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Utilization of recovered wood in cascades versus utilization of primary wood—a comparison with life cycle assessment using system expansion

Karin Höglmeier · Gabriele Weber-Blaschke · Klaus Richter

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Abstract
Purpose A cascading utilization of resources is encouraged especially by legislative bodies. However, only few consecutive assessments of the environmental impacts of cascading are available. This study provides answers to the following questions for using recovered wood as a secondary resource: (1) Does cascading decrease impacts on the environment compared to the use of primary wood resources? (2) What aspects of the cascading system are decisive for the life cycle assessment (LCA) results?
Methods We conducted full LCAs for cascading utilization options of waste wood and compared the results to functionally equivalent products from primary wood, thereby focusing on the direct effects cascading has on the environmental impacts of the systems. In order to compare waste wood cascading to the use of primary wood with LCA, a functional equivalence of the systems has to be achieved. We applied a system expansion approach, considering different options for providing the additionally needed energy for the cascading system.
Results and discussion We found that the cascading systems create fewer environmental impacts than the primary wood systems, if system expansion is based on wood energy. The most noticeable advantages were detected for the impact categories of land transformation and occupation and the demand of primary energy from renewable sources. The results of the sensitivity analyses indicate that the advantage of the cascading system is robust against the majority of considered factors. Efficiency and the method of incineration at the end of life do influence the results.
Conclusions To maximize the benefits and minimize the associated environmental impacts, cascading proves to be a preferable option of utilizing untreated waste wood.

Keywords Cascading · Life cycle assessment (LCA) · Particleboard · System expansion · Recovered wood · Waste wood

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K. Höglmeier (✉) · G. Weber-Blaschke · K. Richter
Chair of Wood Science, Technische Universität München, Winzererstr. 45, 80797 Munich, Germany
e-mail: hoeglmeier@hfm.tum.de

1 Introduction

Although wood is a regrowing and, thus, renewable resource, it is not infinitely available. A continuous substantial increase of the harvested volume cannot be realized in most European countries, either because the total increment is already reaped, additional amounts are located in privately owned forests where wood harvesting is not desired by owners, or due to aspects of nature conservation. Mantau et al. (2010) predicted that by 2030 at the latest, demand will exceed the overall wood supply in the 27 EU countries. As wood products often lead to considerably less impact on the environment during their production and end-of-life phase compared to equivalent products out of mineral and fossil resources (Sathre and O'Connor 2010; Werner et al. 2005; Werner and Richter 2007), an increase of their amount would be beneficial in terms of environmental and resource protection. Rising prices of fossil fuels in combination with feed-in tariffs for electricity produced from biomass have led to an increase of demand and, consequently, price of wood assortments for energy production in Germany over the last few years (Härtl and Knoke 2014; Schwarzbauer and Stern 2010). As the same wood assortments that are utilized for energy production are also the main input for the production of wood-based panels such as particleboard, the competition for those wood assortments has increased considerably.

A cascading utilization is often mentioned as a suitable strategy to bridge this gap between rising demand for wood and stagnating availability of primary wood (i.e., wood which has not been used in a prior application) (Mantau 2012). By using the same resource for multiple successive applications, first as a material and finally as a fuel, the benefit created by one unit of a resource could be multiplied.

Recovered wood or waste wood, i.e., wood which has been already utilized at least in one prior application, is available in progressively good quality and quantity due to advances in sorting technology. Furthermore, the currently increasing use of wood in building applications and transport systems is expected to increase the amount of recovered wood considerably in the upcoming years. Legal requirements, such as landfill bans, additionally drive an increase in the availability for secondary applications. Until now, the majority of this valuable resource is either landfilled or incinerated, partly with energy recovery, throughout the EU. Using this wood first for a material application before the final disposal can help mitigate the scarcity of wood in the future.

1.1 Environmental impacts of wood cascading

A prerequisite for promoting the use of wood in cascades is scientifically sound information concerning the impacts on the environment by using recovered wood multiple times, i.e., in cascades. Up to now, only a few studies dealing with the concept of cascading of wood are available. Overall, they concluded that cascading creates benefits, depending on the specific aspects under study. Fraanje (1997) examined a possible cascade from pine wood in the Netherlands, concluding that cascading can substantially prolong carbon sequestration to mitigate climate change. Sathre and Gustavsson (2006) calculated the primary energy and carbon balances for various wood cascades, taking into account direct cascade effects, substitution effects, and effects of differing land use due to cascading. They concluded that land use effects are the dominating contribution to the overall effects of cascading. A recent study (Sikkema et al. 2013) assesses the consequences of a cascading wood use in Canada on GHG emissions, comparing different cascading scenarios to the IPCC default scenario which assumes an immediate incineration and thereby carbon dioxide release from the wood. They found that noticeable reductions of greenhouse gas emissions can be achieved, yet did not take into account the direct effects of cascading. Gärtner et al. (2013) focused on comparing wood cascades to equivalent nonwood products and credited the cascades for the end-of-life energy production by using life cycle assessment (LCA). The results indicate that cascading creates less environmental burdens than the provision of an equal benefit from nonwood products. Yet, the major part of those benefits by cascading can be attributed to substitution effects. The equivalent fossil- or mineral-based products in most cases have higher environmental burdens than wood products. Therefore, when comparing a whole cascade chain to a multitude of equivalents, benefits add up with each cascade step, leading to considerable overall advantages for the cascaded wood products. In contrast, our goal was to determine whether cascading of wood is beneficial in itself without taking substitution into account. This question is important as not all wood products can and will be substituted by nonwood products if not available, for example due to a lack of suitable raw materials. A major application for particleboard, which is the main product produced from recovered wood in Germany, is furniture: Over 70 % of the particleboards produced in Germany are utilized in this way (Mantau and Bilitewski 2010). However, especially in the take-away market sector, a substitution of particleboards by fossil or mineral products in furniture is unlikely, since competitive prices and a low weight are essential criteria. Therefore, assuming potential substitution benefits for all cascaded wood products does not comprehensively depict the real situation. In order to close this gap, we chose to compare the use of waste wood in cascades, mainly for particleboard production, to the production of the same wood products from primary wood. Thus, we are able to determine those environmental effects from cascading which are directly associated to the cascading itself rather than substitution.

We chose LCA to investigate major applications of waste wood in cascades and compared the results to the production of functionally equivalent products out of primary wood. LCA is a powerful tool to gain comprehensive information on environmental impacts of the production of goods and services. It allows the comparison of different ways of production and the resulting environmental impacts.

LCA is ideally suited to answer the following questions:

1. Does a cascading utilization of waste wood lead to lower environmental impacts from the production of wood based panels, compared to the production from primary wood?
2. What aspects of the cascading systems are decisive for the results? (sensitivity analysis)

1.2 Functional equivalence of cascading systems

A prerequisite to compare different production systems with LCA is the equality of benefit provided by the systems under study (DIN 2006a). Only if both systems create the same benefit, a comparison and eventual ranking is possible and acceptable. Determining the benefit created by a system is often straightforward when considering, for example, cradle-to-gate production processes of a certain good or service. However, a cascading utilization system produces several goods out of a certain amount of wood during its lifetime. A

LCA study investigating such a system encompasses multiple life cycles of different products, including their end of life. Defining the benefit (=functional unit) of such a complex system can therefore be rather challenging. Besides the production of materials and energy out of wood, the system also takes into account for the necessary disposal of waste wood. When comparing this system to the production of products out of primary wood, an equality of benefit from both systems has to be ensured. This problem has been addressed in a number of studies dealing with the approach of open loop recycling in waste management systems in LCA (Ekvall 1999; Finnveden 1999; Heijungs and Guinée 2007; Jungmeier et al. 2002). Although our focus is not primarily on waste management, but rather more on a holistic cascading utilization of waste wood, the challenges are similar. The ISO 14040 standard favors the system expansion method to ensure a functional equivalence of the compared systems.

Yet, system expansion as well as its "inversion," crediting for avoided burdens, is regarded critically by some authors. Heijungs and Guinée (2007) argue that crediting of systems, and thereby the required decision of which process will be assumed to be avoided, is one of the main reasons for strongly varying or even contradictory results when evaluating waste management systems. They propose that partitioning multi-output processes and thereby allocating the burdens to specific products is preferred. Another point mentioned by both Ekvall (1999) and Finnveden (1999) is the fact that applying system expansion approaches does not enable the focus on just one of the products provided by a system, which may lead to a loss of information concerning the single life cycles of the system.

However, the system expansion approach has also a number of strong points. Most importantly, it allows the avoidance of choices on allocation which in some cases also can have considerable influence on the results (economic vs. physical allocation) (Finnveden 1999; Ekvall 1999; Jungmeier et al. 2002; Werner et al. 2007). Finnveden et al. (2009) declare system expansion as suitable if LCA is used as tools to not only investigate the life cycles of single products but rather to examine combinations of several life cycles. As cascading per se leads to a multitude of products over the whole run of the cascade, our focus consequently is not on one product but rather on the overall products made out of the cascaded waste wood (boards, energy). Therefore, to compare the cascading system to products out of primary wood, an approach to LCA with allocation is not applicable. Also losses in information in regard to life cycles of single products as mentioned by Ekvall (1999) are of minor importance in our study, due to the more holistic focus.

For comparing a cascading utilization of waste wood to the use of primary wood resources as intended in our study, system expansion and derived approaches, such as the "avoided burden" concept, can therefore be seen as adequate and preferential. We chose this approach in order to enable the comparison of the two systems in our study. In this context, we derived answers to the following methodological questions from the presented LCA study of cascading uses of waste wood:

3. Is system expansion as described in ISO 14040 a suitable method to compare cascading to noncascading production systems?
4. How do choices of system expansion influence the results?

2 Material and methods

2.1 Systems under study

The starting point for the cascading system was 1 metric ton of untreated waste wood with a moisture content of 18 %. The waste wood was assumed to enter the system under study at the stage of "end-of-waste" of the previous production system. Consequently, it carried no burdens from previous life cycles. However, inherent properties of the material such as the content of biogenic carbon and primary energy were modeled and considered. As particleboard is the most common material application of waste wood in Germany, the basic waste wood cascading system consists of two steps of particleboard production followed by an incineration in a 6.4-MW combined heat and power plant (CHP plant), which is representative for waste wood incineration in Germany (Fig. 1). Between each step of the cascade, collection, sorting, and processing of the waste wood take place in order to ensure a suitable quality for the next application. The reference system was assumed to produce the same amount of particleboard from primary wood, mainly low diameter wood from thinning operations. The end of life of this particleboard also consisted of incineration in the same CHP plant as used in the cascading system. The use phase of the products was outside the scope of the study as it can be assumed to be similar for both systems and, consequently, would not influence the results.

In order to determine the influences of different specifics of the systems on the overall results, various parameter variations were modeled and their impact on the performance of the systems was analyzed (Section 2.2.2).

2.2 Approach to the research questions

2.2.1 System expansion to create equality of benefit

Depicting resource cascading in LCA leads to a rather complex model which comprises several different product life

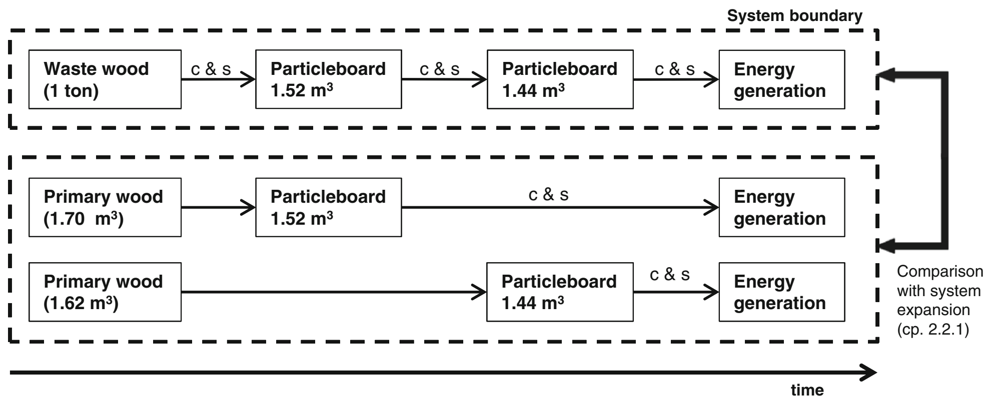

Fig. 1 Systems under study: waste wood cascade (*top*) and equivalent products from primary wood (*bottom*) (*c & s*: collection and sorting of the waste wood)

cycles and produces a number of products and services. A necessary prerequisite for the comparison of two systems in LCA is the equality of the benefits generated by the systems (DIN 2006a). Therefore, when comparing waste wood cascading to the use of primary wood, both systems have to provide the same multiple benefits. The standard ISO 14044 (DIN 2006b) describes a number of approaches to deal with multibenefit systems in LCA. The given stepwise procedure implicitly includes a preference for approaches which avoid allocation if possible. In our study, the primary wood system provides a considerably higher amount of energy from the end-of-life incineration of wood panels compared to the cascading system, since the amount of wood required to produce all panels (particleboard or oriented strand board) from primary wood is higher as each unit of wood is used only once for material production. Contrarily, the cascading system utilizes far less wood than the primary system as it produces two or more products in multiple steps from the same amount of wood. This consequently results in lower end-of-life energy amounts. In order to ensure the comparability of the two systems, we applied a system expansion approach, as described by Fleischer and Schmidt (1996) and previously applied by Bystricky et al. (2010). Figure 2 depicts the concept of our system expansion approach exemplified for two different products provided by the cascading system (e.g., particleboard and oriented strand board).

The functional unit for comparing a cascading use of waste wood to the production of equivalent products from primary wood by means of system expansion is summarized in Table 1. The chosen source of energy for the system expansion approach is assumed to have a great influence on the overall results. In the basic scenario, we assumed the additional energy needed in the cascading system to be generated by incineration of waste wood. Additionally, system expansion (SE) variants were modeled as part of the sensitivity analyses.

An important prerequisite when applying system expansion approaches is the equivalency of the products which are supposed to be substitutes (DIN 2006b; Heijungs and Guinée 2007). In case of differing sources of energy generation, such a declaration of equivalency is rather noncontroversial. Each unit of heat or power, regardless of the energy carrier used for its production, is equivalent. The equivalency of panels out of waste wood and primary wood, however, cannot be declared so easily. Differences in color and—most importantly—the customer's perception of the products out of "waste" as something less valuable might point toward lacking equivalency. Yet, as Fleischer and Schmidt (1996, p. 26) point out, "small differences in the quality of the compared products do not influence the comparability [as] otherwise a comparison would frequently be impossible". As wood-based panels are in most cases not utilized "raw" but painted or coated, differences in color can be seen as not relevant and, therefore, harmless for a comparison. Opinions of customers toward products of secondary materials have to be taken seriously, but should not be taken into account when applying a scientific approach such as LCA. Additionally, all particleboards regardless of the used raw material have to fulfill the standard EN 13986 requirements (DIN 2005) and can thus be assumed to be suitable for the intended purpose. Therefore, the equivalency of the products (energy and panels) from waste wood and primary wood compared in this study can be assumed.

2.2.2 Sensitivity analyses

The robustness of the results toward systemic changes and uncertainties of assumptions was examined by performing sensitivity analyses for a number of aspects of the systems under study. Table 2 gives an overview of the considered parameters and their variations. The basic scenario represents the average German conditions. Generally, changes were done in the cascading system in order to determine the effects on development of the impact categories relative to the primary wood system.

Already in the basic variant of the cascade, transportation distances for waste wood were assumed to be higher than those for primary wood, as there are fewer waste wood power plants and only a certain number of sorting and processing facilities throughout south-east Germany, thereby increasing the distance for transporting the waste wood. In scenario A1,

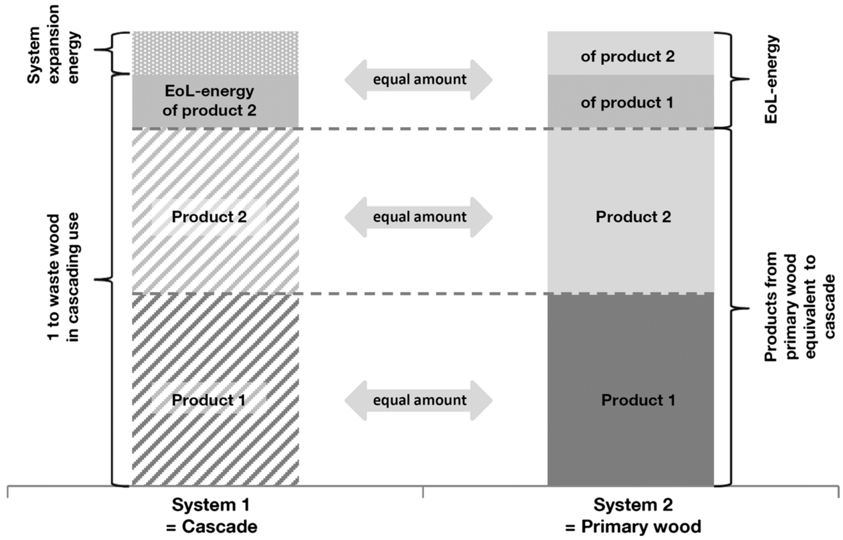

Fig. 2 Scheme of the system expansion applied to compare a cascading use of resources to the use of primary resources for a cascade with two exemplary material production steps

the transportation distances of waste wood were assumed to be equal to those of primary wood, as may be the case in the future, if more waste wood will be used in a cascading application and more processing facilities will be available. Scenario A2 assumed a tripling of the distances of waste wood transportation to 450 km for material application in order to determine whether the performance of a cascading system is dependent on the difference between the transportation of waste wood and primary wood. Finally, scenario A3 assumes a doubling of the distances in both systems to examine the overall effects of transportation on the results. The default case of waste wood processing encompassed an electricity-driven, stationary crusher, as it is the state of the art in larger waste wood facilities in Germany. However, facilities which especially handle only smaller amounts of waste wood per year also operate with mobile diesel-powered crushers. Scenario B assumes the chipping or crushing and sorting to be done in such a way. If taking the effects of material substitution into account, the number of steps of wood cascades influences the environmental performance of cascading (Gärtner et al. 2013). To determine if this is also the case without considering substitution, we increased (C1) and decreased (C2) the number of cascade steps as part of the sensitivity analyses.

Currently, particleboard is the only noticeable material application for waste wood in Germany. Therefore, we considered only this panel type in the basic variant of the systems. In order to determine whether the production of an additional panel type such as oriented strand board (OSB) influences the results, scenario D includes OSB production as a first step of the cascade. Scenarios E to G explore the influence of variations in the energy production of the systems, either by assuming a production of only electricity as end-of-life option (scenario F), applying different degrees of efficiency to the CHP incineration, or examining the effects of waste wood as a resource to generate the process heat to produce particleboard from fresh wood. Finally, scenario group H examines the influence of different fuels to generate the energy for system expansion.

2.3 Data and modeling

2.3.1 Data sources

We used the software GaBi v 6 for all LCA models. If not specified otherwise, the data of ecoinvent v 2.2 (Frischknecht and Jungbluth 2007) was the basis for modeling the systems. Where available, we used data which is representative for German conditions. Table 3 summarizes specifics and data sources for key processes of our LCA models.

The models of OSB and particleboard (PB) are based on the inventory data provided by Rüter and Diederichs (2012), which represents average German conditions. For modeling the waste wood cascading and the primary wood system, adjustments regarding the wood input and the energy input were made. OSB production from waste wood is currently not practiced on an industrial level; consequently, no industry data

Table 1 Composition of the functional unit for the comparison between cascading of waste wood and utilization of primary wood, including the additional energy accounted for in system expansion

	Particleboard (m^3)	End-of-life energy (MJ)		System expansion energy (MJ)	
		Heat	Power	Heat	Power
Cascade	2.96	12,077	1,214	12,699	1,269
Primary wood	2.96	24,776	2,482	–	–

Table 2 Overview of the scenarios considered in the sensitivity analyses of the cascading of waste wood

Scenario	Parameter	Default in basic scenario	Variations
A	Transportation distance of wood resources	Waste wood: 75 km to incineration, 150 km to material application	A1 Equal distances for both wood types
		Primary wood: 50 km to incineration, 100 km to material application	A2 Tripling of distances for waste wood only
			A3 Doubling of all distances
B	Waste wood preparation	Electric crusher	Diesel-powered crusher
C	Number of cascade steps	2 steps of particleboard production	C1 3 steps of particleboard
			C2 1 step of particleboard
D	Panel types	Particleboard only	Oriented strand board (OSB)+particleboard
E	Degree of efficiency of CHP	78 % for end of life incineration in both systems	E1 Reduction to 60 % for cascade system (incl. system expansion)
			E2 Reduction to 40 % for the cascade system (incl. SE)
F	End of life	CHP plant, 6.4 MW	Electricity-only plant, 20 MW
G	Process heat for particleboard production	From primary wood for primary wood panels	From waste wood also for primary wood panels
H	Fuels for system expansion	Waste wood incineration in CHP plant	H1 Forest wood chips in CHP plant
			H2 Fossil energy sources

is available for such a process. Therefore, we based our model on the experiments of Loth and Hanheide (2004), who developed a method to produce strands of suitable quality out of waste wood by producing maxi-chips in a first step, followed by a stranding of the chips. OSB production from waste wood is considered in our study as a sensitivity analysis in order to assess whether the integration of another type of wood-based panel influences the ranking of the systems decisively.

Particleboard from 100 % of waste wood is currently not produced in Germany. Therefore, we adapted the average German life cycle inventory data (Rüter and Diederichs 2012) which assume a waste wood content of 20 %. The adaptions consisted mainly of increasing the wood loss by chipping and of decreasing the energy required for drying of the wood. The extent of the energy reduction was based on industry information from a German particleboard manufacturer. No adaptations were made for the adhesive resin fraction and other chemicals. The process heat for production of panels from waste wood was assumed to be produced from waste wood as is the case in the particleboard industry in south-east Germany, whereas in case of the panels from primary wood, only the production rejects were assumed to be incinerated for energy production and additional energy was generated from other industrial residue wood.

2.3.2 Impact categories

We chose the following impact categories for life cycle impact assessment (LCIA), which were calculated according to CML-IA (Guinée 2002): impact on global warming caused by fossil sources (GW fossil), primary energy consumption of fossil sources (PENR), primary energy demand from renewable sources (PER), acidification (AC), eutrophication (ET), and human toxicity (HT). In case of GW, we excluded biogenic carbon. As all considered systems depict whole life cycles from carbon dioxide uptake from the air during plant growth to a final release of the carbon via incineration, the systems can be regarded as neutral in regard to biogenic carbon. This approach is in accordance with Pawelzik et al. (2013), who recommend accounting for biogenic carbon only in case of cradle-to-gate assessments.

Additionally, the midpoint indicators for land occupation (LO) and transformation (LT) of ReCiPe 1.07 (Goedkoop et al. 2009) were considered in our assessment, since contrary to the production of primary wood, the provision of waste wood has no direct impact on land occupation. By using secondary resources such as recovered wood, the pressure on available land can be decreased.

3 Results

3.1 Basic scenario

When producing the same amount of wood-based panels and energy from both cascading utilization of waste wood and from primary wood, environmental burdens are lower in all considered impact categories for the cascade. Figure 3 depicts the differences for the basic scenario with waste wood as the fuel considered in system expansion. Savings by cascading range from slightly over 10 % for the impact category GW to close to 100 % for the impact category land occupation.

A reason for the relatively minor advantages of cascading over the use of primary wood especially in the categories GW and PENR may be that the production of primary wood does

Table 3 Process specifications and data sources for major processes of modeling waste wood and primary wood utilization

Process	Specifications and assumptions	Data source
Panels		
PB waste wood	• German average technology • Reduction of process heat for drying step due to lower water content of waste wood • Wood input: 100 % waste wood	• Rüter and Diederichs (2012) • Industry data (personal communication)
PB primary wood	• German average technology • Wood input: 100 % industrial round wood	• Rüter and Diederichs (2012) • Industry data (personal communication)
OSB waste wood	• Innovative production process with a 2-step strand production (chipper and strander) • Wood input: 100 % waste wood	• Loth and Hanheide (2004)) • Rüter and Diederichs (2012)
OSB primary wood	• German average technology • Wood input: 100 % industrial round wood	• Rüter and Diederichs (2012)
Energy production/end of life		
Waste wood in CHP plant	• 6.4 MW CHP • SNCR filter for flue gas cleaning • Degree of efficiency: 78 % • Emissions adapted for incineration of waste wood	• ecoinvent v 2.2
Forest wood chips in CHP plant	• 6.4 MW CHP • SNCR filter for flue gas cleaning • Degree of efficiency: 78 %	• ecoinvent v 2.2
Waste wood to electricity	• 20 MW electric output • Flue gas cleaning • Degree of efficiency: 28 %	• BioEnergieDat (www.bioenergiedat.de)
Heat from fossil sources	• Generation from natural gas • Plant size >100 kW; low NO_x status	• ecoinvent v 2.2
Electricity	• German electricity production mix	• ecoinvent v 2.2
Transportation distances		
Waste wood	• Collection to processor: 50 km • Processor to incineration: 75 km	• Industry data
	• Processor to material application: 150 km	• Rüter and Diederichs (2012)
Primary wood	• Forest wood chips to incineration: 50 km • Industrial round wood for PB: 90 km • Industrial roundwood for OSB: 95 km	• Rüter and Diederichs (2012)
Waste wood collection, sorting, and chipping		
	• Manual sorting • Electrical crusher • On-site transportation with wheel loader • Removal of impurities	• Industry data from 3 different production sites in south-east Germany

not create substantial environmental impacts, contrary to the provision of most fossil resources. Consequently, when comparing a recycling system such as the cascading of waste wood to an already rather environmentally friendly system such as products from primary wood, no outstanding amounts of savings can be expected.

In order to get a better understanding of the underlying factors influencing the overall results presented in Fig. 3, the LCIA results of the cascading and primary wood systems are broken down into the contributing process groups for the basic variant (Fig. 4). The light gray section of the cascade columns is the part of the overall impact which is caused by the provision of the additional energy by waste wood required to achieve an equality of benefit by system expansion. The biggest single contribution to nearly all impact categories is made by the process group "chemicals" which contains the impacts of the adhesive resin fraction and other chemicals needed in the panel production. Only in case of land transformation and land occupation, the acquisition of primary wood as a raw material has a higher contribution to the overall impact.

The process group "raw materials" summarizes the impacts created by either the provision of primary wood or recovered

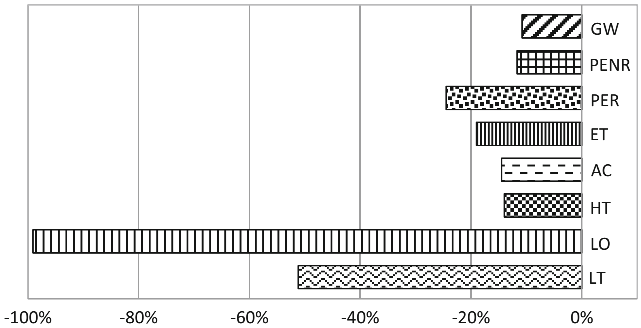

Fig. 3 LCIA results for the basic scenario of the cascading system (SE waste wood). Displayed is the impact of the cascading system relative to the primary wood system as a reference for all considered impact categories

wood, depending on the system. Sorting and crushing the waste wood to produce suitable input material for either panels or incineration leads to considerably less impacts in all categories than providing equivalent raw material from primary wood. The value for GW is 50 % reduced, for PENR nearly 80 %. However, as the contribution of raw material provision to the overall impacts of the systems is lower than 5 % for all categories except PER, LT, and LO, these differences only have a minor influence on the overall impact of the systems.

The process group "transport" includes transportation of all raw materials. Despite the lower distances assumed in the primary wood system, the impacts from transportation are higher because the primary wood is generally transported with a higher moisture content than the waste wood.

The electricity needed in the panel production (part of "energy fossil") is higher for the primary wood system as the chipping or stranding of the industrial round wood takes place at the panel production site, whereas the waste wood is already delivered in chipped form and the associated energy consumption already accounted for in the "raw material" section. Particleboards from waste wood have a lower consumption of process energy ("energy bio"), as the waste wood has a considerably lower moisture content and less energy is needed for drying compared to the production with fresh wood. The aspects where a distinction between the systems is possible—mainly the impacts related to raw material provision—provide minimal contribution to the overall system impact and do not strongly influence the overall results. The albeit small but noticeable advantages of cascading variants using wood as additional energy source should be regarded against this background.

3.2 Sensitivity analyses

3.2.1 Influence of system expansion

The type of fuel accounted for in the system expansion scenarios (group H) strongly influences the performance of the cascading system in comparison to the primary wood reference system. Even if the additional energy is assumed to be generated by incinerating primary wood instead of waste wood (variant H1), cascading still leads to lower impacts on the environment compared to the reference system (Table 4). Yet, for all impact categories, the advantages of the cascade decrease, especially notable in the categories of land occupation and transformation, due to the use of primary wood. The second considered variant (H2), which represents the provision of the system expansion energy by natural gas and the electricity production mix of Germany, leads to a 78 % higher amount of greenhouse gases and a 96 % higher consumption of primary energy from nonrenewable sources by the cascading system, compared to the primary wood system. Eutrophication is the third impact category which depicts an advantage for the use of primary wood, while the four remaining categories depict lower values for the cascading system with a system expansion based on predominately fossil fuels.

3.2.2 Influences of specific processes of the cascading system

The results of the sensitivity analyses focusing on process specifics are summarized in Table 4 (scenarios A to G). Transportation mainly influences the categories GW, PENR, and ET as it consumes fossil fuels. The categories PER, HT, LC, and LO are only marginally influenced since they do not predominately measure the impacts of fossil resource consumption. Consequently, the performance of the cascade in relation to the primary wood system improves, especially in regard to GW, PENR, and ET in the scenario which assumes smaller distances for the cascading system (A1). Scenario A2 represents a tripling of the distances of waste wood transportation to 450 km for material application. Despite this increase, cascading still does not lead to higher environmental impacts than the use of primary wood. A doubling of the distances in both systems (A3) has no major influence on the results, due to the overall low influence of transportation-related impacts. Scenario B was calculated by assuming crushing was done with a diesel-driven device. However, the minor changes in the results compared to the basic variant indicate that the sort of chipper or crusher used in the facility has virtually no influence on the environmental impacts.

The increase of cascading steps in scenario C1 led to a slight reduction of the advantage of the cascading system, whereas the decrease to one particleboard step (C2) led to a better performance relative to the primary wood system. Overall, the number of cascading steps can be seen as inconsequential to the comparison.

Including the production of another wood panel type (OSB) into the waste wood cascade entails a less pronounced advantage of the cascading system. The degree of efficiency of the end-of-life incineration strongly influences the results: decreasing the efficiency in the cascading system including

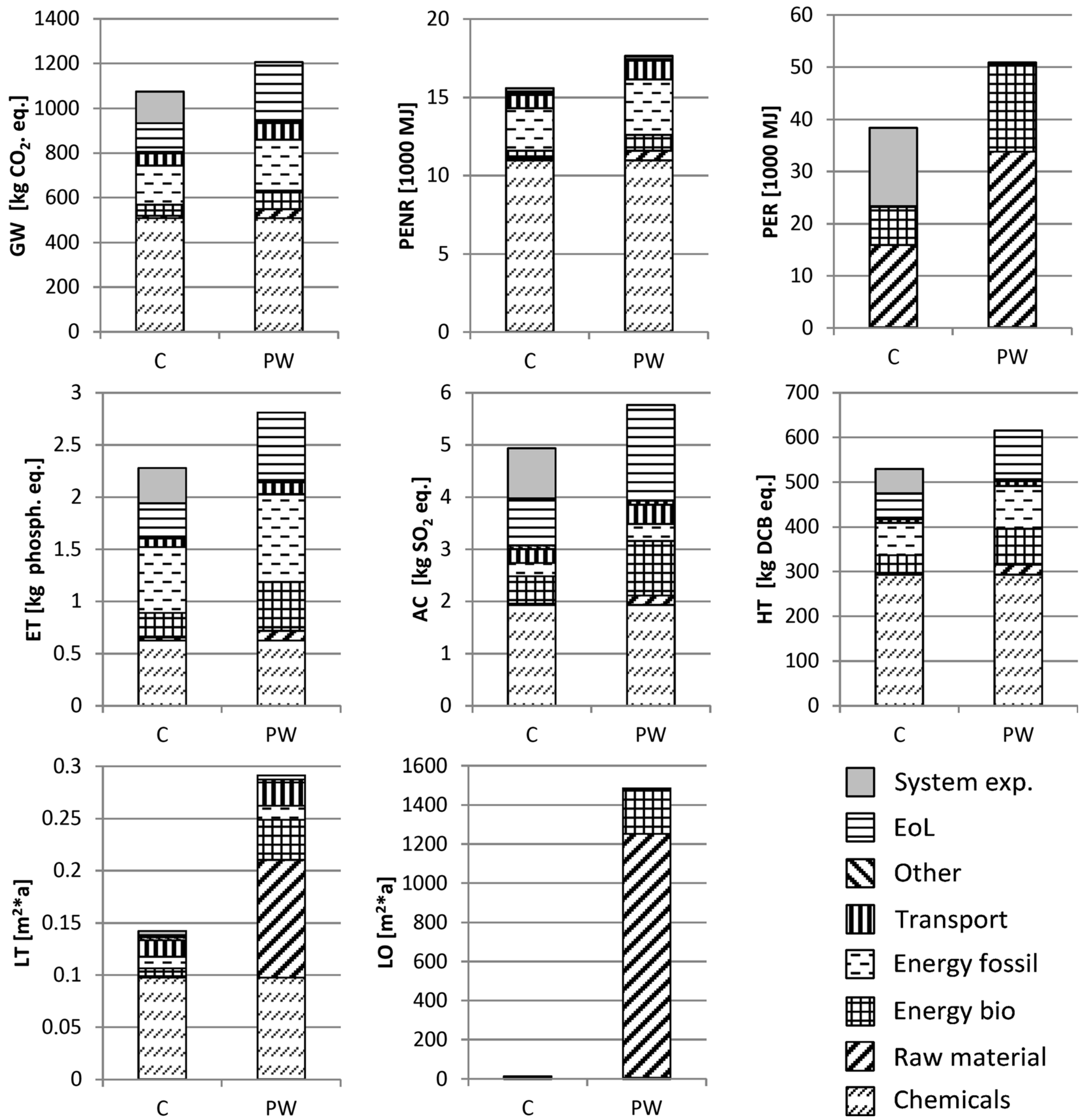

Fig. 4 Contribution of different process groups of the life cycle to LCIA results in the basic scenario for the considered impact cetagories (*C* cascading system, *PW* primary wood system)

the system expansion energy to 60 % substantially diminishes the potential advantages of the cascade for nearly all impact categories. Assuming a decrease to a value as low as 40 % consequently favors the primary wood system considerably.

Changing the incineration at the end of life from a CHP plant to a power plant which generates only electricity improves the performance of the cascading relative to the primary wood system (scenario F). Assuming that the process heat required for particleboard production is generated by incinerating waste wood also in case of the primary wood system does not distinctly influence the results.

The results of the sensitivity analyses confirm the findings based on the analysis of the contribution of the process group to the overall impacts (Section 3.1). Due to the overwhelming influence of the adhesive resin fraction on most impact categories, the system comparison proved to be insensitive to most of the more "technical" aspects which only contribute a small amount to the overall impacts of the systems. Thus, changes in these process groups have no significant effects on the overall comparison. It stands to reason that this may be different when integrating wood products which are manufactured without considerable chemical raw material contribution, e.g., floor boards, in the cascades. However, we decided to focus our assessment on wood panels as they are today the only application of a waste wood as a material resource with an industrial importance.

Table 4 Variations in LCIA for different system variants. Energy for system expansion is assumed to be generated from waste wood in all cases except variants H. The numbers indicate the impacts caused by the cascading system relative to the primary wood system. Positive values, which indicate a relative advantage of the primary wood system, are stated in italics

Scenario	Aspect of analysis	GW (%)	PENR (%)	PER (%)	AC (%)	ET (%)	HT (%)	LO (%)	LT (%)
Basic		−10.8	−11.7	−24.5	−14.5	−19.1	−14.0	−99.1	−51.2
A	Transportation								
A1	Equal distance	−12.2	−13.2	−24.5	−15.9	−20.0	−14.4	−99.1	−52.9
A2	Waste wood tripled	−3.0	−3.3	−24.5	−6.5	−14.0	−11.7	−99.1	−41.6
A3	Doubled both	−11.5	−12.4	−24.5	−15.1	−19.3	−14.2	−99.1	−49.6
B	Diesel chipper (waste wood)	−10.8	−11.6	−24.5	−14.4	−19.1	−13.8	−99.1	−50.8
C	Number of cascade steps								
C1	3 steps	−10.6	−11.4	−24.5	−14.3	−18.9	−13.9	−99.1	−50.9
C2	1 step	−11.5	−12.5	−24.5	−15.2	−19.5	−14.2	−99.1	−52.1
D	Panel types	−7.0	−7.8	−19.5	−9.7	−11.6	−11.2	−99.2	−54.9
E	Efficiency of CHP incineration								
E1	60 %	−3.5	−10.9	−6.2	−4.2	−11.7	−8.4	−99.0	−50.3
E2	40 %	*11.6*	−9.3	*31.9*	*17.1*	*3.6*	*3.1*	−98.9	−48.5
F	Electricity only as EoL	−13.6	−11.8	−24.5	−17.4	−22.5	−15.6	−99.3	−51.7
G	Process heat from waste wood	−12.0	−11.3	−21.1	−14.7	−19.0	−14.1	−98.9	−46.9
H	System expansion								
H1	Forest wood chips	−10.1	−8.9	−18.9	−12.0	−17.3	−12.2	−54.5	−28.1
H2	Fossil fuels	*78.1*	*96.4*	−53.6	−10.0	*9.2*	−1.0	−98.9	−11.8

4 Discussion

4.1 Comparison of the two systems

The differences between the systems which range from 10 to 20 % for most impact categories except LT and LO may be surprising when taking into account the high expectations, especially from legislative bodies, of the cascading of resources (BMU 2012; European Commission 2011). However, our study focuses on the direct effects of cascading. Our results are in accordance with previous findings by Sathre and Gustavsson (2006) who also concluded that direct cascade effects are relatively minor when comparing cascading to the use of primary wood. Yet, most studies focus on greenhouse gases (Sikkema et al. 2013; Werner et al. 2010; Sathre and Gustavsson 2006). When taking into account additional aspects such as land transformation and other impacts on the environment as it is possible with an extensive LCA, cascading proves to be an even more preferable treatment option of waste wood. Gärtner et al. (2013) conducted LCAs of wood-based products in cascades and compared the environmental impacts to those of functionally equivalent nonwood products. They found cascading to be neutral or positive, yet also stated that the results depend on the chosen product equivalent. These presented results depict that even when only considering direct cascade effects and without accounting for the substitution of fossil energy, cascading is a viable option. The categories PER, LO, and LT show the greatest advantages for the cascading system. It indicates that the advantages of cascading are mainly attributed directly to the provision of the respective wood resources (waste wood and primary wood), since the above-mentioned categories account for the use of the resource wood.

4.2 Sensitivity analysis

In our study, the performance of the cascading system depended on the energy source chosen for the additional energy needed to achieve an equality of benefits. If this energy is produced from conventional sources, the respective environmental impacts outweigh any savings from cascading and dominate the overall results of the system. Heijungs and Guinée (2007) state that the selection of the additional process or avoided burden is often highly biased and can be used to influence the results. The basic variant (SE by waste wood) and the scenario H2 (SE fossil based) can be perceived as a "best case" and "worst case," as in reality, the additional energy probably will be a mix of renewable and conventional energy sources.

Most authors dealing with system expansion approaches discuss system expansion in comparison to allocation as ways to deal with multi-output systems (Finnveden 1999; Finnveden et al. 2009; Heijungs and Guinée 2007; Nguyen and Hermansen 2012). In our case, allocation is not a suitable option to achieve the comparability of the two systems as the focus is on waste wood cascades with all resulting products and not on a single desired product. Thus, system expansion is the only viable option to deal with the multibenefit nature of the studied systems. However, one challenge, discussed also by Heijungs and Guinée (2007), became evident: the choice of process to expand the system. The way of additional energy generation can reverse the ranking of the two compared systems, as evident for the two major impact categories of GW and PENR when accounting with conventional energy sources for system expansion. Consequently, in order to determine if cascading is to be the preferred use of waste wood, the choice of the process for system expansion is decisive.

As shown with the sensitivity analysis of group C, the comparison of systems is indifferent to the number of cascade steps. The study design, which compares functionally equivalent systems but does not limit the amount of available wood resources entering the systems, certainly contributes to this outcome. Material losses during collection and recycling are considered but have virtually no influence on the results since both systems are assumed to produce an equal amount of wood products and the major factor influencing the environmental impact of the systems (resin fraction of particleboards, process energy, and transportation) is directly dependent on the product output of the system, not the input of resources.

4.3 Limitations of the study

Our study did not take into account aspects of time when comparing the systems. Contrary to the primary wood system, the cascade systems provide the products not at the same time but over a period which can encompass several decades, depending on the application of the cascaded products. This is important as technologies improve over time, especially in the energy sector but also in the production of wood panels. Consequently, the second or third product step of a cascade will likely “compete” with products which are different from the ones of today. However, as the products compared in our study are rather similar, technological changes will affect both the cascaded products and the primary wood products in a similar way, so that the depicted trends in the comparison of the systems would probably remain unchanged.

Carbon sequestration in wood products and the associated mitigation effects on climate change were also not in the scope of our study. However, these aspects shall be discussed when further assessing cascading wood utilization. Cascading can prolong the time of carbon storage considerably, thereby decreasing climate impacts at least if taking a medium time frame of several decades into account. Currently, several methods exist to integrate the effects of carbon sequestration in wood products in LCA (Brandão et al. 2013).

Factors deliberately not accounted for in our study are the effects of substitution, even though they have a certain influence in reality. If more wood products were manufactured from secondary resources, the overall amount of wood products could increase, thereby substituting for more energy-intensive nonwood products (Gärtner et al. 2013). However, a shift of primary wood resources toward small-scale energy production in households is also a conceivable option, if the demand for primary wood for materials production decreases. Further studies encompassing a regional scale and the consequences of shifting resource allocation are needed to add this perspective to the assessment of a cascading use of waste wood.

Land use impacts by utilizing secondary resources instead of primary ones are difficult to assess with attributional LCA models. We tried to integrate the aspect by taking the impact categories of land occupation and transformation into account. In order to comprehensively assess the effects of a cascading utilization, a systemic approach coupling limited wood availability with the given demand for wood products would be necessary. The system expansion approach chosen in this study should be seen as a first step toward such an assessment. The notably lower land impacts of cascading (impact categories LO and LT) indicate that further investigation on a regional level is needed.

5 Conclusions

To conclude, we can answer the research questions as follows:

1. Utilizing waste wood in cascades is beneficial when considering environmental impacts. Our study approach, which only accounted for direct cascade effects, depicted decreases between 10 and 50 % for the different impact categories. In reality, positive effects from substituting fossil-based materials and the effects of increased land use efficiency will add to these direct benefits of cascading. Therefore, cascading proves to be an environmentally beneficial option of resource use.
2. The performance of the cascading system is especially influenced by the efficiency of the end-of-life incineration when it differs from the compared primary wood system. Transportation, the method of waste wood processing and cleaning, the number of cascade steps, and the type of panels produced have only minor direct effects.
3. System expansion as described in ISO 14040 proved to be a viable option for assessing a multi-output cascading system.
4. The choice of energy used for calculating the system expansion is decisive for the impact categories of GW and PENR. Accounting for conventional energy as system expansion entails distinct advantages of the primary wood system compared to the cascading system. Therefore, the way system expansion is modeled has to be considered carefully.

These conclusions are applicable for untreated wood which is suitable for material applications. Only this share of the overall available waste wood can be utilized in a cascading way. Consequently, our study depicts the best case scenario of dealing with waste wood. Direct incineration of the more contaminated amounts will also be necessary in the future. To maximize the benefits from waste wood and minimize the associated environmental impacts, collection and sorting have to be improved in order to steer the waste wood streams to the best possible application, which in the case of untreated wood should be a cascading application.

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