospheric carbon dioxide. Weighting factors are also applied for delayed release of GHGs.

In March 2011, the Construction Products Regulation (305/2011) was introduced, replacing the Construction Products Directive (89/106/EEC). The Construction Products Regulation states that if a European standard exists, it has to be used. In addition, it states that 'for the assessment of the sustainable use of resources and of the impact of construction works on environment Environmental Product Declarations should be used when available.' The Construction Products Regulation came into full force as of July 2013.

In order to develop a framework that allows for comparability of environmental performance between products, ISO 14025 (2009) was introduced. This describes the procedures required in order to produce Type III environmental declarations (EPD). This is based on the principle of developing product category rules (PCR), which specify how the information from an LCA is to be used to produce the EPD. A PCR will typically specify what the functional unit is to be for the product. Within the framework of ISO 14025, it is only necessary for the production phase (cradle to gate) of the lifecycle to be included in the EPD. It is also possible to include other lifecycle stages, such as the in-service stage and the end-of-life stage, but this is not compulsory.

ISO 14025 also gives guidance on the process of managing an EPD program. This requires program operators to set up a scheme for the publication of a PCR under the guidance of general program instructions. Until recently, PCRs have tended to be developed in an ad-hoc manner by different program operators, although there has been activity to harmonize the different rules. The situation now is one where European Standards are being introduced, which lay down the PCRs. For the construction sector core, the PCR is EN 15804 (2012). The standard that applies to sawn timber is the draft standard EN 16485 (2012), which at the time of writing has not yet been formally adopted. The draft standard allows for the reporting of sequestered carbon in timber products under the following conditions: 'Consideration of the biogenic carbon-neutrality of wood is valid for wood from countries that have decided to account for Art. 3.4 of the Kyoto Protocol or which are operating under established sustainable forest management or certification schemes'. The methodologies for reporting sequestered carbon in timber products in EN 16485 (2012) are similar to those given in PAS 2050, in that different calculations are used for carbon stored in a product between 2 and 25 years and that stored in a product for 26–100 years. There is also a draft standard FprEN16449 (2013), which gives guidance on calculating the amount of sequestered carbon in timber.

Methodologies for accounting for the carbon stored in products are given in the International Reference Life Cycle Data (ILCD) Handbook, published by the European Commission Joint Research Centre (Institute for Environment and Sustainability), which also considers a 100-year assessment period. For carbon storage in products, the relevant sections are Sects. 7.4.3.6.4 and 7.4.3.7.3. It is recommended that fossil and biogenic carbon releases (e.g., CO_2 and CH_4) should be differentiated. Furthermore, all carbon emissions associated with land use changes and from biomass associated with virgin forests should be treated as fossil carbon. Emissions associated with plantation forests are to be inventoried as biogenic carbon. Uptake of atmospheric carbon dioxide is inventoried as 'resources from air'. A methodology is given for accounting for the removal and storage of atmospheric carbon dioxide. One of the issues discussed is that of carbon storage for a long period of time (e.g. 80 years) and how this then relates to the commonly used GWP100 parameter. GWP100 is a value given to the result of the emission of a pulse of a global warming gas in terms of its effect upon the environment for 100 years. Thus, if there is an emission of fossil-derived carbon dioxide into the atmosphere, its radiative forcing effect over a period of 100 years will gradually decrease as it is taken up by various natural sinks (the Bern cycle referred to earlier). For this reason, the parameter GWP100 is used (the global warming potential over a 100-year period).

In the case of carbon storage in a long-life material for 80 years, it would be incorrect to show the emission at end of life in terms of a GWP100 value because the total accounting time being considered is now 180 years. The ILCD methodology deals with this in the following way. The uptake of atmospheric carbon dioxide is inventoried as 'Carbon Dioxide–Resources from Air' and the emissions as 'Carbon Dioxide (biogenic)–Emissions to Air'. These two flows then cancel each other out. Meanwhile, the issue of the storage in the product is calculated by declaring a correction flow for delayed emission of the carbon dioxide and giving it a value of 0.01 times the CO_2 equivalent mass stored per year. The same method is used to calculate the storage of fossil carbon in a long-life product, except that there is no consideration given to the category 'Carbon Dioxide–Resources from Air.' Thus, there is a net effect of the release of the fossil derived CO_2 at the end of life, but the compensatory effect of the delayed emission of the fossil carbon is taken account of. With the introduction of Product Environmental Footprinting, it is likely that ILCD methodologies will be adopted.

4 Influence of Allocation Methods in Carbon Footprint Calculations of Wooden Products

When several products (or functions) from different product systems share the same unit process or group of unit processes, allocation may be required. Shared processes are often referred to as multifunction (or multifunctional) processes.

Allocation is needed in order to attribute the environmental load of the shared processes to the studied product and to each of the additional products delivered by the shared process. Allocation in general is defined in ISO 14040 (1997) as partitioning the input and/or output flows of a process to the product system under study. This means environmental aspects of the production process are apportioned to different co-products. Wherever possible, according ISO 14044 (2006), allocation should be avoided by either dividing the unit process or expanding the product system. If a process must be divided but data is not available, inputs and outputs of the verified system should be divided by its products or functions in such a way that separation shows basic physical relations among them. Where a physical relationship (i.e., mass, area or volume relationships) cannot be established or used as the basis for allocation, the inputs should be allocated between the products and the functions in a way that reflects other relationships between them, as defined in ISO 14041. For example, environmental input and output data might be allocated between co-products in proportion to the economic value of the products.

EN 15804 (2012) states that allocation should be based on physical properties (e.g., mass, volume) when the difference in revenue between co-products is low (of 1 % or less). In all other cases, allocation should be based on economic values. Furthermore, in EN 16485 (2012), allocation recommendations follow EN 15804 (2012), but different examples for the wood processing chain are given. According to EN 16485 (2012), allocations should respect the main purpose of the process studied and the purpose of the plant should be taken into account as well. Market prices from official statistics should be used for determination of revenues for assortments for which no company-specific prices are available. However, a discussion arises as impacts from allocation procedures differ between panels and sawmill industries. Concerning the different raw materials, processes, and co/by-products, a clear rule to harmonize the allocation procedures across all wood industry sectors should be determined in the future.

According to Jungmeier et al. (2002), it is generally agreed that environmental burdens should only be shared among products with a positive economic value—the products that are the intention of the process. Processes in the woodworking industry and manufacturing often produce multiple products. Those products can be either main products or by-products, and the environmental burden of the process should be distributed among these multiple products. As an example, the intended product of sawmills is sawn timber, but co-products with an assigned value, such as saw dust and wood chips, also accrue. The recommended procedure to account for the environmental impact of each of these products is to divide the unit process to be allocated into two or more subprocesses or to expand the product system to include additional functions related to the co-products. In some cases, it is not possible to use a wider approach and allocation within manufacturing processes has to be used. For instance, allocation would be required if an LCA focused on sawn timber production and it was necessary to determine the fraction of the environmental load associated with the sawmill that should be allocated to sawn timber versus to chips.

The treatment of allocation in LCA of wood-based products has been discussed for a long time and different solutions have been presented. It is generally accepted that different allocation procedures significantly influence the results of LCA of wood-based products.

Furthermore, wood is a renewable material that can be used for conventional wood products and energy production, among other uses. Consistent methodological procedures are needed in order to correctly address the entire product spectrum that wood products offer, multifunctional wood processing methods that generate large quantities of co-products (e.g. bark, wood chips), and reuse or recycling of paper and wood. Ten different processes in LCAs of wood-based products are identified where allocation questions can occur (Jungmeier et al. 2002): forestry, sawmill, wood industry, pulp and paper industry, particle board industry, recycling of paper, recycling of wood-based boards, recycling of waste wood, combined heat and power production, and landfill.

Mass and volume are usually used for physical allocation of wood-based products. Because moisture content varies in wood products and leads to enormous mass differences but negligible volume changes, volume should be considered instead of mass for allocation decisions. Different approaches to accounting for moisture content variances resulting from the inherent material properties of wood lead to deviating results. The moisture content of green wood is between 60 and 100 %, while most finished wood products show moisture contents between 7 and 20 %. Furthermore, co-products from the same process may have different moisture contents, which could directly affect the presumed physical relationships between them when allocation is based on mass and volume. On the other hand, the main problem of economic allocation is that, compared to mass or volume, prices are not stable and depend on and vary heavily with market conditions and fluctuations. Variations in the prices of sawn wood can be up to 10 % from year to year.

As a result of the COST Action E9 “Life cycle assessment of forestry and forest products,” Jungmeier et al. (2002) provided the following recommendations for allocation in LCAs of wood-based products:

1. Energy and carbon content are characteristics of the wood and reflect the material and energy aspects of wood. A balance of the biological carbon and energy is necessary. Carbon uptake and the embodiment of energy as inherent material characteristics should always be allocated on a mass basis to avoid artefacts. The biogenic carbon neutrality does not necessarily indicate greenhouse gas neutrality, as carbon emissions can occur as methane or be derived from non-sustainable forestry.
2. Avoid allocation by an extension of system boundaries that combines material and energy aspects of wood. This means a combination of LCA of wood products and of energy from wood (bioenergy) with a functional unit for products and energy (e.g. 1 m^3 particle boards + 3 kWh energy).

3. Substitute energy from wood with conventional energy (e.g., energy from coal) in the LCA of wood products to get the functional unit of the wood product only (e.g. 1 m^3 particle boards), but identify the criteria for the substituted energy (e.g., kind and quality of energy, state of technology).
4. Substitution of wooden products with non-wooden products in an LCA of bioenergy is not advisable because the substitution criteria are too complex.
5. If avoiding allocation is not possible, the reasons should be documented.
6. If an allocation between different co-products is necessary for a certain process (e.g., sawmill), all upstream environmental effects also have to be allocated (e.g., upstream effects of sawmill can be transport and forestry).
7. Different allocation procedures must be analyzed and documented. In many cases, it seems necessary to make a sensitivity analysis of different allocation procedures for different environmental effects. It can also be useful to get the acceptance of the chosen allocation procedure by external experts.
8. For allocation in forestry, it is necessary to describe the main function of the forest from which the raw material is taken. In some cases, different types or functions of forests must be considered and described. The main function often indicates the allocation procedure.

Regarding the experiences from the examples, Jungmeier et al. (2002) identified the following most practical allocation for some specific processes: forestry—mass and volume; sawmill—mass and market price; wood industry—mass and market price.

In terms of the use of materials in the built environment and evaluating their environmental impact, we are still in a situation where there is huge variation in the way that LCA studies are performed. There has been action to make these studies more rigorous and prescriptive, with the introduction of EPDs and (within Europe) PCR for timber products, as well as for construction materials. Although the production of EPDs is presently voluntary, there will rapidly be a necessity to produce EPDs in order to meet the requirements of procurement. If we are to create carbon markets that are able to assign a monetary value to sequestered carbon stored in the built environment, it will become necessary to move towards a system where it is a legal requirement to have proper certification of the carbon footprint of products.

The formalization of procedures related to the chain of custody of forest products provides an opportunity for simultaneously incorporating LCA data. This represents an opportunity for the forest products sector that should be addressed. One of the problems with this sector is the diversity of sources, heterogeneity of material, and huge range of products that are produced. This is a much more complex situation than that faced by the concrete, steel, and polymer sectors. It is essential that the forest products industry adopts chain-of-custody systems that are integrated with LCA tools. The ability to track products through the value chain when they are used in buildings will be possible with the increasing adoption of building information modelling tools. It will be necessary to extend the chain of custody through first life and on to subsequent lives as the material is cascaded down the value chain, as well as at end of life when the sequestered carbon is finally returned to the atmosphere. This will allow for a really effective and accurate tool for informing LCA, policy makers, and the public. The forest products industry has considerable experience in chain-of-custody certification; this expertise should be harnessed in the future to use chain-of-custody procedures to ‘pull through’ environmental information. This information could be in the form of carbon certificates.

5 Conclusion

A cradle-to-gate analysis was used in this chapter to present the carbon footprint of 14 different primary wood products. The largest source of emissions for all sawn timber products is removing the timber from the forest, while for kiln-dried sawn timber the drying process follows closely behind. For fiber composites (MDF and HDF), the extra energy required to convert the raw material to fibers, in addition to the energy required to apply pressure and heat to the products, is responsible for the bulk of the emissions from these products. The adhesives used in particle board, plywood, and OSB are responsible for the largest fraction of emissions from these products. This is especially significant considering the low total volume they represent in the final products. Glulam emissions derive mostly from the harvest and initial production of the softwood, but also from the extra energy required to apply pressure and set the adhesives used. Wood pellets are made mostly from manufacturing residues; therefore, their emissions are derived almost entirely from the energy required during manufacturing, especially compression. Altering the system boundaries would yield different results. Furthermore, results would have been modified if the carbon footprint calculation accounted for carbon sequestration of wood, the use of recycled wood products, and other similar issues pertinent to LCA.

In Europe, carbon footprint is gaining immense importance and is expected to be mandated to accompany products and services. The environmental properties of wood and other construction materials are currently entering in building codes in construction. However, the limited availability of emissions data and its poor integration to real-life decision making within the construction sector have kept construction industries from using environmental arguments for material choices. Several studies have dealt with the LCA of forests and primary wood products (Richter 2001; Petersen and Solberg 2005; Puettmann and Wilson 2005; Rivela et al. 2006a, b; Werner and Richter 2007; Tucker et al. 2009; Cherubini et al. 2009; Lindholm et al. 2010; Oneil et al. 2010; Puettmann et al. 2010; Carre 2011; Cherubini and Strømman 2011).

However, there is still a lack of data. It is essential that research on timber processing and the resultant products place more emphasis on the interactive assessment of processes parameters, developed product properties, and environmental impact, including recycling and disposal options at the end of the service life towards upcycling after their service life based on the cradle-to-cradle concept. Intelligent concepts for reuse and recycling of valuable materials at the end of a single product life could reduce the amount of waste destined for landfills or downcycling. With new and innovative production technologies, reduced overall energy consumption, increased recycling of wood products, and reuse and refining of side-streams, the sector can become a leader on the path to achieving the European Commission's ambitious target of 80 % reduction in CO_2 emissions by 2050. Also, other policy strategies and actions directly impact the forest products industry, such as the EU Sustainable Development Strategy (SDS, European Commission 2009) and the recycling society directive (Directive 2008/98/EC, European Parliament Council 2008). Furthermore, the standardization in the area of sustainability is currently under dynamic development.

Newly published standards for the sustainability of construction works (CEN TC 350 2012) open opportunities for EU-wide harmonization of calculations and reporting of environmental impacts of buildings. The most important standards are EN 15804 (2012) for construction product EPDs and EN 15978 (2011) for assessment of environmental performance. Many of the databases and tools mentioned above date from before the introduction of the CEN TC 350 standards. Furthermore, as the influence of green building programs continues to increase and the field matures, the primary green building programs will shift to the use of LCA as a means of using science and consistent methodology to inform green building decisions (Bowyer 2008) and move towards an integrated design process. It is vitally important to the industry that the PCRs used for the relevant EPDs allow for the reporting of sequestered atmospheric carbon in timber products.

The design of a building is a complex process involving a multitude of disciplines and expertise. Therefore, it is essential that a transparent and standardized approach to LCA is used to assess the ecological and environmental consequences of the materials, use phase of the buildings, and end of life. Unfortunately, the values can differ significantly between studies. The use of different input data, functional units, allocation methods, reference systems, and other assumptions complicates comparisons of the LCAs of green building studies. To be sustainable in a holistic way, an integrated design process should be adopted. Each system or discipline in a project has some effect on another system to varying degrees.

The goals of sustainable development to increase economic efficiency, protect and restore ecological systems, and improve human's well-being—or a combination of the three—are expected to lead to new concepts, products, and processes optimizing the multiple utilization/recycling of forest-based resources. The life cycle analysis and cradle-to-cradle concepts are also expected to be used as key tools in economic development, leading to new business opportunities through innovative products with properties optimized to the end-use requirements and sustainable use of resources.

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