Resources, Conservation & Recycling 186 (2022) 106588

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.elsevier.com/locate/resconrec

Environmental impact assessment of cascading use of wood in bio-fuels and bio-chemicals

Kranti Navare [a,b,1,*], Wouter Arts [c,1], Giorgia Faraca [d], Gil Van den Bossche [c], Bert Sels [c], Karel Van Acker [a,e]

[a] KU Leuven, Department of Materials Engineering, Kasteelpark Arenberg 44, Leuven 3001, Belgium
[b] VITO, Sustainable materials, Boeretang 200, Mol 2400, Belgium
[c] Centre for Sustainable Catalysis and Engineering (CSCE), KULeuven, Celestijnenlaan 200 F, Heverlee 3001, Belgium
[d] European Commission Joint Research Centre, Calle Inca Garcilaso 3, Sevilla 41092, Spain
[e] KU Leuven, Research Centre for Economics and Corporate Sustainability, Warmoesberg 26, Brussels 1000, Belgium

ARTICLE INFO

Keywords:
Dynamic Life Cycle Assessment (LCA)
Biogenic carbon accounting
Carbon neutrality
Reductive Catalytic Fractionation
Lignin valorization

ABSTRACT

Cascading keeps wood in products for a longer duration and delays the embedded biogenic carbon emission. Carbon is kept out of the atmosphere for longer, giving forests time to sequester equivalent amounts of carbon. The storage period and time needed to sequester the same amount of carbon affect the GWP - an aspect often overlooked in LCA. This study compares alternative wood cascading scenarios producing biochemicals and fuel – to examine the influence of the rate of biogenic carbon flows on the net GWP of cascading systems.

GWP decreases with increasing cascade steps. Benefits are higher when considering the temporal information – highlighting that current carbon accounting may underestimate the climate benefit of cascading. The GWP of bio-refinery products depends on their feedstock. GWP is lower when using waste wood, which has served a long time, instead of virgin wood. Benefits enlarge by extending the application lifetimes of these products.

1. Introduction

Wood plays a crucial role in climate change mitigation. Wood-based products often have lower environmental impacts than functionally equivalent fossil- or mineral-based products (Sathre and Gustavsson, 2009). Long-lived wood products act as carbon stock during their service life. Additionally, wood can be burned for energy to substitute fossil sources. Thus, the wood demand is increasing. Although it is a renewable resource, land availability and forest regeneration rates limit the wood supply. In Europe, the wood demand is expected to exceed its supply by 2030 (Mantau, 2012; Material Economics, 2021). Cascading use of wood is thus gaining importance to tackle the possible resource scarcity.

Cascading is the sequential use of a resource in multiple material applications and using it for energy generation only when a material use is no longer possible (Sirkin and Houten, 1994). Cascading use strategies aim to extract the maximum value from the resource to reduce dependency on primary resources and ease the pressure on the ecosystems (Campbell-Johnston et al., 2020; Olsson et al., 2018). Several studies have evaluated the impact of wood cascading, and almost all observed the environmental benefits of cascading. Fraanje (1997) examined the use of pine wood in the Netherlands and found that cascaded use could reduce the need for primary resources. Studies also proved that cascaded use could improve resource use efficiency (Haberl and Geissler, 2000; Risse et al., 2019; M. 2017) and reduce net greenhouse gas (GHG) emissions (Bais-Moleman et al., 2017; Kim and Song, 2014; Rivela et al., 2006; Sathre and Gustavsson, 2006; Sikkema et al., 2013; Taskhiri et al., 2019) by replacing fossil-based resources (Sathre and Gustavsson, 2006; Sikkema et al., 2013), increasing carbon stock (Brunet-Navarro et al., 2018) and delaying emission resulting from incineration or decomposition of wood at the end of products lifetime (Faraca et al., 2019; Mehr et al., 2018).

1.1. Cascade use of wood in the bio-refinery

An increasing number of scientific studies have highlighted the potential benefit of wood cascading. The concept is also becoming a political ambition in European bio-economy policy. However, in practice,

---

[*] Corresponding author.
E-mail address: kranti.navare@kuleuven.be (K. Navare).
[1] These authors contributed equally to this work.

https://doi.org/10.1016/j.resconrec.2022.106588
Received 25 October 2021; Received in revised form 18 July 2022; Accepted 28 July 2022

the cascading use of wood is still in its infancy in Europe. In 2016, around 49% of the recovered waste wood of EU28 was incinerated for energy generation (European Commission, 2018; Eurostat, 2016). The remaining was cascaded primarily for particleboard production (Mantau et al., 2010). Today, particleboard is one of the few established practices for cascading post-consumer wood (Vis et al., 2016). Most of the available studies also evaluated particleboard as the primary cascading option for the recovered wood.

However, novel recycling technologies and applications for biomaterials are emerging, which provide an opportunity to develop more effective and efficient wood cascading pathways. Wood as feedstock for chemical and fuel production is gaining traction and is seen as a solution to tackle the environmental impact of fossil resources. Wood is carbon-rich material composed of cellulose, hemicellulose and lignin. Various compounds are produced already from the (hemi)cellulosic fraction - prominent examples are paper, pulp and ethanol. But most of the lignin fraction, currently recovered as a by-product of conventional wood fractionation processes such as Kraft pulping, is in degraded form and suitable only for incineration for energy recuperation. However, lignin is an aromatic polymer made of interlinked phenolic units and a promising feedstock to replace fossil aromatics.

Recent efforts in biorefinery research focus on *lignin-first* approaches in contrast to conventional carbohydrate-centered biorefineries. In the *lignin-first* refineries, wood is fractionated into lignin oil (ready to upgrade to high-value chemicals) while retaining the pulp as a solid fraction for further processing. A specific type of lignin-first strategy is reductive catalytic fractionation (RCF) which yields a refined and stable lignin oil and solid cellulose-rich pulp. During RCF, lignin is released from the wood matrix and depolymerized by 'cooking' wood at elevated temperatures in a solvent mixture. Given that the lignin fragments formed during the solvolytic depolymerization are prone to re-polymerize, a redox catalyst and hydrogen source (in the form of pressurized hydrogen gas or other donors) are added to the reaction mixture to stabilize the lignin-derived phenolics (Arts et al., 2021; Liao et al., 2020; Sheldon, 2020; Van Den Bosch et al., 2015). It is a promising technology to valorize lignin. Refined lignin oil is a highly depolymerized mixture and can be functionalized to a large variety of bulk and fine chemicals (Sun et al., 2020). It contains chemical substances that have structural similarities to phenol and phenol-derived chemicals and could, therefore, (directly or indirectly) substitute fossil-based phenol in the production of downstream phenolic chemicals - such as bisphenols (Koelewijn et al., 2018; S.F. 2017), polycarbonates (S.F. Koelewijn et al., 2017), phenolic resins (Liao et al., 2020) and epoxy resins (Van Aelst et al., 2021). Its applicability goes beyond the phenol value chains - for example, in polyurethanes as polyols substitutes (Huang et al., 2018; Vendamme et al., 2020). The co-product of RCF – the cellulose-rich pulp - can be fermented to bio-ethanol, which is used as a fuel additive for gasoline bio-enrichment today. Bio-ethanol can also substitute ethylene currently produced by energy-intensive steam cracking of fossil resources.

RCF research has primarily focused on virgin biomass as a feedstock. However, recovered wood (i.e. residues and post-consumer streams) also forms an attractive alternative feedstock for RCF (Tschulkow et al., 2020; Van Den Bossche et al., 2021). Following the cascading principle, virgin wood should be used first for higher material value applications (such as construction material); and could be used for chemicals after losing its structural properties. A chemical application could add an extra cascade step in the value chain before incineration, further lengthening the cascaded chain and the carbon capture time. Refined lignin oil could, in fact, be used to produce thermoplastics or thermosets that form part of the 'synthetic materials' value chain, wherein it might be further recycled multiple times before being incinerated.

However, waste wood is more heterogeneous than virgin wood. It is a mixture of different types of wood (softwood and hardwood) and could contain heavy and toxic metals (Van Den Bossche et al., 2021), which impacts the overall bio-refinery yields. The recovered wood needs treatment (such as sorting and cleaning) to effectively use it in the RCF without affecting the quantity and quality of the output chemicals compared to virgin wood. The yields and treatment process influences the environmental impact of the RCF process using the waste wood. This study has included this novel technology as a potential cascading pathway applied to waste woods to investigate whether it could be environmentally beneficial to use current waste wood streams instead of virgin wood for RCF.

1.2. *Effect of carbon storage*

Most studies evaluating cascading systems showcase the environmental benefits of cascading use. However, the main focus is on the cascade and substitution effect. The cascade effect is when recovered wood is used instead of virgin wood for an application. The benefits are because of the differences in the physical properties of the virgin and recovered wood and the logistics needed to supply them. Virgin wood is usually larger in size than recovered wood and has a higher moisture content, resulting in higher energy demand for drying and treating it. Also, growing, harvesting, and transporting virgin wood often require more resources than recovering, sorting and treating waste wood. The substitution benefit is when wood substitutes fossil- or mineral-based materials that are often more energy-intensive (Sathre and Gustavsson, 2009). However, cascading also contributes to climate benefits by keeping the carbon stored in harvested wood products (HWP) for longer and delaying the emissions resulting from the eventual incineration or decomposition of wood. The longer the wood remains in use in a cascade chain, the further in time are the emissions delayed allowing the carbon to be out of the atmosphere for at least the time it takes to sequester an equivalent amount of carbon in the forest.

The effect of carbon storage and delaying emissions is often not regarded while assessing the carbon balance of cascading systems. None of the LCA studies mentioned above considered this temporal dimension, except Mehr et al. (2018) and Faraca et al. (2019). Sathre and Gustavsson (2006), who categorized the factors affecting the carbon balance of wood cascades into cascade, substitution, land-use and time effects, also only analyzed the first three effects. The justification for disregarding the time effect is that the stock of HWP will stabilize over time. Then, the rate of virgin wood entering the wood products pool will equal the rate of wood leaving the pool. In this case, the rate of carbon dioxide (CO_2) released into the atmosphere equals the rate of CO_2 uptake by plant growth. At that point, the prolonged carbon storage in wood-based products does not affect the atmospheric CO_2 concentration any further. The carbon embedded in biomass, termed biogenic carbon, is thus assumed to be carbon neutral.

This carbon neutrality assumption is not valid for evaluating wood cascading, considering that the wood is cascaded precisely to increase the stock of HWP. Pingoud et al. (2003) and Mason Earles et al. (2012) show that the HWP stock is clearly growing in prominent wood-producing countries like Canada, Finland, Germany, Sweden and the United States. The rate of combustion or decomposition of wood will be lower than that of harvesting virgin wood. So, accounting for the temporal aspects of carbon storage and emissions becomes essential for an accurate valuation of the climate impact of wood cascading.

Additionally, the rate of carbon uptake in the forests from where the wood is sourced also influences the carbon balances. Biomass with a fast growth rate can lead to a higher carbon reduction potential because the carbon is sequestered more rapidly. Thus, CO_2 stays in the atmosphere for a shorter duration and lower cumulative radiative forcing is created in the considered time horizon (Cherubini et al., 2011; Guest et al., 2013).

1.3. *Research objective*

This study aims to evaluate the global warming potential (GWP) of alternative wood cascading scenarios to produce lignocellulosic products and investigate if using waste wood instead of virgin wood lowers the GWP of the bio-refineries. The study also examines the contribution of carbon storage (and delaying emissions) to decreasing the GWP. The biogenic carbon sequestration and emissions are considered using different carbon accounting methods: Firstly, using the traditional accounting method that assumes carbon neutrality and secondly, including time and rate of carbon sequestration and emissions. The objective is to evaluate whether there is a significant difference in the GWP when calculated with two accounting methodologies and consequently highlight the importance of considering the temporal information of biogenic carbon flows.

2. Methodology

2.1. Goal, scope, functional unit and scenarios description

The GWP of alternative cascading scenarios is assessed using the life cycle assessment (LCA) methodology, following the ISO 14,040/14,044 standards. The functional unit for the system chosen is the **sequential use of 1m^3 (450 kg) of virgin sawn wood harvested from the softwood forest to produce refined lignin oil and bio-ethanol.** The time horizon considered for the assessment is 100 years. A short time horizon is chosen because carbon storage in biomass is more crucial for short-term climate mitigation goals and becomes less significant at a longer time horizon of 500 years, as confirmed by Guest et al. (2013) and Faraca et al. (2019). The system boundary of the cascading scenarios is illustrated in Fig. 1 (Refer to annexe A for a detailed system boundary). In scenario 1, the sawn wood is used as a feedstock for RCF to produce refined lignin oil and carbohydrate pulp. The carbohydrate pulp is further hydrolyzed and fermented to bio-ethanol. The cascading scenarios are built upon scenario 1 to evaluate the environmental benefit of wood cascading and the use of waste wood instead of virgin wood for RCF. In scenario 2, fresh (or virgin) wood is used initially for higher material value application, and post-consumer wood is used for RCF. The high-value application chosen is construction material (the representative product under consideration is Glued Laminated timber [GLT] with a lifetime of 50 years). The generated post-consumer wood is then used as a feedstock for the RCF process. In scenario 3, another cascading step is added. Fresh wood is used for construction material (GLT as the representative product). The recovered wood from construction is used as a feedstock first for particleboard production (with a lifetime of 10 years), and then the post-consumer particleboards are used as feedstock for the RCF process. The system boundary is the cradle to the factory gate of the individual sub-systems. The transport between the sub-systems is not included.

The material functions provided by the various systems should be equivalent when comparing their environmental impact. Multiple sequential use of a resource is a characteristic of cascading - different systems with increasing cascading steps often provide varying functions. In the case under consideration, scenario 1 provides RCF products (i.e. refined lignin oil and carbohydrate pulp, which is fermented to produce bio-ethanol), scenario 2 provides GLT and RCF products, while scenario 3 provides GLT, particleboard and RCF products. Additionally, the amount of each product is also different in the different cascading

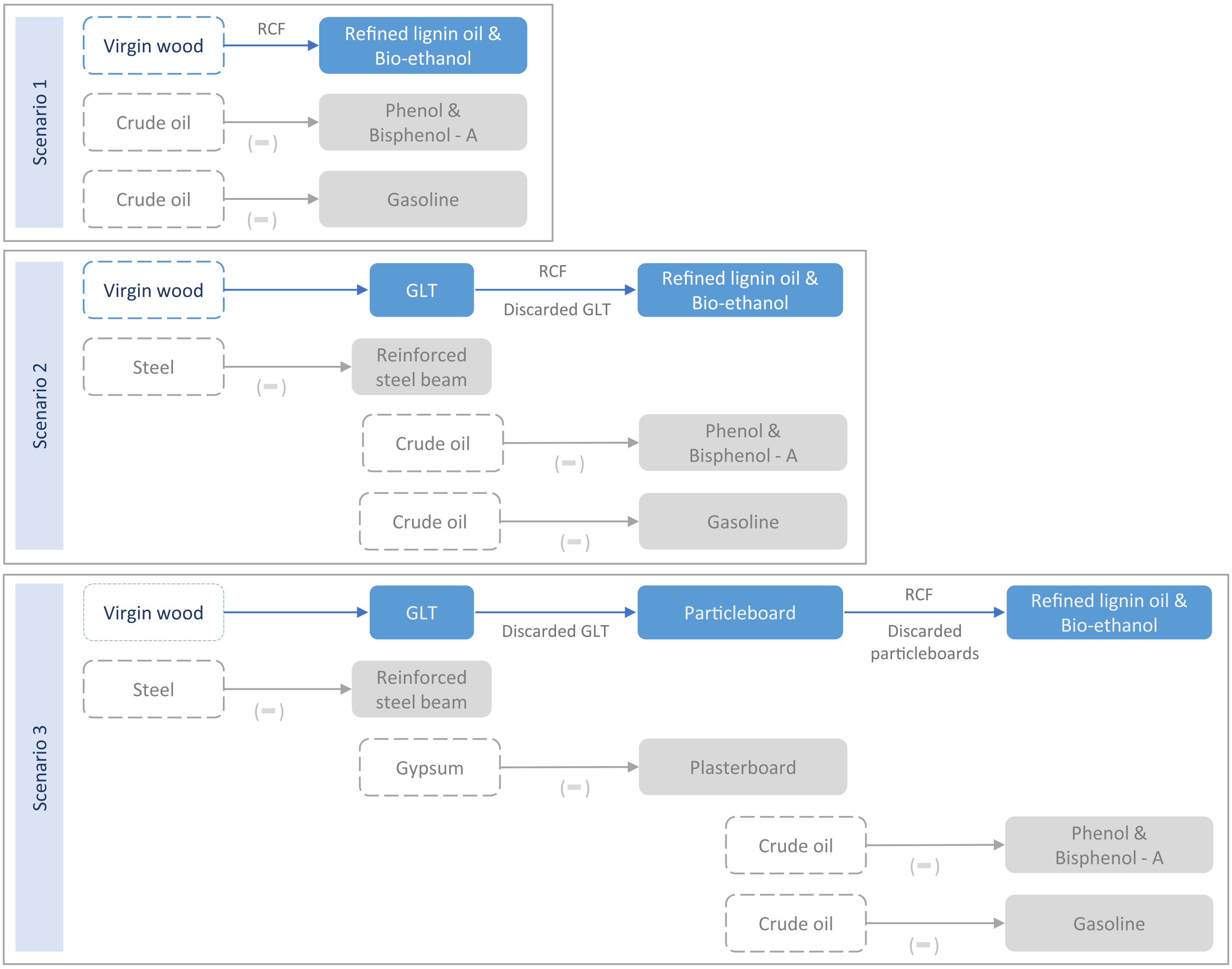

Fig. 1. System boundary of alternative cascading scenarios. Blue boxes represent the service life of wood in different products. Gray boxes represent the non-wood products being substituted. The dashed boxes show the primary resource used for different products.

scenarios. The material losses at each cascading step imply that the amount of valuable products produced reduces the further downstream the application is. For instance, in the case study under consideration, the amount of refined lignin oil and carbohydrate pulp produced in scenario 3 is lower than in scenario 2, which is lower than in scenario 1. The ISO standard recommends system expansion to solve system inequalities. Each cascading scenario is given credit for the products substituted as it avoids the environmental impact of the production of those products.

The products produced in the cascading system are assumed to substitute the functionally equivalent non-wood (fossil- or mineral-based) products with the same service life. The assumption here is that the wood availability is limited. So, in the absence of cascaded use of wood, the material functions are fulfilled by non-wood materials (gray boxes in Fig. 1). GLT substitutes reinforced steel beams, and particleboards replace plasterboard panels made of gypsum. The RCF produces refined lignin oil and carbohydrate pulp. Refined lignin oil consists of phenolic monomers and oligomers. The monomer components have structural similarities to phenol (i.e., the aromatic ring with hydroxyl-group attached) and hence are assumed to substitute phenol produced from fossil-derived benzene (and propylene) via the Hock process. The oligomer components are assumed to be substitute bisphenol A derived from benzene-originated phenol, as the chemical structure of the oligomers resembles that of bisphenol A and the oligomers could potentially serve in similar applications further downstream of the phenol value chain. The carbohydrate pulp fermented to bio-ethanol replaces gasoline from crude oil. The details of the products and the amount of that product substituted are available in Annexe D. The latter is determined by equating the amounts of the two products required to provide the same function. However, the amount substituted in reality is known only by analyzing market dynamics and performing consequential LCA. But it was not considered in this study as functional equivalency was sufficient to achieve the objective.

2.2. Life cycle inventory

The main processes within the life cycle of the three cascading scenarios are GLT and particleboard production (from fresh and waste wood), RCF process and conversion of pulp to bio-ethanol. The data for RCF were collected from laboratory experiments combined with process simulation. Whereas, for the remaining processes, data was from the scientific literature. Data for the secondary processes (such as waste wood chipping and treatment and residue incineration) and production of substituted products (such as steel beam and plasterboard) is from the inventory databases (Ecoinvent). The sources of LCI data are summarized in Table 1. LCI was modelled for the European context - background processes were specific to Europe as far as possible. But when the dataset for the European context was unavailable, data on the global scale had to be used. Table 7 in Annexe C specifies the geographical applicability of each of the processes used for modeling the LCI.

The laboratory experiments for the RCF process were performed with virgin softwood and recovered wood to produce refined lignin oil and carbohydrate pulp. Fresh wood was the feedstock for scenario 1. Grade I and II waste (or waste wood A) was considered the feedstock for scenario 2, and Grade III waste (or waste wood B) was feedstock for scenario 3. Annexe E provides the details on the categorization of waste wood and the reason for choosing them as feedstock for each scenario. The mass balance obtained from these experiments was upscaled to an industrial scale by the process simulation, from which a net mass and energy balance of the RCF process was obtained (Annexe C - Table 5). This simulation model was based on the earlier work of Liao et al. (2020) and Bartling et al. (2021).

2.3. Assessment method

The environmental impact is examined using the global warming potential (GWP) midpoint indicators from the ReCiPe 2016 (Hierarchist). GWP is first calculated for the bio-refinery (scenario 1) to evaluate the environmental performance exclusively of the production of the lignocellulosic products. Subsequently, the GWP is calculated for the cascading scenarios (scenarios 2 and 3) to assess the benefits of wood cascading and compare the environmental performance of bio-refinery using waste wood instead of fresh wood. In each case, the GWP is calculated from cradle to gate - with and without including the emission of the carbon embedded in products. The assessment without embedded carbon emission provides the impact of production processes itself and isolates it from the benefit of using biomass in products. The analysis including the embedded carbon emissions is performed to assess the benefits of wood cascading. The embedded biogenic carbon is traditionally accounted for in LCA by completely excluding biogenic carbon (known as the 0/0 approach) or giving a value of +1 to biogenic carbon emissions and −1 to carbon uptake (known as the −1/+1 approach). This study additionally assesses the impact of embedded carbon by considering the rate of biogenic carbon uptake during tree growth,

Table 1
The source of data for modeling LCI of different processes within the three scenarios.

Products/process	Source for the LCI of the product	Details
GLT production (from virgin wood)	Risse et al. (2019)	Annexe C (Table 2)
Particleboard production (from virgin and waste wood)	Kim and Song (2014)	Annexe C (Table 3 provides LCI for particleboard production from fresh wood and Table 4 is for particleboard production from waste wood). Particleboard from 100% waste wood is currently not produced in Europe but is part of the study to assess the cascading effects.
RCF Process for the production of refined lignin oil and carbohydrate pulp	Experimental work, combined with process simulation in Aspen HYSYS.	Annexe C - Table 5 provides the net mass and energy balance of the RCF process used for LCI modeling
Conversion of carbohydrate pulp to bio-ethanol by hydrolysis and fermentation processes	Modelled based on a Sebastião et al. (2016)	Sebastião et al. (2016) provide the process inventory of paper sludge to bio-ethanol, which was adjusted to suit the conversion of pulp to bio-ethanol. The modification was based on the comparative difference in sugar content in the carbohydrate pulp and the sludge of the paper and pulp industry. The detailed mass and energy balance for the process is specified in Annexe C - Table 6.
Secondary process (such as waste wood chipping, treatment and residues incineration)	Ecoinvent Database (version 3.7.1)	The datasets from the Ecoinvent database, selected for each background process, are documented in Annexe C (Table 7).
Background processes (such as sawn wood production and virgin and waste wood treatment)		
Production of substituted products (such as reinforced steel beam and plasterboard)		

carbon storage period and delay in biogenic carbon emissions resulting from cascaded use of wood and avoiding fossil-based emissions.

In summary, the different accounting methods considered in this study are cradle-to-gate emissions excluding biogenic carbon (method 1a), cradle-to-gate emissions including biogenic carbon with −1/+1 accounting (method 1b), cradle-to-gate and embedded carbon emissions excluding biogenic carbon (method 2a), cradle-to-gate and embedded carbon emissions including biogenic carbon with −1/+1 accounting (method 2b) and cradle-to-gate and embedded carbon emissions including biogenic carbon by considering the rate of carbon sequestration and time of emissions (method 2c).

2.3.1. *Embedded carbon accounting*

The fossil-based CO_2 emissions are a net addition to the atmosphere. In contrast, the biogenic carbon is sequestered from the atmosphere during plant or tree growth and is released back to the atmosphere later when biomass decomposes or is combusted. These two biogenic carbon flows – from and into the atmosphere – are assumed to be equal and considered to cancel each other out. Hence, the biogenic carbon flows are regarded as neutral and accounted for by completely excluding them (0/0 approach) or assigning −1 for carbon uptake and +1 for carbon emission (−1/+1 approach; Garcia and Freire, 2014; Hoxha et al., 2020). However, these accounting methods do not consider carbon sequestration and storage period. A theoretical example demonstrates the influence of these temporal factors on the net carbon balance (Fig. 2). The wood is harvested at year 0 and remains in HWP for a certain period. At the end of this storage period, CO_2 is emitted back to the atmosphere as the wood in these products decomposes or is incinerated (represented by the orange, yellow and green lines in Fig. 2 for three different storage periods). The forestland cleared for wood harvesting is assumed to be revegetated immediately after harvesting with the same biomass species. The biomass regrowth starts sequestering carbon, which creates a net debt in atmospheric CO_2 concentration (Represented by the blue line in Fig. 2). By the end of the rotation period, forest regrowth captures the same amount of CO_2 as that harvested from the forest. The dotted lines represent the net CO_2 in the atmosphere resulting from carbon emission and sequestration, and GWP is proportional to the area under this curve.

The biomass stored for a short life in HWP has a relatively higher GWP because the emissions at the end of the life spend more time in the atmosphere within the considered time horizon (Represented by the orange line in Fig. 2). The GWP of biogenic emissions from short-lived products could be climate positive. The biomass must remain stored in HWP for a certain time for the biogenic carbon emissions to be carbon-neutral. The longer the biomass is stored, the higher the climate benefit. So, the GWP (proportional to the area under the dotted curve) is negative for the long life cascade (i.e. green curve) in the theoretical example in Fig. 2.

Additionally, biomass from a shorter rotation period forest (or fast biomass growth rate, such as in Fig. 2b) will be carbon neutral earlier in time as carbon is sequestered more rapidly. Cherubini et al. (2011) used this reasoning and developed characterization factors (CFs) for biogenic CO_2 emissions considering the rotation period of biomass. These factors are the impact of biogenic CO_2 emissions relative to the same amount of fossil CO_2 emissions. Guest et al. (2013) extended it by considering the time delay in biogenic CO_2 emission due to carbon storage in the harvested wood products over a period before its eventual combustion.

This study used the CFs for GWP provided by Guest et al. (2013) to account for the carbon storage and rotation period. The wood is assumed to be harvested from the European softwood forests with an average rotation period of 60 years (Biermayer, 2020; Nabuurs et al., 2014). Table 2 lists the CFs for different storage periods corresponding to 60 year rotation period. The underlying assumption for these CFs is that the

Table 2
Biogenic carbon GWP characterization factor (CF) values corresponding to the 60 years rotation period (using a 100-year time horizon; Guest et al., 2013).

Embedded carbon storage period (in years)	Characterization factor (rotation period 60 years)
0	0.25
10	0.17
20	0.09
30	0.01
40	−0.07
50	−0.16
60	−0.26
70	−0.36
80	−0.47
90	−0.59
100	−0.75

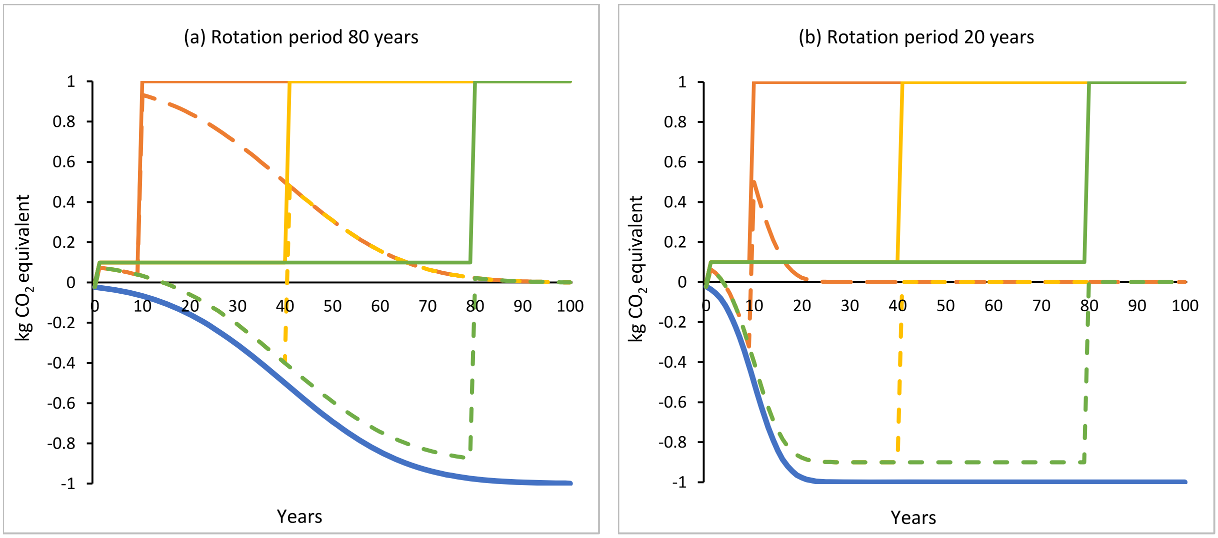

Fig. 2. Theoretical description of net biogenic CO_2 emissions when the wood is sourced from the forest with a rotation period of 80 years (a) and 20 years (b). Blue represents the CO_2 accumulated by the forest regrowth. Solid lines represent biogenic CO2 emissions in the short (orange), medium (yellow), and long (green) service-life cascades. Dotted lines represent the net CO_2 fraction remaining in the atmosphere for the short (orange), medium (yellow), and long (green) service-life cascade. Note that this is a theoretical presentation of the net reduction of biogenic carbon emissions due to biomass growth. Uptake by oceans and terrestrial biosphere is not included.

tree is cut only at the end of its rotation period (i.e. at the optimal harvesting age). The same species is planted in its place, which is also allowed to grow until its rotation length. So, the net carbon in forests remains constant over time. CFs are derived assuming only a single rotation period, and a possible loss of carbon in forests after repeated harvest is ignored.

The contribution of biogenic carbon to GWP for the three cascading scenarios is calculated by multiplying the biogenic carbon emissions occurring in a particular year by the CF corresponding to that year. A disclaimer required here is that the CFs for GWP developed by Guest et al. (2013) consider the storage of harvested wood for a particular period and subsequent emission of biogenic carbon as CO_2 pulse. However, the system boundary of this study does not include the end-of-life of the final products. The biorefinery products are chemicals (like refined lignin oil that are precursors for material applications) with potentially varied end-of-life treatment options and fuel (i.e., bio-ethanol) combusted for energy production. A simplified assumption made for the study is that all the biogenic carbon embedded in the biorefinery products is emitted as CO_2 in a single pulse at the end of the cascade service lifetime. It is a conservative assumption, and the GWP will only decrease with any possible delay in biodegradation of the carbon embedded (in case the products are landfilled or further recycled). The same assumption is made to the carbon-based substituted products, i.e. gasoline, phenol and bisphenol A products. These emissions are fossil-based and accounted for as a net addition of CO_2 to the atmosphere (i.e. CF = 1).

In scenario 1, virgin wood is used as a feedstock for RCF to produce refined lignin oil and carbohydrate pulp. Refined lignin oil can potentially substitute phenol-based products with wide final material applications with varying lifetimes. An average of these products' lifetime, i.e. 10 years (Geyer et al., 2017), is considered for this study. The co-product of RCF, carbohydrate pulp, can be fermented to bio-ethanol and used as a gasoline fuel additive. The fuel is combusted for energy, so the biogenic carbon contained in the bio-ethanol is assumed to be emitted at year 0 itself. The amount of biogenic carbon embedded in these products is multiplied by the CF corresponding to their lifetime (i.e. 0.25 for bio-ethanol and 0.17 for refined lignin oil). In scenario 2, wood is used as construction material for 50 years. Residues produced during GLT manufacturing are combusted for industrial heating. So the biogenic carbon in the residues is considered emitted at year 0, applying CF 0.25. The demolition waste is then used as feedstock for RCF to produce the carbohydrate pulp and refined lignin oil. Similar to scenario 1, refined lignin oil is used in phenol-based products for another 10 years. Biogenic carbon is stored for 60 years in this scenario, so the CF applied is −0.26. The service life of wood used in bio-ethanol from the carbohydrate pulp ends at year 50 (CF = −0.16). Scenario 3 has an additional service life of 10-year, because of the intermediate use of wood as particleboard. Wood is initially used as construction material (GLT) with a lifetime of 50 years. The demolition waste from the construction industry is used for particleboard manufacturing with a lifetime of 10 years. The residues produced during GLT and particleboard production are combusted for industrial heating. The combustion of residues of GLT production is considered to be at year 0 (CF = 0.25), and that of particleboard production is considered at year 50 (CF = −0.16).

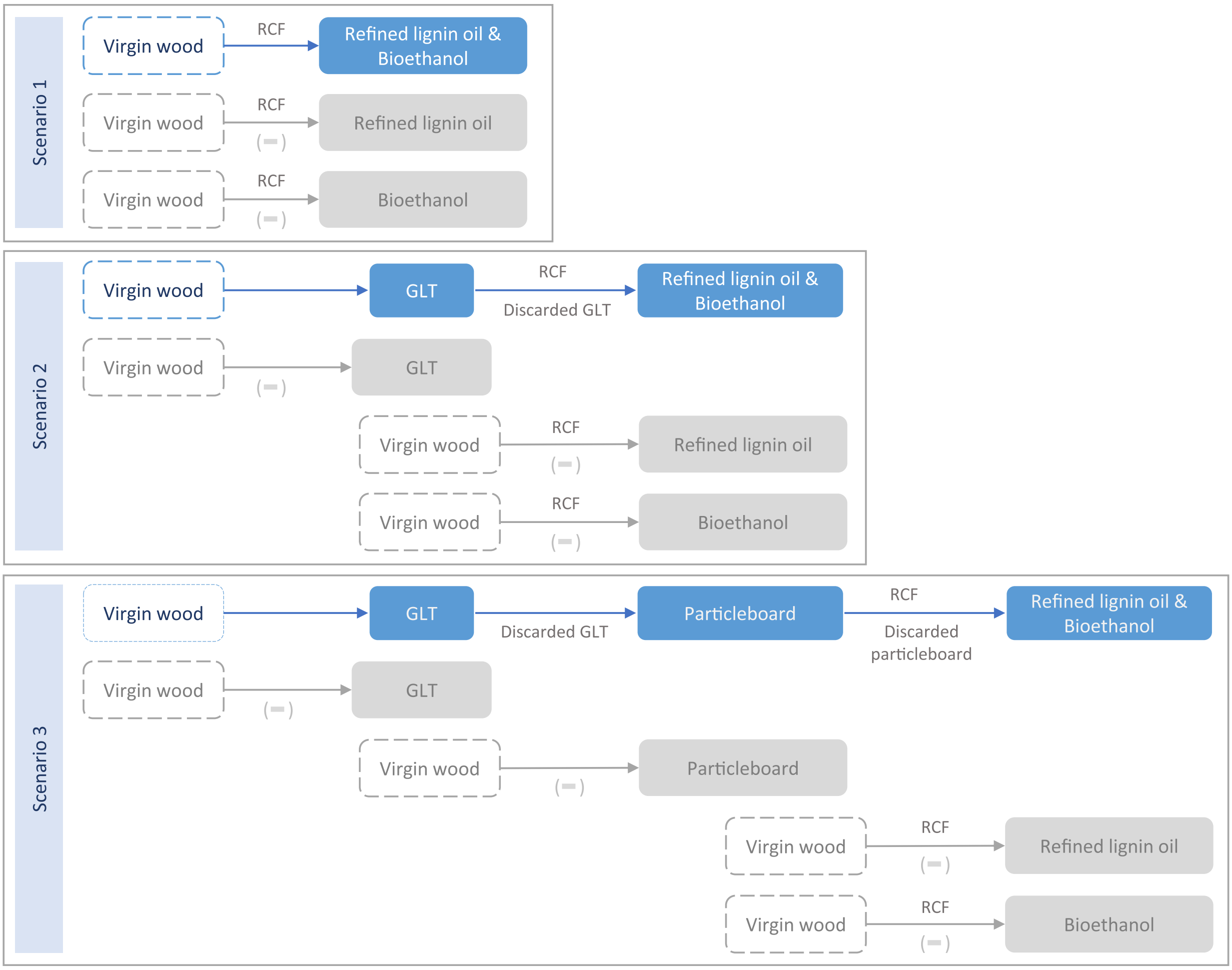

Fig. 3. System boundary of alternative cascading scenarios. Blue boxes represent the service life of wood in different products. Gray boxes represent the use of wood without cascading. The dashed boxes show the primary resource used for different products.

The post-consumer particleboard is a feedstock for RCF, extending the service life of a part of the biomass by 10 years as phenol-based products. The CFs applicable in this scenario for biogenic carbon in refined lignin oil and bio-ethanol are −0.36 and −0.26 respectively. The values are aggregated for each scenario to derive the net GWP.

2.3.2. Scenario analysis

The study also analyzed the case when wood supply from forests is not constrained. So, in the absence of wood cascading, the products are made from virgin wood (Fig. 3). The net GWP of each scenario is assessed based on the impact of producing wood products in cascading and the benefit of avoiding the production of equivalent material functions from virgin wood. This analysis contributes to understanding whether cascading of wood is beneficial even without taking substitution into account.

2.3.3. Sensitivity analysis

The data collected from scientific literature shows a high degree of variability. Annexe G shows the values for the input parameter from different sources. To choose a particular data set for building LCI, a conservative approach was followed (Annexe B lists the assumed values). The parameter value that results in the highest GWP is selected so that the results showcase the worse situation. The GWP will be lower than the LCA results of this study with any other data in the literature. Additionally, sensitivity analysis is performed to see the effect of change in input data on final LCA results.

Sensitivity analysis is performed on the two parameters for which literature provides the most diverse values - substitution rate and storage time. In addition to the variety in values for the lifetime of wood products (i.e. GLT, particleboard), refined lignin oil also has wide final material applications in diverse industries, further increasing the variability in lifetime values. The uncertainty and variability in substitution rate and product lifetime could affect the LCA results. Hence, sensitivity analysis is carried out on these parameters to test the robustness of the LCA results to the variation in their values. The value of each parameter is increased by 10% in a one-at-a-time approach - one parameter is varied while keeping all other parameters fixed at their baseline values. The sensitivity ratio is calculated for each parameter to determine the degree of change in results with a variation in the parameter value.

$$Sensitivity\ ratio = \frac{\frac{\Delta results}{Initial\ \ results}}{\frac{\Delta parameter}{Initial\ \ parameter}}$$

3. Results and discussion

3.1. Global warming potential of the bio-refinery (scenario 1)

Fig. 4 shows the net GWP for scenario 1 with different carbon accounting methods. GWP is positive when the system boundary is cradle-to-gate (method 1a) because the production of fossil-based fuel and chemicals (i.e. phenol, bisphenol-A and gasoline) have a lower GWP than the production of an equivalent amount of the bio-based products (i.e. refined lignin oil and bio-ethanol) in the bio-refineries. The difference is partly because biorefinery processes are immature and unoptimized compared to the high technology readiness level of the Hock and crude oil refining processes to produce phenol, bisphenol-A and gasoline. Biomass conversion technologies need to be monitored and developed further to lower their GWP, which remains a challenge today. So, substituting fossil-based fuel and chemicals with these biobased products could be regarded as environmentally detrimental with the current state-of-the-art technology.

However, when comparing bio-based chemicals and fuels with petrochemical ones with a ‘cradle to gate system boundary’, the bio-based alternatives must receive credit for embedded biogenic carbon - as demonstrated by Pawelzik et al. (2013) and prescribed by European Commission (2009). Since, at the end of life, petrochemicals emit CO_2 that increases the net atmospheric GHGs, while bio-based materials do not. They emit CO_2 already sequestered during plant regrowth (carbon neutrality assumption). Net GWP of scenario 1 becomes negative (method 1b) with this credit. The carbon embedded in the products for the functional unit is 816 kg CO_2 equivalent, resulting in the net GWP of −425 kg CO_2 equivalent (i.e., 299 – 816 = −517, the GWP is higher than −517 because of the biogenic carbon emitted during the production processes – refer Fig. 5). The bio-based materials – refined lignin oil and bio-ethanol – are thus better than an equivalent amount of phenol and gasoline in terms of GWP. This result is in line with earlier studies which observe that bio-based products have a lower GWP than their fossil-based counterparts (Bartling et al., 2021; Liao et al., 2020). However, this assessment method is limited to the production processes and omits the potential impact of the carbon embedded in the products.

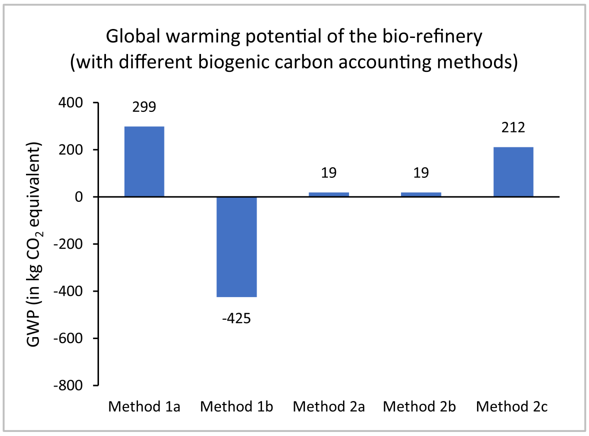

Fig. 4. The GWP of scenario 1 with different accounting methods (all values rounded to the nearest integer) Method 1a: Cradle to gate emissions (excluding biogenic carbon), Method 1b: Cradle to gate emissions (including biogenic carbon: −1/+1 accounting), Method 2a: Cradle to gate and embedded carbon emissions (excluding biogenic carbon: 0/0 accounting method), Method 2b: Cradle to gate and embedded carbon emissions (including biogenic carbon: −1/+1 accounting), Method 2c: Cradle to gate and embedded carbon emissions (including biogenic carbon: with CFs).

When considering the emissions of carbon embedded in the products, the net GWP of the system decreases from 299 to 19 kg CO_2 equivalent. The system receives credit for avoiding fossil-based carbon emissions (Fig. 4& 5 method 2a). The inclusion of biogenic carbon content does not affect the results when the system boundary includes the end-of-life emissions (Fig. 4& 5 method 2b). This accounting still ignores the rate of carbon sequestration and emission, which is accounted for in this study by multiplying the carbon embedded in bio-based products with the CF corresponding to the lifetime of those products, viz. 0.25 for bio-ethanol with a lifetime of 0 years and 0.17 for refined lignin oil with a lifetime of 10 years (method 2c). The net GWP increases to 212 kg CO_2 equivalent, suggesting that the carbon neutrality assumption (0/0 or −1/+1) approach underestimates the GWP of short-lived products.

3.2. Comparing GWP for the cascading scenarios

Fig. 6 shows the net GWP for the different scenarios with the three accounting methods (1) cradle-to-gate process emissions – method 1a, (2) embedded carbon emission with carbon neutrality assumption – method 2a and (3) embedded carbon emission with CFs – method 2c. Method 2b is discarded from subsequent analysis because method 2a (0/0 approach) and 2b (−1/+1 approach) give the same results when the end of life emissions are included. The GWP is highest for scenario 1 and decreases with the increasing number of cascading steps. Annex H provides the detailed calculations, and Fig. 7 illustrates the contribution of individual stages and processes to the net GWP for each scenario. Negative GWP for scenarios 2 and 3 in method 1a are primarily due to

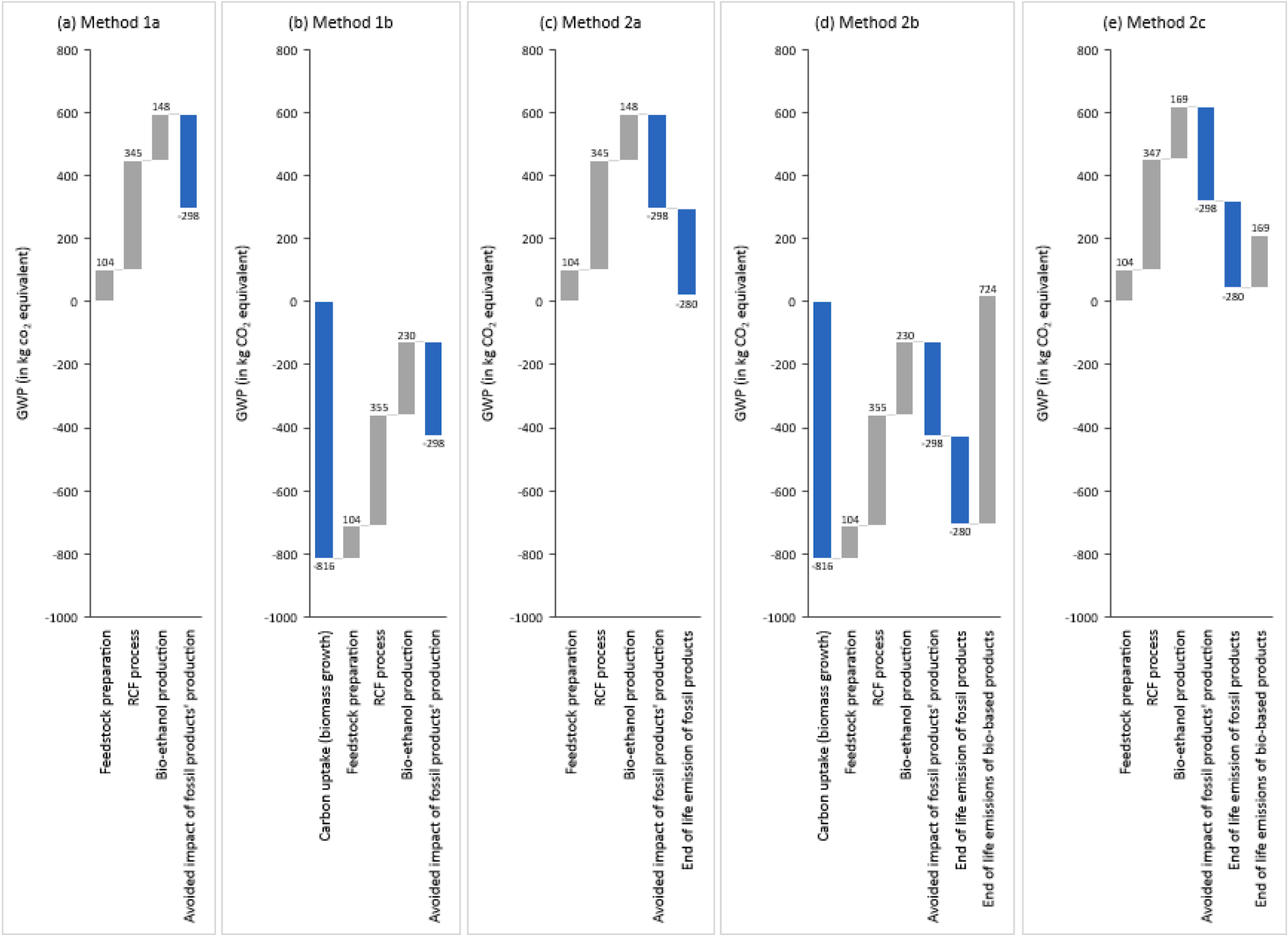

Fig. 5. Waterfall diagram illustrating the contribution of individual processes to the overall GWP in different accounting methods (a) Method 1a: Cradle to gate emissions excl. biogenic carbon (b) Method 1b: Cradle to gate emissions incl. biogenic carbon: −1/+1 accounting (c) Method2a: Cradle to gate and embedded carbon emissions - 0/0 accounting (d) Method 2b: Cradle to gate and embedded carbon emissions - −1/+1 accounting (e) Method 2c: Cradle to gate and embedded carbon emissions with biogenic carbon CFs.

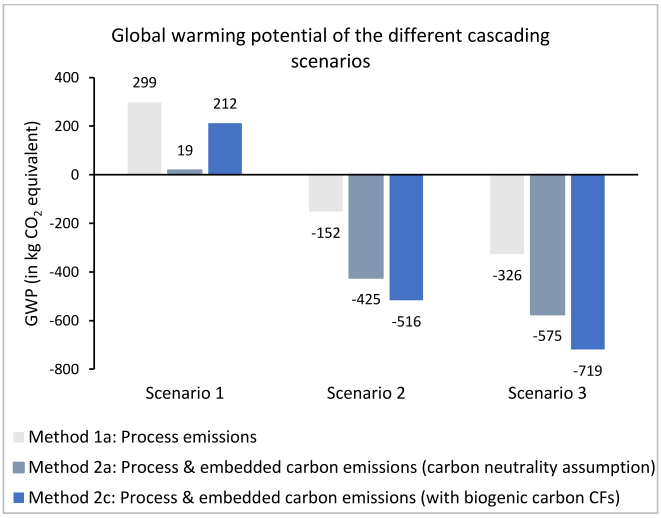

Fig. 6. The GWP of the three cascading scenarios when wood substitutes non-wood material (all values rounded to the nearest integer).

the savings from substituting the energy-intensive products (steel beams and gypsum fiberboard) with the wood-based products (GLT and particleboard). The residues (e.g. sawdust, wood chips) produced during GLT and particleboard production are burned for industrial heating, adding to climate benefit by avoiding the need for natural gas for industrial heating, which has a substantial GWP. Wood use in cascading increases the availability of wood for other functional applications, thereby increasing opportunities to substitute more energy-intensive materials and adding to the substitution benefit.

The net GWP for the three scenarios decreases in method 2a; because the systems avoid fossil carbon emissions embedded in substituted products (i.e. gasoline, phenol and bisphenol-A). In method 2c, the comparative results do not change, but the difference between the scenarios increases. The GWP of scenario 1 is higher when considering the CFs because of the short lifetime of the cascade. For scenario 2, with a cascade lifetime of 60 years, the GWP decreases. In this scenario, wood is used first for construction material. Residues produced during GLT manufacturing are burned for industrial heating. The residues are climate-positive as they reach the end of their life already at year 0. But the wood contained in the construction material remains in the product for 50 years and is further used as feedstock for the RCF process, resulting in negative GWP. Scenario 3, with an additional 10-year lifetime extension, provides further CO_2 savings. The climate benefit of biogenic carbon storage increases with an increased lifetime of the

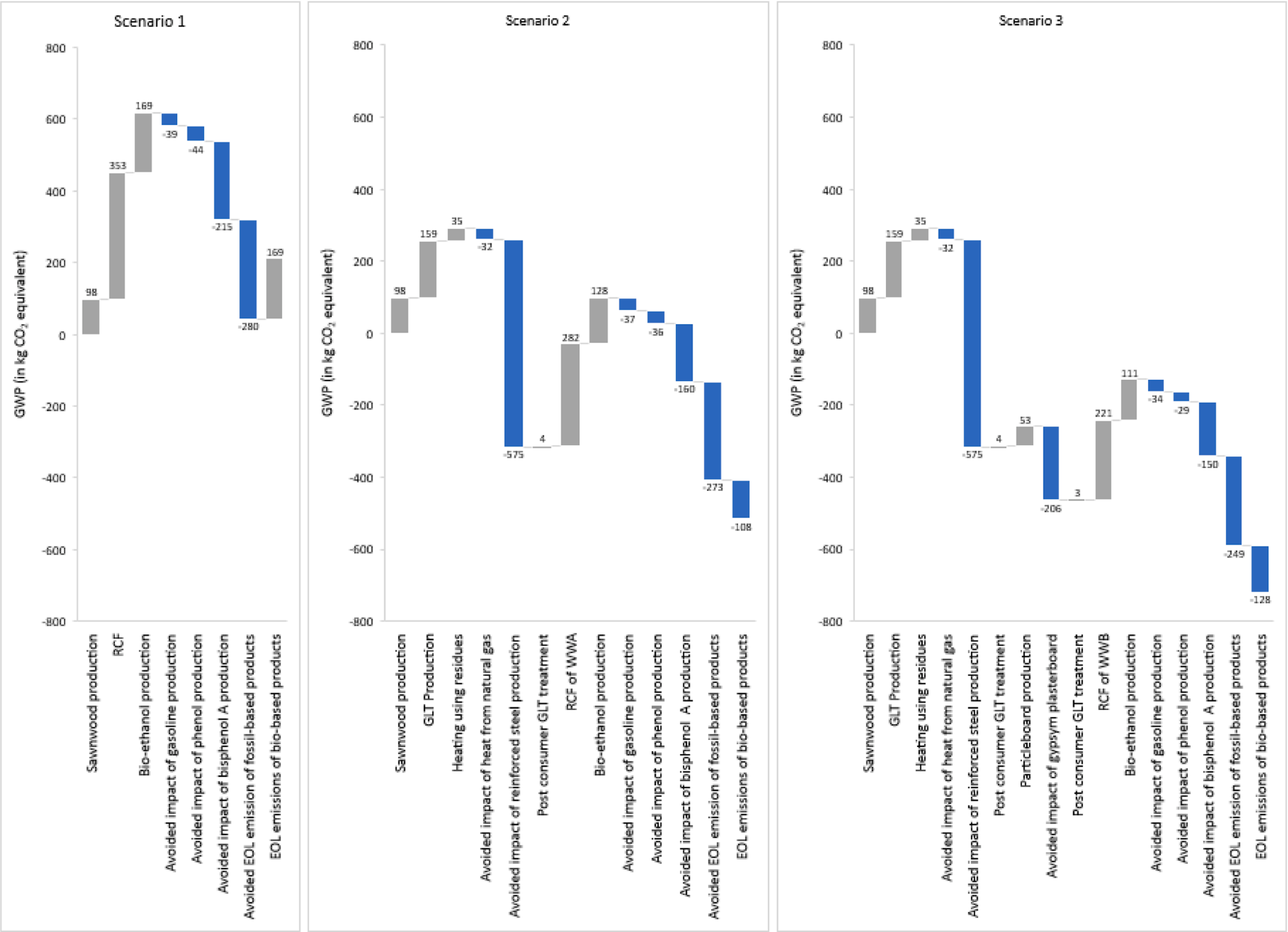

Fig. 7. Waterfall diagram illustrating the contribution of each cascading stage and process to the overall GWP considering cradle to gate and embedded carbon emissions with biogenic carbon CFs (Method 2c).

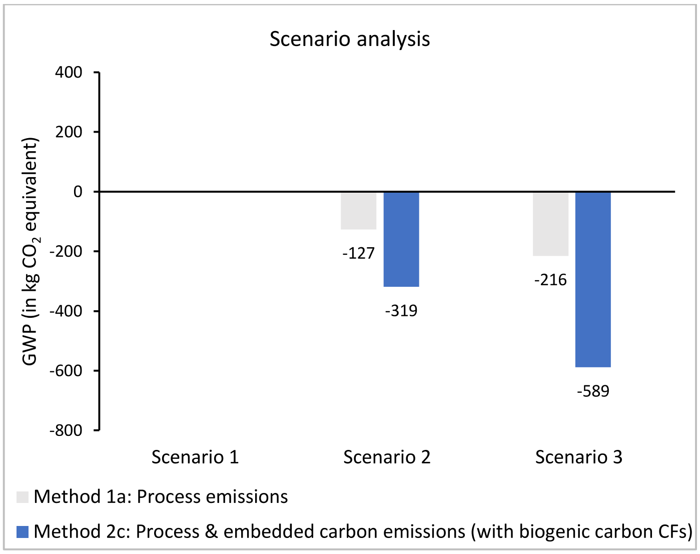

Fig. 8. The GWP of the three cascading scenarios when waste wood substitutes fresh wood to provide the same functions (all values rounded to the nearest integer).

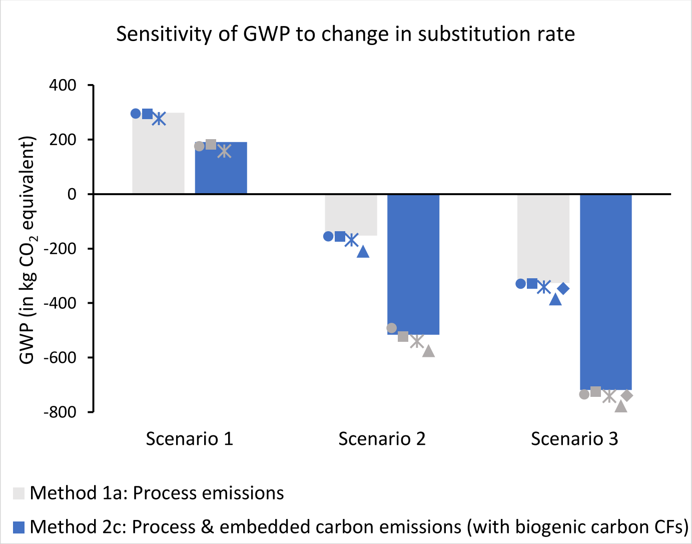

Fig. 9. The change in the GWP of the three cascading scenarios with the increase in substitution rate by 10% (circle – bio-ethanol, square – monomer, star – oligomer, triangle – GLT and rhombus - particleboard).

cascade.

The results highlight that the current accounting of biogenic carbon (assuming carbon neutrality) underestimates the GWP for short-life cascades and overestimates it for long-life cascades. More importantly, in this study, the bio-based chemicals and fuel have a net positive GWP when produced from fresh wood (scenario 1) and negative when produced from waste wood (scenarios 2 and 3) because of their respective service lifetimes. In other words, bio-based products from virgin wood of long rotation period forests can only outperform their fossil-based counterparts in terms of GWP if their lifetimes are sufficiently long. So, virgin wood use is justified only for long-life chemicals and not for fuels or short-life chemicals such as single-use plastics. Furthermore, bio-based chemicals and fuels produced from waste wood (which has already served a long life) are always better than those made from virgin wood and are likely to outperform their fossil-based counterparts. Therefore, considering the service life and rotation time is crucial for accurately evaluating the GWP of bio-based products.

3.3. Scenario analysis

Fig. 8 shows the climate benefit when the waste wood substitutes virgin wood to provide the same material functions. The GWP of scenario 1 is zero because the wood is not cascaded in any case in the baseline scenario. For the other two scenarios, similar to the results when substituting non-wood products, scenario 3 has a lower GWP than scenario 2. Particleboard production from waste wood instead of fresh wood is the primary contributor to decreasing the net GWP. Waste wood is smaller in size and has lower moisture content than virgin wood, which lowers the energy required for chipping and drying processes in particleboard production. The GWP of RCF is comparable in the three scenarios. However, the absolute GWP value of the RCF process in scenario 3 is lower than in scenario 2 because the amount of wood available reduces the further downstream the process is in the cascading chain due to material losses in the intermediate stages. So, lower CO_2 is emitted in RCF in scenario 3 than in scenario 2 (Refer to Annex I for the GWP of individual stages and processes).

The results highlight that the substitution effect is more significant than the cascading effect, confirming the findings of Sathre and

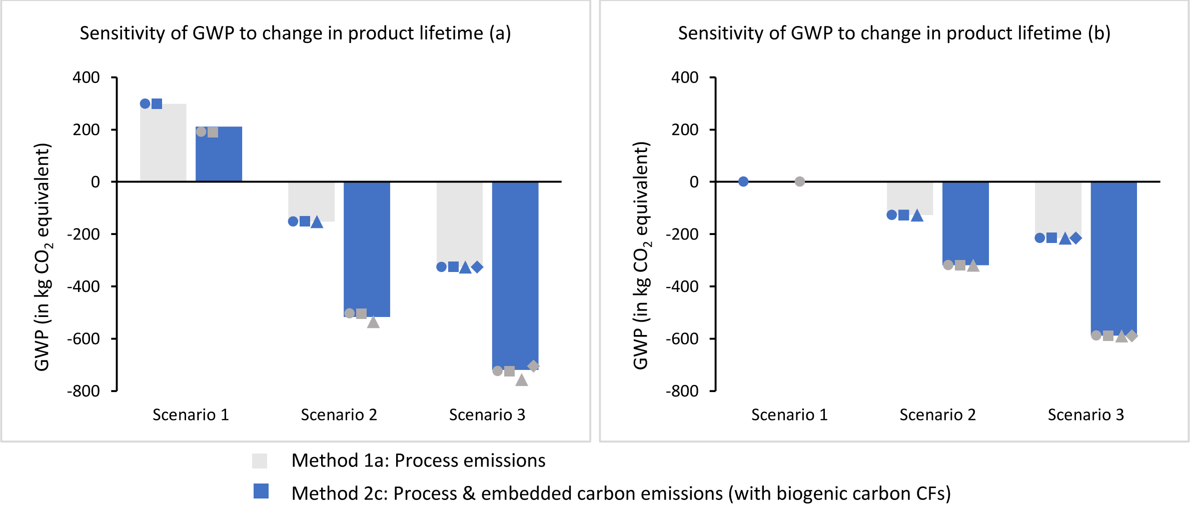

Fig. 10. Change in GWP of the three cascading scenarios with the increase in the lifetime of products by 10% (a) when wood substitutes non-wood products (b) when wood substitutes wood-products (circle – monomer, square – oligomer, triangle – GLT and rhombus - particleboard).

Gustavsson (2006). However, this analysis also demonstrates that cascading use could be beneficial by itself - even without substituting wood products for non-wood products, supporting the findings of Hoglmeier et al. (2014).

The contribution of carbon storage to net GWP is relatively much higher when waste wood substitutes virgin wood (Fig. 8 blue bar) - primarily because cascaded systems avoid multiple short-life cascade chains with a net positive climate impact. The effect is highest for scenario 3; because producing particleboard & RCF products from virgin wood is avoided, which has a net positive climate impact because of the short product lifetime. Cascading can thus accumulate climate benefits as the production of short-life products from virgin wood is avoided with each cascading step.

3.4. Sensitivity analysis

The GWP for each scenario is recalculated after increasing the substitution rates of the products by 10% (Fig. 9). GWP decreases with an increase in the substitution rate. The overall comparative results and ranking of scenarios are not affected. The LCA model appears robust to the change in substitution rates of bio-ethanol, refined lignin oil monomer, and particleboards, as the difference in GWP is not significant. It increases by less than 1% (Annexe L - Table 11 provides the sensitivity ratios). The results are sensitive only to the change in the substitution rate of GLT and refined lignin oil oligomer components, for which the sensitivity ratio is greater than 1%. Hence, the precise value of the substitution rate for these products should be known to accurately estimate the GWP for the different scenarios of the case study under consideration.

Similar to the sensitivity analysis results for the substitution rate, the GWP (including the biogenic carbon) decreases with an increase in the product lifetime (Fig. 10). The overall comparative results and ranking of scenarios are unaffected. The LCA results appear robust as the difference in GWP is not significant in most cases, except in scenario 1 when wood products substitute non-wood products (Annexe L - Table 12 &13 provides the sensitivity ratios).

4. Conclusion

The LCA results comparing different wood cascading scenarios confirm that cascaded use is advantageous - the GWP of the system decreases with an increasing number of cascading steps. When assessing the GWP excluding biogenic carbon, the climate benefits are primarily a result of substituting energy-intensive materials with wood. Wood cascading provides an opportunity to replace more non-wood products, every time adding to the substitution benefit. The analysis also affirms that cascading use is beneficial by itself even without considering the effect of substituting non-wood products – lowering the GWP when the material functions are provided by cascaded use of wood instead of from fresh (or virgin) wood. These results are more pronounced when including the temporal aspect of biogenic carbon, i.e. the time of biogenic carbon emissions and the rate of biogenic carbon uptake. This conclusion is valid in both cases – with and without considering the substitution effect. The study highlights that, although the ranking of scenarios remains the same, the climate impacts of cascading are underestimated without accounting for the temporal details of biogenic carbon flows. Hence, the GWP of bio-refinery products depends on the feedstock - fresh or waste wood. When comparing the bio-refinery products to their fossil-based counterparts, the total carbon storage time and the rotation period (of the forests from which the wood is sourced) could influence which of the two performs better in terms of GWP. It might always be better to use waste wood that has already served a long time instead of fresh wood to produce bio-based fuel or chemicals if the bio-refinery process efficiency is the same irrespective of the feedstock. Additionally, bio-refinery products for long lifetime applications rather than single-use or energetic purposes may further enlarge the environmental benefits.

Disclaimer

The views expressed in the article are the sole responsibility of the authors and in no way represent the view of the European Commission and its services."

CRediT authorship contribution statement

Kranti Navare: Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **Wouter Arts:** Conceptualization, Resources, Writing – review & editing. **Giorgia Faraca:** Conceptualization, Methodology. **Gil Van den Bossche:** Resources. **Bert Sels:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Karel Van Acker:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The authors – K.N. and K.V.A - acknowledge VITO for funding this research. G.V.d.B. and B.S. acknowledge funding from the Biowood (regular SBO VLAIO) and NIBCON (catalysti Moonshot) project. K.V.A too acknowledges funding through catalisti-SBO project NIBCON. Additionally, K.V.A, W.A. and B.S. acknowledge funding from internal funds of KU Leuven (IDN Project – FFASSD) for facilitating this research. The authors also wish to thank our colleagues Katrien Boonen and An Vercalsteren for reviewing the manuscript and providing valuable feedback.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2022.106588.

References

Arts, W., Ruijten, D., Van Aelst, K., Trullemans, L., Sels, B., 2021. The RCF biorefinery: building on a chemical platform from lignin. Advances in Inorganic Chemistry, 1st ed. Elsevier Inc. https://doi.org/10.1016/bs.adioch.2021.02.006.

Bais-Moleman, A.L., Sikkema, R., Vis, M., Reumerman, P., Theurl, M.C., Erb, K.H., 2017. Assessing wood use efficiency and greenhouse gas emissions of wood product cascading in the European Union. J. Clean. Prod. 172, 3942–3954. https://doi.org/10.1016/j.jclepro.2017.04.153.

Bartling, A.W., Stone, M.L., Hanes, R.J., Bhatt, A., Zhang, Y., Heath, G.A., Biddy, M.J., Davis, R., Kruger, J.S., Thornburg, N.E., Luterbacher, J.S., Samec, J.S.M., Sels, B.F., Román-Leshkov, Y., Beckham, G.T., 2021. Techno-economic analysis and life cycle assessment of a biorefinery utilizing reductive catalytic fractionation. Energy Environ. Sci. 1–20. https://doi.org/10.1039/D1EE01642C.

Biermayer, G., 2020. Das Risiko ist entscheidend: baumarten betriebswirtschaftlich kalkuliert. LWF aktuell 125.

Brunet-Navarro, P., Jochheim, H., Kroiher, F., Muys, B., 2018. Effect of cascade use on the carbon balance of the German and European wood sectors. J. Clean. Prod. 170, 137–146. https://doi.org/10.1016/j.jclepro.2017.09.135.

Campbell-Johnston, K., Vermeulen, W.J.V., Reike, D., Brullot, S., 2020. The circular economy and cascading: towards a framework. Resour. Conserv. Recycl. X. https://doi.org/10.1016/j.rcrx.2020.100038.

Cherubini, F., Peters, G.P., Berntsen, T., Strømman, A.H., Hertwich, E., 2011. CO2 emissions from biomass combustion for bioenergy: atmospheric decay and contribution to global warming. GCB Bioenergy 3, 413–426. https://doi.org/10.1111/j.1757-1707.2011.01102.x.

European Commission, 2018. European wood waste statistics report for recipient and model regions 1–48.

European Commission, 2009. Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC, European Commission.

Eurostat, 2016. Waste generation. Eurostat.

Faraca, G., Tonini, D., Astrup, T.F., 2019. Dynamic accounting of greenhouse gas emissions from cascading utilisation of wood waste. Sci. Total Environ. 651, 2689–2700. https://doi.org/10.1016/j.scitotenv.2018.10.136.

Fraanje, P.J., 1997. Cascading of pine wood. Resour. Conserv. Recycl. 19, 21–28. https://doi.org/10.1016/S0921-3449(96)01159-7.

Garcia, R., Freire, F., 2014. Carbon footprint of particleboard: a comparison between ISO/TS 14067, GHG protocol, PAS 2050 and climate declaration. J. Clean. Prod. 66, 199–209. https://doi.org/10.1016/j.jclepro.2013.11.073.

Geyer, R., Jambeck, J.R., Law, K.L., 2017. Production, use, and fate of all plastics ever made. Sci. Adv. 3, 25–29. https://doi.org/10.1126/sciadv.1700782.

Guest, G., Cherubini, F., Strømman, A.H., 2013. Global warming potential of carbon dioxide emissions from biomass stored in the Anthroposphere and used for bioenergy at end of life. J. Ind. Ecol. 17, 20–30. https://doi.org/10.1111/j.1530-9290.2012.00507.x.

Haberl, H., Geissler, S., 2000. Cascade utilization of biomass: strategies for a more efficient use of a scarce resource. Ecol. Eng. 16, 111–121. https://doi.org/10.1016/s0925-8574(00)00059-8.

Höglmeier, K., Weber-Blaschke, G., Richter, K., 2014. Utilization of recovered wood in cascades versus utilization of primary wood—A comparison with life cycle assessment using system expansion. Int. J. Life Cycle Assess. 1755–1766. https://doi.org/10.1007/s11367-014-0774-6.

Hoxha, E., Passer, A., Saade, M.R.M., Trigaux, D., Shuttleworth, A., Pittau, F., Allacker, K., Habert, G., 2020. Biogenic carbon in buildings: a critical overview of LCA methods. Build. Cities 1, 504–524. https://doi.org/10.5334/bc.46.

Huang, Y., Duan, Y., Qiu, S., Wang, M., Ju, C., Cao, H., Fang, Y., Tan, T., 2018. Lignin-first biorefinery: a reusable catalyst for lignin depolymerization and application of lignin oil to jet fuel aromatics and polyurethane feedstock. Sustain. Energy Fuels 2, 637–647. https://doi.org/10.1039/c7se00535k.

Kim, M.H., Song, H.B., 2014. Analysis of the global warming potential for wood waste recycling systems. J. Clean. Prod. 69, 199–207. https://doi.org/10.1016/j.jclepro.2014.01.039.

Koelewijn, S.F., Cooreman, C., Renders, T., Andecochea Saiz, C., Van Den Bosch, S., Schutyser, W., De Leger, W., Smet, M., Van Puyvelde, P., Witters, H., Van Der Bruggen, B., Sels, B.F., 2018. Promising bulk production of a potentially benign bisphenol A replacement from a hardwood lignin platform. Green Chem 20, 1050–1058. https://doi.org/10.1039/c7gc02989f.

Koelewijn, S.F., Van Den Bosch, S., Renders, T., Schutyser, W., Lagrain, B., Smet, M., Thomas, J., Dehaen, W., Van Puyvelde, P., Witters, H., Sels, B.F., 2017. Sustainable bisphenols from renewable softwood lignin feedstock for polycarbonates and cyanate ester resins. Green Chem 19, 2561–2570. https://doi.org/10.1039/c7gc00776k.

Liao, Y., Koelewijn, S.F., van den Bossche, G., van Aelst, J., van den Bosch, S., Renders, T., Navare, K., Nicolaï, T., van Aelst, K., Maesen, M., Matsushima, H., Thevelein, J.M., van Acker, K., Lagrain, B., Verboekend, D., Sels, B.F., 2020. A sustainable wood biorefinery for low-carbon footprint chemicals production. Science 367, 1385–1390. https://doi.org/10.1126/science.aau1567 (80-.).

Mantau, U., 2012. Wood flows in Europe (EV27), project report. Celle, 2012.

Mantau, U., Saal, U., Prins, K., Steierer, F., Lindner, M., Verkerk, H., Eggers, J., Leek, N., Oldenburger, J., Asikainen, A., Anttila, P., 2010. EUwood - real potential for changes in growth and use of EU forests. EUwood.

Mason Earles, J., Yeh, S., Skog, K.E., 2012. Timing of carbon emissions from global forest clearance. Nat. Clim. Chang. 2, 682–685. https://doi.org/10.1038/nclimate1535.

Material Economics, 2021. EU biomass use in a Net-Zero economy - a course correction for EU biomass.

Mehr, J., Vadenbo, C., Steubing, B., Hellweg, S., 2018. Environmentally optimal wood use in Switzerland—investigating the relevance of material cascades. Resour. Conserv. Recycl. 131, 181–191. https://doi.org/10.1016/j.resconrec.2017.12.026.

Nabuurs, G.J., Schelhaas, M.J., Orazio, C., Hengeveld, G., Tome, M., Farrell, E.P., 2014. European perspective on the development of planted forests, including projections to 2065. New Zeal. J. For. Sci. 44, 1–7. https://doi.org/10.1186/1179-5395-44-S1-S8.

Olsson, O., Roos, A., Guisson, R., Bruce, L., Lamers, P., Hektor, B., Thrän, D., Hartley, D., Ponitka, J., Hildebrandt, J., 2018. Time to tear down the pyramids? A critique of cascading hierarchies as a policy tool. Wiley Interdiscip. Rev. Energy Environ. 7, e279. https://doi.org/10.1002/wene.279.

Pawelzik, P., Carus, M., Hotchkiss, J., Narayan, R., Selke, S., Wellisch, M., Weiss, M., Wicke, B., Patel, M.K., 2013. Critical aspects in the life cycle assessment (LCA) of bio-based materials - Reviewing methodologies and deriving recommendations. Resour. Conserv. Recycl. https://doi.org/10.1016/j.resconrec.2013.02.006.

Pingoud, K., Perälä, A., Soimakallio, S., Pussinen, A., 2003. Greenhouse gas impacts of harvested wood products: evaluation and development of methods. VTT Res. Note. 2189.

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. https://doi.org/10.1016/j.scitotenv.2019.01.117.

Risse, M., Weber-Blaschke, G., Richter, K., 2017. Resource efficiency of multifunctional wood cascade chains using LCA and exergy analysis, exemplified by a case study for Germany. Resour. Conserv. Recycl. 126, 141–152. https://doi.org/10.1016/j.resconrec.2017.07.045.

Rivela, B., Moreira, M.T., Muñoz, I., Rieradevall, J., Feijoo, G., 2006. Life cycle assessment of wood wastes: a case study of ephemeral architecture. Sci. Total Environ. 357, 1–11. https://doi.org/10.1016/j.scitotenv.2005.04.017.

Sathre, R., Gustavsson, L., 2009. Using wood products to mitigate climate change: external costs and structural change. Appl. Energy 86, 251–257. https://doi.org/10.1016/j.apenergy.2008.04.007.

Sathre, R., Gustavsson, L., 2006. Energy and carbon balances of wood cascade chains. Resour. Conserv. Recycl. 47, 332–355. https://doi.org/10.1016/j.resconrec.2005.12.008.

Sebastião, D., Gonçalves, M.S., Marques, S., Fonseca, C., Gírio, F., Oliveira, A.C., Matos, C.T., 2016. Life cycle assessment of advanced bioethanol production from pulp and paper sludge. Bioresour. Technol. 208, 100–109. https://doi.org/10.1016/j.biortech.2016.02.049.

Sheldon, R.A., 2020. Biocatalysis and biomass conversion: enabling a circular economy. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences. NLM (Medline), 20190274. https://doi.org/10.1098/rsta.2019.0274.

Sikkema, R., Junginger, M., McFarlane, P., Faaij, A., 2013. The GHG contribution of the cascaded use of harvested wood products in comparison with the use of wood for energy-A case study on available forest resources in Canada. Environ. Sci. Policy 31, 96–108. https://doi.org/10.1016/j.envsci.2013.03.007.

Sirkin, T., Houten, M.ten, 1994. The cascade chain: a theory and tool for achieving resource sustainability with applications for product design. Resour. Conserv. Recycl. 10, 213–276. https://doi.org/10.1016/0921-3449(94)90016-7.

Sun, Z., Cheng, J., Wang, D., Yuan, T.Q., Song, G., Barta, K., 2020. Downstream processing strategies for lignin-first biorefinery. ChemSusChem. https://doi.org/10.1002/cssc.202001085.

Taskhiri, M.S., Jeswani, H., Geldermann, J., Azapagic, A., 2019. Optimising cascaded utilisation of wood resources considering economic and environmental aspects. Comput. Chem. Eng. 124, 302–316. https://doi.org/10.1016/j.compchemeng.2019.01.004.

Tschulkow, M., Compernolle, T., Van den Bosch, S., Van Aelst, J., Storms, I., Van Dael, M., Van den Bossche, G., Sels, B., Van Passel, S., 2020. Integrated techno-economic assessment of a biorefinery process: the high-end valorization of the lignocellulosic fraction in wood streams. J. Clean. Prod. 266 https://doi.org/10.1016/j.jclepro.2020.122022.

Van Aelst, K., Van Sinay, E., Vangeel, T., Zhang, Y., Renders, T., Van den Bosch, S., Van Aelst, J., Sels, B.F., 2021. Low molecular weight and highly functional RCF lignin products as a full bisphenol a replacer in bio-based epoxy resins. Chem. Commun. 57, 5642–5645. https://doi.org/10.1039/d1cc02263f.

Van Den Bosch, S., Schutyser, W., Vanholme, R., Driessen, T., Koelewijn, S.F., Renders, T., De Meester, B., Huijgen, W.J.J., Dehaen, W., Courtin, C.M., Lagrain, B., Boerjan, W., Sels, B.F., 2015. Reductive lignocellulose fractionation into soluble lignin-derived phenolic monomers and dimers and processable carbohydrate pulps. Energy Environ. Sci. 8, 1748–1763. https://doi.org/10.1039/c5ee00204d.

Van Den Bossche, G., Vangeel, T., Van Aelst, K., Arts, W., Trullemans, L., Navare, K., Van Den Bosch, S., Van Acker, K., Sels, B.F., 2021. Reductive catalytic fractionation: from waste wood to functional phenolic oligomers for attractive, value-added applications. In: ACS Symposium Series, pp. 37–60. https://doi.org/10.1021/bk-2021-1377.ch003.

Vendamme, R., Behaghel De Bueren, J., Gracia-Vitoria, J., Isnard, F., Mulunda, M.M., Ortiz, P., Wadekar, M., Vanbroekhoven, K., Wegmann, C., Buser, R., Héroguel, F., Luterbacher, J.S., Eevers, W., 2020. Aldehyde-assisted lignocellulose fractionation provides unique lignin oligomers for the design of tunable polyurethane Bioresins. Biomacromolecules 21, 4135–4148. https://doi.org/10.1021/acs.biomac.0c00927.

Vis, M., Mantau, U., Allen, B., Eds., 2016. Study on the optimised cascading use of wood [WWW Document]. Study optimised cascading use wood. 10.2873/827106.