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Systematic Review

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Systematic Review

Barriers and Potentials for Circular Use of Waste Wood in Construction and Demolition Sector with Special Focus on Germany

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Abstract

The construction and demolition (C&D) industry generates nearly one-third of the total global waste. In response, the European Union is driving urgent efforts to enhance material circularity through the promotion of renewable materials. However, research primarily targets materials such as concrete, plastics, steel, bricks, and gypsum, while wood as a renewable material presents a clear research gap. This study aims to bridge the gap by identifying key barriers and potentials for reusing wood waste in the C&D sector. As a result, factors influencing wood reusability are categorized into economic, societal, environmental, technical, and regulatory dimensions. Economic and environmental factors addressing high costs, unstable markets, and contamination are the most discussed barriers for an enhanced circular use of wood. Specifically, material irregularities and impurities represent technical barriers that may make wood demand less attractive. Societal barriers, such as knowledge gaps regarding the quality of secondary materials, established standards, and legal limits are further barriers that are mentioned in the literature. Therefore, potential future indicators to support a circular approach in the construction sector, including regulatory actions and incentives, are recommended to promote recovered secondary materials. This approach would facilitate shared stakeholder cooperation, knowledge sharing, and market development.

Keywords: circular economy; wood; secondary resources; construction and demolition sector; waste



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1. Introduction

The current European economy functions according to the linear “take-make-dispose” model of resource use, which has produced significant amounts of material waste [1]. This one-directional model continues to degrade natural systems and drive climate change, as materials are not fully utilized and instead end up as waste [2]. Amid today’s climate and economic crises, this outdated practice is no longer viable, and we must adopt new standards that promote material recovery and enhance utilization efficiency [3–5].

A circular economy concept can be the solution, as it has the potential to reduce the overconsumption of raw materials, biodiversity loss, and waste, and to positively

influence climate change [6,7]. It promotes the design for reusability, easier disassembly, modularization of components, maintenance, refurbishment, remanufacture, reuse, and recycling. The circularity concept therefore contributes to an efficient and durable high-quality, safe, and practical economic system [8,9] and is seen as a central factor in achieving Sustainable Development Goals [10].

The building and construction industry contributes to nearly 40% of the global greenhouse gas emissions and energy consumption and approximately 65% of C&D waste ends up in landfills (37.5% of the EU's waste), which can be contaminated with heavy metals and other toxic materials [11–13]. As a consequence, in 2021, the European Commission launched its transdisciplinary initiative, the “New European Bauhaus (NEB)”, to promote sustainability, aesthetics, and comprehensiveness in the built environment. The action aims to generate sustainable and attractive living surroundings by integrating science, technology, culture, art, and design [14]. Creating new spaces and buildings of high quality is as crucial as integrating the restoration, adapted reuse, renovation, and conservation of the existing building stock [15]. In addition, the European Commission introduced the “Communication on Resource Efficiency Opportunities in the Building Sector” in 2014, which focuses on the overall environmental impact throughout the life cycle of the buildings while promoting a more efficient use of resources. This initiative identifies three key sectors with a high environmental impact: Food and Drinks, Buildings, and Mobility [12]. The primary consideration of the “Buildings” sector requires policies to address a wide range of life cycle environmental impacts and recommends that buildings should be renovated and constructed with enhanced resource efficiency [12].

In the recent past, the recycling and recovery rate in the EU has shown measurable progress, particularly in response to policy-driven incentives aimed at reducing landfilling and increasing material recovery [16]. Nevertheless, the EU remains distant from achieving a fully circular economy, as it requires significant further development in resource flows to attain a more resource-efficient value network [17].

Although EU policy frameworks, such as Directive (EU) 2018/2001 [18], promote the cascading use of biomass by prioritizing material applications over energy recovery, in practice, this objective is undermined by classification systems that focus almost exclusively on contamination levels. As a result, large volumes of used timber are still diverted to incineration or landfills despite their potential for higher-value reuse [19]. Wood faces challenges when it comes to recycling, as its inherent structural benefits, derived from its naturally grown hierarchy, are progressively degraded with each mechanical processing step. Thus, the early design phase is critical for efficient resource utilization, as it determines the potential pathways both during and after a building's use phase. Despite growing interest in circular construction, practical barriers to implementing circular wood strategies in the C&D sector remain insufficiently understood. These include uncertainties around the safe recovery of structural elements, regulatory restrictions limiting their reuse, and the broader implications of enhanced reuse practices for the long-term availability of wood resources [20]. Furthermore, there remains a pressing need for robust scientific data to support decision-makers in evaluating the systemic social, environmental, and economic consequences of circular wood policies [17,21,22].

This review aims to critically explore both the opportunities and barriers that shape the circular use of wood in the built environment, with the goal of understanding their implications for the transition towards a more circular economic model.

Due to various factors that impact timber waste from C&D, the goal is to answer the following questions:

1. What are the main barriers that hinder the application of wood waste in the construction and demolition sector?
2. What potentials characterize wood waste in the construction and demolition sector?

Given that German waste wood legislation [23] is expected to undergo bold revisions in the coming years, this research focuses on Germany as a core case study. Additionally, the neighboring countries of Austria, Denmark, and Belgium are included for comparative analysis, as their wood waste classification systems are founded on similar regulatory frameworks. These aspects are further elaborated in the Results and Conclusion sections.

2. Materials and Methods

2.1. Data Collection and Filtration of the Literature

We followed the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) [24] to systematically analyze the relevant literature dealing with circular economy and wood waste in the C&D industry [22]. PRISMA 2020 defines a four-phase flow diagram through different steps of a systematic review: Identification, Screening, Eligibility, and Included [24,25].

The relevant literature was taken from four scientific databases: “Web of Science”, “Scopus”, “Science Direct”, and “Springer Link” using the following keywords: (“circular economy”) AND (“wood waste” OR “secondary resource *” OR “CDW”) AND (construction * OR building *).

The identification phase of scientific databases using the keywords was related to selecting only the articles in the construction industry. The preliminary search was general, with 174 papers from Web of Science, 226 from Scopus, 1370 from Science Direct, and 1307 from Springer Link. During the screening phase of the papers, other records were omitted, such as reviews, book chapters, encyclopedias, and conference abstracts. In the next step, papers that did not contain concrete, sector-specific knowledge, and non-EU papers were excluded. During the third stage, duplicates were removed, and the chosen articles were checked for eligibility. As a result, Web of Science ended up with 16 papers, Scopus with 14 papers, Science Direct with 32 papers, and Springer Link with 4 papers. To ensure that the papers meet this paper’s keyword and goal criteria, each record was checked based on accuracy of fit. Moreover, the last stage of this methodology included analyzing and classifying papers based on research questions focusing on wood waste from the construction industry, where a barrier or potential was mainly discussed.

In addition, articles that did not contain concrete, sector-specific knowledge, and non-EU papers were excluded. Lastly, the duplicates were removed, and the chosen articles were checked to ensure that the papers met the keyword eligibility. The result was a total of thirty-one articles: eight from Germany, seven from the European Union, six from Austria, two from Belgium, and eight from Denmark, which mainly discussed barriers and potentials for the circularity of wood waste in C&D (Figure 1) (see Supplementary Table S1).

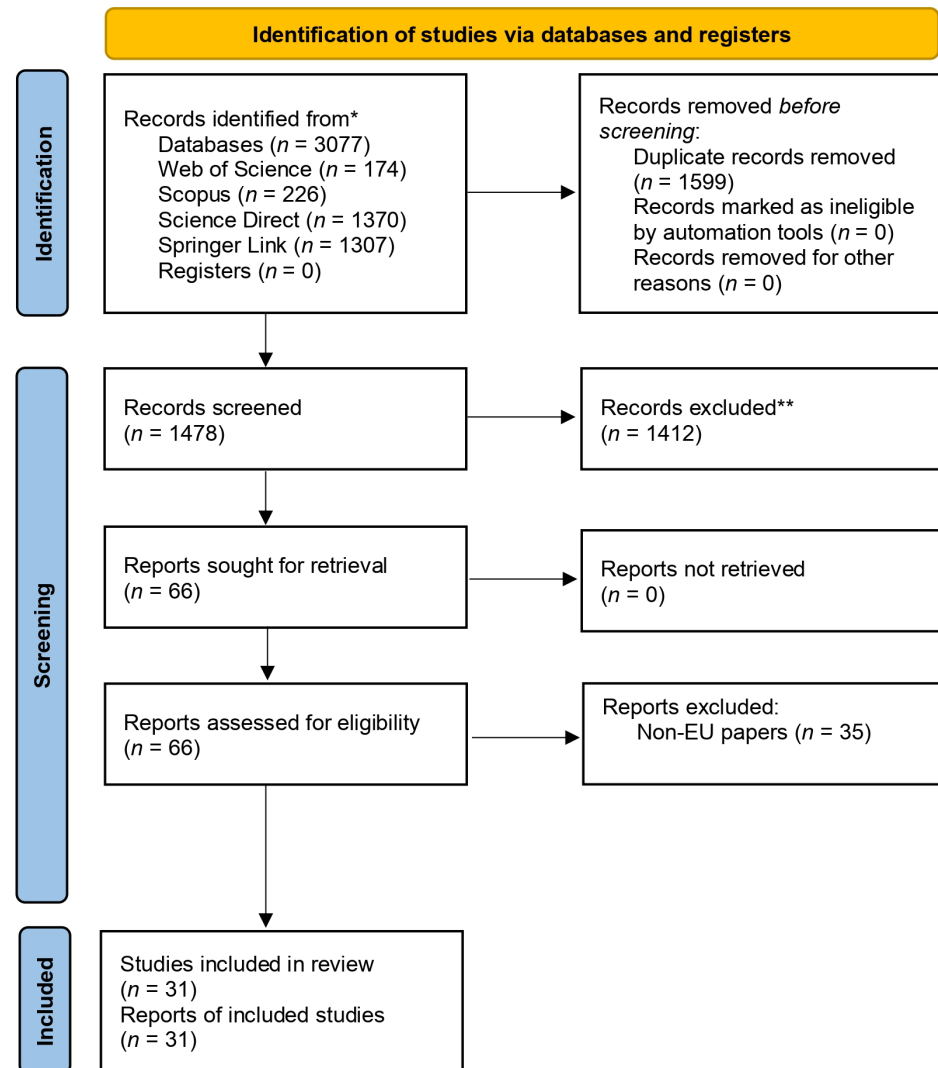


Figure 1. PRISMA flow diagram. * Numbers of records identified from each database/register are reported. ** Records excluded during title/abstract screening; all screening was performed by human reviewers (no automation tools used).

2.2. Selection of Papers from Germany, Denmark, Austria, and Belgium

Only publications from Austria, Belgium, Denmark, and Germany are considered in the review article as their wood waste classification is comparable and modeled after the German scheme of the German Waste Wood Ordinance [26]. The German wood waste classification divides wood into four categories, from AI to AIV, ranging from untreated wood (AI) to hazardous wood (AIV) [23].

Belgium's wood waste system is also divided into four grades identical to the German AI–AIV [27], and Denmark follows a similar four-category classification model (AI–AIV) to sort wood waste [27,28]. On the other hand, the Austrian Wood Ordinance defines 19 categories of wood waste that are suitable for recycling but exhibit similar goals to the German system based on the contamination and treatment classification [29]. Overall, all of these countries display a rooted, strong similarity to the German classification system.

3. Results and Discussion

The literature screening resulted in the distinction of “Barriers”, which hinder the circular economy, and “Potentials”, which promote the circular economy in the C&D industry, with a specific focus on wood. Five categories were formed to better classify

Barriers and Potentials: (1) Economic, (2) Societal, (3) Environmental, (4) Technical, and (5) Regulatory. A total of 26 barriers (Figure 2) and 25 potentials (Figure 3) were identified (see Supplementary Figure S1).

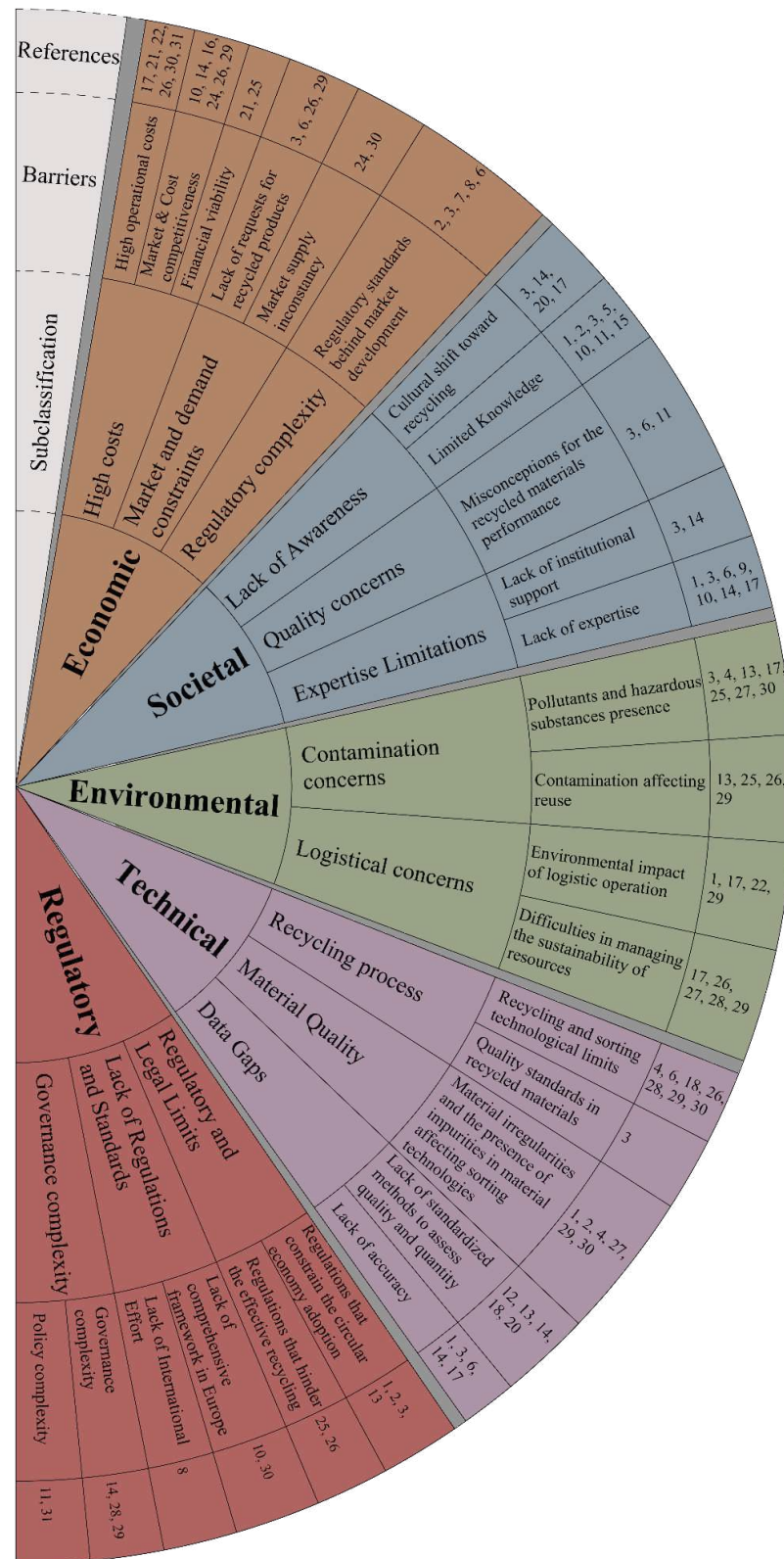


Figure 2. Five barrier categories with subclassification in the C&D sector.

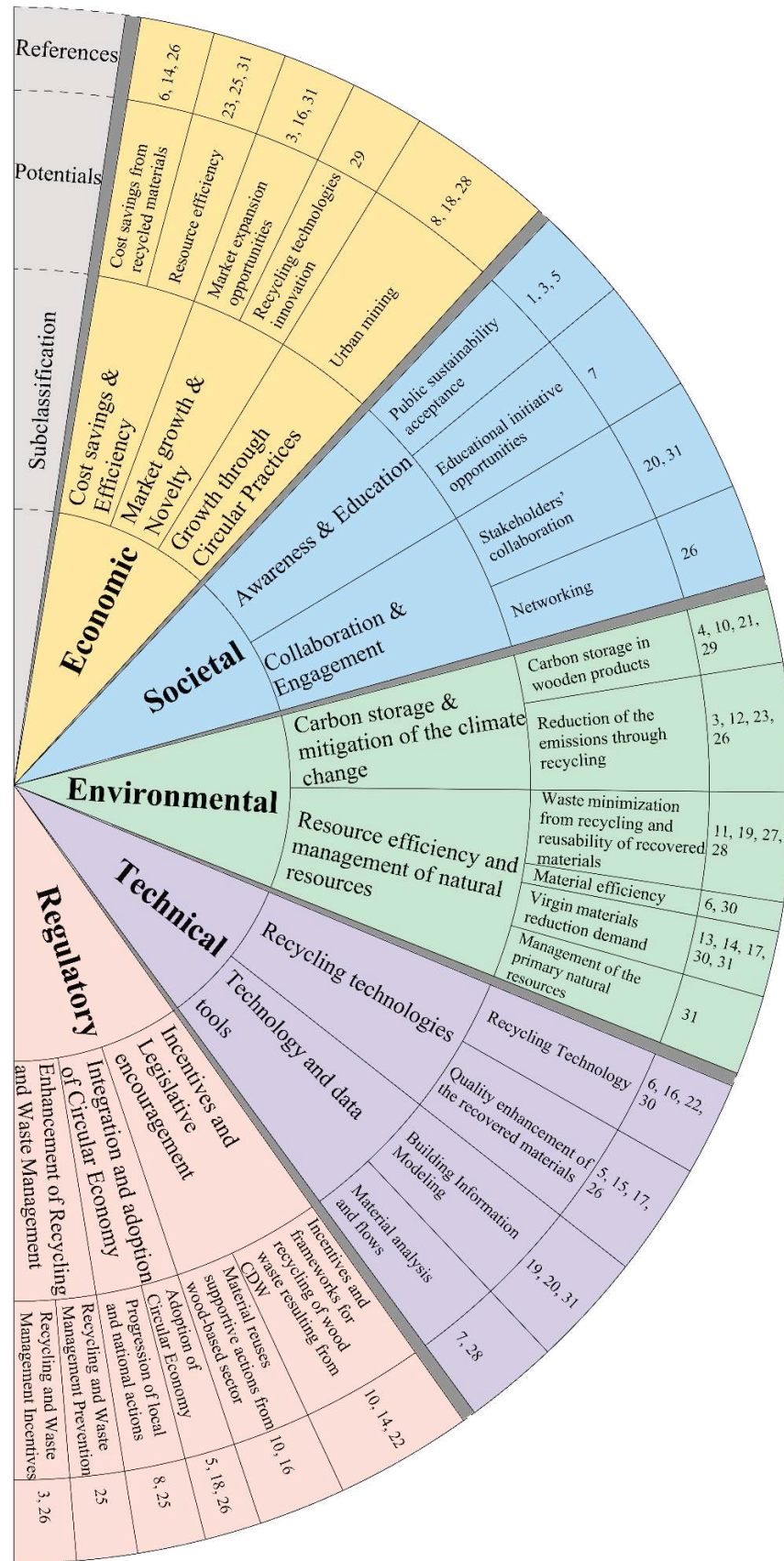


Figure 3. Five potential categories with subclassifications in the C&D sector.

3.1. Economic Barriers and Potentials

3.1.1. Economic Barriers

Economic barriers can be grouped into problems which are related to (1) high costs, (2) market and demand constraints, and (3) regulatory complexity (Figure 2).

High costs are the main economic barriers to the circular economy in C&D and can be grouped into high operational costs, competitiveness, and financial viability. High costs are associated with the C&D of structures, limited market demand for recovered materials, expensive secondary raw materials, low competitiveness against virgin materials, and costly advanced recycling methods [28,30,31]. Transport, processing, and reusability further increase costs, limiting the viability of secondary raw materials. Also, landfill taxes and post-demolition recycling are major cost drivers [32]. Additionally, the traditional lab analysis for wood waste sorting is time-consuming and expensive, making real-time classification unfeasible [33]. Selective demolition, while beneficial, is more expensive than conventional methods, especially when using innovative recycling techniques [30,34]. A key barrier to recycling and reusing wood from C&D is the lack of established marketplaces [31,35–38]. While some countries like Germany, Austria, Belgium, and Denmark are seeing growth in wood construction markets [39], concerns remain about the financial viability and risks of investing in unfamiliar recycling methods [34,40].

Market and demand constraints originate in the lack of marketplaces for demolition waste from wooden constructions [31,38,41]. Consumers are hesitant to buy items made from “waste,” while producers worry about pollutant levels and high recycling costs [41]. This reluctance is also driven by uncertainty around material quality [42] and limited, inconsistent supply [38]. Furthermore, the variability in timber dimensions and conditions discourages producers. Overall, the unpredictable supply of recycled materials makes the market less attractive compared to the reliable availability of virgin materials [37].

Regulatory complexity and unclear market dynamics further impede the recyclability and reusability of wood waste. For example, the German Waste Wood Act classifies wood waste into four categories (AI–AIV) based on contamination and treatment, which affects its potential for reuse [23]. Despite some wood being suitable for reuse, contamination often redirects it to energy recovery instead of recycling, limiting its contribution to the circular economy. These regulatory standards can be difficult to navigate and may unintentionally hinder the optimal reuse and recycling of wood from C&D [41,43,44].

3.1.2. Economic Potentials

Economic barriers can be overcome by potentials linked to (1) Cost savings and efficiency, (2) market growth and novelty, and (3) growth through circular practices (Figure 3).

Cost savings and efficiency are key advantages within the economic aspect of circular C&D. While selective demolition is more expensive due to added time and management, it can reduce waste management costs and offer long-term savings [31]. Risse et al. [42] found that recovered wood was 32% more cost-effective in material reuse compared to using it for energy. Compliance with regulations can also support economic gains in wood recycling in C&D [35]. Economic potential depends on how well local and regional markets are organized for reuse and recycling, which can lead to profitable business models [31]. Redirecting materials from energy recovery to reuse lowers operational costs and supports sustainability [45]. Stakeholder collaboration, early-stage planning, and improved recycling technologies also enhance economic performance and reduce costs [33]. Embracing innovative business models may turn waste into valuable economic opportunities [40].

Market growth and novelty: The growing demand in the wood sector highlights the necessity to develop the (recycled) materials market [36]. Platforms like DECORUM aim to support this by lowering material life cycle costs and promoting market expansion [33].

Market growth depends on a steady supply of high-quality secondary wood from C&D for material cascading [41]. Advancements in recycling technologies and innovative business models also play a key role in boosting reuse and integrating secondary materials, further expanding the market [38].

For instance, the expansion of the traditional recycled wood market has been increasing, as there are numerous ways in which recovered wood has been incorporated into value-added products. Wood-based panels such as particleboard and fiberboard account for a considerable share of post-consumer wood utilization. For example, Risse et al. [42] demonstrated that using recovered wood in glue-laminated timber products proved to be both economically and environmentally viable, further expanding the production of value-added products. Therefore, cascading recycled timber into high-value product uses offers a pathway beyond energy recovery [41].

Growth through circular practices: Urban mining represents a valuable stock of secondary raw materials for buildings [44]. However, each recycling cycle reduces material quality, so early planning of cascading steps is crucial for maintaining long-term value [46]. Circularity is also influenced by climate policies and data availability [47]. Strategically planning cascaded use, considering both quality and application types, optimizes material longevity and maximizes economic returns [46,47]. Nevertheless, the concentration of materials in buildings offers strong potential for economic returns and improved resource performance.

3.1.3. Integrating Potentials to Overcome Barriers

In Germany, implementing the circular use of construction and demolition (C&D) wood presents several practical and institutional challenges. Many existing buildings are not designed for future dismantling or reuse, and current demolition methods prioritize speed and low cost rather than strict material separation [48]. Another significant obstacle is quality assurance; examinations of salvaged wood reveal widespread contamination, with the vast majority of samples having pollution levels beyond the permitted limits set by Germany's Waste Wood Ordinance [49]. Reuse confidence in higher-value applications is limited by these material quality issues. Circularity has also traditionally been hindered by market incentives and policy. For instance, most A I waste wood was burned rather than cascaded since "clean" untreated wood (Altholz A I) was long directed toward energy recovery under national energy policy. Supply chains for recovered lumber are made more difficult by logistical challenges that wood recycling must overcome, such as huge, erratic "peak" amounts of C&D wood and inadequate recovery infrastructure [50]. New federal and regional policy tools will be needed to address these obstacles. For example, Germany's revised Circular Economy Strategy cites expanded producer responsibility and green public procurement as methods to encourage secondary wood markets and suggests amending the Altholz code to prioritize the material reuse of untreated wood [51]. Likewise, sectoral programs (like the Federal Timber Construction Initiative) promote more modular, deconstructable building designs and the use of recycled lumber in public projects [51,52].

Prioritizing circular practices such as selective demolition, although it has higher initial investments, results in cost-efficiency by improving material recovery quality and boosting competitiveness against virgin wood [31,42]. The encouragement of platforms like DECORUM and the promotion of early stakeholder collaboration support address market uncertainties by stabilizing supply consistency, reinforcing consumer confidence, shifting perceptions, and increasing demand for secondary wood products [35,37,41].

Additionally, local governments can also encourage change, like Berlin's Zero-Waste initiative assists design-for-disassembly techniques and "renewable, recyclable building materials such as wood" [52].

Unintended side effects must be avoided. For instance, persistent quality issues or onerous new labeling/certification requirements may erode market confidence, while excessively generous subsidies or required quotas for recycled wood may cause bureaucratic complications or distort traditional timber markets. To put it briefly, Germany has to overcome present obstacles with a logical combination of national and local standards, incentives, and communication tools. However, this needs to be carefully calibrated to avoid quality failures, regulatory overload, or market imbalances [49–52].

3.2. Societal Barriers and Potentials

3.2.1. Societal Barriers

Societal barriers can be grouped into problems which are related to the (1) lack of awareness, (2) quality concerns, and (3) expertise limitations (Figure 2).

The lack of awareness and knowledge of circular economy principles and sustainability among consumers, workers, and other participants from the C&D industry is one of the most significant societal barriers.

The lack of training in deconstruction skills, such as dismantling sequencing, access management, and component labeling at the vocational level (demolition and construction workers), presents the first level of educational hurdles for material recovery and reuse [53]. Meanwhile, the professional level also lacks knowledge in applying design-for-disassembly principles and recycled wood specification expertise among architects, engineers, and contractors; this restricts the use of secondary wood [54].

The lack of data on building material content poses a major challenge at the urban level, requiring urgent action [34]. In addition, raising sustainability awareness among demolition workers, especially non-academic staff, is essential [55].

Limited knowledge during demolition can lead to the loss of valuable secondary materials. Additionally, Design for Deconstruction, a strategy that facilitates the disassembly and recovery of building components, remains underutilized due to a gap between its potential and practitioners' understanding [56,57].

There is also a lack of awareness among stakeholders about wood cascading and recycling techniques [41,58], which hinders sustainable waste management. Improving information sharing can support circular economy adoption [39,58]. To bridge these gaps, [59] proposes a novel approach for the comprehensive documentation of demolition materials, enhancing knowledge and supporting sustainable practices in the sector.

The construction industry's hesitancy to recognize the value of recovered materials reflects a strong behavioral and cultural barrier to wood recycling [41]. Reusability and recovery are key to circularity but require a shift in social behavior [30]. Resistance to sustainability practices, along with challenges in adopting tools like Material Passports and Building Information Modeling (BIM), further illustrates the struggle to change industry norms [35,41].

Expertise limitations: A major barrier to recycling construction waste is the lack of strong government support and effective policy implementation [35]. Despite existing regulations, wood recycling and cascading practices remain underdeveloped due to limited practical application and support [41,42,55]. Schützenhofer et al. [30] highlight a gap in expertise in the C&D sector, such as the limited use of life cycle assessments (LCA), material stock analysis, and circular economy considerations for wood waste. To address these challenges, enhanced material monitoring and stronger policy actions across the EU Member States are essential [39,58].

3.2.2. Societal Potentials

Potentials which enable tackling societal barriers are meant to (1) spread awareness and to educate as well as (2) to build networks to collaborate and engage (Figure 3).

Awareness and Education: The lack of sustainability knowledge among construction workers (social barrier) can be tackled by improving communication aimed at boosting recycling and reuse rates in the C&D industry [55]. Höglmeier et al. [41] highlight the growing awareness of future price increases and the need for recovered materials. To support this, platforms like Madaster aim to standardize the knowledge of materials in the built environment [59]. Educational initiatives, such as rethinking the wood sector's role in the market, further support this shift [43].

Collaboration and Engagement: Collaboration and networking among stakeholders are key to unlocking the societal potential in circular C&D. Platforms like DECORUM foster connections throughout C&D processes [33]. Honic et al. [60] also stress the need for close cooperation to implement digital platforms for managing building material life cycles. Involving private companies and building strong networks helps create circular value chains, promotes knowledge sharing, and broadens stakeholder engagement. Municipal collaboration further strengthens future action and long-term partnerships [37].

3.2.3. Integrating Potentials to Overcome Barriers

The societal adoption of circular wood in C&D is still passive despite encouraging regulatory frameworks like Germany's timber-construction drive and the proposed Waste Wood Ordinance to promote material reuse [51]. Acceptance of secondary wood is hindered by a lack of knowledge about the quality of recycled timber and disjointed stakeholder networks. These elements are apparent in Germany and have also been documented in Austria, Belgium, and Denmark. They suggest that governance initiatives should focus on cooperation and education. In actuality, this can include integrating industry-focused training and collaborative platforms with legislative mandates. For instance, the literature emphasizes the necessity of coordinated legislative action in addition to professional education that is co-developed with businesses [61]. Cities such as Berlin promote university–industry collaborations and skill programs on eco-design, Material Passports, and life cycle costing to develop circular economy knowledge in accordance with OECD guidelines [52].

Rising virgin wood prices and the confirmation of cascading benefits can prompt designers, contractors, and customers to view recovered timber as a valuable resource [41]. Market inventories and Material Passport platforms such as Madaster provide evident quality data, building trust in recycled wood products [39,59]. When these insights are shared through DECORUM stakeholder networks and BIM-guided Design for Deconstruction, behavioral, technical, and policy barriers could be overcome, resulting in a functioning circular economy for construction wood waste [33,56–58].

However, there are trade-offs to such interventions: Rigorous retraining is required to address skill shortages in the workforce, and new compliance standards or certification schemes may cause existing enterprises to resist and increase short-term expenses [61].

3.3. Environmental Barriers and Potentials

3.3.1. Environmental Barriers

Although the environment is not fundamentally a barrier, the indirect negative impacts caused by present technical methods enable the classification of specific challenges as environmental barriers. Specifically, environmental barriers for implementing a circular economy in wood waste from C&D are linked to (1) contamination concerns and (2) logistical concerns (Figure 2).

Contamination concerns: The wide variety of construction materials, including wood, often contains hazardous substances, making recycling and reuse challenging. Contaminants such as PCBs (Polychlorinated Biphenyls), asbestos, lead, and metals in demolition wood waste pose serious environmental and health risks [28,30,40,41,62]. These risks are compounded by physical impurities like preservatives, nails, bolts, and paint [63], especially in low-quality wood with higher contamination levels [64].

Wood should not be treated as a uniform material flow due to its varied sources and pollutant levels [65]. Current technical limitations in sorting, cleaning, and handling wood waste significantly influence the level of contamination, resulting in environmental challenges. Improving wood waste quality and shifting demolition practices are essential, as a significant amount of the waste is currently downcycled or destroyed [40].

Moreover, demolition produces particulate emissions with higher levels of respirable and inhalable dust that negatively impact local air quality and remain a persistent problem. These co-impacts serve as operational constraints that need to be managed in relation to demolition and selective sorting, although a full pollution inventory is beyond the scope of our wood-focused research [66]. Pre-demolition audits are crucial for identifying and removing contaminants prior to demolition, therefore allowing safer reuse and recycling [38,62]. Ultimately, the responsibility lies with the expertise of companies and clients to manage wood waste in C&D safely and effectively [31].

Logistical impacts: According to Rheude et al. [55], logistics play a significant role in Global Warming Potential Emissions, specifically because of the environmental impact of transporting the waste material. Transporting waste to recycling plants contributes significantly to both the environmental footprint and costs [30,32]. To address this, switching to electric vehicles for transport can significantly reduce emissions [55]. Furthermore, improving communication between new C&D projects, as well as analyzing strategic planning on transport distances and local demand, can substantially reduce the carbon footprint [30,38].

Heavy machinery activities and material transport are important factors that impact C&D wood circularity outcomes. Reducing haul distances and synchronizing demolition dates with local demand improve technical and economic viability, since transporting material to sorting facilities increases both costs and life cycle impacts [30,55]. In addition to transportation, wood waste management also has significant environmental impacts. It is especially complex due to varying quality and dimensions [31]. Poor sorting can result in pollutants spreading between materials, which compound the environmental impacts [65]. The lack of incentives for more efficient recovery and the complexities of cascading steps [46] highlight the need for expert management and improved material inventories to ensure sustainable wood waste management [30].

3.3.2. Environmental Potentials

Potentials to tackle environmental barriers are linked to (1) the storage of carbon and mitigation of climate change and (2) the resource efficiency and management of natural resources (Figure 3).

Carbon storage and mitigation of climate change: Building with wood material helps the climate policy goals, as wood is considered a low-carbon material [34,39]. Timber, when utilized as a secondary material, provides considerable reductions in carbon emissions by substituting more environmentally detrimental processes.

Secondary wood greatly enhances climate performance from a life cycle assessment (LCA) standpoint by increasing carbon storage in products and providing substitution advantages, as compared to fossil-based alternatives [67]. Secondary timber materials generally emit 30–50% of the carbon emissions caused by conventional materials [38]. High-

value cascade uses, such as remanufacturing into panels or engineered wood, provide larger greenhouse gas (GHG) reductions than instantaneous energy recovery [68].

Asa et al. [63] presented an innovative approach for carbon sequestration by wrapping timber beams in clay plaster. This method helps to maintain surface imperfections and additionally functions as a barrier of protection against moisture and contaminants, including lead. The waste industry has the potential to reduce greenhouse gas (GHG) emissions [41]. Selective demolition and sorting and separating materials for reuse can save emissions [31]. Höglmeier et al. [41] discovered that 44% of recovered timber from C&D was suitable for high-quality applications like fiberboards, which enhance carbon storage and increase GHG reductions. Cascading wood products may further reduce emissions in the future [34]. Zeller et al. [45] suggested improving the sorting efficiency to enhance emission reductions.

Resource efficiency and management of natural resources: Implementing advanced recycling technologies for C&D wood waste provides a significant advantage to both resource efficiency and the EU's circular economy transition [58]. Faraca et al. [64] came up with a classification system of construction materials based on their source, quality, and type, which enhanced the recycling process. Cascading wood waste implementations are shown in some products, such as recycling timber into glue-laminated products, with 29% lower environmental impacts and costs [42]. Sorting the waste materials in the correct way improves recycling options, maximizes resource efficiency, and helps enhance environmental performance [28]. Managing natural resources, especially wood waste, offers significant environmental benefits by reducing the demand for virgin materials. Recycling wood into value-added products, such as insulation, represents a profitable alternative to energy recovery [62]. Material Passports support both resource efficiency and effective waste management by providing detailed data on material quality, type, and contamination, thereby improving recycling potential and circular practices at a building's end of life [30,69]. The DECORUM project, introduced by Luciano et al. [33], creates a circular economy framework by minimizing raw material use, promoting recycled materials, and refining selective demolition practices. The project also develops sustainable markets for recovered materials. Stakeholders increasingly recognize that reusing waste wood, instead of disposing of it via landfills or incinerators, significantly enhances resource efficiency and reduces environmental impact by promoting the production of recovered wooden products [28,33].

3.3.3. Integrating Potentials to Overcome Barriers

There are several obstacles in Germany that prevent the circular economy from reusing C&D wood. The quality of recovered timber is limited by contaminants including paints, preservatives, embedded metals, and uneven sorting, and there are no official standards or certifications for recycled wood [70]. Technical limitations in sorting and cleaning wood waste critically influence contamination levels, but implementing a detailed classification system based on material source, quality, and type enhances recycling efficiency, significantly reducing contamination [40,64]. Additionally, creating Material Passports improves data accuracy, facilitating better material classification and pre-demolition audits to remove contaminants effectively [30,38,64,69]. Lastly, optimized logistics adopting electric transportation and aligning local demand with demolition planning can substantially minimize carbon emissions [30,38,55].

To address these challenges, new legislative tools are needed such as Germany's updated Waste Wood Ordinance to prioritize the reuse of untreated wood, and secondary markets might be strengthened by extended producer-responsibility programs or recycled-content procurement standards [51]. Even positive actions have risks; for example, reusing

energy waste wood for new construction without taking carbon into account might lead to an increase in the usage of fossil fuels [71]. To make sure that wood reuse policies do not have unforeseen negative effects on the environment or society, circular techniques must be combined with strict life cycle controls like material screening and open material flow accounting.

3.4. Technical Barriers and Potentials

3.4.1. Technical Barriers

Technical barriers hindering the circularity of wood in C&D can be grouped into (1) recycling processes, (2) material quality, and (3) data gaps (Figure 2).

Recycling Process: The heterogeneous nature of wood waste and its current categorization based on visual assessments create significant challenges for effective recycling [28]. The lack of a streamlined sorting process complicates circular practices, making them more complex and time-consuming [28,31,37]. For example, a study in Germany found that, while 97.6% of materials from demolitions were categorized by construction elements, only 19.7% were separated by waste type, resulting in a low recycling rate of 5.3% [55]. Hence, new technologies are necessary to improve the quality and longevity of construction materials, supporting a circular bioeconomy [41]. Additionally, further research is needed to enhance recycling processes [47] and improve the practical performance of these processes [42]. The quality of wood waste is of critical concern: A1 and AII-classified wood is suitable for high-quality products like OSB and particleboards [41]; however, only 27% of wood waste meets the criteria for these products, with particleboard standards allowing recovery up to 45% [41]. On the contrary, Honic et al. [34] emphasize that the industry has been limited to only producing particleboards, as the wood waste quality standards constrain other specialized markets. Thus, strict wood waste quality standards limit the industry's opportunities beyond particleboards.

Material Quality: Material irregularities, such as metal fasteners or dimensional distortions, are major obstacles to recovering construction wood waste. Contamination affects the usability of wood waste [28], while metal fasteners complicate machining processes unless they are cleaned from recovered timber [64]. Sorting materials during demolition is often impractical and expensive [55]. However, improved sorting methods and handling procedures for wood waste are essential to enhance its quality [65].

Most studies show that the mechanical properties of recovered timber are similar to new timber [64]. Untreated wood, such as off-cuts, pallets, and demolition wood, tends to have fewer impurities, making it more suitable for reuse [65]. Recovered solid wood from construction is often of sufficient quality for high-end products, but it must be carefully assessed [56]. Non-destructive tests, like moisture content and density evaluations, are necessary for a more accurate assessment of recovered wood quality [64]. Hence, further research and advancements in material evaluation are critical to improve secondary construction material quality [37,38].

Data Gaps: Technical barriers such as data shortages and a lack of clarity regarding the quality and quantity of construction wood waste hinder efficient recycling. The absence of comprehensive data on recovered timber quality leads to inconsistent and unreliable results [34,35,47,60,62] which must be harmonized for effective circular economy monitoring [47]. Accurate building information throughout its life cycle is essential for better material management [30,35,55]. Detailed data on the materials used in construction and disassembly methods are critical [41,55]. Therefore, a comprehensive data inventory is necessary when modeling building data for future reuse and recycling [42].

3.4.2. Technical Potentials

Potentials to tackle technical barriers are linked to (1) recycling technologies and (2) technology and data tools (Figure 3).

Recycling Technologies: A key technical opportunity lies in advancing recycling technologies to improve the quality and efficiency of recovered materials. Risse et al. [42] highlight the development of new recycling technologies, such as turning recovered wood into glue-laminated products. Prioritizing the improvement of mechanical properties could yield better recycling outcomes [36]. Mancini and Rinnan [28] suggest that online near-infrared (NIR) sorting techniques can enhance wood waste classification, enabling contaminants to be identified and removed for appropriate reuse. Additionally, advancements in recycling technologies benefit not only the timber industry but also other construction materials, such as concrete and brick, by increasing their recyclability potential [28,32,36].

Improving recycling technologies can significantly enhance the quality and reusability of recovered wood waste from the C&D industry. To further enhance material performance, De Lima et al. [57] recommend integrating project support tools, including material selection, connected element methods, and the recycling potential of recovered materials. Such technical enhancements could increase recycling rates and improve material adaptability for future building projects. Christensen et al. [31] also emphasize the importance of selective demolition guidelines and the experience of workers, which can significantly affect the quality of recovered materials.

The integration of Building Information Modeling (BIM) and Radio Frequency Identification (RFID) in the C&D industry offers enormous potential. These technologies provide a detailed understanding of material composition, allowing for a better analysis before deconstruction [30]. An example is the Umar project, which successfully used 95% of renewable and non-virgin materials, achieving up to 92% material reuse. Integrating circular indicators and Material Passports guarantees the quality of recovered materials, paving the way for a transition to a circular construction sector [59]. Hence, BIM and RFID technologies present promising sustainability benefits for the industry's future.

Technology and data tools: Data tools, Building Information Modeling (BIM), and material flow models represent the second key technological opportunity for improving material management in construction. BIM and Material Passports provide a comprehensive framework for evaluating the recycling potential and environmental impact of building materials [60]. The integration of BIM with laser scanning technology for surveying pre-demolition buildings holds promise, offering valuable data on building components. However, these tools currently lack material-specific information [34,69]. Despite this limitation, they remain powerful tools that help inform future approaches to managing building materials.

Additionally, the development of recycling applications, with an emphasis on quality over quantity of wood waste, has been shown to lead to significant greenhouse gas savings [46]. Furthermore, developing models that link the timber industry to various production stages and circular economy strategies contributes to the expansion of the material network structure, fostering greater circularity in construction [43].

3.4.3. Integrating Potentials to Overcome Barriers

Innovative wood reuse techniques face a number of challenges in the German context, which is also somewhat represented in Austria and Belgium. Implementation is hindered by market uncertainties and long-standing regulations, like old-fashioned waste wood classifications, as stakeholders frequently point to regulatory gaps like ambiguous “end of waste” regulations and legacy practices as obstacles [72].

The nature of the heterogeneity of the wood waste, as well as contamination, is linked to improving recycling by utilizing advanced sorting technologies, such as utilizing online NIR techniques, which efficiently make material recovery possible [28,36]. Moreover, documenting the Material Passports, introducing this information in BIM, and using Radio Frequency Identification (RFID) enhances circular practices, shrinks the data gaps, and improves data clarity and material traceability [30,59,60]. Innovative techniques for detection may significantly simplify the process of identifying irregularities and increasing recycling effectiveness [63].

Therefore, reforming standards and implementing financial incentives like subsidies and public procurement requirements to assist with deconstruction and quality assurance are two examples of policy tools that must be in line with technical solutions to address these issues [73]. In order to close legislative gaps and give investors certainty, it is also essential to promote the cooperation between the government and industry [30]. The need for systematic impact assessments in conjunction with new policies is highlighted by the possibility that increasing wood reuse could unintentionally shift environmental burdens like contamination risks or rebound effects from altered timber supply or create economic distortions if not carefully managed.

3.5. Regulatory Barriers and Potentials

3.5.1. Regulatory Barriers

Regulatory barriers portray the (1) regulatory and legal limits, (2) lack of regulations and standards, and (3) the complexity of policies and governance (Figure 2).

Regulatory and legal limits: There is still a gap between what regulations like the German Waste Wood Ordinance are aiming for and what is actually happening on the ground when it comes to recovering wood waste from C&D. Better clarity and practical solutions are needed, especially since monitoring and real implementation still fall short [55]. The ordinance categorizes waste wood based on potential contaminants, explicitly restricting the reuse of recovered timber, primarily due to impurity concerns [56]. As mentioned above, the ordinance allows for the reuse of AI and AII classified wood as secondary feedstock or engineered wood products, but it does not approve the reusability of load-bearing structures [41,56].

Despite this, studies show that even recovered wood from ceilings and roof structures, classified as AIV, could be considered for potential reusability for interior design, board manufacturing, or for being part of load-bearing structures [41]. Meanwhile, high-value wood materials like glue-laminated and cross-laminated timber also show potential [56]. However, Arm et al. [62] highlight that the EU Member States interpret recovery regulations differently, affecting their material classification and recovery procedures. As a result, the implementation of the EU's recovery targets does not ensure fully aligned resource recovery.

To improve the circular economy with wood, regulatory refinements that consider additional wood attributes besides contamination levels could improve reuse potential. Furthermore, variations in national policies can limit or hinder circular economy initiatives [40], emphasizing the need for greater alignment and integration across the EU.

The lack of regulations and standards highlights the need for integrated policies and a comprehensive framework for wood product application in Europe. Highly inconsistent regulations and classifications of wood waste across European countries hinder efficient recycling, management, and international cooperation [28,39]. When a wood product is deemed unfit for reuse, recycling, or energy production in one country due to varying regulations, it may be allowed in another [28].

There is a policy discrepancy among EU cross-border countries' cooperation for the efficient utilization of wood waste trading, as still, the regulations remain very heterogeneous

for wood waste classifications. So, an absence of a harmonized EU waste wood regulatory framework presents the need for a uniform EU waste wood regulatory structure that would address the obstacles to waste wood use while also assisting the cross-border trading of waste wood across the EU [74].

Such regulatory fragmentation limits the development of wood as a sustainable building material, market expansion, and cross-border trade [39].

Therefore, international efforts to enhance knowledge transfer and distinguish between country-specific regulations are crucial, as they help foster awareness of the benefits of the circular economy [44].

Governance complexity: EU countries have developed several policy instruments aimed at promoting resource efficiency in the building sector, including the Waste Framework Directive, the Circular Economy Action Plan, the Roadmap to a Resource-Efficient Europe, and the Communication on Resource Efficiency in the building sector [35,38].

However, while the target of recycling 70% of C&D waste is in place, current efforts primarily focus on material quality, neglecting the importance of material design and production improvements [38,58]. Luciano et al. [35] highlight that the main barrier to increased recycling and reuse is the complexity of governance, along with insufficient governmental support and landfill disposal taxation, which hinders progress toward a circular economy [35,47,58]. Despite this, there is hope for a more widespread adoption of selective demolition, even though it is not yet a mandatory requirement across the EU [35,58].

3.5.2. Regulatory Potentials

Regulatory potentials for implementing a circular economy in wood waste from C&D are linked to (1) incentives and legislative encouragement, (2) integration and adoption of the circular economy, and (3) enhancement of recycling and waste management (Figure 3).

Incentives and Legislative Encouragement: The incentives, supportive policies, and frameworks for recycling wood waste resulting from C&D represent a key regulatory potential. Recommending government requirements, enhancing training on recycled materials, and promoting financial incentives for their use in construction and restoration are seen as the most compelling framework guidance for improving the sector [35]. The frameworks should support strengthening the wood-based building sector in Europe, such as low-carbon incentives for the building industry [39]. Enhancing the highest quality of the construction demolition waste (CDW) can decrease the environmental consequences. Sikkema et al. [39] suggest that raising landfill taxes, recycling plant fees, and the price of recovered materials can drive a shift toward a more sustainable CDW system. At the same time, Sikkema et al. [39] propose repeating material inventories in the future to assess policy effectiveness. In line with the European Green Deal's goal of net-zero emissions by 2050 and the EU Circular Economy Action Plan's focus on long-term carbon storage in construction wood, another potential lies in the promotion of material reuse in the wood-based C&D sector [39]. As a result of the wood construction material recovered, no waste and carbon emissions are effectively produced, as the carbon level remains balanced within the reusability phase and its almost constant concentration in the atmosphere [36].

Integration and Adoption of Circular Economy: The integration of the circular economy, as discussed in several studies, highlights the important role of political incentives in supporting circular principles within national and local frameworks. While the EU has set a transition goal from linear to a circular economy across the Member States by 2050, most research has focused more on how circular practices are applied at the product level, both locally and nationally, although national monitoring systems are still not developed [47]. A key step in this transition is documenting progress through circular indicators. In this

direction, some research projects, like BAMB—buildings as material banks, are working on developing methods and tools [59]. The EU’s Circular Economy Package aims to combine such research with political support in national and local policies but still needs to address challenges like material loss during down-cycling [47]. At the same time, Christensen et al. [31] stress the role of municipalities in driving motivation, for example, by identifying local marketplaces, sharing knowledge, and building stronger cooperation among stakeholders involved in construction with recovered materials. Their involvement is essential for managing local capacities and supporting the shift toward circularity.

Enhancement of Recycling and Waste Management: Another potential way to implement circularity in the regulatory group is to enhance recycling and waste management and improve management incentives. Christensen [40] discusses the potential of closing the urban material construction loop and developing circularity by combining governance with institutions and businesses. Meanwhile, Höglmeier et al. [41] mention that adaptations should be considered in the legal guidelines for improving the waste and recycling of recovered materials regarding contamination and materials quality.

3.5.3. Integrating Potentials to Overcome Barriers

Regulatory obstacles obstruct circular wood recovery despite ambitious policy goals, for example, high-grade wood is frequently burned rather than being recycled in Germany, where the AltholzV enforces strict classifications [75]. By addressing existing regulatory gaps, such as those identified in the German Waste Wood Ordinance, through clearer guidelines and pragmatic local-level solutions, tangible outcomes can emerge. For instance, if municipalities proactively engage in mapping local reuse markets and facilitating active stakeholder dialogs, barriers stemming from fragmented regulatory frameworks could significantly diminish [31]. Consequently, the improved clarity and harmonization across EU Member States could stimulate uniform standards, enabling smoother cross-border recycling and enhanced market opportunities for recycled wood materials [35,38]. As a result, the early integration of these practical regulatory improvements would create conditions favorable for achieving circular goals more effectively and sustainably. Policy tools such as amending the Waste Wood Ordinance, standardizing EU end-of-waste standards, charging landfill or incinerator costs, and increasing producer accountability to promote material usage are necessary to close these gaps. However, such measures may have unexpected consequences, such as discouraging uptake due to greater prices and uncertainty in recycled wood quality [70], and they may also increase the complexity and expense of compliance.

4. Conclusions

The uniqueness of this study lies in its aim to analyze why wood waste is largely recycled, and only a small proportion is reused in construction, and the consequences that higher levels of reuse would bring. Addressing the review questions, our research identifies that the application of wood waste in the C&D sector is primarily hindered by economic barriers (high costs, market constraints, and regulatory complexity), societal barriers (limited awareness of circular practices, quality risks, and expertise and skill gaps), environmental barriers (logistic and contaminants concerns), technical barriers (inadequate sorting and quality data, material irregularities, and heterogeneous streams), and regulatory barriers (legal restrictions on reuse, fragmented standards, and governance complexity).

We found that these factors can individually but also collectively act as enablers for a circular economy model when their specific barriers are identified and overcome. Each of these fields contains specific subcategories that directly influence the effective implementation of circular wood waste management. As shown in sector-specific sessions [76], societal

awareness is key for long-term shifts towards more resource-efficient behavior, which must go along with an enhanced introduction of resource-focused topics in education. Although these measures only act on a long-term perspective, they are the basis for a sustainable shift.

In the short run, simplified regulatory frameworks with a holistic and aligned focus may support the utilization of waste with a better resource value. Still, it is questionable how regulatory frameworks can further be improved to better promote the circular economy within the wood sector. Considering Europe's changing wood resources and growing demand for sustainable alternatives, future regulations must address additional factors. Enhanced policy involvement could contribute greatly to overcome the fragmentation of EU-wide framework regulations and their implementation on national levels to ensure an efficient recovery.

Beyond supporting policy frameworks, concrete governmental recommendations for circularity and incentivization can also be important levers for economic and environmental benefits. The most discussed barriers within the transformation towards the more circular processing of waste wood are high costs, unstable markets, and contaminations. For this, regulations should allow for the effective management of large quantities of wood waste through improved sorting processes that consider additional attributes besides contamination, such as wood quality, dimensions, and carbon storage capabilities in assessing its reusability. This assessment will be operationalized through pre-demolition audits, Material Passports, and BIM plus RFID to ensure traceability and upgrade decisions at scale. Selective demolition, online NIR sorting, and the mixed-use integration of wood with concrete or brick recycling lines strengthen this approach, while the municipal map local reuse markets and coordinated logistics transportation reduce emissions and stabilize the supply.

Addressing these regulatory aspects would establish a framework for the practical application of circular economy principles, thus boosting the adaptability and sustainability of timber markets, as well as strengthening local market dynamics.

This would directly result in environmental benefits, such as reduced emissions and improved logistics efficiency.

Additionally, such advancements would indirectly address social concerns by making secondary wood products more affordable and accessible to consumers. Over time, this would reduce the dependence on virgin resources and further enhance sustainability achievements within the C&D industry.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/urbansci9090367/s1>, Table S1: Selected papers from Germany, EU, Austria, Belgium and Denmark; Figure S1: Five merged barrier and potential categories with subclassifications in the C&D sector.

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Abbreviations

The following abbreviations are used in this manuscript:

C&D	Construction and Demolition
CDW	Construction Demolition Waste
BIM	Building Modeling Information
GHG	Greenhouse Gas
NIR	Near Infrared
RFID	Radio Frequency Identification

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