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Resource and eco-efficiency assessment of utilizing recovered solid wood in cascades

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Summary

The increasing environmental awareness, the scarcity of non-renewable resources and the ambition to transform the economy towards a bioeconomy will likely increase the demand for wood in Germany and Europe. To meet this growing demand, wood cascading is expected to increase the efficiency of wood utilization and has thus found wide support in policy and industry. The concept of wood cascading describes the sequential use of one unit of a resource in multiple material applications with its final use for energy generation. Besides the efficiency increase, wood cascading is expected to decrease the environmental impacts of wood utilization and to offer new opportunities for the production of value added recycled wood products. Despite the political support, the effects of wood cascading with respect to the efficiency of wood use are still unknown. Furthermore, wood cascading is still in its infancies. Thus, for the practical implementation of wood cascading, new environmentally beneficial and economically viable recycling technologies need to be developed. Therefore, this study analyses the resource use and the resource efficiency of a wood cascading system in comparison with a reference system based on primary wood using exergy analysis. For a newly developed technology to recycle recovered solid wood into clean and standardized lamellae for further material use[1], the eco-efficiency is determined using a joint analysis of Life Cycle Assessment and Life Cycle Costing in comparison to a current treatment alternative.

The results indicate that wood cascading leads to a reduction in resource consumption compared to the reference system using primary wood. While the direct cascading effects are of minor relevance, avoiding the primary wood production is the most resource related benefit of wood cascading. It further leads to a higher resource efficiency of wood utilization compared to the use of primary wood (46 % to 21 %), although the results are highly influenced by system expansion modelling. Longer cascades turned out to be not *per se* advantageous in terms of resource efficiency. The efficiency highly depends on the considered products and the reference cascade. To maximize efficiency, the wood should be kept as long as possible in solid wood products, while by-products should be used in material applications as well as material losses and consumption of energy and utilities should be reduced. Exergy analysis proved to be a suitable method for the resource efficiency analysis of wood cascading systems as it accounts

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[1] The machining concept was developed within the framework of the project Cascading Recovered Wood.

for their typical characteristics. However, shortcomings in the accounting for land use in exergy analysis were identified, when applied to natural-industrial hybrid-systems.

With respect to the material recycling of recovered solid wood, the results indicate that the recycling into glued laminated timber products is economically viable and offers possibilities for the production of value added products with low environmental impacts. The environmental impacts and costs of the considered recycling scenarios are up to 29 % and 32 % lower compared to a direct incineration. While the operational processes for the recycling are of minor relevance, present technologies like the lamination and incineration processes are key impact and cost drivers. In general, the material recycling shows a 15-150 % higher eco-efficiency. However, scenario analysis revealed a decisive influence of system expansion modelling on the outcome of the comparison. Scenario analysis and a careful modelling of system expansion processes are therefore recommended to provide transparent results. For the evaluation of emerging wood recycling technologies, qualitative data as well as better knowledge on the properties of recovered wood and its application are crucial for the reliability of future studies.

To conclude, the further development of technical processes for the recycling of recovered wood can be recommended in order to enhance the practical implementation of wood cascading. In most scenarios, the results indicate that the expectations of efficiency optimization, environmental impact reduction and economic viability towards wood cascading and wood recycling are met. For a future bioeconomy, the management of recovered wood in cascading systems can contribute to increase the efficiency of wood utilization, mobilize currently unused materials and thereby contribute to satisfy the growing demand for wood.

Zusammenfassung

Mit dem zunehmenden Umweltbewusstsein, der Endlichkeit nicht erneuerbarer Ressourcen sowie dem politischen Bestreben, die Wirtschaft in eine Bioökonomie umzuwandeln, muss zukünftig von einer steigenden Nachfrage nach Holz ausgegangen werden. Um dieser ansteigenden Nachfrage gerecht zu werden, wird seitens der Politik und Industrie die Kaskadennutzung als Lösungsansatz zur Steigerung der Nutzungseffizienz von Holz gefordert und gefördert. Die Kaskadennutzung beschreibt die sequenzielle Nutzung einer Einheit einer Ressource in mehreren stofflichen Anwendungen mit ihrer finalen Verwendung zur Energiegewinnung. Neben einem Anstieg der Nutzungseffizienz wird erwartet, dass die Kaskadennutzung zu einer Reduktion der Umweltwirkungen im Zusammenhang mit der Holznutzung beiträgt und neue Möglichkeiten für die Herstellung hochwertiger Produkte aus Gebrauchtholz bietet. Trotz der politischen Unterstützung und zahlreicher Studien sind die Auswirkungen der Kaskadennutzung auf die Effizienz der Holznutzung bisher jedoch kaum untersucht. Darüber hinaus steht die Kaskadennutzung von Holz noch ganz am Anfang. Für die praktische Umsetzung müssen daher neue umweltfreundliche und wirtschaftlich tragfähige Recyclingverfahren für die stoffliche Nutzung von Gebrauchtholz entwickelt werden. Folglich wird in dieser Arbeit die Ressourceneffizienz eines Holzkaskadensystems im Vergleich zu einem Referenzsystem auf Basis von Frischholz in einer Exergieanalyse bewertet. Für ein neu entwickeltes Recyclingverfahren zur Produktion von gereinigten und standardisierten Lamellen aus gebrauchtem Vollholz für stoffliche Anwendungen wird die Ökoeffizienz auf Basis einer kombinierten Analyse aus Ökobilanzierung und Lebenszykluskostenrechnung ermittelt und mit der direkten energetischen Nutzung verglichen.

Die Ergebnisse zeigen, dass die Kaskadennutzung von Holz zu einer Reduzierung des Ressourcenverbrauchs im Vergleich zum Referenzsystem beiträgt. Während die direkten Kaskadeneffekte von untergeordneter Bedeutung sind, ist die Einsparung von Frischholz und seiner Produktion der wesentliche ressourcenbezogene Effekt der Kaskadennutzung. Sie führt zudem zu einer höheren Ressourceneffizienz im Vergleich zur Verwendung von Frischholz (46 % zu 21 %), wobei die Ergebnisse stark von der Modellierung der Systemerweiterungsprozesse beeinflusst werden. Längere Kaskaden erwiesen sich dabei im Vergleich zu kürzeren nicht *per se* als effizienter. Stattdessen hängt die Effizienz besonders von den berücksichtigen Produkten sowie der jeweiligen Vergleichskaskade ab. Um die Effizienz zu maximieren, sollte das Holz möglichst lange in wenig bearbeiteten Produkten verwendet

werden. Darüber hinaus sollten Nebenprodukte stofflich verwendet werden, Materialverluste reduziert und Energie- und Materialverbräuche geringgehalten werden. Aus methodischer Sicht hat sich die Exergieanalyse als geeignete Methode zur Ressourceneffizienzanalyse von Holzkaskadensystemen erwiesen, da sie deren charakteristische Eigenschaften, wie z. B. Multifunktionalität, berücksichtigt. Dennoch zeigt sie bei ihrer Anwendung auf hybride Systeme an der Schnittstelle zwischen Ökosphäre und Technosphäre Schwachstellen in der Bilanzierung von Landnutzungseffekten.

Im Hinblick auf das Recycling von Gebrauchtholz deuten die Ergebnisse darauf hin, dass eine Verwendung recycelten Gebrauchtholzes in Brettschichtholzprodukten wirtschaftlich tragfähig erscheint und die Möglichkeit zur Herstellung hochwertiger Produkte mit geringen Umweltwirkungen bietet. Im Vergleich mit der direkten Verbrennung zeigen sich 29 % und 32 % geringere Umweltwirkungen bzw. Kosten für das stoffliche Recycling. Während die Aufbereitungsprozesse für die Umweltwirkungen des Recyclingszenarios von untergeordneter Bedeutung sind, stellen Verklebungs- und Verbrennungsprozesse die wesentlichen Umweltwirkungs- und Kostentreiber dar. Insgesamt weist das stoffliche Recycling eine um 15-150 % höhere Ökoeffizienz auf. Die Ergebnisse verschiedener Szenarien zeigen jedoch einen entscheidenden Einfluss der Modellierung der Systemerweiterungsprozesse auf das Ergebnis des Vergleichs. Es wird daher empfohlen, verschiedene Szenarien zu berechnen sowie auf eine sorgfältige Modellierung der Systemprozesse zu achten, um transparente Ergebnisse zu erzielen. Für die Bewertung in der Entwicklung befindlicher Recyclingverfahren für Gebrauchtholz sind belastbare Daten sowie bessere Kenntnisse über die Eigenschaften von Gebrauchtholz und seine Anwendung entscheidend für die Verlässlichkeit zukünftiger Studien.

Ausgehend von den Ergebnissen der Arbeit kann die technische Weiterentwicklung zum Recycling von Gebrauchtholz empfohlen werden, mit dem Ziel die Kaskadennutzung in der Praxis zu implementieren. Die Ergebnisse zeigen, dass die Kaskadennutzung und ein Holzrecycling zur Steigerung der Ressourceneffizienz und zur Reduktion der Umweltwirkungen beitragen kann und dabei wirtschaftlich tragfähig erscheint. In einer zukünftigen Bioökonomie kann die Kaskadennutzung von Holz gemeinsam mit innovativen Recyclingverfahren dazu beitragen, die Effizienz der Holznutzung zu steigern, bisher ungenutzte Rohstoffe zu mobilisieren und damit der wachsenden Nachfrage nach Holz gerecht zu werden.

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Index of abbreviations

ADP	Abiotic Depletion Potential
ALO	Agricultural Land Occupation
AltholzV	Altholzverordnung (Ordinance on the management of waste wood)
AoP	Area of protection
BIM	Building Information Modelling
BMEL	Bundesministerium für Ernährung und Landwirtschaft (Federal Ministry of Food and Agriculture)
BMU(B)	Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit (Federal Ministry of the Environment, Nature Conservation and Nuclear Safety)
BReg	Deutsche Bundesregierung (German Federal Government)
BT	Deutscher Bundestag
C	Cascading (system)
CaReWood (CW)	Cascading Recovered Wood
CDP	Cumulative Degree of Perfection
CDW	Construction and demolition waste
CED	Cumulative Energy Demand
CEENE	Cumulative Exergy Extraction from the Natural Environment
CExD	Cumulative Exergy Demand
CHP	Combined heat and power
DIN	Deutsches Institut für Normung (German Institute for Standardisation)
EC	European Commission
EE	Eco-efficiency

EEG	Erneuerbare Energien Gesetz (Renewable Energy Act)
ELCA	Exergetic Life Cycle Assessment
EMF	Ellen MacArthur Foundation
EN	Europäische Norm (European standard)
EPF	European Panel Federation
EUWID	Europäischer Wirtschaftsdienst
ExFA	Exergy Flow Analysis
GHG	Greenhouse gas
GWP	Global Warming Potential
ILCD	International Reference Life Cycle Data System
ISO	International Organization for Standardization
JRC	Joint Research Centre
KrWG	Kreislauf-Wirtschaftsgesetz (Closed Substance Cycle and Waste Management Act)
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCCt	Total life cycle costs
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCSA	Life Cycle Sustainability Assessment
MJ_{Ex}	Megajoules of exergy
NPP	Net primary production
OSB	Oriented Strand Board

PCB	Polychlorinated biphenyl
PW	Primary wood (system)
RAM	Resource Accounting Method
RDM	Resource Depletion Method
SE	System expansion
SLCA	Social Life Cycle Assessment
UBA	Umweltbundesamt (German Environment Agency)
UNEP	United Nations Environment Programme
VA	Value added
VDI	Verein Deutscher Ingenieure (Association of German Engineers)
WPC	Wood Plastic Composite
WW	Waste wood (system)

Preface

This dissertation was embedded in the European research project “CaReWood – Cascading Recovered Wood” (2014-2017), funded by the German Federal Ministry of Food and Agriculture (BMEL) and the support by the European Union under the framework of the ERA-NET Plus Initiative Wood Wisdom-Net+.

The projects aimed to develop solutions for the use of recovered solid wood from construction in solid wood material applications. It involved the development of a technological process to handle and process the recovered wood into glued laminated timber products. Additional goals were the quantification of future recovered wood volumes from building deconstruction and the development of reverse logistic scenarios. As part of the project, the research of this dissertation involved the evaluation of the resource efficiency of wood cascading as well as the environmental and economic assessment of the newly developed solid wood recycling technology.

1 Introduction

Currently, the global economy mainly depends on the utilization of fossil and mineral primary resources. However, besides an increasing environmental awareness, the scarcity of these non-renewable resources requires an increase in the efficiency of the utilization of primary natural resources (BMUB, 2015; G20, 2017). Furthermore, due to their contribution to climate change, the use of environmentally friendly and carbon neutral renewable resources such as wood is necessary. Therefore, to meet these challenges, the transition of the fossil-based linear economy towards a sustainable, resource-efficient, low-carbon and bio-based economy is a declared goal of the German and European policy (BMEL, 2014; EC, 2018a, 2015, 2014b, 2012). In a bioeconomy all material and energy products are made from renewable resources. It includes primary resources as well as recovered secondary materials and involves resource-efficient and circular utilization patterns (BMEL, 2014). As such, wood as the most important renewable material in Germany will receive great attention as valuable feedstock for the bioeconomy (BMEL, 2018). Additionally, through the substitution of carbon intensive materials and fuels and its ability to store carbon, utilizing wood can contribute to climate change mitigation and meeting the mitigation targets as specified in the national 2050 climate action plan (BMUB, 2016). Although wood is a renewable material, its availability is limited by the renewability of forests and tied to the laws of a sustainable management. But driven by political incentives like the renewable energy act (EEG) (BT, 2017) to enhance wood use for energy production, Mantau et al. (2010) forecasted that the demand for wood in Europe will likely exceed its supply within the next decades. However, in 2018, the demand for wood for energy generation in Germany is likely to have peaked and will tend to decline once the EEG subsidy expires, which will allow a future increase of a material use (Mantau et al., 2018). Despite this development, the multitude of expectations and societal challenges, i. e. the shift towards a bioeconomy, climate change mitigation, the scarcity of fossil and mineral resources as well as the conservation of biodiversity, pose enormous challenges for the national and European forests. Consequently, further strategies for a sustainable wood supply need to be developed, evaluated and implemented in short term in order to meet the increasing demand for wood in the future.

Since the increase of forest area is limited to the availability of and competition for land area (UNEP, 2014), and since the additional ecosystem services provided from forests (e. g. recreation, water and air purification) require a balance in forest management operations, the mobilization of alternative wood sources like private owned forests or short rotation coppices is politically driven (BMEL, 2018, 2011). However, these sources still do not contribute in large share to the overall wood supply in Germany (Mantau et al., 2018).

Therefore, new concepts are needed, which increase the efficiency of wood utilization. The concept of wood cascading is the one strategy, which is currently widely discussed in politics, industry and research. Wood cascading is understood as the sequential use of one unit of a resource in multiple material applications with its use for energy generation as final step. The cascading concept follows a holistic perspective on the material chain and can include several product life, manufacturing, reuse or recycling cycles, where appropriate, before the energy is recovered at the end-of-life (Risse et al., 2019, 2017). Apart from the efficiency improvement, wood cascading is expected to contribute – among others – to reducing environmental impacts and land use pressure, mitigation of climate change, to create value added products and to generate job positions (BMEL, 2018; EC, 2014a).

To what degree wood cascading is of particular value to reduce environmental impacts has been analysed in previous studies (Gärtner et al., 2013; Höglmeier et al., 2015; Höglmeier et al., 2014; Sathre and Gustavsson, 2006; Sikkema et al., 2013). However, all studies indicate benefits of the cascade use, but remain unclear as to the effect of wood cascading on the efficiency of wood utilization, although being the main goal of the cascading concept.

Despite the political incentives, debates and research, wood cascading is still in its infancies. Only one third of the recovered wood in Europe and Germany is currently used in material applications, usually particleboards, which involve a decrease in material quality. Depending on the countries' ordinance on the management of waste wood, the remaining material is lost in incineration or landfill (Döring et al., 2018; EPF, 2018; Garcia and Hora, 2017). Recycling technologies that preserve the material quality of solid wood and its potential for a downstream material use as well as contribute to mobilize the material currently lost in landfilling and incineration are missing. Thus, to enhance a high-value and multi-step wood cascading, further recycling technologies need to be developed. For their practical implementation, a detailed analysis of their environmental performance and economic viability is essential in order to avoid misleading decisions.

2 State of knowledge and research gap

2.1 Recovered wood as a secondary resource

2.1.1 Legal framework for the use of recovered wood

At European level, the Waste Framework Directive 2008/98/EC (EC, 2008) provides the legal framework for the waste treatment in the European countries. The directive legally defines the main waste-related terminology, the end-of-waste criteria as well as a five-step waste hierarchy, which prioritizes the different waste treatment options: prevent, prepare for re-use, recycle, recover, and dispose (EC, 2008). In Germany, the European Waste Framework Directive was implemented in the form of the Closed Substance Cycle and Waste Management Act (KrWG) (BMUB, 2012a), which adopts and partly expands the regulations given in the European directive and provides the national framework for waste treatment.

The KrWG is further supplemented by specific regulations. One of these regulations is the Ordinance on the Management of Waste Wood (AltholzV) (BMUB, 2012b), which provides a framework for the treatment and disposal of waste wood in Germany. The AltholzV regulates the classification and handling of waste wood, defines relevant terminology, and determines the potential utilization and disposal options. According to the AltholzV, waste wood is classified into four different categories. Category A I includes wood in natural state or only mechanically worked wood. Category A II includes bonded, coated, painted and lacquered waste wood without halogenated organic compounds or wood preservatives. Category A III includes waste wood with halogenated organic compounds. Category A IV comprises waste wood treated with wood preservatives. A special category is defined for waste wood containing polychlorinated biphenyls (PCB). According to these categories, the waste wood can be used for different purposes. A I and A II wood is allowed to be used in particleboards, whereas A III wood requires a removal of lacquers and coatings prior material recycling. Wood classified in A IV must be incinerated or can along with A I - A III be used for the production of synthetic gas for chemical use or industrial charcoal (BMUB, 2012b). Waste wood containing PCBs must be incinerated in hazardous waste incineration plants. In general, if waste wood cannot be clearly assigned to one category, it is classified into a higher category instead. However, since in many cases technical effort would be required to identify halogenated organic compounds or wood preservatives during waste wood sorting, it is estimated that 50-75 % of the wood potentially useable in material applications is lost due to this worst-case sorting (Meinlschmidt et al., 2016).

Due to the landfill ban of biodegradable material in Germany, the disposal of waste wood in landfill sites is prohibited (BMU, 2009). For the energetic use of waste wood, the Federal Emission Control Act (Bundesimmissionsschutzverordnung) applies. Depending on the waste wood category, the incineration plants have to fulfil higher requirements for A III and A IV wood (BMUB, 2013a) than for A I and A II wood (BMUB, 2013b, 2010).

Although the waste hierarchy favours the material use of waste wood, the EEG from 2000 financially supported the energy generation from waste wood in Germany. This contradictory policy likely hindered the practical implementation of wood cascading and material recycling processes as being less economically attractive (German Bioeconomy Council, 2016; Ludwig et al., 2016). With the abolition of the funding of energy production from waste wood with the EEG 2014, waste wood industry receives new opportunities to establish new recycling technologies. Due to the research activities, the technological and market development, the AltholzV is currently under revision in order to adapt to the new and current situation of the waste wood market (BMU, 2017), ideally at European level (Strohmeyer and Sauerwein, 2016).

2.1.2 The market of recovered wood in Germany and the European Union

Despite the political incentives and research activities, wood cascading is still in an early stage of development in Europe and Germany. Only one third or 1.5 m t/y of the 5.6 m t/y of recovered wood in Germany is processed in material applications, mainly particleboards (Döring et al., 2018). Two thirds or 3.7 m t/y are incinerated for energy recovery. About 0.35 m t/y are exported (Döring et al., 2018). The disposal in landfills is negligible, due to the landfill ban of biodegradable waste in Germany (BMU, 2009) and the regulations given in the AltholzV (BMUB, 2012b). At European level, landfilling is still a common practise, e. g. in France, Hungary or the UK and Ireland. In average, one third of the recovered wood in Europe is currently disposed on landfill sites (16 m m^3/y), with great differences across the countries. Due to the ongoing landfilling of wood potentially available for energy recovery or material use, the European Union defined targets for the quantity of biodegradable waste that each country can sent to landfills and even proposed to ban landfilling of biodegradable waste until 2025 (EC, 2014b). The other two thirds are incinerated (19.6 m m^3/y) and used in particleboard manufacturing (16.8 m m^3/y) (Mantau et al., 2010; Vis et al., 2016).

The share of recovered wood used in particleboards differs among the member states of the European Union. In Italy, recovered wood amounts to 90 % of the input material of particleboards, whereas in Sweden, Norway or Finland, no recovered wood, but 83-100 % of sawmill by-products are used. In Germany, recovered wood amounts to a share of 45 % in particleboards (EPF, 2018).

Most of the recovered wood in Germany is classified in the categories A II and A III with 35 % and 31 %, respectively. The shares of A I and A IV with 17 % each are much lower. With a share of 27 %, construction and demolition waste (CDW) is the largest contributor to the recovered wood supply. The packaging sector and municipal waste contribute 21 % each (Benthem et al., 2007). However, these numbers significantly differ between studies. Sommerhuber et al. (2015) mentions a share of 70 % in category A III. This is also contradictory to the numbers given for Bavaria, which amount to 46 % of wood waste from CDW (A III/A IV) and 11 % for packaging waste (A I, partly A II) (Weidner et al., 2016). The differences between the numbers indicate the complexity and the opacity of the waste wood sector. Furthermore, these statistical surveys are influenced by data uncertainties, double counting and refer to different reference years and terminologies as well as differ in terms of considered material flows, e. g. cross-border trade.

2.2 The concept of cascading

2.2.1 Definition and concept of wood cascading

In general, a cascade describes the sequential use of a resource in different applications with the goal to maximize the functional output provided from the resource over its lifetime. However, despite 20 years of research on (wood) cascading and the intense discussion in both research and politics, the term cascading still lacks a commonly agreed definition.

The theoretical concept of cascading has first been described by Sirkin and Houten (1994) as a method to optimize resource use through the repeated and successive use of the remaining quality from previously used materials in the best possible application. Although cascading is not unique to the wood sector, it was quickly adapted to the forest wood chain by Fraanje (1997) as a concept to maximize resource efficiency of biomass utilization. Until today, the description by Fraanje (1997) serves as the basic definition of wood cascading and has since then been specified and revised.

Although a common definition is missing, all available definitions share central elements. Most importantly, cascading is understood as a sequential use of a resource with the use for energy generation as a final step. Furthermore, the main goal of the concept is to increase the efficiency of wood utilization (e. g. Arnold et al., 2009; BMUB, 2015; BMEL, 2014; EC, 2018a; EC, 2014b; Essel et al., 2014; Fehrenbach et al., 2017; Fraanje, 1997; Höglmeier et al., 2016; Keegan et al., 2013; Sirkin and Houten, 1994). The direct use of primary wood for energy generation is usually excluded from the definition. The same applies to the material use of by-products (e. g. from sawmills), which *per se* does not yet correspond to a cascade use. As such, the concept of cascading follows the idea of the waste hierarchy.

A main difference of cascading definitions relate to the number of cascade steps considered to be defined as a cascade. The definition given by Essel et al. (2014), Fehrenbach et al. (2017) and Vis et al. (2016) distinguish between a single-stage cascade use and a multi-stage cascade use. The single-stage cascade use describes any material use of wood as a cascade, given its energy use at the end-of-life. Although this contributes to the main goal of increasing the efficiency of wood utilization compared to a direct incineration of primary wood, this definition might weaken the initial intention of Sirkin and Houten (1994) and Fraanje (1997) to maximize the efficiency of resource utilization through its sequential and multiple use. In contrast, the multi-stage cascade use comprises at least two material life cycles before incineration.

A cascade can be described and modelled in relation to three main aspects: time, value (i. e. quality) and function. The aspect of time relates to the number of cascade steps and the lifetime of products. In relation to value, the material is used for the most economically valuable product or application in each cascade step. The function relates to the use of the main and by-products to achieve the most efficient use of biomass (Odegard et al., 2012). A material flow can be optimized along a cascade focusing on one aspect only – or ideally – all aspects, which are considered and balanced on each cascade step. However, optimizing the cascade under the consideration of all aspects is not always possible without trade-offs in one aspect. For example, the use of recovered solid wood in a nearby particleboard plant instead of its use in a faraway solid wood recycling plant, acknowledges the aspect of function (in terms of efficient use of the biomass), but disregards the aspects of time and value (assuming a higher economic value and longer lifetime for a solid wood product).

In its cascading guideline, the European Commission (EC, 2018b) describes cascading as a circular concept, which covers multiple, interlinked pathways including technological developments, new markets and organisational changes. Compared to the definitions given in other publications, this definition is less technical and precise, but rather political in order to support industrial innovations. This leads to the consideration of any (new) material use of woody biomass as aspect of cascading, but thereby disregards the aspect of a sequential and multiple use from the initial idea. Consequently, the good practise examples presented in the guideline have a stronger focus on technical efficiency improvements or the use of wood biomass in innovative processes or products, rather than extending the cascade chain through recycling or remanufacturing processes.

In this dissertation, cascading is defined as the sequential use of one unit of a resource in multiple material applications with the final use for energy generation. Cascading follows a holistic perspective on the material flow and can include various reuse, remanufacturing and recycling processes as well as different end-of-life treatments. Due to the twofold characteristic of wood as a material and fuel, a wood cascade is composed of different levels, taking the main material flow as well as the flow of by-product utilization and waste streams into account.

Along with the efficiency increase of wood utilization, wood cascading is expected to reduce the environmental impacts in product manufacturing through the use of recovered wood. In relation to resource efficiency, cascading is expected to reduce pressure on forestry systems and contribute to safeguarding primary resources, in particular land area. The concept further offers possibilities to develop innovative products and recycling technologies, which will likely generate new job positions and diversify the wood-based product portfolio (BMEL, 2018; EC, 2014a).

In the combination of the given definitions, cascading is considered as an important aspect of a circular economy, as it keeps the added value in materials for as long as possible and enables an efficient recycling of limited resources (EC, 2015, 2014b; EMF, 2013; Jarre et al., 2019; Lewandowski, 2016; Mair and Stern, 2017). Although cascading is intensively discussed for wood, the concept of cascading also applies to bioplastics or textiles (Fehrenbach et al., 2017).

As a response to the upcoming challenges of a bioeconomy, climate change mitigation and the scarcity of primary resources, today, wood cascading is implemented in several political directives at the European (EC, 2018a, 2014a, 2012, 2011) and the national level in Germany (BMEL, 2018, 2014; BMUB, 2015; UBA, 2014).

2.2.2 Wood cascading in practice and research

To enhance a high value and multi-step wood cascading, new strategies are required to mobilize the recovered wood currently lost in landfill sites for material applications as well as optimize the material management before incineration. Thus, alternative recycling concepts of recovered wood in different material applications are under development.

Besides the use of recovered wood in particleboards as described in section 2.1.2, a further material use of recovered wood is niched. Small amounts of recovered solid wood are for example used in material applications such as flooring, construction material or furniture, and most often offered regionally limited and by small companies and carpentries only (e. g. Altholz Bayern, 2019; Baumgartner, 2019). Additionally, beams and floorboards from recovered wood can today be purchased in hardware stores, although the beams are presented as decorative elements, rather than building materials.

Apart from this small-scale use of recovered wood, research studies were conducted to develop new technologies for recovered wood use at industrial level. In relation to particleboards, an early study analysed the use of recovered wood for the production of oriented strand boards (OSB) (Loth and Hanheide, 2004). The same applies to the use of recovered wood from construction in cement bonded boards (He et al., 2019; Hossain et al., 2018). Slightly different results are found in recent studies focusing on recovered wood as feedstock for wood plastic composites (WPC) (Sommerhuber et al., 2015; Teuber et al., 2016) as well as in biorefinery processes for the production of bio-based chemicals and biofuels (Lesar et al., 2016; Peist, 2017). As outcome of the research project Cascading Recovered Wood (CaReWood), a business model and manufacturing process for a window from recovered wood is currently under development (MSora, 2018). As a result of industrial research activities, new windows made from recovered wood from demolition were installed in recently erected buildings in the Netherlands as demonstrators and are now evaluated regarding their commercial viability (VELUX, 2018).

Until today, most of these applications have not yet found their way from research into practical implementation. In order to motivate the industry to further stress the use of recovered wood in product manufacturing, the European Commission published a non-binding guidance for wood cascading containing good practice examples from various wood industries across Europe (EC, 2018b). However, the examples presented in the guidance mainly refer to the use of primary wood and by-products as opportunities to increase the efficiency and competitiveness of wood industry rather than extending the cascade chain by technologies using recovered wood.

Additionally, most recycling technologies for recovered wood in practice and under research involve the degradation of the material quality, in particular in terms of dimensions, i. e. from solid shape into particles, fibres or chemicals and thus its potential applications. Furthermore, most new technologies require recovered wood from class A I, according to the German AltholzV, which is already used in material applications. Processes that maintain the qualities and dimensions and thereby the economic value of solid wood as well enable the use of wood from class A III and A IV (considering a change in legislation) are missing. However, large quantities of dimensional wood products from buildings (12,026 m³ in Bavaria in 2011 (Höglmeier et al., 2013)) show high potential for wood cascading (Höglmeier et al., 2013; Husgafvel et al., 2018; Kalcher et al., 2017; Sakaguchi et al., 2016), but are currently incinerated for energy generation or landfilled, depending on the national regulations. This bypass is contradictory to the principles of the cascading concept and leaves the opportunity of the cascading benefits unused. Furthermore, technical studies indicate that the mechanical and physical properties of recovered wood are comparable with those of primary wood (Cavalli et al., 2016; Meinlschmidt, 2017), which would allow the use of the recovered wood in solid wood applications. Both, the technical suitability and the quantitative availability highlight the need for new recycling technologies, which contribute to mobilize currently unused material deposits and additionally maintain the dimensions and the economic value of recovered solid wood and preserve the potential for a downstream cascade use. This applies to solid recovered wood from all categories (A I - A IV), but in particular to the currently lost shares from CDW.

Therefore, a recovered solid wood recycling process was developed in the CaReWood project, which allows the transformation of solid and potentially contaminated wood into clean and standardized lamellae, which can be used for engineered timber products, e. g. glued or cross laminated timber (Irle et al., 2018; Irle et al., 2015; Privat et al., 2016).

2.3 Sustainability assessment of wood utilization

2.3.1 Studies on the environmental and economic aspects of recovered wood treatment

Although studies on recovered wood treatment and wood cascading are closely related, they differ in terms of their goal and scope. The analysis of different recovered wood treatment alternatives usually focuses on a process following a gate-to-gate perspective. In contrast, wood cascading systems cover the entire material life and thus various products and recycling processes as well as the end-of-life treatment. While studies on the treatment of recovered wood are conducted since the beginning of Life Cycle Assessment (LCA), LCA studies focusing on wood cascading are relatively new. Due to the different goal and scope of each study type, studies on the recovered wood treatment are presented in this section, whereas research on (wood) cascading is presented in the following section 2.3.2.

With the first application of LCA to wood products, the influence of the end-of-life treatment on the environmental performance of a wood product became apparent. As derived from several LCA studies, the end-of-life treatment (recycling or disposal) can significantly influence the outcome of a life cycle-based study of wood products, which is why the consideration of different end-of-life treatment options in comparative LCA was recommended (Jungmeier et al., 2001; Richter, 2001). One of the first studies directly comparing the material recycling of recovered wood with an alternative treatment was conducted by Rivela et al. (2006). In this study, the recycling of ephemeral wood structures in particleboard production was compared with its use for energy generation using system expansion to achieve functional equivalence. The results indicate that the recycling in particleboards performs better in most considered impact indicators. However, in the impact categories for fossil fuel consumption, the recycling scenario performs worse due to the modelling of fossil fuels as energy carriers in the system expansion. Similar conclusions were obtained from Merrild and Christensen (2009) and Kim and Song (2014) for the use of recovered wood in particleboard production. Both studies showed benefits in the global warming potential for the recycling scenario. A comparison between the use of recovered wood from construction also in particleboard production and alternative treatments in landfill and energy generation was conducted by Hossain and Poon (2018) using the avoided burden approach in LCA. Due to large greenhouse gas (GHG) emission savings obtained from the considered substitution of fossil fuels, the energy generation scenario performed best from an environmental perspective, with the recycling scenario as second best. The European research project DemoWood (Hakala et al., 2014) compared the environmental impacts of a proportionate use of recovered wood for paper, particleboard, bioethanol and energy with the production of the same outputs entirely made from primary wood. For most impact categories, the material recycling in particleboard performs best, although greater savings are obtained from the use for energy production in the global warming potential indicator (Hakala et al., 2014). A study focusing on the resource consumption in wood recycling as well as using a life cycle-based approach, was presented by Cornelissen and Hirs (2002). They compared the wood and fossil fuel resource consumption of different recovered wood treatment alternatives using Exergetic Life Cycle Assessment (ELCA). The results indicate a smaller resource consumption for the use of recovered wood in particleboard production compared to the co-combustion in a power plant. However, a full life cycle-based impact assessment was not applied.

Apart from these studies focusing on the environmental aspects of recovered wood use, studies are available focusing on the recycling of CDW, some of which combined an analysis of LCA and Life Cycle Costing (LCC). However, these studies focus on mineral or steel aggregates, whereas wooden material is disregarded (Braga et al., 2017; Coelho and de Brito, 2013; Di Maria et al., 2018; Mah et al., 2018) or analysed from mechanical perspectives only (e. g. Wang et al., 2016).

Although several LCA studies analysed the environmental aspects of recovered wood utilization, most focus on the use of recovered wood for particleboard production, following the current technology in practice. No study is available that focuses on the environmental aspects of recycling recovered solid wood, nor on an eco-efficiency analysis of a wood recycling process by the joint application of LCA and LCC.

Thus, to enhance wood cascading, not only the development of new technologies is required (see section 2.2.2), but also a parallel evaluation of their environmental and economic potential. This is of particular importance, since economic reasons are considered among the main barriers that hinder the implementation of wood recycling processes (Husgafvel et al., 2018). Thus, for a successful and practical enhancement of wood cascading, politics and industry rely on information about the economic viability as well as the environmental performance of new technologies. Such kind of information provide guidance in decision-making on investments, the identification and improvement of key processes and in avoiding rebound effects or misleading expectations from the implementation of recycling processes (Risse and Richter, 2016).

2.3.2 Studies on the environmental and efficiency aspects of wood cascading

With his adaptation of the cascading concept to the forest wood chain, Fraanje (1997) studied the effects of cascading pine wood in the Netherlands on resource consumption, time and carbon emissions. He concludes that cascading can lead to large savings in primary resource use and increase the efficiency of resource use. Furthermore, Fraanje (1997) argues that cascading extends the time of carbon storage and postpones CO_2 emissions.

Before LCA was applied to determine the environmental effects of wood cascading, indicator-based studies on biomass cascading were conducted. Haberl and Geissler (2000) studied the effects of cascading biomass using the appropriation of net primary production (NPP) as indicator. The results show that cascading can increase the socio-economic benefits obtained from a limited amount of harvested biomass due to the efficiency increase of biomass use, but without increasing NPP appropriation (Haberl and Geissler, 2000). Dornburg and Faaij (2005) studied different cascade chains for poplar wood from short rotation with respect to the land use, CO_2 emissions and their economic performance. They found that cascading can improve the CO_2 emission reduction per ha and CO_2 mitigation costs of biomass utilization. The main influencing factors are the market prices, the efficiency of biomass production as well as the energy demand of substituted materials and fuels (Dornburg and Faaij, 2005).

With awareness of climate change rising, research focused on the contribution of wood cascading to climate change mitigation. Sathre and Gustavsson (2006) studied the primary energy consumption and carbon balance of various wood cascading systems for recovered wood in comparison to primary wood products. Their results show that the energy and carbon balances are mainly influenced by land use, followed by the substitution effects, whereas the direct cascading effects are of minor relevance (Sathre and Gustavsson, 2006). A comparison of the GHG emissions between the cascade use and the direct energetic use of wood from Canadian forest resources shows that the cascade use in harvested wood products can lead to a significant decrease in GHG emissions. The benefits mainly relate to the substitution of fossil fuels and non-wood materials as well as temporary carbon uptake (Sikkema et al., 2013). A wood product model was used by Brunet-Navarro et al. (2018) to analyse the influence of wood cascade chains on the carbon stock in wood products in Germany. The results indicate that the carbon stock in wood products can be increased by optimizing the cascade chains by using long-lived products, high recycling rates and long cascade chains.

As a result of the political awareness for cascading, several studies were performed using LCA methodology to analyse the environmental impacts of wood cascading. Gärtner et al. (2013) analysed different wood cascade chains in comparison to a reference scenario providing the same products derived from non-wood materials. In Höglmeier et al. (2014), a cascading system using recovered wood in particleboards was compared with a reference system using primary wood to provide the same functions. Both studies indicate environmental advantages of the cascading systems compared to the references systems for most of the considered impact categories and scenarios. In comparison, the advantages of the cascading system are smaller when compared to the use of primary wood, due to the high environmental credits obtained from substituting non-wood materials. Both studies validate the conclusion from Sathre and Gustavsson (2006) that the direct cascading effects from using recovered wood instead of primary wood are of minor relevance. Instead, the main benefits of cascading are saving of primary natural resources, such as land area or fossil fuels, depending on the considered reference scenario. However, sensitivity analysis revealed that in some scenarios, wood cascading can lead to higher environmental impacts compared to the reference system (Höglmeier et al., 2014). In general, the direct cascading effects are relatively small. This can be attributed to the overall low impacts of wood product manufacturing as well as the little differences between the processing of recovered and primary wood.

The first approach to integrate market effects in the assessment of a wood cascading scenario was presented by Höglmeier et al. (2015). An LCA and material flow model were combined to analyse the environmental impacts of wood use under the consideration of different cascade chains as well as a limited wood supply and constant product demand. The results validate previous observations and determine the environmental benefits of wood cascading to approx. 10 % (Höglmeier et al., 2015). A similar approach was applied for the wood utilization in Switzerland by Suter et al. (2017). This study confirms the environmental benefits of wood cascading, although these are rather small, in particular if forests are underused. However, Suter et al. (2017) recommend that wood cascading should not lead to an increasing use of primary wood for energy production, while the recovered wood is used in materials, but to increase the amount of wood used in materials in order to substitute non-wood products. Furthermore, they state that the environmental benefits of wood cascading highly depend on the substituted products as well as on how efficiently the energy can be recovered during incineration, which is similar to the observations from Sathre and Gustavsson (2006) and Höglmeier et al. (2014). The combination of material flow analysis, LCA and mathematical optimization was also used by Mehr et al. (2018) to determine the environmentally optimal wood use for Switzerland, with a focus on climate change and particulate matter formation. Overall, the results indicate that wood cascading can further improve the environmental performance of wood utilization (Mehr et al., 2018). Although most studies applied LCA to analyse the environmental impacts of wood cascading, the results are difficult to compare. Each study has a different modelling approach, functional unit and spatial resolution as well as different system boundaries and reference systems, which can significantly influence the results and thus their comparability.

Although Gärtner et al. (2013) and Höglmeier et al. (2014) concluded that the main benefits of cascading are the savings of primary natural resources, a detailed analysis of the resource consumption and the resource efficiency along the life cycle of a wood cascading system was still missing at the beginning of this dissertation, as outlined in Risse and Richter (2016). Although resource related impacts were quantified, the ratio between the resource inputs required and the desired output were not expressed. This is surprising, as the efficiency increase of wood utilization is the main goal of wood cascading. A similar conclusion was drawn by Thonemann and Schumann (2018), who recommended developing studies focusing on the resource efficiency of cascading systems and the influence of the number of cascade steps.

Besides the research presented in this dissertation (Risse et al., 2017), Bais-Moleman et al. (2018) also showed that wood cascading can improve the efficiency of wood utilization, by applying the cascading factor (Mantau, 2015). The cascading factor quantifies the ratio between the total amount of wood used for materials or energy and the wood resources from forests, but disregards other primary resources (e. g. fossil fuels, minerals) or impacts derived from resource use. A similar approach is presented in Vis et al. (2014), who calculated the resource efficiency of wood cascading as the amount of primary wood used per functional unit. However, both the use of other natural resources as well as a life cycle perspective were disregarded.

3 Objectives and research questions

The overall goal of this dissertation is to identify and apply suitable life cycle-based methods to analyse the resource and eco-efficiency of wood cascading and recycling systems. To achieve this goal, two main objectives are defined: First, to identify and apply a suitable method for a resource efficiency assessment of a wood cascading scenario and, second, to analyse the eco-efficiency of a new recycling technology for recovered solid wood by combining a life cycle-based environmental and economic analysis.

Based on the research gaps identified in the previous section, the main research questions of this dissertation are as follows.

1. Does wood cascading lead to a reduced consumption of resources and a higher efficiency of wood use and what are the main influencing factors?
2. Is exergy analysis a suitable method to analyse the resource consumption and efficiency of wood cascading while accounting for the characteristics of wood cascading systems and what are the key technical and methodological factors influencing the resource efficiency assessment?
3. Is the recycling of recovered solid wood an eco-efficient treatment alternative to current end-of-life treatments?
4. What are the technical and methodological factors influencing the life cycle-based eco-efficiency assessment in comparative recovered wood treatment studies?

Detailed research questions related to each publication can be found in chapter 11.

To answer the first two research questions, a resource efficiency assessment and resource use analysis of a wood cascading system is performed. As a basis for the life cycle oriented study, the characteristics of a wood cascading system with respect to an efficiency analysis are described. In order to identify a method, which accounts for these characteristics in an efficiency assessment, various life cycle-based resource accounting methods and resource efficiency indicators are analysed. With exergy analysis identified as potential method, its suitability for a life cycle-based resource efficiency assessment of wood cascading is evaluated in a comparative study analysing the resource use and efficiency of a wood cascading system and a functionally equivalent system using primary wood.

The third and fourth questions are answered by the joint application of LCA and LCC in an eco-efficiency analysis for a newly developed process for recycling recovered solid wood into glued laminated timber products. This combined analysis follows the rationale of a Life Cycle Sustainability Assessment (LCSA) although disregarding the social dimension of sustainability and is for the first time applied on a wood recycling process. It provides valuable insight in the eco-efficiency of the recycling process, but also highlights the benefits and limitations of the applied methods.

4 Methodological background of sustainability assessments of wood utilization and recycling

4.1 Methodological aspects of Life Cycle Assessment and Life Cycle Costing

4.1.1 The methodological framework of Life Cycle Assessment

Since the 1970ies, Life Cycle Assessment is a commonly used method to analyse the environmental impacts of a product or service along its life cycle, i. e. cradle to grave (DIN EN ISO 14040:2009-11). Today, LCA is an internationally standardized method with the normative standards DIN EN ISO 14040:2009-11 and DIN EN ISO 14044:2006-10 as main guidelines (Klöpffer and Grahl, 2009).

To conduct an LCA, four phases are defined in the ISO 14040:2006: goal and scope definition, inventory analysis, impact assessment and interpretation. In the first phase, the main goal of the LCA study is defined and it is described why the study is being conducted. Additionally, some of the main methodological decisions are made, such as the definition of the system boundaries, the functional unit, allocation procedures, impact categories and necessary assumptions. In the second phase, the inventory data is collected in order to model the input and output flows for each of the considered processes within the system boundaries. In the third phase, the environmental impacts of the system under study are calculated by combining each emission or resource flow with a characterisation factor. In the last phase of an LCA, the interpretation, the environmental impacts are analysed with respect to the goal and scope of the study as defined in the first phase. To provide reliable results, sensitivity, uncertainty and scenario analyses can be conducted. An LCA study is an iterative process, which allows for subsequent adjustments in each phase of the study (Klöpffer and Grahl, 2009).

4.1.1.1 Modelling of system boundaries

The system boundary describes which of the physical processes are part of the systems under study. It defines the boundary between the analysed system and the remaining technosphere and the ecosphere. The instructions given in the ISO 14040:2006 for modelling the system boundaries are very vague to allow flexibility in adjusting the system boundaries to meet the goals of the study.

With respect to comparing the impacts of different waste treatment options, the DIN EN 15804:2014-07 provides better instructions for modelling the system boundaries. In general, all waste treatment processes are included in the product system, in which the waste is generated, until the point where the waste reaches the end-of-waste status. Thus, in waste treatment or recycling systems, the system boundary begins at the point where the waste reaches the end-of-waste status. This status is reached when the following criteria are met: the recovered material is used for a specific purpose; it has a dedicated market with a positive economic value and a market demand; it complies with the applicable legal regulations; its use is not harmful for human health or the environment. These criteria are defined in the European Waste Framework Directive (EC, 2008) and adapted in the DIN EN 15804:2014-07. When the waste material reaches the end-of-waste status, it can be considered as free from any environmental burdens from previous life cycles, i. e. product systems.

4.1.1.2 Solving multifunctionality

An essential condition of a comparative LCA study is the functional equivalence between the systems under study, which is defined with the functional unit. If a system or process provides several useful outputs, i. e. products, and thus serves different functions, it is described as multifunctional system.

To solve multifunctionality, the ISO 14044:2006 provides three different methods, following a hierarchic order. The first method is the subdivision of the multifunctional process into mono-functional single processes, for which the input and output flows are collected separately. If subdivision is not possible, the second method is system expansion. Those processes, which provide the functions obtained in one system, are added in the comparative system where the functions are missing, by expanding the system boundaries (system expansion). The added processes usually reflect the average market conditions. Alternatively, if the additional functions can be obtained from an individual process, these individual processes can be subtracted from the product system with the additional functions in order to achieve functional equivalence. This approach is called “avoided burden approach” or “crediting”, as the system receives a credit for providing the additional function and thereby avoiding the production of the same function from an alternative process. The third method is the allocation of the input and output flows to each obtained function based on physical relationships like mass, energy, exergy or alternative characteristics like the economic value of each product. However, allocation should be avoided wherever possible, by using subdivision or system expansion instead (DIN EN ISO 14044:2006-10; Klöpffer and Grahl, 2009).

The problem of allocating input and output flows to different products can occur at process level (e. g. in a sawmill), but also at system level, when different products or services are obtained. The latter is often the case in waste treatments as well as in cascading systems. Along a cascade, multiple products (e. g. sawn timber, particleboard, energy) and thus functions are provided, depending on the considered cascade steps. Thus, if a cascading system is compared with a non-cascading system, multifunctionality needs to be solved in order to achieve functional equivalence between both systems.

In studies comparing different waste treatments, the main function is the treatment itself. Depending on the treatment process, the treatment can result in additional products, i. e. functions, for example energy from incineration or a useful product from recycling. This can result in multiple, but also different functions between the systems. Usually, system expansion is applied to account for the additional functions provided in each system and to achieve functional equivalence. In waste treatment studies, system expansion is also referred to as basket of benefit method. As a consequence, the functional unit not only includes the treatment of the waste but further includes the additionally provided functions (Finnveden, 1999; Klöpffer and Grahl, 2009).

According to the ISO 14044:2006 standard and the ILCD handbook (JRC, 2010), system expansion is the recommended approach to solve multifunctionality in comparative studies, when subdivision is not possible. However, system expansion can be decisive for the outcome of a comparison, depending on the choice of system expansion modelling. If more than one process is available to provide the additional function, the definition of the alternative process can be challenging. Usually, the average market process would be modelled. However, in reality, it, for example, depends on the market dynamics and the availability of production capacities and resources, which alternative process provides the additional function or which is avoided. Thus, depending on the study, the effects at market level can be difficult to foresee. The influence of the system expansion processes is of particular importance when energy generation processes are modelled. As seen from previous studies (e. g. Höglmeier et al., 2014), the choice of energy carrier in the system expansion can have a significant influence on the results. Other difficulties in system expansion modelling relate to the market and production demand as well as if the functions of the alternative product are identical with the one substituted. This is certainly the case for electricity and heat, but recycled products might not directly substitute functionally equivalent products from primary material. To what extend the latter aspects influence the outcome of the study, depends on the goal and scope of the study (Finnveden, 1999; JRC, 2010; Klöpffer and Grahl, 2009).

4.1.2 Life Cycle Sustainability Assessment

Initially, LCA was deliberately limited to the ecological dimension of sustainability to reduce the complexity in the assessment. However, sustainable products can only be produced if all dimensions of sustainability are considered and analysed. Originating from the LCA, an LCSA approach developed, which applies the life cycle thinking to the other two dimensions of sustainability. LCSA is understood as the evaluation of all environmental, social and economic impacts and benefits along the life cycle to be used in decision-making processes in order to provide more sustainable products. LCSA combines LCA with LCC and Social Life Cycle Assessment (SLCA). It supports identifying trade-offs between the dimensions, different life cycle stages and products as well as supports the identification of key drivers in each dimension. It provides industries with a broader picture on the impacts and optimization potential of their products and their value chains. In general, LCSA follows the same principles and phases as described in the ISO standards for LCA. However, all methodological decisions, e. g. definition of the functional unit or system boundaries, need to account for the aspects relevant to each of the individual assessment methods. In practical application, the consideration of all three dimensions of sustainability is an ambitious task. It leads to a complex methodological approach that has to face the trade-off between validity and applicability, as the individual challenges of each assessment method jointly occur (Finkbeiner et al., 2014; Finkbeiner et al., 2010; Klöpffer, 2008; UNEP and SETAC, 2011).

4.1.3 Resource use accounting in Life Cycle Assessment

4.1.3.1 Definition of primary natural resources

Primary natural resources are objects of nature, which are extracted by man to be used as raw materials, fuels or feedstock for the production of materials, products or energy (usually expressed in the functional unit) in economic processes. For the separation and categorization of primary resources, several approaches are available. A common separation can be drawn between biotic and abiotic resources or renewable and non-renewable resources. Abiotic resources usually comprise fossil fuels, water, atmospheric resources (e. g. air components), metals, minerals, abiotic renewable resources (e. g. wind, solar energy) and land area. Biotic resources are derived from living organisms and are understood as species and ecosystems, which are independent from human activities. Some biotic resources additionally have an intrinsic value and are thus classified as non-renewable, for example primary forests including plants and animals or endangered species. To these resources, human interactions would cause irretrievable damage and their sustainable use is not possible. Renewable biotic resources for example include wild fish or game, considering their potential sustainable use. As this study deals with wood reproduced in forestry systems, it is important to mention that forest products from managed forests are not defined as biotic resources in LCA. Instead, managed forests are understood as human-made systems and are processes within the technosphere. The same applies to agriculture, fish farms, forest plantations or livestock (Klöpffer and Grahl, 2009; Swart et al., 2015). The term primary wood hereafter thus refers to material reproduced in human-made forestry systems. Additionally, materials recovered from waste resources are considered as secondary resources.

In publication 1 (Risse et al., 2017), the classification of primary resources is as follows: water, abiotic renewable resources, fossil fuels, minerals, metal ores, nuclear resources, atmospheric resources and land resources.

Besides this narrow and rather traditional definition of primary resources, a broader understanding of the term resources can be applied. Different approaches are available which account secondary resources or economic and social aspects into the resource definition (Bach et al., 2016; Huysman et al., 2015).

4.1.3.2 Resource use indicators in Life Cycle Impact Assessment

Life Cycle Impact Assessment (LCIA) offers a broad variety of impact indicators to quantify the resource use at flow and at impact level. While the abiotic resource use is covered with a large number of indicators, only a few indicators account for biotic resource use (Klinglmair et al., 2014). Dedicated indicators for biotic resource use have found no scientific agreement or are only applicable for specific LCA studies (e. g. Langlois et al., 2014). Since biotic resources are less relevant for the presented study, only an overview of the indicators for abiotic resource use is given.

At flow level, resource accounting methods (RAM) sum up all resources consumed along the life cycle, usually expressed in a physical unit (e. g. mass, energy). RAMs are close to the inventory data and account for resource use at flow level. They are far from the areas of protection (AoP) and thus do not directly express the environmental impacts. However, they still provide insight into the resource utilization following the less-is-better principle (Swart et al., 2015). Typical LCIA RAMs are the Cumulative Energy Demand (CED) (VDI 4600:2012-01), Cumulative Exergy Demand (CExD) (Bösch et al., 2007) and Cumulative Exergy Extraction from the Natural Environment (CEENE) (Dewulf et al., 2007). Even some commonly applied midpoint indicators like the Abiotic Depletion Potential (ADP, for fossil fuels) (van der Voet et al., 2009) and the fossil resources depletion and water use indicator from ReCiPe (Huijbregts et al., 2017) can be classified as RAMs (Swart et al., 2015). Apart from the units used to express the indicator results, the type and amount of primary resources covered per indicator can vary significantly and is important to consider when choosing the indicator method (Klinglmair et al., 2014).

Resource depletion methods (RDM) at midpoint or endpoint level are closer to the AoPs and account for the scarcity of resources (midpoint) and the future extraction costs (e. g. marginal costs) (endpoint) in impact assessment. In contrast to the RAMs, the resource use is quantified at impact level (Swart et al., 2015). Common LCIA indicators for resource use at midpoint and endpoint level are for example the Abiotic Depletion Potential (ADP, for metals and minerals) (van der Voet et al., 2009), ReCiPe (Huijbregts et al., 2017) and the Eco-Indicator (Goedkopp and Spriemsma, 2000).

Although the midpoint and endpoint indicators are considered to be more scientifically sound as they are closer to the AoP, they cover less numbers of resources due to the increasing complexity in developing the characterization factors. A higher number of resources covered by an indicator, however, increases the reliability of the results. The risk of unintentionally disregarding resources that are relevant for the product or system under study as well as disregarding trade-offs between resource uses is lower. Furthermore, the use of a common unit makes the aggregation in a single unit easier and avoids weighting of different indicator results. A single unit thus makes the use of the indicator results in efficiency calculations straightforward. Therefore, in resource and efficiency oriented studies, it is of particular importance to carefully choose the resource use indicator in order to account for the relevant resources and enable its use in efficiency metrics.

4.1.3.3 Exergy in resource use accounting

Among the RAMs, exergy-based indicators are considered the most scientifically sound methods, which cover the largest number of resources (Klinglmair et al., 2014). For this reason and as exergy analysis was found appropriate to account for the characteristics of cascading systems while being easy to be used in efficiency assessments, exergy analysis was applied in publication 1 (Risse et al., 2017). Therefore, a brief overview of the exergy-based impact indicators is given.

The exergy of a resource or material is defined as the maximum of potential work that can be obtained from the resource or material when bringing it into equilibrium through reversible processes with the natural environment (Dewulf et al., 2008; Szargut et al., 1988). Exergy analysis was initially developed for industrial analysis to optimize thermal and chemical processes, e. g. incineration plants. For resource use accounting, the conversion of resources for energy production into its exergy content is straightforward. In contrast to energy resources, metals or minerals are not extracted from the environment to provide work, but still they contain exergy. This is due to the different chemical composition and concentration, which the resources have in natural state, compared to when being in the reference environment. This difference in chemical composition and concentration can potentially be used to produce work (Swart et al., 2015). Thus, originating from industrial analysis, with its wider application exergy analysis developed towards a life cycle oriented method until exergy-based LCIA indicators were operationalized for LCA.

The first exergy-based resource use indicator for LCA was the CExD (Bösch et al., 2007). Due to the shortcomings in land use accounting in the CExD, Dewulf et al. (2007) developed the CEENE indicator and integrated characterisation factors to account for land use. In the first version of CEENE, the solar irradiation was used as a proxy to account for the land area (Dewulf et al., 2007). The approach was further developed by Alvarenga et al. (2013), who provided spatial explicit characterization factors for land as a resource, taking both land occupied in human-made systems (e. g. agriculture, urban area) and biomass from natural systems (e. g. timber from primary forests) into account. For natural systems, the exergy value of the extracted biomass was used as a proxy, whereas the natural potential NPP was used for land use accounting in human-made systems. The same proxy was applied by Taelman et al. (2014) for the development of characterization factors for the land occupation in marine environments. The proxy was further developed to provide spatially-differentiated characterization factors for land occupation by combining the NPP with a factor representing the naturalness of the occupied land (Taelman et al., 2016). The NPP approach overcomes the shortcomings of the use of solar irradiation, as it also accounts for the loss of natural resources (Alvarenga et al., 2013). However, it does not differentiate between the intensity of land use (urban area is characterized the same way as forests), neither does it assign a natural value to the remaining NPP after the land use (Taelman et al., 2016). By including the naturalness of the NPP in the calculation of the characterisation factors, the version of Taelman et al. (2016) overcomes these shortcomings.

In comparison with other energy- or exergy-based resource accounting indicators, the advantage of CEENE is the coverage of a broad range of resources (Klinglmair et al., 2014; Swart et al., 2015). In contrast to the energy-based CED (VDI 4600:2012-01), CEENE accounts for water, minerals and metals as well as for land occupation as a resource and not for the biomass extracted from it and is thus in line with the definition of primary resources.

The aggregation of the different resources by weighting with a scientifically sound approach in one unit, is one advantage of exergy analysis (Dewulf et al., 2008). In other single impact indicators, the aggregation of impacts from resource (and emission) flows is influenced by personal choices, e. g. the Ecological Scarcity Method (Frischknecht and Büsser Knöpfel, 2013). The use of a single unit can make the comparison of the resource use between different products (e. g. energy and materials) as well as decision-making easier. In this regard, exergy is of particular value for the analysis of products or services that require a lot of energy resources or are useable as energy resource, such as wood. However, single score indicators avoid insight into the complexity of a system, because of the low detail resolution of the results. Although exergy analysis accounts for resource use in a scientifically sound way, it disregards the scarcity of resources and thus has the typical shortcomings of RAMs in expressing environmental sustainability, in comparison to RDMs (see section 4.1.3.2).

4.1.4 Efficiency analysis using Life Cycle Assessment

4.1.4.1 Definition of efficiency

The term efficiency generally describes the ratio between the useful outputs (or benefits) and the inputs required to derive the useful outputs (Equation 1). In the context of LCA, the useful outputs are usually the desired products or services under study, which are often described by the functional unit. The inputs refer to the resources or materials required to obtain the desired output. Depending on the goal and scope of the study, different indicators can be applied for the quantification of the useful outputs and the required inputs. In general, an efficiency assessment provides relative results. A system itself cannot be efficient, but only be more or less efficient in comparison to another system (DIN EN ISO 14045:2012-10).

Equation 1

$$Efficiency = \frac{Outputs}{Inputs}$$

4.1.4.2 Indicators for the efficiency assessment using Life Cycle Assessment

Although it is widely used, a broad consensus on the terminology and definition of efficiency indicators in the context of LCA is still missing. Therefore, a systemized framework for efficiency indicators was proposed by Huysman et al. (2015). The efficiency metrics can be structured according to the economic scale and perspective as well as the level of input flow quantification. With respect to the economic scale and perspective, efficiencies can be calculated from micro- to macro scale, representing a gate-to-gate, life cycle or global perspective. Depending on the economic scale and perspective of the study, the input and output flows can be quantified with different indicators.

The output is usually the product or service under study and thus represented by the functional unit. Depending on the scope and functional unit of the study, the outputs can be expressed in physical metrics like mass, volume or energy as well as economic metrics like the added value, life cycle costs or market price. The inputs are quantified by different indicators either at flow or at impact level. At flow level, the resources or emissions are directly accounted for, e. g. using the life cycle inventory, whereas at impact level, the impacts derived from the resource and/or emission flows are considered.

The choice of the appropriate indicators for the outputs and inputs depends on the goal and scope of the study, which can also specify the terminology of the efficiency analysis. In a resource efficiency analysis, only resource related inputs are quantified, either at flow or at impact level. An eco-efficiency analysis can include the quantification of the resource- and emission-based input flows, either at flow or at impact level. Following the framework from Huysman et al. (2015), the eco-efficiency thus has a broader scope compared to the resource efficiency, which can also be part of an eco-efficiency assessment.

This understanding is in line with the DIN EN ISO 14045:2012-10 standard, which defines eco-efficiency as the relation between the environmental performance, i. e. impacts, and the value (for stakeholders) of the studied product system. The ISO 14045:2012 standard provides a guideline for a life cycle oriented eco-efficiency assessment using LCA. Thus, LCIA is used to quantify the inputs, while physical, economic or alternative indicators can be used to quantify the outputs (DIN EN ISO 14045:2012-10).

At this point, LCSA and efficiency analysis meet. The joint application of LCA and LCC as intended within the framework of an LCSA, enables the calculation of the (eco-)efficiency. Here, the LCC is used to quantify the useful outputs in terms of life cycle costs, market price or value added, while the inputs required to provide the desired outputs are quantified using LCA.

If multiple input indicators as well as different metrics for inputs and outputs are used, the efficiency is either expressed for each LCIA indicator individually (cf. Risse et al. (2019)) or normalization and weighting is necessary to aggregate the results in a single score.

Alternatively, single score indicators can be applied, such as exergy analysis. Following the same rationale as the ISO 14045:2012 standard, exergy analysis usually focuses on resources only and is based on a single unit. Exergy analysis can be applied at gate-to-gate and at life cycle level. At gate-to-gate level, Exergy Flow Analysis (ExFA) is used to analyse the exergetic flow of a system and to identify hotspots for improvement. As part of ExFa, the ratio between the exergetic output and the exergetic input can be used for an exergetic efficiency assessment at gate-to-gate level. For efficiency assessments in an Exergetic Life Cycle Assessment (ELCA) at life cycle level, the Cumulative Degree of Perfection (CDP) was developed. The CDP describes the efficiency of a system as the ratio between the exergy content of the useful output and the exergy content of the resource inputs (Szargut et al., 1988). In an ELCA, exergy-based resource use indicators like CEENE or CExD are applied to quantify the resource inputs at life cycle level (see section 4.1.3.3). Until today, exergy analysis found wide application in environmental studies on resource use and in efficiency analyses (e. g. Amini et al., 2007; Cornelissen and Hirs, 2002; Huysveld et al., 2013; Nhu et al., 2016; Özilgen and Sorgüven, 2011; Schaubroeck et al., 2016; Talens Peiró et al., 2010; Vargas-Parra et al., 2013).

The possibility to express all input and output flows (resources, materials, products, energy) in a single unit makes efficiency calculations straightforward and easy to communicate in decision-making.

5 Overview of publications

5.1 Publication 1

Resource efficiency of multifunctional wood cascade chains using LCA and exergy analysis, exemplified by a case study for Germany

Michael Risse, Gabriele Weber-Blaschke, Klaus Richter
2017 · Resources, Conservation and Recycling · Volume 126 · Pages 141 - 152
DOI: 10.1016/j.resconrec.2017.07.045

Abstract

Driven by the scarcity of non-renewable resources and the transition to a bioeconomy, the demand for wood is likely to increase. To meet this demand, wood cascading is expected to increase the efficiency of wood utilization. Therefore, in this study, the resource use and resource efficiency of wood cascading in comparison to the use of primary wood is determined. In order to find a suitable evaluation method, the characteristics of wood cascading systems in relation to LCA and resource efficiency assessments are analysed. At the process level, Exergy Flow Analysis was used to identify key drivers of exergy dissipation and hotspots for improvement. At the life cycle level, Exergetic Life Cycle Assessment was applied to determine the resource use and resource efficiency. The results show that wood cascading leads to a reduction in resource consumption compared to the use of primary wood for providing the same multiple outputs. In addition, the cascading system has a higher efficiency at the life cycle level than the primary wood system (46 % to 21 %). Cascading shows its greatest potential to save primary resources through avoiding the primary production of wood. Exergy analysis proved to be a viable method to analyse the resource consumption and efficiency of wood cascading systems under the consideration of their characteristics. However, exergy analysis showed shortcomings in the accounting for land use, when applied to natural-industrial hybrid-systems.

Contribution

Michael Risse developed the research questions, designed the methodological approach, modelled the systems and inventory data, conducted the analysis of the results and wrote the manuscript. Gabriele Weber-Blaschke and Klaus Richter supported the development of the study concept, the research questions and critically reviewed the manuscript.

5.2 Publication 2

Eco-efficiency analysis of recycling recovered solid wood from construction into laminated timber products

Michael Risse, Gabriele Weber-Blaschke, Klaus Richter

2019 · Science of the Total Environment · Volume 661 · Pages 107 - 119
DOI: 10.1016/j.scitotenv.2019.01.117

Abstract

Today, wood cascading in practise is still in its infancies and limited to the downcycling of wood. Therefore, a new recycling technology for recovered solid wood from construction into glued laminated timber products was developed in the CaReWood project to maintain the material quality and enhance wood cascading. To analyse the environmental and economic performance of the process, the eco-efficiency was assessed by the joint application of Life Cycle Assessment and Life Cycle Costing. As reference system, the incineration of the recovered wood was analysed. System expansion was applied to solve multifunctionality. The results indicate that the recycling of recovered wood into glued laminated timber products is economically viable and offers possibilities for the production of value added products with low environmental impacts. The recycling shows up to 29 % of lower environmental impacts and 32 % of lower costs compared to the incineration. The operational processes required for the recycling are of minor relevance for the overall performance. Instead, technologies like glue lamination as well as the incineration are key drivers. In all scenarios, the material recycling has a 15-150 % higher eco-efficiency compared to the incineration. Thus, to enhance wood cascading, the further development and refinement of the recycling process is recommended.

Contribution

Michael Risse developed the research questions, designed the methodological approach, modelled the systems and inventory data, conducted the analysis of the results and wrote the manuscript. System and data modelling was supported by supervised master theses from Diana Mehlan and Benjamin Buck. Gabriele Weber-Blaschke and Klaus Richter developed and supervised the associated research project, supported the development of the study, participated in scientific discussions and critically reviewed the manuscript.

6 Materials and methods

6.1 Resource efficiency of multifunctional wood cascade chains using LCA and exergy analysis (Publication 1)

6.1.1 Goal and scope

In publication 1 (Risse et al., 2017), the resource consumption and resource efficiency of a wood cascading system in comparison to a primary wood system providing the same multiple outputs was analysed. Exergy analysis was applied as it was found suitable to account for the characteristics of a wood cascading system while analysing the resource use.

6.1.2 Characteristics of a wood cascading system in relation to resource efficiency analysis

The first characteristic of a cascading system relates to its holistic perspective on the material flow. From this perspective, a cascade is a multifunctional system as various products or services (i. e. functions) are provided along the cascade. Depending on the number of cascade steps, the functional unit, i. e. the useful output, of cascading systems can therefore be rather complex and comprise various different products or services, which are expressed in different units. The second characteristic of cascading systems relates to the various recycling processes that can be included in the system, depending on the system boundaries. This characteristic becomes important when the system is analysed from a resource use perspective. As the recovered material from the recycling process is the main resource for the production of the subsequent product in the next cascade step, the recycled material needs to be accounted as an input flow in a resource efficiency assessment.

Both characteristics indicate the complexity of cascading systems, in particular with respect to efficiency analyses. Hence, it becomes apparent that a reduction of this complexity would support the comprehensibility of the study results and its potential for dissemination and decision-making. The complexity is essentially caused by the various input and output flows (products, primary and secondary resources). The aggregation of both input and output flows in one single unit would therefore simplify the handling of cascading systems in efficiency assessments and would provide the practitioner with a single score for the use in decision-making.

The third characteristic relates to the focus on wood. In a resource oriented assessment, land resources are considered a mandatory resource category to be covered by a resource indicator. This is not only recommended for all bio-based product systems in general (Pawelzik et al., 2013), but also due to the attention land area will receive as a resource of competition in a bioeconomy (UNEP, 2014).

As described in section 4.1.3.2, several indicators are available to account for the resource consumption in LCA. The method that was found suitable to account for resource use and the described characteristics is a thermodynamic-based exergy analysis. Exergy analysis offers resource use indicators, which account for a broad variety of resources, including land, expressed in a single unit (see section 4.1.3.3). Furthermore, for the efficiency assessment, exergy analysis not only enables the quantification of the input flows (i. e. primary and secondary resources) in one unit, but also the expression of all functional outputs, i. e. products, in the same unit, which reduces the complexity of efficiency assessments of multifunctional cascading systems and provides the practitioner with a single score.

6.1.3 Definition of the system boundaries

An LCA study was conducted following the guidelines given in the ISO 14040/14044 standards. Two systems were modelled to compare the cascading use with the use of primary wood (Figure 1). In the cascading system (C), the use of 1 t of untreated recovered solid timber for the sequential use as sawn timber (cf. publication 2 (Risse et al., 2019)), particleboard and energy is considered. In the primary wood system (PW), the same multiple functions are provided from primary round wood. The process heat required in the manufacturing plants are produced in boilers fuelled in shares with recovered or primary wood and process waste fractions. After the use phase, the waste sawn timber and particleboards are incinerated in a combined heat and power (CHP) plant with energy recovery. The use phases were excluded from the systems as they were considered to be identical for each product. For easier comparison, it is assumed that the sawn timber and the particleboards are made entirely from recovered wood, although this is not common practise in Germany today.

Due to the sequential use and the material loss in energy production, the cascade provides less energy at the end-of-life compared to the primary wood system. However, in comparative studies, the functional equivalence between both systems is mandatory according to the DIN EN ISO 14040:2009-11. As recommended in the standard and successfully applied on a cascading system in Höglmeier et al. (2014), system expansion was used to achieve system equality. Because system expansion modelling can significantly influence the outcome of a study (Finnveden, 1999; Heijungs and Guinée, 2007; Höglmeier et al., 2014), different energy carriers were modelled in the expansion of the cascade system: waste wood, German grid mix and primary wood.

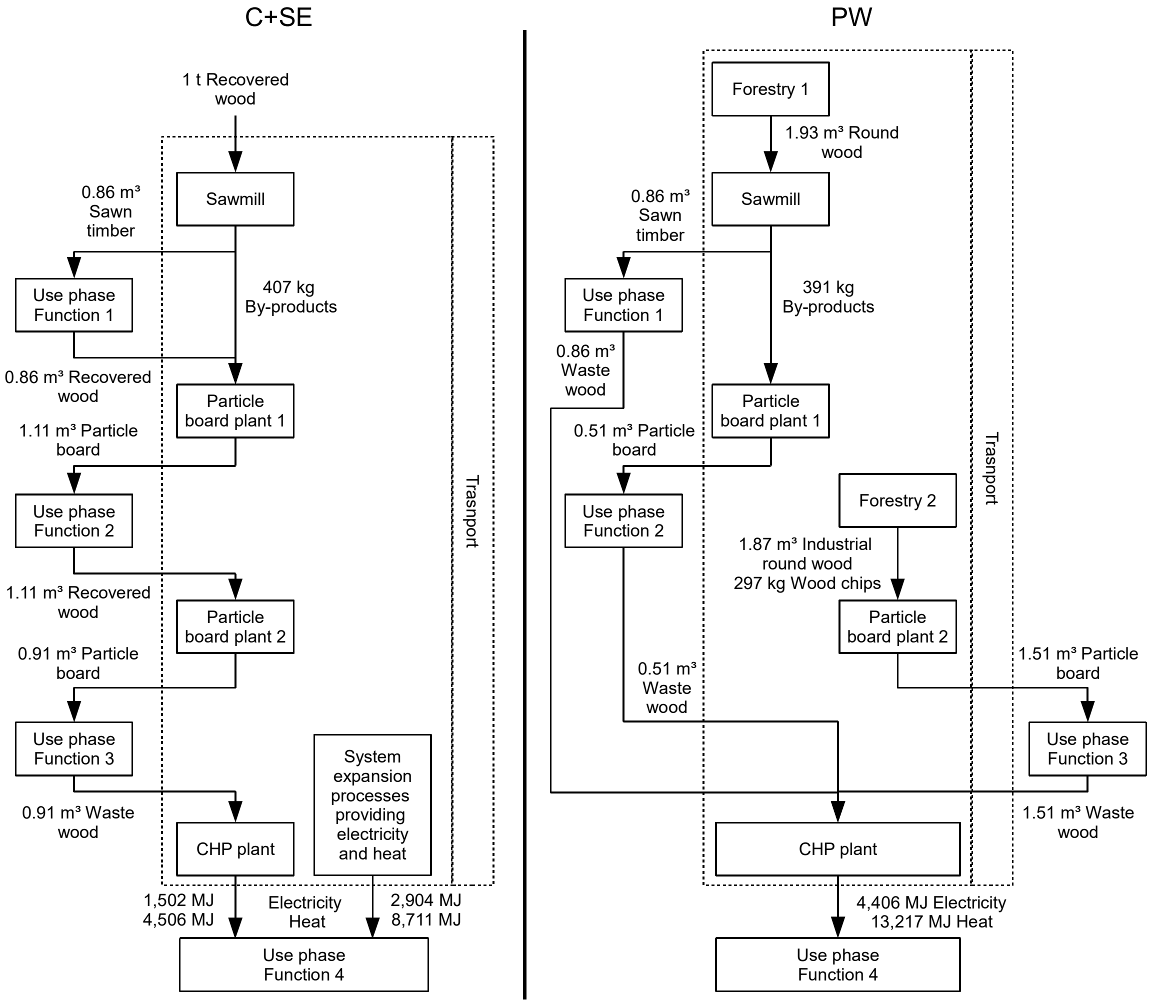

Figure 1 **System boundaries for the cascading (C) and primary wood system (PW). SE = System expansion, CHP = Combined heat and power. Figure obtained from Risse et al. (2017).**

6.1.4 Functional unit

The functional unit is defined as the "production of 0.86 m³ sawn timber, 2.02 m³ particleboard, 13,217 MJ heat and 4,406 MJ electricity". The amount of sawn timber and particleboard is determined by processing 1 t of recovered wood in the cascading system. Because of the direct incineration of the products after the first use phase, the energy output of the primary wood system is higher, which determines the energy content of the functional unit. The difference between the energy outputs of both systems is produced in the system expansion of the cascade system.

6.1.5 Environmental and exergetic life cycle inventory modelling

The modelling of the inventory data was based on average data representing the technological standard in Germany. The main inventory data was obtained from Rüter and Diederichs (2012) and adjusted with data from literature and the ecoinvent database v. 3.3 (Wernet et al., 2016). For the background data, the cut-off model of the ecoinvent database v. 3.3 (Wernet et al., 2016) was used.

For the exergy analysis, all input and output flows were converted into their exergy content using thermodynamic data from literature and own calculations (see Risse et al., 2017).

6.1.6 Exergy analysis

6.1.6.1 Exergy Flow Analysis

At gate-to-gate level, ExFA is applied for resource use analysis. In the ExFA, the input and output flows of each sub-system as modelled in the inventory data, are converted into their exergy content and used to establish an exergetic balance of the sub-system. This allows the analysis of the resource flow of a system and the identification of hotspots for improvement. The balance is used to calculate the exergetic gate-to-gate efficiency (μ) of a sub-system, as the ratio between the amount of exergy contained in the useful outputs and the total exergy content of the energy, material and utility inputs of the respective sub-system.

6.1.6.2 Exergetic Life Cycle Assessment

In ELCA, an exergy-based LCIA indicator is used to account for the resources extracted from the natural environment and to determine the exergetic efficiency at life cycle level. For resource accounting, the CEENE indicator in the version of Alvarenga et al. (2013) and Taelman et al. (2014) was used. With respect to land resources, CEENE accounts for biomass from natural systems (e. g. timber from primary forests) as well as land occupation in human-made systems for biomass production (e. g. agriculture) or alternative use (e. g. urban area) (Alvarenga et al., 2013).

6.1.6.3 Resource efficiency analysis

The CDP (Szargut et al., 1988) was applied for the efficiency calculation at life cycle level, specified to account for the characteristic of a multifunctional system (Equation 2). In a multifunctional system (CDP_{mfs}), the denominator of the efficiency formula comprises different terms. The primary resources required along the cascade are quantified with the CEENE indicator ($CEENE_{Ex}$). Although it is not extracted from the natural environment, the recovered wood entering the system delivers the raw material for a subsequent production process, and must therefore be considered as a material input ($Recovered\ Material_{Ex}$). The same applies to any product manufactured and recycled along the cascade. The useful outputs, which are recycled within the system, are considered as input material in the denominator ($Recycled\ Material_{Ex}$). The useful outputs ($Useful\ Outputs_{Ex}$) are identical to the functional unit. Numerator and denominator are expressed in exergy terms (MJ_{ex}).

Equation 2

$$CDP_{mfs} = \frac{\sum(Useful\ Outputs_{Ex})}{\sum(Recovered\ Material_{Ex} + Recycled\ Material_{Ex} + CEENE_{Ex})}$$

6.1.7 Scenarios

To determine the influence of the number of cascade steps on the resource consumption and the efficiency of wood cascading, three additional cascading scenarios were analysed. Scenario A is extended by another particleboard step, scenario B is limited to two particleboard cascade steps and scenario C is reduced to one sawn timber and one particleboard step.

6.2 Eco-efficiency analysis of recycling recovered solid wood from construction into laminated timber products (Publication 2)

6.2.1 Goal and scope

In publication 2 (Risse et al., 2019), the environmental impacts and the economic viability of recycling recovered solid wood (e. g. beams, laths) into glued laminated timber are compared with those of the currently common treatment alternative in Germany (BMUB, 2012b), i. e. the incineration in a CHP plant. Knowledge about the economic viability and environmental impacts of processes under development in comparison to alternative treatments is necessary for the further development and future practical implementation. The recycling process was developed in the CaReWood project (Irle et al., 2018; Irle et al., 2015; Privat et al., 2016).

6.2.2 Definition of the system boundaries

The system boundaries are visualized in Figure 2. To address the multifunctionality of both systems and achieve functional equivalence and comparability between both systems, system expansion was applied. System expansion is recommended in ISO 14044:2006 to avoid allocation in multifunctional systems, and has proven its suitability for comparative waste treatment studies (e. g. Höglmeier et al., 2014; Finnveden, 1999; Rivela et al., 2006). The comparison is based on the treatment of 1 t of recovered wood entering the system, which is assumed to have reached the end-of-waste status and is thus free from environmental burdens from previous life cycles (DIN EN 15804:2014-07). This assumption is in line with the definitions given in the European Waste Framework Directive (EC, 2008) and other studies on wood utilization (Höglmeier et al., 2014).

The CaReWood (CW) system was modelled according to the descriptions given in Irle et al. (2015), Irle et al. (2018) and Privat et al. (2016). Beginning at the place of origin (e. g. construction site), the recovered wood is transported, sorted and sawn into lamellae. After drying, the lamellae are used in glulam manufacturing. The overall yield from the construction site to the glulam product amounts to 26 % (Irle et al., 2018; Privat et al., 2016). Contaminated rejects and offcuts are incinerated in a CHP plant for process energy production, with the surplus energy provided to grid. The system is expanded by the production of electricity and heat from primary wood chips in order to have both systems based on wood. Since system expansion modelling can be a decisive factor for the outcome of a study (Finnveden, 1999;

Höglmeier et al., 2014; Risse et al., 2017), the energy provision from grid was modelled in the system expansion as scenario of the CW system (scenario SEg).

The reference system describes the incineration of the recovered solid wood in a CHP plant, including a sorting and chipping process in advance. In the system expansion, the production of glulam from primary wood was modelled. Process energy is generated from the on-site incineration of by-products, with the surplus energy provided to the grid.

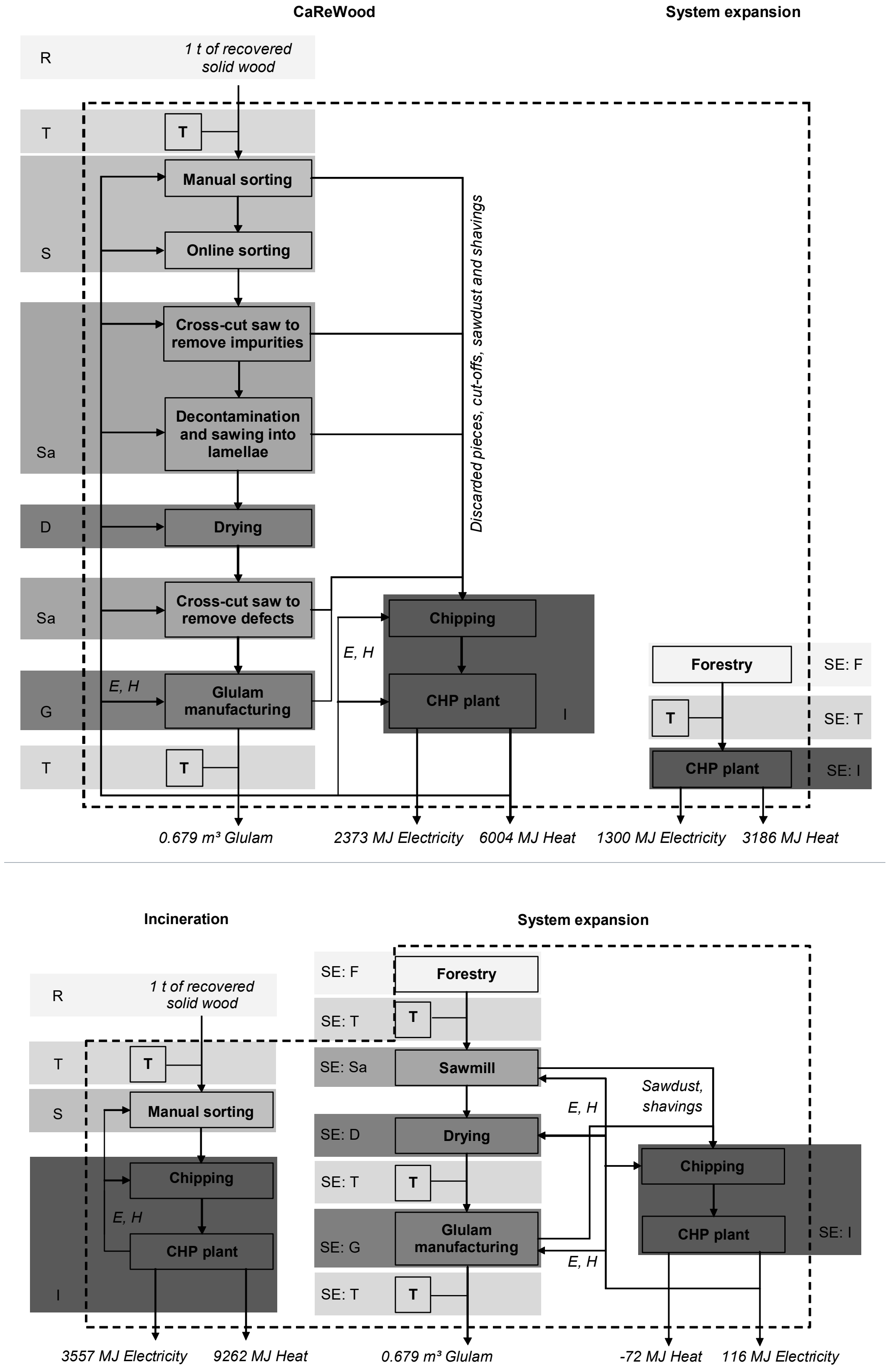

Figure 2 **System boundaries for the CaReWood (top) and the reference system (bottom). The colouring refers to the process grouping: R = Recovered wood, T = Transport, S = Sorting, Sa = Sawing, D = Drying, G = Glulam manufacturing, I = Incineration, F = Forestry, SE = System expansion, CHP = Combined heat and power, Glulam = Glued laminated timber, E = Electricity, H = Heat. Figure obtained from Risse et al. (2019).**

6.2.3 Functional unit

The functional unit is defined as the "treatment of 1 t of recovered solid wood as well as the production of 0.679 m^3 of glulam, 3676 MJ of electricity and 9190 MJ of heat". The maximum of products in each system is defined by the treatment of 1 t of recovered wood in either the recycling or the incineration system. The products, which cannot or not in the required amount be produced from recovered wood, are produced in the system expansion from primary wood.

6.2.4 Environmental and economic life cycle inventory modelling

Since the CaReWood process is not yet in practice, primary inventory data was not available. Therefore, each manufacturing step is modelled based on data from unit processes describing similar manufacturing steps of existing technologies. This data was modified following the descriptions and recommendations by the project partners involved in the development of the process and as described in Irle et al. (2015), Irle et al. (2018) and Privat et al. (2016). Manufacturing steps which are similar or identical in both systems, were modelled using the same data and were then modified and supplemented to the specifications of the respective system. This approach was chosen to achieve data accuracy between both systems and a better comparability and reliability of the results. For the joint economic assessment in LCC, each inventory flow from the LCA was assigned with cost data for operational cost calculation. Each process was supplemented with costs for maintenance, investment and labour as they are not considered in the inventory flows of the LCA. LCA data is obtained from literature and the cut-off model of the ecoinvent database v. 3.3 (Wernet et al., 2016). Cost data was collected from literature, statistical databases and German industry, representing the status-quo in Germany.

6.2.5 Impact assessment and economic calculation

The environmental impacts of each system were calculated with the midpoint indicators from the ReCiPe 2016 method (Huijbregts et al., 2017). The LCC was performed following the guidelines given in Swarr et al. (2011) and Hunkeler et al. (2008). The total life cycle costs (LCC_t) were calculated as the sum of the costs of each process. Additionally, the value added (VA) of each system was calculated, indicating the difference between the revenues obtained and the LCC_t. The VA describes a profit margin and provides insight into the economic viability of the process under study. In the revenue and VA calculation, the volatility and uncertainty of the market price for products from recovered wood (in particular the glulam) was taken into account by considering a variation of ± 20 % for all market prices.

6.2.6 Calculation of the eco-efficiency

The eco-efficiency (EE) was calculated according to DIN EN ISO 14045:2012-10 as the ratio of the value added (describing the desired functional output) and each LCIA indicator result (describing the input needed for the production or provision of the desired output). The value added was chosen as it includes the life cycle costs and revenues.

6.2.7 Scenarios

Different scenarios were modelled to identify the influence of specific parameters on the results and outcome of the comparison. Scenario analysis is important in the analysis of emerging technologies to provide reliable and robust results and identify hotspots for improvement (Arvidsson et al., 2017; Cucurachi et al., 2018).

The yield describes the share of the recovered wood which remains in the glulam product and has been obtained from Irle et al. (2018), Irle et al. (2015) and Privat et al. (2016). The influence of the yield on the environmental and economic performance of the recycling system is analysed in two scenarios, one with a lower (18 %, Y18) and one with a higher yield (35 %, Y35) compared to the base scenario (26 %, BS). The impact of a protection of the wood from moisture through optimized logistics on costs and environmental impacts was analysed by a lower (13 %, M13) and a higher (26 %, M26) moisture content compared to the base scenario (22 %, BS). The sawing effort describes the amount of energy and utilities necessary to process the recovered solid wood into lamellae. Its analysis accounts for the uncertainty of the inventory data modelling originating from the laboratory scale of the process (see section 6.2.4). Four scenarios with a variation of ± 20 % and ± 40 % were analysed (S-40, S-20, S+20, S+40). Currently, long transportation distances for sawn wood for the production of glulam are common (Rüter and Diederichs, 2012). To analyse the impact of optimized logistics and to be consistent with the on-site manufacturing pattern considered in the CaReWood system (Figure 2), in the reference system two scenarios with a transportation distance for sawn wood reduced to 413 km and 0 km are studied (T413, T0). Since the price for recovered wood is very volatile (EUWID, 2017; LWF, 2018), different scenarios are calculated to determine the economic viability of the processes under changing market conditions. While at present a gate fee has to be paid for the disposal, scenarios are considered which assume a reduced gate fee (P0, P40, P80) as well as a payment for the recovered wood as a resource of competition (P-40). The influence of modelling the energy provision from grid in the system expansion of the CaReWood system is analysed in scenario SEg.

7 Results and discussion

7.1 Resource efficiency of multifunctional wood cascade chains using LCA and exergy analysis (Publication 1)

7.1.1 Exergy Flow Analysis and gate-to-gate efficiency

The results from the ExFA are visualized in Figure 3 for the default scenario. Both forestry sub-systems were identified in the ExFA as hotpots in exergy dissipation of the primary wood system because of the large occupation of land area required for round wood production. Consequently, efficiencies of 0.2 % are calculated for the forestry sub-systems. According to these observations, the forestry sub-systems offer the greatest potential for efficiency improvement. However, the consideration of primary round wood as the single useful output of the land occupation through a forestry system indicates the shortcomings related to an efficiency assessment of forestry systems using exergy analysis as discussed in section 7.1.4.

The by-product valorisation of the sawmill in the particleboard manufacturing leads to a high efficiency of the sawmill sub-systems. The key driver for the exergy dissipation in the sawmill and particleboard sub-systems is the use of some of the input material for process energy production. Since the inputs and process energy required in the sawmill sub-systems are smaller compared to the particleboard manufacturing, the sawmill sub-systems have a higher efficiency.

The use of recovered wood instead of primary wood leads to an increase of the efficiency in the sawmill of 2 % and in the particleboard plant of 4-5 %. These results confirm the observations from previous studies that the direct cascading effects from the use of recovered wood are relatively low (Gärtner et al., 2013; Höglmeier et al., 2014; Sathre and Gustavsson, 2006), since the processing of primary wood is already very efficient, as indicated by the results for the PW system. Although a potential increase of the efficiency of 1-3 % is available in both plant types through the use of a CHP plant instead of a boiler, the results only indicate a small potential to improve the efficiency of wood processing through the use of recovered wood and optimized processing technologies.

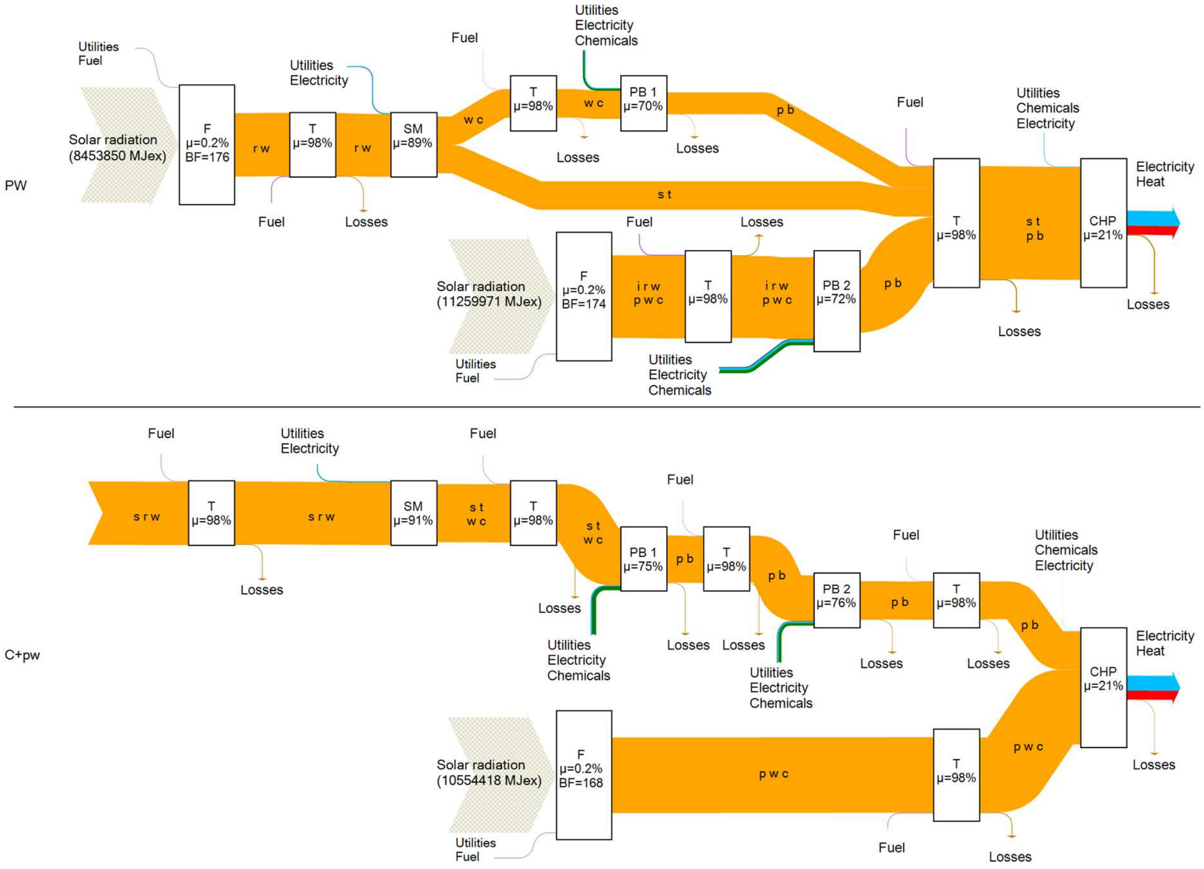

Figure 3 Flow diagram for the Exergy Flow Analysis of the default scenario. PW = Primary wood system, C+pw = Cascade system incl. system expansion from primary wood, μ = Gate-to-gate efficiency, rw = Round wood, wc = Wood chips, st = Sawn timber, pb = Particleboard, srw = Solid recovered wood, pwc = Primary wood chips, irw = Industrial round wood, F = Forestry, SM = Sawmill, T = Transport, PB = Particleboard plant, CHP = Combined heat and power. Losses include wood losses during transportation and chipping. The solar radiation flows are not to scale with the other flows. Figure modified from Risse et al. (2017).

7.1.2 Exergetic Life Cycle Assessment

In the default scenario, the total resource consumption of the cascade only amounts to 10 % (C+ww), 22 % (C+g) and 58 % (C+pw) of the resource consumption of the primary wood system, as visualized in Figure 4. Land resources are the main resources saved through cascading, due to the avoidance of wood production. Although a broader range of resources is considered, the results are comparable to the observations from Cornelissen and Hirs (2002), Gärtner et al. (2013) and Höglmeier et al. (2014).

A comparison of the CEENE value between the sawmill and the particleboard plants of both systems reveals that the direct primary resource saving potential from using recovered wood amounts to 8 % in the sawmill and to 5 % in the particleboard plant only (Figure 4 in Risse et al., 2017). As already discussed in section 7.1.1, using recovered wood does not achieve substantial resource savings, because of the similarities in using recovered and primary wood. As a consequence, the small savings obtained at plant level from using recovered wood are compensated at life cycle level from the resource use in the system expansion processes.

Cascading proved to be more resource-efficient compared to the use of primary wood to provide the same functional output (Figure 4). Due to the large amount of land resources required in the forestry systems, the overall efficiency of the primary wood system is reduced. A maximum increase in the efficiency of wood production (e. g. forest plantations, genetically modified organism) could therefore be the nearest conclusion. However, this disregards aspects of sustainability and ecosystem services, as further discussed in section 7.1.4. Since fossil fuels are the second most consumed resources in both systems, renewable raw materials for electricity generation and as feedstock for adhesives should be used to make particleboard production independent from fossil fuels.

The constant increase in the consumption of energy and fuel as well as material losses for energy production leads to a decrease of the efficiency with every cascade step. The main efficiency decrease is between the sawmill and the particleboard plant, which can be explained by the larger amount of energy and utilities required in the particleboard plant. Keeping the material in solid wood applications can therefore increase the efficiency of the cascade. Both results confirm the assumption of Sirkin and Houten (1994) that the resource efficiency of a wood cascade is optimized by limiting the decline in resource quality and reducing the efforts required to maintain the resource quality for the next cascade step.

Although system expansion modelling can decisively influence the outcome of a study (Höglmeier et al., 2014), all cascading systems show smaller CEENE values and higher efficiencies than the reference system. However, system expansion modelling influences the composition of the resource profile. For example, in the default scenario, land resources from the system expansion contribute with 89 % to the total resource consumption of the C+pw system, while the entire system expansion processes only contribute 5 % to the overall resource consumption in the C+g system. Even though the system expansion modelling is not decisive for the overall resource consumption, the composition of the resource profile is relevant for emission-based indicators. As a consequence, the global warming potential (GWP) of system C+g is 75 % higher than the GWP of the primary wood system. Thus, a carefully composed indicator set including resource and emission oriented indicators is required to provide reliable results (Steinmann et al., 2016).

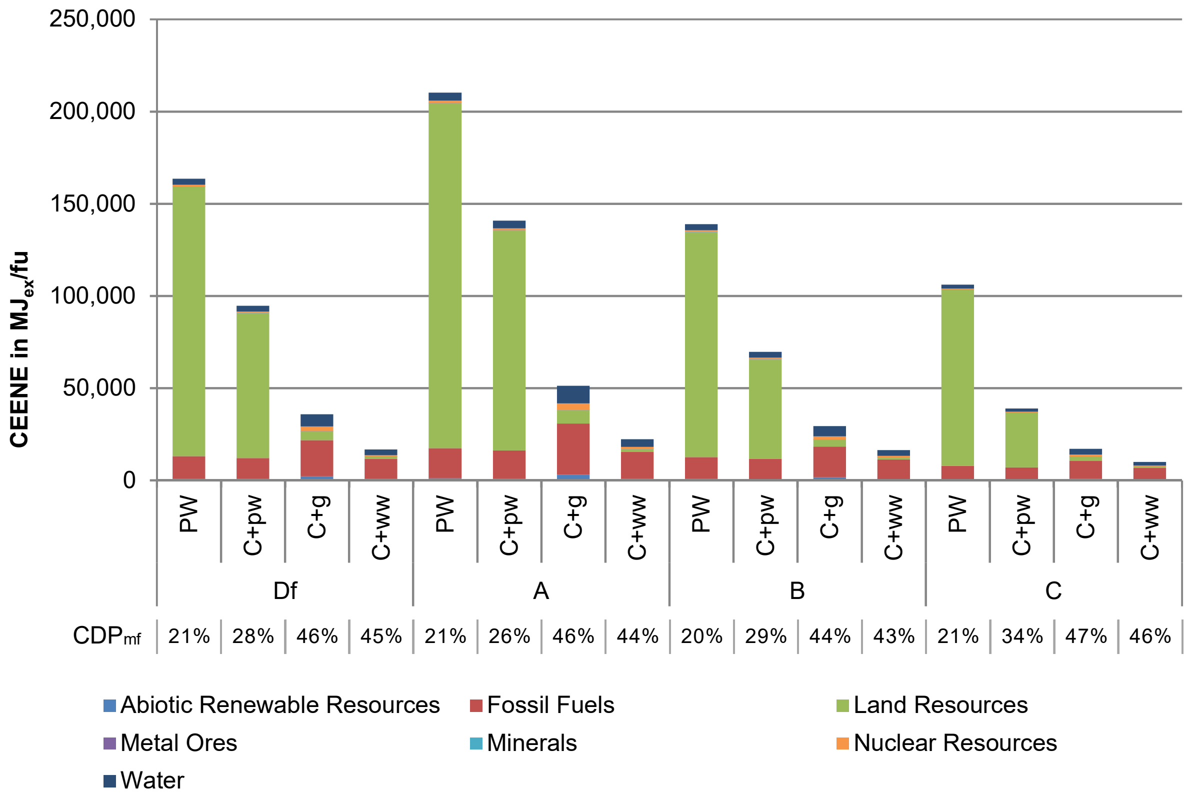

Figure 4 **Total resource consumption (CEENE) and resource efficiency (CDP_{mf}) for each system and scenario. Df = Default (RW→ST→PB→PB→CHP), A (RW→ST→PB→PB→PB→CHP), B (RW→PB→PB→CHP), C (RW→ST→PB→CHP), RW = Recovered wood, ST = Sawn timber, PB = Particleboard, CHP = Combined heat and power, C+pw = Cascade system incl. system expansion from primary wood, C+g = Cascade system incl. system expansion from grid, C+ww = Cascade system incl. system expansion from waste wood, PW = Primary wood system, fu = Functional unit. Figure modified from Risse et al. (2017).**

7.1.3 Influence of the number of cascading steps

Scenario analysis revealed that each additional cascade step reduces the resource efficiency of the cascading system, if the recycling of sawn timber is modelled as the first step (Comparing the scenarios in the order of C, Df, A). In contrast, if starting with scenario B, the efficiency of the systems C+g and C+ww is higher in the scenarios Df and A (Comparing the scenarios in the order of B, Df, A). Thus, an additional cascade step increases the efficiency at least in two systems. Overall, the results are, however, unclear in terms of a general relation between the number of cascade steps and the efficiency. Whether a longer or shorter cascade is advantageous depends rather on the composition of the manufactured products along each cascade, the underlying reference cascade as well as the processes modelled in system expansion. Although this result is not decisive for the comparison, it is contradictory to the expectation that the efficiency of the cascade increases with an additional step. However, a direct comparison between the different cascades is difficult as they provide different functions.

An efficiency increase with each cascade step can be observed if the cascade itself is analysed excluding the system expansion (see row “CHP” in Table 5 in Risse et al., 2017). At life cycle level, however, the system expansion processes influence the results. Since every cascade step involves a reduction of the amount of recovered material through losses and uses for energy production, the required inputs and energies generated in the system expansion increase with every step. Due to the small efficiency of the energy generation in the system expansion, the overall efficiency of the system decreases with every additional step due to the increasing relative share of the system expansion processes.

Similar results were obtained from Höglmeier et al. (2014), who found that the environmental benefits of the cascading scenario decreased with additional cascading steps relative to the primary wood system. In contrast, a higher number of cascading steps was found beneficial in the studies from Gärtner et al. (2013). These contradictory results can be attributed to the different system models. Gärtner et al. (2013) used an input-based, whereas Höglmeier et al. (2014) and Risse et al. (2017) used an output-based functional unit. Both approaches are correct from a methodological perspective. However, with an input-based functional unit along with an avoided burden approach, the environmental effects add up with every additional cascade step.

7.1.4 Exergy approach for resource efficiency analysis of multifunctional systems

The study shows the feasible application of the exergy concept for the resource efficiency analysis of a wood cascading system. As described in section 6.1.2, exergy analysis accounts for the multifunctionality of cascading systems, allows considering internal recycling flows in the efficiency calculation and covers a broad range of resources including land area. Furthermore, all input and output flows (i. e. resources, materials, products) are aggregated in the same unit, which makes the efficiency assessment of cascading systems straightforward.

Apart from the shortcomings of the exergy approach described in section 4.1.3.3, the method shows shortcomings in the characterisation of land use with respect to the application on forest ecosystems. Certainly wood production in sustainable forests requires a long-term occupation of land area. However, the land occupation leads to the description of forests as inefficient systems, which require significant reduction of land occupation and efficiency improvements in the land use. Although land area is increasingly perceived as a resource of competition in highly populated countries like Germany (UNEP, 2014) and silviculture offers strategies to improve the efficiency of wood production through optimized thinning or species selection (Diaconu et al., 2015; Pretzsch, 2005), this conclusion holds a potential for conflict, considering the diverse demands already placed on forests today (BMEL, 2011) and the sustainability concept of forest management (BMEL, 2011).

In this respect, the shortcomings in land use accounting in exergy analysis lies in reducing the functions provided from a forest to its provisional services. Additional ecosystem services like recreational or regulating services (MEA, 2005) are disregarded. However, these services are only provided from the long-term land occupation and forest development. The exergetic value of biomass growth and land occupation should thus not only be allocated to wood production, but also transferred into other functional and useful outputs. For the efficiency assessment of forest systems, the additional services therefore either have to be considered as useful outputs of the system or the resource inputs have to be allocated to other services besides the wood production. Several concepts and methods were developed to overcome these shortcomings, but have not yet found wide application (Hau and Bakshi, 2004; Schaubroeck et al., 2016; Zhang et al., 2010b; Zhang et al., 2010a).

Exergy analysis proved to be a viable method to analyse the efficiency of a multifunctional wood cascading system. However, it is recommended to apply exergy analysis as part of an indicator set to generate reliable and transparent results. One major shortcoming of the study is disregarding the aspect of time, which is relevant in two aspects of the study. First, the cascade considers a time horizon of 50-100 years. During this time span, technologies and legal frameworks evolve, which makes a cascading study using data of current technologies quite uncertain. Future studies should therefore consider future technologies in scenario analyses, e. g. on the electricity mix. Second, the timing of resource consumption and environmental emissions is disregarded, although biogenic carbon accounting is recommended for LCAs of forest-based products (Pawelzik et al., 2013; Røyne et al., 2016), and of particular importance for cascading studies considering the extended time of carbon storage and delayed emissions. Several methods are available to account for the carbon storage and delayed emissions in LCA (Brandão et al., 2013; Cherubini et al., 2011; Levasseur et al., 2013; Levasseur et al., 2010; Pawelzik et al., 2013; Røyne et al., 2016), and should be applied in future cascading studies similar to Faraca et al. (2019). A preliminary application of dynamic LCA (Levasseur et al., 2010) on a wood cascading system based on the recycling process analysed in publication 2 (Risse et al., 2019), was presented by Rassel (2017), indicating a lower GWP for the cascading system compared to the direct incineration of the recovered wood.

7.2 Eco-efficiency analysis of recycling recovered solid wood from construction into laminated timber products (Publication 2)

7.2.1 Results from Life Cycle Assessment

The comparison of the environmental impacts of the recycling and incineration treatment alternative indicate a better performance of the recycling system in all impact categories and for most considered scenarios (Figure 5 and Table 1). The recycling of the recovered wood leads to relative benefits between 11 % and 29 % with the exception of human toxicity potential of only 1 %. The overall results of the study are in line with those observed in other recovered wood treatment studies, such as Hossain and Poon (2018), Rivela et al. (2006), Hakala et al. (2014) and Merrild and Christensen (2009), although a direct comparison of the studies is difficult due to different methodological approaches.

One of the largest savings of the CW system is observed for the category of agricultural land occupation with 29 % lower impacts. This result is due to the smaller amount of wood required for the energy production in the system expansion of the CW system, compared to the production of glulam in the reference system. The saving of land area through wood recycling and cascading has also been described by Höglmeier et al. (2014) as well as in publication 1 (Risse et al., 2017). However, these results should not lead to a reduction in primary wood consumption, as this disregards the carbon storage and substitution potential of harvested wood products and fuels, and hinders the realization of the environmental benefits of cascading (Lippke et al., 2011; Rüter et al., 2016; Suter et al., 2017; Werner et al., 2005). Likewise, it should not lead to the use of the saved primary wood for energy production satisfying an increasing demand for energy wood as described by Knauf (2015), as it would bypass the cascading concept. However, the recent national report on the monitoring of wood resources shows a stagnation of wood used for energy production due to the abolition of financing under the EEG (Mantau et al., 2018). Thus, the saved primary wood should rather be used to increase the material use of wood, which will increase the carbon and product pool and additionally avoid impacts from alternative non-wood products, as intended in national policy (BMEL, 2018; BMUB, 2016) and concluded by Suter et al. (2017). However, this scenario certainly requires a corresponding market demand for wood-based products.

For the further development and implementation of a new technology, an analysis of key drivers is necessary to identify opportunities for improvement. The results indicate that the key machining steps of the CaReWood process, i. e. sorting, sawing and drying, are of minor importance for the overall impacts of the system. Instead, present technologies at the end of the processing chain, i. e. glulam manufacturing and incineration, as well as the system expansion processes, are the key contributors to the environmental impacts. These results confirm the observations of previous studies on wood product manufacturing and incineration (Werner and Richter, 2007; Wolf et al., 2015).

Scenario analysis reveals a robust performance of the recycling system against most of the analysed parameters (Table 1). Processing parameters like the yield, the moisture content or the sawing effort are of minor relevance for the overall impacts, similar to the observations for the CaReWood processes. If the transportation distance in the reference system is reduced, considering an on-site sawing and glulam manufacturing, the recycling system performs worse in most impact categories. Thus, a practical implementation near existing plants is recommended to minimize transportation distances, which is in line with the recommendations from Garcia and Hora (2017), who identified the collection and transportation as important factors in the recovered wood treatment.

System expansion modelling has a strong influence on the results of the comparison as already described by Heijungs and Guinée (2007) and Finnveden (1999) and observed in other studies related to wood recycling (Höglmeier et al., 2014; Hossain and Poon, 2018; Rivela et al., 2006). A change of energy production in the system expansion (scenario SEg) from wood chips to energy from grid, leads to much higher impacts of the recycling system (Table 1). The same effect was observed by Rivela et al. (2006), who applied a similar system modelling approach. It is also similar to the DemoWood study, in which the substitution of fossil-derived energy leads to greater benefits in comparison to the material recycling of recovered wood (Hakala et al., 2014). The environmental performance of a (wood) recycling process therefore highly depends on its integration at market level as well as the market conditions. These dependencies illustrate the relevance of scenario analysis and, ideally, estimations of the probability of occurrence of each alternative considered. As it is likely that the future energy mix is provided from renewable resources with less environmental impacts, the material recycling system might still be a favourable option if a renewables-based grid mix is considered in system expansion. To account for these market or indirect effects, consequential LCA was developed (Earles and Halog, 2011; Ekvall and Weidema, 2004).

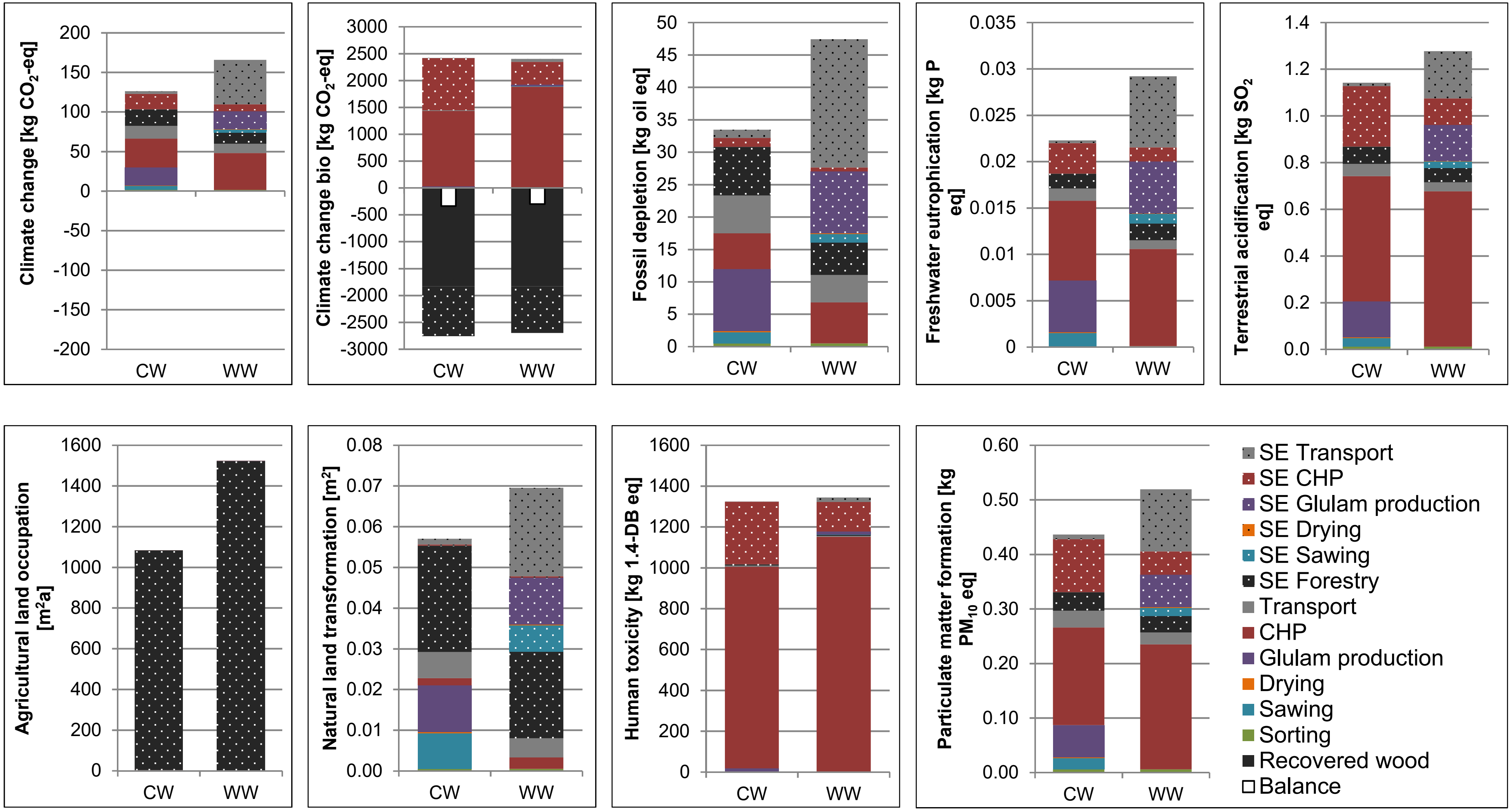

Figure 5 **Environmental impacts of the CaReWood (CW) and reference system (WW) for the base scenario. The dotted segments indicate system expansion processes (SE). A balance is expressed for the climate change including biogenic carbon impact category. Figure obtained from Risse et al. (2019).**

7.2.2 Results from Life Cycle Costing

The LCC_t (Figure 6) of the recycling system are 31 % lower compared to the reference system (Table 1), which equals a difference of 106 € between the recycling (230 €) and the reference system (336 €). These results can be explained by the higher costs for the glulam production from primary wood compared to the production of glulam from recovered wood. The main benefit of the recycling system is that the glulam is made from recovered material with low economic value, whereas in the reference system, primary wood has to be purchased. Similar to the LCA results, the incineration, glulam manufacturing and system expansion processes (mainly forest operations) are the driving processes, while the CaReWood-specific processes are of minor importance for the total costs. The large contribution of the primary wood to the overall costs is a characteristic aspect of a wood product and can amount to a share of up to 70 % of the total manufacturing costs, depending on the product and the company size (Binder, 2002; Schulte et al., 2003; Seintsch, 2011).

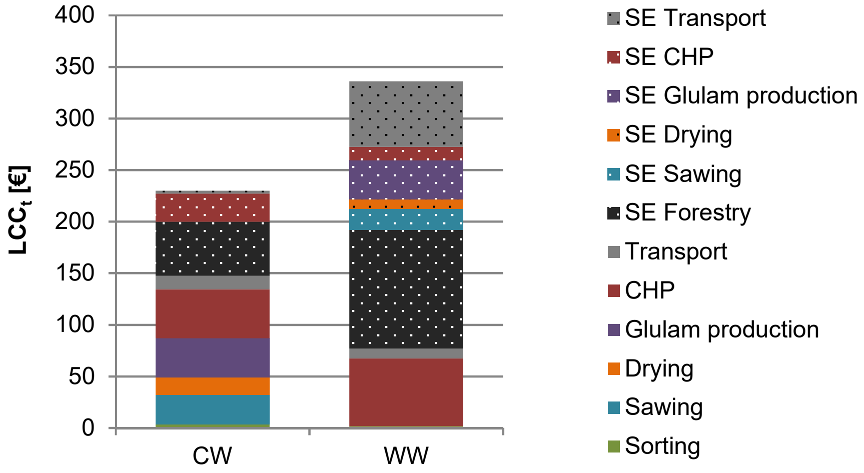

Figure 6 **Total life cycle costs (LCC_t) for the CaReWood (CW) and reference system (WW) in the base scenario. Processes from system expansion are indicated by dots (SE). Figure modified from Risse et al. (2019).**

The revenues amount to 614 € in the CaReWood and to 598 € in the reference system, due to the different market prices as described in section 6.2.5 (Figure 7). In both systems, a positive value added of 384 € in the recycling and 262 € in the incineration system is calculated, indicating the economic viability of both treatment alternatives (Figure 7). The positive value added remains, when 20 % lower market prices are considered, indicating an economic flexibility against changing prices and the uncertainty towards the societal acceptance of the recovered wood product on the market.

In contrast to the LCA results, the yield has a stronger influence on the costs, revenues and value added of both systems. A comparison of the scenarios further shows a slightly higher or comparable influence of the yield on the results, compared to the market price for recovered wood, the moisture content and the sawing effort. Similar to the LCA results, the transportation distance in the reference system shows the largest influence on the reduction of the benefits of the CaReWood system (6 % in T413, 12 % in T0 in Table 1). Nevertheless, the impact of the transportation distance on the economic results is not decisive for the comparison as it is in the LCA.

The consideration of different market prices for recovered wood accounts for the volatile market of recovered wood in recent years and thus allows an analysis of the robustness of the processes against changing market conditions. The scenarios P-40 and P0 represent the future situation of an increasing demand for recovered wood in an evolved bioeconomy with the consequence of a limited market availability for recovered wood. The scenario results indicate that even if the consumer of the recovered wood pays for the material, the value added remains positive in both systems.

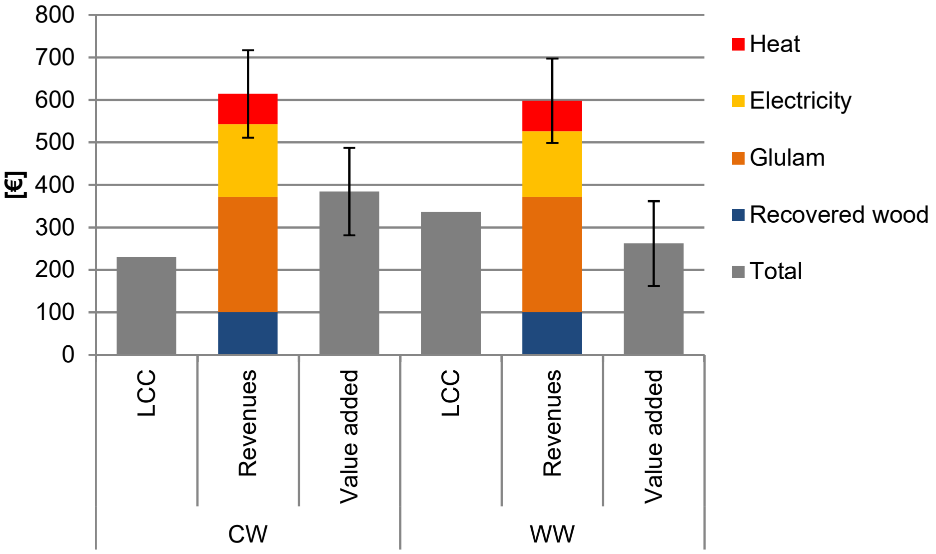

Figure 7 **Life cycle costs (LCC_t), revenues and value added for the base scenario of the CaReWood (CW) and the reference system (WW). The bars reflect the variation of ± 20 % of the considered market prices for glulam, electricity and heat. Figure modified from Risse et al. (2019).**

Table 1 **Relative performance of the CaReWood system compared to the reference system for each of the considered scenarios including the LCA and LCC results. Negative values indicate a better relative performance of the CaReWood system. Positive values indicate a relative better performance of the reference system. The latter are underlined for visualisation. The scenarios P0, P40, P80 are not shown, as they do not influence the LCA and LCC results. FD = Fossil depletion, CC = Climate change excl. bio. CO_2, CC bio = Climate change incl. bio. CO_2, FE = Freshwater eutrophication, TA = Terrestrial acidification, HT = Human toxicity, PMF = Particulate matter formation, ALO = Agricultural land occupation, NLT = Natural land transformation, n/a = not assessed. For scenario descriptions, see section 6.2.7. Table obtained from Risse et al. (2019).**

	BS	Y18	Y35	M13	M26	S-40	S-20	S+20	S+40	P-40	T413	T0	SEg
LCC_t [€]	-32%	-27%	-35%	-36%	-32%	-35%	-33%	-30%	-28%	-28%	-26%	-20%	n/a
FD [kg oil eq]	-29%	-25%	-33%	-29%	-30%	-31%	-30%	-29%	-28%	-29%	-16%	4%	158%
CC [kg CO_2-eq]	-24%	-19%	-28%	-23%	-24%	-25%	-25%	-23%	-23%	-24%	-12%	3%	157%
CC bio [kg CO_2-eq]	-13%	-18%	-14%	-13%	-13%	-14%	-14%	-13%	-13%	-13%	-6%	1%	90%
FE [kg P eq]	-24%	-17%	-29%	-23%	-24%	-26%	-25%	-23%	-22%	-24%	-15%	-4%	979%
TA [kg SO_2 eq]	-11%	-6%	-15%	-10%	-11%	-12%	-11%	-10%	-9%	-11%	-5%	2%	0%
HT [kg 1.4-DB eq]	-1%	3%	-7%	-1%	-2%	-2%	-2%	-1%	-1%	-1%	-1%	0%	-9%
PMF [kg PM_{10} eq]	-16%	-11%	-20%	-16%	-16%	-18%	-17%	-15%	-14%	-16%	-8%	1%	-10%
ALO [m^2a]	-29%	-29%	-30%	-27%	-30%	-30%	-30%	-29%	-29%	-29%	-29%	-29%	-98%
NLT [m^2]	-18%	-14%	-21%	-17%	-18%	-23%	-21%	-15%	-13%	-18%	-7%	8%	4%

7.2.3 Eco-efficiency

The results from eco-efficiency analysis are expressed in Figure 8. In all scenarios and indicators considered, the recycling system has a better eco-efficiency compared to the incineration system.

Scenario analysis reveals that a higher yield results in a reduction of the eco-efficiency of the incineration system and in some impact categories of the recycling system. This result is contradictory to the expectation of a higher yield being beneficial for the efficiency of a process. This expectation is likely to be true for the main manufacturing process, but may not hold if the life cycle perspective and system expansion processes are taken into account, as already observed in publication 1 for the efficiencies of the cascading system (Risse et al., 2017) (see section 7.1.3). The reason for this result is the different relative influence of the environmental and economic perspective as well as the efficiency of the system expansion processes. Thus, with an increasing yield, the relative increase in value added (32 % in CW and 5 % in WW) is lower than the increase in environmental impacts due to the additional production effort (e. g. 100 % ALO in both systems). In other words, in the reference system and for some indicators of the recycling system, the increase in value added cannot compensate the increasing environmental impacts (trade-offs). The differences between both systems can be attributed to the higher costs and impacts for product manufacturing from primary materials compared to the energy generation. This results in a higher influence of the system expansion processes in the incineration system than the recycling system. This effect is additionally strengthened by the fact that the production of a wood product from primary wood is less efficient than the production from recovered wood (Risse et al., 2017).

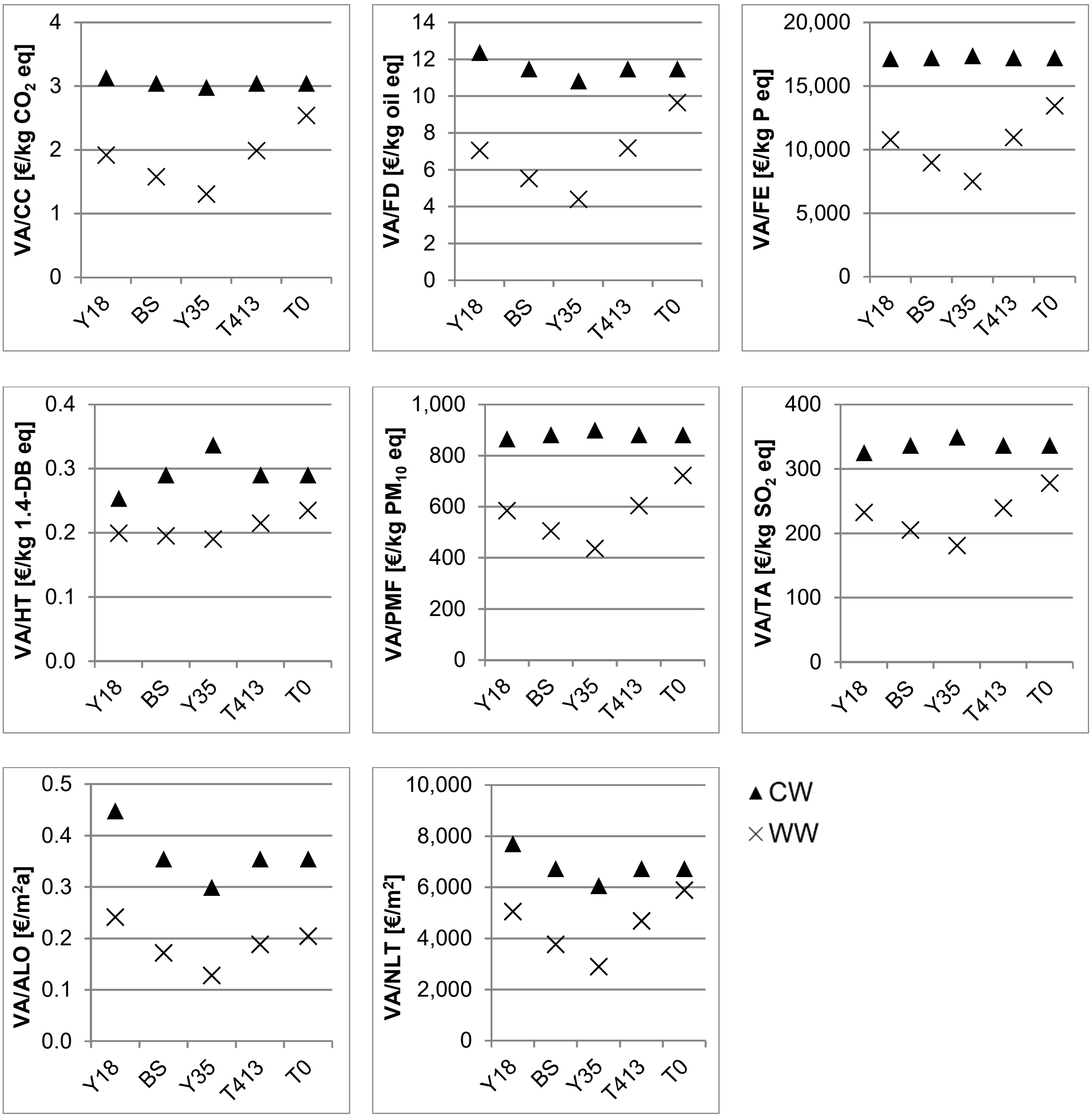

Figure 8 Eco-efficiency for selected scenarios. The indicator is based on the value added (VA) and each LCIA indicator. CW = CaReWood system, WW = Reference system, SE = System expansion, CHP = Combined heat and power, FD = Fossil depletion, CC = Climate change excl. bio. CO_2, FE = Freshwater eutrophication, TA = Terrestrial acidification, HT = Human toxicity, PMF = Particulate matter formation, ALO = Agricultural land occupation, NLT = Natural land transformation. Figure obtained from Risse et al. (2019).

7.2.4 Methodological discussion

The material recycling of recovered solid wood is an emerging process, which is currently not in practise. The data and system modelling is therefore based on assumptions and recommendations from wood processing experts (e. g. from the CaReWood project). This is typical for the evaluation of emerging technologies (Cucurachi et al., 2018), but involves a certain level of uncertainty. From technological perspective, the overall modelling approach is considered as reasonable, because none of the machining required is beyond current technologies (Irle et al., 2015) and a functional and technical comparability between primary and recovered wood can be assumed (Cavalli et al., 2016; Meinlschmidt, 2017). Yet, uncertainties related to the properties, the grading, the potential applications, the consumer acceptance and the market price of recovered wood products remain. With respect to data modelling, the technical similarities between the new machining concept and existing processes allowed the use of inventory data from databases, which provides a reliable and consistent data background. However, due to the approach of using the same data background and adjusting it to each system's requirements to avoid influencing the results using data of different origin and level of detail, the results are based on the assumptions from engineers and the authors only, but not on differences determined from existing processes. Higher uncertainties have to be accepted for the economic results, due to the limited availability and the spatial volatility of economic data.

Along with the technical comparability between recovered and primary wood, a similar market price for the recycled glulam was assumed. However, other quality losses (e. g. aesthetical features like nail or screw holes, stain) are disregarded, but might affect the market price, the technical properties and thus the possible applications. In future studies, the consideration of a quality factor for recycled wood, as suggested by Rigamonti et al. (2018), should be applied to account for the influence of different quality losses on the economic and environmental performance.

Studying the performance of an emerging process poses challenges related to time, data and market conditions. Before the CaReWood process becomes an incumbent technology, among other developments, the existing technologies will evolve, the legal framework will change and the consumer and industry habits will develop. Additionally, the implementation of new recycling processes will change the market itself and rearrange market conditions and material flows, create new products and affect consumer decisions. These future conditions for the environment of the new technologies are disregarded in the current study, but could be addressed by scenario analysis using evolved methods from system thinking or statistical analysis (Arvidsson et al., 2017; Cucurachi et al., 2018). This approach can be combined with a consequential LCA to account for changes at market level (Earles and Halog, 2011). The impacts of rearranging the material flows on carbon emissions and storage can be analysed with dynamic LCA (Levasseur et al., 2013), taking the timing of the emissions into account, as already described in section 7.1.4.

8 Synthesis and outlook

8.1 Conclusions

The presented research describes the assessment of the resource efficiency of wood cascading as well as the eco-efficiency analysis of a newly developed recycling process for recovered solid wood.

With respect to the overall goal of this dissertation, it can be concluded that wood cascading is not *per se* superior in terms of the efficiency of wood use. It strongly depends on the considered perspective and market context applied for the systems under study, if at all and to what extend wood cascading and recycling leads to the expected benefits in wood use. In most scenarios, however, wood cascading contributes to increasing the efficiency of wood utilization and can thus be recommended for practical implementation. The same applies to the recycling of recovered solid wood, which provides opportunities for an economically viable production of products with low environmental impacts. Yet, the studies show that each scenario and technology has to be analysed individually in order to avoid misleading conclusions.

With respect to the application of an efficiency indicator on life cycle-based studies, it can be concluded that the application on systems with an identical output does not provide more information than the results for the input indicators, which is the case for most LCA studies. The benefits lie in the comparison of systems, assessed from different perspectives (e. g. environmental and economic) and thus different quantification methods for the inputs and outputs. As such, the efficiency indicator offers greater potential for application, when for example an economic, aesthetic or other aspect influences the *value* of the output (given the technical equivalence of the outputs). This is the case in Risse et al. (2019), where the different economic values of the outputs (although the product provides the same function) are accounted for in the efficiency assessment. For further application, it is recommended to use an eco-efficiency indicator rather than a resource-based indicator only, as it provides a broader perspective comprising flows or impacts derived from resource and emission flows. The indicators for the quantification of inputs and outputs should then be chosen under the consideration of the scope of the study.

Both studies focus on Germany as a case region, because of the spatial volatility of LCA and LCC data. Since the data can significantly vary between regions within and across countries, the results cannot be directly transferred to other regions, but can provide guidance for other regional studies.

The research questions developed in chapter 3 can be answered as follows:

1. **Does wood cascading lead to a reduced consumption of resources and a higher efficiency of wood use and what are the main influencing factors?**

Wood cascading leads to a significant reduction of resource extractions from the natural environment compared to the use of primary wood providing the same functional output. The greatest resource saving potential is obtained from avoiding the production of primary wood, with land area as the main resource saved. In other words, the land occupation for wood production significantly decreases the efficiency of the primary wood system. As a result, the resource efficiency of the cascading system is 7-25 percentage points higher than of the primary wood system, depending on the energy carrier modelled in the system expansion.

The direct cascading effects from the use of recovered wood instead of primary wood lead to an efficiency increase of 2 % at the sawmill and of 4-5 % at the particleboard plant. These values relate to savings of primary resources of 8 % in the sawmill and of 5 % in the particleboard plant. In conclusion, the use of recovered wood instead of primary wood does not contribute to large resource savings and efficiency benefits at plant level, due to the similarities between the processing of recovered and primary wood. Nonetheless, the valorisation of by-products in material applications, a reduction of material losses and a reduction of energy and utility (e. g. adhesives) inputs obtained from optimized processing technologies, are the key drivers to increase the efficiency of wood product manufacturing at both the sawmill and particleboard plant level. Furthermore, since higher processed wood products like particleboard require a larger input of primary resources and energies (e. g. fossil fuels), it is worthwhile to keep the wood as long as possible in solid form to increase the efficiency of the cascade.

At the life cycle level, the resource benefits from the direct cascade effects are compensated from the resource use in the system expansion processes. When comparing the systems at the life cycle level, the resource savings (e. g. fossil fuels) at the plant level from the use of recovered wood are superimposed by the land resource savings. In conclusion, the potential of wood cascading to reduce resource consumption and increase the resource efficiency is therefore limited to the avoided primary wood production, but relatively small in the technical manufacturing steps.

Overall, the results are unclear in terms of a general relation between the number of cascade steps and the resource efficiency. Whether the efficiency of a cascade increases with the number of cascade steps highly depends on the considered manufacturing steps, the initial reference cascade and the modelling of the system expansion processes. However, in most cases, an additional cascades step leads to a reduction of the resource efficiency. This is due to the relative inefficiency of the system expansion processes, which cannot be compensated by the efficiency increase of the material cascade itself.

Recommendations

- The implementation of wood cascading should be supported, as it is likely to increase the efficiency of wood utilization.
- To maximize the efficiency of a cascade, the wood should be kept as long as possible in low processed solid wood products. In addition, by-products should be used in material applications and material losses should be reduced.

2. Is exergy analysis a suitable method to analyse the resource consumption and efficiency of wood cascading while accounting for the characteristics of wood cascading systems and what are the key technical and methodological factors influencing the resource efficiency assessment?

To analyse the resource efficiency of a wood cascading system, the resource accounting indicator as well as the resource efficiency indicator need to be suitable to account for the characteristics of a wood cascading system: multifunctionality, internal recycling processes and the accounting of land area. Exergy analysis proved to be a suitable method to account for these characteristics and provide consistent results, which are easy to use in decision-making. However, exergy analysis showed shortcomings in the land use accounting when applied on natural-industrial hybrid systems like managed forests. In the current form of the method, the exergetic value of the land occupation is fully allocated to the provisional ecosystem service (i. e. wood production) provided from the forest system, but disregards the additional services obtained from forest formation. For the application on hybrid systems like managed forests, further methodological development is necessary to account for the broad range of ecosystem services provided.

The system expansion modelling highly influences the total resource consumption and thus the efficiency of each system. Depending on the modelled processes in the system expansion, the resource efficiency varies between 28 % and 46 %. From resource perspective, system expansion modelling did not decisively influence the outcome of the study. However, as indicated with the GWP calculation, if emission-based indicators are assessed, some wood cascading systems would perform worse compared to the primary wood system. The influence of the system expansion processes as well as the limitations of using a single indicator, highlight the importance of a careful and transparent modelling of different system expansion processes, as well as the application of a complete indicator set to provide transparent and reliable results.

Recommendations

- Exergy analysis is a suitable method for a resource efficiency analysis of wood cascading systems, but should be applied as part of an indicator set to account for impacts derived from resource and emission flows to avoid misleading conclusions from single indicator analysis.
- Due to the complexity of wood cascading systems, different reference systems, products, and modelling parameters should be analysed in scenario analysis to derive transparent results.
- Further methodological development of exergy analysis to improve land use accounting, when applied to natural-industrial hybrid-systems.

3. Is the recycling of recovered solid wood an eco-efficient treatment alternative to current end-of-life treatments?

The results indicate that the recycling of recovered solid wood into glued laminated timber products is environmentally and economically beneficial compared to the direct incineration, if both systems are based on wood as raw material. In the base scenario, the recycling system shows 1-29 % lower environmental impacts, depending on the impact category. The main savings are obtained in the category of agricultural land occupation, which results from avoiding the primary production of wood. This forest area is available for primary wood production in order to satisfy the increasing demand for wood, as expected in a future bioeconomy. Following the rationale of the cascading concept, contradictory policies like the renewable energy act need to be revised and concepts for the support of the material use of wood need to be developed.

The costs of the recycling system are 32 % lower than for the incineration and a positive value added is obtained in all scenarios. Even if recovered wood becomes a resource of competition in a bioeconomy or higher prices are established from a recycling-oriented (i. e. quality-preserving) deconstruction process, the recycling process remains viable if the consumer has to pay for the material. However, the break-even point is of course further defined by the price of the recovered wood and the processing costs.

In the combined eco-efficiency analysis, a 15-150 % better performance of the recycling system was observed, depending on the impact category. The efficiency analysis revealed trade-offs between the environmental and economic aspects of the process when optimizing parameter values. This observation indicates the complexity of the system and the dependencies between production parameters and underlines the relevance for the joint analysis of both perspectives.

The main CaReWood processes like sorting, decontamination and drying are of minor relevance for the environmental and economic performance of the CaReWood system. From an environmental perspective, the new processes, i. e. the sorting and decontamination, are not decisive and neither a barrier for the practical implementation. From a cost perspective, the results are similar, but further indicate that the main drivers for the viability of the process are the market prices for the recovered wood and for the final product. The possible savings from an optimization of the technical process, e. g. through a full automation, are small. This is similar to the current production of wood products, in which the raw material can make up a large share of the total manufacturing costs, which limits the possibilities for a cost efficient optimization. Here, the recycling of recovered wood can help to relieve the market for primary wood. The greatest potential for improvement and a successful and long-term establishment of the recovered wood product on the market therefore relies on the product quality and the possible applications. It is therefore necessary to continue researching the technological properties of recovered solid wood as well as its potential applications in solid wood products.

The benefits of the recycling system are robust against most of the parameters analysed in scenario analysis. A reduction of the transportation distance in the reference system, however, can lead to a better performance of the incineration system in most impact categories of up to 4 %. It is thus recommended to locate the CaReWood facility near existing processing plants to minimize transportation efforts. Suitable industries are the ones already involved in recovered wood treatment like particleboard manufactures, who additionally benefit from their infrastructure certified for the incineration of preserved wood. In addition, some companies also have glulam timber plants, which would provide a cross-company basic structure for the recycling process. If these structures were in place, there would be good opportunities to diversify the product portfolio at low investment costs (Risse and Richter, 2017).

The consideration of energy from grid in the system expansion leads to a worse environmental performance of the recycling system. This not only highlights the effects of system expansion modelling on the outcome of the comparison, but also indicates that the environmental savings from wood recycling are limited. As wood product manufacturing has very low environmental impacts itself compared to the primary production, and the use of recovered wood hardly differs from the use of primary wood, very little environmental savings are obtained from wood recycling. The sum of these savings along a cascade is described as the direct cascade effects, which have been extensively described in previous studies (Gärtner et al., 2013; Höglmeier et al., 2014; Sathre and Gustavsson, 2006). Thus, the expectations towards the benefits of wood recycling are higher than actually measured. Therefore, for the analysis of new technologies, comparative studies and scenario analysis representing for example different market situations, reference products and energy carriers are important to provide transparent results for decision-making.

The environmental benefits and in particular the profitability of the recycling process is a positive response to the barriers seen by industrial stakeholders (Husgafvel et al., 2018) for the viability of recovered solid wood recycling. In this regard, the results should motivate politics as well as industry to contribute further to the development and refinement of the recovered solid wood recycling process for the implementation of a pilot plant. It allows the extension of the cascade chain in the foremost step in order to increase the efficiency of wood utilization as recommended in publication 1.

Recommendations

- Further development and refinement of a technology for recovered solid wood recycling.
- Different reference systems, products, and modelling parameters should be analysed in various scenarios to provide transparent results in future studies.

- To support the implementation of new recovered wood recycling processes and the mobilization of currently unused material deposits, a revised ordinance on the management of waste wood is required.
- For a successful establishment of a recovered wood product on the market, a better knowledge of its technological properties, social acceptance and potential applications should be gained.

4. What are the technical and methodological factors influencing the life cycle-based eco-efficiency assessment in comparative recovered wood treatment studies?

In the preliminary evaluation of an emerging process, system and data modelling are based on assumptions, which involves a certain level of uncertainty. Since the functional equivalence between the recovered and primary wood can be assumed (Cavalli et al., 2016; Meinlschmidt, 2017) and the level of machining required is not beyond current technology (Irle et al., 2015), the results are considered as reasonable from technical perspective. Yet, uncertainties related to the properties, the grading, the potential applications, the consumer acceptance and the market price of recovered wood products remain. Apart from the necessary technological research, these uncertainties should be taken into account in future studies.

Using the same data background to model the inventory data and adjusting it to each system's requirements, leads to results based only on the assumptions from engineers and the authors, but not on differences determined from existing processes. Due to the limited availability and spatial volatility of economic data, a higher uncertainty of the economic results is assumed. Future studies should therefore focus on the economic assessment using updated and improved data.

Scenario analysis revealed that system expansion modelling can decisively influence the results and the outcome of the comparison. Therefore, whether a recycling technology achieves the expected benefits depends on its integration at market level, the legal framework and developments in related market sections. It is thus advised to model different system expansion processes to cover a broad range of scenarios, by e. g. representing different market situations, reference products or a changing legal framework, in order to provide reliable and transparent results.

The attributional modelling approach disregards the indirect effects at market level induced from reallocated material flows through the implementation of new technologies. The effects from withdrawing a material from its current utilization and the substitution of products through the recycled material should be analysed in future studies using consequential LCA.

The joint analysis of LCA and LCC in an eco-efficiency analysis is a suitable combination to identify main drivers as well as trade-offs between the environmental and economic dimension of sustainability. However, the application requires the availability of processing and inventory data with the same level of detail, quality and geographic scope, which makes the application on emerging technologies an ambitious task.

Recommendations

- An updated inventory of LCI and LCC data should be compiled in order to improve the reliability of LCA and LCC studies on new wood processing technologies.
- Technical research is necessary to obtain better knowledge on the properties of recovered wood, which should then be used to account for potential quality losses in future LCAs.
- If system expansion is applied, a variety of scenarios should be studied to analyse different market situations, reference products or a changing legal framework.

8.2 Outlook

For the transition towards a bioeconomy and the satisfaction of the increasing demand for wood, the implementation of wood cascading is necessary. However, to enhance wood cascading, new technologies at different cascade steps for the use of recovered wood in material applications are required. With wood cascading implemented, the wood industry can act as a role model for a resource-efficient and sustainable bioeconomy.

The implementation of new technologies and the mobilization of currently unused categories of recovered wood requires a change in legislation for the material use of recovered wood in Germany. For the ongoing revision of the Ordinance on the Management of Waste Wood (BMU, 2017; BReg, 2018) the material use of wood from construction has to be enabled if a reliable decontamination and sorting is ensured. Taking the current trading of recovered wood in Europe into account, a European ordinance on the management of waste wood should be developed in order to reduce present barriers through the different national regulations in waste wood management. New technologies and a legal change will allow the mobilization of currently unused resources from urban deposits in material applications and contribute to satisfying the growing demand for wood. This may be of particular importance in view of a temporary supply gap for coniferous trees, as the proportion of deciduous trees in forests increases as a result of adaptation to climate change.

From 2020, with the expiry of subsidies for energy generation from recovered wood in Germany under the renewable energy act (BT, 2017), equal competitive conditions will be created for the material and energetic use of recovered wood, which offers possibilities to establish new recycling technologies. Economic barriers and reservations about recovered wood need to be tackled for market implementation by raising consumer awareness and certifying the safety and mechanical suitability of the material.

The attributional modelling approach as applied in the studies focuses on the direct cascading effects. This approach disregards the indirect effects as well as trade-offs or/and rebound effects at market level induced from shifts through the reallocation of material flows. A consequential system modelling should therefore be applied in future studies as recommended in DIN EN ISO 14044:2006-10. For the identification of the marginal technologies and affected market segments, the use of heuristic methods or economic market models should be applied in future studies (Earles and Halog, 2011; Ekvall and Weidema, 2004).

Although biogenic carbon is accounted for in Risse et al. (2019), the effects of carbon storage and delayed emissions are disregarded, in particular in the cascading study. As wood cascading increases the time of carbon storage and leads to delayed emissions of biogenic carbon, future LCA studies should focus on carbon accounting by using evolved methods like dynamic LCA (Brandão et al., 2013; Cherubini et al., 2011; Levasseur et al., 2010; Pawelzik et al., 2013; Røyne et al., 2016). The aspect of time also affects the uncertainty of the assessment. In a cascade system as considered in Risse et al. (2017), the material lifetime can span 200 and more years. Within this time, technologies, legal regulations and energy provision among others will significantly change and define a new framework for every cascade step. Apart from the uncertainty of cascading studies, they require regular updates on process modelling and inventory data to constantly evaluate the concept. As a first approach, future studies should include scenarios representing future energy mixes and emerging technologies (Arvidsson et al., 2017; Burchart-Korol et al., 2018; Cucurachi et al., 2018).

Uncertainties remain with regard to the technical properties, material fatigue, possible applications, grading and processing technologies of recovered wood. Due to these knowledge gaps, the use of recovered wood in structural and load bearing applications is currently unlikely. However, within the project, it has been proven by demonstrators that semi-finished products can be produced from recovered wood using laminating technology. Thus, future studies should focus on the technical properties, the grading and sorting of recovered wood and the possible applications in order to enable the industrial use of recovered wood. In midterm, a pilot plant should be established in cooperation with industry partners, which can then be used to collect primary inventory data for a cost-benefit analysis and impact assessment. For LCA, quality factors such as the ones developed by Rigamonti et al. (2018) should be applied to account for the quality loss of recycled material, if a one-to-one substitution of primary material cannot be assumed.

The recycling of recovered solid wood maintains the quality and sequential applications of solid wood. However, Privat et al. (2016) show that the broad variety of dimensions and the adherent impurities lead to a low yield of the recycling process. Thus, in order to maintain the quality and improve the recycling potential of recovered (solid) wood, a design for recycling concept in wood construction and products should be established. Design for recycling offers potential to maintain the dimensions and quality of wood elements during disassembly and thus their recyclability through e. g. the use of easy release joints or the omission of wood preservatives (Hillebrandt et al., 2018; Jordan and Weege, 1979; Teischinger et al., 2016; Thormark, 2001). Along with an on-site sorting and collection of the recovered material by type (Strohmeyer, 2014), the yield and efficiency of recovered wood recycling can likely be increased. For a successful implementation of design for recycling, the use of building information modelling (BIM) can support the integration of disassembly and recycling strategies in the planning phase as well as in providing a material and recycling passport. These passports can support the documentation of a building as well as its changes over its lifetime, in order to make the necessary information on materials, elements and constructions available for a future disassembly (Heinrich and Lang, 2019). To determine the potential of design for recycling in wood construction, the environmental and economic effects of a recycling oriented construction in wood building are currently being analysed in the European research project "InFutUReWood" ("Innovative design for the future – Use and reuse of wood (building) components", 2019-2022) (InFutUReWood, 2019), which was developed from this dissertation.

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10 List of publications

10.1 Reviewed publications

Risse, M., Weber-Blaschke, G., Richter, K. (2019) Eco-efficiency analysis of recycling recovered solid wood from construction into laminated timber products. Sci. Total Environ. 661, 107-119. 10.1016/j.scitotenv.2019.01.117.

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11 Publications in the context of this dissertation

Publication 1

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Resource efficiency of multifunctional wood cascade chains using LCA and exergy analysis, exemplified by a case study for Germany. Michael Risse, Gabriele Weber-Blaschke, Klaus Richter. 2017, Resources, Conservation and Recycling, Volume 126, Pages 141-152.

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Eco-efficiency analysis of recycling recovered solid wood from construction into laminated timber products. Michael Risse, Gabriele Weber-Blaschke, Klaus Richter. 2019, Science of the Total Environment, Volume 661, Pages 107-119.

The original can be accessed at doi.org/10.1016/j.scitotenv.2019.01.117

12 Statement made in lieu of an oath

(Eidesstattliche Erklärung)

Ich erkläre an Eides statt, dass ich die bei der promotionsführenden Einrichtung, dem Wissenschaftszentrum Weihenstephan für Ernährung, Landnutzung und Umwelt der TUM zur Promotionsprüfung vorgelegte Arbeit mit dem Titel:

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München, den 04. Juni 2019 Michael Risse

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Full length article

Resource efficiency of multifunctional wood cascade chains using LCA and exergy analysis, exemplified by a case study for Germany

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ABSTRACT

Driven by the scarcity of non-renewable resources and a growing environmental awareness in Germany, the demand for wood could likely exceed its sustainable supply within the next decades. In response to this development, cascading, i. e. the sequential use of one unit of material in material applications with energy generation as final step, is expected to enhance the resource efficiency of wood utilization. In this context, the objective of this paper is to determine the resource consumption and resource efficiency of wood cascading compared to the use of primary wood to provide the same multiple functions. To account for resource use and calculate the efficiency, exergy analysis was applied. The exergy of a material is the potential work that can be obtained from the material in the natural environment. By using Exergy Flow Analysis, key drivers of exergy dissipation and thus hotspots for improvement were identified. Exergetic Life Cycle Assessment was applied to determine resource use and the resource efficiency at a life cycle level. The results indicate that cascading leads to less resource consumption compared to the use of primary wood, indicated by higher resource efficiency (46% vs. 21%) at life cycle level. The main resource saving potential through cascading arises from avoiding primary production in forestry systems. In conclusion, cascading reduces the primary resource extraction and makes wood utilization highly efficient. Exergy analysis proved to be a viable method to study the resource use of multifunctional cascading systems, although showing some limitations with respect to land use accounting.

1. Introduction

In Europe, the demand for wood will likely exceed its supply within the next decade (Mantau et al., 2010), driven by the subsidized use for energy generation and the scarcity of finite non-renewable resources. Despite the renewability of wood, its harvest intensity is limited by the growth rate and the sustainability concept of forest management. Therefore, to meet the increasing demand for wood, new concepts of wood utilization are needed. Considering wood as a limited material, a discussion on the most efficient utilization arises. In this context, a widely recognized concept is the cascaded use of biomass. For the presented study, cascading is understood as the sequential use of one unit of a resource in various material applications with its energetic use as a final step. Cascading follows a holistic perspective on a material flow over different life cycles, which can include various reuse, recovery and/or recycling steps, depending on the considered system boundaries, as well as the end of life treatment.

Currently, the cascade use of wood is in its infancies. Across Europe, one third of the total waste wood volume is used in particle board manufacturing (EPF, 2014). The use of recovered wood in solid applications is niched. However, there will likely be enough wood suitable for cascading purposes available in the future (Kalcher et al., 2016).

The cascading concept finally became a political aim in European and German policy for future biomass utilization (EC, 2011, 2014; BMUB, 2015). Applied on wood products, it is expected to decrease the environmental impacts through the recycling of wood material, to increase the resource efficiency of wood utilization, to create higher added value as well as to contribute to climate change mitigation through extended carbon storage.

The theoretical framework of the cascading concept was first introduced by Sirkin and Houten (1994) as a tool to achieve sustainable resource management by an appropriate design of products and production processes. Its application on wood chains was conducted by Fraanje (1997), describing the theoretical potentials of cascading wood to increase resource efficiency and reduce the environmental impacts. A first study, focusing on the resource consumption using exergetic life cycle assessment (ELCA) was presented by Cornelissen and Hirs (2002), who compared the wood and fossil fuel resource consumption of

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different waste wood treatment routes. The results indicate less resource consumption when the waste wood is used for particle boards instead of the co-combustion in a power plant. Sathre and Gustavsson (2006) studied the primary energy use and carbon balance of different wood cascades. Their results show that the primary energy use and the carbon balance are mainly influenced by land use and substitution effects. A comparison of the global warming potential between a cascade use of wood products and the use for energy generation indicates significant greenhouse gas savings that can be obtained from a combination of fossil fuel and material substitution as well as temporary carbon uptake in wooden products (Sikkema et al., 2013). Along with the rising political awareness for the cascading concept in recent years, several studies on the environmental effects of wood cascading have been conducted using Life Cycle Assessment (LCA) to determine the environmental impacts at life cycle level. Gärtner et al. (2013) compared a wood cascading to a reference scenario providing the same functions from non-wood (mineral, metal, fossil) derived counterparts. Höglmeier et al. (2014) compared a cascading system using recovered wood in particle boards with a reference system providing the same functions using primary wood. Gärtner et al. (2013) and Höglmeier et al. (2014) presented environmental advantages of the cascading system over the reference systems for most considered impact categories: the benefits are less in comparison to the primary wood system and higher in comparison to the non-wood reference systems. They draw the same conclusion as Sathre and Gustavsson (2006) stating that the direct cascade effects obtained from the use of recovered instead of primary wood are little. Gärtner et al. (2013) and Höglmeier et al. (2014) further concluded, that the main benefits of cascading lie in the fact of saving primary natural resources. The combination of LCA and a material flow model to optimize the environmental impacts of wood utilization at a regional level under the consideration of wood cascading indicated that cascading can improve the environmental performance of wood utilization (Höglmeier et al., 2015). The resource efficiency of wood cascading was calculated by Vis et al. (2014) as the amount of primary wood used per functional unit, without considering the life cycle perspective and the use of other primary natural resources. Although most studies compared the environmental impacts of a cascading scenario with a reference system, the results are hardly comparable due to different system boundaries, functional units and reference systems.

However, all studies showed shortcomings in the analysis of primary natural resource use and their approach towards the calculation of the resource efficiency, which has also been concluded by Thonemann and Schumann (2016).

To support the understanding of the terms natural resources and resource efficiency, a clear definition is needed. In this study, natural resources are categorized as follows: water, abiotic renewable resources (e. g. wind), fossil fuels, minerals, metal ores, nuclear resources, atmospheric resources and land resources. The category land resources accounts for biomass that is produced in natural systems without human intervention (e. g. timber harvested from primary forests) and land area that is occupied in human-made systems and either used for producing biomass (e. g. forestry) or not (e. g. urban area) (Alvarenga et al., 2013). As the focus of this study is on wood reproduced in forestry systems, the term primary wood hereafter refers to material from human-made forestry systems. Materials recovered from waste products are considered as secondary resources.

Resource efficiency is defined as the ratio between the output and the input flows of the system under study. Depending on the perspective of the study, different metrics for efficiency calculations can be applied. At gate-to-gate level (here: sub-system), resource efficiency is described as the ratio between the useful outputs (or benefits) and the inventoried resource or material inputs. At life cycle level, resource efficiency is calculated as the ratio between the useful outputs (or benefits) and the environmental impacts associated with the production of the desired outputs (Huysman et al., 2015).

Although the cascading concept is widely emphasized to increase the resource efficiency of wood utilization (e. g. Arnold and Geibler, 2009; Fraanje, 1997; Keegan et al., 2013; Sirkin and Houten, 1994) a detailed analysis of the resource consumption and the resource efficiency along the life cycle of a wood cascading system is missing. A stronger focus on the resource efficiency of cascading systems and the influence of the number of cascade steps, is further emphasized by Thonemann and Schumann (2016). Therefore, the following three objectives are addressed in this study:

1) To quantify the total resource consumption of a wood cascading scenario in comparison to a functionally equivalent production system using primary wood, exemplified by a German case study.
2) To evaluate the resource efficiency of both systems, to identify key effects of wood cascading as well as to highlight opportunities for efficiency improvement at gate-to-gate and at life cycle level. In order to identify the influence of the number of cascade steps on resource consumption and resource efficiency, different scenarios will be studied.
3) To analyse the suitability of exergy analysis for the determination of the resource consumption and resource efficiency of a cascading system, as exergy analysis has been identified as applicable method for cascading systems (also see Section 2.1).

2. Materials and methods

2.1. Towards the resource use analysis of wood cascading

As cascading scenarios follow a holistic perspective on the whole material life cycle, a multitude of functions is provided from the system (in LCA terms: multifunctional system). Depending on the number of cascade steps, the functional unit, i. e. the useful outputs of the system, can be rather complex and comprise several products, expressed in different units. A second characteristic of cascade systems is the consideration of several product life cycles, including internal recycling processes. Each product is sequentially manufactured from recycled material recovered from a previous product. To account for these internal recycling processes, the recycled material has to be counted as input flow in the efficiency assessment. It becomes apparent that the comprehensibility of a multifunctional system can be improved by aggregating the various input and output flows in one single unit, in particular for efficiency analysis. This would allow dealing with complex systems and provides the practitioner with a single score that can easily be used in decision making. With respect to the scope of the study, land resources were considered as a relevant resource category to be covered by an indicator when quantifying the resource use and efficiency of bio-based systems. Not least, since land area will receive more attention as a valuable resource in a future bio-based economy (UNEP, 2014).

An approach that was found appropriate to account for these characteristics of cascading systems is a thermodynamic-based exergy analysis. Exergy analysis proved to be a suitable methodology in environmental studies to account for resource consumption and efficiency calculations (e. g. Amini et al., 2007; Cornelissen and Hirs, 2002; Huysveld et al., 2015; Huysveld et al., 2013; Nhu et al., 2016; Schaubroeck et al., 2016; Schaubroeck et al., 2013; Talens Peiró et al., 2010). The exergy of a resource or material is defined as the maximum of potential work that can be obtained from the resource or material when bringing it into equilibrium through reversible processes with the natural environment (Dewulf et al., 2008; Szargut et al., 1988). Hence, for products that use a lot of energy resources or are usable as energy resources, such as for wood, the use of exergy is of particular value.

Exergy analysis was originally applied on single processes and first extended to life cycle level by Szargut et al. (1988), introducing the Cumulative Exergy Consumption (CExC). The operationalization as impact indicator in LCA was first presented by Bösch et al. (2007),

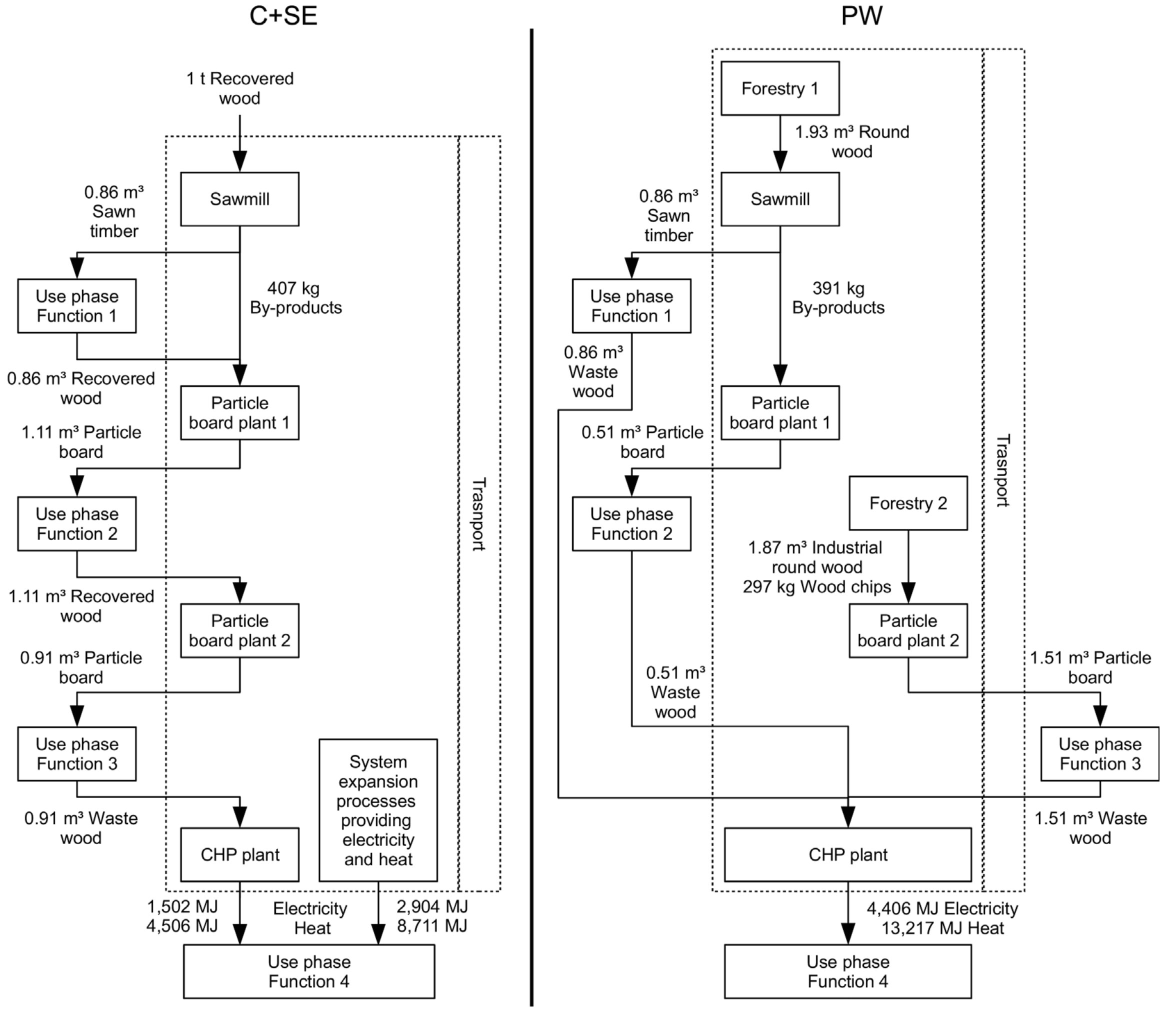

Fig. 1. Scheme of the foreground systems as studied in the default scenario. C = Cascading system including system expansion (SE), PW = primary wood system, CHP = Combined heat and power.

developing the Cumulative Exergy Demand (CExD). The CExD was further developed by Dewulf et al. (2007) with the Cumulative Exergy Extraction from the Natural Environment (CEENE) life cycle impact indicator. CEENE aims to compensate for methodological shortcomings of CExD, especially with respect to accounting for land area as a primary natural resource. In the first version, land area was accounted with solar irradiation as proxy (Dewulf et al., 2007). Further improvement was proposed by Alvarenga et al. (2013), providing spatial explicit characterization factors for land as a resource, taking both land occupied in human-made systems and biomass from natural systems into account. Compared to Dewulf et al. (2007), Alvarenga et al. (2013) used the exergy value of biomass to account for its extraction from natural systems and the natural potential net primary production (NPP) as proxies for land occupation from human-made systems. Characterization factors for the land occupation of marine environments were implemented by Taelman et al. (2014), using the same methodological approach. In the latest version of CEENE, spatially-differentiated land occupation characterization factors are provided, combining the NPP with a factor to represent the naturalness of the occupied land (Taelman et al., 2016). The advantages of CEENE compared to other energy or exergy-based resource accounting methods is the broad range of resources covered (Klinglmair et al., 2014; Swart et al., 2015). With respect to human-made systems, CEENE accounts for land occupation as a natural resource and not for the biomass extracted from it, as it is done in CExD or the Cumulative Energy Demand (CED) (VDI 4600:2012-01). In contrast to CED, also water, minerals and metals are covered by the indicator. The CEENE indicator quantifies the resource use in the following categories, expressed in Megajoules of exergy (MJ_{ex}): fossil fuels, land resources, metal ores, nuclear energy, abiotic renewable resources, minerals, water and atmospheric resources.

To analyse the exergy flow of a system and to determine hotspots for improvements at gate-to-gate level, Exergy Flow Analysis (ExFA) is a feasible approach. To determine the resource efficiency at gate-to-gate and life cycle level, the Cumulative Degree of Perfection (CDP) can be applied (Szargut et al., 1988). The CDP describes the efficiency of a system as the ratio between the energy or exergy content of the useful output and the energy or exergy content of the inputs required to produce the desired output. At life cycle level, the CDP is applied as part of the Exergetic Life Cycle Assessment (ELCA) using the results from the energy- or exergy-based impact indicators described above to account for the input flows. A further approach based on the CDP for the comparison of bio-based products with their fossil counterparts is an indicator framework presented by Huysveld et al. (2015), taking bio-productive land resources into account while addressing the non-renewable character of fossil resources.

The advantages of the exergy concept to analyse bio-based multi-functional systems are considered as manifold: exergy-based resource accounting methods cover a broad range of resources (Klinglmair et al., 2014; Swart et al., 2015), some of which include land resources. The exergy approach further allows the expression of all input and output flows of a system – including internal recycling flows – in the same unit (Dewulf et al., 2008). This makes resource efficiency calculations

Table 1
Functional unit of the systems under study for the default scenario. The values refer to the processing of 1 ton of recovered wood in the cascading system. C = Cascading system, PW = Primary wood system.

System	Sawn timber in m^3	Particle board in m^3	Electricity in MJ	Heat in MJ	System expansion	
					Electricity in MJ	Heat in MJ
C	0.86	2.02	1,502	4,506	2,904	8,711
PW	0.86	2.02	4,406	13,217		

of complex multifunctional cascading systems straightforward, with results expressed in a single score.

2.2. Systems definitions

To compare the resource use and the resource efficiency of a cascading system with a reference system using primary wood, a LCA study according to the ISO 14040/14044 standards has been conducted (DIN EN ISO 14040:2009-11; DIN EN ISO 14044:2006-10). In the cascading system (C), the sequential use of 1 ton of untreated recovered solid timber in material applications with a final use for energy generation is considered. In the primary wood system (PW), the same multiple functions are provided by using primary wood. Both systems were modelled under the consideration of German state-of-the-art technologies. The system modelling followed the approach applied in Höglmeier et al. (2014). In contrast, we used an updated data inventory (see section 2.4) and extended the system boundaries by adding the manufacturing of sawn timber from solid recovered wood. The processing and use of solid recovered wood in a sawmill is currently not in practice at industrial level, but under research in a European research project (CaReWood – Cascading Recovered Wood 2017) and should thus highlight the future potential of wood cascading.

For the default scenario (Df), the system boundaries of the C and the PW foreground system are illustrated in Fig. 1. The C system begins with the collection and sorting of 1 t of untreated recovered solid timber with a moisture content of 18% (Höglmeier et al., 2014). It is assumed that the wood would be classified as waste and thus be free of any environmental burdens from previous life cycles (DIN EN 15804:2014-07). The recovered wood is processed into sawn timber at a sawmill. After a use phase, the recovered sawn timber product is collected, sorted and then manufactured into particle boards. The cascading system comprises two steps of particle board production. The last step in the C system describes the incineration of the waste particle boards in a combined heat and power plant (CHP plant) with energy recovery. Incineration is the mandatory treatment for waste wood in Germany according to the German Waste Wood Ordinance (2012), when recycling is not possible. Also across Europe, landfilling is planned to be banned because of its environmental burdens (EC, 2014). Although this is not in practice today, sawn timber and particle boards were assumed to be fully made from recovered wood to enable an easier comparison between both systems. The process heat required at the sawmill and particle board plant was produced in boilers, fuelled with a share of the recovered wood and process waste fractions.

In the PW system, the same functions as in the cascading system were provided from using primary wood. Sawn timber was produced at a sawmill from round wood delivered by a forestry process. The sawmill by-products were used for process heat production and as raw material for particle board production (PB 1 in Fig. 1), which accounts for the common use of sawmill by-products today. Further particle boards (PB 2 in Fig. 1) were manufactured from primary industrial round wood. The process heat was generated in a boiler fuelled with primary wood chips and process waste fractions. After the use phase, the waste sawn timber and particle boards are collected, chipped and incinerated in a CHP plant with energy recovery. The use phases were excluded from the study as they were considered to be identical for each product and would thus not influence the results.

For the comparison of different production systems with LCA, their provided functions need to be equivalent (DIN EN ISO 14040:2009-11). Because of the sequential use and material loss for process energy generation, the cascade provides less energy at the end of life compared to the primary wood system (Table 1). The ISO standard recommends system expansion as the preferred approach to solve system inequalities (DIN EN ISO 14044:2006-10). In their study, Höglmeier et al. (2014) proved that system expansion is a viable option to achieve system equality in cascading studies. Accordingly, in the presented study, the C system was extended with energy providing processes. Because Höglmeier et al. (2014) concluded that the assumptions in system expansion modelling can significantly influence the outcome of a study, different energy carriers were considered to obtain transparent results: waste wood, incinerated in a CHP plant (C + ww); electricity and heat supply from German grid mix (C + g); energy generation from primary wood chips in a CHP plant (C + pw). For comparability reasons, all scenarios are simultaneously presented.

2.3. Functional unit

The functional unit for the study is described as the “Production of 0.86 m^3 sawn timber, 2.02 m^3 particleboard, 13,217 MJ heat and 4,406 MJ electricity” as represented in Table 1. The amount of sawn timber and particle board is determined by processing 1 ton of untreated recovered solid timber in the cascading system. Incinerating the second particle board at the end of the cascade, 1,502 MJ of electricity and 4,506 MJ of heat are recovered. By providing the same material functions, but considering the direct incineration of the products after the first use phase, the energy output of the PW system is higher. The difference between the energy outputs of both systems is thus compensated in the cascade system by system expansion to make both systems functionally equivalent.

2.4. Life cycle inventory

For the sawmill and particle board processes, data was taken from Rüter and Diederichs (2012), representing the average technology in Germany. For the CHP plant, a 6667 kW CHP plant was considered. A stationary electric chipper was modelled in both systems for chipping the wood used in particle board production and the CHP plant. The transportation distance of recovered wood and waste wood to the processing plant was assumed to be 100 km, based on information from a German particle board manufacturer. As transportation processes are negligible for the overall environmental impacts (Höglmeier et al., 2014), further specifications were omitted. The CHP plant, chipping and transportation processes were modelled using the ecoinvent database v. 3.3 (Wernet et al., 2016). In the primary wood system, round softwood was considered as raw material for sawn timber production, industrial round wood and forest wood chips for particle board manufacturing respectively. Both processes were modelled as sustainable softwood (spruce) forestry in Germany from ecoinvent database v. 3.3 (Wernet et al., 2016). The forestry processes are represented by spruce only, as it is the most relevant wood species for the German wood industry (Thünen, 2017). Data for additional background processes was retrieved from ecoinvent database v. 3.3 (Wernet et al., 2016). We used the cut-off system model from ecoinvent database as it considers recyclable materials as burden-free from previous life-cycles and is thus in line with the modeling approach.

For the cascading system, the inventory data for sawmilling and particle board manufacturing was modified to account for the use of recovered wood instead of primary wood, e. g. to account for a reduced drying demand because of a lower moisture content of recovered wood. All modifications and specifications applied to the inventory data are

Table 2
Specifications and modifications of the Life Cycle Inventory data. C = Cascading system, PW = Primary wood system, SE pw = System expansion from primary wood, SE ww = System expansion from waste wood, SE g = System expansion from grid, B = Both systems.

Process	System	Data source	Specifications and modifications
Producing kiln dried, planed sawn timber at a sawmill	C	(Rüter and Diederichs, 2012)	- Reduction of electricity consumption for no debarking (Rüter and Diederichs, 2012) - Reduction for process heat and electricity, utilities and lubricants because of lower moisture content of recovered wood to 79% (Own assumption according to the data for particle board manufacturing in Höglmeier et al. (2015)) - Wood input: 100% recovered wood
	PW	(Rüter and Diederichs, 2012)	- Wood input: 100% round wood
Particle board manufacturing	C	(Rüter and Diederichs, 2012)	- Reduction of electricity consumption for no debarking (Rüter and Diederichs, 2012) - Reduction of process heat and electricity consumption to 79% because of lower moisture content of recovered wood (Höglmeier et al., 2015) - Wood input: 100% recovered wood
	PW	(Rüter and Diederichs, 2012)	- Wood input: 100% industrial round wood and primary wood chips for process energy
Electric stationary chipper	B	Ecoinvent v. 3.3	- 1% material loss during chipping (BioEnergieDat, 2015)
Transportation	B	Ecoinvent v. 3.3	- Transportation distance for recovered/waste wood to sawmill, particle board plant and CHP plant: 100 km (Industry data, personal communication) - 1% material loss during transportation (BioEnergieDat, 2015)
	PW	Ecoinvent v. 3.3	- Transportation distance for primary round wood to sawmill: 111 km (Rüter and Diederichs, 2012) - Transportation distance for primary wood to particle board plant: 89 km (Rüter and Diederichs, 2012) - 1% material loss during transportation (BioEnergieDat, 2015)
System expansion	SE pw	Ecoinvent v. 3.3	- Transportation distance for primary wood chips to CHP plant: 50 km (Rüter and Diederichs, 2012) - 1% material loss during transportation (BioEnergieDat, 2015) - Incineration in 6667 kW CHP plant
	SE ww	Ecoinvent v. 3.3	- Incineration in 6667 kW CHP plant
	SE g	Ecoinvent v. 3.3	- Electricity provided from German grid mix - Heat provided from German heating mix, modelled with values from national statistics on the net heat production in Germany (Destatis, 2017)

presented in Table 2; otherwise the original values from the given source were used.

2.5. Influence of the number of cascading steps

Analyses of different systems were performed to determine the influence of the number of cascading steps on the resource consumption and resource efficiency. The scenarios described in Table 3 refer to the cascading system. The primary wood system was modelled in relation to the respective cascading scenario following the same approach as described for the default scenario to maintain functional equivalence and thus comparability between both systems.

2.6. Exergy analysis

2.6.1. Exergy flow analysis

Exergy Flow Analysis (ExFA) was performed to analyse the gate-to-gate efficiencies of the sub-systems (e. g. sawmill, CHP plant) in the foreground system and to identify hotspots for improvement. In ExFA, all input and output flows of a sub-system are expressed in their exergy content and used to establish an exergetic balance of the sub-system. The balance can be used to calculate the exergetic gate-to-gate efficiency of the sub-system. The data for the ExFA was obtained from the inventory flows from the LCA model and converted into their exergy content (Section 2.6.5). The exergy flows as well as the gate-to-gate efficiency of each sub-system are visualized in a Sankey Diagram.

Table 3
Scenarios studied to analyse the influence of the number of cascading steps. Df = Default scenario, RW = Recovered Wood, ST = Sawn timber, PB = Particle board, CHP = Combined heat and power.

Abbreviation	Scenario
Df	RW → ST → PB → PB → CHP
A	RW → ST → PB → PB → PB → CHP
B	RW → PB → PB → CHP
C	RW → ST → PB → CHP

The gate-to-gate efficiency (μ) of a sub-system was calculated as the ratio between the amount of exergy contained in the useful outputs ($Useful\ Outputs_{Ex}$) and the total exergy content of the energy, material and utilities inputs ($Inputs_{Ex}$) of the respective sub-system, expressed in MJ_{ex}:

$$\mu = \frac{\sum (UsefulOutputs_{Ex})}{\sum (Inputs_{Ex})} \tag{1}$$

In contrast to the Exergetic Life Cycle Assessment, in ExFA the surface solar radiation was accounted as resource input of the forestry sub-systems instead of land area. The solar radiation is used to calculate the efficiency of both forestry sub-systems in the PW system.

2.6.2. Exergy breeding factor

To obtain a better picture on the efficiency of the forestry sub-systems, the exergy breeding factor (*BF*) was calculated. The BF describes the amount of renewable materials (i. e. wood) that can be harvested ($Useful\ Outputs_{Ex}$) from non-renewable resources in bio-productive systems (Dewulf et al., 2005). To calculate the BF, solar radiation as the major renewable input to the forestry sub-system was subtracted from the total exergy inputs ($Inputs_{non\text{-}renewableEx}$). Other renewable inputs such as rainfall were disregarded. All flows are expressed in MJ_{ex}.

$$BF(-) = \frac{\sum (UsefulOutputs_{Ex})}{\sum (Inputs_{non-renewable_{Ex}})} \tag{2}$$

2.6.3. Exergetic life cycle assessment

ELCA was applied to account for the amount of resources extracted from natural environment to provide the functional unit using an exergy-based LCIA indicator and to determine the exergetic efficiency at life cycle level. The impact indicator applied was the Cumulative Exergy Extraction from the Natural Environment (CEENE) method, in the version of Alvarenga et al. (2013) and Taelman et al. (2014). As the geographic scope of this study is Germany, a characterization factor of 26.5 MJ_{ex}/m^2 x yr for land occupation from Alvarenga et al. (2013) was used for all processes.

2.6.4. Resource efficiency analysis

Resource efficiencies were quantified with the Cumulative Degree of Perfection (CDP) (Szargut et al., 1988). The CDP was developed to quantify the efficiency of industrial systems at life cycle level. To calculate the CDP of a multifunctional system at life cycle level (CDP_{mfs}), the denominator of the efficiency formula comprises different terms. The recovered wood entering the system is considered as a material input ($Recovered\ Material_{Ex}$). Although it is not extracted as a primary resource from the natural environment, it yet delivers the raw material for a subsequent production process. The same applies to any product manufactured along the cascade: the product that provides function “n” is subsequently recycled into a product providing function “n + 1”. Consequently, the useful outputs that are recycled within the system in internal recycling processes are counted as input material and added as such in the denominator ($Recycled\ Material_{Ex}$). The additional primary resources extracted from the natural environment along the supply chain of the useful outputs are quantified with the CEENE indicator ($CEENE\ of\ Supply\ Chain_{Ex}$). Numerator and denominator are expressed in exergy terms (MJ_{ex}).

$$CDP_{mfs} = \frac{\sum (UsefulOutputs_{Ex})}{\sum (RecoveredMaterial_{Ex} + RecycledMaterial_{Ex} + CEENEofSupplyChain_{Ex})} \tag{3}$$

Considering the recycled material as resource input appears as a double counting of the same material. However, accounting the recycled materials as resource input in efficiency calculations of cascading scenarios is due to double counting being an inherent aspect of cascading scenarios. The functional unit itself describes functions obtained from the multiple use of the same material and not from the actual amount of material entering the system. Thus, if the recycled material was not accounted for in the input, the main source material for manufacturing the products would be disregarded. This would mean that the functions, i. e. the products, are manufactured from “nothing”, further indicated by efficiencies above 100%.

2.6.5. Exergetic data inventory

Thermodynamic data from literature was used to express the input and output flows in exergy values. Table 4 presents the chemical exergies for the materials and products considered in the ExFA and the efficiency calculations in the ELCA. Own calculations are described in the supplementary information. The value of solar radiation refers to the 1981–2010 average annual surface solar radiation in Germany (Deutscher Wetterdienst, 2015).

The exergy content of a heat stream is determined by the ratio of its temperature (T_u) in Kelvin (K) and the ambient temperature (T_o), the so-called Carnot coefficient (QF_{Ex}).

$$QF_{Ex} = \left(1 - \frac{T_o}{T_u}\right) \tag{4}$$

To determine the exergy content of a heat stream, the ambient temperature T_o was assumed as the temperature of 298.15 K from the reference environment (Szargut et al., 1988). For T_u, a temperature of 100 °C (373 K) was assumed, as this reflects the temperature of the heat stream leaving a CHP plant into a district heating system.

Table 4
Exergy values of various materials and products. For chemicals, the physical state is given as follows: s = solid, g = gaseous, l = liquid.

	Chemical exergy content	Unit	Reference
Softwood (Spruce)/ Recovered Wood/Sawn timber/Wood chips	21.55	MJ_{ex}/kg	Own calculation
Particle board	21.16	MJ_{ex}/kg	Own calculation
Diesel	44.4	MJ_{ex}/kg	(Szargut et al., 1988)
Electricity	1	MJ_{ex}/MJ	(Szargut et al., 1988)
Natural gas	38.28	MJ_{ex}/Nm^3	(Dewulf et al., 2007)
Steel	7.1	MJ_{ex}/kg	(Szargut et al., 1988)
Heating oil	42.85	MJ_{ex}/kg	(Szargut et al., 1988)
Water	0.05	MJ_{ex}/kg	(Dewulf et al., 2007)
Soy oil	41.66	MJ_{ex}/kg	(Özilgen and Sorgüven, 2011)
Gravel	0.09	MJ_{ex}/kg	(Dewulf et al., 2007)
Ammonia (g)	19.84	MJ_{ex}/kg	(Szargut et al., 1988)
Urea (s)	11.5	MJ_{ex}/kg	(Szargut et al., 1988)
Chlorine (g)	1.743	MJ_{ex}/kg	(Szargut et al., 1988)
Sodium chloride (s)	0.245	MJ_{ex}/kg	(Szargut et al., 1988)
Methylene diphenyl diisocyanate (s)	30.16	MJ_{ex}/kg	(Dewulf et al., 2010)
Melamine (s)	16.813	MJ_{ex}/kg	(Ayres and Ayres, 1999)
Formaldehyde (g)	18.18	MJ_{ex}/kg	(Ayres and Ayres, 1999)
Phenol (s)	33.243	MJ_{ex}/kg	(Szargut, 2005)
Heat stream (100 °C)	0.2	MJ_{ex}/MJ	Own calculation using Eq. (4)
Solar radiation	3,606	MJ_{ex}/m^2 x yr	(Deutscher Wetterdienst, 2015)
Exergy-energy ratio for solar radiation	0.9327	MJ_{ex}/MJ_{en}	(Szargut et al., 1988)
Lubricants	Because of a lack of data, the exergy content of diesel was considered		
Paraffin	Because of a lack of data, the exergy content of oil was considered		

3. Results and discussion

3.1. Exergy flow analysis and gate-to-gate efficiency

ExFA was applied to both foreground systems to analyse the exergy flow and to determine the gate-to-gate efficiencies of each sub-system (Fig. 2). The ratio between the output and input flows indicates the exergy losses within a sub-system and can be used for the gate-to-gate efficiency analysis. Chipping was considered as a part of the particle board and the CHP plant, respectively.

The ExFA identifies both forestry sub-systems (round wood and industrial round wood production) as hotspots in exergy dissipation of the PW system. As biomass production occupies a large amount of land area, solar radiation is the major contributor to the forestry sub-systems. Taking the solar radiation in exergy efficiency calculations into account, efficiencies of 0.2% are obtained. As solar radiation can be considered as a renewable resource, the exergy breeding factor was calculated to express how much biomass is produced from non-renewable inputs. Values of 176 for the round wood and 174 for industrial round wood (incl. wood chips) production were calculated by subtracting the solar radiation from the total exergy inputs. The small difference is due to the production of wood chips required for process energy in particle board manufacturing. Because of the high influence of the forestry systems on the overall results, a discussion on forestry ecosystems in exergy analysis is given in Section 3.4.

The high efficiencies of the sawmill sub-systems can be explained with the valorisation of the by-products in subsequent particle board manufacturing and thus their consideration as useful output. The

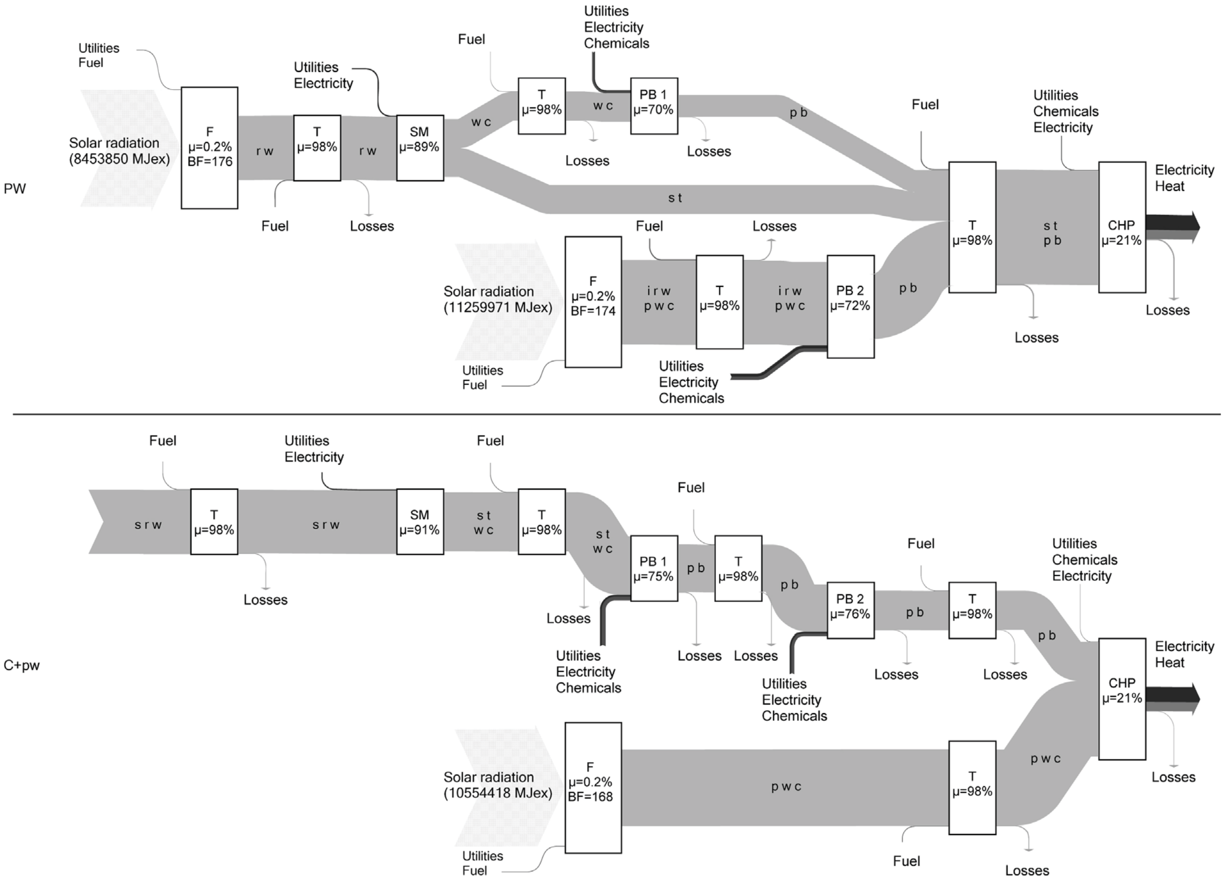

Fig. 2. Sankey diagram of the exergy flow analysis (ExFA) for the default scenario (Df) of both foreground systems. PW = Primary wood system, C + pw = Cascade system incl. system expansion from primary wood, μ = Gate-to-Gate efficiency, rw = Round wood, wc = Wood chips, st = Sawn timber, pb = Particle board, srw = Solid recovered wood, pwc = Primary wood chips, irw = Industrial round wood F = Forestry, SM = Sawmill, T = Transport, PB = Particle board plant, CHP = Combined heat and power. Losses include wood losses during transportation and chipping. The input and output flows of a sub-system are considered in the efficiency calculation. The solar radiation flows are not to scale with the other flows.

exergy dissipation in the sawmill and the particle board sub-systems can primarily be attributed to the combustion of wood for process heat production and the consumption of electricity. The adaptations made to account for the use of recovered wood instead of primary wood in the inventory data of the C system yield an increase in efficiency of 2% in the sawmill and of 4–5% in the particle board plant. However, the adaptations in the sawmill process were based on the values for particle board manufacturing, because no practical experience is available from the use of recovered wood in a sawmill. Although these results are highly uncertain, they highlight the potential of future wood cascading. The gate-to-gate efficiencies for the particle board plant of the presented study are lower than the efficiency of 89% that can be calculated based on the data from Cornelissen and Hirs (2002). The differences can probably be explained by the higher level of detail of the inventory data used in our study, in particular regarding adhesives, electricity and other utilities.

Efficiency increases of 1–3% in sawmilling and particle board manufacturing could be achieved by replacing the wood fuelled boilers with a CHP plant. Both sub-systems could be further improved by reducing the demand for drying heat through optimized reverse logistics to maintain a low moisture content of the recovered wood, although the reductions already considered in the adaptations only indicate small direct cascading effects.

ExFA identifies the CHP plants with a gate-to-gate efficiency of 21% as hotspots of exergy dissipation. The efficiency result can be assigned to the low exergetic potential of the heat stream, indicated by the Carnot factor. The closer the temperature of the heat stream is to the temperature of the reference environment, the lower is the exergy content of the heat stream.

3.2. Exergetic life cycle assessment

The ELCA was applied to account for the resource consumption per functional unit (fu) using CEENE as life cycle impact assessment indicator and to determine the overall resource efficiency at life cycle level using the CDP. The CEENE values are illustrated in Fig. 3 for all scenarios studied (Df, A–C). Key sub-systems contributing to the overall resource consumption are identified in process analysis and shown in Fig. 4. Table 5 contains the CDP values for the PW and C systems as well as the sub-systems illustrating the efficiency development when using either primary or recovered wood and is in accord with the holistic perspective at the life cycle. For the CDP calculation of a sub-system, the useful output includes all upstream functions provided from the cradle to the factory gate of the respective sub-system. For example, the CDP of the particle board plant 1 in the PW system was calculated from primary wood production till the manufacturing of the particle board. However, this approach does not allow the comparison of the CDP of a sub-system between different systems. In this section, all results refer to the default scenario (Df).

The total resource consumption of the PW system is 163,437 MJ_{ex}/fu with a CDP of 21%. The total resource consumption of the cascading systems ranges between 94,628 MJ_{ex}/fu for C + pw, 35,833 MJ_{ex}/fu for C + g and 16,729 MJ_{ex}/fu for C + ww respectively (Fig. 3, Df). The associated CDPs are calculated as 28%, 46% and 45%, respectively (Table 5, Df). In terms of the overall natural resource extraction, cascading proves to be more favourable than the use of primary resources. This is similar to the results from Cornelissen and Hirs (2002), Gärtner et al. (2013) and Höglmeier et al. (2014), who found that cascading wood can decrease resource consumption compared to the respective

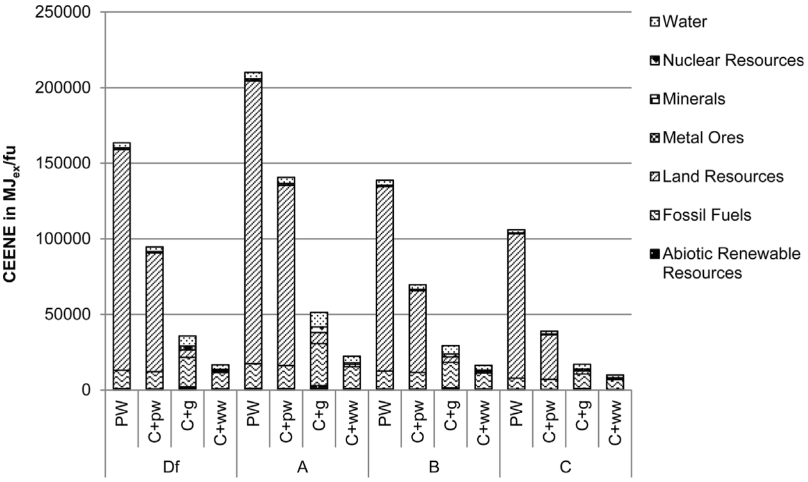

Fig. 3. Total resource consumption (CEENE) of each system within the scenarios Df = Default (RW → ST → PB → PB → CHP), A (RW → ST → PB → PB → PB → CHP), B (RW → PB → PB → CHP) and C (RW → ST → PB → CHP) with RW = Recovered wood, ST = Sawn timber, PB = Particle board, CHP = Combined heat and power. C + pw = Cascade system incl. system expansion from primary wood, C + g = Cascade system incl. system expansion from grid, C + ww = Cascade system incl. system expansion from waste wood, PW = Primary wood system.

reference scenario. Cascading also proves to be the more resource-efficient way to provide the same functional unit, indicated by the higher CDPs.

Table 5 illustrates that the CDP decreases from one sub-system to another, because of the exergy dissipation increasing with every step through e. g. the consumption of electricity or fuel. The main efficiency decrease in the C system is observed between the sawmill and the particle board plant 1 and amounts to 23% (Table 5, Df). This can mainly be attributed to the large input of process energy during particle board manufacturing, which is irreversibly lost. Thus, keeping the material in solid applications before allocating it to the next cascade, can improve the efficiency of the system. This supports the argumentation of Sirkin and Houten (1994), according to whom the decisive factors to optimize resource efficiency are to reduce the loss of resource quality along the chain and to decrease the efforts required to maintain resource quality for the next step in the chain.

In the PW system, the forestry sub-systems are the main contributors to the total resource consumption (94%), with land resources as the dominating resource category (Fig. 4, Df). Land resources are also dominating the CEENE values for the forestry systems studied by Schaubroeck et al. (2013) and Schaubroeck et al. (2016). In contrast, their CEENE values are much higher due to a ten times higher land occupation per m^3 round wood considered for their Scots pine forest in Belgium. In our study, forestry sub-systems cause the main difference in resource consumption and the CDP between the PW and the C systems. The high resource consumption in the forestry sub-systems causes the main efficiency loss within the PW system, which affects all downstream sub-systems, indicated by their small CDPs. Therefore, by optimizing the forestry sub-systems, the resource efficiency of the whole PW system will improve. A further discussion on forest systems in exergy analysis is given in section 3.4.

Besides land resources, fossil fuels are the main resources consumed. They are required as energy carrier (in particular in the C + g system) and as feedstock for chemicals, mainly wood adhesives. A share of 80% of the total fossil fuel consumption of the PW system is located in the particle board sub-systems. It is 81% for the C + pw system, 47% for the C + g system and 85% for the C + ww system respectively. This observation is in accordance with the results from Werner and Richter (2007) and Höglmeier et al. (2014). To make the resource composition of the particle board plant less dependent on fossil fuels, adhesives based on renewable raw materials could be used in the future.

In section 3.1 we mentioned that the adaptations made to account for the use of recovered wood (reduction of process heat and electricity consumption) lead to a small increase in the gate-to-gate efficiencies of the sawmill and particle board sub-systems. The same results are obtained at life cycle level when comparing the CEENE values of the sawmill (C: 1,378 MJ$_{ex}$/fu; PW: 1,686 MJ$_{ex}$/fu) and particle board (C: 14,082 MJ$_{ex}$/fu; PW: 14,785 MJ$_{ex}$/fu) sub-systems (Fig. 4). This comparison reveals that the direct resource saving potential through the use of recovered wood amounts to 8% in the sawmill and to 5% in the

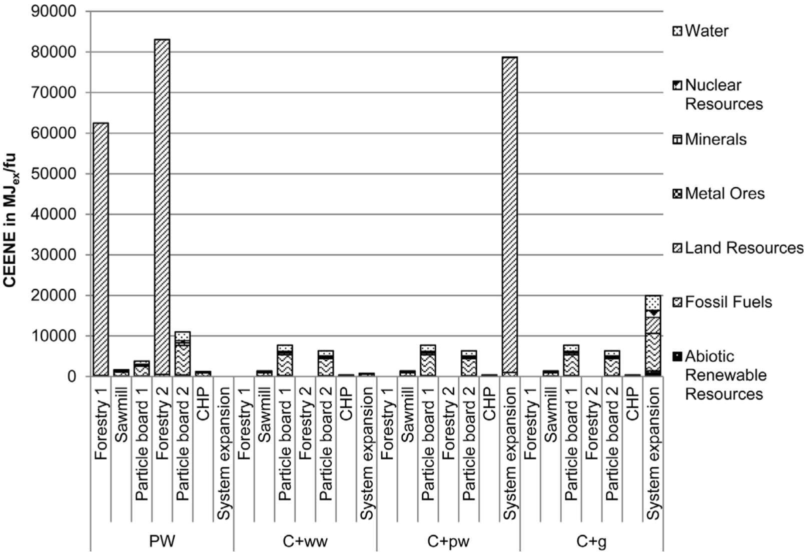

Fig. 4. Total resource consumption (CEENE) of each sub-system in the default scenario (Df). C + pw = Cascade system incl. system expansion from primary wood, C + g = Cascade system incl. system expansion from grid, C + ww = Cascade system incl. system expansion from waste wood, PW = Primary wood system.

Table 5
Resource efficiencies for each system and sub-system of each scenario Df = Default (RW → ST → PB → PB → CHP), A (RW → ST → PB → PB → PB → CHP), B (RW → PB → PB → CHP) and C (RW → ST → PB → CHP) with RW = Recovered wood, ST = Sawn timber, PB = Particle board, CHP = Combined heat and power. C + pw = Cascade system incl. system expansion from primary wood, C + g = Cascade system incl. system expansion from grid, C + ww = Cascade system incl. system expansion from waste wood, PW = Primary wood system. The CDP values for the sub-systems describe the CDP from cradle to the factory gate of the respective sub-system, including all upstream functions. Sawn timber is a useful output in scenario Df, A and C only.

		Useful output	CDP/Scenario			
			Df	A	B	C
Whole System	PW	sawn timber, particle board, energy	21%	21%	20%	21%
	C + pw		28%	26%	29%	34%
	C + g		46%	46%	44%	47%
	C + ww		45%	44%	43%	46%
System expansion	ww	energy	20%	20%	20%	20%
	g		23%	23%	23%	23%
	pw		6%	6%	6%	6%
Forestry 1	PW	round wood	30%	30%	–	30%
	C	–	–	–	–	–
Sawmill	PW	sawn timber, by-products	26%	26%	–	26%
	C		85%	85%	–	85%
Particle board 1	PW	sawn timber, particle board	22%	22%	–	22%
	C		62%	62%	56%	62%
Forestry 2	PW	industrial round wood	30%	30%	30%	30%
	C	–	–	–	–	–
Particle board 2	PW	sawn timber, particle board	20%	20%	20%	20%
	C		60%	60%	56%	–
Particle board 3	PW	sawn timber, particle board	–	20%	–	–
	C		–	59%	–	–
CHP	PW	sawn timber, particle board, energy	21%	21%	20%	21%
	C		53%	54%	39%	50%

particle board plant. Thus, even when primary wood is completely replaced with recovered wood, the manufacturing differences are too small to achieve substantial resource savings. Furthermore, in such a comparative study at life cycle level, the direct resource savings from processing recovered wood are compensated by the resource use in the system expansion processes, which has also been communicated by Sathre and Gustavsson (2006).

Similar to the results from Höglmeier et al. (2014), transportation, fossil energies and lubricants are small contributors to the total resource footprint of the systems.

3.2.1. The choice of system expansion

Höglmeier et al. (2014) concluded that system expansion modelling (SE) is decisive for the impact results of a comparison between a cascade and primary wood system. However, in this study all C systems have smaller CEENE values than the PW system. Although SE modelling is not decisive for the total resource consumption, it affects the composition of the resource profile. The CEENE value of the C + pw scenario is dominated by land resources (89%) from the forestry process in the SE. The C + g system is dominated by fossil fuels (47%) from the SE processes. In contrast, the SE processes only contribute 5% to the overall resource consumption of the C + ww system, because the main energy carrier (waste wood) is not accounted for in CEENE. Although SE modelling is not decisive for the resource consumption, it becomes relevant when emission-based indicators such as the global warming potential (GWP) are assessed: the GWP_{100} of the C + g system is 75% higher than the GWP_{100} of the PW system and 101% and 94% higher than for the C + ww and C + pw, respectively (excluding biogenic carbon). Hence, if SE modelling is decisive for the results of a comparison, depends on the considered impact indicator. This further highlights the importance of a carefully composed indicator set in decision making.

With respect to resource efficiency, SE modelling influences the CDP of the whole C system, but without being decisive for the studied systems. Although the incineration technology considered was similar in the ww and the pw SE, the inefficiency of round wood production in the pw SE reduces the efficiency of the pw SE to 6% compared to 20% of the ww SE (Table 5, Df).

3.3. Influence of the number of cascading steps

Different cascading scenarios (Df, A–C) were studied to determine the influence of the number of cascading steps on the total resource consumption and the resource efficiency.

With each additional cascading step producing particle boards, the total CEENE value increases from C to Df to A by 54% and 29% in the PW system, by 143% and 49% in the C + pw system, by 110% and 43% in the C + g system and by 69% and 33% in the C + ww system (Fig. 3). The material loss for e. g. process heat generation in each cascading step leads to the relative reduction of the increasing demand for primary resources (CEENE) required for product manufacturing.

In the PW and C systems, the increasing resource consumption between two scenarios (C and Df, Df and A) originates from the additional particle board plant sub-system and its upstream processes. With respect to the C system, the resource consumption further increases with every additional cascading step, because the amount of energy generated in the SE increases with every cascading step. Although the amount of energy produced in the SE is identical across all C systems within one scenario, primary wood for energy generation (pw) leads to a higher CEENE value (and lower CDP) compared to grid (g) or waste wood (ww). Consequently, the influence of the SE on the overall resource consumption and the CDP, increases with every additional cascading step and depends on the defined energy carrier. Although the CDP of the material cascade increases with the number of cascading steps (row “CHP” in Table 5), the CDP of the whole C systems decreases with every additional particle board step. However, this correlation is not decisive for the comparison between both systems.

Similar results were retrieved from Höglmeier et al. (2014), who found that the environmental benefits of the cascading scenario decreased with additional cascading steps relative to the primary wood system. In contrast, Gärtner et al. (2013) found that a higher number of cascading steps leads to an increase of the environmental benefits of the total system. These contradictory results can be assigned to the system modelling. Gärtner et al. (2013) defined an input-based functional unit in contrast to Höglmeier et al. (2014) and our study, where an output-based functional unit was used. By using an input-based functional unit, the environmental effects add up with every additional cascade step.

3.4. Exergy approach for resource efficiency analysis of multifunctional systems

As mentioned in section 2.1, exergy analysis was chosen to account for the characteristics of cascading systems, i. e. multifunctionality and internal recycling processes. The advantage of exergy analysis was considered as the aggregation of all resource and material flows along the life cycle of a system in a single unit. This aggregation includes secondary materials from recycling processes, which is in line with the waste-as-resource concept from industrial ecology (Dewulf et al., 2008). In exergy analysis, different resources are aggregated by weighting materials and energies with a scientifically sound approach. This is an advantage over traditional LCA where weighting is influenced by personal preferences in order to aggregate indicator results in a single score. The advantage of a single score is to allow an easy comparison of the resource use of different products or scenarios and facilitates decision making. A single score further allows the comparability between material and energy resources, which can contribute to solve the discussion between feedstock and fuel (Dewulf et al., 2008). In resource efficiency calculations, a single score makes the calculation straightforward. On the downside, single score indicators avoid insight in the complexity of a system through data loss and only describe a limited set of its actual impacts. Although exergy analysis accounts for resource use in a scientifically sound way, it does not assess scarcity or resource depletion. In this regard, the thermodynamic concept does not express the value of goods or resources for mankind and natural entities besides its energetic value and therefore has shortcoming in its application to express environmental sustainability (Schaubroeck, 2014). Besides its application for resource accounting, efforts were made to use exergy analysis to assess the environmental impacts of emissions. However, as the exergy value of emissions does not refer to their environmental impact, the use of exergy analysis in emission-based impact assessment is questionable (Dewulf et al., 2008).

Although exergy analysis is a feasible approach to compare the resource use of multifunctional cascade systems, the approach as applied in this study shows shortcomings in the characterisation of land use with respect to the suitability for forest ecosystems. In exergy analysis, land area is accounted using either the solar radiation available for photosynthesis (Dewulf et al., 2007; Huysveld et al., 2015) or – as applied in this study – the net primary production (NPP) (Alvarenga et al., 2013; Taelman et al., 2016; Taelman et al., 2014) as a proxy for the value of land. Such a proxy does not follow the same rationale as for other resources or materials, which are directly characterised by their exergy value. In some respects, the use of a proxy can thus be considered as a weighting step. Although the weighting is not influenced by personal preferences, the results rather depend on the choice of methodology to calculate the characterisation factor (e. g. NPP, photosynthetic efficiency) (Huysveld et al., 2015). Consequently, the different rationales need careful consideration when comparing land area and material or energy resources during the interpretation of the indicator results. Taelman et al. (2016) further mention, that the NPP approach by Alvarenga et al. (2013) indeed accounts for the loss of natural resources, but neither differentiates between the intensity of land use (urban area is characterized the same way as forests), nor assigns a natural value to the remaining NPP after the land use. Their approach to include the naturalness of the NPP in the calculation of characterisation factors is a first step to overcome these shortcomings (Taelman et al., 2016).

In general, the results from exergy analysis for the forestry subsystems are reasonable and scientifically sound, considering land occupation as mandatory for biomass growth. However, the results indicate that land use accounting determines the resource footprint and resource efficiency of a bio-based system. As a consequence, sustainable forests are described as inefficient systems where a significant reduction in land occupation is necessary to increase resource efficiency. Indeed, optimising land use efficiency is inevitable, since land area is increasingly perceived as a resource with limited availability, which makes it subject of competition (UNEP, 2014). Thus, possible strategies to improve forest productivity, such as optimized thinning (Diaconu et al., 2015; Pretzsch, 2005) or intensively managed forest plantations (Fox, 2000), might lead to an increase in resource efficiency. To avoid misleading conclusions, however, these strategies have to be discussed with respect to the sustainability concept of forest management (BMEL, 2011) and under the consideration of ecosystem services provided by forests. Ecosystem services are understood as the benefits people can obtain from an ecosystem, such as provisioning (e. g. wood) or regulating services (e. g. affecting climate, water quality) (MEA, 2005).

Considering ecosystem services seems to be of particular relevance when assessing the efficiency of forest systems, in particular when defining the useful outputs. This is due to the fact that the inefficiency of the forestry sub-systems cannot be fully attributed to natural exergy losses during forest growth. In fact, some exergy can be considered to be used to provide ecosystem services, some of which are of high value for society (useful output). Thus, the current allocation of land occupation to biomass production only (and thus wood products as single useful outputs) disregards the ecosystem services provided from a forest ecosystem (established through tree growth) in efficiency analysis. Therefore, the integration of additional ecosystem services besides provisioning services in exergy analysis is important to account for the true benefits of ecosystems in studies focusing on the resource efficiency of bio-based value chains. A first approach in exergy analysis was presented by Hau and Bakshi (2004) introducing the Ecological Cumulative Exergy Consumption (ECEC) to account for ecosystem services by including the exergy consumed by ecological processes. As no method was available that considered a broad range of ecosystem services (Zhang et al., 2010b), the Eco-LCA methodology was developed to account for several ecosystem services by combining conventional LCA, ECEC and exergy analysis amongst other methods in a discrete tool (Zhang et al., 2010a). A more integrative way to account for ecosystem services in product LCA was presented by Schaubroeck et al. (2013). They propose a framework to account for the interrelation between ecosystems and their surrounding environment. In the respective case study, a regulating service was integrated by modelling the uptake of harmful substances in a forest system at inventory level. This approach has been further elaborated by Schaubroeck et al. (2016), by including other ecosystem services using a monetary ecosystem service valuation. In further studies, to model the delivery of ecosystem services at inventory level, quantification and mapping models to assess ecosystem services could be used. Despite the broad approaches to account for ecosystem services in exergy analysis and LCA – either at inventory or impact assessment stage – accounting for ecosystem services offers large potential for further research and methodological improvement (Othoniel et al., 2016).

3.5. Representativeness and limitations of the study

The presented study follows a holistic perspective on the material chain of wood to determine the efficiency of wood cascading compared to the use of primary wood. Today, wood cascading is at its beginning. Processing recovered solid wood in a sawmill to produce new sawn timber is currently not in practise at industrial level, but in small carpentries and in the scope of ongoing research (CaReWood – Cascading Recovered Wood 2017). Its integration should highlight what might be possible in future wood utilisation and determine if it is viable to support the cascading concept. The use of recovered sawn timber products such as pallets in particle board manufacturing is the common treatment of such waste wood in Germany (Waste Wood Ordinance, 2012). Consequently, scenario B best describes the use of recovered wood today. The single recycling of particle board is technologically feasible, before the particle board decreases in quality (Michanickl, 1996). Based on this, the studied scenarios can be considered as technically possible. Especially when keeping in mind that in reality particle boards are not manufactured from 100% recovered wood, but with a share of 20% (Rüter and Diederichs, 2012).

The results provide insight into the potential of future cascading systems to make the use of wood in Germany more efficient. But taking the lifetime of the considered products into account, the time horizon of the systems could reach 50–100 years. During this time span, technology, end of life treatment or energy generation will change significantly. Not least due to using data from current technologies to study such future systems, the uncertainty of the results from cascading studies in general is consequently very high.

An attributional modelling approach was applied in the study, focusing on the direct cascading effects. But as cascading will likely induce shifts at market level through reallocating material flows, a consequential modelling would be appropriate as stated in the ISO standards (DIN EN ISO 14044:2006-10). To identify the affected technologies and market segments, market models should be used (Earles and Halog, 2011). With this approach, direct and indirect cascading effects including rebound effects, i. e. consequences of shifts at market level, would be assessed.

Our study focuses on the resource use of cascading systems using one single indicator. To provide transparent results for decision making and avoid misleading conclusions, a wider range of environmental impact indicators should be applied (Steinmann et al., 2016). As cascading scenarios include incineration processes, the assessment of particulate matter (PM) is advised, because of the great importance of PM emissions in wood energy systems (Wolf et al., 2015). In addition, a focus on climate change impact methods under the consideration of extended carbon storage is advised when studying the environmental performance of forest products (Pawelzik et al., 2013; Røyne et al., 2016). Especially the effects of carbon storage and delayed emissions are of significant interest when studying long cascade chains (Gärtner et al., 2013; Höglmeier et al., 2014; Thonemann and Schumann, 2016).

4. Conclusions

The presented study analysed the resource consumption and the resource efficiency of a cascade use of recovered wood in Germany by comparing it to the use of primary wood providing the same multiple functions along the life cycle using LCA and exergy analysis.

Cascading wood leads to less resource extractions from the natural environment compared to the use of primary wood to provide the same functions. The greatest resource savings through cascading can be obtained from the avoided primary production of round wood, with land area as the main resource. The use of recovered wood in product manufacturing leads to small resource savings and resource efficiency increases correspondingly, because the use of recovered wood instead of primary wood hardly affects the production. Particle board manufacturing is the key driver to resource consumption in both systems, with fossil fuels as main resources.

Cascading generally proves to be a more resource-efficient way to provide the same multiple functions than the use of primary wood. Although the efficiency of the material cascade increases with every additional cascade step, the efficiency gain does not compensate for the relative negative influence of the system expansion on the total resource consumption and efficiency. Therefore, it is important to carefully model system expansion processes, although it is not decisive for the comparison of the resource use and efficiency between a cascading and primary wood system.

Exergy analysis as applied in this study proved to be a viable option to compare the resource use and resource efficiency of multifunctional cascading systems. It allows considering the characteristics of wood cascades: multifunctionality, internal recycling processes and accounting for land occupation. While this study focused on resource use only, it is recommended to apply exergy analysis as part of an indicator set to obtain a complete profile of the environmental impacts of the system. As this study identified limitations in the current land use accounting methodology when applied on forestry systems, only cascading optimization strategies can be reliably concluded. For the exergetic optimization of natural-industrial hybrid-systems like managed forests, further methodological development is necessary to fully account for the broad range of ecosystem services provided.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.resconrec.2017.07.045.

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Eco-efficiency analysis of recycling recovered solid wood from construction into laminated timber products

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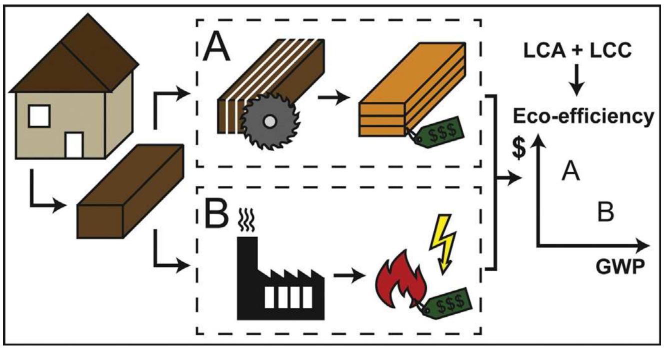
GRAPHICAL ABSTRACT



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ABSTRACT

To establish a bioeconomy, the demand for renewable resources like wood is likely to increase. To satisfy the demand, cascading, i.e. the sequential use of one unit of a resource in multiple applications with energy recovery as the final step, is a key concept to improve the efficiency of wood utilization. Today, the systematic wood cascading is still in its infancies and limited to the downcycling of wood, i.e. the degradation of material quality. New recycling technologies are needed, which maintain the material quality at the beginning of the cascade chain and mobilize yet unused resources. Therefore, a new recycling technology for recovered solid wood from construction into glued laminated timber products was developed.[1] To identify the environmental and economic performance of the process, the eco-efficiency was assessed by the joint application of life cycle assessment (LCA) and life cycle costing (LCC). As reference system, the incineration of the recovered wood was analyzed, representing the common treatment for recovered wood from construction in Germany. System expansion was applied to solve multifunctionality. The results indicate that the recycling of recovered wood into glued laminated timber products is environmentally and economically viable and offers possibility for the production of value added products. The recycling further shows up to 29% of lower environmental impacts and 32% of lower costs compared to the incineration, if system expansion is based on wood energy. The operational processes required for the solid wood cascading are of minor relevance for the economic and environmental performance. Instead, primary technologies like glue lamination and the incineration are key drivers. In all considered scenarios, the material recycling has a 15–150% higher eco-efficiency compared to the incineration. In conclusion, the further development for the practical implementation of the recycling process is recommended to enhance the implementation of the cascading concept.

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1. Introduction

The alteration of the fossil based economy towards a sustainable bioeconomy will likely increase the demand for renewable resources, in particular of wood. It is expected that the demand for wood in Europe will exceed the supply within the next decade (Mantau, 2012). To meet the growing demand, the concept of wood cascading is widely discussed to increase the efficiency of wood utilization. Cascading is defined as the sequential use of one unit of a resource in multiple material applications with its use for energy generation as final step. The ideal cascade can include various reuse or recycling steps, before the material is incinerated for energy recovery at the end of life (Risse et al., 2017). The cascading concept has been implemented in European directives (EC, 2012, 2011) and on national level in Germany as concept for a resource efficient utilization of wood and is a declared goal in the national bioeconomy strategy (BMEL, 2014; BMUB, 2015; UBA, 2014). Cascading is an important aspect of the circular economy, as it keeps the added value in materials for as long as possible and increases the circulation of the materials (EC, 2014; EMF, 2013; Lewandowski, 2016; Mair and Stern, 2017).

Cascading has first been described as theoretical concept by Sirkin and Houten (1994) and adapted to the forest wood chain by Fraanje (1997). Several recent research studies highlighted the environmental benefits of wood cascading in comparison to either the use of primary wood or non-wood materials (Gärtner et al., 2013; Höglmeier et al., 2015; Höglmeier et al., 2014; Suter et al., 2017; Vis et al., 2014). Other studies proved the beneficial carbon balance for the cascade use of wood over alternative scenarios (Brunet-Navarro et al., 2018; Sathre and Gustavsson, 2006; Sikkema et al., 2013). It was further shown that wood cascading can improve the efficiency of wood utilization (Bais-Moleman et al., 2018; Risse et al., 2017). A review on wood cascading studies is provided by Thonemann and Schumann (2018).

Despite the political incentives and research activities, wood cascading is still in its infancies. Only about one third of the recovered wood in Europe and Germany is currently used for particle board manufacturing (EPF, 2014; Mantau et al., 2018). Alternative material utilizations are niched.

Thus, to enhance wood cascading in practice, further recycling technologies are needed. In recent studies, the use of recovered wood as feedstock for wood plastic composites (Sommerhuber et al., 2015; Teuber et al., 2016), cement bonded boards (He et al., 2019; Hossain et al., 2018) or in biorefinery (Lesar et al., 2016) was analyzed. However, present recycling concepts involve the degradation of the material quality, i.e. from solid wood to particles, fibers or chemical substances. Processes that preserve the dimensional and economic quality of solid wood are missing. Yet, large quantities of dimensional wood products from buildings show high potential for wood cascading (Höglmeier et al., 2013; Husgafvel et al., 2018; Kalcher et al., 2017; Sakaguchi et al., 2016), but are directly used in bioenergy generation. This bypass is contradictory to the cascading concept and leaves the opportunity to increase the resource efficiency of wood utilization unused (Risse et al., 2017) and hinders the transition of the wood sector into a circular economy. To fill this gap, a new recycling concept for the processing of recovered solid wood into clean and standardized lamellae for a use in engineered wood products (e.g. glued laminated timber (glulam)) was developed (Irle et al., 2018; Privat et al., 2016; TUM, 2017). It is hypothesized that the quality and economic value of the material is maintained and the time of carbon storage can be extended by several decades when used in building products. To determine whether the efforts required for the processing of the recovered wood are worthwhile, the presented study strives to evaluate the eco-efficiency of the recycling process by combining environmental and economic assessments. It supports the identification of possibilities on extending the cascade chain in the foremost step, in order to achieve a higher efficiency and circularity in wood utilization.

To our knowledge, no studies on the joint analysis of the environmental and economic aspects of the treatment of recovered solid wood from construction are available. Most studies focus on the environmental aspects of recovered wood used in particle board production or energy generation. Rivela et al. (2006) showed that the recycling of ephemeral wood structures in particle board production is environmentally beneficial compared to the use for energy generation. Merrild and Christensen (2009) and Kim and Song (2014) derived similar conclusions for the use of recovered wood for particle board production, while focusing on the global warming potential. Hossain and Poon (2018) compared the use of recovered wood from construction in particle board production with alternative treatments in landfill and energy generation using life cycle assessment (LCA). In this study, the energy generation is beneficial over the recycling scenario, due to greenhouse gas emission savings from the substitution of fossil fuels.

Studies combining LCA and life cycle costing (LCC) are available for the treatment of construction or demolition waste (CDW). However, these studies focus on mineral and steel aggregates (Braga et al., 2017; Coelho and de Brito, 2013; Di Maria et al., 2018; Mah et al., 2018) or the technological properties of the recycled wood product only (e.g. Wang et al., 2016).

The novelty of this study is the joint assessment of the environmental and economic impacts using LCA and LCC of a recovered solid wood recycling concept in comparison to an alternative treatment option. Combining LCA and LCC follows the rationale of a life cycle sustainability assessment (LCSA), where the three dimensions of sustainability are taken into account: environment, economy and social aspects. Each dimension has to be analyzed when a product or process is developed or improved to meet sustainability criteria. LCSA supports the identification of trade-offs between the dimensions and allows better decision making in politics and industry (Finkbeiner et al., 2014; Klöpffer, 2008). However, the social dimension is not considered because the methodology has not been fully developed yet, least of all for an application on emerging technology (Klöpffer, 2008; UNEP, 2009). Yet, the combination of environmental and economic perspectives allows an eco-efficiency analysis, which relates the environmental performance of a system to its obtained value (DIN, 2012).

Therefore, the research questions of the study are:

1. Does the utilization of recovered solid wood from construction in new solid wood applications lead to lower environmental impacts compared to its incineration for energy recovery?
2. Is the utilization of recovered solid wood from construction in new solid wood applications an economically viable alternative compared to its incineration for energy recovery?
3. Which are the relevant process groups and scenario parameters for the environmental and economic performance of both systems?
4. Which treatment alternative has a higher eco-efficiency considering different scenarios?

2. Methodology

2.1. Goal and scope

The goal of the study is to compare the environmental and economic performance of a new recycling concept for recovered solid wood from construction (i.e. beams, boards, laths) with the current treatment option, i.e. the incineration in a combined heat and power plant (CHP). The incineration is currently the only use for wood from construction in Germany, due to its potential contamination with wood preservatives (BMUB, 2012). In order to maintain the dimensions and solid state of the material, a technological process for the decontamination of recovered solid wood was developed in the research project 'Cascading Recovered Wood' (CaReWood) (Irle et al., 2018; Privat et al., 2016; TUM, 2017). The process is hereafter referred to as CaReWood process. The process includes the sorting and processing of the recovered wood into clean lamellae, suitable for a use in glulam manufacturing. For this study, a change of legislation is assumed, enabling the use of recovered wood from construction in material applications when an effective and reliable decontamination process is conducted. Although the lamellae dimensions from recovered wood are likely to be smaller than those from primary wood, a comparable quality of glulam from both wood sources is assumed. Studies on the technological properties of recovered wood underpin this assumption (Meinlschmidt, 2017).

In both systems, the use phase is excluded from the study as it is considered as identical for both systems. The geographic scope of the study is Germany. This regionalization is necessary to compensate for the temporal and spatial volatility of the LCA, but especially of the LCC data (Hunkeler et al., 2008), as well as to account for the regionally diverse recovered wood management.

The LCA study has been performed according to the DIN ISO 14040:2009-11 and DIN ISO 14044:2006-10 standards (DIN, 2006a, 2006b). The environmental LCC has been conducted following the guidelines given in Swarr et al. (2011) and Hunkeler et al. (2008). It is based on the same system boundaries, functional unit and inventory flows compiled for the LCA study, but expanded by the integration of investment, labor and maintenance costs. The eco-efficiency analysis was conducted according to the DIN EN ISO 14045:2012-10 standard (DIN, 2012).

The functional unit is defined as 'the treatment of 1 t of recovered solid wood as well as the production of 0.679 m^3 of glulam, 3676 MJ of electricity and 9190 MJ of heat', as given in Table 1 for the base scenario. The values were calculated for the treatment of 1 t of recovered solid wood with a moisture content of 22% in the CaReWood process as well as for the energy generation in the reference system.

2.2. Definition of the system boundaries

The system boundaries are outlined in Fig. 1. Both systems begin with 1 t of recovered solid wood entering the system. Based on DIN EN 15804:2014-07 (DIN, 2014), it is assumed that the wood is free of any environmental burdens from the previous life cycle. To address the multi-functionality of both systems, system expansion was applied to achieve system equality and comparability as recommended in the ISO 14044 standard (DIN, 2006a) to avoid allocation procedures. For the comparison of waste treatment options, the system expansion approach is suitable in order to account for the additional services obtained from each waste treatment (Finnveden, 1999; Klöpffer and Grahl, 2009).

2.2.1. CaReWood system

The CaReWood (CW) system was modelled according to the technological outline developed in the project, described by Irle et al. (2015, 2018). The CaReWood process starts with 1 t of recovered solid wood entering the system at the place of origin (e.g. at construction site). The wood is collected and transported to the processing facility. The next step includes a manual and online sorting using optical detection devices to reject for example curved or damaged pieces. The further step includes the removal of impurities such as metal or plastic pieces adherent to the wood using a cross-cut saw. A multi-blade saw is then used for the mechanical cleaning of the surfaces, i.e. by cutting off the surface layers which carry the coatings, finishes, or wood preservatives potentially applied to the primary products, and the sawing of the pieces into boards of standardized cross section dimensions. The contaminated rejects are sent to the CHP plant. Depending on the moisture content (22% in the base scenario), the clean boards are kiln dried to a moisture content of 13%. To prepare for glulam production, further defects from demolition or of natural origin are cut off the boards and lamellae are produced by finger-jointing. The processing ends with joining the lamellae to a glulam product. The final step is the distribution of the glulam. The total yield of the process is calculated as 26% in the base scenario (Irle et al., 2018; Privat et al., 2016). It is assumed that all rejects, sawdust, shavings and off-cuts are chipped and incinerated in an on-site CHP plant to provide the process energy. The surplus energy is provided to the grid.

To achieve comparability with the reference system, the CaReWood system was expanded with the production of electricity and heat from primary wood chips, provided from sustainable forest management. Primary wood was chosen in order to have both systems based on wood.

2.2.2. Reference system

The reference system describes the incineration of the recovered solid wood in a CHP plant. Like the CaReWood system, the reference system begins with the collection of 1 t of recovered solid wood. Before incineration, the wood is manually sorted to remove impurities, and chipped.

The reference system was expanded with the production of glulam from primary wood to achieve comparability with the CaReWood system. The primary wood is obtained as sawlog from a sustainable forest management in Germany. The sawlog is transported and then processed in a sawmill into kiln dried sawn wood, which is then transported to the glulam manufacturer. Such transportation reflects the current practice in Germany, whereas the on-site production of sawn timber and glulam is rare. After glulam production, the product is distributed. To be consistent with the modelling of the CaReWood system, it has been considered that the bark, off-cuts, shavings and sawdust are incinerated in an on-site CHP plant, providing the process energy. Surplus energy is provided to the grid.

2.3. Modelling of the environmental and economic life cycle inventory (LCI)

For modelling the LCI, data was collected from literature and LCI databases for each of the considered physical or energy flows in the unit processes. Processes similar in both systems were modelled using the same data source and were then adjusted to the specifications of the respective system. This approach was chosen to achieve equal data accuracy between both systems and enable a more reliable and robust comparison. As a consequence, the differences in the results between the systems thus relate to the modifications made to represent the specifications of each system, but not to differences in data origin or accuracy. The LCI data of the foreground processes is reported in the supplementary information. Background data was modelled using the cut-off model of the Ecoinvent database v. 3.3 (Wernet et al., 2016).

Table 1
Composition of the functional unit for the comparison between the two systems under study. The values refer to the treatment of 1 t of recovered wood in the base scenario. SE = system expansion.

	Unit	CaReWood system (CW)		Reference system (WW)		Functional unit
		CaReWood	SE: energy from primary wood	Incineration	SE: glulam from primary wood	
Recovered wood	t	1		1		1
Glulam	m^3	0.679			0.679	0.679
Electricity	MJ	2373	1300	3557	116	3673
Heat	MJ	6004	3186	9262	−72	9190

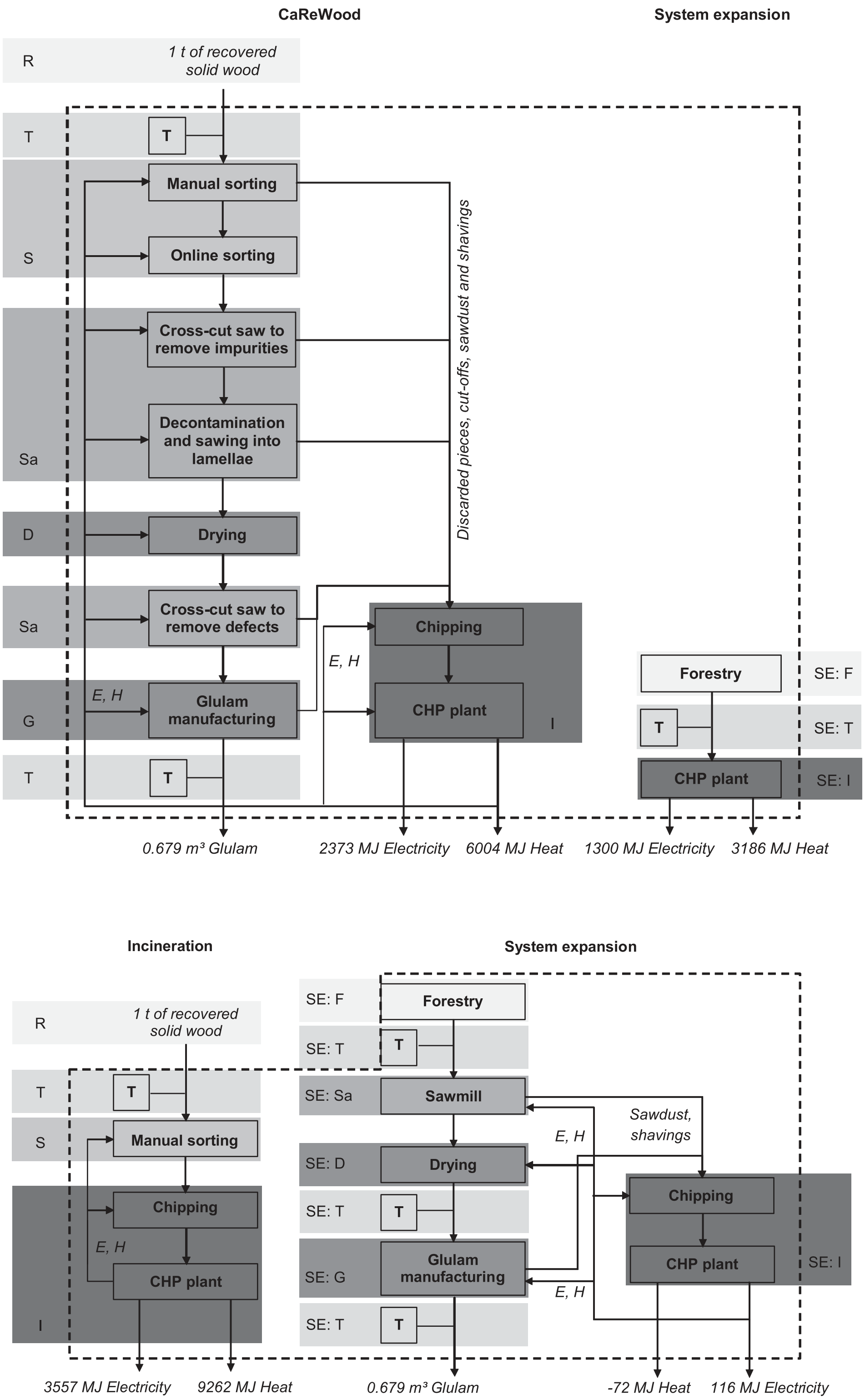

Fig. 1. System boundaries for the comparison of the CaReWood (top) and the reference system (bottom). The values refer to the base scenario. The colouring refers to the process grouping: R = recovered wood, T = transport, S = sorting, Sa = sawing, D = drying, G = glulam manufacturing, I = incineration, F = forestry, SE = system expansion, CHP = combined heat and power, Glulam = glued laminated timber, E = electricity, H = heat.

For LCC modelling, data for the operational, investment, maintenance and labor costs were collected from literature, statistical databases and German industry. For the estimation of the operational costs, cost information was assigned to each physical inventory flow of the LCA. Additionally, data on the investment, maintenance and labor costs was collected for each process as they were considered as relevant cost categories. Due to different technological standards, prices or income, LCC data often has a higher volatility than the physical flows used in LCA (Hunkeler et al., 2008). Therefore, LCC data representing the present status-quo in Germany was used when available. Otherwise average data was used. All LCC data along with the references is available from the supplementary information.

2.4. Calculation of the life cycle environmental impacts

For the life cycle impact assessment, midpoint indicators from the ReCiPe 2016 (hierarchist) method (Huijbregts et al., 2017) were applied. Indicator results are expressed for the following impact categories: climate change including (CC bio) and excluding biogenic carbon (CC), fossil depletion (FD), freshwater eutrophication (FE), terrestrial acidification (TA), particulate matter formation (PMF), human toxicity (HT), natural land transformation (NLT) and agricultural land occupation (ALO).

2.5. Calculation of the life cycle costs

The total life cycle costs (LCC_t) were calculated using Eq. (1). The cost separation follows the grouping visualized in Fig. 1 and is identical to the process groups of the LCA.

$$\begin{aligned} LCC_t = {} & C_R + C_S + C_{Sa} + C_D + C_G + C_I + C_T + C_{SE_F} + C_{SE_{Sa}} + C_{SE_D} \\ & + C_{SE_G} + C_{SE_I} + C_{SE_T} \end{aligned} \tag{1}$$

with LCC_t = total life cycle costs for each system, C_R = costs for recovered wood (applies to scenario P-40 only), C_S = costs for sorting, C_{Sa} = costs for sawing, C_D = costs for drying, C_G = costs for glulam manufacturing, C_I = costs for incineration, C_T = costs for transportation, C_{SEF} = costs for forestry in the system expansion, C_{SESa} = costs for sawing in the system expansion, C_{SED} = costs for drying in the system expansion, C_{SEG} = costs for glulam manufacturing in the system expansion, C_{SEI} = costs for incineration in the system expansion, C_{SET} = costs for transportation in the system expansion.

Additional to the LCC_t, the value added (VA) for each system was calculated. The VA is defined as the difference between revenues and the total life cycle costs. Due to the gate fee for recovered wood, the processing plants receive revenue for their treatment services. Therefore, the price for recovered wood is included as revenue in most scenarios, except P-40 and P0 (see Section 2.6). The VA describes a profit margin and provides useful insight into the economic feasibility of the manufacturing process. The VA was calculated using Eq. (2).

$$VA = (MP_R + MP_G + MP_E + MP_H) - LCC_t \tag{2}$$

with VA = value added, MP_R = market price for recovered wood (applies to all scenarios except P-40, P0), MP_G = market price for glulam, MP_E = market price for electricity, MP_H = market price for heat, LCC_t = total life cycle costs.

The market prices for provided products are expressed in Table 2. The market price for recovered wood is available from Table 3. As the price for electricity from renewables and waste depends on the fuel and the capacity of the plant, different prices are considered. In Germany, a distinction is made between the incineration of primary wood chips and industrial residues in plants ≤500 kW and the incineration of recovered wood. To account for their volatility as well as the uncertainty of the market price for the glulam from recovered wood, a variation of ±20% for all prices is considered in the VA calculation, and expressed as bars in the figures of the results section.

Table 2
Market prices for the provided products.

	Market price				
	−20%	Avg.	+20%	Unit	Source
Glulam	320	400	480	€/m^3	Industry data
Electricity primary wood ≤500 kW	0.044	0.056	0.067	€/MJ	Industry data
Electricity recovered wood ≤500 kW	0.033	0.042	0.050	€/MJ	Industry data
Heat (co-produced)	0.018	0.022	0.027	€/MJ	Industry data

2.6. Calculation of the eco-efficiency

The eco-efficiency (EE) was calculated with Eq. (3), according to the ISO 14045:2012-10 standard (DIN, 2012). The eco-efficiency is a tool to assess the environmental impacts of a product system along with its value for a stakeholder (DIN, 2012). The EE is calculated as the ratio of the value added, which describes the desired functional output, and each LCIA indicator result, which describes the input needed to obtain the desired output. The VA was chosen as it includes both, the LCC_t and revenues. The EE is expressed for each LCIA indicator (except CC bio) to avoid influence from weighting and normalization.

$$EE = \frac{\text{Value added}}{\text{LCIA indicator}} \tag{3}$$

2.7. Scenarios

The base scenario (BS) refers to the functional unit as described in Section 2.1. In the base scenario, the yield of the CaReWood process is 26%, the moisture content of the recovered wood is 22% (Privat et al., 2016) and the price of the recovered wood is 100 €/t (Industry data). The transportation distance for sawn wood in the system expansion of the reference system is 827 km (Rüter and Diederichs, 2012). To determine the influence of these parameters on the results, the scenarios described in Table 3 are calculated.

The yield of the CaReWood process describes the share of the recovered wood which remains in the glulam product and has been obtained from modelling and experimental work, described by Irle et al. (2018, 2015) and Privat et al. (2016). The calculation of the yield is described in Section 1.3 of the supplementary information. Scenarios with a minimum and maximum yield of 18% and 35% were calculated (Y18, Y35).

Because of the high energy demand during wood drying processes, the influence of the initial moisture content of the recovered wood on the overall costs and environmental impacts were analyzed in scenarios M13 and M26. In M13, it is assumed that the moisture content (13%) of the recovered wood at construction site is maintained through keeping it protected from moisture. In M26, the maximum moisture content as measured for recovered wood in Privat et al. (2016) was used.

The sawing effort describes the amount of energy and utilities necessary to mechanically decontaminate and process the recovered solid wood in lamellae. It only affects the amount of inputs required, but not the yield of the process. To account for the uncertainty of the inventory modelling, scenarios with a variation of ±20% and ±40% are analyzed (S-40, S-20, S+20, S+40). Further information on the sawing effort is provided in Section 1.3 in the supplementary information.

In the BS, the transportation of sawn wood from the sawmill to the glulam plant is modelled in the reference system to reflect the most common situation today. However, to be consistent with the CaReWood system where the glulam manufacturing is located on the same site as the decontamination process, scenarios are calculated to determine the influence of a reduced transportation distance for the sawn timber in the reference system (T413, T0).

To account for the volatility of the price for recovered wood and to determine the influence of the price on the economic viability of each treatment option, different price scenarios are calculated. Currently the waste wood producer (e.g. the owner of the deconstructed building) has to pay the treatment company (both, the recycling and incineration plant) 80 to 120 € per ton of waste wood (average of 100 €/t in BS), depending on the geographic region (Industry communication). The treatment therefore creates revenue for the treatment company. However, the price might 'increase' for the treatment company when the material becomes a demanded resource. This effect is analyzed in scenarios considering prices from −40 €/t (P-40) to 80 €/t (P80), which in parts represents the price range within the past 5–10 years in Germany (EUWID, 2017). In contrast to the other scenarios, in P-40, the treatment

Table 3
Scenarios analyzed in the study.

Scenario		Yield	Moisture content	Sawing effort	Price of recovered wood	Transportation distance
		%	%	%	€/t	km
Base scenario	BS	26	22	100	100	827
Change of yield of the CaReWood process	Y18	18				
	Y35	35				
Change of moisture content of the recovered wood	M13		13			
	M26		26			
Change of the sawing effort in the CaReWood process	S-40			60		
	S-20			80		
	S +20			120		
	S +40			140		
Change of the price of recovered wood	P-40				-40	
	P0				0	
	P40				40	
	P80				80	
Change of the transportation distance for sawn timber in the reference system	T413					413.5
	T0					0
Change of system expansion modelling	SEg	Energy in the SE of the CW system is provided from grid				

company has to pay for the recovered wood, which results in additional costs. All scenarios can also be understood as an increase in costs through a selective deconstruction at the construction site to preserve the quality of the recovered wood. The higher quality increases the yield of the recycling process and therefore allows the waste wood producer to charge for the recovered material. Because some parameter variations result in a different functional unit, the systems are adjusted to maintain comparability as described earlier.

Since SE modelling can be a decisive factor for the outcome of a waste wood treatment study (Finnveden, 1999; Höglmeier et al., 2014; Risse et al., 2017), in scenario SEg, the generation of energy from grid (German power mix, heat from natural gas) was modelled in the SE of the CW system. Due to data limitations, no LCC was conducted.

3. Results and discussion

In Sections 3.1 and 3.3 the results from the LCA and LCC are presented, followed by a comparison of both approaches in Section 3.5. The eco-efficiency analysis follows in Section 3.6. To determine the key contributing processes, process group analysis was performed by grouping the manufacturing steps as described in Fig. 1 and analyzing their relative contribution to the overall impacts. Since the process energy is provided from the CHP plants on-site, no impacts are associated with the energy consumption.

3.1. LCA results for the base scenario

The LCA results for the base scenario are shown in Fig. 2. System expansion processes are visualized through a dotted filling. In all impact categories, the CW system shows less environmental impacts compared to the reference system. The relative benefits of the CW system range from 1% for the impact category HT to 29% for FD and ALO (Table 4, column 'BS'). In CC and CC bio, 24% and 13% lower impacts were obtained for CW compared to WW. In the FE, TA and NLT categories, CW shows 24%, 11% and 18% lower impacts than WW.

The key CaReWood processes, i.e. sorting, sawing and decontamination and drying, are of minor relevance, and thus not decisive, for the overall impacts of the system. Instead, glulam manufacturing and incineration processes as well as the system expansion processes are key contributors to the environmental impacts of the system and offer greater potential for improvement. In glulam manufacturing, the consumption of adhesives is the key driver. During wood incineration in CHP plants, substantial quantities of particulate matter, sulphurous and nitrogenous compounds are emitted (Kaltschmitt, 2009; Werner and Richter, 2007; Wolf et al., 2015). These emissions result in a share of up to 98% (CW, HT) of the incineration processes in both systems to the TA, PMF and HT indicators. When biogenic carbon is taken into account (CC bio), the incineration along with the forestry processes dominate the results through greenhouse gas emissions and carbon sequestration. As some biogenic carbon is stored in the glulam product, an overall negative balance for both systems is calculated. Because both systems are wood based and provide the same products, the CC bio indicators are almost identical. The transportation of the sawn wood in the SE of the WW system shows great contributions to most indicators, in particular to CC, FD, FE, PMF and NLT, and is thus a decisive factor in the comparison. These impacts are avoided in the CW system due to the consideration of the on-site decontamination and glulam manufacturing. For the implementation of the CaReWood process, it is thus recommended to locate the process close to existing processing plants to minimize transportation distances. Besides CC bio, the forestry processes from the SE of both systems, dominate the land related ALO and NLT indicators.

The small contribution of the key CaReWood processes can further be explained by the system modelling. Since the electricity and heat is provided from the CHP plant, no environmental impacts associated with energy consumption are allocated to the CaReWood processes. Furthermore, the contribution of a process group is linked to the yield of the CaReWood process: as 70% of the input material is incinerated, a larger contribution of the respective process group can be expected.

Environmental benefits for the material recycling of wood has also been observed in the studies by Höglmeier et al. (2014), Rivela et al. (2006) and Merrild and Christensen (2009), although the different scopes and modelling approaches limit a direct comparison. Hossain and Poon (2018) used the avoided burden approach to compare the use of recovered wood from demolition in particleboards and energy production. Due to the assumption that fossil fuels are avoided through the energy production, the incineration scenario performs better than the material use.

3.2. Scenario analysis for the LCA

Different parameters were studied in a scenario analysis to determine their influence on the outcome of the study and to analyze the robustness of the results. The relative performance of the CW system compared to the WW system is displayed for each scenario in Table 4.

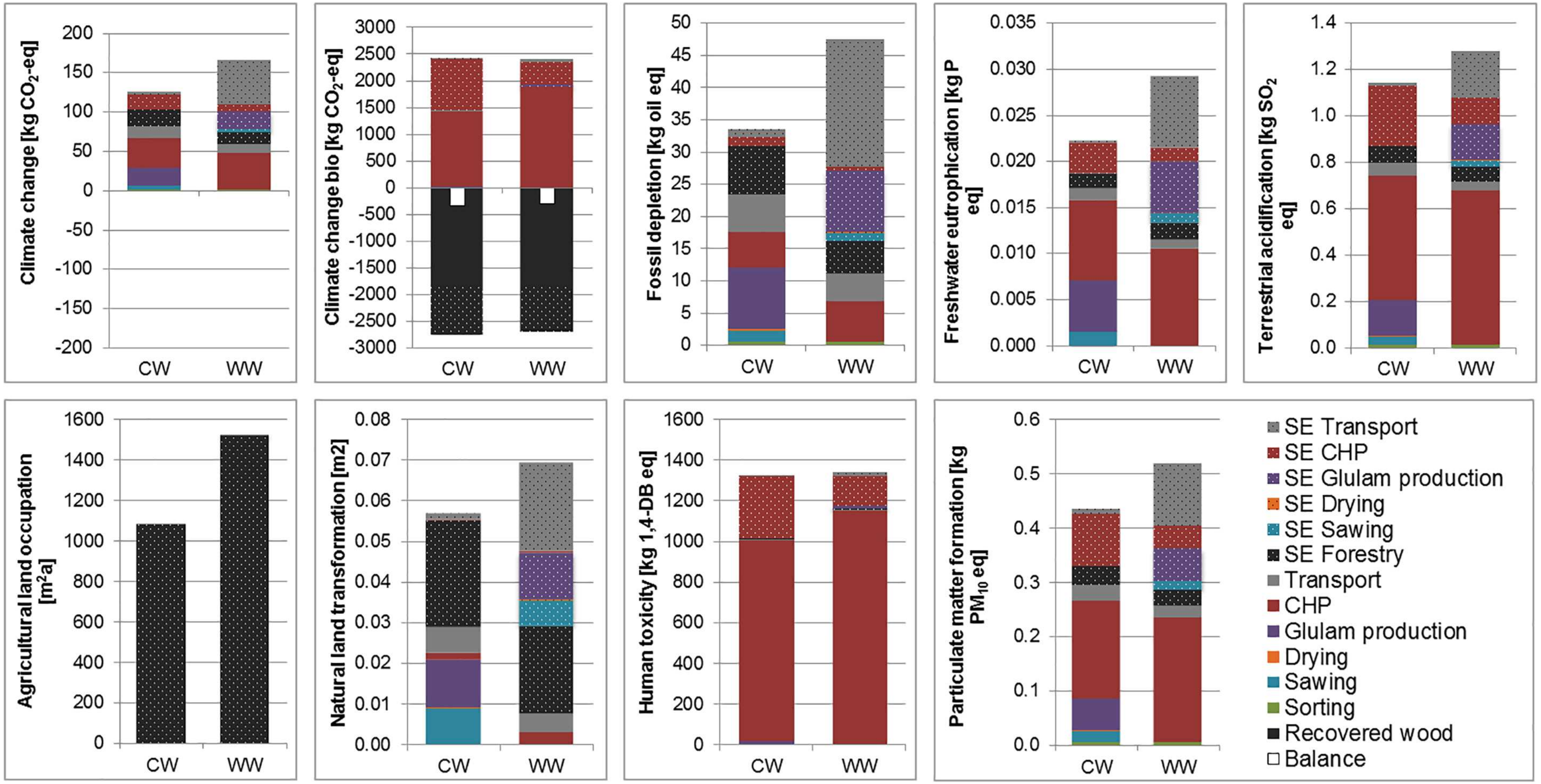

Fig. 2. Environmental impacts (LCA) of the base scenario for the CaReWood (CW) and reference system (WW). The dotted segments indicate processes from system expansion (SE). For the climate change including biogenic carbon impact category, a balance is expressed.

Table 4
Relative performance of the CaReWood system compared to the reference system for each of the considered scenarios including the LCA and LCC results. Negative values indicate a better relative performance of the CaReWood system. Positive values indicate a relative better performance of the reference system. The latter are underlined for visualisation. The scenarios P0, P40, and P80 are not shown as they do not influence the LCA and LCC results. FD = fossil depletion, CC = climate change excl. bio. CO_2, CC bio = climate change incl. bio. CO_2, FE = freshwater eutrophication, TA = terrestrial acidification, HT = human toxicity, PMF = particulate matter formation, ALO = agricultural land occupation, NLT = natural land transformation, n/a = not assessed.

	BS	Y18	Y35	M13	M26	S-40	S-20	S+20	S+40	P-40	T413	T0	SEg
LCC_t [€]	−32%	−27%	−35%	−36%	−32%	−35%	−33%	−30%	−28%	−28%	−26%	−20%	n/a
FD [kg oil eq]	−29%	−25%	−33%	−29%	−30%	−31%	−30%	−29%	−28%	−29%	−16%	4%	158%
CC [kg CO_2-eq]	−24%	−19%	−28%	−23%	−24%	−25%	−25%	−23%	−23%	−24%	−12%	3%	157%
CC bio [kg CO_2-eq]	−13%	−18%	−14%	−13%	−13%	−14%	−14%	−13%	−13%	−13%	−6%	1%	90%
FE [kg P eq]	−24%	−17%	−29%	−23%	−24%	−26%	−25%	−23%	−22%	−24%	−15%	−4%	979%
TA [kg SO_2 eq]	−11%	−6%	−15%	−10%	−11%	−12%	−11%	−10%	−9%	−11%	−5%	2%	0%
HT [kg 1,4-DB eq]	−1%	3%	−7%	−1%	−2%	−2%	−2%	−1%	−1%	−1%	−1%	0%	−9%
PMF [kg PM_{10} eq]	−16%	−11%	−20%	−16%	−16%	−18%	−17%	−15%	−14%	−16%	−8%	1%	−10%
ALO [m^2a]	−29%	−29%	−30%	−27%	−30%	−30%	−30%	−29%	−29%	−29%	−29%	−29%	−98%
NLT [m^2]	−18%	−14%	−21%	−17%	−18%	−23%	−21%	−15%	−13%	−18%	−7%	8%	4%

In Table 20 in the supplementary information, the performance of each scenario compared to the base scenario is expressed.

The yield of the CaReWood process was changed from 26% in the BS to 18% (Y18) and 35% (Y35). By reducing the yield (Y18), the benefits of the CW system over the WW system decrease by 1% to 7%, depending on the impact category. For HT, it can be observed that the CW system performs 3% worse than the WW system. This can be attributed to the increased emissions from the CHP plant of the CW system, while the emissions from transportation and glulam processes in the SE of the WW system decrease. Increasing the yield to 35%, the environmental benefits of the CW system increase within a range from 1% to 6%. Although increasing the yield causes 5%–47% higher environmental impacts in both systems, it leads to greater advantages of the material recycling.

The moisture content affects the incineration, transportation and drying processes. In scenario M13, no energy is required for wood drying and more energy is recovered due to the higher energy content of the waste fractions. Consequently, a larger amount of surplus energy is provided from the CW system, thus, a smaller amount of energy needs to be produced in the SE. The transportation effort is reduced due to the lower weight of the material. Despite these effects, the indicator results of M13 and M26 remain similar to the base scenario (−1–3%). The moisture content thus has no relevance for the performance of each system or the outcome of the comparison. It is important to mention that the moisture content also influences the emissions from incineration. However, no inventory data was available, which allows the parameterisation of emissions depending on the moisture content.

Changing the sawing effort in the CW system, in all scenarios small changes of −6–6% compared to the BS can be observed. This result supports the observation that the key CaReWood processes (sorting, decontamination, sawing) are of minor relevance for the environmental performance and viability of the system.

Bisecting the transportation distance of sawn wood in the SE of the WW system (T413), the impacts decrease by 1% (HT) to 16% (FD), while a total avoidance of the transportation (T0) leads to a reduction of up to 32% (FD). As a consequence, the benefits of the CW system decrease by 0% to 13%. In T0, the WW system performs 1% to 8% better than the CW system in the FD, CC, CC bio, TA, PMF and NLT indicators. Thus, the transportation of sawn wood is a decisive factor for the comparison. It supports the recommendation to minimize transportation distances when the CaReWood process is implemented.

Since the SE processes have the biggest contribution to the overall impacts, the energy generation from grid was modelled as an alternative SE process in the CW system in the LCA scenario analysis (SEg). Due to the large share of fossil fuels used for energy generation in Germany, the CW system has much higher impacts in the FD, CC, CC bio and FE impact categories compared to WW (Table 4). As trade-off, the CW system performs better than the WW system in the ALO category, since less primary wood is used in the SE. However, in this scenario, both systems are no longer based on wood as main raw material. The decisive influence of the SE modelling on the outcome of a system comparison has already been observed and discussed in other studies, e.g. Finnveden (1999), Höglmeier et al. (2014) or Risse et al. (2017).

3.3. LCC results for the base scenario

In Fig. 3, the LCC_t of both systems are expressed for the BS. The LCC_t of the CW system amount to 229.77 € compared to the CW system with 335.77 €. The benefit of the CW system amounts to 31% (Table 4). The main contributors to the life cycle costs of the CW system are the incineration (21% and 12% from the SE), glulam manufacturing (16%) and forestry (23%) processes. The sorting, decontamination and drying processes are only small contributors to the LCC_t of the CW system. The LCC_t of the WW system are dominated by the costs from the SE, in particular the forestry (34%). The incineration processes amount to 20% and 4% (SE). Excluding the SE, the LCC_t of the CW system is higher than the LCC_t of the WW system. The LCC_t of the SE of the CW system, in contrast, is smaller than the LCC_t of the SE of the WW system. These differences can be attributed to the cost intensive material processing compared to incineration processes. Furthermore, in CW a high value product is made from recovered wood, whereas low priced energy is made from comparably cheap primary wood chips. In the WW system, the recovered wood is used to produce a low value product, while primary logs for glulam manufacturing are acquisitioned for a high market price.

For the BS, revenues (from recovered wood, glulam, electricity, heat) of 614.16 € for the CW and 597.71 € for the WW system were calculated, as displayed in Fig. 5. Both systems receive the same revenue for the treatment of recovered wood as well as for the glulam. Although the energy provided is identical in both systems (functional unit), the total

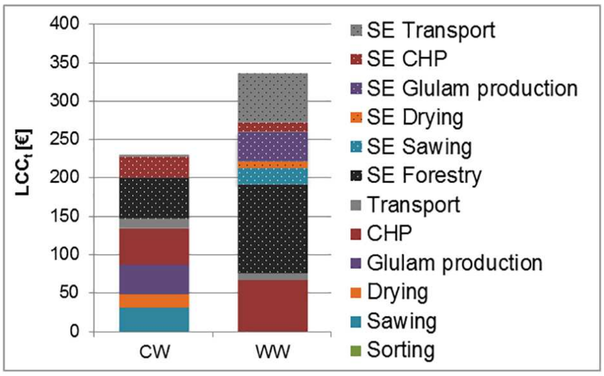

Fig. 3. Total life cycle costs (LCC_t) of the base scenario for the CaReWood (CW) and reference system (WW). The dotted segments indicate processes from system expansion (SE).

revenues are different. This is due to different market prices for the electricity generated in each system (see Table 2). However, these differences are not decisive for the economic feasibility of each system, as indicated by a positive VA (Fig. 5). The VA amounts to 384.39 € in the CW system and 261.94 € in the WW system in the BS. A positive VA still remains, when 20% lower market prices are considered (bars in Fig. 5), indicating a high economic viability as well as a flexibility towards price volatility for both treatment alternatives.

3.4. Scenario analysis for the LCC

The results for the scenario calculations are presented in Table 4, indicating the relative performance of the CW system compared to the WW system. The LCC_t of each scenario is presented in Fig. 4. In Fig. 5, the LCC_t, revenues and VA are shown for selected scenarios. In Table 20 in the supplementary information, the performance of each scenario compared to the BS is expressed.

A yield of 18% leads to a decrease of the LCC_t of 18%, as more material is directly incinerated, which reduces the costs compared to the material utilization. This also reduces the revenues obtained since less high value glulam, but more low value energy is produced. In consequence, the VA of the CW system is reduced. With a reduced yield in the CW system, the LCC_t, revenues and VA of the WW system decrease as well. Increasing the yield to 35% consequently leads to higher costs, revenues and VA in both systems. In the Y18 scenario, the cost benefits of the CW system reduce to 27% compared to the WW system and increase to 35% in Y35. Compared to the moisture content and the sawing effort, the yield has the greatest effect on the economic performance of both systems. The yield also has a greater influence on the economic performance than the market price of the recovered wood.

With a low moisture content, the LCC_t decrease to 214.38 € and the benefits of the CW system increase to 36% compared to the WW system. This result can mainly be attributed to the avoidance of the drying costs. These savings are reduced by the higher energy recovery in the WW system, which results in higher costs for wood chips in the SE of the CW system. In M26, the fix costs, e.g. for kiln preparation, remain similar to the BS, whereas the variable costs, e.g. energy consumption, increase. Since the variable costs have a small contribution to the total drying costs, the effects of a higher moisture content on the LCC_t are minor.

A reduction of the sawing effort in the CaReWood process improves the LCC_t performance of the CW system by 2% (S-20) and 4% (S-40). Increasing the sawing effort has the opposite effect.

Changing the transportation distance of sawn timber in the SE of the WW system, leads to a reduction of 6% (T413) and 12% (T0) of the benefits of the CW system and thereby shows the greatest influence of the studied parameters on the comparison.

To account for the volatility of the market price for recovered wood, four scenarios were calculated to analyze the prices' influence on the economic viability of both systems. These scenarios further visualize an increase of the market price, induced from a growing demand. In P-40, a positive market price was assumed, i.e. the treatment company buys the material from the waste producer. In the other scenarios P0, P40 and P80, lower prices than currently in practice (100 €/t) are assumed, but the waste producer still pays for the treatment. Although the price of recovered wood is accounted as costs in the LCC_t of the P-40 scenario (instead of as revenue), the VA of both systems remains positive, indicating the systems robustness against the price volatility of recovered wood. However, in the WW system, the minimum value of the bar describes a VA of 22.39 €, indicating the minimum market prices to achieve economic viability of the WW system (Fig. 5).

3.5. Comparison between the LCA and LCC results

In LCA and LCC, the CW system performs better than the WW system. From economic perspective, both systems are economically viable. In LCA and LCC, the key technological processes of the CaReWood system, i.e. sorting, decontamination and drying are of minor importance for the overall results. Instead, available technologies like glulam manufacturing and incineration are dominating the results of the system.

The main difference between the LCA and LCC results is the contribution of the primary wood production in the SE. In the LCA, the primary wood production only dominates the ALO and NLT indicators. The key processes in the LCA, in contrast, are the incineration and glulam manufacturing as well as the transportation in the SE of the WW system. In contrast, the production of primary wood has the highest contribution to the LCC_t of both systems. The costs for the primary wood can have a share of up to 70% of the total manufacturing costs, depending on the product and company size, which is characteristic for the wood industry (Binder, 2002; Schulte

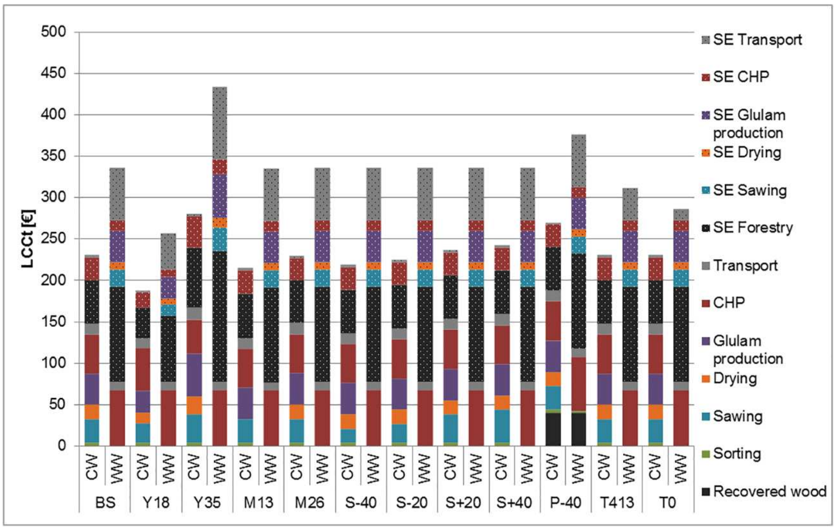

Fig. 4. LCC_t of the CaReWood and reference system for selected scenarios as described in Table 3. The scenarios P0, P40, and P80 are not shown as they do not influence the LCC_t. The dotted segments indicate processes from system expansion (SE). CW = CaReWood system, WW = Reference system.

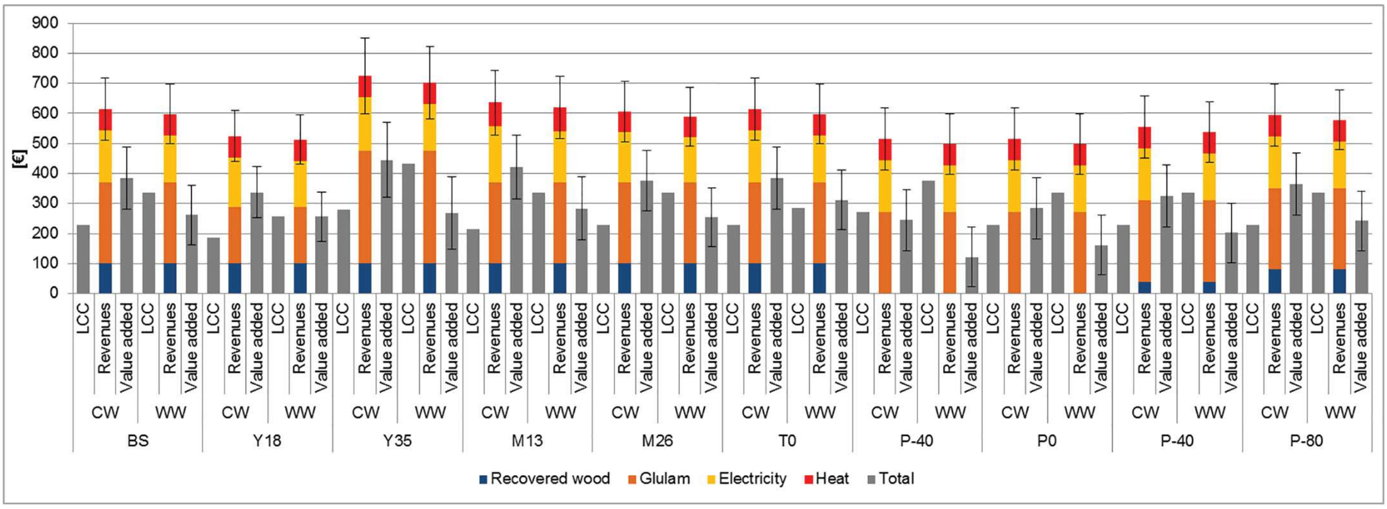

Fig. 5. Life cycle costs (LCC_t), revenues and value added for selected scenarios as described in Table 3. The bars reflect the variation of ±20% of the considered market prices for glulam, electricity and heat. CW = CaReWood system, WW = Reference system.

et al., 2003; Seintsch, 2011). However, this share cannot be observed in the presented study due to methodological aspects, such as the life cycle perspective and the system expansion, which results in the consideration of processes outside the main manufacturing process, which is uncommon in alternative economic assessments.

Similarities between the LCA and LCC results can be observed for the transportation of sawn timber in the SE of the WW system. For most impact indicators in LCA and the LCC, the transportation process is among the most contributing processes. Changing the transportation distance to 0 km (T0), the WW system performs better than the CW system in most LCA indicators. However, the LCC_t of the CW system remains smaller than in the WW system. Thus, the transportation distance is not as decisive for the LCC_t as it is for the LCA based comparison.

3.6. Eco-efficiency

The results for the eco-efficiency analysis are expressed in Fig. 6 for selected scenarios. The scenarios were chosen as they show the greatest

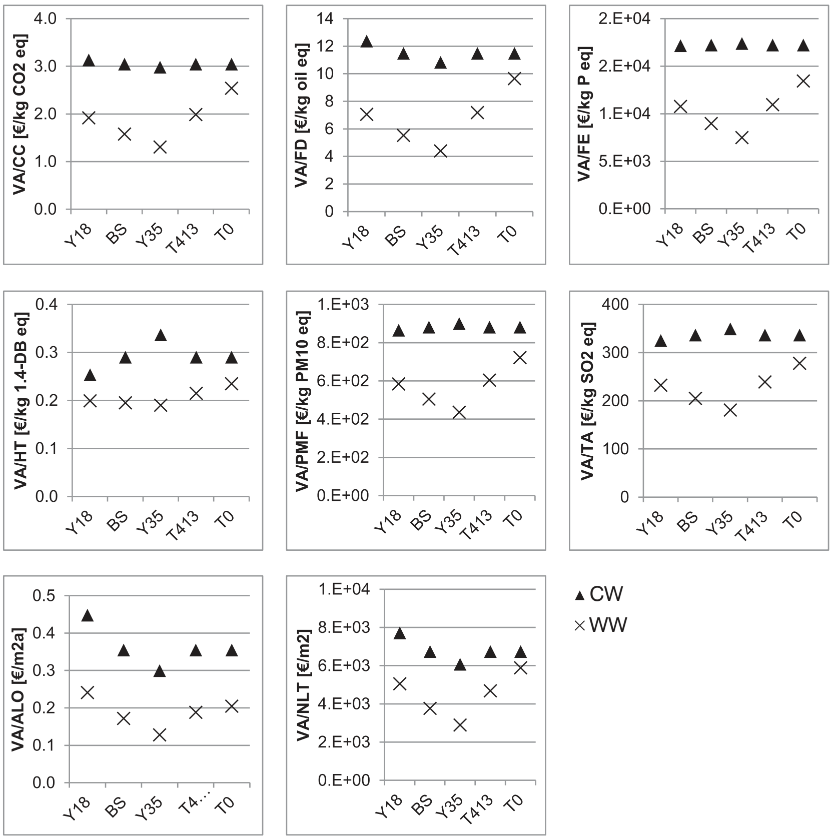

Fig. 6. Eco-efficiency calculated from the value added (VA) and each LCIA indicator for selected scenarios as described in Table 3. CW = CaReWood system, WW = reference system, SE = system expansion, CHP = combined heat and power, FD = fossil depletion, CC = climate change excl. bio. CO_2, FE = freshwater eutrophication, TA = terrestrial acidification, HT = human toxicity, PMF = particulate matter formation, ALO = agricultural land occupation, NLT = natural land transformation.

influence on the comparison (see Table 4). A higher eco-efficiency indicates a better performance of the system. For CC bio, no EE is calculated, because of the negative balance.

The eco-efficiency of the CW system is better in all presented scenarios and indicators. For the resource related indicators ALO, FD and NLT as well as the CC (CC is an emission based indicator, but strongly relates to fossil fuel consumption) it can be observed that an increasing yield leads to a reduction of the eco-efficiency. This is contradictory to the expectation that an increasing yield is beneficial for the eco-efficiency. But in both systems, the relative increase of the VA through a higher yield is smaller (32% in CW and 5% in WW) than the increase of the environmental impacts associated with the additional manufacturing effort (e.g. 100% for ALO in both systems).

For the emission based indicators FE, HT, PMF and TA, an increase of the eco-efficiency for the CW system and a decrease for the WW system can be observed. For the CW system, the increase of the VA (32%) is slightly higher than the increase of the impacts (30% for FE). In the WW system, the increase of the VA (5%) cannot compensate for the increase of the impacts (50% for FE), which explains the decline of the eco-efficiency in WW.

In both cases, the processes from the SE are decisive for the results. Since glulam production from primary wood is more cost and impact intensive than the energy generation from primary wood, the WW system is stronger influenced than the CW system. Additionally, product manufacturing from primary material is less efficient than from recovered material (Risse et al., 2017), which further increases the influence of the SE processes.

Reducing the transportation distance (T413, T0), the eco-efficiency of the WW system converges to the one of the CW system, but remains lower. Thus, although the LCA results indicate similar and for some indicators better results of the WW system, the eco-efficiency of the CW system remains better, due to the higher VA obtained.

3.7. Limitations of the study

In this study, the material recycling of recovered solid wood was compared with its direct incineration. The results apply for an emerging technological process, which is not yet in practice. Thus, the modelling of the machining steps and the LCI and LCC data are based on assumptions made in respect to current machining technologies and with the help of wood processing experts. As none of the machining required is beyond current technologies (Irle et al., 2015), the results are considered as viable enough for a first estimation.

In LCC, costs for research and development, subsidies or external costs are disregarded due to data availability. With respect to data quality, it is important to mention that a detailed documentation and allocation of costs was hardly available from most companies. Data uncertainties therefore were accepted during the modelling of a consistent data inventory. Due to the spatial volatility of the economic data, the results are not directly transferable to other regions.

Based on the technological properties of recovered wood (Meinlschmidt, 2017), a functional equivalence between the glulam from recovered wood and primary wood was assumed. However, it is likely that the market price for recovered wood glulam will be different, which is why different price scenarios were analyzed in the LCC. In the LCA, a potential quality loss of the recovered wood was disregarded. When information on the material quality are available from the process, a quality factor for recycled wood, as suggested by Rigamonti et al. (2018), could be used in future studies to account for the quality loss.

System expansion is the recommended approach to achieve functional equivalence between multifunctional systems in comparative studies (DIN, 2006a). However, the modelling of the system expansion processes can decisively influence the results of a study, as described above. To account for this influence, in our study, one alternative system expansion process was modelled in scenario analysis. However, further modelling of SE processes is limited to data availability, in particular in the LCC, as the focus of the study is the joint application of both methods. For future studies, it is recommended to focus on updating the data inventory and include alternative and future energy carriers (e.g. renewables, waste) as well as non-wood based products (e.g. steel joists) in the system expansion processes. In this regard, the application of a consequential LCA can be considered to account for the changes on market level induced from changing the wood streams.

Studying emerging technologies poses challenges regarding system modelling, time and data (Cucurachi et al., 2018). The CaReWood process is still on lab scale and further development is required before it might become an incumbent technology. During that time, existing technologies will develop or the legal framework will change, giving more evidence to resource efficiency and circularity. The practical implementation will further induce changes of material streams on market level with the associated economic and environmental impacts. Under the consideration of different timeframes, these changes and developments can be studied in scenario analysis or different modelling approaches. Scenario and data modelling can be conducted following concepts from system thinking, learning curves or statistical analysis (Arvidsson et al., 2017; Cucurachi et al., 2018).With consequential or dynamic LCA market effects and temporal aspects can be taken into account (Earles and Halog, 2011; Levasseur et al., 2013; Pawelzik et al., 2013). However, the application of these methods is not yet proven for the joint application of LCA and LCC on emerging technologies. While the joint application of LCA and LCC provides helpful insight for technological development and decision making related to emerging technologies, at the same time, it hinders the application of evolved LCA methods. Therefore, further studies are required, which stress the application of such methods for system or data modelling in the joint application of LCA and LCC.

4. Conclusions

A joint application of LCA and LCC was conducted to analyze the environmental and economic potential of recycling recovered solid wood from construction into glued laminated timber products in comparison with the current treatment of recovered wood from construction in Germany, which is the incineration with energy recovery. The joint application of LCA and LCC supports the identification of key drivers as well as trade-offs between environmental and economic aspects, but limits the application of advanced LCA methods suitable for emerging technologies.

To conclude, the research questions can be answered as follows:

1. The results show that the recycling of recovered wood is environmentally beneficial compared to the incineration, if both systems are based on wood as raw material. Depending on the impact category, the recycling system shows 1–29% lower impacts than the incineration in the base scenario. Scenario analysis revealed that a reduction of the transportation distance leads to a better performance of the incineration in some impact categories of up to 4%. However, if the system expansion of the CW is based on fossil fuels, the system performs worse in most categories. In total, a further development of the recycling technology for its practical implementation can be recommended.
2. Using recovered solid wood for material applications is economically viable and shows 32% lower costs compared to the incineration system of the base scenario. In all scenarios calculated, a positive value added was obtained.
3. The main processes of the recycling system like sorting, decontamination and drying are of minor relevance for the environmental and economic performance of the system. Instead, existing processes like the glulam production and incineration are the key drivers in both systems. However, system expansion modelling influences the results, and as shown from scenario analysis, the outcome of the

comparison. For implementation, it is recommended to increase the yield of the process as well as to avoid transportation to maximize the value added and decrease the environmental impacts.
4. In all scenarios, the eco-efficiency of the recycling system is 15–150% higher. Eco-efficiency analysis supports the recommendation to enhance the implementation of the recycling technology.

To develop a circular bioeconomy and enhance wood cascading, new recycling technologies are required. The process adds an additional step to the cascade chain and contributes to the mobilization of yet unused resources from urban deposits and maintains the quality of solid wood products. It extends the time of carbon storage and allows a further sequential material and energetic use. For the implementation, a change of legislation in Germany is necessary as well as better knowledge on the properties of recovered wood. To increase the yield of the recovery process, a recycling oriented wood construction is needed, which allows maintaining the quality of recovered wood during disassembly. In future studies, alternative treatment scenarios, such as the use in particleboard or in biorefinery, could be included in the comparison as well as the assessment of an entire cascade chain.

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Appendix A. Supplementary information

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