Forest Policy and Economics 110 (2020) 101872

Contents lists available at ScienceDirect

Forest Policy and Economics

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

Transforming the bio-based sector towards a circular economy - What can we learn from wood cascading?☆

Matteo Jarre[a], Anna Petit-Boix[a], Carmen Priefer[b], Rolf Meyer[b], Sina Leipold[a,*]

[a] Chair of Societal Transition and Circular Economy, University of Freiburg, Tennenbacher Str. 4, 79106 Freiburg i. Br, Germany
[b] Institute of Technology Assessment and Systems Analysis (ITAS), Karlsruhe Institute of Technology (KIT), Karlstr. 11, 76133 Karlsruhe, (Germany)

ARTICLE INFO

Keywords:
Sustainability policy
Bioeconomy
Circularity
Forest sector
Wood products

ABSTRACT

The circular economy has become the focus of a recent major EU policy program, which aims at the transformation towards environmentally sustainable modes of production and consumption. This has moved parts of the forest and related bio-based industries to envision their operations in terms of a circular economy. However, the meaning and implementation pathways of the concept often remain vague and ambiguous. At the same time, bio-based industries have a long history of discussing and partly realizing wood cascading. This concept strongly overlaps with circular economy ideas as it describes activities to increase the efficiency of biomass utilization. This article takes stock of wood cascading research and identifies major influencing factors for its realization to provide a comprehensive knowledge base for discussions about the circular economy in forest and related bio-based industries. Based on a review of peer-reviewed literature, we find substantial knowledge available on the factors influencing the realization of wood cascading. These factors largely resemble what is currently being discussed as barriers and enablers of circular economy. Some crucial influencing factors, like policy limitations, are frequently highlighted but remain barely investigated. In addition, the various influencing factors are interdependent, making a conclusive assessment of the environmental impacts of a change to certain cascading activities extremely challenging. The challenges of quantitative assessments combined with the substantial knowledge gaps on political and socio-economic factors result in certain assumptions and political recommendations that hardly appear to be based on empirical evidence. We therefore suggest scrutinizing these assumptions and filling knowledge gaps, especially related to product design, potentials and limitations of long-lived products, and avoidance of waste generation.

1. Introduction

The circular economy (CE) research landscape is rapidly growing in response to an increasing political promotion that seeks to overcome global sustainability challenges. In this context, the scientific community aims to reach a consensus on the meaning of this concept and on which approaches will enable its successful implementation. Several review articles have already collected a wide variety of CE definitions, principles and interpretations in order to provide a systematic overview for further research and practical applications (e.g., Blomsma and Brennan, 2017; Geissdoerfer et al., 2017; Ghisellini et al., 2016; Kirchherr et al., 2017; Murray et al., 2017). Closing resource loops is the main idea behind CE (Murray et al., 2017), which is also often described as regenerative and restorative due to the circulation of materials and nutrients in the biosphere (Ellen MacArthur Foundation, 2015). When dealing with its core principles, scholars mainly refer to the R framework (i.e., reduce, reuse, recycle or remanufacture), the waste hierarchy, a systems perspective based on implementation scales (i.e., micro, *meso* and macro), and sustainable design strategies (Ghisellini et al., 2016; Kirchherr et al., 2017; Prieto-Sandoval et al., 2017). The relationship between CE and environmental, social and economic sustainability, however, remains unclear as the literature views CE in disparate ways, as a precondition, a benefit or a tradeoff to sustainability (Geissdoerfer et al., 2017). This variety of definitions results in a lack of agreement about the relationship to sustainability; a major challenge for current research is to determine the main factors influencing the success or failure of transitioning into a more sustainable CE. While the analysis of these factors is slowly emerging, results

☆ This article is part of a special issue entitled Forest-based circular bioeconomy: matching sustainability challenges and new business opportunities published at the journal Forest Policy and Economics 110C, 2020.

* Corresponding author.
E-mail address: sina.leipold@transition.uni-freiburg.de (S. Leipold).

https://doi.org/10.1016/j.forpol.2019.01.017
Received 15 August 2018; Received in revised form 6 December 2018; Accepted 29 January 2019
Available online 31 January 2019

are not always in agreement. Kirchherr et al. (2018) determine, through surveys and expert interviews, that cultural aspects are the main barriers to CE implementation in the EU, whereas technological limitations are not core challenges. In contrast, de Jesus and Mendonça (2018), in a review of policy documents and academic literature, identify technological and financial factors as the main pressing barriers.

To contribute filling this research gap, this article takes stock of wood cascading studies and identifies major influencing factors for its realization to draw lessons for potential transformation pathways towards a sustainable CE in the bio-based sector. The EU Action Plan for the Circular Economy (European Commission, 2015) lists biomass and bio-based products as a priority area, as the bio-based sector is one of the most resource intensive in Europe (Lutter et al., 2016). Additionally, the so-called "bioeconomy" is promoted in European policies to achieve a transition from an economy mainly based on fossil fuels to a more resource-efficient economy using bio-based resources (e.g., German Federal Ministry for Education and Research, 2010; European Commission, 2012; FORMAS, 2012). This approach, however, is contested in scientific and societal debates, as it has a strong focus on technology but does not sufficiently reflect alternative implementation pathways or sustainability requirements (Priefer et al., 2017). With 15 billion tons of biomass used worldwide in 2011, the prospects of a sustainable bio-based sector will highly depend on the availability of sustainable biomass resources (Scarlat et al., 2015). The cascading use of bio-based products is promoted in bioeconomy strategies as an answer to potential biomass limitations (Meyer, 2017). In this sense, the EU Action Plan promotes the cascading use of biomass in the CE for a more efficient resource use (European Commission, 2015).

Wood cascading is a concept with a long history of debate and analysis in EU bio-based industries (Olsson et al., 2016). It strongly overlaps with CE ideas as it describes activities to increase the efficiency of biomass utilization, which provides a comprehensive knowledge base for discussions about CE in forest and related bio-based industries. The cascading analogy to "a river flowing over a sequence of plateaus" was first introduced by Sirkin and ten Houten (1994) as a general tool for achieving sustainability in resource use. The concept of cascading aims to increase the efficiency of biomass utilization by reusing, recycling and ultimately generating energy, but there is no common definition and understanding of it. Based on Odegard et al. (2012), three approaches can be distinguished. The first approach, *cascading in time*, is conceptualized as a sequential use of biomass (Fig. 1). This implies reusing or recycling a bio-based product, with energy production at the end of the life cycle; paper recycling and particleboards are conventional examples, but more innovative solutions including bioplastics are also possible. In the second approach, *cascading in value*, the time steps of the cascade can be optimized by prioritizing the highest possible value over the whole life cycle. The third approach, *cascading in function*, optimizes co-production. In these two cases, more efficient biomass use is intended by a successive processing of the total biomass into different products for varying areas of use. This understanding is primarily applied in the context of biorefineries, which involve both conventional waste-to-energy strategies and new pathways for energy use out of waste wood, such as chemicals or bioplastics. Overall, conceptual considerations and practical applications of cascading are very popular in the wood sector.

Despite the political promotion of cascading use, research has yet to study this strategy in the CE context. Both concepts share some similarities but most research has been conducted independently (Mair and Stern, 2017). In fact, cascading is thought to help understand the meaning of circularity (Bezama, 2016). As the barriers and enablers to a sustainable CE have yet to be addressed in detail, taking stock of existing knowledge in the field of wood cascading could shed light on the challenges of CE implementation in the bio-based sector. This leads to two questions: (i) What are the main factors influencing the realization of wood cascading? (ii) What can we learn from wood cascading to achieve a sustainable CE in the bio-based sector, and specifically, which potential gaps in wood cascading studies are relevant for CE research?

To answer these questions, we conducted a review of the scientific literature dealing with wood cascading. The paper has the following structure: Section 2 describes the collection of research articles and the structure of the data analysis. The factors influencing the implementation of cascading are described in Section 3, along with their prominence and coverage in the literature. Section 4 wraps up the analysis by highlighting our main findings, research gaps and recommendations for further research in the context of a CE in the bio-based sector.

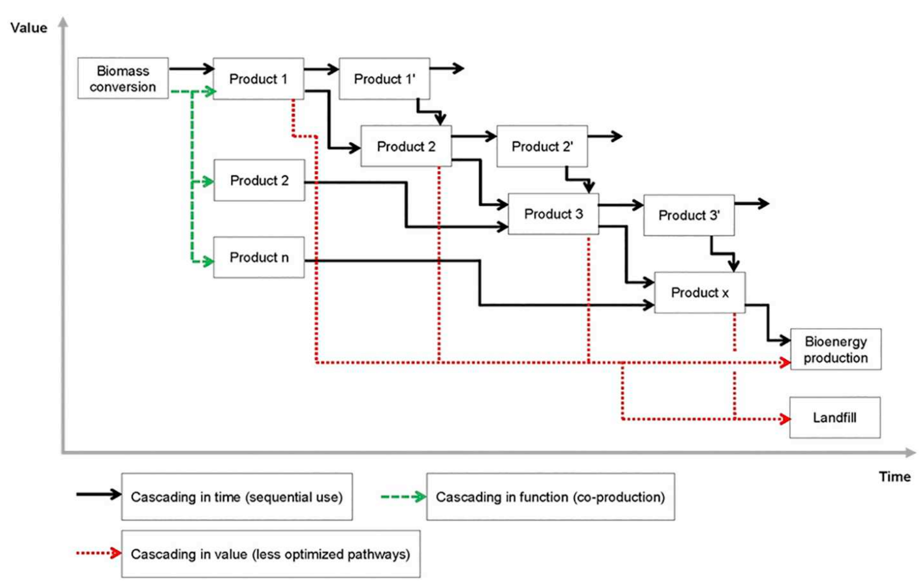

Fig. 1. Defining cascading through time, value and function based on Odegard et al. (2012). [Value does not express monetary value but the fitness of the product for repurposing, reusing, remanufacturing or recycling.]

Table 1
Categorization of the factors influencing the implementation of wood cascading.

Category	Subcategory	Influencing factor
Policy	Waste wood regulation	National regulations on waste pollutants in wood
		Incentives for recycling/material use
		Legislation on wood recycling
		Compulsory recycling rates
	Energy and resource policy	Resource taxation
		Incentives for renewable energy
		Separate legislation for renewable energy and waste
		Wood cascading as a long-term renewable energy strategy
Market	Economic competitiveness	Exports of cascaded products
		Economic costs
		Energy vs. material competition for wood use
	Market risks	Reputation risk
		Availability of recovered wood
		Dependence on upstream products
		Rebound effects in consumption
Technical implementation	Design	New technologies
		Project planning quality
		Building codes
		Incentives for companies that use small pieces of wood
		Incentives to design cascade chains
	Physical requirements	Quality
		Pollutant and chemical content
		Particle size
		Recycling of wood composites
		Recovery from buildings
		Logistics
		Wood tracking
		Technically feasible production
		Moisture
	Infrastructure	Existing incineration plants
		Quality of waste wood collection and sorting process
		Material losses in sorting process
		Current and future technologies for energy production
Environmental effects	Quantitative assessment	Allocation criteria
		Data availability and reliability
		Knowledge on environmental consequences
		Time gap/Future technologies
		System boundaries
		Assessment costs
	Forest management and carbon storage	Forest exploitation
		Biomass yield
		Biodiversity
		Landfill storage
		Product type and durability
		Hypothesis on carbon neutrality
		Prolonged storage in products
Stakeholder involvement	Communication	Shared information among organizations
		Networking within the supply chain
		Changing role of actors
		General knowledge
		Certification system and information on end-of-life management
	Producers and consumers	Willingness to use
		Information about material composition
		Attention to the end of life of products
		Long-term responsibility

2. Material and methods

2.1. Data collection

This article builds on existing wood cascading research in order to identify the main factors influencing its practical implementation. Our research started in December 2017 with a collection of peer-reviewed journal articles and book chapters published in English since 2007 to gain insights into the most recent scientific discourses in the wood sector. We used the search terms “wood AND cascad*,” “wood cascad*,” “wood recycl*,” “wood upcycl*,” “wood AND recycl* AND cascad*,” and “wood AND circular economy.” Through ScienceDirect, Web of Science, and Scopus, we retrieved 694 papers that contain the search terms in the title, keywords and/or abstract. Furthermore, we applied a snowball process to cover additional articles deemed important in the cascading literature; thereby older studies, including conference proceedings, were added to the sample. Papers dealing with unrelated topics (e.g., chemical processes using wood) or those mentioning wood cascading very briefly were excluded. This ensured that the topic coverage of the studies aligned with our research questions. The analysis included 41 peer-reviewed publications. All publications are listed in Table S1 in the Supporting Information, which consist of empirical assessments, conceptual papers on wood cascading and literature reviews.

2.2. Data analysis

The analyzed publications include theoretical discussions on wood cascading, as well as empirical results providing preliminary guidance on the performance of cascading. We screened each publication for contents that directly or indirectly point to the factors affecting the implementation of cascading use. In addition, several authors reported on the limitations of their studies, potential applications and recommendations, which were then included in our list for a more comprehensive assessment of current views and debates. This process resulted in a list of 186 statements (i.e., quotations) and, when too broad, key messages of the paper (i.e., summary of paper statements on a specific issue) (see Table S2 in the Supporting Information). Based on the data collected from the literature, we organized the information using a concept map (see Fig. S1 in the Supporting Information). While concept maps follow a top-down approach (Eppler, 2006), data were analyzed from a bottom-up perspective to classify the information inductively and subsequently identify associations. To do so, we went through the statements and retrieved the underlying influencing factor (s) of each statement. An influencing factor refers to a particular issue raised in one or more statements. Take, for instance, the statements "the presence of adhesive may be a barrier further on in the cascade," (Fraanje, 1998) and "because it has not been possible hitherto to determine the (chemical) contamination of waste wood [...] the priority with waste wood lies in its use for energy recovery" (Werner et al., 2010): these and similar statements were categorized under the influencing factor *pollutant and chemical content*. We generated a list of 55 influencing factors, which are grouped into categories to ease the analysis of results (see Section 3.1). These categories are defined inductively to depict common features of the influencing factors. For instance, pollutant and chemical content was classified under *physical requirements*. Additionally, in their assessments of the barriers to CE, de Jesus and Mendonça (2018) and Kirchherr et al. (2018) note that potential interactions among barriers might happen. In light of this, we used to the concept map to help identify relationships among influencing factors. Werner et al. (2010) quote mentioned above is an example that interlinks chemical contamination with final use prioritization, i.e., energy production over material cascading. Any nuances in the statements that might hinder a clear interpretation were also discussed by the authors to reach intersubjective plausibility (Sousa, 2014), a shared understanding of the statements.

After listing the influencing factors addressed in the literature, we investigated their prominence. This is determined based on the frequency of influencing factors mentioned in the publications. As most publications refer to more than one influencing factor, we account for the presence or absence of each influencing factor in each paper. In this sense, one mention means that the influencing factor appears only in one paper. Any influencing factor is accounted for only once even if it is mentioned more than once in a single paper. A detailed account of the prominence is shown in Table S3 in the Supporting Information.

3. Results

3.1. Mapping the influencing factors

The literature review sheds light on a large number of factors that could affect the implementation of wood cascading. Using a concept map, we identified 55 influencing factors referring to 5 categories, namely policy, market, technical implementation, environmental effects and stakeholder involvement. This categorization partially aligns with the findings and classification of barriers to CE from de Jesus and Mendonça (2018) and Kirchherr et al. (2018), as we identified some additional factors related to environmental effects.

Table 1 shows the resulting classification. For a more detailed analysis, most categories were disaggregated into subcategories. The main discussions on legislation and incentives are categorized as *policy*, whereas the access to secondary wood resources and industrial competition are examples of factors categorized as *market*. The *technical implementation* of wood cascading is divided into design practices, physical requirements (e.g., wood material properties), and processes related to the waste management infrastructure. The *environmental effects* reflect forest management issues and current results and limitations of quantitative studies dealing with wood cascading. The influencing factors retrieved from the latter studies refer to both empirical results and assumptions on carbon storage in wood products, as well as the main methodological barriers that environmental assessments need to overcome. Finally, *stakeholder involvement* consists of both the role of producers and consumers in the acceptance and feasibility of secondary wood use, and the degree of communication and information exchange along the supply chain.

3.2. Significance of the individual influencing factors in the literature

The results retrieved from the literature were analyzed for frequency. First, Fig. 2 presents the prominence of each category and subcategory based on the number of times they are mentioned in the publications. The main discussions refer to physical requirements, quantitative assessments of the environmental effects of wood cascading, and waste wood regulation. These subcategories are present in the literature 34, 25 and 22 times, respectively. Second, we show the influencing factors mentioned five or more times in Table 2 to gain insight into the most prominent factors. Legislation on wood recycling as well as pollutant and chemical content were each identified in 11 publications. Their relationship is described in Sections 3.3 and 3.5.3. The challenges of conducting quantitative assessments are also broadly discussed, with data availability and reliability being key influencing factors. In contrast, less attention is paid to design aspects and stakeholder involvement. In particular, influencing factors related to the role of producers and consumers are only mentioned five times in the literature (Fig. 2). All influencing factors are listed along with their prominence in Table S3 in the Supporting Information. The main discussions about all categories and influencing factors are described in detail in Sections 3.3 to 3.7.

3.3. Policy

The main policy factors influencing the cascading practice are linked to existing legislation on wood recycling (e.g., Bergeron, 2014; Fraanje, 1997; Garcia and Hora, 2017; Höglmeier et al., 2017; Husgafvel et al., 2018; Kalcher et al., 2017; Keegan et al., 2013; Sommerhuber et al., 2017, 2015; Werner et al., 2010) and the lack of specific incentives to promote and sustain the material use of wood (e.g., Husgafvel et al., 2018; Taskhiri et al., 2016; Winder and Bobar, 2018).

3.3.1. Waste wood regulation

National policies on waste wood and its recycling are well discussed in the literature. For instance, Bergeron (2014) and Werner et al. (2010) show how the legislation in Switzerland plays a fundamental role in determining the end-use of wood. In particular, due to the possible presence of chemical compounds and pollutants, waste wood does not comply with the precautionary principle, which constitutes a fundamental pillar of Swiss environmental legislation in wood. Additionally, identifying wood contamination is complex (see Section 3.5). For these reasons, reuse and recycling of waste wood "has remained an exception with small volumes" in the Swiss context and thermal energy recovery has been prioritized (Werner et al., 2010). In Germany, Höglmeier et al. (2017) describe regulations as "strict," in particular in light of future improved sorting technologies for waste wood separation (see Section 3.5). The German Waste Wood Ordinance (German Government, 2003) classifies waste wood into five categories (AI, AII, AIII, AIV and PCB waste wood) based on the wood treatment, the amount and type of

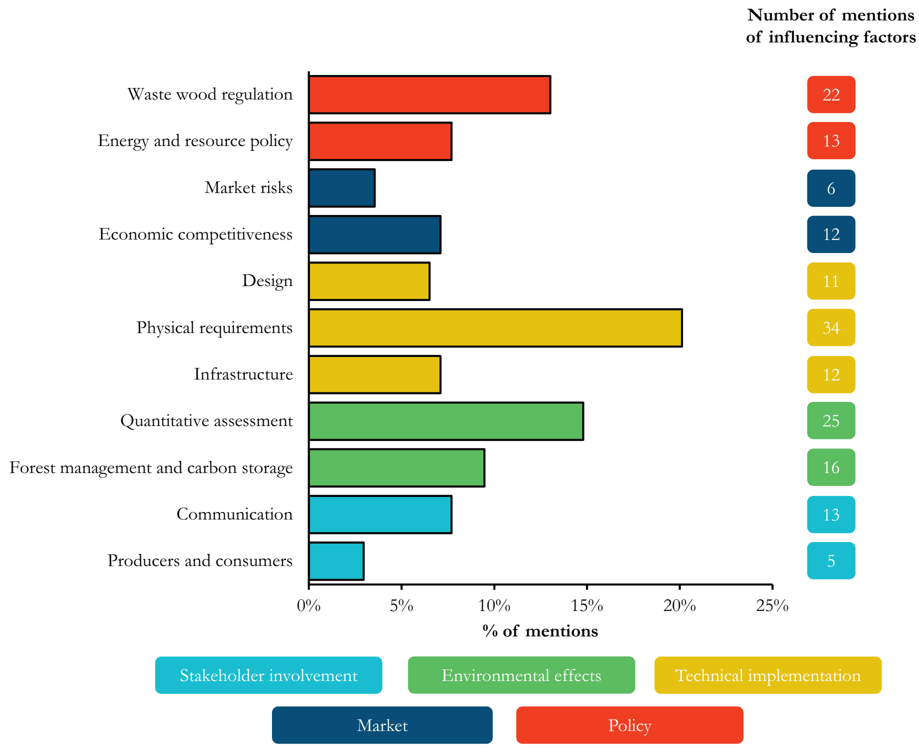

Fig. 2. Appearance frequency of each category and subcategory in the literature. Note that each category can be mentioned in the same paper through different influencing factors.

Table 2
Main influencing factors identified in the literature. These were mentioned in at least five publications.

Category		Influencing factors	Number of papers
Policy	Waste wood regulation	Legislation on wood recycling	11
		Incentives for recycling and material use	8
	Energy and resource policy	Incentives for renewable energy	5
		Separate legislation for renewable energy and waste	5
Market	Economic competitiveness	Energy vs. material competition for wood use	9
Technical implementation	Physical requirements	Pollutant and chemical content	11
		Quality	6
	Infrastructure	Quality of waste wood collection and sorting process	6
Environmental effects	Quantitative assessment	Data availability and reliability	9
		System boundaries	6
Stakeholder involvement	Communication	Shared information among organizations	5

chemical additives and components (paints, glues, preservatives etc.). A similar classification exists in Finland,[1] as described by Suominen et al. (2017). A suitable end of life is then indicated (i.e., material use, energy use or non-hazardous disposal) depending on the level of danger associated with chemical compounds (see Garcia and Hora, 2017 or Höglmeier et al., 2017 for further details). In particular, only categories AI and AII allow for further material use without pre-processing because wood has been treated with paints and glues instead of more dangerous compounds. Although in principle the highest application in the waste pyramid should always be favored (i.e., material over energy over disposal), this is not always the case. In fact, not all the AI and AII wood is destined to material use but is often sent to incineration facilities, since the legislative requirement for these categories leaves this option open despite the suitability of material use (Garcia and Hora, 2017).

[1] Categories are labeled A, B, C and D and are analogous to the AI, AII, AIII and AIV classes in German regulation.

3.3.2. *Energy and resource policy*

The prioritization of the energy conversion of wood is addressed by several scholars, who highlight the existence of incentives to energy production as one of the key factors that are currently limiting the potential of cascading (Bergeron, 2014; Garcia and Hora, 2017; Husgafvel et al., 2018; Keegan et al., 2013; Sikkema et al., 2013). Particularly in Europe, current policies tend to favor the conversion of wood into energy because of the CO_2 emission reduction requirements of the energy sector, thus favoring the increased use of renewable sources to meet short-term energy targets (Bais-Moleman et al., 2018).

In parallel, there is a lack of incentives for the material use of wood. Several authors share the idea of providing a “level playing field” between energy and material uses of wood through proper policy incentives (Fraanje, 1997; Keegan et al., 2013; Sikkema et al., 2013). Similarly, the necessity to reform the taxation mechanisms is also mentioned as a type of sub-optimal legislative framework. In particular, Fraanje (1997) discusses the need to shift tax burdens away from labor and onto resources, thus incentivizing a more efficient use of resources. Keegan et al. (2013) also mention the taxation of fossil fuels and non-renewable carbon as a way “to promote a level playing field between fossil and biomass resources" and "to promote biomaterial use". An additional limiting factor is that policies dealing with energy and waste are independent from one another (Bergeron, 2014; Husgafvel et al., 2018; Keegan et al., 2013; Suominen et al., 2017). Thus, a comprehensive policy-making process is needed to develop procedures aimed at optimizing the exploitation of resources.

3.4. Market

3.4.1. Economic competitiveness

Following the policy discussions, the competition between energy and material uses of wood is a prominent topic among scholars and a feature of cascading influenced by many other factors. The increased demand for wood products is often characterized by two mutually exclusive options: thermal energy conversion through combustion or material transformation into a product (Haberl and Geissler, 2000; Höglmeier et al., 2015a).

Prioritizing one use over the other depends on many factors and in general varies with the selected evaluation criteria (Bais-Moleman et al., 2018; Suter et al., 2017; Werner et al., 2010). The prioritization of the conversion of wood into energy and the respective policy instruments cause a greater profitability for thermal energy conversion, thus incentivizing waste wood collectors to sell their products to energy conversion facilities instead of re-entering them into the cascading chain (Garcia and Hora, 2017). In addition, country policies tend to support thermal energy conversion due to the "sunk cost" in existing combustion facilities. Werner et al. (2010) argue that the unique prioritization of the thermal energy conversion of wood "cannot be considered efficient from a climate perspective" and should therefore be changed, implementing the energy conversion of wood only when no further material use is possible.

3.4.2. Market risks

In the aforementioned context, cascading might play an important role in influencing the economic risks of the involved stakeholders. In particular, it is important to mention the greater complexity of the material use of wood over energy use (Husgafvel et al., 2018). While the latter only requires collection, transportation to the incinerator and minor treatment, wood recycling or reuse requires additional sorting, cleaning, chemical or mechanical treatment, transportation to the processing facility and additional administrative work. All these phases add up to the final cost of re-entering wood into a cascading chain and make material use less competitive. Additionally, the demand for cascaded products is small and each market segment has to be properly incentivized to supply products with a particular quality (see Section 3.5.2). Moreover, cascading use inherently depends on upstream wood flows, meaning that any industry using waste wood as its primary material has little to no control on its supply (Husgafvel et al., 2018).

3.5. Technical implementation

3.5.1. Design

For a product to be reused/recycled, its initial design phase is crucial. In particular, improvements in project planning (Fraanje, 1998; Höglmeier et al., 2017; Winder and Bobar, 2018) and the emergence of new technologies for better design of wooden products (Brunet-Navarro et al., 2018; Winder and Bobar, 2018) have been mentioned as enabling factors for more and better cascading implementation.

In the building demolition sector, the problem of product design is particularly relevant: building elements are usually tailored to the given building's needs and not constructed for reuse (Kalcher et al., 2017). The disassembly and reuse of building components is particularly difficult when wood is incorporated into construction elements, which are then typically landfilled (Sathre and González-García, 2014). Höglmeier et al. (2017) suggest that a deep level of knowledge is necessary during the design phase of the materials as well as the construction and deconstruction phases.

The design phase of buildings, in addition, is strictly related to prescriptive policies and quality codes. In this sense, the design phase would benefit from improved legislation implementing specific building codes that should address the need to design buildings and building elements that can be reused or recycled at the end of their lifetime (Bates et al., 2017; Winder and Bobar, 2018). Finally, architects and designers should also be properly incentivized to consider cascading principles in the conception of their products. Husgafvel et al. (2018) indicate that incentives for companies using wood products with small dimensions could help overcome the profitability barriers that currently hinder the development of this particular market segment.

3.5.2. Physical requirements

Physical requirements are also a fundamental aspect for implementing cascading. Many influencing factors were included in this group but the presence of chemicals in waste wood is the most prominent factor in preventing the reuse or recycling of waste wood (Table 2) (e.g., Bergeron, 2014; Kalcher et al., 2017; Suominen et al., 2017; Teuber et al., 2016). In particular, the presence of chemical components prevents waste wood from being classified as reusable or recyclable due to health issues, thus making incineration the only feasible end-of-life option (Section 3.3).

Although often addressed as a key barrier, the presence of additives is not discussed in the literature in terms of necessity, i.e. none of the analyzed papers investigates the production practices that lead to the use of chemical additives that prevents the possibility for material uses of waste wood. This could be due to a lack of knowledge about the specific production processes and requirements in the industry from academics and policy-makers. In their conclusions, Keegan et al. (2013) doubt that implementing more regulation to foster cascading is enough, arguing that this needs to be accompanied by an increased technical knowledge concerning the specific production processes in the wood sector.

Another set of fundamental physical requirements includes wood quality (Höglmeier et al., 2017; Husgafvel et al., 2018; Kalcher et al., 2017; Rettenmaier et al., 2014; Winder and Bobar, 2018), particle size (Höglmeier et al., 2017; Höglmeier et al., 2015a; Husgafvel et al., 2018; Kalcher et al., 2017) and moisture content (Husgafvel et al., 2018; Knauf, 2015; Rettenmaier et al., 2014). These factors are directly connected to the main characteristics of the original wood products and collected waste wood.

Particle size represents a significant limitation to material use. Husgafvel et al. (2018) conclude that packaging has the highest potential for using recycled wood, as well as other processes where small sizes are not a barrier, such as "finger jointing" (specific junction between two wooden parts). Höglmeier et al. (2015a) specify a maximum of three cascading steps for wood panels because particle size decreases after each step. In contrast, building deconstruction is a suitable cascading source because larger wood portions can be recovered (Höglmeier et al., 2017).

3.5.3. Infrastructure

The most relevant influencing factor in the infrastructure category is the quality of waste wood collection and the state of sorting facilities and technologies. Bergeron (2014) explains that the predominance of the thermal energy conversion of waste wood is due to the presence of a large number of incinerators coupled with the total absence of waste wood sorting facilities.

Winder and Bobar (2018) reveal a strict connection between infrastructure capabilities, existing policies and cost considerations, all of which might limit or foster an increased implementation of cascading. In particular, due to the poor quality of wood sorting infrastructure, several German companies have declared they do not follow the legal requirements of classifying wood according to the AI-AIV categories (Section 3.3) mainly because of increased direct and indirect (time and organizational) costs. In practice, sorting procedures still represent a barrier across the whole spectrum of waste wood (Husgafvel et al., 2018) and in many cases happens only based on "visual assessments" (Höglmeier et al., 2015b). Costly chemical analyses are often required for proper sorting, which motivates companies to choose the "safest" category in case of uncertainty (Winder and Bobar, 2018). In addition, the material use of wood is dismissed in favor of the energy conversion because of the wood material losses that could occur within waste sorting facilities and during recycling operations (Höglmeier et al., 2017; Höglmeier et al., 2015a; Suter et al., 2017). In this context, increased "intelligence" in wood products and components from the design phase might facilitate the sorting process and increase the amount of collected waste wood that is classified as suitable for cascading (see Section 3.7.2).

Finally, one aspect that lies between the realm of infrastructure and communication-related factors is the existence of appropriate logistic chains. In particular, Garcia and Hora (2017), Keegan et al. (2013) and Taskhiri et al. (2016) name logistics as a factor that limits the implementation of cascading practices due to the sheer difficulty and economic expenses related to the collection of waste wood and its transportation from a collection site to a recycling facility and then, to a distribution network. In many cases logistics represent one of the largest costs for these networks. Taskhiri et al. (2016) find that transportation accounts for 89% of total logistics costs and conclude that a greater incentive towards cascading use would arise from the optimization of the overall logistics chain.

3.6. Environmental effects

3.6.1. Quantitative assessment

About half of the publications included an environmental assessment of wood cascading using tools such as life cycle assessment (LCA) or greenhouse-gas emission accounting. As a result, modeling principles or data sources are key issues for quantification (Table 2). Almost all of these studies point to the lack of reliable data as a major source of uncertainty and ambiguity in their results (Bais-Moleman et al., 2018; Bates et al., 2017; Bergeron, 2014; Fraanje, 1998; Höglmeier et al., 2015a; Kalcher et al., 2017; Lafleur and Fraanje, 1997; Mantau, 2015). Such uncertainty complicates the translation of cascading principles into effective policies, in particular when the competition between material and energy uses of wood must be assessed (Section 3.3). Some authors obtain mixed results when comparing different solutions for waste wood utilization; in particular, the comparison between energy and material uses is not conclusive since the evaluation depends on the criteria chosen for the comparison and initial data quality.

In general, most LCA studies cannot be compared because they use different functional units and system boundaries. In their review of LCA publications on wood cascading, Thonemann and Schumann (2018) note that assessments focus on either single or multiple steps of the cascading system, which generates a variety of results. In terms of modeling, allocation methods (e.g., cut-off, substitution, closed loop) also play a key role in determining the best cascading configurations (Nicholson et al., 2009). Additionally, identifying the products that cascade uses are substituting is not straightforward. Most studies expand the system boundaries to include the credits of substituted equivalent products, such as electricity, reinforced concrete, floorboards or ceramic tiles (e.g., Höglmeier et al., 2015b; Kim and Song, 2014; Sikkema et al., 2013). However, uncertainties about proper time scales and, in particular, evolution in time of the wood sector lead scholars to create a variety of substitution scenarios. Material cascading implies a delayed production of energy that can be counterproductive in environmental terms, as future technologies might be more environmentally friendly than wood combustion (Höglmeier et al., 2015b; Sandin et al., 2014). A similar problem arises when accounting for biogenic carbon emissions, as their impacts are negligible in the long term (Suter et al., 2017). These environmental analyses are meant to ease decision-making and approach sustainability by using empirical data. Nevertheless, Winder and Bobar (2018) note that conducting LCAs is costly and not mandatory for companies, which complicates the definition of sustainability criteria for supply chain management.

3.6.2. Forest management and carbon storage

One particular group of factors that influences the development and implementation of the cascading practice concerns the capability of wood products to store carbon and thus contribute to climate change mitigation. In this perspective, the main consequence of cascading is the lifetime extension of wood products and the postponed release of carbon stored in products into the atmosphere.

Bates et al. (2017) develop a 100-year analysis of carbon storage in wooden products for carbon offset projects and conclude that the cascading practice should be incorporated into accounting protocols for its carbon storage characteristics, which vary greatly according to the context, the type and lifespan of products and the available end-of-life options. On the one hand, Bates et al. (2017) note that landfilling products would be the only option to guarantee permanent (or at least very long-term) storage of carbon in wood; on the other hand, long lifespan wood products (e.g. construction elements) could offer similar time horizons with the advantage of an effective utilization of wood. Other authors point out that the long lifespan of wooden construction elements is one of the barriers to increasing the responsibility of producers for the end-of-life phase (see Section 3.7.1). These inconsistencies underline the difficulty of developing a regulatory system that establishes a long-term perspective (e.g., 100 years of carbon storage) in a political system that focuses on stakeholder perspectives with short- to medium-term (economic) planning horizons.

Similarly, Suter et al. (2017) conclude that when forests are underexploited, an increased cascading use would lead to an underutilization of their full carbon storage potential. In contrast, Risse et al. (2017) conclude that the most important environmental benefit of increased wood cascading comes from the avoidance of resource extraction from the natural environment and, in particular, "from the avoided primary production of round wood." This shows again that the promise of a better resource utilization of cascading is strongly context dependent.

Sathre and Gustavsson (2006) find that the most relevant factor in determining the carbon balance of a cascading chain is the (positive) effect on the land-use, followed by the material substitution effect (i.e. the avoided resource exploitation due to reusing/recycling a product). This result suggests that cascading practices should be fostered since they enable the intensification of wood use (Sathre and Gustavsson, 2006). This is particularly important with regard to the current intense competition between the uses of wood resources for different purposes. Moreover, it has been argued that the exploitation of the full potential of wood harvesting in many forests is not optimal for biodiversity concerns; Werner et al. (2010) argue that the current level of knowledge is still insufficient to reach meaningful conclusions about the role of deadwood to protect and enhance biodiversity in forests.

In addition, the environmental benefits of cascading are also a function of the product type and durability, since they influence the whole cascade chain. Dornburg and Faaij (2005) find that biomass cascading has the potential of decreasing CO_2 emissions associated with biomass use, but that the extent of such reduction is largely dependent on the number of steps in each specific cascading chain.

Finally, the assessment of material and energy uses of wood (see Section 3.4) is also fostered by the hypothesis that the energy use of wood is carbon neutral. In other words, the assumption that the combustion of wood does not emit additional CO_2 into the atmosphere because of previous carbon sequestration in the wood. Such a simplifying hypothesis has undergone major debates (see Zanchi et al., 2012), and Keegan et al. (2013) specifically call for its correction, claiming that it would deliver a strong case for favoring material over bioenergy use of wood.

3.7. Stakeholder involvement

3.7.1. Producers and consumers

Numerous authors identify non-technical and non-policy related aspects as relevant influencing factors for the implementation of cascading principles. In particular, some authors indicate the difficulty of involving the most relevant stakeholders of the wood product chains -, producers and consumers - as a relevant limiting factor (Fraanje, 1997; Höglmeier et al., 2017; Keegan et al., 2013).

Höglmeier et al. (2017) indicate that producers and consumers are "resistant" to manufacture or purchase particleboards from waste wood products. A major factor for this is a general lack of attention about end-of-life disposal of products and for consumers, a lack of information about the composition of the materials (Keegan et al., 2013).

In addition, Fraanje (1997) points at the inherent difficulty of having wood manufacturers accountable for the disposal phase of their products. While the direct responsibility of producers for the end-of-life phase can be integrated into the production and distribution cycle for many materials (e.g., plastics or glass), the managing of many wood products is complicated by their very long lifespan (e.g., in construction). Production and end-of-life phases are thus considerably separate in time. Fraanje (1997) calls for additional regulations in this direction, but does not specify if this approach is suitable for all wood products or only specifically for those with a short lifespan. As previously mentioned, Husgafvel et al. (2018) suggest that the high potential for cascading lies in products such as packaging because of their small size and their short utilization phase.

Finally, particleboard producers are reluctant to use waste wood within their products because of the possible presence of chemical components (Höglmeier et al., 2017) which, in particular, could damage their reputation when selling products containing waste wood (Bergeron, 2014).

3.7.2. Communication

The low level of information sharing among organizations and companies is a prominent factor linked to communication issues in the supply chain (Brunet-Navarro et al., 2018; Fraanje, 1997; Keegan et al., 2013; Winder and Bobar, 2018; Zander et al., 2016). A general lack of knowledge about cascading is the basis of these problems. Lafleur and Fraanje (1997) deal with the possibility of increasing the implementation of cascading practices and indicate a strong barrier in the difficulty to correlate possible measures with end users. Similarly, Winder and Bobar (2018) find that "cascade use [is] a term unknown to some entrepreneurs."

Brunet-Navarro et al. (2018) specifically address that the private sector should be encouraged to disclose information about quality parameters of wood, especially since these actors have first-hand information that is otherwise difficult for researchers and policy-makers to gather in a reliable fashion. Winder and Bobar (2018) address the production side of the wood sector by tackling the lack of communication among architects and construction firms, which leads to a product design that does not favor the cascading use of wood material.

Moreover, Husgafvel et al. (2018) point at the necessity to implement "product-related intelligence" in the form of product declarations or other certification schemes to overcome market-based barriers deriving from poor information. Similarly, Suominen et al. (2017) call for the design and labeling of products based on considerations of circularity and inclusion of end-of-life options. Certified production and labels aim at increasing information sharing and, thus, at incentivizing cascading implementation.

3.8. Interrelations between influencing factors

Many studies mention and/or discuss several influencing factors; we identify some potential causal relationships among the main categories, summarized in Fig. 3. Existing relationships among sectors were identified when categorization tends to overlap, i.e., when a statement dealt with more than one influencing factor at a time.

For example, the direct connection between the technical implementation and policy aspects of wood cascading is evident because of the many statements that deal with the need for legislative support to develop technology and expertise. Further links exist between environmental effects and policy. On the one hand, legal framework conditions such as the European Waste Framework Directive can guide the environmentally sound production, reuse and recycling of commodities. On the other hand, politics are promoting energy production from bio-based products rather than cascading. This is partly due to the challenges of determining the environmental impacts of cascading and the lack of data on possible benefits for CO_2 mitigation. Moreover, infrastructure and collection/sorting procedures are intertwined with policy and market aspects as well as design features. Finally, legal requirements like product codes or mandatory cascading could enhance communication between the production and recycling sector. The design phase will also determine the characteristics of collected wood products.

4. Discussion and conclusions

This paper set out to tap into the knowledge that research on wood cascading has built to inform current political and industry debates about possible transformation pathways to a CE. First of all, our findings demonstrate that cascading can be understood in diverse ways (e.g., cascading in time, in value or in function, Odegard et al., 2012), that it encompasses a number of very different activities (e.g., recycling, reuse, remanufacture) and is, most of the time, a cross-sectoral concept (e.g., spanning across waste management, design, and energy management). Notably, these features resemble CE concepts as described in scientific reviews as well as in policy documents (European Commission, 2015; Geissdoerfer et al., 2017; Ghisellini et al., 2016). Hence, the main factors influencing a transformation to wood cascading will likely provide important lessons for the establishment of a CE in bio-based sectors, i.e., a circular bioeconomy, as envisioned by several political debates in Europe (cf. Leipold and Petit-Boix, 2018). To be sure, cascading is not as comprehensive as the concept of a circular bioeconomy. It is predominantly forest industries and related bio-based industries, such as pulp and paper, that discuss cascading. These industries face particular challenges that may not be comparable to others (e.g., a large variety in the lifetime of products). Hence, this analysis does not aim to generalize the particular findings on cascading to the wider CE debate. Instead, it aims to identify critical influencing factors and knowledge gaps to provide a starting point for a more structured debate about CE solutions in bio-based sectors. In the following, we first summarize the major lessons learned from the wood cascading literature that appear noteworthy with respect to current discussions on the transformation to a sustainable CE in bio-based sectors before outlining further research needs.

4.1. Lessons learned from the wood cascading literature

Substantial knowledge is available about influencing factors of cascading, which largely resemble barriers and enablers currently discussed under CE. For instance, a current analysis of barriers and enablers of a CE among EU stakeholders (Kirchherr et al., 2018) highlights lacking policies and lacking market viability as barriers to a CE. Our findings show that political incentives/barriers and market mechanisms are two of the most crucial factors that impact the realization of wood cascading. This importance is reflected both in the frequency of these two factors in the literature and in the multiple connections with many other influencing factors as described in Section 3.8. Furthermore, our study highlights that technical barriers are a significant influencing factor for implementation approaches to cascading. In particular, the wood cascading literature shows wood quality, additives and

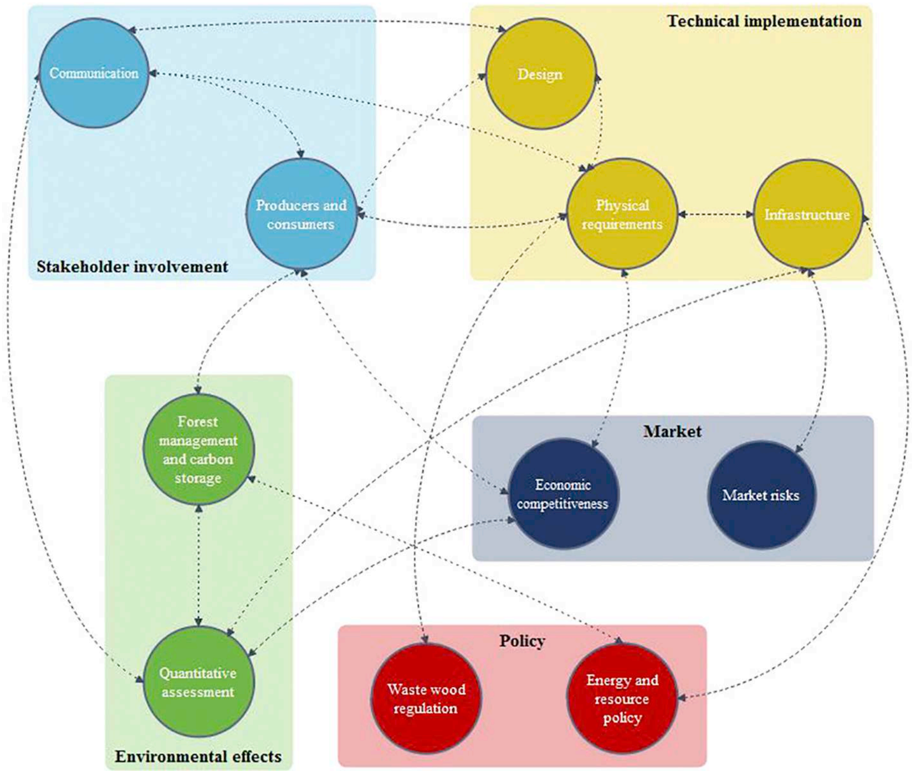

Fig. 3. Interdependencies of identified categories in the analyzed wood cascading literature.

particle size to be obstacles for successful implementation. Notably, these potential technical barriers appear to remain under-appreciated in current political and stakeholder debates on the CE (Kirchherr et al., 2018; Leipold and Petit-Boix, 2018). These technical barriers could potentially be of more relevance in a circular bioeconomy because natural fiber does not have the same properties for circulation as, for instance, metals or minerals (which usually can be recycled many times).

Some crucial influencing factors for cascading implementation are frequently highlighted but remain ill understood. One aspect that struck us most in the study is that while the cascading literature shows a certain consensus on the importance of some influencing factors, these have hardly been investigated. For instance, political incentive structures, the link between waste and energy policies or taxation policies were some of the influencing factors that featured in the majority of publications. At the same time, our review did not uncover a substantial body of peer-reviewed studies directly concerned with these policy issues. Instead, most publications we found had a technical, engineering or environmental science focus. Furthermore, many publications conclude that stakeholder involvement, awareness and communication are critical for the success of any transformation of current production and consumption towards more wood cascading. Yet, there is hardly any research specifically investigating what this involvement, awareness raising or communication needs to look like to be successful. In addition, the role of consumers and producers, which certainly is closely tied to stakeholder involvement and awareness, does not feature prominently in the literature. For instance, much of the cascading literature appears to operate under the assumption that the presence of chemical additives, paints and glues is required, even though it creates major problems for cascading. Very little research has been found that analyzes the technical necessity of or the consumer demand for chemical compounds. The wood cascading literature does not provide us with many insights on how to address these issues. As current CE debates often rely on or refer to the R framework, this knowledge gap is crucial as the framework calls for the intervention of different actors and processes and a strong involvement of society. Finally, social and political factors are not the only ones that lack an understanding, we also find that questions of design, currently a hot topic in CE debates (e.g., Bocken et al., 2016; European Commission, 2015), are rarely explored in the cascading literature. One reason for this may be that cascading debates are often embedded in wider bioeconomy discussions that focus on waste wood mobilization (Fehrenbach et al., 2017; Haberl and Geissler, 2000).

Influencing factors are interdependent. As Fig. 3 highlights, not a single influencing factor operates independently. While this is certainly not surprising, it still gives an indication of the expansive nature of any substantial change to production and consumption systems, as aimed for by recent CE policies (European Commission, 2018, 2015). Although substantial knowledge is available on the different influencing factors, there is little evidence about the causal links between them. The multifaceted interdependencies make it difficult to separate causes from consequences, as well as to measure the degree of influence one factor has on another. This results in a high degree of uncertainty and, thus, disagreement about leverage points to improve cascading use and to foster a sustainable CE. Nevertheless, scholars discuss solutions that may have the potential to cut across different influencing factors. For instance, Husgafvel et al. (2018) argue that product declarations, certification schemes and databases with information on quantity, quality and relevant properties of wood products and waste could improve communication along the value chain and may overcome market-based barriers. Yet, the benefits of these informational instruments remain to be seen.

Not surprisingly, this **high degree of interdependence makes a conclusive assessment of the environmental (or likewise social) benefits of certain cascading activities extremely challenging.** Although current research and policy initiatives seek to develop coherent monitoring frameworks for a CE (e.g. Blomsma and Brennan, 2017; Elia et al., 2017; Pauliuk, 2018), our review underlines a lack of accuracy and high degree of uncertainty related particularly to environmental assessment. For instance, several authors underline how complex it is to determine whether a cascaded product will embed more carbon than harvested products. Based on the variety of assumptions and results (e.g., diverging system boundaries, choosing single or multiple steps of cascading, identifying different substitute products), assessing the environmental benefits of cascading options is challenging. In addition, the majority of studies that incorporated environmental assessments point to the lack of reliable data as a major source of uncertainty and ambiguity in their results. Moreover, LCA studies cannot be compared because of the different functional units and system boundaries used. In addition, both cascading and CE solutions are inherently future-oriented. Predictions about the future present an even greater challenge for the assessment of environmental, social or economic benefits. Wood cascading is an excellent example of this challenge because of the long life cycle of some wood products, which can cover years, decades or longer, especially in the construction sector. The resulting loss of information, the different sectors involved and the missing responsibility of producers for end-of-life phases that are far in the future cause a challenge for reuse and recycling. Additionally, competition between material and energy uses of wood will determine the market trends and transacted volumes of wood (Hetemäki, 2014), which are also difficult to predict. In consequence, cascading is easier to implement for in-sector circulation and products with a short lifetime. Besides the separated and efficient collection, the relatively short lifetime of paper and cardboard products is a main reason for the high rate of cascading use in this sector. With these examples, the cascading literature gives a good indication of the practical challenges for policy and business to identify and realize environmentally, socially and economically sustainable pathways.

Based on the knowledge gaps and high degree of interdependency between different influencing factors, some of the proposed political measures appear very optimistic. For example, several scholars point to a change in taxation and a cut in subsidies for fossil resources to support a change towards more wood cascading. Yet, even if subsidies for fossil resources and energy production from biomass are abolished, it is not certain whether cascading will gain importance because other barriers persist, like the high investments required for incineration facilities. In addition, a lack of specific incentives to promote and sustain the material use of wood is stated in the literature as an important barrier (e.g., Husgafvel et al., 2018; Taskhiri et al., 2016; Winder and Bobar, 2018). However, detailed proposals for creating the desired level playing field are more concentrated on eliminating barriers such as the abolishment of subsidies for energetic uses and less on direct support for wood cascading. Finally, the insufficient coordination between energy and waste policies points to an incoherent policy framework. Such incoherencies are well known from other policy areas such as the bioeconomy (Meyer, 2017). Yet, coordination of policies across government ministries and policy areas is needed and remains a challenge in complex operating systems (Hetemäki et al., 2017; Organisation of Economic Co-Operation and Development, 2009) and there are few signs that this will change in the near future. Based on our findings, it also remains unclear to what degree coherence is possible at all.

4.2. The most relevant research needs to establish a circular economy in the bio-based sector

The analysis of the cascading literature highlights how complex the current production and consumption system of wood products is, and how many different, interlinked changes would be required to achieve more cascading or circular production and consumption. At the same time, we find that the cascading literature tends to list barriers for implementation from different viewpoints and gives policy limitations a high relevance. What is missing is a good understanding of causal relationships between the influencing factors, system dynamics and path dependencies as well as actor coalitions, conflicts of interest and policy formation. More research is needed on these issues. Furthermore, our review shows that some studies tend to operate on certain assumptions that have yet to be scrutinized empirically. Therefore, we propose the following research areas as the most relevant for further investigation:

- The analysis shows that the physical properties of wood products such as particle size or the presence of chemicals lay the foundation for reuse and recycling. It is assumed that the product design is the most important factor in this respect. Yet, the possibilities to influence product design have barely been explored. Important open questions remain regarding the drivers for current design (often assumed to be consumer demand), the most suitable incentives and starting points to foster design for a CE, and the benefits and limits of the establishment of responsibilities over the whole life cycle.
- The assessment of long-lived products is particularly challenging because changes in the design have no short-term impact on the possibilities of reuse and recycling. Instead, benefits occur with a considerable time lag. As long-lived products are of importance in the bio-based sector and political programs aim to expand and support this sector, it is urgently required to investigate possibilities and constraints of the sustainability assessment, carbon balancing and governance procedures related to such products.
- Our results underline that cascading research is focused on best utilization pathways for waste products. The same priority is observable in discussions on the bioeconomy (Priefer et al., 2017) and CE (Ghisellini et al., 2016). Comprehensive analyses of the potentials of waste mitigation, both on the consumption and production side, are missing. Hence, we consider it worthwhile to investigate the potential contribution of changes in consumer behavior and production patterns aimed at the avoidance of waste generation for a sustainable CE. Although some research exists on new ownership models (e.g., Rückert-John and Jaeger-Erben, 2016) and collaborative use (e.g., sharing platforms, Hamari et al., 2016), little is known about their market potential as well as possible rebound effects.

Acknowledgments

The authors are grateful for the financial support of this research from the German Federal Ministry of Education and Research, research group “Circulus - Opportunities and challenges of transition to a sustainable circular bio-economy”, grant number 031B0018, and the Ministry of Science, Research and the Arts of Baden-Württemberg, research project “Bioeconomy in Baden-Württemberg” within the framework of the Bioeconomy Research-Program Baden-Württemberg. We also thank Amelia Pope for the professional language editing.

Author contributions

All authors were responsible for the conception and design of the study. Sina Leipold conceived the original idea of the article. Matteo Jarre and Anna Petit-Boix undertook the literature review and data analysis and took the lead in writing the manuscript. Rolf Meyer, Carmen Priefer and Sina Leipold wrote individual sections of the manuscript and critically revised the draft for important intellectual content. All authors gave their final approval to the manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.forpol.2019.01.017.

References

Bais-Moleman, A.L., Sikkema, R., Vis, M., Reumerman, P., Theurl, M.C., Erb, K.-H., 2018. 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.
Bates, L., Jones, B., Marland, E., Marland, G., Ruseva, T., Kowalczyk, T., Hoyle, J., 2017. Accounting for harvested wood products in a forest offset program: Lessons from California. J. For. Econ. 27, 50–59. https://doi.org/10.1016/J.JFE.2017.02.004.
Bergeron, F.C., 2014. Assessment of the coherence of the Swiss waste wood management. Resour. Conserv. Recycl. 91, 62–70. https://doi.org/10.1016/J.RESCONREC.2014.07.011.
Bezama, A., 2016. Let us discuss how cascading can help implement the circular economy and the bio-economy strategies. Waste Manag. Res. 34, 593–594. https://doi.org/10.1177/0734242X16657973.
Blomsma, F., Brennan, G., 2017. The emergence of circular economy: a new framing around prolonging resource productivity. J. Ind. Ecol. 21, 603–614. https://doi.org/10.1111/jiec.12603.
German Federal Ministry for Education and Research, 2010. Nationale Forschungsstrategie Bioökonomie 2030 (National Research Strategy Bioeconomy 2030). Unser Weg zu einer biobasierten Wirtschaft, Berlin, Germany Available online. https://www.bmbf.de/pub/Nationale_Forschungsstrategie_Biooekonomie_2030.pdf.
Bocken, N.M.P., de Pauw, I., Bakker, C., van der Grinten, B., 2016. Product design and business model strategies for a circular economy. J. Ind. Prod. Eng. 33, 308–320. https://doi.org/10.1080/21681015.2016.1172124.
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.
Dornburg, V., Faaij, A.P.C., 2005. Cost and Co2-emission reduction of biomass cascading: methodological aspects and case study of SRF poplar. Clim. Chang. 71, 373–408. https://doi.org/10.1007/s10584-005-5934-z.
Elia, V., Gnoni, M.G., Tornese, F., 2017. Measuring circular economy strategies through index methods: a critical analysis. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2016.10.196.
Ellen MacArthur Foundation, 2015. Growth within: A Circular Economy Vision for a Competitive Europe. Ellen MacArthur Found, pp. 100 (doi:Article).
Eppler, M.J., 2006. A comparison between concept maps, mind maps, conceptual diagrams, and visual metaphors as complementary tools for knowledge construction and sharing. Inf. Vis. https://doi.org/10.1057/palgrave.ivs.9500131.
European Commission, 2012. Innovating for sustainable growth: a bioeconomy for Europe. In: Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. COM(2012) 60, Available online. http://ec.e.
European Commission, 2015. Closing the Loop - an Action Plan for the Circular Economy. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Brussels. https://doi.org/10.1017/CBO9781107415324.004.
European Commission, 2018. Circular Economy Strategy - Environment - European Commission. Retrieved from. http://ec.europa.eu/environment/circular-economy/index_en.htm.
Fehrenbach, H., Köppen, S., Kauertz, B., Detzel, A., Wellenreuther, F., Breitmayer, E., Essel, R., Carus, M., Kay, S., Wern, B., Baur, F., Bienge, K., von Geibler, J., 2017. Biomassekaskaden. Mehr Ressourceneffizienz durch Kaskadennutzung von Biomasse – von der Theorie zur Praxis. (Endbericht. UBA-Texte 53/2017).
FORMAS, 2012. The Swedish research council for environment, A.S. and S.P. In: Swedish Research and Innovation. Strategy for a Bio-based Econom. FORMAS, Stockholm, Sweden (Available online). http://www.formas.se/PageFiles/5074/Strategy_Biobased_Ekonomy_hela.pdf.
Fraanje, P.J., 1997. Cascading of pine wood. Resour. Conserv. Recycl. https://doi.org/10.1016/S0921-3449(96)01159-7.
Fraanje, P.J., 1998. Poplar wood for purlins; an evaluation of options and environmental aspects. Holz als Roh - und Werkst. https://doi.org/10.1007/s001070050291.
Garcia, C.A., Hora, G., 2017. State-of-the-art of waste wood supply chain in Germany and selected European countries. Waste Manag. 70, 189–197. https://doi.org/10.1016/J.WASMAN.2017.09.025.
Geissdoerfer, M., Savaget, P., Bocken, N.M.P., Hultink, E.J., 2017. The circular economy – a new sustainability paradigm? J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2016.12.048.
German Government, 2003. Verordnung über Anforderungen an die Verwertung und Beseitigung von Altholz: Altholzverordnung- AltholzV.
Ghisellini, P., Cialani, C., Ulgiati, S., 2016. A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2015.09.007.
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.
Hamari, J., Sjöklint, M., Ukkonen, A., 2016. The sharing economy: why people participate in collaborative consumption. J. Assoc. Inf. Sci. Technol. https://doi.org/10.1002/asi.23552.
Hetemäki, L. (Ed.), 2014. Future of the European forest-Based Sector: Structural Changes Towards Bioeconomy. European Forest Institute.
Hetemäki, L., Hanewinkel, M., Muys, B., Ollikainen, M., Palahí, M., Trasobares, A., 2017. Leading the Way to a European Circular Bioeconomy Strategy. From Science to Policy. vol. 5 European Forest Institute.
Höglmeier, K., Steubing, B., Weber-Blaschke, G., Richter, K., 2015a. LCA-based optimization of wood utilization under special consideration of a cascading use of wood. J. Environ. Manag. 152, 158–170. https://doi.org/10.1016/J.JENVMAN.2015.01.018.
Höglmeier, K., Weber-Blaschke, G., Richter, K., 2015b. Evaluation of wood cascading. In: Sustainability Assessment of Renewables-Based Products. John Wiley & Sons, Ltd, Chichester, UK, pp. 335–346. https://doi.org/10.1002/9781118933916.ch22.
Höglmeier, K., Weber-Blaschke, G., Richter, K., 2017. Potentials for cascading of recovered wood from building deconstruction—a case study for south-East Germany. Resour. Conserv. Recycl. 117, 304–314. https://doi.org/10.1016/J.RESCONREC.2015.10.030.
Husgafvel, R., Linkosalmi, L., Hughes, M., Kanerva, J., Dahl, O., 2018. Forest sector circular economy development in Finland: a regional study on sustainability driven competitive advantage and an assessment of the potential for cascading recovered solid wood. J. Clean. Prod. 181, 483–497. https://doi.org/10.1016/J.JCLEPRO.2017.12.176.
de Jesus, A., Mendonça, S., 2018. Lost in transition? Drivers and Barriers in the Eco-innovation Road to the Circular Economy. Ecol. Econ. 145, 75–89. https://doi.org/10.1016/J.ECOLECON.2017.08.001.
Kalcher, J., Praxmarer, G., Teischinger, A., 2017. Quantification of future availabilities of recovered wood from Austrian residential buildings. Resour. Conserv. Recycl. 123, 143–152. https://doi.org/10.1016/J.RESCONREC.2016.09.001.
Keegan, D., Kretschmer, B., Elbersen, B., Panoutsou, C., 2013. Cascading use: a systematic approach to biomass beyond the energy sector. Biofuels Bioprod. Biorefin. https://doi.org/10.1002/bbb.1351.
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.
Kirchherr, J., Reike, D., Hekkert, M., 2017. Conceptualizing the circular economy: an analysis of 114 definitions. Resour. Conserv. Recycl. https://doi.org/10.1016/j.resconrec.2017.09.005.
Kirchherr, J., Piscicelli, L., Bour, R., Kostense-Smit, E., Muller, J., Huibrechtse-Truijens, A., Hekkert, M., 2018. Barriers to the circular economy: evidence from the European Union (EU). Ecol. Econ. 150, 264–272. https://doi.org/10.1016/j.ecolecon.2018.04.028.
Knauf, M., 2015. Waste hierarchy revisited — an evaluation of waste wood recycling in the context of EU energy policy and the European market. For. Policy Econ. 54, 58–60. https://doi.org/10.1016/J.FORPOL.2014.12.003.
Lafleur, M.C.C., Fraanje, P.J., 1997. Towards sustainable use of the renewable resource wood in the Netherlands — a systematic approach. Resour. Conserv. Recycl. 20, 19–29. https://doi.org/10.1016/S0921-3449(97)01195-6.
Leipold, S., Petit-Boix, A., 2018. The circular economy and the bio-based sector - perspectives of European and German stakeholders. J. Clean. Prod. 201, 1125–1137. https://doi.org/10.1016/J.JCLEPRO.2018.08.019.
Lutter, S., Giljum, S., Lieber, M., Manstein, C., 2016. The Use of Natural Resources. Report for Germany 2016, German Environment Agency. https://www.umweltbundesamt.de/publikationen/the-use-of-natural-resources.
Mair, C., Stern, T., 2017. Cascading utilization of wood: a matter of circular economy? Curr. For. Rep. https://doi.org/10.1007/s40725-017-0067-y.
Mantau, U., 2015. Wood flow analysis: Quantification of resource potentials, cascades and carbon effects. Biomass Bioenergy 79, 28–38. https://doi.org/10.1016/J.BIOMBIOE.2014.08.013.
Meyer, R., 2017. Bioeconomy strategies: contexts, visions, guiding implementation principles and resulting debates. Sustain. https://doi.org/10.3390/su9061031.
Murray, A., Skene, K., Haynes, K., 2017. The circular economy: an interdisciplinary exploration of the concept and application in a global context. J. Bus. Ethics. https://doi.org/10.1007/s10551-015-2693-2.
Nicholson, A.L., Olivetti, E.A., Gregory, J.R., Field, F.R., Kirchain, R.E., 2009. End-of-life LCA allocation methods: open loop recycling impacts on robustness of material selection decisions. In: 2009 IEEE International Symposium on Sustainable Systems and Technology. IEEE, pp. 1–6. https://doi.org/10.1109/ISSST.2009.5156769.
Odegard, I., Croezen, H., Bergsma, G., 2012. Cascading of Biomass, 13 Solutions for a Sustainable Bio-based Economy, Making Better Choices for Use of Biomass Residues, By-products and Wastes. CE Delft, Delft, The Netherlands.
Organisation of Economic Co-Operation and Development, 2009. The Bioeconomy to 2030. Designing a Policy Agenda. Main Findings and Policy Conclusions. OECD, Paris, France.
Olsson, O., Bruce, L., Roos, A., Hektor, B., Guisson, R., Lamers, P., Hartley, D., Ponitka, J., Hildebrandt, J., Thrän, D., 2016. Cascading of Woody Biomass: definitions, policies and effects on international trade. IEA Bioenergy Task 40 (April 2016).
Pauliuk, S., 2018. Critical Appraisal of the Circular Economy Standard BS 8001:2017 and a Dashboard of Quantitative System Indicators for its Implementation in Organizations. Resour. Conserv. Recycl. pp. 129. (Under review). https://doi.org/10.1016/j.resconrec.2017.10.019.
Priefer, C., Jörissen, J., Frör, O., 2017. Pathways to shape the bioeconomy. Resources. https://doi.org/10.3390/resources6010010.
Prieto-Sandoval, V., Jaca, C., Ormazabal, M., 2017. Towards a consensus on the circular economy. J. Clean. Prod. https://doi.org/10.1016/J.JCLEPRO.2017.12.224.
Rettenmaier, N., Keller, H., Reinhardt, G.A., 2014. Life cycle greenhouse gas emissions of furniture and bioenergy production from oil palm trunks. GCB Bioenergy 6, 509–520. https://doi.org/10.1111/gcbb.12085.
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.
Rückert-John, J., Jaeger-Erben, M., 2016. Alternative Konsumformen als Herausforderungen für die Verbraucherpolitik. In: Bala, C., Schuldzinski, W. (Eds.), Prosuming und Sharing − Neuer Sozialer Konsum: Aspekte kollaborativer Formen von Konsumtion und Produktion. Verbraucherzentrale NRW, Düsseldor.
Sandin, G., Peters, G.M., Svanström, M., 2014. Life cycle assessment of construction materials: the influence of assumptions in end-of-life modelling. Int. J. Life Cycle Assess. 19, 723–731. https://doi.org/10.1007/s11367-013-0686-x.
Sathre, R., González-García, S., 2014. Life cycle assessment (LCA) of wood-based building materials. Eco-efficient Constr. Build. Mater. 311–337. https://doi.org/10.1533/

9780857097729.2.311.
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.
Scarlat, N., Dallemand, J.F., Monforti-Ferrario, F., Nita, V., 2015. The role of biomass and bioenergy in a future bioeconomy: policies and facts. Environ. Dev. https://doi.org/10.1016/j.envdev.2015.03.006.
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. Pol. 31, 96–108. https://doi.org/10.1016/J.ENVSCI.2013.03.007.
Sirkin, T., ten Houten, M., 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.
Sommerhuber, P.F., Welling, J., Krause, A., 2015. Substitution potentials of recycled HDPE and wood particles from post-consumer packaging waste in Wood–Plastic Composites. Waste Manag. 46, 76–85. https://doi.org/10.1016/J.WASMAN.2015.09.011.
Sommerhuber, P.F., Wenker, J.L., Rüter, S., Krause, A., 2017. Life cycle assessment of wood-plastic composites: analysing alternative materials and identifying an environmental sound end-of-life option. Resour. Conserv. Recycl. 117, 235–248. https://doi.org/10.1016/j.resconrec.2016.10.012.
Sousa, D., 2014. Validation in qualitative research: general aspects and specificities of the descriptive phenomenological method. Qual. Res. Psychol. 11, 211–227. https://doi.org/10.1080/14780887.2013.853855.
Suominen, T., Kunttu, J., Jasinevičius, G., Tuomasjukka, D., Lindner, M., 2017. Trade-offs in sustainability impacts of introducing cascade use of wood. Scand. J. For. Res. 32, 588–597. https://doi.org/10.1080/02827581.2017.1342859.
Suter, F., Steubing, B., Hellweg, S., 2017. Life cycle impacts and benefits of wood along the value chain: the case of Switzerland. J. Ind. Ecol. 21, 874–886. https://doi.org/10.1111/jiec.12486.
Taskhiri, M.S., Garbs, M., Geldermann, J., 2016. Sustainable logistics network for wood flow considering cascade utilisation. J. Clean. Prod. 110, 25–39. https://doi.org/10.1016/J.JCLEPRO.2015.09.098.
Teuber, L., Osburg, V.-S., Toporowski, W., Militz, H., Krause, A., 2016. Wood polymer composites and their contribution to cascading utilisation. J. Clean. Prod. 110, 9–15. https://doi.org/10.1016/J.JCLEPRO.2015.04.009.
Thonemann, N., Schumann, M., 2018. Environmental impacts of wood-based products under consideration of cascade utilization: a systematic literature review. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2016.12.069.
Werner, F., Taverna, R., Hofer, P., Thürig, E., Kaufmann, E., 2010. National and global greenhouse gas dynamics of different forest management and wood use scenarios: a model-based assessment. Environ. Sci. Pol. https://doi.org/10.1016/j.envsci.2009.10.004.
Winder, G.M., Bobar, A., 2018. Responses to stimulate substitution and cascade use of wood within a wood use system: experience from Bavaria, Germany. Appl. Geogr. 90, 350–359. https://doi.org/10.1016/J.APGEOG.2016.09.003.
Zanchi, G., Pena, N., Bird, N., 2012. Is woody bioenergy carbon neutral? A comparative assessment of emissions from consumption of woody bioenergy and fossil fuel. GCB Bioenergy. https://doi.org/10.1111/j.1757-1707.2011.01149.x.
Zander, S., Trang, S., Kolbe, L.M., 2016. Drivers of network governance: a multitheoretic perspective with insights from case studies in the German wood industry. J. Clean. Prod. 110, 109–120. https://doi.org/10.1016/J.JCLEPRO.2015.03.010.