



Review paper

## Navigating circular economy in key construction materials – Part 1: general regulations and reuse, recycling, and circular practices for steel and timber

Mirjana Malešev<sup>\*1)</sup>, Vlastimir Radonjanin<sup>1)</sup>, Rand Askar<sup>2)</sup>, Ana Nadaždi<sup>3)</sup>, Bilge Bas<sup>4)</sup>, Milena Rajić<sup>5)</sup>, Evrim Celik Madenli<sup>6)</sup>, Edip Avşar<sup>7)</sup>, Anka Starčev-Čurčin<sup>8)</sup>, Vesna Bulatović<sup>8)</sup>, Ayfer Dönmez Çavdar<sup>9)</sup>, Ivan Lukić<sup>8)</sup>, Tatjana Kočetov-Mišulić<sup>8)</sup>

<sup>1)</sup> Institute for testing, assessment and repair of structures, Novi Sad, Serbia

<sup>2)</sup> University of Minho, Department of Civil Engineering, Guimaraes, Portugal

<sup>3)</sup> University of Belgrade, Faculty of Civil Engineering, Belgrade, Serbia

<sup>4)</sup> Istanbul Bilgi University, Department of Civil Engineering, Istanbul, Turkey

<sup>5)</sup> University of Nis, Faculty of Mechanical Engineering, Nis, Serbia

<sup>6)</sup> University of Liverpool, Liverpool, UK

<sup>7)</sup> Bilecik Şeyh Edebali University, Department of Environmental Protection Technologies, Turkey

<sup>8)</sup> University of Novi Sad, Faculty of Technical Sciences, Novi Sad, Serbia

<sup>9)</sup> Karadeniz Technical University, Trabzon Turkey

### Article history

Received: 23 January 2026

Received in revised form:

23 March 2026

Accepted: 25 March 2026

Available online: 14 April 2026

### Keywords

construction and demolition waste,  
circular economy,  
construction materials,  
steel,  
timber,  
recycling rates,  
recycling efficiency,  
reuse processes,  
reuse potential

### ABSTRACT

Construction and demolition waste represents one of the largest waste streams worldwide and plays a central role in achieving circular economy objectives in the built environment. This study aims to systematize and synthesize recent knowledge on the potential for reuse and recycling of key construction materials - steel, timber, concrete, and bricks and blocks - at the end of their service life. The research is structured in two papers: Part 1 focuses on regulatory frameworks, recycling rates, and reuse and recycling practices for steel and timber, while Part 2 addresses concrete and bricks and blocks. The objective was to identify opportunities for reuse and higher-value recycling as more effective circular solutions. The results indicate that, although the European regulatory framework for C&DW is well developed and aligned with circular economy principles, significant gaps remain, particularly the lack of harmonized end-of-waste criteria and quality standards for most material fractions. Consequently, high reported recovery rates often conceal downcycling practices and limited material circularity. Steel exhibits consistently high recycling rates, driven by strong market demand and established regulatory criteria, while direct reuse remains marginal. In contrast, timber recovery is dominated by energy recovery, with material recycling and reuse constrained by heterogeneous material quality, limited classification systems, and insufficient policy support.

## 1 Introduction

As the world progresses towards an urban future, the linear economic model, characterized by the "take, make, and dispose" pattern, has experienced significant growth. However, this model presents challenges, including resource supply risks and increased waste generation. The idea of developing a circular economy (CE) model was inspired by natural ecosystems that produce no waste. Therefore, the circular economy aims to close the loops in industrial ecosystems by applying the principles of "reduce", "reuse", and "recycle" (3Rs), thereby preventing the creation of waste and transforming waste into resources. The main concept of CE is to limit resource consumption, reduce waste, and decrease gas emissions, while ensuring global economic development is not disrupted. Circular Economy is described

by Geissdoerfer et al. 2017 as "a regenerative system in which resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops. This can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling" [1]. Construction and demolition waste (C&DW) is the primary source of gross waste generation in modern society. The amount of C&DW grows along with worldwide urbanization. EU-28 has good practice thanks to an advanced C&DW management system supported by policies, laws, regulations, and technologies for C&DW management. Thus, in 2018, the C&DW recovery rate in the EU-28 was about 90% [2].

\* Corresponding author:

E-mail address: [miram@uns.ac.rs](mailto:miram@uns.ac.rs)

C&DW is the largest waste stream in the European Union (EU), which accounts for almost 40% of all waste generated in the EU. Expanding the construction sector leads to a corresponding increase in construction materials. In 2020, demolition and renovation were responsible for 83% and 17% of material flows, respectively. Corresponding percentages for 2050 are expected to be 87% and 13% [3]. C&DW is composed of different waste fractions and materials registered under specific codes according to two main coding systems applied within the EU: the List of Waste (LoW), which is administration-oriented, and the European Waste Code Statistics (EWC-Stat), which is substance-oriented. The average composition of C&DW is presented in Fig. 1 [4].

According to Fig. 1, concrete, bricks, metals, and wood are dominant fractions of C&DW.

The Waste Framework Directive 2008/98/EC (WFD) [5] is a milestone of modern waste management in the EU. A notable contribution of the WFD is the introduction of the waste hierarchy. Contrary to the 3Rs framework of circular economy, which focuses on reducing, reusing, and recycling, the waste hierarchy prioritizes waste management strategies through a five-stage inverted pyramid. The hierarchy ranges from the most preferred option of "prevention" to the least preferred option of "disposal" (Fig. 2).

From a life cycle perspective, both the waste hierarchy and circular economy consider the whole life cycle of a product, including the pre-use phase, use phase, and post-use phase. (1) The first stage of the waste hierarchy pyramid

is prevention, which is considered the pre-use phase. To meet the basic requirements of prevention, the smarter creation and use of products should be prioritized. (2) The second stage involves preparing for reuse during the use phase, aiming to extend component life through reuse. (3) The third stage of the hierarchy pyramid involves recycling, other recovery methods, and disposal, which are part of the post-use phase. It is important to identify useful applications for waste materials and to minimize disposal. The minor difference is that the waste hierarchy still allows disposal, while the framework of a circular economy does not [2].

Directive (EU) 2018/851 [6] introduces a new concept within the waste hierarchy, namely "material recovery." This term refers to forms of recovery other than energy recovery and excludes the reprocessing of waste into materials used as fuel or other means of generating energy. It includes preparing for re-use, recycling and backfilling and other forms of material recovery such as the reprocessing of waste into secondary raw materials for engineering purposes in construction of roads or other infrastructure. In addition, the Directive defines the term "backfilling" as any recovery operation in which suitable non-hazardous waste is used for the reclamation of excavated areas or for engineering purposes in landscaping.

Taking these newly introduced concepts within the waste hierarchy into account, we modified the original "waste hierarchy pyramid" as defined in [5]. The revised structure of waste hierarchy pyramid is presented in Fig. 3.

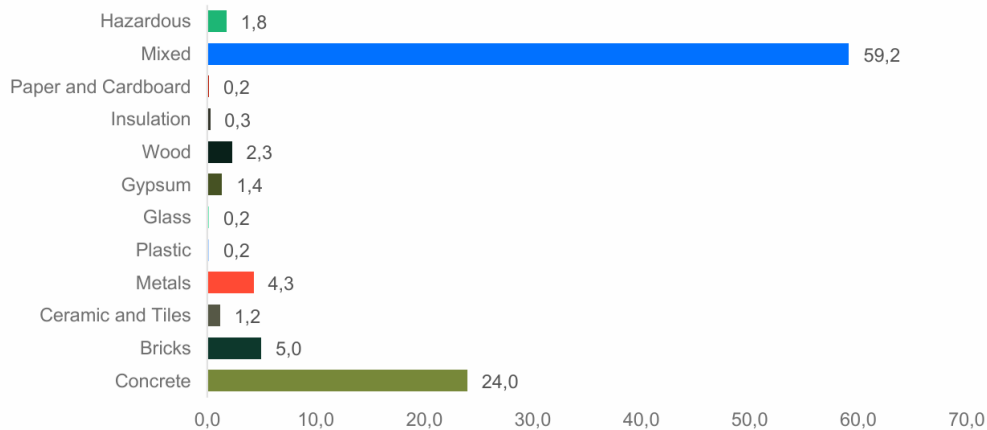


Figure 1. C&DW composition in the EU [4]



Figure 2. Waste hierarchy pyramid according to WFD 2008/98/EC [5]

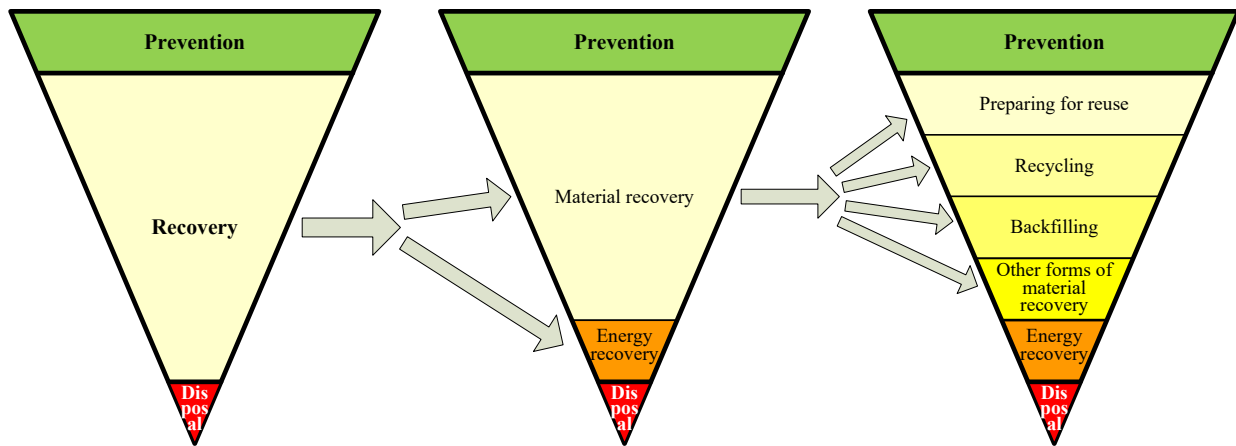


Figure 3. Adapted waste hierarchy pyramid according to Directive 2018/581/EC, [5]

Although Directive [5] proposes the selective collection of waste, Directive [6] provides additional clarifications aimed at improving the waste management system. In this context, Member States shall take the necessary measures to ensure that waste undergoes preparation for reuse, recycling, or other recovery operations in accordance with the waste hierarchy and respecting the protection of human health and the environment. These measures include, where necessary, the application of separate collection to prevent mixing with other waste or materials with different properties. When it comes to C&DW, Member States shall take measures to promote selective demolition to enable the removal and safe handling of hazardous substances and to facilitate re-use and high-quality recycling through the selective removal of materials, as well as to ensure the establishment of sorting systems, at least for wood, mineral fractions (concrete, bricks, tiles and ceramics, stones), metal, glass, plastic, and plaster.

In the case of buildings and construction materials, "prevention" is ensured by achieving "Longevity" and "Durability". This is achieved primarily by appropriate design, comprehensive quality control during construction, and proper maintenance.

Reuse is using an object or material again, either for its original or a similar purpose, without significantly altering the physical form of the object or material. In a fully circular economy, the reuse of a manufactured product is considered in the earliest design phases of its creation [7]. Reuse makes good environmental sense, saving both resources and carbon emissions [8]. It is a high priority that the natural resource extraction for construction should be slashed down by developing alternative technologies, such as direct reuse in construction, to reduce the unsustainable pressure on the environment [9].

Existing buildings can be reused in situ or dismantled and re-erected at a different location. By reusing existing buildings, not only is demolition waste minimized, but the new resources required to renovate and refurbish the building are much less than those required to construct a new building. In addition, reusing existing buildings can preserve the cultural and historic value of older buildings [10].

It is also possible, but less desirable, to reuse building structural components/products individually by sending them to warehouses and building material suppliers to be used for new purposes.

By promoting circularity in construction and fostering trust in recycled materials, the most recent Joint Research Centre report on the management of C&DW in the EU, published in 2024, aims to improve C&DW management [11]. The report emphasizes the significance of transparent waste logistics, selective demolition, and pre-demolition audits. Additionally, to encourage circularity in construction, it highlights the necessity of policy frameworks that foster cooperation between industry, government, and society.

Our two papers (Parts 1 and 2) address the reuse and recycling processes and the end-of-life potential of key construction materials—steel, timber, concrete, and bricks and blocks. The objective was to systematically compile and analyze the most recent data on reuse and recycling practices for these materials through collaborative research, in order to provide an objective assessment of the current state and future potential for implementing circular economy principles in the construction sector. Both papers are based on joint work conducted within COST Action CA21103 Circular B and aim to contribute to a clearer understanding of the current level of circularity in construction, while identifying opportunities for improvement and innovation, as well as key barriers that need to be addressed.

## 2 Materials and methods

### 2.1 Paper organization

In the scope of this work, an analytical and comprehensive literature review was conducted. The literature was gathered from multiple sources, including official documents and directives of the EU, reports of EU C&DW management projects, reports of official associations for specific construction materials, and articles in journals.

The EU WFD (2008) was taken as the basis for definitions of the waste hierarchy and other associated terms related to C&DW management. The information on the developmental trajectory of the waste hierarchy and circularity framework was collected from EU documents and directives, as well as scientific articles. Since we decided to analyze and present the current circularity level of four key construction materials, we divided our work into two related papers.

The algorithm describing the organization, structure, and content of the papers is shown in Fig. 4.

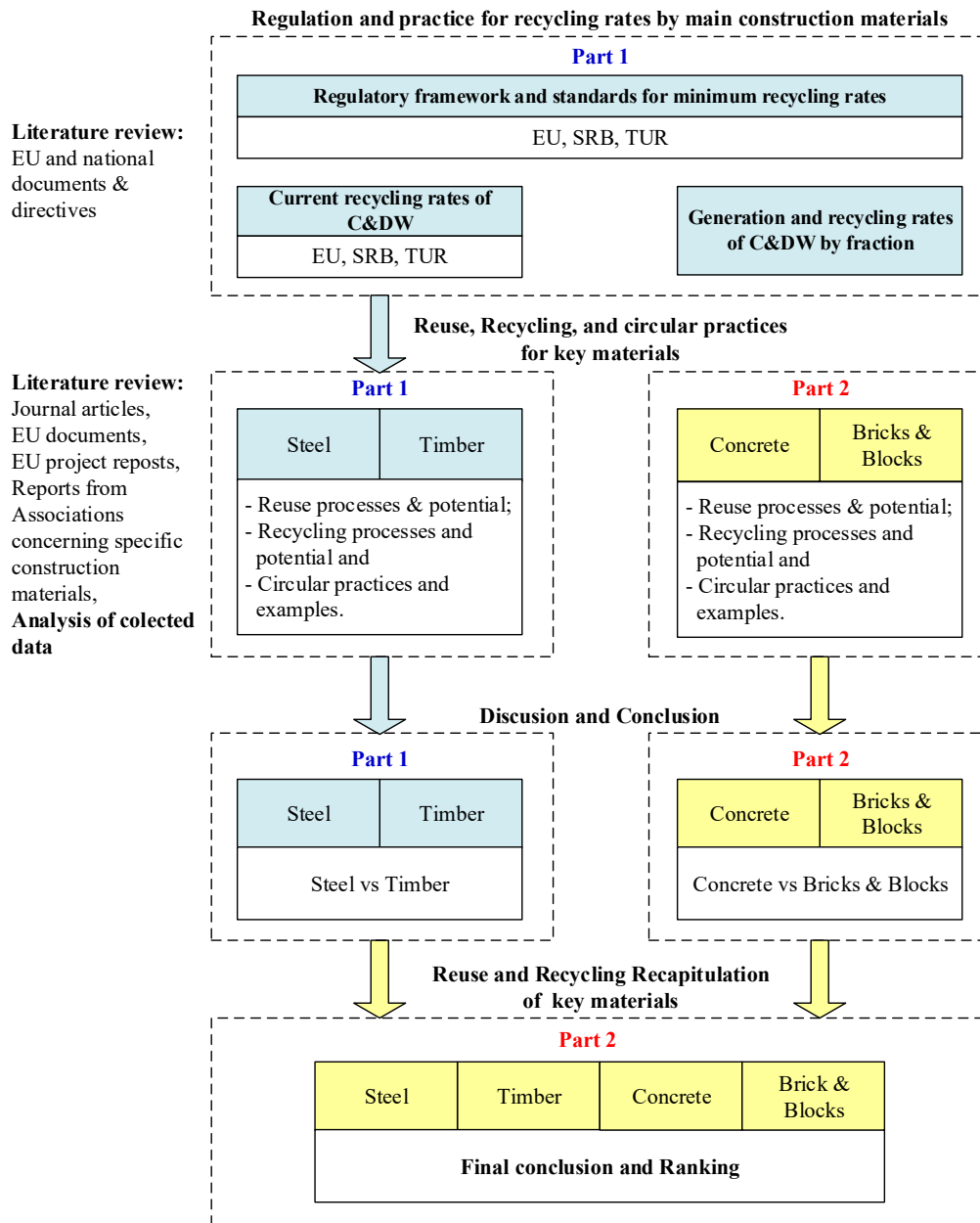


Figure 4. Organization of papers

## 2.2 Literature selection and review approach

To ensure transparency and reproducibility in the selection and thematic organization of the cited literature, a light PRISMA-informed approach was applied to all 174 references. The analysis was structured in three phases: (1) references were classified by source type, distinguishing between peer-reviewed journal articles, official EU and governmental reports, technical and professional websites, books and technical reports, and conference proceedings; (2) each reference was assigned to one or more of seven thematic areas - general circular economy frameworks, waste management, regulatory frameworks, steel reuse, steel recycling, timber reuse, and timber recycling; (3) the temporal distribution of references was examined by publication year to assess the recency and evolving focus of the reviewed literature. Tab. 1 presents the distribution of the references across five source types.

Peer-reviewed journal articles represent the largest single source category with 62 references (35.6%), providing the scientific backbone of the review. Technical and professional websites and portals account for 41 references (23.6%), reflecting the importance of industry-facing knowledge bases and organizational repositories in this field. Books, book chapters and technical reports contribute 34 references (19.5%), while official EU and governmental documents account for 29 references (16.7%), underpinning the regulatory and policy dimensions of the analysis. Conference proceedings represent the smallest category with 8 references (4.6%). Among all source types identified in the analysis, peer-reviewed journal articles were selected for further examination due to their scientific rigor and direct relevance to the research themes. The 62 peer-reviewed journal articles were published in 38 journals, indicating a broad and diverse scientific base. The five most frequently

cited journals, together with the number of references and primary themes covered, are presented in Tab. 2.

As shown in Tab. 2, the five most frequently cited journals together account for 25 out of 62 peer-reviewed articles (40.3%). *Journal of Cleaner Production* is the most represented journal with 8 articles (12.9%), followed by *Resources, Conservation and Recycling* with 5 articles (8.1%) and *Sustainability* with 4 articles (6.5%). The remaining 37 articles are distributed across 33 journals (one article each or two), reflecting broad coverage across the field.

Each of the 174 references was assigned to one or more thematic labels using a multi-label coding approach. Tab. 3 presents the resulting distribution across seven identified thematic areas.

The distribution of references across research themes reflects broader trends in the construction sector. The dominance of the general circular economy category (94 references) indicates that, in recent years, material use, waste management, and resource efficiency are increasingly framed within the overarching CE paradigm rather than as isolated technical topics. This reflects a fundamental shift in how the sector approaches sustainability, moving from

material-specific solutions towards integrated systemic thinking. Among the material-specific themes, timber recycling is the most represented with 54 references, which is consistent with the long-standing tradition of wood recycling in the construction sector and the continuously expanding range of products in which recycled timber can be incorporated, from particleboard and MDF to engineered wood products such as CLT and glulam. The remaining material-specific themes, steel recycling (35 references), steel reuse (34 references), and timber reuse (29 references), are comparably represented, suggesting a relatively balanced, though still emerging, body of evidence across these areas. Waste management (31 references) and regulatory frameworks (36 references) complete the thematic landscape, reflecting the growing legislative attention to construction and demolition waste streams at both EU and national levels.

Regarding the annual distribution, 146 of 174 references have an identifiable publication year. The remaining 28 are URL-only sources for which no dateable publication year could be established and are therefore excluded from the temporal analysis. The results of temporal analysis are presented in Tab. 4.

Table 1. Distribution of references by source type

Source Type	n	%
Peer-reviewed journal articles	62	35.6%
Technical/professional websites & portals	41	23.6%
Books, book chapters & technical reports	34	19.5%
Official EU/Government reports	29	16.7%
Conference proceedings	8	4.6%
TOTAL	174	100%

Table 2. Distribution of peer-reviewed journal articles in top 5 journals (multi-label thematic coding applies)

No.	Journal	Number of papers	References	Primary theme(s)
1	Journal of Cleaner Production	8	[44], [57], [82], [100], [109], [117], [143], [165]	CE, Steel recycling, Timber reuse/recycling
2	Resources, Conservation and Recycling	5	[54], [56], [60], [81], [112]	Steel reuse, Steel recycling, Timber recycling
3	Sustainability	4	[134], [140], [142], [144]	Timber recycling, CE
4	Construction and Building Materials	3	[114], [125], [156]	Timber reuse/recycling
5	Journal of Building Engineering	3	[84], [105], [166]	CE, Timber reuse/recycling

Table 3. Distribution of references by research theme (multi-label coding)

Research Theme	n	Description / scope
General circular economy	94	Overarching CE frameworks, LCA studies, broad construction sector topics
Timber recycling	54	Wood waste, panel products (MDF, OSB, CLT), cascading use, biomass
Steel recycling	35	EAF/BOF processes, scrap flows, green steel, decarbonization
Regulatory frameworks	36	EU Directives, national legislation, standards, policy documents
Steel reuse	34	Pre-demolition audit. direct structural reuse, demountable connections, material passports
Waste management	31	C&DW streams, treatment, waste hierarchy, data and statistics
Timber reuse	29	Reclaimed wood, salvage, reversible connections, design for disassembly

Note: Since thematic coding was applied using a multi-label approach, whereby a single reference could be assigned to more than one thematic category if its content spans multiple topics - the sum of references across all seven themes (n = 313) exceeds the total number of unique references analyzed (n = 174).

Table 4. Distribution of references by publication period

Publication Period	n	%	Observation
≤2014	14	10%	Foundational & methodological references
2015–2017	11	8%	Early CE framework development
2018–2019	18	12%	EU Green Deal preparation period
2020–2021	22	15%	New CE Action Plan (2020) impact
2022–2023	37	25%	Intensified EU policy & research activity
2024–2025	44	30%	Most active period; 2024 alone: 36 references
Total number of references with identified year	146	100%	28 URL-only references have no identifiable year

The temporal distribution reveals a pronounced recency profile, consistent with a review focused on the current state of circular economy practice in construction. References published between 2020 and 2025 account for 70% of all dated references (103 out of 146). The year 2024 alone contributes the largest single-year count (36 references), and 2025 already contributes 8 references despite being an incomplete publication year at the time of the literature search.

### 3 Regulation and practice for recycling rates by key construction materials

#### 3.1 Regulatory framework and standards for minimum recycling rates of C&DW

Since 2008, when WFD was adopted, C&DW has been a priority stream in the EU. This directive has set a target for 2020 of having 70% by weight of a non-hazardous C&DW pre-treated for reuse, recycling, and other forms of recovery [5]. The target aimed to divert non-hazardous C&DW from landfills and increase the use of secondary resources. By 2018, the EU average for disposal was about 10%, with a recycling rate above 80% [12]. Nevertheless, there were several issues with these figures, which came from Eurostat. The statistics are usually unreliable, as most companies from less developed countries are not motivated to report the actual amounts of waste generated and treated. Apart from this, the information on the treatment lacked details regarding the particular waste streams inside the C&DW, their potential use in the future, and their eventual return to the resource loop - that is, whether they were downcycled or upcycled. The latter would facilitate the transition to a circular economy, one of the EU's ambitions since the first Circular Economy Action Plan - Closing the Loop, came into force in 2015 [13].

With the adoption of the Green Deal Strategy, this plan has become one of the EU's key objectives: "to make Europe the first climate-neutral continent by 2050." Aside from reducing gas emissions by 55% by 2030 (compared to 1990) and eliminating net emissions by 2050, this strategy also foresees the separation of economic development from the use of resources [14]. The New Action Plan for the Circular Economy "For a cleaner and more competitive Europe" is one of its 47 main actions. It emphasizes sustainable consumption, more resource-efficient production and use, waste reduction, reuse, and recycling to double the rate of circularity in the next ten years [15].

Construction is one of the key economic sectors for achieving these goals, and the New Circular Economy Action Plan calls for adopting a comprehensive strategy for a sustainable built environment to increase material efficiency

and decrease climate impact. As part of this strategy, the Construction Products Regulation should be revised to include requirements for recycled content in construction products. In this context, Directive (EU) 2018/851 [6] amends Article 11 (Preparing for re-use and recycling) by introducing a new obligation for Member States to promote selective demolition. This measure aims to ensure the safe removal and handling of hazardous substances and to facilitate re-use as well as the high-quality recycling of C&DW. In addition, Member States are required to establish sorting systems for C&DW covering at least six material fractions: wood, mineral fractions, metals, glass, plastics, and plaster. Mineral fractions include concrete, bricks, tiles, ceramics, and stones.

Aside from the forthcoming Strategy for a Sustainable Built Environment and the recent amendments of the WFD, the strategic and regulatory framework for higher C&DW hierarchy treatments has been set. However, the lack of end-of-waste (EoW) criteria and quality standards currently hinders the broader application of reused and recycled C&DW fractions. At this point, end-of-waste criteria have only been established for copper scrap (Commission Regulation (EU) No. 715/2013), glass cullet (Commission Regulation (EU) No. 1179/2012), and iron, steel, and aluminum scrap (Council Regulation (EU) No. 333/2011).

Without other EoW criteria, an EoW definition from WFD may help. The WFD states that waste no longer qualifies as waste if it has undergone a recovery operation, is widely used for specific purposes, meets market or demand, satisfies technical requirements, complies with current laws and standards, and won't harm the environment or public health [6]. While wider usage and market demand fall under the regulatory framework and fiscal instruments, the existing standards may be used for the quality assurance procedure. According to EN 206:2013+A2:2021, for example, up to 50% of coarse recycled concrete aggregate may be used in concrete for in situ structures, precast structures, and structural precast products for buildings and civil engineering structures, depending on the type of recycled aggregate and the intended use of the concrete [16].

Although having been created for 2022–2024, the Serbian Circular Economy Development Program [17] has established a course that Serbia will take in the following years. Initially planned as part of the Green Agenda for the Western Balkans [18], the program focused on the need to increase waste reuse and recycling, with a particular focus on C&DW, identified as one of the program's priority streams. This is further elaborated in the Waste Management Program for the period 2022-2031 [19], which was adopted at the beginning of 2022. According to this program, 40% of C&DW is expected to be recovered by 2029, and 70% of C&DW will be pretreated by 2034 [19]. Recovery is related to the entire C&DW stream without specifying individual

waste streams such as concrete, clay, etc. Although they have not yet been determined, the program anticipates setting recycling rate targets for particular C&DW streams.

Building on these strategic documents, Serbia has actively established the regulatory framework necessary to achieve these goals in recent years. In addition to amendments to the Waste Management Act [20], a significant step was taken with the recent adoption of the Construction and Demolition Waste Management Regulation in 2023 [21] and preparing a Rulebook on Construction and Demolition Waste Management. These documents, however, focused primarily on the pre-demolition audit and the primary separation, collecting, and storage of C&DW; they did not address the financial incentives and taxes that would have increased the motivation of waste operators to invest in treatment facilities and, consequently, increase the recovery rates.

Similar to the EU, one of the key obstacles to the broader adoption of recycled C&DW in Serbia is the absence of EoW criteria. This is a pressing issue that needs to be addressed. Like the EU, Serbia currently only has EoW criteria for iron, steel, aluminum, copper, and glass cullet [22]. Likewise, the use of recycled concrete aggregate is governed by harmonized EU standards (SRPS EN 206-1:2021).

Türkiye is actively working on the transition to a circular economy and published the Green Deal Action Plan in line with the EU Green Deal, which includes 32 targets and 81 actions under 9 main titles, and 'housing and construction' is one of the sectors focused on for the preparation of the National Action Plan for Sustainable Consumption and Production [23]. Targets related to the circular economy are also included in the Twelfth Development Plan (2024-2028) [24]. The National Waste Management and Action Plan includes required actions on C&DW, such as the establishment of a C&DW collection system, an effective vehicle tracking system for collecting vehicles, recycling at maximum levels, obligatory selective demolition of buildings, usage of soil in recreational areas, etc. [25].

In terms of legislation, C&DW in Türkiye is regulated by the By-law on Excavation Soil and Construction and Demolition Waste Control [26]. According to them, minimizing at source, recovery, and reuse of waste are essential. However, there is no stated recycling target in the mentioned document. In addition, the By-law on Zero Waste is also connected to the C&DW despite not specifically including the waste type [27],[28].

Similar to the EU, Türkiye uses a harmonized EU standard for the use of recycled aggregate (TS EN 206+A2, 2021) [29]. In the cited standard, a limit for the replacement of natural normal-weight coarse aggregates by coarse recycled concrete aggregate ( $d \geq 4$  mm) is defined in the range of 0% to 50% in relation to recycled aggregate type, exposure classes for risk of corrosion induced by carbonation, and the intended use of the concrete.

### 3.2 Current recycling rates of C&DW

Driven by a strong commitment to the circular economy, the EU has made significant progress in managing C&DW. Many member states have already exceeded the target of 70% recycling and non-hazardous C&DW recovery by 2020, established by the WFD. The EU's average C&DW recovery rate as of 2020 was over 80% [30]. A leading example is Germany, with a high recovery rate of 94% from 2010 to 2020 [30]. All four construction materials under investigation are currently being recycled. Concrete recycling involves crushing and reusing the material for foundations, road

construction, and other uses. Since steel scrap has great economic value, its recycling is quite efficient. Bricks and blocks are often crushed and used as an aggregate in new construction projects. Denmark also boasts strong rates of recycling, especially for metals and concrete, with recovery rates around 97% [30]. Spain has achieved gains in its C&DW recycling rates, with 73%, while Italy reached 80.1% of C&DW in 2020. Strong market demand for recycled products and strict regulatory systems help to explain these high rates of recycling.

According to Eurostat [31] for the EU-27 countries, the total waste treated increased from 779 million tonnes in 2004 to over 1 billion tonnes by 2020. This shows a significant improvement in waste management infrastructure and practices, aligning with the EU's broader environmental goals to improve recycling and reduce landfill usage. Notably, the EU-28 (2013-2020 configurations) also shows substantial waste treatment achievements, with over 1 billion tonnes managed annually in the years reported. The data from 2016 provides insights into the performance of various EU member states not only in percentages but also in millions of tonnes of C&DW [32]. Germany reported a high recycling rate of 83.7%, processing over 70 million tonnes of C&DW. Despite this high recycling rate, 7.3% of the waste was still sent to landfills and other disposal methods, totaling over 6.1 million tonnes. Additionally, 1.2% was directed to energy recovery, involving more than 1 million tonnes. According to [33], Denmark reported a recycling rate of 89.2%, processing over 3 million tonnes of C&DW. The country used landfills for 4.1% of the waste, and backfilling was not practiced. Then, Spain recorded a recycling rate of 70.5%, managing around 6.5 million tonnes of C&DW. However, 21.2% of the waste was directed to landfills, and 8.3% to backfilling. In Estonia, concrete, bricks, and ceramic waste are classified as C&DW, which accounted for 14% of all waste in 2024. The Ministry of Environment manages C&DW data in databases from 2010 to 2019. In 2019, C&DW generation was 1.2 million tonnes, with a recycling rate of 84%. According to the paper [33] that analyzes the construction waste disposal practices in Romania, it highlights the current state and potential improvements in the recycling and recovery of C&DW. Romania's waste recovery level is significantly below the European Union's target of 70% set for 2020. Most of the C&DW collected in Romania is disposed of in landfills, with minimal recovery or reuse efforts. This waste includes materials such as concrete, bricks, wood, glass, metals, plastic, solvents, asbestos, and excavated soil. Among these, concrete, bricks, tiles, and ceramics constitute approximately 78% of the total C&DW. Despite the potential for recovery, Romanian practices have largely focused on landfilling. Data from the Romanian Ministry of Environment show that from 2006 to 2011, although there was an increase in the amount of C&DW collected (from around 200,000 tonnes in 2006 to over 800,000 tonnes by 2011), the recovery rates remained low. Romania declared a C&DW recovery rate of 46% in 2020, which includes reuse, recycling, and backfilling of all non-hazardous C&DW streams. In 2020, it is estimated that the UK generated 59.4 million tonnes of non-hazardous C&DW, of which 55.0 million tonnes were recovered. England generated 53.9 million tonnes of this waste, of which 50.3 million tonnes were recovered. In 2022, England generated 63.0 million tonnes of non-hazardous C&DW, of which 59.4 million tonnes were recovered [34].

Aiming to raise recycling rates and support the circular economy, Serbia has been trying to match its waste management methods with EU norms. The Waste

Management Program of the Republic of Serbia for the Period 2022-2031 presents the strategic objectives, legislative environment, and the current status of the waste management situation [35]. The initiative establishes particular targets for the recycling and recovery of C&DW and emphasizes compliance with the EU Waste Framework Directive. By 2029, Serbia wants a 40% recovery rate for C&DW and by 2034 a 70% pre-treatment rate. According to the program, Serbia's recycling rates of different materials are still developing. The current focus is on improving infrastructure and data collection to achieve higher recycling rates. Specific recycling rates for C&DW materials such as concrete, steel, bricks, and timber are not detailed in the program.

In Türkiye, the general application in the field related to building demolition is dismantling the plastic, wooden, and metal components with the aim of reuse and recovery. Most of the scrap materials and metal reinforcement are recovered after the demolition of the buildings, and the rest of the generated C&DW, which is a mix of waste concrete, brick, ceramic, and other materials and constitutes almost 80% of C&DW in weight, is collected and used as a filler or disposed of at landfills. C&DW disposal plants, which are licensed for storage, temporary storage, incineration, pre-treatment, land reclamation, and physicochemical processes, are located mostly in large cities. Also, except for six cities, there is at least one plant that is licensed for recovering C&DW in each city of Türkiye [30]. For the waste concrete, there are 428 licensed plants (346 pre-treatment plants (R12); 37 recycling/reclamation plants for other inorganic materials than metals (R5); 14 temporary storage plants (R13); 7 landfills; 6 recovery plants for pollution abatement (R7); 5 physical blending or mixing plants (D13), 3 specially engineered landfills (D5), who may accept this type of waste and dispose or recover it according to the current legislations. This information is based on the list of licensed plants, and it does not guarantee that all the licensed plants are currently accepting C&DW waste and waste concrete [36]. There is no published statistical data on the recycling rate of C&DW for Türkiye [36], [37], [38]. Preparation of this statistical data is under the responsibility of the Ministry of Environment, Urbanization, and Climate Change, and it is planned for 2026, with the requirement of a variation of related legislation [36], [37]. Similar to the EU, in Türkiye, there is no existing EoW criteria for C&DW. The studies related to the definition of EoW criteria for specific waste streams in Türkiye, in line with the Waste Framework Directive (2008/98/EC) and the Directive (2018/851) amending Directive 2008/98/EC, are still ongoing in the context of the Technical Assistance for Development of End-of-Waste Concept in Türkiye Project [39].

### 3.3 Generation and recycling rates of C&DW by fraction

When it comes to the generation and treatment of C&DW (other than reuse), the most comprehensive and trusted source of data is Eurostat. This European statistical office collects and aggregates C&DW-related data at the national level. Companies that generate and treat C&DW send this

data to the relevant national statistical offices. Although this is a legal requirement, companies in many countries perceive it as voluntary, as national statistical offices often mention limited reporting coverage. Furthermore, the guidelines for reporting are not explicit enough for non-experts and may result in misleading information. As a result, there is a lack of trust in this data, which is often observed in academic circles. However, with reasonable caution, these statistics may indicate the distribution and scale of specific C&DW streams and their treatment rates.

Figures regarding the generation of mineral, wood, and metal C&DW fractions in the EU for 2020 are illustrated in Fig. 5 and Fig. 6 [40]. Both figures display the generation statistics for every European country (where data were available); however, they are split into two parts for better visibility. The upper chart shows only nations whose quantities are less than 10% of the lead quantity.

The notable difference (about 30 times) in the generation between the mineral C&DW fraction (Fig. 5) and wood and metal waste stream (Fig. 6) can be observed by comparing these two figures [40]. Germany, France, Italy, the Netherlands, and Belgium are leaders in generating all three specified waste streams. Minor variations among nations can be attributed to differing national construction methods and practices. For instance, Sweden, Norway, and Finland rank in the top ten for generated wood and metal waste, primarily due to the high prevalence of timber-based construction. Conversely, Spain and Austria are among the top generators of the mineral fraction of C&DW.

It is noteworthy that when all countries from the upper chart of C&DW mineral fractions (Fig. 5) are combined, the total waste generation equals that of Italy. Similarly, for wood and metal fractions (Fig. 6), the aggregate amount is slightly higher than that of Belgium. This analysis suggests that countries leading in waste production should bear the primary responsibility for the EU's transition toward a circular economy.

On the other hand, based on the mineral fraction of the C&DW treatment rate statistics [41], it can be seen that new countries emerge as leaders in Europe's C&DW treatment, such as Slovenia, Latvia, Bulgaria, and the Czech Republic (Fig. 7). These countries reported recycling more than 75% of the mineral C&DW fraction. Slovenia, the Netherlands, and Italy are leaders in European mineral C&DW recycling. Nearly all mineral C&DW fractions (concrete, bricks, tiles, ceramics, and stones) are recycled in these countries. However, the subsequent usage of secondary material obtained with this treatment remains unknown.

Finally, as with reuse, there is currently a lack of harmonized and transparent data regarding the specific recycling rates of wood and metal fractions within the C&DW stream across Europe. While metals are largely recovered due to their high market value, wood often flows into energy recovery rather than material recycling, making it difficult to accurately track its circularity. This data is becoming increasingly important as Europe strives to separate resources from economic growth. The EU should consider revising its statistics laws to better promote and monitor construction circularity.

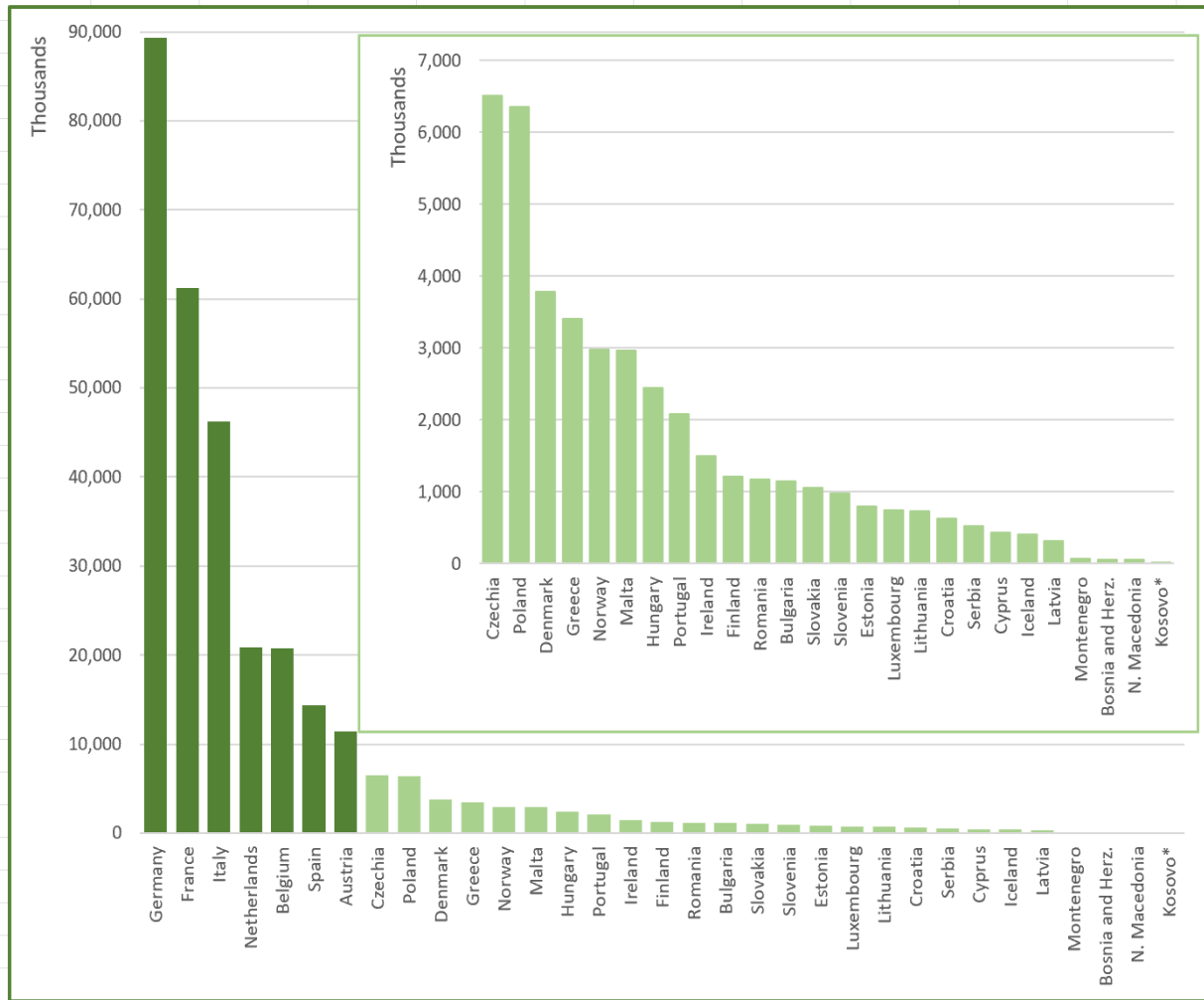


Figure 5. Generation of mineral C&DW fraction in Europe in 2020 [40]

In the absence of official EU statistics detailing the recycling rates of key construction materials derived from C&DW, we aimed to gather complementary data at the national level. Accordingly, a questionnaire was prepared and circulated among MC members representing EU and non-EU countries participating in COST CA21103 Circular B. We set 2 basic and 6 optional questions for each key construction material. The example of set questions for steel is given below. The basic questions are marked with (1) and (2).

(1) *Is there an official recycling rate for steel in your country?*

(1a) If yes, please state the official rate and the source (e.g., report name, link, institution).

(1b) If no official rate is available, please provide your estimated recycling rate for concrete based on your professional knowledge or experience.

(1c) Additional comments about steel recycling

(2) *Is there an official reuse rate for steel in your country?*

(2a) If yes, please state the official rate and the source (e.g., report name, link, institution).

(2b) If no official rate is available, please provide an estimated reuse rate based on your knowledge or experience.

(2c) Additional comments about steel reuse.

These questions were repeated for other key construction materials: timber, concrete, and bricks and blocks. Representatives of 11 EU countries (Austria (AUS), España (ESP), Hungary (HUN), Italy (ITA), Estonia (EST), Romania (ROU), Lithuania (LTU), the Czech Republic (CZE), Latvia (LVA), Portugal (PRT), and Luxembourg (LUX)) and 3 non-EU countries (Switzerland (CHE), North Macedonia (MKD), and the United Kingdom (GBR)), participated in the survey. The Excel document with all the information gathered from the survey is given as a supplementary file to this paper. This file contains many helpful statements, figures, and links. Some basic information on the survey's findings is shown in Tab. 5 and Tab. 6. The meanings of the abbreviations (1) in the table are: "Yes" - there are official data, "N/S" - I am not sure, "No" - there are no official data

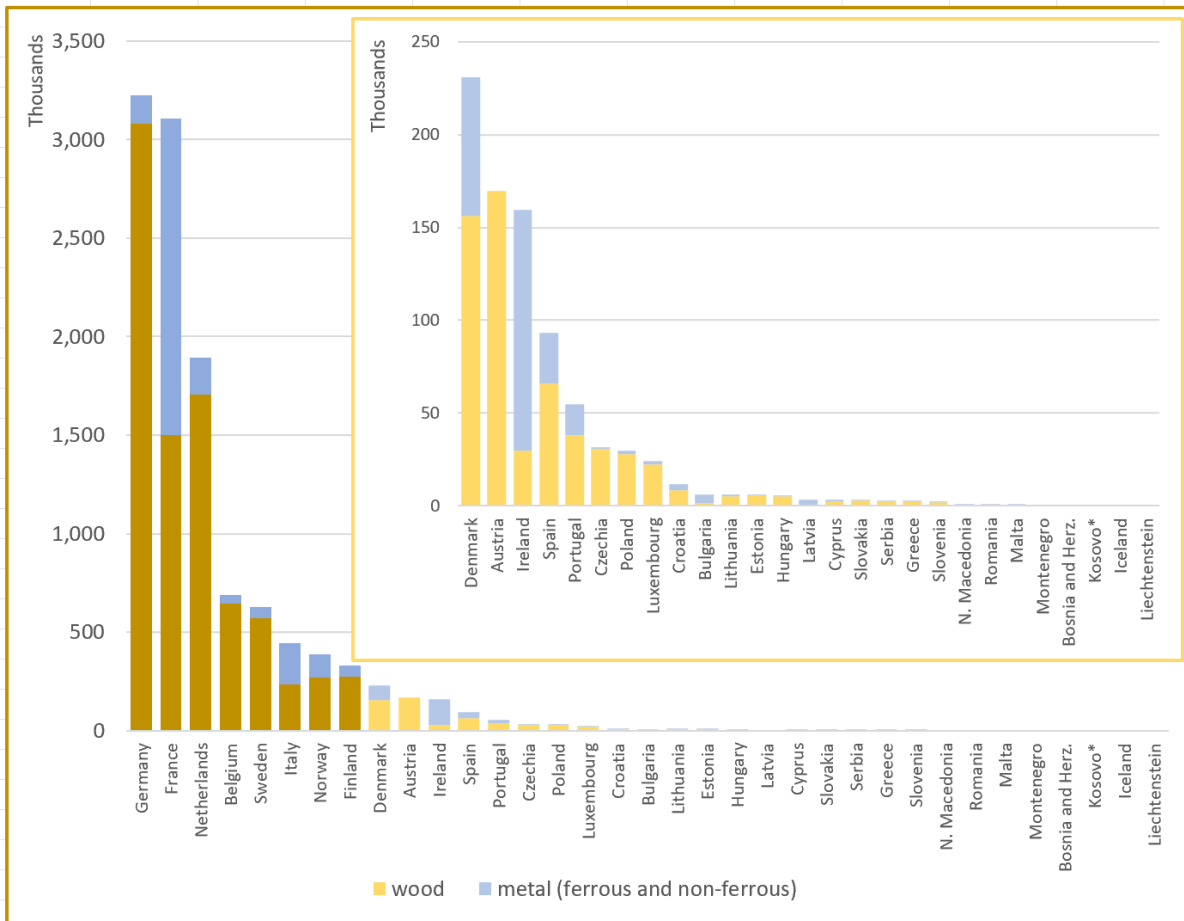


Figure 6. Generation of wood and metal fractions (from construction activity) in Europe in 2020 [40]

Table 5. Questionnaire findings on recycling rates of key construction materials

Country	Steel			Timber			Concrete			Bricks & Blocks		
	(1)	(1a)	(1b)	(1)	(1a)	(1b)	(1)	(1a)	(1b)	(1)	(1a)	(1b)
AUS	Yes	30%	-	No	-	55%	N/S	-	14%	No	-	45%
ESP	N/S	-	-	N/S	-	-	N/S	-	-	N/S	-	-
HUN	No	-	70%	Yes	98,4%*	-	No	-	3,4%	No	-	75%
ITA	Yes	~85%	-	Yes	-	64,9%**	Yes	10%	-	Yes	80,1%*	-
EST	Yes	52%	-	Yes	50,7%	-	Yes	-	46%*	Yes	98%	-
ROU	No	-	70-76%*	No	-	5-10%	No	-	20-25%	No	-	5-10%
LTU	N/S	-	-	N/S	-	-	N/S	-	-	N/S	-	-
CZE	No	-	98%	No	-	80%	No	-	90%** 15% RCA	No	-	-
LVA	No	-	-	No	-	-	No	-	-	No	-	-
PRT	Yes	78%	95-100%	No	-	77%***	Yes	-	-	Yes	-	-
LUX	Yes	-	-	Yes	-	-	Yes	-	-	Yes	-	-
CHE	Yes	-	-	Yes	-	-	Yes	-	-	Yes	-	-
MKD	No	-	<1%	No	-	<1%	No	-	<1%	No	-	<1%
GBR	Yes	96%** 86%***	-	Yes	60%*	-	Yes	-	-	N/S	-	-
	* Data includes construction, industrial and consumer sources ** Recovery rate for all steel construction products *** Recycling rate of structural sections			* Related to "waste wood" ** As reported by "Rilegno" *** Combined with glass and plastic			* Mineral C&DW (concrete, bricks, and ceramic waste) ** Recovered concrete waste			* Recycling rate of C&DW		

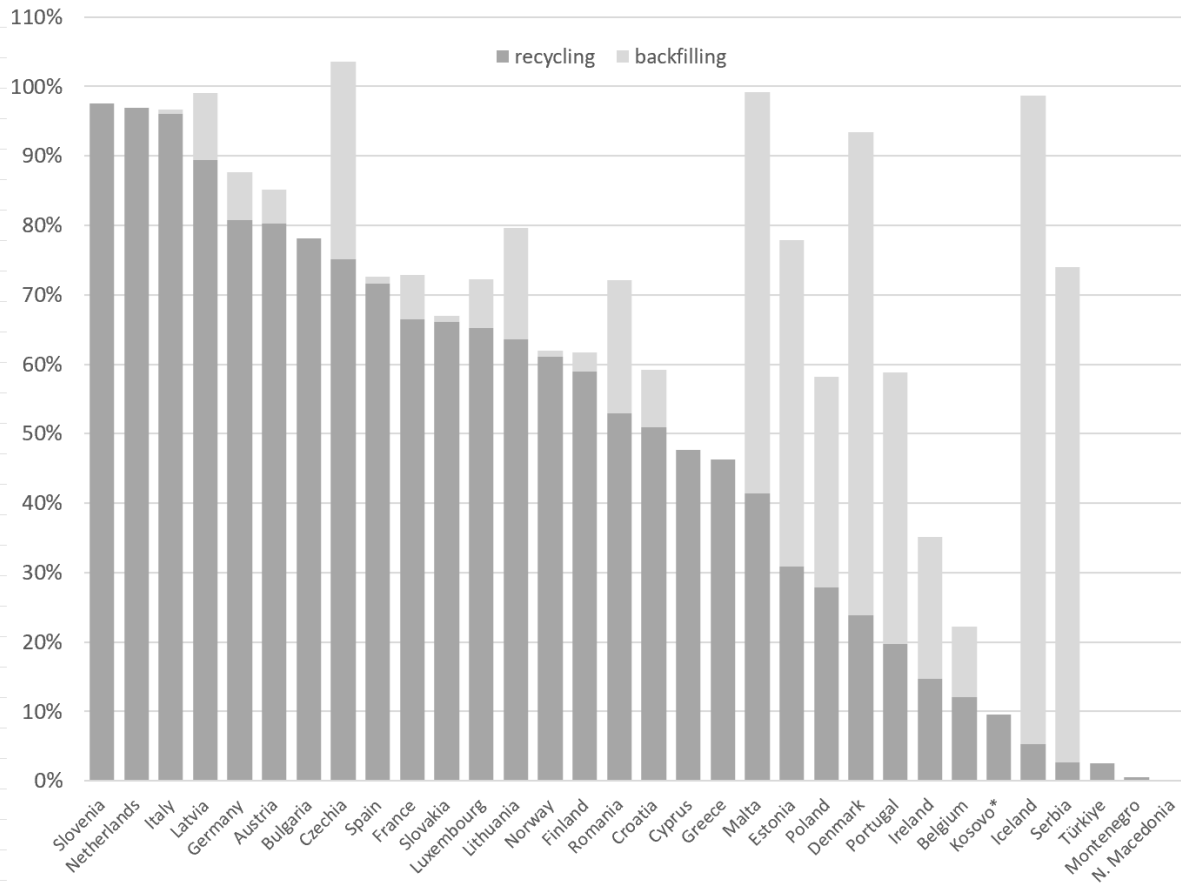


Figure 7. Share of treatment of mineral C&DW fraction in Europe in 2020 [41]

Table 6. Questionnaire findings on reuse rates of key construction materials

Country	Steel			Timber			Concrete			Bricks & Blocks		
	(1)	(1a)	(1b)	(1)	(1a)	(1b)	(1)	(1a)	(1b)	(1)	(1a)	(1b)
AUS	N/S	-	-	N/S	-	25%	N/S	-	10%	N/S	-	8%
ESP	N/S	-	-	N/S	-	-	N/S	-	-	N/S	-	-
HUN	No	-	1-5%	No	-	<5%	No	-	<10%	No	-	<5%
ITA	No	-	-	Yes	-	30%*	Yes	0,4%*	-	N/S	-	-
EST	Yes	-	-	Yes	-	-	Yes	-	-	No	-	-
ROU	No	-	<1%	No	-	5-15%	No	-	<1%	No	-	1-3%
LTU	N/S	-	-	N/S	-	-	N/S	-	-	N/S	-	-
CZE	No	-	-	No	-	10%	No	-	-	No	-	<1%
LVA	No	-	-	No	-	0%	No	-	-	No	-	-
PRT	No	-	<1%	No	-	0%	Yes	0%	-	No	-	-
LUX	Yes	-	-	Yes	-	-	Yes	-	-	Yes	-	-
CHE	Yes	-	-	Yes	-	-	Yes	-	-	Yes	-	-
MKD	No	-	<1%	No	-	<20%	No	-	<1%	No	-	<5%
GBR	N/S	-	13%*	N/S	-	-	Yes	-	-	No	-	<5%
	* Reuse rate of structural sections			* Reuse rate related to packaging			* Reuse of components of fresh concrete (percentage of total production of fresh concrete)					

The questionnaire results were analyzed separately for the recycling rate and the reuse rate, according to key construction materials. Based on the results presented in Tab. 5, it can be concluded:

– An official recycling rate for steel exists in 7 countries, while the remaining 7 have no official data available. 5 out of 7 countries reported an official recycling rate for steel,

ranging from 30% (AUS) to 96% (GBR), whereas 4 out of 7 countries provided estimated rates ranging from 70% (HUN) to 100% (PRT). Regardless of whether the data are official or estimated, it is evident that steel recycling from C&DW is widely implemented and achieved at high rates across the EU and the United Kingdom. This result was expected because steel has an established end-of-waste criterion.

– An official recycling rate for timber exists in 6 countries, while the remaining 8 have no official data available. 3 out of 6 countries reported an official recycling rate for timber, ranging from 51% (EST) to 98% (HUN), whereas 6 out of 8 countries provided estimated rates ranging from 5% (ROU) to 80% (CZE). Regarding official data, only Estonia reported a recycling rate for timber generated from C&DW (waste code 17 02 01), while the recycling rates provided by Hungary and the UK refer to waste wood. The wide range of estimated values for the timber recycling rate can be explained based on the additional comments (question 1c), which indicate that in countries with low timber recycling rates, waste wood is predominantly used for incineration.

– Six countries reported having official concrete recycling rates, while the remaining eight stated that no official data were available. Only Italy gave an official recycling rate for concrete (10%), however, this data is not official since it was published on a commercial website ([Ingenio Web](#)). Five out of eight countries provided estimated rates ranging from 3% (HUN) to 25% (ROU). It is noted that the Estonian data include recycling of bricks and ceramic waste in addition to concrete (mineral fraction), so its estimated concrete recycling rate (46%) was excluded from the analysis. Based on available information, it can be concluded that the concrete recycling rate is relatively low, which can be explained by the high share of mixed waste in C&DW (approximately 59%, Fig. 1). Furthermore, official concrete recycling data are generally unavailable because concrete is included in the mineral fraction of C&DW together with bricks, ceramics, and tiles. We believe that the concrete recycling rate in the EU is significantly higher, regardless of the results of our survey, since countries, such as the Netherlands, Denmark, and Belgium, that are known to have high utilization of recycled concrete, did not participate in the survey.

– An official recycling rate for bricks and blocks was declared for five countries, while the remaining nine had no official data available. Only Estonia and Italy reported official figures for bricks and blocks recycling rates (98% and 80.1%, respectively). However, the Italian data had to be excluded from further analysis, as they refer to the recycling of total C&DW. Four out of the nine countries provided estimated rates, ranging from 5% (ROU) to 75% (HUN). A wide range of estimated rates might be a consequence of a personal estimation in the case of the absence of available public sources. The small number of collected data is a consequence of the fact that bricks and blocks are included in the mineral fraction of C&DW together with concrete, ceramics, and tiles.

According to the results shown in Tab. 6, the following conclusions can be drawn:

– Three countries reported having official steel reuse rates, but none of them provided an actual figure. Among the remaining eleven countries, only five provided an estimated steel reuse rate, ranging from 1% (HUN, ROU, PRT, MKD) to 13% (GBR). It is clear that the reuse of steel from C&DW is still not widely implemented across the EU, because recycling is considerably easier than reusing. Additional reasons include the high rate of steel recycling, the lack of legislation supporting steel reuse, and limited market interest.

– An official reusing rate for timber was reported by four countries, although none of them provided an actual figure. The remaining ten countries have no official data available, while eight reported estimated rates ranging from 0% (LVA, PRT) to 30% (ITA). However, since the data provided by Italy

refers to the reuse rate of packaging, the highest actual timber reuse rate is even lower-25% (AUS). Overall, the low estimated timber reuse rates can be attributed to the fact that waste wood is predominantly used for incineration.

– Six countries declared an official reuse rate for concrete, while the remaining 8 had no official data available. Only Italy and Portugal reported official figures for concrete recycling rates (0.4% and 0%, respectively). However, the Italian data had to be excluded from further analysis, as it refers to the recycling of fresh concrete instead of concrete from C&DW, which means that the official reuse of concrete in participating countries is zero. Four out of the eight countries provided estimated rates, ranging from 1% (ROU, MKD) to 10% (AUS, HUN). Given that the data reported by Austria and Hungary have no associated source, these figures should be treated with caution. We assume that the actual concrete reuse rate is lower than 10%. Possible reasons include the lack of regulations, the absence of quality assurance protocols and design standards for reusing old concrete structural elements in new buildings, as well as limited market interest.

– Two countries reported having official reuse rates for bricks and blocks, although none of them provided an actual figure. Among the remaining twelve countries, eight reported estimated reuse rates ranging from 1% (CHE) to 8% (AUS). It is evident that the reuse of bricks and blocks from C&DW is still not widely implemented. One possible reason is that preparing old bricks and blocks for reuse is a time- and labor-intensive process.

## **4 Steel**

### **4.1 Reuse of steel**

Steel is one of the most utilized metals in the world, especially in the construction sector. It is an iron alloy, meaning it is made up of a combination of metals and non-metals, including iron, tin, and carbon [42]. Steel's durability allows for the reuse of many products at the end of their life cycle. Existing steel buildings can be reused in situ, relocated, or deconstructed into elements such as cold-formed or hot-rolled sections, sheets, panels, frames, or truss girders. Reuse helps extend the product's lifespan and eliminates the need for long-distance transporting, re-melting the steel, and manufacturing new products. This has significant advantages for the environment by minimizing the use of natural resources.

This chapter reviews how steel can be reclaimed and reused in buildings, outlines the main reuse pathways, and summarizes practical protocols and requirements for integrating reclaimed steel into new designs.

#### **4.1.1 Reuse processes and their efficiency**

Construction steel can be reused at both the building and product level, in situ or relocated. All building structures could be specified in a range from fixed to deconstructable. Circular economy, from the point of reuse view, tends towards deconstructable structures, since they can be reused in many different ways. Reusing fixed steel buildings is also possible, but only in two situations: in situ, when service life is extended by renovating and adapting building structures, and for certain small-scale structures, if it is feasible to move the whole building or its main components over a short distance without disassembling them, using appropriate vehicles. Therefore, identifying the type of steel

building, whether fixed or demountable, is of crucial importance.

Regardless of the type of steel buildings, the following circular pathways for the reuse processes of load-bearing systems and components are possible [43]: (1) In-situ adaptive reuse and renovation of building structures; (2) System reuse at the new location for the same purpose; (3) System reuse at the new location for a different purpose; (4) Component reuse at a new location for the same purpose; (5) Component reuse at a new location for a different purpose. Option (1) reduces interventions to a minimum on existing load-bearing systems and prevents demolition. However, buildings are often not designed to accommodate new uses easily within existing load-bearing systems. The more probable options are (2) and (3), where the structure or its parts can be disassembled and reassembled at different locations for identical or new purposes, respectively. Examples of this are modular systems, such as building blocks, containers, scaffolds, etc., and hall or tent structures. Options (4) and (5) may be easier to implement and are more

commonly found in the literature [43]. Additional environmental and economic analyses, such as life cycle costing (LCC) and life cycle assessment (LCA), are required in order to determine the most favorable scenario.

Similarly, a group of authors [44], developed their own types of reuse, distinguishing between in-situ reuse and relocated reuse, for whole buildings, component systems, and individual elements (Tab. 7).

In practice, the reuse scenario depends on technical feasibility, environmental impacts, and financial costs [44]. The decision for the reuse of steel can be made early, in the project phase, for on-site reuse, or at a later stage, during tendering for steelwork, for the relocated elements. The design team is therefore critical in determining the reuse scenario [44]. Three potential options are shown in Fig. 8, which illustrates the various procurement routes for obtaining reused steel: sourcing directly from a demolition contractor, from a traditional steel stockist, or, more recently, from specialized reused steel stockists.

Table 7. Different types of reuses [44]

	In-Situ Reuse	Relocated Reuse
Building Reuse	Reuse of a sizable portion of a building, e.g., entire structural frame, façade, or envelope, in situ	Deconstruction and reassembly on a new site of a building frame/envelope
Component System Reuse	Reuse of a small part of a building in situ, e.g., foundations	Reuse of the system of components, e.g., a steel truss, on a new site
Element Reuse	Deconstruction and reuse of elements in a new configuration	Reuse of individual elements, e.g. steel section(s), on different sites

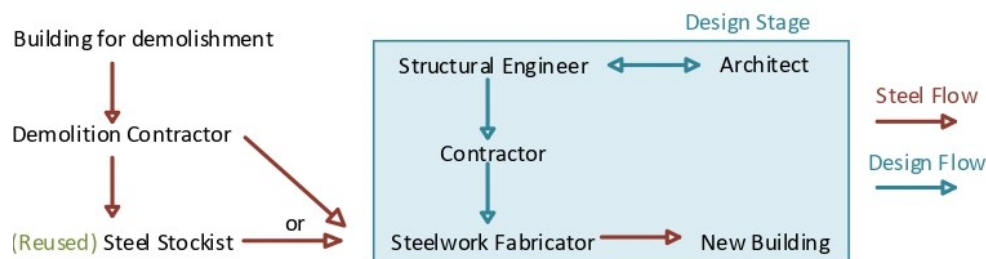


Figure 8. Steel reuse flows for relocated reuse [44]

Regardless of the scenario (type), the steel reuse process includes the following phases (adapted from [45]):

- *Pre-deconstruction audits and assessment for reuse of existing structures*: this phase involves assessing the existing structure before deconstruction to determine the potential for reuse of steel components. It includes a detailed inspection of the condition of structural elements, identification of corrosion or deformation, documentation of material properties, and evaluation of the types of connections used. The aim is to identify which elements are suitable for safe and efficient reuse.

- *Preparation for safe demounting, deconstruction, and labeling of component elements*: before dismantling, a deconstruction plan should be prepared to ensure that elements can be removed without damage. This phase covers on-site preparation, labeling and documentation of each component, selection of appropriate lifting and handling methods, and ensuring workers' safety. Proper labeling and cataloguing are essential to preserve traceability and facilitate reuse in future projects.

- *Testing and verification*: after removal, steel components must be tested to confirm their structural integrity and mechanical properties. Certainty in material properties, both mechanical and chemical, is important in the context of warranting reclaimed steel structures and the professional indemnity insurance of the designers. Destructive and non-destructive tests may be performed to check tensile strength, ductility, weldability, and possible material fatigue. Verification also includes visual inspection, geometric measurements, and assessment of compliance with current standards for reuse in new constructions. Reclaimed steel members should meet the performance requirements for mechanical, physical, dimensional, and other relevant properties to ensure their adequacy in design according to EN 1993.

- *Integration of reused steel elements in new building design*: in this phase, the verified components are integrated into the design of a new building. The design must account for the dimensions, mechanical properties, and connection types of the reused elements. Adaptation or modification of

existing components may be required to ensure compatibility with the new structural concept. The relevant standard for structural design is EN 1993.

– *Environmental and economic assessment*: finally, environmental and economic evaluations are carried out to quantify the benefits of reuse compared to recycling or producing new steel. Life Cycle Assessment (LCA) and cost-benefit analyses (LCC) help determine potential reductions in CO<sub>2</sub> emissions, energy use, and overall project costs. This phase supports the development of sustainable and economically viable reuse strategies.

The reuse process phases described above are further supported by CEN/TS 1090-201:2024 [174], a technical specification prepared by the Technical Committee CEN/TC 135, which provides complementary provisions to EN 1090-2 for the use of reclaimed structural components in steel structures designed in accordance with the EN 1993 series and executed in accordance with EN 1090-2. The specification applies to structures in execution classes EXC1 to EXC3, designed for quasi-static loading and not subject to fatigue loading.

In accordance with CEN/TS 1090-201 [174], the assessment of reclaimed structural steel components comprises two interconnected stages. The first is the *reusability assessment*, which involves data collection and condition evaluation to determine whether a component is admissible for reuse. The second is the *quality assessment*, which establishes the mechanical and geometrical properties required for structural design, including yield and tensile strength, elongation, tolerances on dimensions and shape, heat treatment delivery conditions, and weldability. These two stages align directly with the *pre-deconstruction audit and testing and verification* phases described above, providing a standardized framework for their execution.

The practical implementation of these two stages follows a structured sequence of steps. It begins with *initial data collection*, whereby available records of the source structure are gathered, including construction drawings, material specifications, age of the structure, and any evidence of prior damage or repair. This is followed by *visual inspection and admissibility screening*, in which each component is examined for signs of significant corrosion, plastic deformation, impact damage, or unverifiable weld repairs, any of which would disqualify the element from the reuse pool. Components that pass admissibility screening proceed to *non-destructive testing (NDT)* and *material characterization*, primarily through hardness testing to establish the material grade, with optional destructive testing to determine the carbon equivalent value (CEV) and impact toughness where greater precision is required. To manage the scope of testing efficiently, admissible members are organized into *groups of fundamentally identical elements*, with one or more representative members tested on behalf of the entire group. Once testing is complete, the holder of the salvaged stock is responsible for *declaring the material properties*, enabling the reclaimed steelwork to be CE marked in accordance with EN 1090-2 and CEN/TS 1090-201. Finally, *structural design verification* is carried out by the design engineer, using the declared or conservatively assumed material properties as the basis for member calculations in accordance with the EN 1993 series.

Although all EU member states have adopted and published CEN/TS 1090-201 at the national level, it remains a voluntary technical specification whose implementation relies on contractual agreements or specific regulatory references rather than automatic legal enforcement, making

it widely accessible compared to other similar guidance documents.

The assessment of the existing steelwork is essential for making a decision on reuse. The overall framework to reclaim existing structural steel elements is explained in detail in [45]. The importance and role of the pre-deconstruction audit in the case when the entire primary structure is assessed to be reused (existing steelwork) was especially emphasized. Pre-deconstruction audit summarizes the data about building systems, components, and materials that can be reused or treated as waste. Also, it offers recommendations for the reconditioning of reclaimed products and waste management. The main steps in the pre-deconstruction audit are preliminary and comprehensive assessments. Preliminary assessment is mandatory and includes analysis of available documentation and limited inspection with optional minimal testing. The limited inspection should assess the condition of the existing steelwork. The goal of this inspection is the evaluation of the feasibility of reclaiming and reusing the existing steelwork. The comprehensive assessment shall be undertaken if the existing steelwork was classified as "suitable for reuse" by the preliminary assessment. In a comprehensive assessment, a detailed evaluation of the condition of existing steelwork should be done; thus, a prescribed percentage of members and details have to be checked for geometry and dimensions in accordance with EN 1090-2. Also, all members and details must be visually inspected to detect defects, damage, or other problems in line with EN 13018. The primary goal is to determine admissibility for reuse.

After approval for reuse the basic mechanical and chemical properties of the steel should be obtained. Methods for obtaining property information include: (1) destructive testing, (2) non-destructive testing, and (3) based on the steel age. [46]. Mechanical testing includes both destructive testing, which can measure tensile strength, yield strength, and elongation, and non-destructive testing, such as hardness parameters. Non-destructive testing of steel is highly developed, with various portable testers available for use in steel production, fabrication, and scrap processing industries. The chemical composition of reclaimed steel can be quickly determined by XRF, which efficiently analyzes the steel's chemical composition. Sometimes, the basic data on steel properties may be found based on the age of the building and the steel within it, through knowledge of the history of steel section production and engineering judgment [46].

Deconstructed sections without evaluation of actual condition can be subsequently inspected to verify their dimensional characteristics and tested to confirm their basic properties [46], [47].

After verification, the sections are usually shot or sandblasted to remove any coatings, refabricated, and primed according to the requirements of the new project. This usually involves cutting the ends of the sections to the specified length. To help facilitate the reuse of existing structural steel, the Steel Construction Institute (SCI) has published a protocol (SCI P427) setting out recommendations for data collection, inspection, and testing to ensure that reclaimed structural steelwork can be reused with confidence. Also, the British Constructional Steelwork Association (BCSA) published a model specification for the purchase of reclaimed steel sections, to be used in conjunction with the National Structural Steelwork Specification for Building Construction (NSSS) Annex J – Sustainability Specification [48].

#### 4.1.2 Possibility and potential of steel for reuse

The possibility of reusing steel structures mainly relies on the design approach, where everything must be initially suited for disassembling the structure into individual components. The main characteristics of deconstructable structures are: (1) the use of accessory joint types, (2) the application of parallel instead of sequential assembly/disassembly, (3) the use of mechanical connections in place of chemical ones, and (4) open hierarchy [49]. To enable the deconstruction and efficient reuse of steel components, the connections between steel elements need to be modified. For instance, Xianghe Dai et al. [50] examined the potential application of a novel block shear connector in demountable frame structures. Also, standardization of components and connections, and modular construction can significantly improve the steel construction capacity of the industry.

Many projects focus on steel reuse possibility, such as: REDUCE - Reuse and Demountability using Steel Structures and the Circular Economy, and PROGRESS - European recommendations for reuse of steel products in single-story buildings [8], [45]. The primary goal of the project REDUCE was to provide practical tools and steel-based technologies for designing steel and composite structures that can be deconstructed and reused. The other goal of this project was to assess methodologies for quantifying the benefits of demountable buildings and reuse, including LCA and circularity benchmarks. Additionally, the project examined how BIM can provide information for easy adaptation and deconstruction of buildings, facilitating component reuse at end-of-life [8]. Project PROGRESS cited similar possibilities for the reuse of steel in single-story buildings depending on the level of disassembly: D0: reuse of the entire steelwork or its part, in situ without disassembly; D1: reuse of the disassembled steelwork; D2: reuse of the fabricated components; D3: reuse of the constituent products; as well as from the deconstruction and transport point of view: DA: in-situ reuse without disassembly; DB: reuse on the same site in the same configuration; DC: reuse on the same site in different configuration; DD: reuse on different site in the same configuration; and DE: reuse on different site in different configuration [45].

Reusing steel offers many benefits. Fig. 9 illustrates the benefits of steel reuse, which were analyzed in [9], [44], [51], and [52] in terms of their frequency.

We indicated eight benefits of construction steel reuse; seven of them (reduced embodied carbon and energy, reduced use of virgin materials, reduced waste generation and landfill usage, economic advantage by lowering fabrication cost, expanding business opportunities for fabricators, improved sustainability, and additional salvage of other construction materials) belong to general ones, which are also applicable to other materials. The potential growth of a reused steel market is specific to construction steel. The most often mentioned advantage of reusing steel is the reduction in embodied carbon and energy.

The primary benefit of reusing structural steel elements is the reduction in embodied carbon. The carbon reduction for reused steel is greater than that of recycled steel, since no electric arc furnaces are required to re-melt and re-form the scrap steel. Reusing steel can extend the design life of buildings since structural elements are often over-designed due to material availability [53]. To estimate the amount of steel saved, two different structural models for the designed building have been carried out and compared. In the first one, the structure has been designed on the assumption of the reuse of recovered structural elements; in the second one, the same structure has been designed considering the use of new elements only. The final result of the analysis shows that steel reuse allowed for savings of up to 30% of steel [54].

Despite the cited benefits, there are also many barriers and challenges when it comes to steel reuse. To identify the main barriers to the reuse of steel structures, a literature review [44], [46], [47], [51], [52], [55], [56] - was conducted. A total of 33 barriers were identified, reflecting the diversity of perspectives and the variety of approaches used to define them. It was concluded that the large number of barriers results primarily from a lack of consistency in terminology, as many barriers share the same or similar meanings but are referred to by different names.

An analysis of the identified barriers revealed that they can be summarized into three categories: economic and market barriers, technical and logistical barriers, and others. Within these categories, we proposed unified names for barriers with the same or similar meanings. The results of our analysis are presented in Tab. 8.

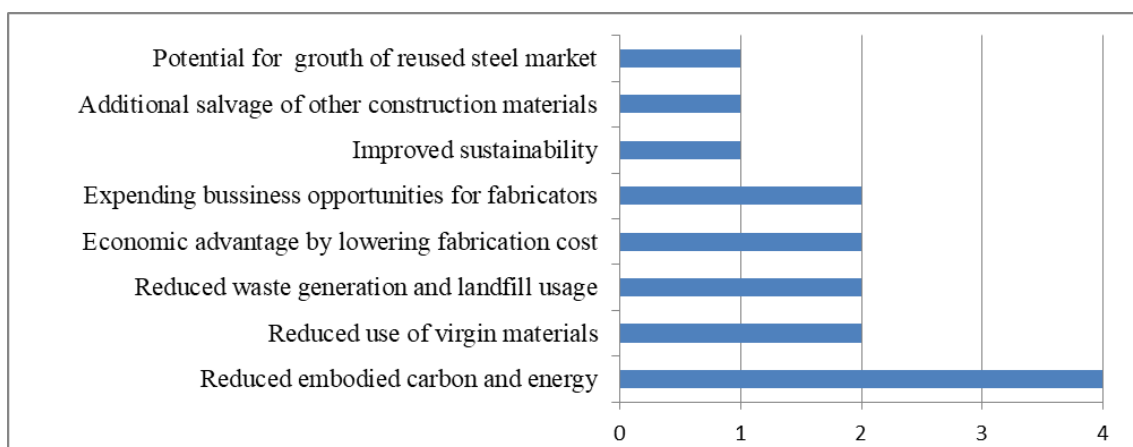


Figure 9. Frequency diagram of benefits of steel reuse, [9], [44], [51] and [52]

Table 8. Proposed categories and unified names of barriers to steel reuse

Economic and market barriers	
Identified barriers	Unified barriers
Cost/economic, Lack of incentives No clear financial incentive The complexity of the construction value chain	High cost
Availability and storage Supply chain gaps and a lack of supply chain integration Fragmentation and collaboration issues Lack of information about existing structures and materials Lack of information/communication Lack of defined benefits	Supplier and market gaps
Client perceptions No client demand	Lack of demand
Technical and logistical barriers	
Identified barriers	Unified barriers
Lack of traceability Lack of information about existing structures and materials	Traceability and performance
Quality assurance Ambiguity on the strength of the use of structural members	
Delay in deconstruction due to the complexity and irreversible nature of structural connections Potential time constraints of incorporating the deconstruction of an existing building into the project plan Overlooked the carbon impact of demolition prior to construction	Deconstruction challenges
Lack of adequate design rules, regulations, and standards for steel reuse Design for deconstruction Impact on design/design codes focus on new materials Lack of principles towards construction design sustainability Lack of designer knowledge	Design and standards
Jointing technique, i.e., welded steel work/inaccessible joints	Jointing and composite construction
Other barriers	
Identified barriers	Unified barriers
CE marking Automation and health and safety The need to engage and coordinate the complete construction ecosystem	Health and safety
Limited knowledge and experience of circular economic principles	Circularity
The lack of infrastructure for a circular economy	
Inertia in the construction sector	
Uncommon practice	

The most important demand in analyzing the possibility of steel structures reusing is design for deconstruction (DfD). It should be fulfilled in the pre-use phase. To reduce the environmental impact, the DfD of steel structures has recently received more attention. DfD considers the end-of-life scenario of buildings at the (early) design stage so that they can be fully or partially deconstructed without disproportionate effort and material loss. Steel structures have the potential to reuse components, whereby the connection between steel frame systems is a key member that allows the adaptability of construction member reuse. In the DfD the basic principles are: (1) simplicity, through a limited number of different material types and component sizes (fewer larger elements which are more durable and easier and quicker to remove); (2) standardization and regularity in design building systems, using repeating patterns consisting of the standardized construction elements; (3) simplification of building element separation by connection details that allow efficient construction and deconstruction and (4) facilitates reuse without modification after deconstruction [8]. Steel, as a construction material/product, with its performance, can fulfill all these

principles. However, DfD principle requires improvement, since some technical challenges arise from DfD; for example, welded shear studs are traditionally used to connect metal decks to beams, making it challenging to salvage these elements without causing significant damage. Thus, the other types of connections, i.e., bolted stud connections, are suggested to be used. However, in that case, it would be more labor to deconstruct the resulting quantity of bolted connections, increasing costs. Therefore, the following upgraded principles were created: Design for Manufacture and Assembly (DfMA), Design for Disassembly and Adaptability (DfD/A), Design, Build, Maintain, and Remove (DBMR), and Design for Deconstruction and Reuse (DfDR) [9]. Also, using the components from the donor structure may impact the design practice, since structural geometry and topology will be influenced by the stock element characteristics, i.e., of available components and their cross-sections and lengths. For instance, there might not be enough elements of a specific length and cross-section available, or the new structure will be oversized compared to the structures made of newly produced

elements [51]. Yet, there is a lack of adequate design rules and standards.

Reused steel is somewhat more expensive than new elements, except in certain circumstances, such as when the reused elements are available from a nearby site, or when testing elements can be avoided for the efficient use of materials [57]. Many fabricators are moving to fully automated fabrication lines where the difficulties of working with previously used sections are exacerbated. The costs include structural design, deconstructing, additional transport and storage of the reclaimed sections, and chemical and mechanical testing of the properties of the reclaimed sections. These additional activities are highly variable and project-dependent. Also, the pricing of structural steel is usually on a ‘per ton basis’, whereas some activities, e.g., testing, are generally on a piece basis [57]. Although the cost of reusing steel is currently relatively high, the reuse of steel has the potential to become more economically viable due to increased competition between product manufacturers [58].

The carbon footprint of a building constructed with reused steel depends on the required level of repair and reconditioning of the reused elements [58]. This is largely influenced by various parameters, including the condition, connection design, and material degradation, as well as the recovery method used for the components from the old construction. The paper [58] illustrates how these factors impact buildings’ life environmental aspects (LCA). The paper considered different case studies where the building is constructed from new or reused components, and in which the components will be reused or recycled in the future. LCA and global warming potential (GWP) evaluation are based on the modular building life cycle approach, which includes the product stage, construction process stage, use stage, end-of-life stage, and loads beyond the system boundary. The LCA result for the product stage shows that GHG emissions in the steel reuse case are significantly lower than in the case where the steel structure is used for the first time and for the whole building life cycle. However, due to the large variation of materials and building practices, LCA calculations are recommended to be carried out on a case-by-case basis, as the results could differ significantly from the present study [58].

To support the greater reuse of steel structures and help facilitate the reuse of structural steel sections reclaimed from existing building structures, the Steel Construction Industry has developed a protocol [59] for reclaiming and reusing individual members for new purposes. The protocol recommends data collection, inspection, and testing to ensure reclaimed structural steel sections are safe for reuse. It focuses on individual members rather than entire structures and lays out investigation and testing procedures to determine material characteristics. Responsibilities of those handling salvaged steelwork include identification, assessment, control procedures, and conformity declarations. Salvaged steel needs different handling from new steel due to potential obsolete standards and a lack of test results. This protocol suggests declaring properties of reclaimed structural steel as follows: (1) steel grade (non-destructive tests), (2) steel sub-grade (conservative assumption or optional destructive tests), (3) tolerances (inspection), and (4) maximum carbon equivalent (conservative assessment or optional test).

According to the recommendations, all structural steel recovered for reuse is subject to control and testing. Several requirements must be fulfilled: (1) Steelwork must be from 1970 or newer, (2) no built-up members, (3) no spliced members (individual lengths with bolted splice may be reclaimed), (4) no localized section loss, (5) no plasticity or corrosion protection issues, and (6) members must meet geometric tolerances. The evaluation of the reclaimed steel structure begins before the deconstruction of the existing structure, with the collection of relevant data. All information and relevant data according to [59], should be collected for reclaimed steel and divided into (1) the building information and (2) the information for individual members. They are shown in Tab. 9.

The document “Guidance on establishing European rules for the design of reclaimed steel components for reuse” represents one of the most comprehensive recent efforts to link existing steel reuse practices with the Eurocode-based structural design framework [173]. Developed in close alignment with the principles of Eurocode 3, the guidance aims to support the future formalization of reclaimed steel within European structural design standards, while maintaining consistency with established safety and reliability concepts.

*Table 9. Information and relevant data necessary to be collected for the reclaimed steel [59]*

Building information	Individual members
<ul style="list-style-type: none"> <li>• Building age</li> <li>• Form of construction</li> <li>• Any related information, such as drawings, modifications, and records.</li> </ul>	<ul style="list-style-type: none"> <li>• Section size</li> <li>• Length</li> <li>• Member group</li> <li>• Tolerance check</li> <li>• Comments: e.g., stiffeners or fabricated features</li> <li>• Coating:                             <ul style="list-style-type: none"> <li>– Coating type (and thickness if determined) and</li> <li>– Condition of coating</li> </ul> </li> <li>• Material properties:                             <ul style="list-style-type: none"> <li>– Yield and ultimate strengths (non-destructive or destructive tests)</li> <li>– Carbon equivalent value (assumed, or by test)</li> <li>– Impact toughness (assumed or by test)</li> </ul> </li> </ul>

A key contribution of the guidance lies in its clarification that reclaimed steel components may be designed within the existing Eurocode 3 philosophy, provided that their material properties, geometric characteristics, and structural condition are adequately verified. Rather than proposing an entirely new design framework, the document builds upon familiar limit state design concepts and partial safety factor approaches, thereby facilitating the integration of reclaimed steel into conventional structural engineering practice. The guidance places particular emphasis on the verification of reclaimed steel components prior to reuse. It distinguishes between elements with available documentation (e.g., known steel grade, production standards, and service history) and those without such information, proposing different levels of material testing, inspection, and assessment accordingly. This verification process is presented as a prerequisite for reliable structural design and is directly linked to the selection of appropriate safety factors within the Eurocode framework.

From a structural reliability perspective, the document underlines that the reuse of steel components should achieve safety levels equivalent to those required for new steel structures [173]. Where uncertainties related to material properties, fatigue, or prior use cannot be fully eliminated, the guidance allows for conservative assumptions or adapted partial factors, ensuring that target reliability levels are maintained without compromising structural safety. Although the guidance does not yet constitute a binding European standard, it provides a pragmatic and technically grounded framework for designers, regulators, and standardization bodies. Its inclusion in the discussion of steel reuse highlights the ongoing transition from practice-driven reuse approaches toward formally codified, Eurocode-consistent design methodologies, thereby strengthening the regulatory and practical relevance of steel reuse within the European circular economy context.

The reuse of steel in practice has potential in the future despite numbered barriers, such as costs, availability, storage of elements, lack of adequate design rules, regulations, standards, supply chain gaps, etc. These challenges can be overcome by introducing the mandatory use of reclaimed components up to a certain percentage, then with better fiscal incentives, design for deconstruction, design of reclaimed steel components for reuse, standardization, etc.

Also, the economic conditions must be conducive, minimizing environmental impact, and frameworks to connect different stakeholders in the steel industry and illustrate their contributions to the reuse process should be well-developed [60].

## 4.2 Recycling of steel

From bridges and cars to paper clips, steel is the most versatile material on earth that has led to the most progress in the living standards of humanity. Even more, steel demand is forecasted to increase over the next decades. But manufacturing this shiny, ductile metal is a dirty, old-fashioned process that's changed little in the past 150 years. Traditional steel production methods have contributed significantly to carbon emissions, resource depletion, and environmental degradation. Yet, as with all other emitting economic sectors and materials production, the steel industry needs to decarbonize to meet the climate challenge. Global crude steel production is over 1.9 Gt annually and it is responsible for approximately 3 Gt of CO<sub>2</sub> emissions. Since steel accounts for around 8% of total global carbon

dioxide emissions, finding cleaner, commercially viable ways to make it is vital. According to the International Energy Agency, to meet global net-zero goals, steel industry emissions must fall by at least half by 2050. Steel recycling is a widely used technology in the decarbonization process of steel production. Steel can be continuously recycled without any damage to its properties, regardless of the product or form it takes. Steel recycling includes melting steel products at the end of their lifecycle (EoL) to make new steel. Today, instead of using raw materials, it is essential to bring materials into the circular economy as much as possible according to the 9R approach. This approach is provided by the use of scrap, which is a secondary resource in steel production. Unfortunately, the utilization of scrap in steel production is not enough to achieve a net-zero economy. The concept of "green steel," which embraces innovative and environmentally friendly technologies, offers a potential solution to balance industrial advancement with environmental responsibility. [61], [62], [63], [64], [65].

Scrap is a term used to describe steel that has reached the end of its life, known as 'post-consumer scrap', or has been generated during the manufacture of steel products, known as 'pre-consumer scrap'. The "scrap" is a valuable raw material used in every steelmaking process. Due to its inherent magnetism, steel is very easy to separate and recycle after demolition, making steel the most recycled material in the world. Melting steel scrap at the end of its life allows the creation of new steels, adjusting the chemistry and shape of the new product. Almost every steel plant uses scrap as part of its raw materials mix, and therefore almost every steel plant is also a recycling plant. Also, using scrap in steel production enables reduction of greenhouse gas emissions [66].

In theory, all new steel could be made from recycled steel. However, currently, this is not feasible due to the scarcity of scrap. This is because of the long service life of steel products, given steel's strength and durability [66].

Long-term sustainability and recycling in the steelmaking sector primarily depend on scrap quality. The ideal scrap for steelmaking is called black. This scrap is undesirable to contain metallic and organic coverings/coatings, attachments, and tramp elements [63].

### 4.2.1 Recycling processes and their efficiency

In 2023, the global raw steel production per capita was 234.8 kg [65]. The construction industry has the highest steel demand of 52% (Fig. 10) [67].

Although steel is theoretically 100% recyclable, in practice the recycling rate is around 70% due to corrosion and losses that occur over time [63]. Moreover, in some developed countries, steel stocks have reached saturation or are even declining. This situation increases the share of scrap used in steel production. Consequently, the recycling rate is expected to rise further in the coming years and may reach 80% by 2050 [64]. The recycling process of steel consists mainly of three phases: (1) dismantling, (2) shredding and sorting, and (3) melting at the furnace. The dismantling phase focuses on collecting and separating steel components from end-of-life products, such as vehicles and buildings. This can be done manually or mechanically, depending on the waste type. In construction, it involves deconstructing to recover steel beams and rebars, while in the automotive sector, it means removing reusable or hazardous parts before shredding. The main goal is to maximize steel recovery with minimal contamination from materials like concrete and plastics, enhancing recycling

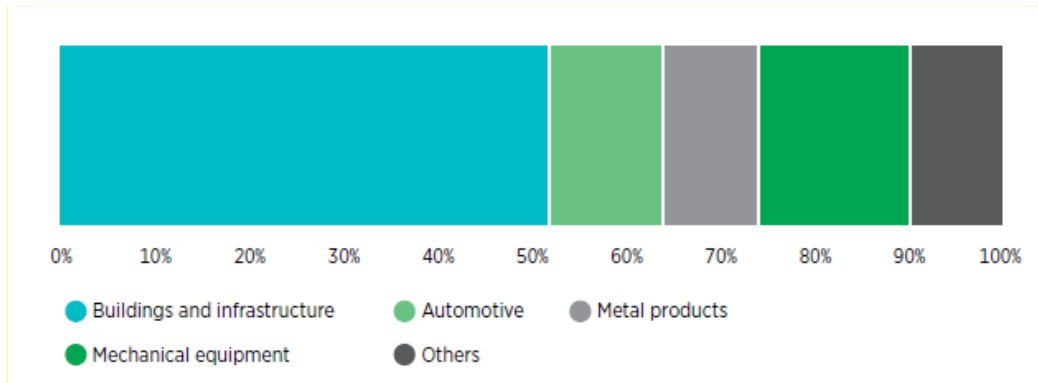


Figure 10. Breakdown of steel demand by sector, adopted from [67]

efficiency and quality. After dismantling, the recovered steel parts are transported to recycling facilities where they undergo mechanical size reduction and material separation. In the shredding stage, large steel components are broken down using powerful hammer mills or rotary shredders into smaller, more manageable fragments. This not only facilitates handling and melting but also exposes embedded non-metallic materials. The shredded mixture then enters a multi-stage sorting process designed to separate ferrous metals (containing iron) from non-ferrous metals and non-metallic residues [68]. The outcome of this phase is clean, well-classified steel scrap suitable for melting.

There are two main processes in steel production. The first is the Basic Oxygen Furnace (BOF) process, also known as ore-based steelmaking, which primarily uses iron ore but typically includes about 10–30% scrap as a coolant. The second method is the Electric Arc Furnace (EAF) process, commonly referred to as scrap-based steel production,

where recycled steel scrap serves as the main feedstock, even up to 100% [64], [66]. BOF process, which uses raw materials (iron ore, coal, and limestone) and scrap steel for steel production, is one of the most common and efficient production methods. This process converts molten pig iron into steel by blowing oxygen through a lance into the molten pig iron inside the converter. The injected oxygen reacts with dissolved impurities such as carbon, silicon, manganese, and phosphorus, oxidizing them and generating heat autothermally through exothermic reactions. These oxidation and purification reactions reduce the impurity and sulfur content of the melt, transforming it into steel. In the subsequent stage, alloying elements are added to achieve the desired composition, and the steel is then cast - typically using continuous casting - and cooled with water [69]. Steps of BOF process and the interior view of an oxygen furnace are given in the Fig. 11.

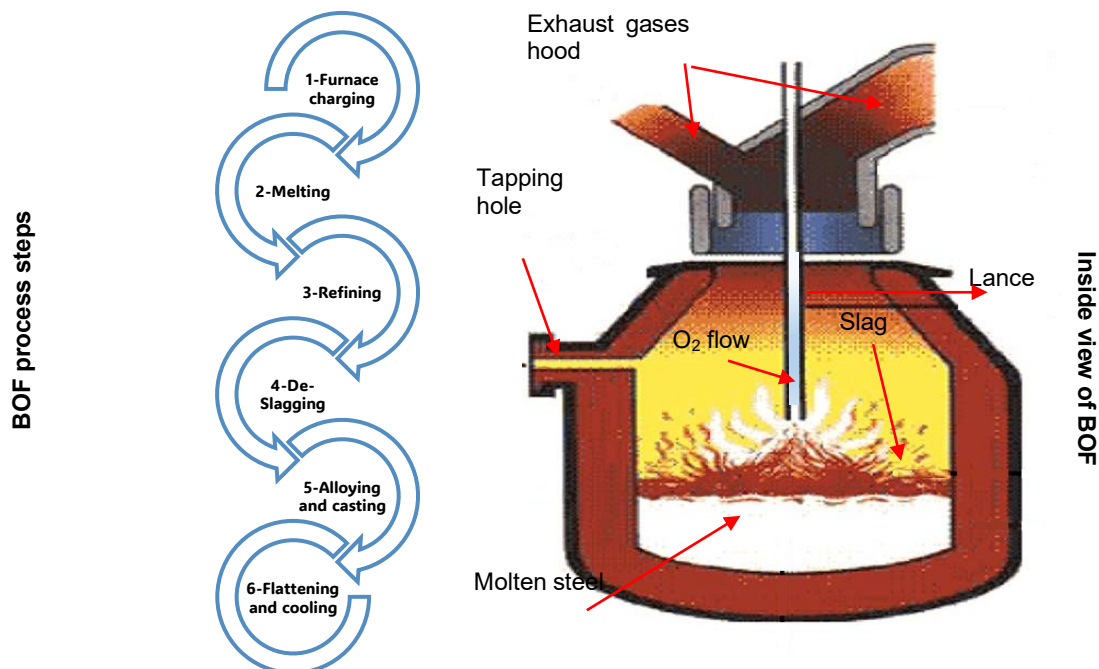


Figure 11. BOF process steps and inside view of an BOF, adopted from [69], [70]

The Electric Arc Furnace, (EAF), is an even more modern method of steel production by remelting steel scrap into new steel and is called scrap-based steel production. Steel scrap is secondary-sourced material i.e., discarded steel that becomes available from manufacturing waste generation and from recovered steel in buildings, infrastructure, equipment, vehicles and products discarded at their end of life. The EAF process lasts about 60 minutes and includes six main steps. First, scrap and slag-forming materials are charged into the furnace. An electric arc is then created to melt the scrap. Next, impurities such as phosphorus and silicon are removed, while gases like hydrogen and nitrogen are reduced. Oxygen and natural gas are injected to speed up reactions and improve steel quality. The oxidized impurities form slag, which is drained when the furnace is tilted. Finally, the steel's composition and temperature are adjusted before it is poured into a ladle for the next stage [69]. Process steps of EAF and the interior view of an electric arc furnace are given in the Fig. 12.

The amounts of key raw materials used to produce 1000 kg of crude steel, depending on the applied production method, are given in Tab. 10.

**Iron ore:** Steel is an alloy primarily composed of iron with less than 2% carbon. Therefore, iron ore is a crucial raw material in steel production. Approximately 98% of all mined iron ore is used for this purpose. High-quality iron ore typically contains about 60–65% iron. Mining operations take place in around 50 countries, with Australia and Brazil together accounting for one-third of global exports. In 2021,

worldwide iron ore exports reached 1.65 billion tonnes [66], [71].

**Limestone:** Limestone plays an essential role in steel production as a fluxing agent. During the smelting process, it is added to remove impurities such as silica, phosphorus, and sulfur from the molten iron. When heated in the furnace, limestone decomposes into lime (CaO) and carbon dioxide (CO<sub>2</sub>). The resulting lime reacts with impurities to form slag, which floats on the molten metal and can be easily separated.

**Coke and Coal:** Since iron occurs in the Earth's crust mainly as iron oxides, it must be reduced to metallic iron using carbon. The primary carbon source for this process is coking coal, which is converted into coke through a heating process known as carbonization. Coke then serves as both the fuel and reducing agent in the blast furnace, where it reacts with the iron ore to produce molten iron, which contains a high carbon content. There are about 80 countries worldwide with significant coal reserves. The largest reserves are found in the United States, China, Russia, Australia, and India. Each year, approximately 1 billion tonnes of metallurgical (coking) coal are used in global steel production, accounting for about 15% of total coal consumption worldwide. In 2021, the global metallurgical coal export market amounted to 0.31 billion tonnes, of which Australia accounted for around 0.2 billion tonnes. The largest producer of coking coal, however, is China [71].

**Recycled Steel (Scrap):** Steel has excellent circularity properties. Whereas other materials are often downcycled at

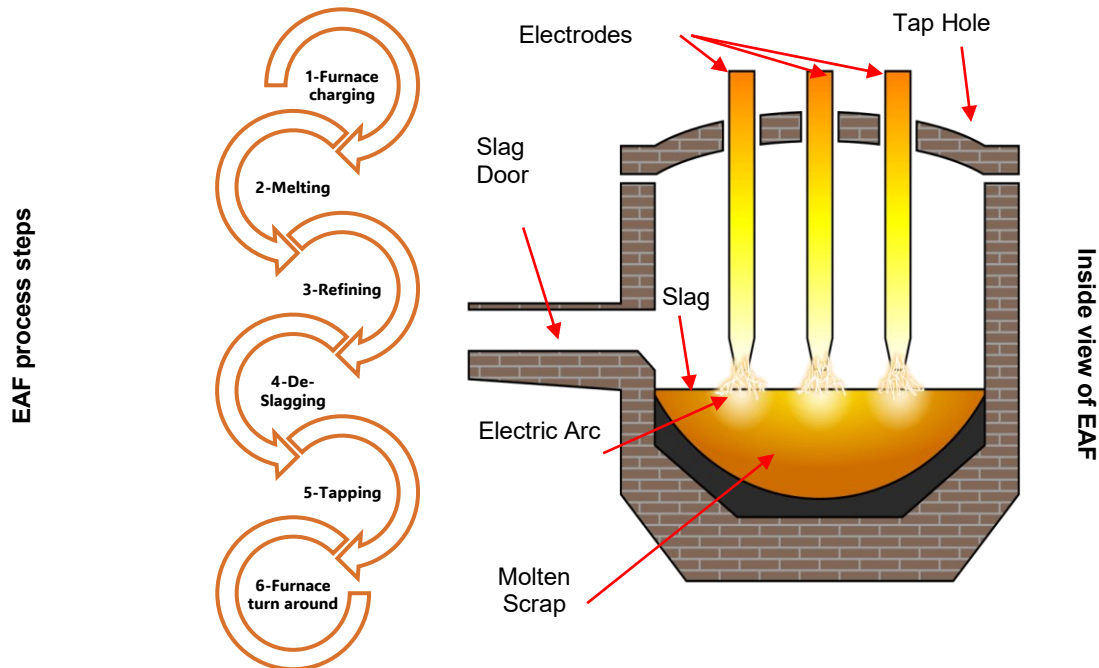


Figure 12. EAF process steps and inside view of an EAF, adopted from [69], [70]

Table 10. Consumption of key raw materials and energy sources to produce 1000kg of crude steel, depending on the technological processes used, adapted from [71]

Raw materials/energy source	BOF process	EAF process
Iron ore, kg	1370	586
Recycled steel (scrap), kg	125	710
Limestone, kg	270	88
Coal, kg	780 (metallurgical coal)	150 (coke)
Electricity	-	2.3GJ

their end of life, for many applications, steel scrap can be turned back repeatedly into new steel, retaining its original properties [72]. Scrap is an essential raw material in modern steel production, offering both economic and environmental advantages. It reduces the need for primary raw materials such as iron ore and coke, while cutting energy consumption by up to 70% and CO<sub>2</sub> emissions by more than half. Globally, about 30–35% of total steel output comes from recycled scrap, making it one of the most sustainable materials in the industry [73]. For example, in 2021, the global steel industry consumed around 0.65 billion tonnes of scrap steel for production, in the context of a total crude-steel output of about 1.9 billion tonnes [66]. This scrap usage contributes significantly to sustainability: it is estimated to avoid approximately 975 Mt CO<sub>2</sub> annually and reduces the consumption of iron ore, coal and limestone.

By sector, global steel recovery rates are estimated at approximately 85% for construction, 90% for automotive (reaching close to 100% in the US), 90% for machinery, and 50% for electrical and domestic appliances [71].

The world's crude steel production in 2021, was 1.95 billion tonnes, from which produced through the BOF process is 1.38 billion tonnes (70.8% of total production), while 0.56 billion tonnes (28.9% of total production) were produced through the EAF process. However, the involvement of these two technological processes in steel production varies greatly between continents. For instance, in the EU-28, BOF accounts for 57.3% and EAF for 42.7%; in North America, BOF is 31% and EAF 69%; while in Asia, the situation is reversed, with BOF at 81.7% and EAF at 19.3%. However, since Asia accounts for 72% of global steel production, it gives the impression that the BOF process is still dominant worldwide [74]. From these analyses, it can be concluded that scrap is used much more in steel production in the EU and North America than in Asia.

According to the World Steel Association data for 2022, the CO<sub>2</sub> intensity of the BF-BOF process is around 2.33 tonnes CO<sub>2</sub>/tonne crude steel cast. In the EAF process using direct reduction iron (DRI) for production, the CO<sub>2</sub> intensity is 1.37, and in the EAF process using scrap, the CO<sub>2</sub> intensity is around 0.68 tonnes CO<sub>2</sub>/tonne crude steel. In this context, steel production from raw materials causes approximately 2 times more greenhouse gas formation than production from scrap [75].

According to ArcelorMittal [72], producing 1 tonne of crude steel from a primary source (iron ore) emits 1–2 tonnes of CO<sub>2</sub>, whereas using a secondary source (scrap) results in only 0.1–0.4 tonnes of CO<sub>2</sub> emissions per tonne of crude steel. Similarly, the energy required for steel production from primary sources is 18–22 GJ (solid fuel for iron production plus electricity for steelmaking), while production from secondary sources requires only 5–7 GJ of electricity per tonne of crude steel.

#### 4.2.2 Possibility and potential of steel for recycling

The global steel sector is already circular to an extent. About 30% of the steel produced today comes from scrap recycling. It is also possible to rely on renewable power sources in steelmaking. However, most steel produced today still relies on fossil fuels as energy sources and reducing agents for iron ore processing.

There are numerous benefits associated with the use of steel scrap in steelmaking. However, there is no unified systematization of these benefits, as their categorization varies across authors - some explicitly name the benefits, while others describe them in a more narrative form. By

reviewing relevant scientific papers, as well as technical and industrial reports ([61], [68], [76], [77], [78], [79]), we identified and systematized the most significant benefits into four main categories: environmental, economic, social, and technological (Tab. 11).

Stell construction industry faces several barriers and challenges in spite of the environmental, economic and other benefits of using recycled steel. Some of main barriers and challenges are: (1) Limited scrap recycling potential, (2) Decarbonization of steelmaking, (3) Scrap quality and contamination, (4) Market dynamics - supply-demand mismatch, (5) Regulatory, standardization, and legal impediments.

*Limited scrap recycling potential.* The limited circularity of the global steel flow is not due to poor waste management. In fact, 85 % of end-of-life scrap was collected and recycled in 2019. Instead, the key limiting factor is the growing in-use steel stock – the steel embedded in products, buildings, and infrastructure [80]. According to forecasts, global demand for crude steel is expected to rise from 1.9 billion tonnes in 2021 to over 2.6 billion tonnes per year by 2050. Although the share of end-of-life steel scrap in total steel production will increase substantially by 2050, it will still represent only about 44% of global steel production [72], [81]. Scrap availability depends on the average life and the volume of steel products. The average service life of steel products varies from a few weeks for steel packaging to up to 100 years for buildings and infrastructure, with the average lifespan of a steel product being 40 years [80]. It is estimated that global end-of-life ferrous scrap availability will reach approximately 600 million tonnes in 2030 and 900 million tonnes in 2050. Increased reuse and remanufacturing may alter the amount of scrap availability in the future [72].

*Decarbonization of steelmaking.* The steel industry has a significant challenge ahead to decarbonize the industry [72]. The global steel sector is the second largest in GHG emissions after cement, heavily relying on fossil fuels. It accounts for 7-9% of CO<sub>2</sub> emissions. As steel demand grows, the decarbonization to meet the Paris Agreement's 2050 net-zero goal is a significant challenge [82]. Studies exploring emission reduction potential in the steel sector, show that the capacity to reduce emissions using traditional energy-efficiency measures is limited to collectively abating around 25–40% of average CO<sub>2</sub> emissions per ton of crude steel produced [82]. To achieve further reductions, advance technologies are required, such as carbon capture, utilization, and storage (CCUS), using hydrogen or biomass as reducing agents, or electrolysis (i.e., using electricity to reduce iron ore) [82]. CCUS is one of novel climate mitigation technologies; in this process CO<sub>2</sub> emissions are captured from sources such as fossil power generation and industrial processes, and further either reused or stored [83]. In terms of biomass research shows that the CO<sub>2</sub> footprint of a direct reduction plant fed with biomass-based reducing gas is more than 80% lower compared with the conventional blast furnace route and could be even more if carbon capture and utilization is applied [82]. In terms of electrolysis, high temperature electrolysis (HTE) has the potential to reduce the specific electricity consumption of liquid steel production by 21% compared to the low temperature electrolysis case [84]. Tab. 12 shows several initiatives promoting the use of breakthrough technologies in steelmaking. Steel produced using these technologies is referred to as "fossil-free", "carbon-lean", "CO<sub>2</sub>-lean", or "CO<sub>2</sub>-neutral" steel. Recently, the term "responsible steel" has been adopted to describe steel products that are responsibly sourced and produced [82].

Table 11. Classifications of steel recycling benefits

Basic groups	Identified benefits	Efficiency
<b>Environmental benefits</b>	Resource conservation	Reduction of virgin iron ore, coal and water
	Energy savings	Using steel scrap can cut energy consumption in steelmaking by up to 70%
	Lower CO <sub>2</sub> emissions	The use of EAF with scrap reduces CO <sub>2</sub> emissions by up to 80% compared to BOF process
	Waste reduction	Recycling steel reduces waste by repurposing end-of-life products into new raw materials
	Pollution control	Recycling steel can lead to an 86% reduction in air pollution and a 76% reduction in water pollution
<b>Economic benefits</b>	Cost savings	Using recycled scrap as a primary feedstock allows steel manufacturers to significantly reduce material costs compared to the expensive and energy-intensive extraction of virgin ore
	Reduced operational expenses	Scrap-based production through EAF requires less energy and has shorter production cycles, leading to lower operational costs
<b>Social benefits</b>	Job creation	The steel recycling industry is labor-intensive, creating numerous jobs in the collection, sorting, processing, and resale of scrap metal
	Infinite recyclability	Steel can be recycled indefinitely without losing quality
	Support for the circular economy	Steel recycling is essential to the circular economy, ensuring materials are used longer and resources are conserved for future generations
	Healthier communities	Steel recycling reduces pollution from mining and manufacturing, leading to cleaner air and water and improved public health in surrounding communities
	Stable domestic supply chains	Increasing the use of locally sourced scrap can reduce reliance on imported raw materials, stabilizing supply chains and enhancing economic resilience
<b>Technological benefits</b>	Automated sorting	Sensor-based sorting technologies, like X-ray fluorescence (XRF) and artificial intelligence (AI), have significantly enhanced the speed and accuracy of separating various metals from complex waste streams
	Advanced furnace techniques	Modern EAF technologies incorporate digital controls for precise temperature and composition management, resulting in improved efficiency and higher-quality recycled steel
	Digital traceability	Technologies like blockchain are being explored to create transparent supply chains that track recycled materials from source to destination, enhancing accountability and fostering trust among stakeholders

Table 12. Recent steelmaking project/technologies, adapted from [82]

Company	Project/technology	Location	Target
ArcelorMittal	Hydrogen reduction with grey hydrogen derived from natural gas; Blast furnace + electrolysis for hydrogen production; Hybrid blast furnace with direct reduced iron (DRI) gas injection; Coke oven gas with grey hydrogen; hydrogen in DRI-EAF;	Hamburg, Germany	Fossil free by 2050
		Bremen, Germany	
		Dunkirk, Germany	
		Asturias, Spain	
HYBRIT (SSAB, LKAB and Vattenfall)	Replacing coking coal with hydrogen and fossil-free electricity	Sweden	Fossil free by 2045
Voestalpine Primetals Tech.	Hydrogen as reducing agent to process iron ore concentrates	Linz, Austria	80% carbon emissions reduction by 2050
Salzgitter AG (Salcos project)	Electrolysis/hydrogen-based steelmaking	Wilhelmshaven, Germany	2 million tonnes per year of DRI, expected in 2025
Celsa, Statkraft & Mo industrial park AS	Electrolysis/hydrogen-based steelmaking	Norway	50% emissions reduction by 2030, decarbonization by 2050
H2 Green Steel Initiative	Hydrogen-based steelmaking	Northern Sweden	Planned production to start in 2024. Annual production target of 5 million tonnes of green steel by 2030

However, these technologies are still in the early research stages, and others are only at the pilot/demonstration phase [82]. Also, all of them are very expensive in terms of utilization for production [83], [85], [86].

**Scrap quality and contamination.** The scrap provided to the steelmaker, known as merchant scrap, is typically a mixed material that lacks adequate chemistry measurement. This deficiency limits accuracy, consistency, and compatibility with the required product chemistry. Recycled scrap accumulates residual alloying elements such as Cu, Sn, Sb, Pb, Zn and Cr. These elements will not be removed as slag or off-gas through oxidation or reduction during EAF steelmaking, leading to an increased concentration in the metallic products [80]. Changes in steel chemistry due to increased scrap use can have both negative and positive effects on processing and final properties, requiring careful consideration to determine what modifications in composition, processing parameters, and product performance may be caused. For example, copper (Cu) is generally regarded as beneficial for improving corrosion resistance and is therefore intentionally added to produce weathering steels. On the other hand, concentrations of copper exceeding 0.1 wt.% lead to hot shortness, a phenomenon that results in surface cracking during hot rolling and forming [87]. Therefore, improved scrap sorting and quality control are essential to ensure the supply of low-residual scrap suitable for producing all steel grades [80]. There are two possibilities to avoid unwanted element accumulation: diluting virgin material to reduce concentration without recovery or removing them during sorting.

**Market dynamics - supply-demand mismatch.** Scrap availability and location don't always match where secondary steelmaking capacity or demand exists; this causes regional shortages, price volatility, and exports/imports that complicate domestic circularity strategies. Forecasting and market coordination are weak in many regions [80], [81]. Steel scrap is often found far from regions with high steel demand. Consequently, both steel products and their inputs are traded in large quantities on an international scale. Currently, around 17% of the world's annual scrap supply, equivalent to about 110 million tonnes, is traded internationally. For example, Turkey depends on the EU, the USA, the UK, and Russia to import roughly 25 million tonnes of low, grade scrap each year. In contrast, the United States faces a shortage of prime scrap and relies on imports from Canada to bridge the gap, while Japan exports its surplus prime scrap to South Korea, Southeast Asia, and China [88]. The steel scrap market will be unstable in the future as demand for recycled steel grows faster than the amount of scrap steel available.

**Regulatory, standardization, and legal impediments.** Environmental regulations governing waste management and recycling are continuously evolving to promote greater sustainability. For the steel industry, which operates under some of the most stringent environmental standards, this presents ongoing challenges. Regulations often differ across countries and regions, covering aspects such as emissions control, waste disposal, and recycling practices. As a result, recyclers must constantly adapt to shifting requirements while ensuring full compliance, which can create administrative complexity, increase operational costs, and cause confusion for companies operating globally [89]. Further, unclear classification (waste vs product) and lack of standards/certification for recycled steel hinder high-value recycling. There are only several available steel scrap specifications, including the UK Ferrous Metals Specifications, EU-27 Steel Scrap Specification, Japanese

standards for ferrous scrap, and ISRI Scrap Specifications; however, these specifications do not include complete chemistry requirements [80].

Overcoming these barriers is essential for advancing circularity in steel production [90].

#### 4.3 Circular practices and examples for steel

The primary aim for the circular economy in the built environment is to reduce material and resource consumption, to optimize the lifespan of materials, to design for disassembly, reuse, and recycling, and to ensure positive contribution to the natural ecosystem [91].

A key aspect of circular economy in built in environment is to extend the life of building materials, components, and systems beyond the end-of-life of the building through disassembly, reutilization, and recycling. This requires a holistic approach in which specific design strategies can be developed for reversibility, adaptability, and flexibility. Design in the circular economy consists of designing buildings for easy disassembly and materials reuse and recycling, hence reducing demolition costs and consumption of resources. The major strategies are reducing material inputs, standardizing connections for easy disassembly, and keeping information about materials [92].

Designing buildings for disassembly aims to create structures that adapt to future changes and ultimately disassembles. The process involves maximizing economic value and minimizing environmental impact through reuse, repair, re-manufacture, and recycling by planning construction methods and management systems [93].

Closed-loop material cycles are another tool supporting circular economy in built environment. The target of the closed-loop material cycles is to achieve zero waste and resource efficient construction by using byproducts from one process for another. Steel is a closed-loop cycle material because it can be recycled back into its original forms. This outstanding characteristic results in strong circular economic credentials [94].

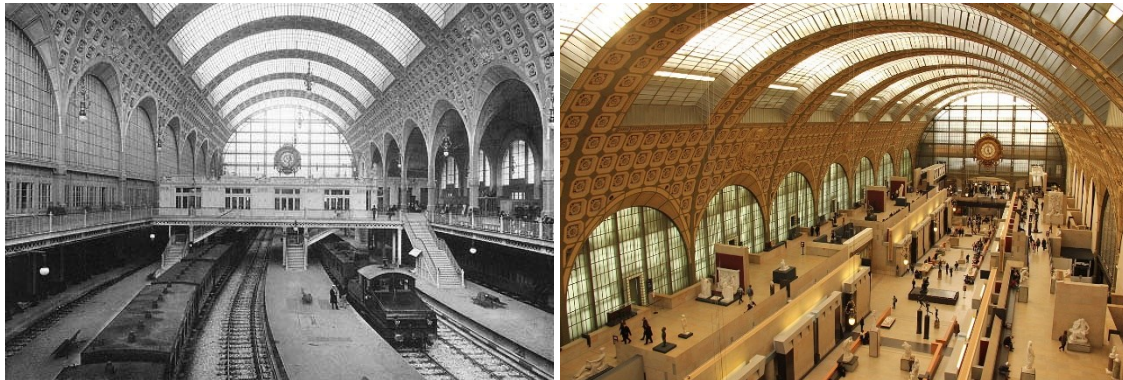
Options for improve the circularity in steel sector are: (1) Material efficiency in steel use, (2) Steel scrap recycling, (3) Process efficiency and (4) Renewables-based steel production. Material efficiency measures can contribute to advancing the circularity of the iron and steel sector by optimizing the use of steel products, like producing lighter steel products and structures, refurbishing and reusing steel products, and redesigning products with alternative materials when justified based on life cycle analysis. Recycling steel improves circularity by reducing the need for primary steel production. Process efficiency enhances circularity by minimizing the need for resources, especially for energy, in steel production, which would contribute to reducing the environmental impact. A shift to renewable-based steel production replaces fossil fuels with renewable energy and green hydrogen, improving environmental performance, reducing fossil fuel dependence, and supporting circularity [67].

Circularity in the built environment can be achieved through various strategies, such as repurposing entire buildings, reusing building structures, or reusing individual structural components [95]. In the following section, one example is provided for each of the three main strategies of circularity in the built environment. Below, one example is provided for each of the three main strategies of circularity in the built environment.

One well-known example of repurposing an entire building is the Musée d'Orsay in Paris, France. The museum,

which opened in 1986, originally functioned as the Gare d'Orsay railway station, inaugurated in 1900 for the Exposition Universelle. When long-distance trains began terminating at Gare d'Austerlitz in 1939, Gare d'Orsay was used primarily for suburban services. In the following decades, the building served several other purposes, including housing a theatre company and hosting film productions. Recognizing its architectural and historical significance, the station was classified as a historical monument in 1973, and later transformed into the Musée d'Orsay [96]. Fig. 13 shows images of the former station and the present museum [97].

Argentinian Warehouse is an example of reusing the building structure. It was built in 1915 in Amsterdam for storage and transshipment site for coffee and cocoa beans. After 80 years of service storing cocoa and coffee beans, the 200 m long steel structure was dismantled to its original components. The components were recoated and reused for reconstruction in the same configuration into a new shopping center - Brazilian Shopping Center [98], [99]. The appearance of the steel structure and façade of the old and new building is shown in Fig. 14 and Fig. 15.



*Figure 13. The Gare d'Orsay (on the left) and Musée d'Orsay (on the right) [97]*



*Figure 14. Original steel structure of Argentinian Warehouse (left) and reused steel structure in Brazilian Shopping Center (right), Amsterdam [99]*



*Figure 15. Argentinian Warehouse on the left and Brazilian Shopping Center on the right [98]*

A new floor extension was made on the top of an existing “Grosvenor Estate” building. This office building was built in 1980. By extending for one floor additional 25% of available floor space was obtained. The aim of net zero was primarily achieved by relying on reclaimed steelwork and Cross Laminated Timber (CLT). In the building, 34% of the steel elements were reused from demolition on 2 existing Grosvenor projects and from reused stock from Cleveland Steel. The test results allowed the structural properties of the sections to be proven, and hence, the structure can be CE marked according to legislative requirements. This project involved approximately 67 tonnes of steelwork involving reused elements. 25 tonnes were reused material interconnected with new ones and not designated to specific areas. This allowed a carbon saving of approximately 60 tonnes. The reconstruction and extension of the Holbein Gardens building were completed in 2023 as part of Grosvenor’s net-zero carbon development program [77]. Reclaimed steel elements, a detail of upgrading and final appearance of the extended building are shown in Fig. 16.

## 5 Timber

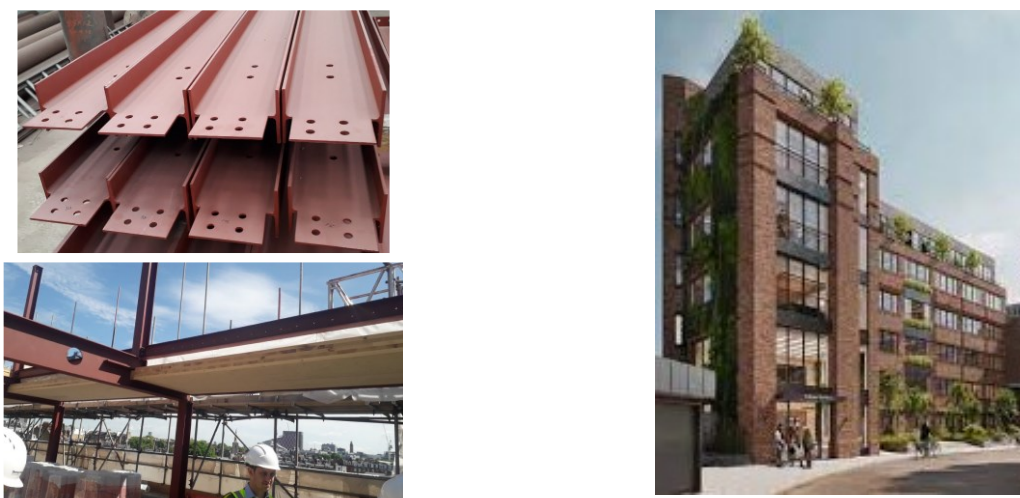
### 5.1 Reuse of timber

One of the most promising eco-friendly sustainable building materials is wood. When sustainably sourced from managed forests, this renewable material not only acts as a carbon sink but also permits a decrease in embodied energy when compared to traditional materials like steel and concrete. This presents a significant opportunity to lessen the effects of the built environment on our climate and natural habitats, especially when combined with the effective use of wood in design. Furthermore, the carbon stored in timber during sequestration usually outweighs the carbon emissions related to timber production. However, the potential to fully utilize the sequestered carbon in timber is limited because structural timber is typically only used for a single service life in construction [100]. Thus, imposing the demand for responsible wood waste management to achieve low carbon emissions and environmental benefits, such as the conservation of natural resources through forest preservation and the reduction of landfill waste by decreasing methane emissions from decomposing wood.

Improving the industrial economics through cost savings and job creation represents the additional but essential aspect of timber waste reuse and recycling as a key step in the circular economy (CE) of timber use.

To reduce the impact of the built environment on CO<sub>2</sub> emissions and consumption of non-renewable materials, it is essential to apply bio-based materials, i.e., increase the amount of sustainable timber in construction. To achieve a total CO<sub>2</sub> reduction of 18% (37 Mt) in 2030, 50% of new residential buildings should be bio-based. This requires 566 million m<sup>3</sup> of round wood by 2030. Since only 3.6% (18.5 million m<sup>3</sup>) of roundwood is used for the production of Engineered Wood Products (EWPs), such as cross-laminated timber (CLT), glue-laminated timber (GLT), and laminated veneer lumber (LVL), therefore the production capacity of EWPs has to be increased significantly in the coming years [101]. For comparison, data on wood production and processing taken from Eurostat are given: roundwood production in the EU in 2022 reached an estimated 510 million m<sup>3</sup>. This is 26% more than at the beginning of the millennium. Wood has been increasingly used as a source of renewable energy. Almost a quarter (24 %) of the EU’s roundwood production in 2022 was used as fuelwood, while the remainder was industrial roundwood mostly used for sawnwood and veneers or for pulp and paper production. Sawnwood production in EU was approx. 105 million m<sup>3</sup> in 2022 [102]. By comparing the demands with the actual timber availability, it is clear that roundwood and EWP production should be significantly increased. However, there is a limit to how much sustainable wood can be harvested without jeopardizing the crucial functions the forests provide. One of the viable solutions to compensate for the increased need for timber lies in reusing “old” timber elements for structural purposes.

Commonly, wood waste could be generated from main structural elements from old buildings, construction and demolishing processes, engineered wood products industry, and municipal-wide spectra use (furniture, packaging material, pallets, etc). EWPs, like GLT, CLT, or LVL, as well as mass solid timber elements, have a great potential to be reused as structural elements in new assemblies or, depending on their state condition, into non-structural but new useful function, such as urban or home “do it yourself” (DIY) furniture, etc.



*Figure 16. “Grosvenor Estate” building reclaimed steel (upper/left); new structure made of reclaimed steel (bottom/left); appearance of extended building in London (right) [77]*

The data for the EU28 indicates an annual production of 52.9 million tonnes of wood waste. Of this waste, 48% is found in municipal solid waste, 38% in C&DW, and the rest as wood industry waste [103]. According to the same source, in 2016, 87% of wood waste was treated, from which 49% was recycled, 48% was combusted for energy recovery, and 3% was landfilled or incinerated. The fate of the untreated waste wood is unclear. In EU27, in 2020, 99.38 % of waste wood was recovered from which 46.02 % was recycled, 53.36 % was used for energy recovery, while only 0.59 % of waste wood was disposed [107]. The amount of wood treated has reached its maximum over four years, but a slight drop in the participation of waste wood in recycling processes is noted. Currently, no information is available regarding the reuse of waste wood for both structural and non-structural uses.

It was estimated that 2.3 million tonnes of timber were reclaimed across the UK in 2018 from construction and demolition activities. However, most reclaimed timber is recycled or used for energy recovery, and only around 2.5% is kept in its original form for reuse or remanufacturing. On the other hand, reclaimed timber can be easily worked and transformed, allowing it to serve various functions. However, as a biogenic material that releases carbon dioxide and methane at its end of life, it is critical to prolong the retention of sequestered carbon [104]. For comparison's sake, in 2023, the total amount of waste wood generated was 4.5 million tonnes. More than 97% of this wood waste was processed, meaning that less than 3% was sent to landfill. Of the processed waste wood, 65% was reprocessed for biomass, 22% was used as feedstock for the panel board industry, and 5% was exported, while animal bedding, equine surfaces, and other recycling and reuse processes accounted for the remaining 8% [100]. Although these figures are not directly comparable, it can be concluded that from 2018 to 2023, there was no significant shift toward reusing wood.

Ahn et al. [105] prepared a state-of-the-art review on the circular economy in mass timber construction, noting that the environmental benefits and CE potential of EoL and post-EoL timber structures are still underemphasized. The report indicates a lack of knowledge and the need for urgent research in creating holistic approaches to circularity in mass timber buildings.

There are two classification systems at the EU level which are particularly relevant to waste wood – the European List of Waste (LoW) and the European Waste Classification for Statistics (EWC-Stat). The LoW provides a harmonized catalogue of wastes for administrative purposes, such as statistical reporting of waste quantities. This list is organized by waste codes based on the origin and composition of waste and whether the waste is considered hazardous. The EWC-Stat is a substance-based catalogue of waste used for reporting waste statistics to Eurostat, with categories which can be transposed to LoW codes via an annexed table of equivalence. Beyond classifications, there are also several environmental regulations and directives which are relevant to waste wood classification and management, including the Waste Framework Directive (WFD), the Landfill Directive, and the POPs Regulation. National waste wood approaches vary from one EU Member State to the next. However, several common features emerge across the various national waste wood schemes. These common features include the use of quality criteria related to mechanical processing and chemical treatment, as well as presence of hazardous substances and preservatives to classify waste wood. Individual waste wood approaches are given for five EU Member States - Germany, the Netherlands, Finland,

France, and Slovenia, as examples [107]. In the listed countries, wood classification, the criteria for each class, and the use prescriptions by class are defined. Germany, the Netherlands, Finland, and Slovenia classify wood waste into four classes, while France uses three classes (Tab. 13). These classifications are predominantly designed for wood waste from the perspective of its potential use as fuel and for energy production, although some countries also allow alternative applications. For example, the German waste wood classification scheme includes use prescriptions by class, distinguishing between “*material recycling procedures*”, “*energy recovery*” according to the conditions set out in the Federal Immission Control Act (BImSchG – Bundes-Immissionsschutzgesetz), and “*disposal*”. Wood waste classified as Classes AI, AII, or AIII can be used in “*material recycling procedures*”. Under the Waste Wood Ordinance, material recycling procedures include three different processes: processing of waste wood into wood chips, production of synthesis gas for further chemical use, and production of activated carbon/industrial charcoal. Wood from C&DW is mostly allocated to AII-AIV. The waste wood classification scheme in the Netherlands is a part of the National Waste Management Plan 3 (LAP3). Although the sectoral plan recognizes that classes A and B of wood waste can be “*materially recycled*”, it also includes “*other useful applications*”, such as “*energy recovery*”. The Finnish classification scheme focuses primarily on the fuel and energy use of waste wood, setting use prescriptions that specify whether wood in each class can be recovered for energy and in which types of energy plants. It does not include material-use prescriptions. However, the Finnish Waste Act mandates adherence to a waste management hierarchy that prioritizes preparation for reuse, followed by recycling. This hierarchy is explicitly applied to C&DW under the Government Decree on Waste. In France, for material recovery, waste wood must not be hazardous, which limits material recovery to wood belonging to Class A and Class B. In Slovenia, the wood waste classification has been developed solely to assess the potential for processing wood into solid fuel. The Slovenian Waste Regulation also sets reuse and recycling targets for household waste; however, wood is not included in this target, although it is included in the overall preparation for reuse and recycling of C&DW.

This small analysis revealed that although the EU Waste Framework Directive (WFD) introduced the waste management hierarchy and promotes its application through the limited use of economic instruments and incentives such as Extended Producer Responsibility (EPR) schemes, separate collection obligations, and sectoral reuse, recycling, and recovery targets, [107] the actual situation in waste wood management is different. Unfortunately, cited national Waste wood classifications consider wood waste predominantly as an energy source. Drawing from the abovementioned waste wood classifications and favoring the highest priority uses, in line with the EU waste hierarchy, Project CEPS wood2wood proposed a possible harmonized classification scheme in terms on quality criteria and priority uses (Tab. 14), [107]. The proposed new classification comprises five classes: Clean, Non-Hazardous I, Non-Hazardous II, Hazardous I, and Hazardous II. This classification is primarily based on content and type of chemical substances, which can help prevent downgrading and upgrading of wood waste classes. As can be seen, priority use is not strictly prescribed. Priority uses aim to maximize the value of each waste wood class, adopting a flexible approach that permits waste wood to be used in various ways (i.e., reuse, repurposing, recycle etc.), including the priority uses.

Table 13. Waste wood classification in Germany, The Netherlands, Finland, France, and Slovenia, adapted from [107]

Germany			
A I	A II	A III	A IV
Untreated, non-hazardous	(Surface) Treated, non-hazardous	Contaminated, non-hazardous	Hazardous
The Netherlands			
A	B	C (non-wolmanized)	C (wolmanized)
Untreated, non-hazardous	Treated, non-hazardous	Hazardous	Hazardous
Finland			
A	B	C	D
Untreated, non-hazardous	Chemically treated, non-hazardous	Chemically treated, non-hazardous (HOCs or heavy metals above thresholds)	Preservative treated, hazardous
France			
A1	A2	B	C
Natural, untreated, and uncoated, non-hazardous wooden packaging waste	Natural, untreated, and uncoated, non-hazardous wood from processing industry	Surface treated, non-hazardous	Heavy metal or HOC treated, hazardous
Slovenia			
Unpolluted biomass waste	Contaminated biomass waste	Other waste	Hazardous biomass waste
Non-hazardous	Non-hazardous	Non-hazardous	Hazardous

Table 14. Proposed classification scheme in terms of quality criteria and priority uses, adopted [107]

	Clean	Non-hazardous I	Non-hazardous II	Hazardous I	Hazardous II
Quality criteria	Mechanically processed	Chemically treated. HOCs in coating. HOC, heavy metals below thresholds.	Chemically treated. HOCs in coating. HOC, heavy metals below thresholds.	Chemically treated. HOC, heavy metals above thresholds. PAH-treated.	PCB, CC/CCA treated.
Priority uses	Material recovery	Material recovery	Material recovery (coating removed).	Material recovery (limited). Energy recovery	Disposal

### 5.1.1 Reuse processes and their efficiency

Timber, as a natural material, is one of the most promising sustainable construction materials that can help mitigate climate change. However, there is currently no guidance or framework within existing business models to facilitate its circularity, meaning the reuse and repurpose of the material, and to assess its suitability for various purposes. Reusing timber helps maintain the material's highest value while also eliminating the need to source new materials. To promote and encourage reuse of structural timber in building redevelopment projects a various recommendations and guides have been proposed ([100], [106], and [108]). By combining them, we prepared a general, simplified proposal, which includes following stages: (1) a pre-demolition visual inspection and audit, (2) a feasibility assessment and a reuse/repurposing plan, (3) careful deconstruction/disassembly and reconditioning, (4) testing and structural characteristic assessment, and (5) sorting, grading, and proper storage.

**Pre-demolition visual inspection and audit:** A visual inspection should be performed to make an inventory of the timber elements to be salvaged such as beams, columns, rafters, etc. Pre-demolition audits estimate the amount of wooden materials likely to be generated from demolition

projects and offer recommendations on those waste management routes. They also provide a list of hazardous wooden materials and those with potential for reuse or recycling. The LoW and EWC-Stat systems can help identify hazardous waste wood.

**Feasibility assessment and reuse/repurposing plan:** Timber that is about to be sourced directly from demolition sites needs to be evaluated for careful deconstruction and preparation for reusing or repurposing. Since the additional time and cost are associated with the reuse/repurposing of structural timber, a feasibility plan serves to provide detailed information on suitable demolition methods to recover the identified materials, as well as to estimate the time needed to enable reusing/repurposing.

**Careful deconstruction/disassembly and reconditioning:** According to a thoughtfully prepared plan of deconstruction of the old timber building, the disassembly of timber members will be done. This operation includes dismantling, handling, separation, and stockpiling on-site, and transporting and storing the timber members. A specific skill set is required during the deconstruction to ensure the timber is salvaged without further damage. Further, cleaning and preparation processes have to be done, such as removing fasteners (nails, staples, screws, etc.), cutting out splits and notches, repairing and cleaning wood by washing to remove

dirt, grime, and mildew. Also, a metal detector can be used to ensure that all metal is removed before re-milling.

**Testing and structural characteristic assessment:** This operation can be performed before or after deconstruction, depending on the availability of elements for testing, their condition (they should be without paint or coat) investigation company's ability to conduct testing in situ, and other factors. Since, there are no standards available for the assessment of reclaimed timber, the structural characteristics should be verified according to current EU standards (EN 338:2016, EN 14081-1:2020, EN 1309-3:2018, EN 1912:2024) [108]. Therefore, it is crucial to prepare carefully the testing program to best assess the reclaimed wood for the intended purpose. Different non-destructive test methods are available; however, their accuracy depends on consistency in the shape and size of the reclaimed timber members, thus a certain prior processing is requested. Furthermore, any fixings, splits, notches, etc. could hamper this process, so it is important to remove them before testing. Also, visual grading plays very important role in assessing timber residual performances. If the timber element is planning to be reused for structural purposes, the visual grading according to the parameters set by current regulations/standards should be performed.

**Sorting, grading, and proper storage:** After the deconstruction and testing, the salvaged timber elements are to be sorted based on their quality and condition. They can additionally be reconditioned if a possible future application requires it. Then, the wood is grouped according to its potential end-use, such as for structural, non-structural, or decorative applications. Any small sections or fragments from the resizing (i.e. waste) can be sorted, developed into by-products or sent out for recycling. The whole timber pieces can then be sorted and grouped into the materials that are going to be reused and upcycled. High-quality timber can be re-milled to its original size and used for the same or similar structural purposes - *reuse*; if direct reuse isn't viable, the timber can be used for other products, such as flooring, decking, or furniture - *repurposing*; In some cases, the timber can be manufactured into new structural products with enhanced properties (CLT, GLT or LVL) - *upcycling*. When the timber can no longer be reused, it can be recycled into products like particleboard, insulation, or animal bedding or recovered as biomass energy.

To optimize reuse in the new life cycle, it is essential to note down the information from the first life cycle of the used timber element at the time of demolition regarding the structural position (column, beam, rafters, etc.), the endured loads, as well as the environmental conditions to which the used timber element was subjected [108]. Moreover, this data could be very helpful during visual grading, since this operation must be carried out considering the area of maximum stress according to the structural scheme detected in the first life cycle.

To reuse the wood the visual characterization is critical, and it needs strict selection due to its nature of weakness in bio-attack, insects and moisture. For instance, Markues et al. [110] investigated mechanical properties of the removed utility poles for structural application. Based on the visual characterization results, 41% of specimen was damaged by biological attack, while 20% of the specimens had woodpecker holes and minor mechanical damage. They concluded that 47.2 % of specimens could be reused for structural applications.

Stefania De Gregorio [108], suggested visual grading as a method for determining residual structural performances of used timber. This method is internationally regulated by

specific standards (in the EU, this is EN 1912:2024). Also, visual grading is not affected by boundary conditions, and it is immediately applicable at the construction site after disassembly. The visual grading classes have been defined through the standard as a function of the species, the strength classes, and the characteristic values.

There are numerous nondestructive methods for assessing timber mechanical properties for structural use (ultrasound grading, near infrared reflectance spectroscopy, resistograph, sclerometer test, etc.) but their correlations are mainly established for new timber elements and cannot be directly use for "old" timber. Accordingly, new correlations should be established for timbers to be reused [108].

To ensure the viability of reusing structural timber, it is essential to incorporate reclaimed timber in the early phase of design. In such cases, the design should be based on the actual structural properties (characteristic strength, stiffness, density) of the reused timber. Besides, a comparison of this reuse-based design with other construction options to determine if the project is still feasible with reuse has to be done [106]. Also, UNECE [103] states that reuse timber constructions should be prioritized with holistic-circular approaches from the early stages of design.

However, none of those processes are currently in place, thus it is impossible to assess reuse efficiency.

#### 5.1.2 Possibility and potential of timber for reuse

The potential for reusing wooden elements largely depends on the methods used for building demolition. Currently, many buildings are demolished using heavy machinery that crushes the structure. As a result, wooden components often cannot be salvaged for reuse. However, intact wooden beams and columns with larger cross-sections can be reused effectively, provided they have suitable fixings in place. Glued connections are typically instable, as they cannot be separated without damaging the components. Carpenter joints can be appropriate, but notches may lead to stress concentrations when the elements are configured differently. Nails and staples might also be suitable; however, they tend to fail under bending forces and can be difficult to remove without causing damage. Screws are generally a good option; thus, the same connector does not remain effective in the same hole after removal. The best choices are bolts and dowels, but it is important to inspect both the holes and any cracks carefully [111].

Höglmeier et al. [112] investigated the potential for reuse wood after deconstruction in South-East Germany and noted that 26% of recovered wood was suitable for reuse, with 38% of this having potential for residential buildings and other part was suitable for non-residential buildings. Another state-of-the-art discussion (InFuUReWood project) on timber structure reuse in Sweden, UK, Ireland, Spain, Slovenia, Finland, and Germany also addresses the technological underpinnings of possible circular use of timber in building construction. It particularly emphasizes Design for Deconstruction and Reuse (DfDR) in low-rise timber structures up to three stories [1]. DfDR covers how to dismantle the components readily and separate them from each other for reuse or recycling in building construction. This report indicates that digital tools as log books, material passport, BIM etc. would be highly effective way to ensure detailed documentation about the use and performance of recycled and reused building components [1].

Finch and Marriage [113] investigate reuse of recovered buildings materials using computer-aided design and manufacturing (CAD/CAM) technology. They found that

using CAD/CAM to produce advanced assemblies could lead to a 67% reduction in the time required to reuse of the recovered building materials.

Desk-based research revealed that there is no single list of wood reuse benefits, so we compiled what we found in papers: ([100], [103], [113], [114], [115], [116], [117], and [153]). The results are summarized in Tab. 15. As shown, they are classified into four main groups of benefits: environmental, economic, social, and technical. In a similar vein, we addressed the barriers associated with wood reuse. In addition, a proposal was added on how to mitigate specific barriers. The analyzed literatures are [100], [117], [119], [120], [121], [122], [123] and [153]. The results are summarized in Tab. 16.

As can be seen, the lack of specific regulations for the reuse of timber elements for structural purposes belongs to the group of major barriers to timber reuse, since applicable

standards are limiting factors. Even if the timber element has performed its structural function for a certain number of years and has proved to be suitable because it has not failed structurally and no degradation has occurred, when it is disassembled for reuse, it should be verified according to current EU standards and would probably be discarded due to safety margins. It is clear that information from the first life cycle is an added value to understanding the component but is currently not taken into consideration [108].

Reconditioning stands as a vital technology in waste wood processing, as it necessitates careful manual operations like segregation, de-nailing, and de-screwing of timber waste to prevent further damage to the reclaimed timber components. Afterwards, reconditioned timber elements need to be moved and stored again. All listed operations are labor-intensive and increase costs; therefore, this logistics process should be carefully planned [124].

*Table 15. Benefits of timber reuse*

Environmental Benefits	Conservation of natural resources	Lower demand for virgin wood that needs to be harvested from forests, and consequently, reduction of deforestation.
	Long-term carbon storage	By reusing timber elements, the carbon absorbed during tree sequestration remains locked in the built environment for longer.
	Reduction of CO <sub>2</sub> emissions	Lower demand for virgin timber -lower CO <sub>2</sub> emissions. By preventing CO <sub>2</sub> emissions associated with felling, processing, and transportation of new wood.
	Waste minimization	By redirecting usable wood from landfills for reuse purposes, construction waste will be reduced.
	Reduced energy consumption	Timber reuse requires less processing compared to the production of new timber.
Economic	New market value	Cost benefits through the prolonged life of wood waste.
	Economic resilience and value chain development	Coherent financial structure and viability of the case companies. Employment and value creation for partners in the value chain network.
	Local availability	Timber prepared for reuse is often available locally and, thus, faster.
Social Benefits	Job creation & skills development	Deconstruction for reuse purposes is labor-intensive and can create more jobs than traditional demolition. Wood reuse initiatives offer valuable training and job opportunities, particularly for individuals excluded from the traditional job market.
	Community empowerment & inclusion	Reuse projects often involve local social enterprises, giving communities ownership over material reuse and enabling participation in sustainable practices. Community-driven wood-waste reuse enhances skills and fosters knowledge exchange, empowering residents to participate in sustainable waste management.
	Stronger community ties & social cohesion	Deconstruction and reuse processes can foster cooperation across engineers, architects, local governments, and social enterprises, strengthening community networks.
	Cultural heritage preservation and valorization	Timber craftsmanship (carpentry, joinery) has deep cultural roots; reusing wood supports these traditions and connects modern construction to local heritage. Timber reuse helps maintain local identity and craftsmanship possibility to preserve the heritage value of the components and valorize the technical know-how embedded in the reclaimed components.
Technical Benefits	Dimensional stability	Mature timber usually has balanced humidity with the environment in which the wood is used; consequently, it is dimensionally more stable making it less prone to warping, splitting, or shrinking.
	Potential aesthetic value	Weathered or aged timber can offer a unique visual appeal.

Table 16. Identified barriers for reuse of timber and possible mitigation solutions

Barrier category	Specific barrier	Barrier description	Proposed mitigation measures
Technical and logistical barriers	Insufficiently developed processing technologies	Unprofessional dismantling causes additional damage of timber components.	Enforcement of the requirement that only licensed professional demolition companies are permitted to dismantle buildings.
		Lack of knowledge on sorting technologies.	Improve sorting technologies.
		Lack of efficient waste wood reconditioning processes.	Develop step-by-step reconditioning protocol.
	Complex design	Iterative design process due to adaptation to currently available timber elements on stock.	Consecutive and parametric design. An integrated design process and the use of digital tools.
Lack of appropriate regulation and standards	Salvaged timber elements must fulfill current design regulations and quality standards.	Revision of regulations and standards.	
Economic and market barriers	Underdeveloped supply-demand chain market	The market currently lacks any available reused wood.	Create a market for reused timber. It is necessary to develop circular distribution centers. Better cooperation between all stakeholders.
		No demand for reuse timber.	
		Lack of cooperation of all parties.	
	Extra costs	Pre-demolition audit and careful dismantling of obsolete structure. Sorting, grading and reconditioning of salvaged timber elements. Customized design and adjustment of joints.	Introducing automatic classification, sorting, and storing. Implementation of new digital technologies in a framework for the supply chain. Implementation of a business model that combines deconstruction/demolition with the sale of salvaged timber elements within the same company.
		Different stakeholders require different data and information.	Unique digital information platform.
Higher investment	Increased expenses at all stages for the reuse of timber in new construction.	Provide the economic incentive for all stakeholders.	
Other barriers	Knowledge and awareness gap	Lack of awareness of waste conservation practices.	Require building rating systems certification. The development of plans for dismantling.
		Lack of knowledge and education.	Persuade all stakeholders to design for deconstruction based on CE strategies. Encourage the reuse of materials from demolished buildings.
	Renewable energy source	Biomass is a major part of the EU's renewable energy sources, accounting for its largest single source.	Significant shifting towards solar and wind sources according to EU Renewable Energy Directive III (2023).

Piccardo and Hughes [117] explored the possibility of reusing wood in buildings by employing two circular strategies referred to as “upstream” and “downstream” methods. The terms upstream and downstream are generally used to describe the early and late stages of a process, supply chain, etc., respectively. In this study, upstream strategies were those developed during the design phase to facilitate the future reuse of wood elements throughout the building life cycle, especially during maintenance and end-of-life phases. These strategies pertain to the Design for Disassembly and Adaptation (DfD/A) concept. Downstream strategies concern the salvage of wood materials from buildings in the process of

being renovated, deconstructed, or demolished, and their subsequent use in new buildings through their design phase. This case-study research revealed that upstream strategies are effective in increasing the potential cascading of wood for reuse, regardless of the construction system of the building. The downstream strategies can also be implemented regardless of the construction system of the building, in both load-bearing and non-load-bearing elements. Upstream strategies can facilitate the future reuse of wood elements if a few challenges, such as extra costs due to customized design and manufacturing of fastenings, as well as the need to adapt to new building standards, are overcome. Similarly, downstream strategies can enhance

the reuse of wood by addressing challenges such as lower quality of salvaged wood, the difficulties in grading salvaged wood to be reused as load-bearing elements and increased construction time due to re-manufacturing operations. Additionally, the implementation of upstream and downstream strategies in wood buildings might be more complex compared to a conventional use of wood, as they entail the use of specific expertise in DfD/A as well as in the procurement of salvaged wood.

Ottenhaus et al. [125] stated that design for adaptability is crucial to extend the service life of buildings during the construction sector's transition to CE. Possible process of circular timber buildings based on DfA principles, where entire buildings can be reused, repurposed, relocated, reconfigured, etc., is presented in Fig. 17. They recommended that multiple reuse scenarios for timber building components at the end of their service life should be considered during the initial design and planning stage.

The main challenge of reusing timber and primary construction materials in urban areas is optimizing the waste-to-resource loops [126]. Digital technologies can help identify material stock existing in obsolete buildings that will no longer serve society, enabling their relocation to new purposes. In the scope of the project "Sirklåve" [153], the possibility of implementation of new digital technologies in a framework for the supply chain, encompassing five essential steps: Data, Detection, Disassembly, Distribution, and Design, was investigated. This innovative framework, known as the 5 "D"s, was developed by Catherine De Wolf. The brief descriptions of these five steps are: (1) *Data* stands for the collection of macro-level data to track which material stocks are or will be available soon, helping planners to prioritize which stocks to reclaim. (2) *Detection* refers to the collection of micro-level data that are necessary for material and building passports or building information models. (3) *Disassembly* refers to a careful process of deconstructing structures with the goal of retrieving valuable components or materials for future design applications. (4) *Distribution* includes logistics: transport and storage. As materials are often not reused directly after dismantling, the workflow

requires a physical circular hub, material banks, and other spaces where the salvaged material can be collected and pretreated. (5) *Design*: Salvaged timber materials can be returned to the supply chain and marketed to those who build new buildings or refurbish current ones. When these materials are intended for use as load-bearing elements, it is advisable to employ a consecutive design or parametric design approach. Wuyts et al investigated the implementation of high-technologies in step "Detection", like scan-to-BIM (laser scanning, photogrammetry, GIS, etc.), automation detection and artificial intelligence (i.e. deep learning methods). Regarding the quality of built-in materials, they used conventional destructive and nondestructive testing methods. Their final observation was that this model is not competitive on its own. However, insights can aid in shaping future research designs, focusing on balancing the costs of data collection and storage against the benefits for various actors in different regulatory and economic contexts.

The timber structures, especially single-story buildings, are common in Middle and North European countries (e.g., Austria, Germany, Denmark, Finland, Norway and Sweden) and in South America. In other European countries timber is mainly used in roof structures. In developed countries, such as Australia or the United States, numerous government programs were created to support and encourage the processing and use of construction wastes as well as taking into consideration the idea of reuse the whole structures or structural elements [127]. For example, to support reuse of timber, the directory of companies in the United States involved in wood-framed building deconstruction, dismantling, and reused building materials, as well as those specializing in value-added wood products, including reclaimed and antique lumber is published [128]. It serves as a resource for individuals and businesses looking for suppliers of reclaimed and antique lumber, as well as value-added wood products. Additionally, it aims to promote environmental sustainability and support the market for salvaged and value-added wood products.

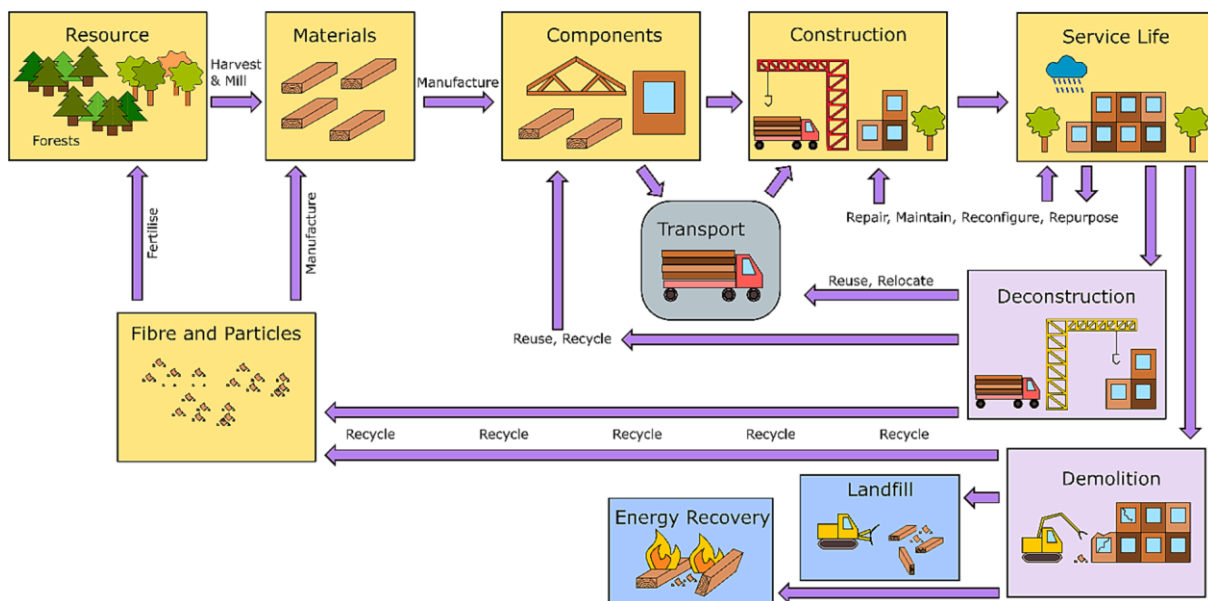


Figure 17. Circular solutions for timber buildings in the technosphere adopted from [125]

Norway utilizes most of its wood waste in biofuel production. Besides, the main obstacles for the direct reuse of wood are demands for altered dimensions and better thermal properties in new construction [120]. Junginger et al. [129] stated that the increasing demand for wood waste-based energy production is the biggest obstacle to reuse of wood in many European countries.

Passarelli [130] reported the building industry in Japan is based on the constant renewal of the building stock, leading to a short average lifespan and an unsustainable system from both environmental and economic perspectives. As an alternative to this situation, a modular mass timber system using CLT is designed for consecutive reuse. This system fulfills the criteria for reusability, portability, and adaptability.

The possibilities for reusing structural timber would be mainly for private builders working in the residential sector (e.g., homes, extensions, or sheds), temporary works, and historical buildings with timber structures. This is because the retail market for constructing these types of structures is not overly concerned with recertification, which is assumed to be expensive due to the additional testing required. The possibility of using reclaimed timber as the structural material for building types other than residential, such as commercial and industrial, is very improbable. Some of the repurposing opportunities identified include floorboards, feature timber, cladding, and temporary elements used in construction (e.g., shutters) [124].

Additionally, the reuse of old wooden products can be increased by encouraging their use in new constructions thanks to their architectural aesthetic value [121]. Architects are important actors in the construction industry. They are the key drivers of the first life-cycle phase of buildings, that is, the design, i.e., the critical decision-makers whose decisions impact all later phases of the life cycle of buildings and determine the environmental impact through those phases. The reuse of wood elements in architectural projects has gained popularity in recent years due to potential benefits in terms of sustainability and cost-effectiveness. Architects who incorporate reused wood elements into their designs may experience a range of advantages and challenges. Besides, reuse can be more cost-effective than buying new wood and can add value to a building by creating a rustic or vintage look that appeals to clients [111]. Also, research on possibilities of application of upstream and downstream strategies [117] emphasized the importance of the role of architects in enhancing the reuse of wood.

## 5.2 Recycling of timber

Wood is generally considered to be a recyclable material. Logging and wood-processing residues have posed a utilization challenge for those involved in harvesting and manufacturing wood products due to their large volume. For example, in a sawmill or plywood plant, residual materials account for up to 60% of the log volumes delivered. Thus, early commercial efforts have sought to maximize the use of these residues for charcoal, poultry bedding, and heating fuels. The modern history of timber recycling processes began with the use of wood residues to produce hardboards (made from pulp mats) in the 1920s. It continued in the United States in the 1940s with the production of nonstructural particleboard (a composite panel product). The first industrial production of particleboards in Europe occurred in 1941 in Germany, using phenolic binders and spruce particles. Medium-density fiberboard (MDF) was first manufactured commercially in 1965. Until the 1970s, the USA was generally oriented towards the production of

plywood (made from veneers), which was widely used for wood-framed houses. However, the lack of suitable timber for plywood production encouraged the development of technologies for producing structural types of particleboards. The invention of oriented strand boards (OSB) made them a leading commercial competitor to plywood in structural sheathing markets in the 1980s. Further inventions and production of MDF/HDF boards with particles the size of dust and with wax/resin binders, dating back to the 1980s, led to their widespread production in the 1990s [131].

Recyclable wood waste is dominantly generated from logging and wood-processing residues, but nowadays there are numerous other materials that have the potential to be treated in the same way, such as waste wood coming from different businesses, home renovation, or construction and demolition activities. However, not all waste wood is recyclable. It depends on its classification and grade, since additional features, like paint, varnish, nails, plastics, and contaminants, can all lead to additional processing before the wood can be recycled or sent to landfills [132]. Therefore, waste wood other than logging and wood-processing residues should be graded before recycling can proceed. However, the European member states are lacking a common legislation scheme about the recycling of wood regarding classification and thresholds [133].

The European List of Waste (LoW) can help in the classification of waste wood. Also, the national classifications, which are predominantly designed for waste wood from the perspective of its potential use as fuel and for energy production (see chapter 5.1) or [107], can also be used in making a decision whether waste wood is recyclable, since they allow for certain classes alternative applications of waste wood. To support waste hierarchy and circular economy in waste wood management a new categorization was adopted in the UK [146]. This classification prioritizes recycling to biomass fuel. According to the Wood Recycling Association's guide [146], there are four grades of waste wood:

- **Grade A: clean, untreated wood.** Grade A waste wood is free from contaminants, including paint, preservatives, or coatings. It typically consists of materials like solid, soft, and hardwood, pallets, crates, and various packaging waste. This waste wood has the highest recycling potential.

- **Grade B: Treated and non-hazardous wood.** (Industrial feedstock). This category includes wood with minor contamination, such as painted or varnished surfaces and binders or glue. Mainly consist of grade A materials mixed with construction and demolition waste wood (C&DWW) and domestic furniture made of solid wood. Before recycling, Grade B waste wood requires processing to remove impurities. It is commonly used for production of board panel materials, mulch, compost, or as biomass fuel.

- **Grade C: Treated and non-hazardous wood.** (Fuel grade) Comprising contaminated or treated wood, mostly board products. Grade C waste wood requires specialized treatment to remove (potentially) hazardous substances before recycling. It is often repurposed for biomass energy generation or converted into engineered fuels-

- **Grade D: Hazardous.** Comprising heavily contaminated wood with hazardous substances - such as railway sleepers, telegraph poles, trailer beds, agricultural fences, etc. Requires special disposal.

Based on the waste code (LoW) or, if needed, chemical analysis, waste wood items arising from household, commercial, industrial, construction/demolition, and agricultural sources should be classified into wood waste grades. Categorized waste wood can be more easily directed

into the appropriate processing funnel. This also helps to match the waste wood with its most suitable application in the recycling process.

A typical appearance of certain types of wood waste [153] is given in Fig. 18, Fig. 19. and Fig. 20.

### 5.2.1 Recycling processes and their efficiency

The process of recycling waste wood considers several key steps. We identified the most frequently used terms and descriptions by comparing the key steps of the recycling process from the cited literature ([132], [134], [136]). By gathering them, the recycling procedure would consist of:

- **Collection and transportation:** Waste wood is collected from various sources, including construction sites, manufacturing facilities, and waste management centers, and transported to recycling plants.

- **Sorting according to grading:** Waste wood is graded by quality and contamination level and sorted. This step helps identify the most suitable recycling route for each type of wood.

- **Cleaning and pre-treatment:** Depending on the grade, this step may include removal of contaminants and impurities, such as metals, coatings, paints, or adhesives. Different mechanical treatments are commonly used, but chemical cleaning treatments may be required in some cases.

- **Processing - size reduction:** Depending on the grade of waste wood and the selected repurpose, various processes may be used, such as cutting, planing, chipping, sanding, shredding, or grinding, to make suitable recycled wood raw material (chips, fibers, or lamellae) for new purposes.

- **Repurposing:** In this step, the processed waste wood is repurposed into a new wood-based product, which dominantly depends on grade.

The described key steps of the recycling process are typical for processing waste wood into chips or fibers, which are usually repurposed into different types of wood-based boards. However, lamellae must undergo additional strength grading, visual inspections, and moisture level adjustments when repurposed into structural engineering wood products like CLT and GLT.

Faraca et al [138] analyzed the resource quality of 8 tonnes of post-consumer waste wood from three Danish recycling centers. The authors subdivided collected waste into 34 individual material fractions, distinguished by source, type, and a quality grade (Grade I - Clean waste wood; Grade II - Clean waste wood with some contamination; Grade III - Waste wood with considerable contamination;

Grade IV - Hazardous waste wood). Then, they analyzed each fraction regarding physical impurities and chemical contamination. The findings showed that contaminant levels (both physical and chemical) vary significantly depending on the type and source of waste wood. Regarding the implementation of a circular economy in waste wood management, the authors concluded that waste wood should be sorted more carefully—not as a monolithic “waste wood” category, but as a heterogeneous resource requiring sorting according to quality grading and chemical screening.

First step in proper segregation of waste wood is to separate clean, solid wood from wood-based panel products (particleboard, chipboard, OSB, plywood, and MDF), i.e., from products that contain glue, varnishes, and other coatings [132]. This operation is labor-consuming; thus, utilization of advanced solutions for waste wood sorting, such as systems based on X-rays and deep-learning sorting technologies, can save time and money, as well as improve the quality of segregated fractions. Also, physical and mechanical contaminants in waste wood can be removed using appropriate sorting techniques. Therefore, focusing on improving sorting methods will bring benefits in cleaning the waste wood mix [133].

Waste wood from construction and demolition activities, as well as other sources, is typically sent to wood recycling companies for processing. To increase the recycling potential of waste wood, it is necessary to create many small market enterprises for salvaged timber, boards, or other components, which, after screening the size of the required particular pieces of elements or fiber requirement, could send the product to processing facilities for repurposing into new products.

Depending on the source and classifications after pre-treatments, different recycling processes could be done:

- For clean wood, the processes are relatively easy to achieve; clean, untreated wood has the broadest range of applications in a second life. In the sense of new wood-based building materials, the sawn timber from construction and demolition processes could be used for the production of GLT [139] or CLT elements [114], [140], as well as for LVL production.

- Industrial wood may be repurposed into products such as panel board products, insulation, animal bedding, mulch, compost, or biomass fuel. Pre-treatments involve mechanical and chemical decontamination processes, after which the selected repurposing method requires similar operations, like using new wood raw materials. This type of waste wood should be favored in the production of wood-based boards.



Figure 18. Clean, untreated wood



Figure 19. Treated and non-hazardous wood, mostly solid wood



Figure 20. Treated and non-hazardous wood, mostly board products

- For heavily but non-hazardous contaminated or treated waste wood, such as plywood, MDF, chipboard, and blockboard plywood, the recycling processes are challenging. [133]. Wood-based boards are made by gluing timber pieces together. The gluing process makes it quite difficult to recycle, so the prevailing view is that they cannot be recycled; thus, they often end up for biomass energy generation or, rarely, for panel board in controlled volumes. However, certain companies [141] made progress that enables the MDF boards to be recycled, enabling them a "second life". The innovative recycling process for MDF/HDF boards includes moistening of the boards, then heating and subjecting them to high pressure, and releasing the pressure to free the fibers.

The aforementioned recommendation concerning suitable recycling processes gives a wide spectrum of waste wood potential utilization. However, waste wood is not a homogeneous material even after grading, since it originates from various resources. Therefore, there are still some limitations that need to be overcome before waste wood can be used as a raw material for wood composite production. Thus, Nguyen et al. [133] investigated the quality of wood-based panels produced from recycled wood resources. They drew several conclusions: (1) Particleboard is nowadays the most favorable product to be made from waste wood materials. It is simpler and cost-efficient to process all types of old wood-based panels into particles by mechanical treatment (e.g., chipping) than into fibers by chemical methods. Also, converting old fiberboard into fiber or old OSB and plywood into strands is quite demanding. Furthermore, waste wood streams are typically a mixture of wood-based panel products, so producing the proper strand size would require additional segregation of already graded waste. (2) Waste wood materials are not used for plywood production because it is impossible to process them into veneers. (3) Using waste wood for production of wood-based panels increases the risk of formaldehyde emissions in particleboard and OSB products. However, this risk can be addressed by applying pretreatment steps to reduce formaldehyde emission (e.g., hydrothermal process) or using formaldehyde-free adhesives (e.g., PMDI).

The effectiveness and expenses associated with the recycling process are significantly influenced by the source and type of waste wood, along with the categorized grades

of waste. Therefore, further improvements of all processes are needed to optimize and reduce the variability of wood properties, enabling more efficient processing and production of more reliable products. Emphasis should be placed on establishing a unique EU classification of waste wood for recycling and setting thresholds, as well as on the improvement of waste sorting techniques.

### 5.2.2 Possibility and potential of timber for recycling

Although wood is a renewable resource, its growth and processing require time, effort, and energy. Thus, recirculating waste wood, which is already on the market, eliminates a significant portion of this, making it more sustainable and easier to acquire [132]. Waste wood in the form of engineered/industrial wood products is widely present in our society and can be found in construction and demolition, packaging, and municipal waste streams [142]. In the European Union, common management methods for dealing with waste wood include converting it into energy or recycling it, because the EU Waste Framework Directive 2008/98/EC prohibits landfilling waste unless it is the only option available for disposal. The priority for each country is a stable and independent energy market, so 60-95% of collected waste wood in European countries is used for energy, often for district heating. However, the EU is committed to increasing the recycling of materials as part of its drive to a fully circular economy and suggested using the cascade principle in waste wood management.

The concept of "cascading" was developed in the Netherlands to improve resource efficiency by Sirkin and ten Houten (1994). The term "cascading" applies the same principle to all materials, simply put, prioritizing material use first and energy use last. The concept was later adapted to wood by Fraanje (1998) and is visually represented in Fig. 21 [1]. This cascade approach illustrates the true long-term potential of wood circularity.

Bais-Moleman et al. [143] using a life-cycle approach found that cascading use of wood could increase wood-use efficiency in the European wood sector by 23 to 31%, with the added benefit of reductions in global warming potential of 42 to 52%.

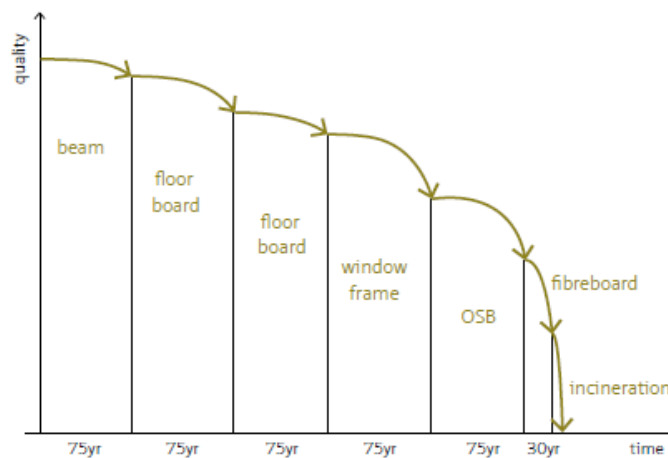


Figure 21. Potential cascading of pine wood; Fraanje (1998), adapted by Icbaci (2019); [1]

The recent world review given by Jahan et al. [144] indicates that the world leaders in wood production and export are Canada, the USA, Sweden, Finland, Germany, Russia, and Brazil. They produce 31, 19.5, 18.5, 16, 14.5, 14, and 11 million tonnes of wood annually, supplying the industries with raw wood material for producing industrial round wood, sawn timber, wood-based products, engineering wood products, pallets, paper, pulp, furniture, and other products for global economic growth. A green economy that favors wood as a sustainable material contributes to the increased use of wood and wood-based products in the building and construction sector. This extensive use of wood as a material generates significant and heterogeneous waste wood streams. Fig. 22 shows trends in the total waste wood generation by sectors in the EU27 from 2004 to 2020 based on Eurostat data. Between 2004 and 2020, waste wood generation decreased by 22.25 %, but it seems to be at almost same level from 2016 to 2020 [107].

As of 2020, waste wood in the EU-27 mainly comes from three sources: the construction and demolition sector, the commercial and industrial sector, and the waste collection sector (municipal waste). The total estimated potential of waste wood in the EU is about 50 million tonnes, with a share of about 11.5% from the commercial and industrial sector, 48.7% from municipal waste, and 38.8% from C&DW. The leaders in the production of waste wood are Germany, France, the UK, Italy, and Spain. Considering the way of final waste wood use, three strategies were distinguished: energy recovery, recycling, and mixed. Sweden, Finland, Portugal, Slovenia, and Hungary are dominantly determined to energy recovery; Poland, the Netherlands, Belgium, Romania, Austria, Croatia, Ireland, Estonia, Latvia, Bulgaria, and Greece are practicing mixed solutions. Germany and Slovakia are also practicing mixed solutions, but towards energy-oriented solutions, while the UK, France, Denmark, Lithuania, and the Czech Republic are oriented to mixed solutions as well, but oriented to recycling. Finally, Spain, Italy, and Malta are dominantly oriented to recycling [145].

Pazzaglia and Castellani [137] reported that in 2020, the EU27 generated 48.28 million tonnes of waste wood, of which 40.20 million tonnes (~83%) were treated. Among the treated waste wood, only 0.24 million tonnes were disposed of (0.60%), with the remaining 39.96 million tonnes (96.40%) being recovered. Of the recovered waste wood, 21.45 million tonnes were used for energy recovery, while 18.51 million tonnes were utilized for recycling and backfilling,

representing 9.88 million tonnes (53.36%) and 8.63 million tonnes (46.04%), respectively. According to new data released by Wood Recyclers' Association [146], the UK's waste wood sector generated 4.5 million tonnes of waste wood in 2024, with more than 96% (4.33 million tonnes) processed for reuse, recycling, or recovery. The primary destination of processed waste wood is the energy production sector, with 2.8 million tonnes (68%). The panel board manufacturing sector is the second largest user, processing over 920,000 tonnes (21%). Other recycling and reuse outlets, including applications such as animal bedding, equine surfacing, and landscaping, account for 310,000 tonnes. At the same time, Donaldson [119] reported that the waste wood recycling rate in Canada is still less than 8% due to cheap virgin wood material, its availability, and the ease of obtaining incineration permits.

Recently, the EU policy has shifted to prioritize waste wood recycling (as a part of material recovery) over energy recovery, aiming to transform waste wood into a secure industrial resource within the framework of a circular economy. This means future rates of material recycling are expected to increase.

Pazzaglia et al. [137] proposed the necessary joint measures for the treatment of waste wood in EU member states: waste wood management policy should establish a common European law for waste wood, encompassing pollutant limit values for material recovery (recycling) and energy recovery, mandatory extended producer responsibility (EPR) for waste wood, EoW criteria for waste wood, and compulsory separate post-consumed wood collection to enhance waste wood quality. Each of these measures should be carefully studied to make the system dynamic and suitable for the diverse environmental, economic, and social contexts of the European Union.

Austria is the only the EU state with EoW criteria related to waste wood [137]. EoW criteria have the potential to prevent the unnecessary continuation of waste status, facilitating the trade and utilization of wood from waste wood in products. The EoW status for recycled wood is tied to designated use and can be declared. Waste wood intended for recycling may be used only in installations serving to produce wood-based materials. The waste owner must adhere to the Austrian standard for solid recovered fuels, ÖNORM EN 15358, which outlines the necessary quality management systems and external quality assurance requirements for declaring the EoW status of recycled wood.

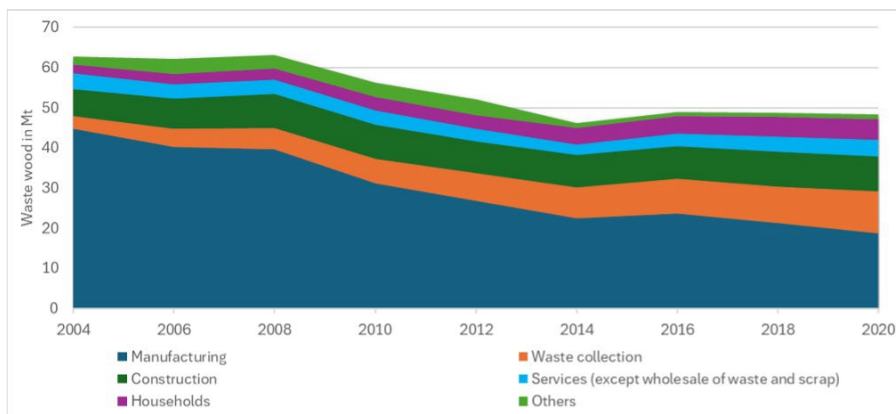


Figure 22. Total waste wood generated in the EU-27 (million tonnes) from 2004 to 2020 based on Eurostat data (2024a) [107]

After reviewing relevant scientific papers and various technical and industrial reports ([132], [142], [147], [154], [155]), we reached the same conclusion we initially assumed: there are no significant differences between the benefits of reusing and recycling waste wood. The benefits of recycling can be organized into three main categories: environmental, economic, and social. Key *environmental benefits* include (1) conserving natural resources by reducing logging, which helps preserve forests, biodiversity, and habitats; (2) mitigating climate change through long-term carbon storage and lowering CO<sub>2</sub> emissions; and (3) decreasing landfill burden by diverting organic waste and reducing the space required for landfills. *Economic advantages* are summarized as (1) new market value instead of being treated as waste; (2) cost savings since recycled materials are cheaper to buy and process than new timber; (3) economic resilience and value chain development; (4) local availability; and (5) a broad range of uses such as engineered wood, panels, bio-composites, insulation, and animal bedding. Since the waste wood recycling in a wider definition comprises "renewable energy source", the additional benefits can be energy production to reduce fossil fuels. *Social benefits* include (1) supporting the circular economy by maximizing material use; (2) job creation and skill development by fostering new industries and jobs in collection, processing, and manufacturing; and (3) community empowerment and inclusion by promoting sustainable practices and material awareness. Green practices are an integral part of modern business, demonstrating that participating in and respecting recycling practices will improve public perception, resulting in higher returns in the future.

Cakaj et al. [147], through a systematic literature review, identified, then sorted and classified the barriers that hinder the implementation of a circular economy in general waste wood management. Respecting their proposal, we created a comprehensive systematization of barriers to wider waste wood recycling. The proposed systematization is more than just a "copy-paste" from selected literature ([107], [137], [138], [147], [148], [150], [152], and [154]) it also includes our interpretation and barrier perception. The results are summarized in Tab. 17.

The main barrier to reusing/recycling waste wood is the widely held belief that wood, in any form, is a natural and biodegradable material that can be returned to nature without restriction or used as solid fuel. The importance of a specific barrier varies across EU regions, as forest resources, timber construction traditions, and economic and legislative developments all play important roles. Also, the barriers listed above complement and intertwine, resulting in the final cost of recycled waste wood, which varies by region and may be unacceptably high for some countries.

The use of waste wood as a renewable energy source represents a strategic barrier to expanding material recycling because energy security remains a high national priority for many countries. Governments increasingly rely on biomass to reduce dependence on fossil fuels, stabilize energy supply, and meet renewable energy targets, which makes the redirection of waste wood away from combustion politically and economically difficult. As a result, large volumes of potentially recyclable timber are consistently channeled into energy recovery, limiting the availability of suitable material for higher-value recycling processes. Although current energy-from-waste policies limit the

material availability of waste wood suitable for recycling, this situation may gradually improve in the future. The EU aims to significantly increase the share of solar and wind energy in its power mix, which is expected to reduce the reliance on biomass for energy generation. In such a scenario, a certain portion of waste wood that is currently diverted to energy recovery may become available for higher-value recycling and material reuse. Besserer et al. [151] concluded that current waste wood recycling processes require improvement to prioritize material recovery over energy recovery. A comprehensive study about the Swedish experience in waste wood recycling [142] revealed that energy recovery and true recycling of waste wood shouldn't be competing methods. They have to be complementary, even in countries with advanced incineration facilities, like Sweden.

The lack of new production lines for utilizing waste wood generated from construction and demolition sites and the municipal/commercial sectors in new products also presents an important barrier. For instance, only one of particleboard manufacturers in Norway can use waste wood. Thus, it would be important to plan new production lines for increased recycling. However, the economic viability of the project could be an additional barrier if recycling stations can sell wood chips for energy recovery at the same or higher price as for particleboard production [150].

The sorting and classification of waste wood must be more accurate, as certain repurposing processes restrict the use of specific original wood products, such as fiberwood boards, which are limited to a 3% share in the panel board industry [150]. Utilizing established advanced technologies like near-infrared (NIR), fluorescence spectroscopy (XRF), and GC-Drift Tube Ion mobility spectrometry enables the detection of chromatid copper arsenate (CCA) and pentachlorophenol (PCP), while also allowing for the separation of undesirable fiberboard and wood-plastic composite materials. Besserer et al. [151] stated that a better understanding of the composition and quality of waste wood, as well as improvements to current sorting techniques, are required. They suggested improving recycling routes by purifying wood particles or fibers. This purification can be accomplished by physicochemical methods and biological approaches based on using fungi.

Waste wood is usually derived from a variety of resources, demonstrating a lack of homogeneity as a material. Furthermore, it is characterized by a variety of physical and chemical contaminants, which pose significant challenges during recycling processes and affect the properties of the resulting recycled products [152]. According to the UK Waste and Resources Action Program [156], 74% of waste wood, which comes from construction and building sites, is treated with toxic preservatives, such as CCA, PCP, and creosote, to prevent or delay decay caused by fungi or termites. Since the beginning of the 21st century, the EU has established stringent regulations on CCA and waste wood recycling due to the leaching of heavy metals and arsenate poisoning. A large amount of CCA-treated wood remains out of service, and there is concern about disposal and recycling applications.

Overcoming these barriers requires a holistic approach that combines policy refinement, technological innovation, and a significant shift in industry culture and economic incentives.

Table 17. Identified barriers for recycling of waste wood and possible mitigation solutions

Barrier category	Specific barrier	Barrier description	Proposed mitigation measures
Technical and logistical barriers	Insufficiently developed processing technologies	Unprofessional demolition/dismantling is causing mixing and additional contamination of waste wood.	Better control of demolition companies' qualifications to selectively dismantle buildings.
		Lack of adequate sorting infrastructures and technologies. Lack of new/adapted production lines.	Implementation of advanced sorting technologies for efficient sorting, better cleaning, and non-destructive quality assessment of mixed waste wood. Proper planning and investment in new/adapted production lines for increased recycling.
	Unstable composition	Physical impurities and hazardous substances complicate sorting and cleaning processes, limiting the potential for high-value recycling. High levels of inhomogeneity caused by variations in the source, size, and moisture content make it difficult to ensure the consistent quality required for high-quality products.	Introducing a unique classification system and grading method, as well as thresholding for waste wood to be recycled.
Economic and market barriers	Underdeveloped supply chain market	Low demand for recycled waste wood.	Create a stable market for recycled waste wood, especially in supplying manufacturers. Better cooperation between all stakeholders. Unique digital information platform.
		Market instability.	
		Lack of cooperation among all parties.	
	Extra costs	Selective demolition/ dismantling is often more expensive and labor-intensive than traditional mechanical demolition and disposal. Collection, segregation, classification, and pre-treatment of waste wood require quite costly modern technical equipment to be properly recycled. Logistics and transport to specialized facilities.	Introducing automatic classification, sorting, and storing. Improvements to current sorting techniques to be more accurate. Implementation of new digital technologies in a framework for the supply chain.
Higher investment	Increased expenses to adapt manufacturing for the implementation of recycled waste wood into new products.	Provide the economic incentive for all stakeholders.	
Renewable energy source	Biomass is a major part of the EU's renewable energy sources, accounting for its largest single source. Incineration to produce energy is a more profitable and convenient option for waste wood.	Significant shifting towards solar and wind sources according to the EU Renewable Energy Directive III (2023). Government incentives for recycling to support circularity in waste wood management.	
Regulatory and institutional barriers	Inconsistent regulation and standards	A fragmented landscape of policies and standards across different regions creates confusion and complicates the wood recycling process. The lack of a harmonized EU classification system for waste wood limits cross-border trade and market expansion.	Revision of regulations and standards. Prioritize material recovery over energy recovery.
	Weak enforcement and policy gaps	Insufficient policy support, a lack of law enforcement for proper waste management, encouragement of biomass for energy production, and low penalties for illegal dumping all work against sustainable practices.	Strengthening legislation, improving supervision, increasing penalties, investing in infrastructure, and raising public awareness.
Social barriers	Knowledge and awareness gap	Lack of awareness of waste recycling practices.	Raising awareness about the importance and the potential of waste wood to be recycled, efficient collection techniques, and the environmental benefits. Encourage the recycling of materials from demolished/renovated buildings.
		Lack of knowledge and education among stakeholders.	
	Perceived risk	The industry views using recovered materials as risky due to quality and liability uncertainties.	Significant shift in industry culture and economic incentives.

The rates of waste wood recycling vary significantly among the EU member states. For instance, due to the high availability of virgin wood, some highly developed countries, such as Norway, recycle a negligible percentage of waste wood [150]. Waste wood management in Norway is oriented toward energy recovery (90% of waste wood) [157]. Finland has also reported significant use of waste wood for energy purposes and has a well-developed system for categorizing waste wood as fuel, established even before 2015. Therefore, the country still faces challenges in promoting the reuse and recycling of waste wood [158]. On the other hand, some EU countries strive to improve their relatively high percentage of waste wood recycling, like Italy [137].

Shifting towards renewable energy sources, such as solar and wind energy will raise volumes of wood waste from forestry, industry, and construction activities, offering opportunities for recycling lignocellulosic residuals into sustainable building materials. There are many types of waste wood that are suitable for recycling. An overview of the waste wood fractions commonly found in waste collections, along with their potential for recycling is given in Tab. 18.

Contemporary wood composites are engineered wood-based products manufactured from a wide range of raw materials, including virgin wood, waste wood, and other non-wood lignocellulosic materials. These materials are bonded using either synthetic or natural bio-based adhesive systems, increasingly replacing conventional formaldehyde-based resins. Traditional wood-based composites produced with formaldehyde-based adhesives are associated with the emission of hazardous volatile organic compounds (VOCs),

many of which are carcinogenic and harmful to both human health and the environment. In addition, the presence of such adhesives poses significant challenges for the recycling of these materials. The adoption of bio-based adhesive systems in wood composite production can substantially reduce harmful emissions and improve the recyclability and environmental performance of wood-based composites [118].

Buschalasky and Mai [160] investigated the recyclability of MDF bonded with modern urea–formaldehyde (UF) resins. The study examined the properties of recovered fibers and newly produced MDF panels. They produced three generations of panels: Generation I with virgin fibers (VF), Generation II with fibers recovered from first-generation MDF (RF1), and Generation III with fibers recovered from second-generation MDF (RF2). For the disintegration of MDF panels and the release of fibers, a thermo-hydrolytic method was used. The results showed that MDF could be disintegrated under milder conditions than previously investigated, and that using up to 100% recovered fibers did not significantly reduce panel strength or increase formaldehyde emissions. The disintegration process altered the chemical properties of the fibers, increased their pH, and led to formaldehyde release from remaining UF resin, while repeated recycling could enhance internal bond strength and reduce emissions. The authors conclude that recovered fibers from MDF represent a feasible and environmentally friendly raw material for new MDF production.

The possibilities for implementing recycled waste wood in material production are presented in Tab. 19.

Table 18. Recyclability of waste wood (post-industrial and post-consumer solid woods and wood-based products), adapted from [159]

Type of waste wood	Description	Recyclability
Post-industrial wood	Clean, untreated wood scrap and untreated board products such as chipboard, MDF and plywood.	High recyclable potential.
<b>Post-consumer solid woods</b>		
Commercial	Untreated wood-based packaging (pallets, crates, transport bases) and cable drums.	High recyclable potential.
	Treated and non-hazardous wood materials from joinery activity and manufacturing processes.	Possible recycling, but with pre-treatment processes.
Construction and demolition	Treated and non-hazardous wood from renovation and demolition activities (softwood fence panels/posts, timber components).	Possible recycling. Material must be sorted and pre-treated.
Household/Municipal	Untreated softwood or hardwood beams and natural wood furniture (kitchens, tables, shelves, wardrobes) that have not been coated or veneered.	High recyclable potential, but with pre-treatment processes.
	Treated and non-hazardous wood items (doors, plywood frames, staircases) that have not been exposed to excessive moisture.	Possible recycling, but with pre-treatment processes.
<b>Wood-based products*</b>		
Particleboard	An engineered wood product made of compressed wood particles and a synthetic resin or binder.	Possible recycling, but with pre-treatment processes.
Oriented Strand Board (OSB)	An engineered wood product made of compressed rectangular-shaped wood strands arranged in a specific pattern and cured with a waterproof resin.	Possible recycling, but with pre-treatment processes.
Plywood	An engineered wood product manufactured by gluing thin layers of wood veneers.	High recyclable potential, but with pre-treatment processes.
Medium-Density Fiberboards (MDF)	An engineered wood product made from lignocellulosic fibers.	Generally, MDF is not recycled. However, a few companies have developed innovative technologies for recovering fibers from MDF on an industrial scale.

\* A vital step in improving the recyclability of engineered wood is to sort waste wood by type (e.g., MDF, plywood, OSB) to create clean, mono-material fractions.

Table 19. Recycled waste wood in material production

Type of recycling	Product category	Product
Upcycling	Wood composites: Structural engineered wood products	CLT and GLT (both products are developed and used in R&D and specialized projects).
Recycling	Wood composites: Engineered Wood-Based Panels	Chipboard, particleboard, Medium-Density Fiberboard (MDF), High-Density Fiberboard (HDF), Oriented Strand Board (OSB), Hardboard.
	Wood composites: Wood-Cement (Wood-Concrete) Composites	Wood particle-cement boards. Wood fiber cement panels. Wood wool cement boards. Lightweight aggregate. Lightweight wood-concrete blocks.
	Wood composites: Wood-Polymer (Wood-Plastic) composites	Molded or extruded hollow core or solid products with any shapes even of complex forms.
Downcycling	Thermal and acoustic insulation materials	Loose-fill wood fiber insulation.
	Landscaping, horticulture, and secondary products	Mulch and horticultural substrate. Compost additives. Equestrian surfaces. Playground and sports surfaces. Animal bedding. Pallets and pallet blocks.
	Adsorbent in industrial and environmental remediation processes	Coal and biochar from low-cost waste wood have adsorption capacity for heavy metals, dyes, pharmaceuticals, and other priority pollutants in water treatment.

The primary use of recycled wood is currently in the particleboard industry. Since engineered wood-based panels are made from processed wood, these products do not need to use fresh timber, making them the perfect target for wood recycling efforts [132]. The proportion of recycled wood in particleboard varies widely by country. For instance, in Italy, the percentage is 100%, while in Belgium, the United Kingdom, and Denmark, it is 50%. In Germany, France, and Spain, the percentage ranges from 15% to 30%. Switzerland has a percentage of 0% [151]. However, there appears to be room for improvement in many European countries. Manufacturing particleboards from waste wood can reduce greenhouse gas emissions from 34 to 77% across impact categories [171].

The second group of products based on recycled waste wood is lightweight cement and polymer/plastic composites. Wood processing residuals such as sawdust and powders can be added to lightweight cement mortars, ranging from 2.5 to 10% by mass, without a significant reduction in compressive strength, while improving thermal resistivity by 25%. Wood aggregate concrete is a lightweight, mineral-organic composite material made by replacing some or all of the traditional stone coarse and fine aggregate with organic materials like wood chips, fibers, or sawdust. It combines the properties of concrete (durability, fire resistance) with those of wood (thermal and acoustic insulation). Consequently, wood aggregate concrete has better thermal insulation, sound absorption, reduced weight, lower carbon footprint, and satisfactory strength. This is not a new material, as it has been utilized for almost 100 years; however, steel remains challenging due to its high potential for improvement in terms of properties and sustainability. For instance, pre-processing via drying techniques helps address these limitations, such as high moisture absorption and dimensional stability. Also,

chemical or thermal modification can tailor the hydrophobicity, adhesion, and degradation resistance of recycled wood particles [171]. Adding a certain percentage of processed waste wood, such as chips, fibers, and sawdust, contributes to the sustainability of wood - cement composites. It is also ideal for prefabricated building elements, such as blocks, slabs, panels, and boards; therefore, there are various commercial products available in the construction and do-it-yourself markets. Recycling waste wood into lightweight aggregate is one of the sustainable solutions available. The method of obtaining lightweight aggregate, so-called roasted free or cold hardening, is based on the granulation of the mix in a disc granulator. The mix includes 40 to 60 % of waste wood sawdust, 40 to 60 % of cement, and 25 to 32 % of water (relative to the mass of cement). With this composition, the bulk density of the resulting aggregate corresponds to 750 - 850 kg/m<sup>3</sup>. The composition of the mix can be improved by using two binders, cement and polymer, i.e., combining two matrices from cement hydration and polymerization [161].

Wood-plastic composites (WPCs) are non-structural materials manufactured from industrial wood residues, waste wood from other sources, and recycled or virgin plastics. WPCs can be produced in a wide variety of shapes and sizes and may have either solid or hollow-core cross-sections, including curved or geometrically complex forms. In North America, WPCs are predominantly used for outdoor applications such as residential decking and railings, whereas in Europe they are more commonly applied in the automotive industry. Wood typically accounts for approximately 30–65% of the total mass of finished WPC products. The lignocellulosic raw material, recovered from sawdust, pulp fibers, or other sources such as bamboo and straw, must be dried to a moisture content of around 0.5%

and processed promptly to prevent moisture reabsorption. It is then ground into very fine particles to ensure uniform mixing with the plastic matrix. During processing, various chemical additives may be incorporated to tailor the material properties to specific end-use requirements. Finally, the composite material is molded or extruded to produce solid or hollow-core profiles for the intended applications [162].

Additionally, waste wood can be upcycled into engineered wood products (EWPs), such as CLT and GLT [104]. Compared to the direct reuse of reclaimed timber, EWPs produced from secondary wood are not limited to residential applications and can be employed in a wider range of structural uses. Furthermore, upcycled timber is well-suited for modern construction approaches, including modular and prefabricated systems, as well as designs for demountable timber products. Reclaimed timber intended for upcycling into EWPs should meet strength classes C16 or C24 and have a minimum cross-section of approximately 20 × 70 mm [124]. However, legislative, commercial, and technical barriers currently limit the structural use of secondary timber. Study [104] evaluated a comprehensive process for reusing demolition timber in new structural applications, encompassing sourcing, processing, characterization, manufacturing, and testing of glulam beams produced from reclaimed timber. The results highlight several critical requirements: appropriate on-site storage and pre-demolition surveys to prevent unnecessary scraping; retention of the longest possible timber elements to improve commercial viability by minimizing finger joints; and suitability criteria for material characterization, including adequate aspect ratios and trimming of damaged ends. The study further emphasizes the need for process automation, particularly for the safe removal of metallic fasteners. Additionally, a hierarchical reuse strategy is proposed, in which high-quality timber is directly reused, while shorter or defective elements are upcycled into EWPs. Despite these opportunities, the limited availability of large-scale manufacturing facilities remains a significant barrier to wider adoption of EWPs made from reclaimed timber.

While waste wood represents a versatile renewable resource, its large-scale and responsible utilization requires further technological development, robust quality control, and supportive policy frameworks. Continued research focused on technical performance, economic feasibility, and environmental impacts is essential to unlock its full potential. Equally important is the integration of the entire supply chain through effective communication and cooperation among waste generators, processors, and end users. With coordinated efforts from both public and private stakeholders, wood waste can play a meaningful role in circular economies and sustainable material systems [171].

In light of these considerations and following the strategic decision to design efficient supply chains that maximize overall process profitability while minimizing environmental impacts, EU countries have initiated several large-scale projects focused on waste wood. For example, in Germany, the *H2Wood - BlackForest* project (2021–) aims to convert regional waste wood into a local hydrogen resource. In addition, *Recycling for Future* and *Recycling for Reuse* are nationally funded projects addressing resource-efficient management of construction and demolition waste wood (2024–2026). In Norway, the Norwegian Institute of Bioeconomy Research has initiated the R&D project *CircWOOD's* (2022–), which seeks to enhance the reuse and recycling of wood. This project investigates the quantity and quality of reclaimed wood resources, material flows, digitalization approaches, environmental and climate

impacts, economic implications, and relevant policy and regulatory frameworks [157].

### 5.3 Circular practices and examples for timber

This chapter presents one representative example for each category of material recovery: reuse, upcycling, and recycling of waste wood. The selected examples illustrate current trends in innovative repurposing and end-use applications of reused and recycled wood products.

Examples of reuse are quite rare in practice and are mostly implemented within research and development projects. The Durley Chine Environmental Hub is an example of sustainable design and the reuse of timber in construction. The hub is a seafront visitor center in Bournemouth, which was built using low-carbon and repurposed materials [135]. It is located at Durley Chine beach, and serves as an educational, welfare, and exhibition space for the public. It comprises a 2-storey welfare and education building, an exhibition space covered with a green roof canopy, a café kiosk, and public toilets. Its key features include the use of reclaimed groyne timbers from the local beachfront, decking from a decommissioned submarine base, and recycled newspaper insulation. The welfare and education building was built and certified to Passivhaus standards, using a structural insulated panel frame, supplied and installed by Eden Insulation Ltd, triple-glazed windows, and solar paneling on the roof. The façade was built from ungraded groyne timber, resized and milled by a local Salisbury-based mill. Low-carbon ground granulated blast-furnace slag concrete was used to form the walls of the kiosk and toilet block, and ring beams, while reclaimed ekki (Azobe) beams were used for the roof structure. The decking primary structure was constructed using graded, unmilled groynes. The reclaimed basralocus, previously in place in a German naval dockyard, was used for the decking boards. 45 tons of reclaimed groyne timber were used to create the secondary structure of the canopy roof, the decking primary structure, fence, parapets, and the (non-structural) cladding on the education building. Since the groynes had already completed one use-life in the water, their remaining durability did not need to be determined. The structural isometric view, the detail of canopy roof isometric view, and the ground floor plan of the Durley Chine Environmental Hub are illustrated in Fig. 23, while its overall appearance is shown in Fig. 24.

The basic data regarding the project includes *Date of completion*: 2022; *Gross (internal & external) floor area*: 887 m<sup>2</sup>; *Architect*: Footprint Architects; *Client*: BCP Council; *Structural engineer*: WSP; *MEP engineer*: WSP Products; *Main contractor*: Seascope South. The basic data regarding the building properties are: upfront embodied carbon (A1-A5): 210 kgCO<sub>2</sub> e/m<sup>2</sup>; operational energy (B6): 75.862 kWh/m<sup>2</sup>/yr; design life: 40+ years.

Bergsagel et al [139] conducted a feasibility study to demonstrate whether reclaimed (secondary) timber from demolition sites can be successfully reused as feedstock for new structural glued laminated timber (GLT). The research forms part of the CIRCUIT (Circular Construction in Regenerative Cities) project and aims to support circular economy principles in construction. The study began with an analysis of existing timber waste flows and reuse practices in London, identifying that although large quantities of timber are reclaimed annually, only a very small percentage is reused in structural applications. Secondary timber was sourced from multiple demolition sites in London, primarily from internal structures such as raised floors and suspended ceilings. These sources were selected because they provide

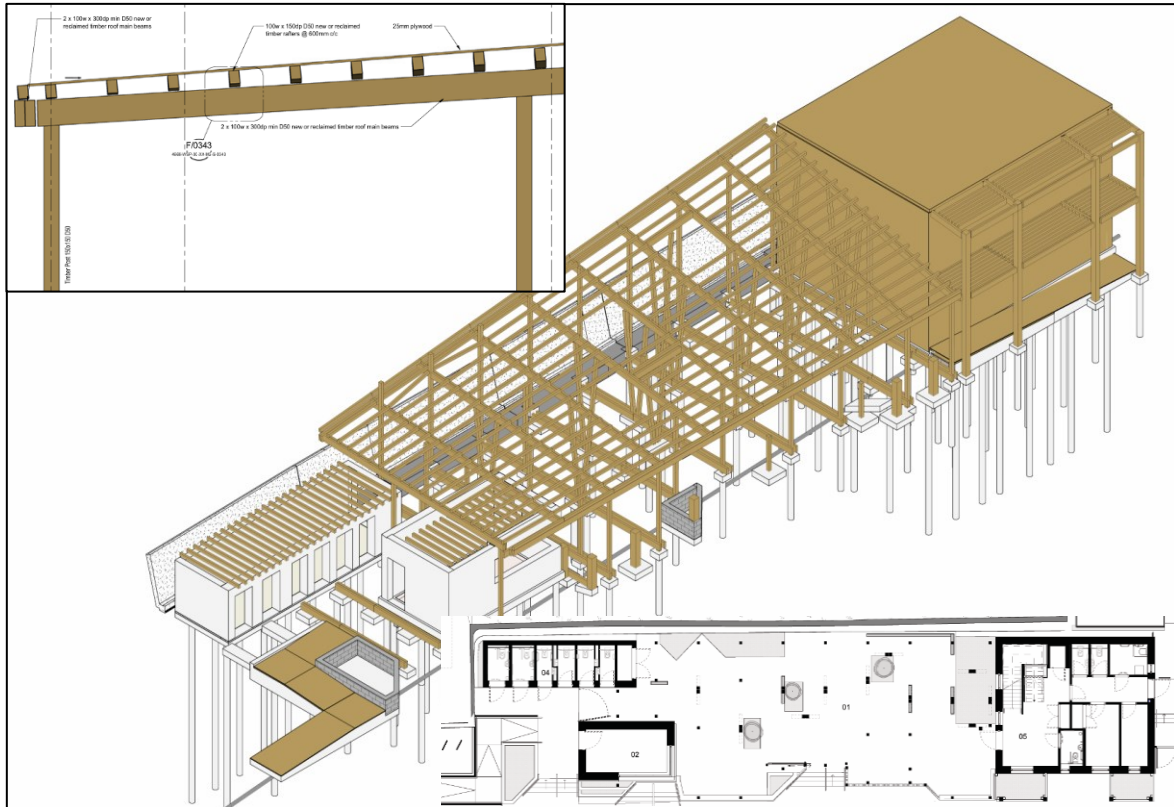


Figure 23. Structural isometric view and Detail of canopy roof isometric view, drawing by WSP. Ground floor plan showing exhibition space, kiosk, WCs, and education space, drawing by Footprint Architects [135]



Figure 24. The Durley Chine Environmental Hub in Bournemouth [135]

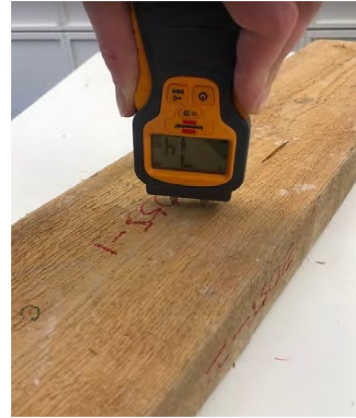
relatively dry, homogeneous timber with minimal degradation and limited exposure to weather. A key part of the work involved systematic non-destructive characterization of the reclaimed timber population. Each timber element was individually recorded and tested for dimensions, moisture content, density, visual characteristics (slope of grain, ring width, knots, fasteners, damage), and mechanical properties. Mechanical stiffness was estimated using longitudinal acoustic resonance testing, allowing an approximate assessment of dynamic modulus of elasticity. Based on visual and mechanical data, the authors assessed whether the reclaimed timber met the minimum grading requirements for glulam feedstock. Despite variability and damage typical of demolition timber, a filtered subset of the population achieved stiffness values equivalent to C14 strength class, which is sufficient for lamella used in GLT production according to BS EN 14080. The reclaimed timber was then processed and manufactured into GLT beams by a certified UK glulam manufacturer. This included additional

metal detection and removal, planning, finger-jointing short lengths into lamella, gluing, and pressing. Fig. 25 outlines sourced secondary timber, measuring of moisture, removing of fasteners, and the produced GLT beams.

The study highlighted challenges specific to secondary timber, particularly undetected embedded metal, higher defect rates, and increased processing time compared to primary timber. Finally, six full-scale GLT beams (width 100mm, height 214-215mm, length 4612-4613mm) made from reclaimed timber, were structurally tested in bending and glue-line shear. The four-point bending tests showed that all specimens reached failure stresses exceeding the characteristic bending strength specified for GL24h (BS EN 14080). In addition, the measured global moduli of elasticity (MOE) were consistently higher than the corresponding characteristic MOE values for GL24h. However, the average value obtained for the glue line shear strength fell below the minimum required by BS EN 386 (3.5 N/mm<sup>2</sup> average compared with 6 N/mm<sup>2</sup> required). In recognition of these



Timber sourced from multiple demolition sites in London



Measuring of moisture



Removing fasteners



Completed GLT beams

Figure 25. Process of upcycling the structural timber from construction sites into glulam products [139]

limitations, the authors conducted additional shear testing using an alternative test setup. These supplementary tests yielded substantially higher average shear strength values (approximately  $8.37 \text{ N/mm}^2$ ) and wood failure percentages that satisfied the requirements of the relevant standards. The results showed that the beams achieved satisfactory strength, stiffness, and bonding performance, confirming the technical feasibility of manufacturing structural GLT from secondary timber. Overall, the authors demonstrated that upcycling of demolition timber in GLT is technically viable, provided that appropriate sourcing, testing, grading, and processing protocols are followed. The work identifies key barriers, such as logistics, grading uncertainty, and metal contamination, while establishing a strong proof of concept for circular use of timber in engineered wood products.

Besides the recycling of all kinds of particleboards and fiberboards, the most challenging innovations striving toward a circular economy were made in recycling of MDF/HDF boards. UNILIN Company [141] invented in 2021 the recycling process of MDF based on pressure cooker operation. Thanks to advanced sorting and cleaning facilities, wood waste is cleared of all impurities using magnets, wind sifters, centrifuges, infrared scanning, and AI to separate a clean MDF fraction. MDF recycling, based on innovative processes, enables the retention of  $\text{CO}_2$  at least twice. Recovered wood fibers (Fig. 26) can be used in the same way as virgin ones. UNILIN plan to replace 25% of all fibers in the MDF wood mix with recycled fibers.



Figure 26. Recycled wood fibers from MDF [141]

Another company, “MDF Recovery”, patented its own MDF recycling technology that can be easily integrated into every existing production line. Main phases of MDF recovery process are sorting, ohmic disaggregation, and multi-stage cleaning. Sorting process is based on AI-powered optical scanner that ensures MDF waste purity of over 95%. Using “ohmic disaggregation process” the fibers are gently released from MDF without compromising their integrity and length. Advanced multi-stage cleaning processes are used to remove contaminants, leaving clean, reusable fibers. Fig. 27 outlines the MDF recovery process [163].

Both examples of recycling the MDF boards are an important step in worldwide CE practice because of massive commercial production (not pilot project).

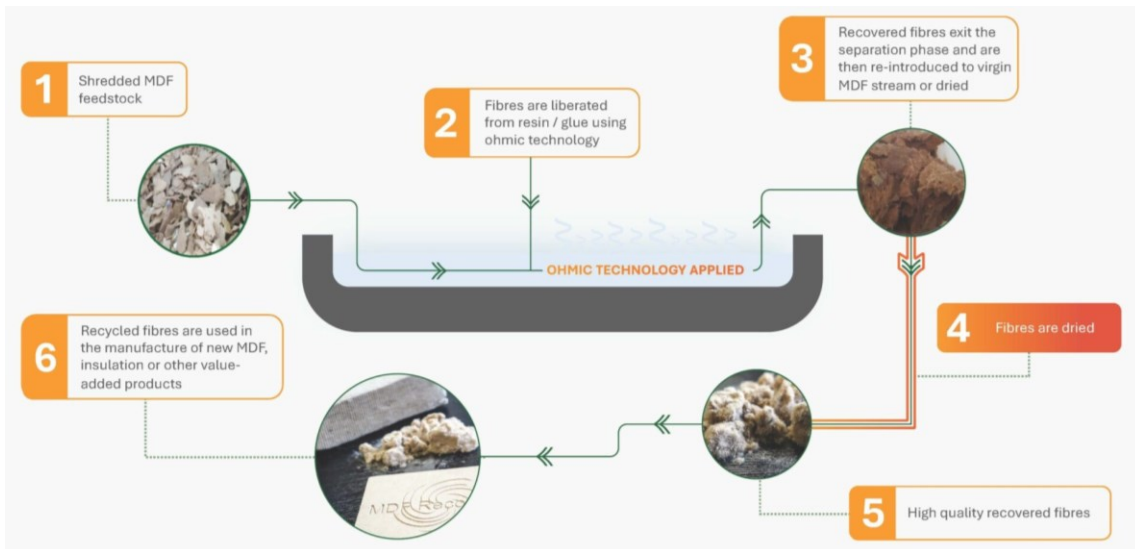


Figure 27. MDF recycling technology, adopted from [163]

## 6 Discussion and Conclusion

### 6.1 Key findings on regulation and recycling rates for construction materials

At the European level, the regulatory framework for C&DW is well established and increasingly aligned with circular economy principles. The Waste Framework Directive, with its amendments, provides clear policy direction by prioritizing material recovery (preparing for reuse, recycling, backfilling, and other forms of material recovery) to energy recovery. Also, selective demolition and separate collections of C&DW in at least six fractions are required to facilitate reuse and high-quality recycling. However, despite ambitious targets and strategic coherence, significant regulatory gaps exist, particularly the absence of end-of-waste criteria and harmonized quality standards for most C&DW fractions. This shortfall continues to hinder the effective uptake of reused and recycled materials. At this point, end-of-waste criteria have only been established for glass cullet and for copper, iron, steel, and aluminum scrap. Globally, regulatory approaches remain fragmented, with significant disparities between regions in terms of targets, enforcement, and market integration.

In Serbia, the regulatory framework for C&DW management is under active development and increasingly aligned with EU policies. Strategic documents adopted in recent years have recognized C&DW as a priority waste stream and established medium- and long-term recovery targets. According to the new Waste Management Program, 40% of C&DW is expected to be recovered by 2029. It is evident that this is far lower than the current C&DW recovery target in the EU; however, a significant increase is expected in a relatively short period, as 70% of C&DW is planned to be pretreated by 2034. The introduction of regulations addressing pre-demolition audits and source separation represents a significant step forward. Nevertheless, the regulatory focus remains primarily on waste management rather than on enabling higher-value reuse and recycling. The absence of end-of-waste criteria limited economic incentives, and insufficient market-support mechanisms continue to hinder broader implementation of circular practices.

Türkiye has made notable progress at the strategic level through the adoption of the Green Deal Action Plan and national development plans that emphasize circular economy objectives. C&DW is addressed through sectoral regulations, such as the By-law on Excavation Soil and Construction and Demolition Waste Control, which prioritize waste minimization and recovery. Furthermore, EU-harmonized standards are applied to recycled aggregates. However, the regulatory framework does not yet define explicit recycling or reuse targets for C&DW, nor does it include end-of-waste criteria for construction materials. As a result, implementation remains uneven, and regulatory support for high-quality reuse and recycling is still limited.

European statistics (Eurostat) on C&DW are essential for understanding waste scale and treatment trends; however, their reliability is significantly undermined by inconsistent reporting, vague guidelines, and a lack of expert trust. Nevertheless, these statistics remain valuable, provided they are used with 'reasonable caution' as high-level indicators rather than absolute facts. Recycling rates for C&DW in the EU are generally high, with many Member States exceeding the 70% recovery target set by 2020, established by the WFD. The EU's average C&DW recovery rate as of 2020 was over 80%. However, the management of C&DW varies widely across European countries, reflecting differences in regulatory frameworks, infrastructure, and recycling practices. For instance, countries like Germany, Denmark, and the UK show high C&DW recovery rates of 94%, 97%, and 92%, respectively. Romania presents a contrasting situation, with waste recovery levels significantly below the EU target. Most collected C&DW in Romania is landfilled, with minimal reuse or recycling efforts. In 2020, Romania declared a C&DW recovery rate of 46%. In contrast, reliable data on reuse rates remain scarce. Globally, reuse rates are consistently low, reflecting persistent technical, regulatory, and market barriers that favor recycling over direct reuse.

In Serbia, recycling and recovery rates for C&DW are still developing, with official targets set for future years rather than achieved outcomes. Current practices focus primarily on collection and basic treatment, while material-specific recycling and reuse rates are largely undocumented.

In Türkiye, demolition practices generally involve the dismantling of plastic, wooden, and metal components for

reuse and recovery. Scrap materials and metal reinforcement are largely recovered, while the remaining mixed C&DW (concrete, brick, ceramics, and other materials), which accounts for almost 80% of total C&DW by weight, is either used as filler or sent to landfills. Licensed C&DW disposal and recovery plants are present in most cities, dedicated to various activities, including pre-treatment, recycling/reclamation, temporary storage, landfills, and specialized recovery processes. However, no official statistical data on the recycling rates of C&DW are currently published.

Since C&DW must be sorted, figures on the generation of mineral, wood, and metal fractions indicate that the quantity of collected mineral fractions is notably higher (about 30 times) compared to the wood and metal waste streams. Germany, France, Italy, the Netherlands, and Belgium are the leaders in generating all three specified waste fractions. With 80% of the C&DW mineral fraction recovered and approximately 71% recycled, the 2020 WFD target has ostensibly been fulfilled at the EU27 level. However, while this high recovery rate might suggest that secondary raw materials are widely used for new construction products (such as concrete), challenges related to material quality and technical standards mean that only a small fraction is truly returning to the economy in high-value applications. Furthermore, another factor impeding the construction industry's efforts to close the resource loop is the substantial share of backfilling in many countries, which remains classified as recovery despite being a downcycling activity. Finally, there is a prevalent lack of harmonized and transparent data regarding the specific recycling rates of wood and metal fractions within the C&DW stream across Europe. While metals are largely recovered due to their high market value and defined end-of-waste criteria, waste wood often flows into energy recovery rather than material recycling, making it difficult to accurately track its circularity.

Reuse of construction materials remains marginal, constrained by limited infrastructure, insufficient data, and the absence of regulatory and economic incentives that would support higher-value circular solutions.

Due to the lack of official EU statistics providing detailed information on the recycling and reuse rates of key construction materials derived from C&DW, such as steel, timber, concrete, and bricks and blocks, complementary data were collected from Management Committee (MC) members representing EU and non-EU countries participating in COST Action CA21103 Circular B. Representatives from 11 EU countries, 3 non-EU countries, and the UK took part in the survey. Both national official and estimated rates indicate that steel recycling from C&DW is widely practiced, achieving consistently high rates across the EU and the UK. This outcome was expected, given that steel has an established end-of-waste criterion. Although a wide range of estimated values for the timber recycling rate is noticed, the disparity can be explained by the fact that countries with low timber recycling rates prefer to use waste wood for energy recovery. Official recycling figures for concrete and for bricks and blocks are generally unavailable, as these materials are typically reported within the aggregated C&DW mineral fraction. Although the estimated concrete recycling rates reported in the survey are predominantly low, it is likely that the actual concrete recycling rate in the EU is significantly higher. This assumption is based on the absence of participation from countries such as Germany, France, the Netherlands, Denmark, and Belgium, which are known for their high levels of recycled concrete utilization. For bricks and blocks, the limited amount of data and the large variation in estimated recycling rates prevented the formulation of a

reliable conclusion. National official reuse rates for all analyzed construction materials are currently unavailable, as none of the participating countries provided reliable figures. This indicates that such data are not systematically collected or reported officially. The reuse of steel from C&DW remains limited across the EU, primarily because recycling is considerably easier to implement. In addition, several participating countries identified the lack of supportive legislation and limited market demand as the main barriers to steel reuse. Regarding timber, the relatively low estimated reuse rates can be attributed to the prevailing practice of utilizing waste wood primarily for energy recovery and, to a lesser extent, for recycling. Romania reported that the reuse of timber from construction and demolition activities remains limited due to the absence of certification schemes, insufficient industrial demand, and a lack of consistent deconstruction practices. Selective demolition or deconstruction and reuse of concrete structural components is rarely implemented in practice. This is due to multiple barriers, including the absence of regulatory frameworks, national guidelines, and quality assurance protocols. Furthermore, precast concrete components are typically heavy, difficult to extract intact, and often structurally tailored to their original designs, which significantly limits their reuse potential. These challenges were confirmed by several participating countries, including Romania, the UK, and Latvia. Approximately half of the participating countries reported estimated reuse rates for bricks and blocks ranging between 1% and 8%, indicating that reuse of these materials from C&DW is not yet widely implemented. When practiced, it is generally limited to specific applications, such as historic building renovation, architectural reuse, low-grade construction, and self-build projects.

## 6.2 State of steel reuse and recycling

Reuse represents a fundamental principle of the circular economy, prompting extensive research and engineering efforts aimed at enhancing the practical reuse of key construction materials. Nevertheless, despite its clear benefits, the implementation in practice remains limited due to numerous unresolved barriers. Even in the case of steel that is considered as the material with the greatest reuse potential, only a few successful examples have been documented in construction practice. Main barriers to implementing steel reuse include additional costs, uncertainty of structural properties, the availability and storage of dismantled elements, supply chain gaps, and a lack of adequate design rules, regulations, standards, and frameworks to connect stakeholders in the steel reuse market and the construction industry.

The main obstacle to using reused steel is the uncertainty of structural properties since steelmaking processes, standards, and testing were different before 1970. Namely, before 1970, most structural steels were produced using open-hearth furnaces or Bessemer converters, which characterized with less precise control over temperature and chemical composition. Thus, pre-1970 steel had different chemical composition and content of impurities, microstructure, mechanical and fabricating and manufacturing properties [167]. The construction period of steel buildings is important because it can help identify the type of iron or steel used. For instance, if the buildings were constructed up until the middle of the 19th century, they likely employed wrought iron or cast iron. Between 1850 and 1950, mild (carbon) steel was predominantly used. From 1950 to 1970, medium and high-strength steel became the standard

materials for construction [168]. To identify the required properties, reused steel can be categorized based on the size and function of the original building components. Samples from each category should be tested using both non-destructive and destructive methods. However, the results may vary significantly between groups due to the aforementioned factors. Another challenge is the availability of reused components. New buildings need to be designed based on the available stock, which can change frequently [53].

The reuse of steel elements is often more expensive than the use of new ones under current market conditions, due to additional direct costs related to the dismantling of obsolete structures, inspection, testing and certification of dismantled elements, as well as the need to adapt new designs to the dimensions and properties of existing components. These challenges can be mitigated by introducing mandatory quotas for the use of reclaimed components, providing stronger fiscal incentives, promoting design for deconstruction, and establishing harmonized standards for steel reuse. Despite the higher upfront costs, steel reuse can result in overall savings when considering its environmental benefits, such as the conservation of raw materials and energy, the reduction of CO<sub>2</sub> emissions, and lower costs for waste transport and disposal.

Today, reuse is complicated because most obsolete buildings lack relevant information to assist the demolition contractor in deconstructing the building or the designers in creating new designs using the reclaimed steel sections. Collecting the necessary information about the obsolete building during the pre-demolition phase is time-consuming, costly, and difficult, especially if the structure is inaccessible and/or occupied. The future reuse of contemporary buildings, however, may be different, because those structures are progressively designed as systems and their design information can be easily maintained, for instance, as a building information model (BIM) [164]. The traceability of new steel used today to provide an audit trail of the structural steel in buildings could be fairly robust and straightforward with existing manufacturing and BIM software. This could lead to the inspection document related to the steel's manufacture, which will include all relevant chemical and mechanical properties [164]. If other aspects, such as carbon savings, social benefits, and reputational advantage, could be rigorously quantified (economically), the case for reuse would be stronger.

There is growing pressure on the construction industry to be more resource efficient, reduce waste and lower embodied carbon impacts [169].

What is the future of steel reuse?

Widespread steel reuse in the construction industry is still unpredictable for the future. The main reason is the long life of steel structures, during which the changes in steel quality standards, design codes, and construction details are inevitable. This is supported by the fact that major revisions of regulations occur approximately every 15 years and that pre-1970 steel differ significantly from modern steel as well as the obsolescence of connection details. It is certain that the steel structures we design today will face similar challenges in 50-100 years. Furthermore, there is no guarantee that steel reuse will occur, even if the obsolete structures can be dismantled and meet current steel quality standards, due to a potential mismatch between supply and demand. Additionally, there are limitations in the application of reused steel. For example, because the load history of reused elements is often unknown, reclaimed steel is not recommended in structures exposed to seismic actions,

since these structures demand reliable ductile behavior [169].

Although numerous technical and economic barriers hinder the implementation of steel reuse, environmental protection and the transition toward a circular economy represent higher societal goals that demand its faster and broader adoption in construction practice. To make this transition both scalable and safe, clear regulatory frameworks, technical guidelines, and standardized procedures are required. Today, the first steps have been taken towards these goals, as protocols, technical specifications, and recommendations have been developed and introduced. The documents already introduced include:

- Steel Construction Institute SCI: Protocol for reusing structural steel P427
- Steel Construction Institute SCI: A Supplementary Guide to Reusing Pre-1970 Steelwork (1932-1970) P440
- CEN/TS 1090-201: Execution of steel structures and aluminium structures - Reuse of structural steel
- CEN/TC 250/SC 3/WG 24: Design of reclaimed steel components for re-use
- European Recommendations for Reuse of Steel Products in Single-Storey Buildings, Provisions for greater reuse of steel structures (Project "PROGRESS")

These documents establish a harmonized approach for testing, certification, traceability, and accountability, thereby reducing legal uncertainty, supporting engineering reliability, and fostering market confidence in reused steel as a competitive alternative to new steel production. Establishing a real-time digital platform for reused steel components will also be of crucial importance.

In contrast, recycling has not only been extensively studied but also successfully implemented in practice in the previous period, serving as one of the fundamental principles of sustainable construction. Steel is one of the most widely recycled materials in the world, with an estimated recycling rate of even higher than 90% in developed countries. Since the end-of-waste criteria for steel were established in 2011, the utilization of scrap in steel production reached its maximum. Thus, in developed economies steel is very close fulfilling circularity criterion - no waste disposal.

Nowadays, steel obtained from C&DW is predominantly recycled rather than reused, even in highly developed economies. For instance, in the United States, approximately 74% of all steel waste generated in the construction sector including structural sections, reinforcement, and other components, is recycled. Moreover, up to 97% of steel structural sections are processed into scrap [170]. These figures indicate that the direct reuse of steel remains limited, occurring mainly as isolated examples of good practice rather than as a widespread practice. Our survey results (see Chapter 3.3) indicate that none of the EU countries have an official steel reuse rate. The estimated rate ranges from 1 % to 5 %, which aligns with the figures reported in [60].

The challenge for society is that steel demand far exceeds the supply of steel scrap, with only an estimated 25 % of steel demand currently met from recycled steel. Achieving full circularity, where sufficient steel scrap is generated to meet demand, will only be possible once the world possesses enough buildings, infrastructure, equipment, vehicles, and products to satisfy the needs of a fully developed global economy. This transition will take time. While steel consumption in many mature economies has plateaued, demand in developing countries continues to grow strongly as they converge with developed-world standards. At the same time, the global shift toward a carbon-neutral economy is accelerating the replacement of

energy and manufacturing assets, infrastructure, and buildings, which will temporarily increase demand for materials, including steel [72]. Moreover, the use of scrap negatively affects steel quality due to the accumulation of residual elements (particularly copper), so a certain amount of raw materials will still be required in steelmaking to mitigate the negative effects of contaminated scrap. Additionally, recycling is not enough to reduce CO<sub>2</sub> emissions by 50% according to Sustainable Development Scenario (International Energy Agency), so this goal must be achieved by implementing the reuse of structural steel in construction practice.

The future decision-making regarding the reuse or recycling of steel components could be more effective if digital twin models of the buildings were established. These comprehensive models will obtain essential information such as the original design model, construction data, operation and maintenance history, real-time building condition, and decommissioning data. By integrating a material passport into the digital twin model, full traceability of materials and components could be achieved. An economic and environmental analysis of future buildings, including different scenarios, are also important. These analyses are essential for optimizing design, selecting materials/components, and ensuring sustainability by balancing financial goals with environmental protection.

### 6.3 State of timber reuse and recycling

Timber has the highest positive environmental impact among other construction materials [103]. Waste wood represents a strategically important secondary resource within the transition toward a circular bioeconomy, but its full material recovery potential is only partially exploited. Since forest regeneration is slow and resource-intensive, the recirculation of post-industrial and post-consumer wood products offers substantial environmental, economic, and societal benefits. Waste wood should be considered a heterogeneous material resource whose value depends strongly on origin, contamination level, and degree of prior processing. Increasing the amount of wood planned for reuse or recycling requires an understanding of the composition of waste wood [137]. To recover as much clean wood as possible, it is important to begin with efficient sorting of waste wood at sites during careful dismantling or selective demolition. This process then continues at recycling centers or facilities. The challenges of reusing and recycling waste wood stem from its unique properties, which set it apart from other building materials, a renewable natural material of organic origin. These properties also explain why its use as an energy source is still dominant.

The total estimated potential of waste wood in the EU is approximately 50 million tonnes, of which nearly 40 million tonnes are currently recovered. Of this recovered amount, approximately 18.5 million tonnes are used for material recovery, i.e., recycling and backfilling, while about 21.5 million tonnes are used for energy recovery. The data regarding the waste wood reuse in structural purposes is still unavailable. The actual distribution of recovery pathways is highly uneven, as forest-rich countries, such as Norway, Finland, and Germany prioritize the use of waste wood for energy recovery. In many EU member states, waste wood is mainly used as biomass fuel due to priorities related to energy security, existing incineration infrastructure, and favorable economic conditions. While energy recovery is an important part of renewable energy systems, its prevalence creates a systemic barrier to the circular use of waste wood,

as it irreversibly removes potentially recyclable wood from the material loop. However, the new EU Renewable Energy Directive III is shifting the focus from energy recovery to material recovery, particularly to recycling. This change, along with the goal of achieving climate neutrality by 2050, will lead to significant modifications in waste wood management policies.

The cascade approach of utilizing salvaged wood yields beneficial environmental effects, linked to the manufacture of new products, and aids in climate change mitigation by extending the duration of carbon storage and delaying carbon emissions [1]. From the first life cycle to the ultimate end of life, numerous opportunities exist to use salvaged wood by gradually diminishing the level of waste hierarchy, aiming to maximize the number of life cycles through methods such as reuse, repurposing/upcycling, recycling, downcycling, and energy recovery/incineration. Nowadays, the cascade approach exists, but not in full range. For example, the reuse of mass structural timber is limited to individual cases, such as residential low-rise or historical buildings, since modern timber construction is not currently aligned with circular economy principles and is seldomly taking buildings end-of-life-into account. In contrast, recycling, downcycling, and especially energy recovery are widely incorporated into everyday practice. Upcycling into engineered wood products, such as CLT or GLT, is a very promising possibility for wood waste utilization. For the successful implementation of the full cascade approach in wood waste management, it will be essential to incorporate it into the current EU legislation and secure supportive policy.

Waste wood recycling holds considerable untapped potential to contribute to climate mitigation, resource conservation, and sustainable construction. Unfortunately, the term "recycling" of wood waste is often used in the case of energy recovery. According to the WFD 2008/98/EC definition, recycling refers to materials being transformed into new products but does not include energy recovery and the reprocessing into materials that are to be used as fuels. Thus, the published data concerning the percentage of waste wood recycling must be taken with some suspicion.

Recyclable wood waste mainly originates from logging and the wood processing industries. However, other sources, such as commercial, municipal, and construction and demolition waste, also represent a significant potential resource. Since not all waste wood can be recycled, its suitability depends on its classification and grade, as surface treatments, fasteners, plastics, and more often require extra processing or even block recycling. Therefore, waste wood must be properly graded before recycling. Quality-driven classification and sorting constitute the critical enablers of high-value recycling. There is no harmonized European classification system for waste wood recycling since energy production policy in the EU favors the use of renewable resources. Thus, EU Member States have introduced national waste wood classification schemes primarily designed for energy recovery. This situation significantly limits the potential for material recovery. Without standardized grading for recycling, waste wood is frequently diverted to energy recovery, even when material recycling would be technically feasible. The UK is the only country that has introduced grading for wood waste recycling through national regulations. Although the EU Waste Framework Directive introduced the waste management hierarchy, extended producer responsibility (EPR) schemes, separate collection obligations, and sectoral reuse, recycling, and recovery targets, the actual situation in waste wood management is different, since national waste wood

classifications consider wood waste predominantly as an energy source. These classifications have several common features, such as the use of quality criteria related to mechanical processing, chemical treatments, and the presence of hazardous substances and preservatives. National waste wood classifications grade waste wood most often into four basic classes: Untreated, clear solid wood, Treated, non-hazardous solid wood, Treated, non-hazardous mostly board products, and Hazardous wood. Illustrated classification can help in sorting waste wood to be recycled. Further improving the recyclability of waste wood requires the implementation of effective, high-quality sorting and segregation processes into well-defined fractions. Advanced sorting technologies, such as NIR, XRF, and AI-assisted systems, emerge as essential tools for improving material purity, reducing contamination risks, and enabling reliable downstream applications in composite manufacturing. For instance, a vital step in improving the recyclability of board products is to sort waste wood by type (e.g., MDF, plywood, OSB) to create clean, mono-material fractions for higher value recycling.

Although the benefits of recycling waste wood are obvious, economic and market-related barriers remain significant. Recycling waste wood often entails higher short-term costs due to selective demolition, logistics, sorting, and pre-treatment requirements. At the same time, low prices and the availability of virgin timber undermine the competitiveness of recycled alternatives. These challenges underscore the need for system-level interventions, including extended producer responsibility schemes, End-of-Waste criteria, targeted subsidies, and the creation of stable demand for recycled wood products. Without such measures, technological progress alone is unlikely to shift prevailing practices. Social and institutional dimensions are equally influential. Persistent perceptions of waste wood as a low-quality and high-risk material and a lack of law enforcement for proper waste management continue to limit its acceptance in the construction and manufacturing sectors. Addressing these concerns requires not only strengthening legislation, improving supervision, increasing penalties and level of responsibilities, and investing in infrastructure, but also raising public awareness through education and knowledge transfer.

Also, the growing number of national and EU-funded research initiatives represents a positive trend toward evidence-based policy and industrial transformation.

Regardless of the obstacles, there is a wide spectrum of possibilities for the implementation of recycled waste wood into material production. They vary from high-value to low-grade recycling products. Such diversity in the products

indicates the high potential of wood waste to be recycled and to obtain unique EoW criteria, as well as that of steel waste. Austria is the only the EU state with EoW criteria related to waste wood. Realizing this potential requires a holistic and coordinated approach that integrates regulatory harmonization, technological innovation, market development, and cultural change across the entire value chain. Under such conditions, waste wood can evolve from a marginal by-product into a reliable and valuable secondary raw material within circular material systems. From a technological perspective, the findings indicate that particleboard production currently represents the most robust and economically viable outlet for recycled waste wood, particularly in mixed and heterogeneous waste streams. The core layer of OSB panels can be made from waste wood particles. The percentage of substitution is limited by the low slenderness ratios of particles and the presence of contaminants. Recycling MDF into fibers or waste timber into higher-value products, such as structural engineered wood products (i.e. CLT, GLT), remain theoretically possible but are constrained by additional sorting into more clean fractions, very demanding pre-treatments, and limited industrial infrastructure. Nevertheless, recent advances, especially in the recycling of MDF through thermo-hydrolytic fiber recovery and the adoption of bio-based adhesives, demonstrate that these barriers are not fundamental but transitional. Continued innovation in pre-treatment, purification, and bonding technologies is therefore likely to expand the feasible application range of recycled wood. The use of waste wood in wood–cement and wood–plastic composites also requires sorting, cleaning, and, in many cases, specific pre-treatment. Although these composite systems are generally more tolerant to lower-grade and more heterogeneous wood waste than fiberboards or structural engineered wood products, contaminants such as coatings, metals, plastics, and mineral impurities must still be removed. Proper pre-treatment is particularly important for wood–cement composites to avoid inhibition of cement hydration, while wood–plastic composites mainly require control of particle size, moisture content, and material homogeneity to ensure stable performance.

#### 6.4 Final findings on steel vs. timber

Tab. 20 synthesizes the available treatment options for ferrous metals (iron and steel) and wood as construction and demolition waste (C&DW), highlighting key differences in regulatory classification and practical implementation across the EU.

Table 20. Available treatment options for ferrous metals and wood as C&DW (adapted from [11])

C&DW	Available treatment options	Classification according to WFD
Ferrous metals (iron and steel)	Ferrous metals (iron and steel) can be remelted and used for production of new metal. This is largely common practice across Europe, as ferrous metals are easy to identify and sort, and recycling is typically economically sustainable.	Recycling EoW directive (Regulation 333/2011) Preparation for reuse (CEN/TS 1090-201)
Wood	Depending on the quality and the content of hazardous substances, wood from construction activities can be recycled or used for energy recovery. If waste wood is clean, it can be used in the production of particleboards ( <i>recycling</i> ). If contaminated, incineration with energy recovery is often the preferred solution. In rare cases, wood is prepared for <i>reuse</i> , e.g. for structural purposes	Energy recovery. Recycling (if used for particleboard production, or in wood cement and wood plastic composites). EoW criteria only in Austria. Preparation for reuse, in rare cases.

### CRedit authorship contribution statement

Mirjana Malešev: Conceptualization; Methodology; Formal analysis; Investigation, Supervision, Writing-original draft, Writing - review and editing.

Vlastimir Radonjanin: Conceptualization; Methodology; Formal analysis; Investigation, Supervision, Writing-original draft, Writing - review and editing.

Rand Askar: Conceptualization; Methodology; Formal analysis; Investigation, Writing-original draft, Writing - review and editing.

Ana Nadaždi: Data curation, Formal analysis, Investigation, Writing – original draft.

Bilge Bas: Data curation, Formal analysis, Investigation, Writing – original draft.

Milena Rajić: Data curation, Formal analysis, Investigation, Writing – original draft.

Evrin Celik Madenli: Data curation, Formal analysis, Investigation, Writing – original draft.

Eđip Avšar: Data curation, Formal analysis, Investigation, Writing – original draft.

Anka Starčev-Čurčin: Data curation, Formal analysis, Investigation, Writing – original draft.

Vesna Bulatović: Data curation, Formal analysis, Investigation, Writing – original draft.

Ayfer Dönmez Çavdar: Data curation, Formal analysis, Investigation, Writing – original draft.

Ivan Lukić: Data curation, Formal analysis, Investigation, Writing – original draft.

Tatjana Kočetov-Mišulić: Data curation, Formal analysis, Investigation, Writing – original draft.

### Declaration of Competing Interest

The authors declare no conflict of interest.

### Declaration of generative AI in scientific writing

During the preparation of this work, the authors partially used generative AI tools (Grammarly and ChatGPT) in order to do language editing and proofreading. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article. The authors confirm that the content, methodology, and conclusions presented are entirely their original contributions, and the use of AI does not conflict with ethical guidelines or scientific publishing standards.

### Acknowledgments

This research paper is the result of a collaborative effort by a multinational team of researchers, reflecting diverse expertise and perspectives in advancing the principles of the circular economy in building design. The authors thank and acknowledge the contributions of the experts who participated in this study for their support, time, and knowledge. The authors acknowledge the support of the COST Action CA21103 Circular B (<https://circularb.eu/>; <https://www.cost.eu/actions/CA21103/>).

### References

- [1] Cristescu, C., Honfi, D., Sandberg, K., Shotton, E., & Walsh, S. J., et al (2020): Design for deconstruction and reuse of timber structures-state of the art review, InFutUReWood Report:1., doi: 10.23699/bh1w-zn97
- [2] C. Zhang, M. Hua, F. Di Maio, B. Sprecher, X. Yang, A. Tukker (2022): An overview of the waste hierarchy framework for analyzing the circularity in construction and demolition waste management in Europe, Journal „Science of the Total Environment“ 803,

149892.  
<https://doi.org/10.1016/j.scitotenv.2021.149892>
- [3] García, C. et al. (2024): Techno-economic and environmental assessment of construction and demolition waste management in the European Union Status quo and prospective potential. Luxembourg. doi: 10.2760/721895.
- [4] Damgaard, A. and Lodato, C. (2022): Background data collection and life cycle assessment for construction and demolition waste (CDW) management, doi: 10.2760/772724.
- [5] The European Parliament and the Council of the European Union (2008): Directive 2008/98/EC on waste and repealing certain directives. Official Journal of the European Union L312/3
- [6] The European Parliament and the Council of the European Union (2018): Directive 2018/851 amending Directive 2008/98/EC on waste Framework. Official Journal of the European Union L150/109
- [7] <https://worldsteel.org/circular-economy/> (accessed June 16, 2024).
- [8] <https://steel-sci.com/reduce-and-progress.html> (accessed June 7, 2024).
- [9] Sivaganesh, S., Chan, T., M. (2024): Recommendations for Implementing Circular Economy in Construction: Direct Reuse of Steel Structures; Journal of Constructional Steel Research 214 (2024) 108439.  
<https://doi.org/10.1016/j.jcsr.2023.108439>
- [10] [https://www.steelconstruction.info/Recycling\\_and\\_reuse](https://www.steelconstruction.info/Recycling_and_reuse) (accessed August 21, 2025)
- [11] EU Construction & Demolition Waste Management Protocol including guidelines for pre-demolition and pre-renovation audits of construction works, Updated edition 2024, European commission B-1049 Brussels.
- [12] Eurostat (2024): Treatment of waste-by-waste category, hazardousness and waste management operations. (accessed September 10, 2024).
- [13] European Commission (2015): Closing the loop - An EU action plan for the circular economy. COM (2015) 614 final.
- [14] European Commission (2019): The European Green Deal. COM (2019) 640 final
- [15] European Commission (2020): A new Circular Economy Action Plan. For a cleaner and more competitive Europe. COM (2020) 98 final
- [16] European Committee for Standardization (CEN). CEN/TC 104 (2022): EN 206:2013+A2:2021. Concrete - Specification, performance, production and conformity.
- [17] Government of the Republic of Serbia (GOV RS) (2022): Circular Economy Development Program for the Republic of Serbia for 2022-2024 (In Serbian). The Official Gazette of the Republic of Serbia No.137/2022.
- [18] Regional Cooperation Council (RCC). (2020): Sofia Declaration on the Green Agenda for the Western Balkans (Issue November 2020).
- [19] Government of the Republic of Serbia (GOV RS). (2022): Waste Management Program in the Republic of Serbia for 2022-2031 (In Serbian). The Official Gazette of the Republic of Serbia No.12/2022
- [20] National Assembly of the Republic of Serbia (NARS). (2023): Waste Management Act (In Serbian). The Official Gazette of the Republic of Serbia No.35/2023

- [21] Government of the Republic of Serbia (GOV RS). (2023): Construction and Demolition Waste Management Regulation (In Serbian). The Official Gazette of the Republic of Serbia No.94/2023
- [22] Ministry of Environmental Protection of the Republic of Serbia (2019): Rulebook on End-of-Waste Criteria (In Serbian). The Official Gazette of the Republic of Serbia No.78/2019
- [23] Republic of Türkiye Ministry of Trade (MT) (2021): Green Deal Action Plan. : (accessed July 12. 2024 - in Turkish)
- [24] Presidency of Strategy and Budget (2023): Twelfth Development Plan (2024-2028). Retrieved from: (accessed July 12. 2024)
- [25] Republic of Türkiye Ministry of Environment, Urbanization and Climate Change (MEUCC) (2023): National Waste Management and Action Plan. Retrieved from: (accessed July 12, 2024 - in Turkish)
- [26] Official Gazette of the Republic of Türkiye (2004). By-law on Excavation Soil, Construction and Demolition Waste Control (accessed March 18, 2004 - in Turkish)
- [27] Official Gazette of the Republic of Türkiye (2019): By-law on Zero Waste (Date: 12 July 2019, No 29314) (In Turkish). (accessed July 12, 2024)
- [28] Official Gazette of the Republic of Türkiye (2021): Change in By-law on Zero Waste (Date: 09 October 2021, No 31623) (In Turkish). (accessed July 12, 2024)
- [29] TS EN 206+A2 (2021): Concrete - Specification, performance, production and conformity (Standard No: TS EN 206+A2:2021). Turkish Standards Institute, Ankara, Turkey.
- [30] [https://db.nomics.world/Eurostat/cej\\_wm040?tab=list](https://db.nomics.world/Eurostat/cej_wm040?tab=list)
- [31] [https://ec.europa.eu/eurostat/databrowser/view/env\\_wastrt\\_custom\\_12356695/default/table?lang=en](https://ec.europa.eu/eurostat/databrowser/view/env_wastrt_custom_12356695/default/table?lang=en)
- [32] [https://www.eea.europa.eu/data-and-maps/daviz/mineral-waste-from-construction-and#tab-googlechartid\\_chart\\_13\\_filters=%7B%22rowFilters%22%3A%7B%7D%3B%22columnFilters%22%3A%7B%7D%3B%22sortFilter%22%3A%5B%22obsValue\\_recycling%22%5D%7D](https://www.eea.europa.eu/data-and-maps/daviz/mineral-waste-from-construction-and#tab-googlechartid_chart_13_filters=%7B%22rowFilters%22%3A%7B%7D%3B%22columnFilters%22%3A%7B%7D%3B%22sortFilter%22%3A%5B%22obsValue_recycling%22%5D%7D)
- [33] Puskás, A., Corbu, O., Szilágyi, H., & Moga, L. M. (2014): Construction waste disposal practices: The recycling and recovery of waste. WIT Transactions on Ecology and the Environment, 191, 1313-1321.
- [34] UK statistics on waste - GOV.UK (accessed August 21, 2025)
- [35] [https://www.ekologija.gov.rs/sites/default/files/2022-03/program\\_upravljanja\\_otpadom\\_eng\\_-\\_adopted\\_version.pdf](https://www.ekologija.gov.rs/sites/default/files/2022-03/program_upravljanja_otpadom_eng_-_adopted_version.pdf)
- [36] SKD Türkiye (The Business and Sustainable Development Council, Türkiye) (2024): Guide for the Management of Demolition Waste Resulting from Urban Transformation, Earthquake and Possible Disasters (In Turkish) (accessed July 11, 2024)
- [37] Türkiye Official Statistics Portal (2024). (Under Waste Statistics Tab). Date of Access: 11th July 2024.
- [38] Eurostat (2024): Data on Recycling rate of all waste excluding major mineral waste, (accessed September 2, 2024)
- [39] Republic of Türkiye Ministry of Environment, Urbanization and Climate Change (MEUCC) (2024): Technical Assistance for Development of End-of-Waste Concept in Türkiye. (accessed September 2, 2024)
- [40] Eurostat (2024): Generation of waste-by-waste category, hazardousness and NACE Rev. 2 activity. (accessed September 10, 2024)
- [41] Eurostat (2024): Treatment of waste-by-waste category, hazardousness and waste management operations. (accessed September 10, 2024)
- [42] <https://www.rubicon.com/blog/steel-recycling/> (accessed June 14, 2024)
- [43] Brutting, J., Wolf, C., D., Fivet, C. (2019): The reuse of load-bearing components; SBE19 Brussels BAMB-CIRCPATH, IOP Conf. Series: Earth and Environmental Science 225 (2019) 012025, doi:10.1088/1755-1315/225/1/012025
- [44] Tingley, D., D., Cooper, S., Cullen, J. (2017): Understanding and overcoming the barriers to structural steel reuse, a UK perspective, Journal of Cleaner Production, 148 (2017) 642-652, <https://doi.org/10.1016/j.jclepro.2017.02.006>
- [45] Girao Coelho, A., M., Pimentel, R., Ungureanu, V., Hradil, P., Kesti, J. (2020): European Recommendations for Reuse of Steel Products in Single-Storey Buildings, Provisions for greater reuse of steel structures (Project "PROGRESS"). chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.steelconstruct.com/wp-content/uploads/PROGRESS\_Design\_guide\_final-version.pdf
- [46] <https://asbp.org.uk/wp-content/uploads/2016/08/Barriers-to-structural-steel-reuse-and-means-of-overcoming-them-SCI-Report-1.pdf>. (accessed 9 November 2024).
- [47] Smeets, A., Wang, K., Drewniok, M., P. (2019): Can Material Passports lower financial barriers for structural steel re-use? SBE19 Brussels BAMB-CIRCPATH, IOP Conf. Series: Earth and Environmental Science 225 (2019) 012006, doi:10.1088/1755-1315/225/1/012006.
- [48] [https://www.steelconstruction.info/Recycling\\_and\\_reuse](https://www.steelconstruction.info/Recycling_and_reuse)
- [49] Durmisevic, E., Noort, N.: Re-use potential of steel in building construction, Netherlands, <http://www.irbnet.de/daten/iconda/CIB890.pdf> (accessed June 23, 2024)
- [50] Dai, X., Yang, J., Lam, D., Sheehan, T., Zhou, K. (2022): Experiment and numerical modeling of a demountable steel connection system for reuse; Journal of Constructional Steel Research 198 (2022) 107534. <https://doi.org/10.1016/j.jcsr.2022.107534>
- [51] Tingley, D., D., Allwood, J. (2014): Reuse of structural steel: the opportunities and challenges, Conference paper for European Steel Environment & Energy Congress 2014, 15-17 September, Teeside University UK
- [52] Cervantes Puma, G., C., Salles, A., Turk, J., Ungureanu, V., Braganca, L. (2024): Utilization of Reused Steel and Slag: Analyzing the Circular Economy Benefits through Three Case Studies, Buildings 2024, 14 979. 3390/buildings14040979
- [53] <https://architecturetoday.co.uk/ask-the-expert-steel-reuse/>, (accessed June 22, 2024)
- [54] Pongiglione, M., Calderini, C. (2014): Material savings through structural steel reuse: A case study in Genoa, Resources, Conservation and Recycling 86 (2014) 87-92
- [55] Kanyilmaz, A., Birhane, M., Fishwick, R., Castillo, C. (2023): Reuse of Steel in the Construction Industry:

- Challenges and Opportunities; International Journal of Steel Structures (2023) 23(5):1399-1416.
- [56] Dunant, C., F., Drewniok, M., P., Sansom, M., Corbey, S., Allwood, J., M., Cullen, J., M. (2017): Real and perceived barriers to steel reuse across the UK construction value chain, Resources, Conservation & Recycling, 126 (2017) 118-131
- [57] Dunant, C., F., Drewniok, M., P., Sansom, M., Corbey, S., (2018): Options to make steel reuse profitable: An analysis of cost and risk distribution across the UK construction value chain, Journal of Cleaner Production 183 (2018) 102-111,
- [58] Vares, S., Hradil, P., Sansom, M., Ungureanu, V.: Economic potential and environmental impacts of reused steel structures, Structure and Infrastructure Engineering, Maintenance, Management, Life-Cycle Design and Performance, ISSN: 1573-2479 (Print), 1744-8980 (Online) Journal homepage://www.tandfonline.com/loi/nsie20
- [59] [https://www.istructe.org/journal/volumes/volume-101-\(2023\)/issue-3/reusing-structural-steel-new-istructe-guide/](https://www.istructe.org/journal/volumes/volume-101-(2023)/issue-3/reusing-structural-steel-new-istructe-guide/) (accessed November 12, 2024)
- [60] Yeung, J., Walbridge, S., Hass, C. (2015): The role of geometric characterization in supporting structural steel reuse decisions; Resources, Conservation and Recycling, 104 (2015) 120–130. DOI: 10.1016/j.resconrec.2015.08.017
- [61] Harvey, L., D., D. (2021): Iron and steel recycling: Review, conceptual model, irreducible mining requirements, and energy implications, Elsevier, Renewable and Sustainable Energy Reviews, Volume 138.
- [62] Griffin, P., W., Hammond, G., P. (2021): The prospects for 'green steel' making in a net-zero economy: A UK Perspective, Global Transitions 3, 72-86.
- [63] Kreschel, T., Volkova, O. (2024): Chapter 19 – Steel, Handbook of Recycling (Second Edition) State-Of-the-art for Practitioners, Analysts, and Scientists, 301-318
- [64] Björkman, B., Samuelsson, C. (2024): Chapter 6 - Recycling of Steel, Handbook of Recycling (Second Edition) State-Of-the-art for Practitioners, Analysts, and Scientists, 65-83
- [65] Ghosh, D. (2023): Evaluating Green Steel Production Viability DOI:10.13140/RG.2.2.24406.22088.
- [66] <https://worldsteel.org/steel-topics/raw-materials/>, (accessed, October 15, 2024)
- [67] IRENA 2023: Towards a circular steel industry, International Renewable Energy Agency, Abu Dhabi, ISBN: 978-92-9260-538-4
- [68] Horno, B., P., Feldmann, A., Samuelsson, P. (2025): Mapping the dynamics shaping the future of steel recycling, Discover Sustainability vol 6, art 808, 2025. DOI: 10.1007/s43621-025-01750-4
- [69] Singh, R. (2012): Production of Steel. Applied Welding Engineering, 33–50.
- [70] Kubat, C., Taşkin, H., Artir, R., Yilmaz, A. (2004): Bofy-fuzzy logic control for the basic oxygen furnace (BOF), Robotics and Autonomous Systems 49, 193–205.
- [71] World steel association, Steel and raw materials, <https://worldsteel.org/wp-content/uploads/Factsheet-raw-materials-2023-1.pdf>, (accessed, October 15, 2024)
- [72] Bonapata, J. (2023): What is steel scrap and how can it help us reach net zero? <https://www.weforum.org/agenda/2023/01/davos23-steel-scrap-decarbonization/> (accessed October 13, 2024)
- [73] Metal Recycling Factsheet, EuRIC AISBL – Recycling: Bridging Circular Economy & Climate Policy ([www.euric-aisbl.eu](http://www.euric-aisbl.eu)) (accessed, October 19, 2025)
- [74] World Steel Recycling in Figures 2017-2022, Steel Scrap -Row Material for Green Steel Making, Bureau of International Recycling, Ferrous Division, 13<sup>th</sup> edition.
- [75] <https://worldsteel.org/data/world-steel-in-figures-2024/>, (accessed October 15, 2024)
- [76] James, S. (2022): From Waste to Resource: The Importance and Benefits of Steel Recycling, J Steel Struct Constr 8 (2022): 163.
- [77] Katta, B., Sambandam, M., Premalatha, M. (2025): Life cycle and economic assessment of recycled steel sing waste heat in industry, Journal of Environmental Engineering and Science (2025), <https://doi.org/10.1680/jenes.25.00067>
- [78] Broadbent, C. (2016): Steel's recyclability: demonstrating the benefits of recycling steel to achieve a circular economy, Int J Life Cycle Assess (2016) 21:1658–1665, doi 10.1007/s11367-016-1081-1
- [79] World steel association (2025): Steel – the permanent material in the circular economy, worldsteel-circular-economy, PDF ([decarbonization.unido.org](http://decarbonization.unido.org)), (accessed, October 28, 2025)
- [80] Davis, C., Hall, R., Hazra, S., Debattista, K., Zhuang, S., Duan, J., Li, Z., Shenton, J., Panni, A. Halfpenny, D. (2024): Reuse, remanufacturing and recycling in the steel sector, Philos Trans A Math Phys Eng Sci, 2024 Nov 4;382(2284):20230244. doi: 10.1098/rsta.2023.0244
- [81] Watari, T., Fishman, T., Wieland, H., Wiedenhofer, D. (2025): Global stagnation and regional variations in steel recycling, Resources, Conservation and Recycling, Volume 220, 2025, 108363, ISSN 0921-3449, <https://doi.org/10.1016/j.resconrec.2025.108363>
- [82] Muslemani, H., Liang, X., Kaesehage, K., Ascui, F., Wilson, J. (2021): Opportunities and challenges for decarbonizing steel production by creating markets for 'green steel' products, Journal of Cleaner Production,
- [83] Yan, J., Zhang, Z. (2019): Carbon Capture, Utilization and Storage (CCUS), Applied Energy 235 (2019) 1289–1299, <https://doi.org/10.1016/j.apenergy.2018.11.019>
- [84] Illankoon, C., Vithanage, C., C. (2023): Closing the loop in the construction industry: A systematic literature review on the development of circular economy, Journal of Building Engineering, Volume 76, 2023, 107362,
- [85] Hammerschmid, M., Müller, S., Fuchs, J., Hofbauer, H. (2021): Evaluation of biomass-based production of below zero emission reducing gas for the iron and steel industry, Biomass Conversion and Biorefinery 11:169–187, <https://doi.org/10.1007/s13399-020-00939-z>
- [86] Krueger, A., Andersson, J., Gronkvist, S., Cornell, A. (2020): Integration of water electrolysis for fossil-free steel production, International Journal of Hydrogen Energy, doi:10.1016/j.ijhydene.2020.08.116

- [87] Daehn, K., E., Serrenho, A., C., Allwood, J. M. (2017): How Will Copper Contamination Constrain Future Global Steel Recycling?, *Environmental Science & Technology*, Vol 51/Issue 11, April 26, 2017, doi: 10.1021/acs.est.7b00997
- [88] Boston Consulting Group (2024): Shortfalls in Scrap Will Challenge the Steel Industry, by Janice Lee, Nicole Voigt, Martin Feth & Gaurav Chhibbar. Published March 12, 2024.
- [89] Fischer, L. (2024): Recycling in the steel industry - the environmentally friendly process from scrap to new steel, *Swiss Steel Group Journal*, 29/08/2024, <https://swisssteel-group.com/en/journal/recycling-in-the-steel-industry>
- [90] Bukowski, H., Fabrycka, W. (2023): *Circular construction in practice*, INNOWO, Warsaw, 2019.
- [91] Jackson, A., Brady, C., Owen, C., M. (2023): *The Circular Built Environment Playbook*, World Green Building Council, 2023.
- [92] Rahla, K., Mateus, R., Bragança, L. (2021): Implementing Circular Economy Strategies in Buildings—From Theory to Practice, *Applied System Innovation*, vol. 4, no. 2, p. 26, 2021.
- [93] Guy, B., Ciarimboli, N., Hendrickson, K. (2013): *Design for Disassembly in the Built Environment: A Guide to Closed-Loop Design and Building*, Hamer Center for Community Design, The Pennsylvania State University, Seattle, 2013.
- [94] Little, J., M., K. (2019): *Zero-waste buildings and the circular economy in practice*, 2019.
- [95] Sustainable in Steel (2024): Examples of reuse, [https://www.sustainableinsteel.eu/p/539/examples\\_of\\_reuse.html](https://www.sustainableinsteel.eu/p/539/examples_of_reuse.html)
- [96] Schneider, A., K. (1998): *Creating the Musees d'Orsay the Politics of Culture in France*, Pennsylvania: The Pennsylvania State University Press.
- [97] Wikipedia (2024): Gare d'Orsay, [https://en.wikipedia.org/wiki/Gare\\_d%27Orsay](https://en.wikipedia.org/wiki/Gare_d%27Orsay). (Accessed October 28, 2024).
- [98] Winkelcentrum, B. (2024): De Historie Van Winkelcentrum Brazillie, <https://www.winkelcentrumbrazillie.nl/de-historie-van-winkelcentrum-brazillie/> (accessed October 28, 2024).
- [99] [https://www.sustainableinsteel.eu/p/539/examples\\_of\\_reuse.html](https://www.sustainableinsteel.eu/p/539/examples_of_reuse.html) (accessed, October 19, 2025)
- [100] Godina, M., Gowler, P., Rose, C., M., Wiegand, E., Mills, H., F., Koronaki, A., Ramageb, M., H., Shah, D. U. (2025): Strategies for salvaging and repurposing timber elements from existing buildings in the UK, *Journal of Cleaner Production* 489 (2025) 144629; <https://doi.org/10.1016/j.jclepro.2024.144629>
- [101] Metabolic (2023): Impact scan for timber construction in Europe. <https://globalabc.org/resources/publications/impact-scan-timber-construction-europe>
- [102] Eurostat (2024): Wood products - production and trade - Statistics Explained, [https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Wood\\_products\\_production\\_and\\_trade#Roundwood\\_production](https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Wood_products_production_and_trade#Roundwood_production).
- [103] United Nations Economic Commission for Europe (2023): *Circularity Concepts in Wood Construction*, Geneva Timber and Forest Study Papers, July 2023, ISBN: 9789210024174
- [104] Bergsagel, D., Isaac, P., Koeck, A. (2022): *Reusing Timber in Construction Feasibility Study Exploring Turning Reclaimed Timber into Structural Glulam*. Grimshaw, Simple Works.
- [105] Ahn, N., Dodoo, A., Riggio, M., Muszynski, L., Schimleck, L., & Puettmann, M. (2022): Circular economy in mass timber construction: State-of-the-art, gaps and pressing research needs. *Journal of Building Engineering*, 53, 104562.
- [106] Ridley-Ellis, D., Porter, S. (2025): Planning the reuse or recycling of structural timber in redevelopment projects, a practical guide, ECOS - Environmental Coalition on Standards, Brussels.
- [107] Ikenze, N., Rizos, V., Nipius L. (2024): Improving Waste Wood Circularity in the EU: Classification Frameworks and Policy Options, *Wood2Wood project*, 69p.
- [108] Gregorio, S. (2022): Reuse process for timber elements to optimize residual performances in subsequent life cycles. *VITRUVIO-International Journal of Architectural Technology and Sustainability*, 7(2), 88-99.
- [109] Li, Y., Zhang, X. (2024): Intelligent X-ray waste detection and classification via X-ray characteristic enhancement and deep learning, *Journal of Cleaner Production*, Volume 435, 2024, 140573, ISSN 0959-6526, <https://doi.org/10.1016/j.jclepro.2024.140573>.
- [110] Marques, A., F., S., Martins, C., E., J., Dias, A., M., P., G., Costa, R., J., T., Morgado, T., F., M. (2016): Assessment of Reuse Potential of Maritime Pine Utility Poles for Structural Applications after Removal from Service, *BioResources* 11(4), 9340-9349.
- [111] Kuzman, K., Zbašnik-Senegačnik, M., Kosanović, M., Miloshevska Janakieska, S., Novaković, M., Rajković, N., Grošelj, P. (2024): Architectural Perspectives on Wood Reuse within Circular Construction: A South-Central European Study. *Buildings*, 14(3), 560.
- [112] Höglmeier, K., Weber-Blaschke, G., Richter, K. (2017): Potentials for Cascading of Recovered Wood from Building Deconstruction - A Case Study for South-East Germany. *Resource Conservation and Recycling* 117 (2017): 304-314
- [113] Finch, G., Marriage, G. (2019): Eliminating building and construction waste with computer-aided manufacturing and prefabrication. In *Advances in Informatics and Computing in Civil and Construction Engineering: Proceedings of the 35th CIB W78 2018 Conference: IT in Design, Construction, and Management*, pp. 805-814, Springer International Publishing.
- [114] Llana, D., F., González-Alegre, V., Portela, M., & Íñiguez-González, G. (2022). Cross Laminated Timber (CLT) manufactured with European oak recovered from demolition: Structural properties and non-destructive evaluation. *Construction and Building Materials*, 339, 127635. <https://doi.org/10.1016/j.conbuildmat.2022.127635>.
- [115] Kaltimber (2024): How Reclaimed Wood Helps Reduce CO<sub>2</sub> Emissions, October 7, 2024, (accessed November 27, 2025)
- [116] Agyemang, E., Ofori-Dua, K., Dwumah, P., Forkuor, J., B. (2024): Towards responsible resource utilization: A review of sustainable vs. unsustainable reuse of wood waste. *PLoS ONE* 19(12): e0312527. <https://doi.org/10.1371/journal.pone.0312527>

- [117] Piccardo, C., Hughes, M. (2022): Design strategies to increase the reuse of wood materials in buildings: Lessons from architectural practice. *Journal of Cleaner Production*, 368, 133083. <https://doi.org/10.1016/j.jclepro.2022.133083>
- [118] Reh, R., Kristak, L., Antov, P. (2022): Advanced Eco-Friendly Wood-Based Composites, *Materials* 2022, 15, 8651. <https://doi.org/10.3390/ma15238651>
- [119] Donaldson, J. (2022): The Growth of the Canadian Wood Recycling Industry, 2022. Canadian Wood Waste Recycling Business Group.
- [120] Bohne, R. A., Waerner, E. R. (2014): Barriers for deconstruction and reuse/recycling of construction materials in Norway. *Barriers for deconstruction and reuse/recycling of construction materials* 89-107, CIB publication 397, ISBN 978-90-6363-085-0.
- [121] Earle, J., Ergun, D., Gorgolewski, M. (2014): Barriers for deconstruction and reuse /recycling of construction materials, in Canada, *Barriers for deconstruction and reuse/recycling of construction materials* 20-37, CIB publication 397, ISBN 978-90-6363-085-0.
- [122] Nakajima S., Russel, M. (2014): Barriers for deconstruction and reuse/recycling of construction materials, CIB Publication, Working Commission W115 Construction Materials Stewardship 397 ISBN 978-90-6363-085-0.
- [123] Falk, R. H., Guy, G. B. (2004): *Directory of Wood-framed Building Deconstruction and Reused Building Materials Companies*, 2004 (No. 150). US Department of Agriculture, Forest Service, Forest Products Laboratory.
- [124] Godina, M. (2022): Strategies for salvaging and repurposing timber elements from existing buildings. Elliott Wood Partnership Ltd Strategies, CIOB, UCEM.
- [125] Ottenhaus, L. M., Yan, Z., Brandner, R., Leardini, P., Fink, G., Jockwer, R. (2023): Design for adaptability, disassembly and reuse—A review of reversible timber connection systems. *Construction and Building Materials*, 400, 132823.
- [126] Tsui, T., Venverloo, T., Benson, T., Duarte, F. (2024): Spatial optimization of circular timber hubs. *npj Urban Sustainability*, 4(1), 13.
- [127] Brol, J., Dawczy, S., Adamczyk, K. (2015): Possibilities of timber structural members' reuse. In *Proceedings of the 3rd International Conference on Structural Health Assessment of Timber Structures*, Wroclaw, Poland (pp. 9-11).
- [128] Falk, B. (2002): Wood frame building deconstruction: A source of lumber for construction? <http://www.fpl.fs.fed.us/documnts/pdf2002/falk02a.pdf>
- [129] Junginger, M., Järvinen, M., Olsson, O., Hennig, C., Dadhich, P. (2019): Transboundary Flows of Woody Biomass Waste Streams in Europe. *IEA Bioenergy: Task 40*: 2018: 12.
- [130] Passarelli, R., N. (2019): Environmental benefits of reusable modular mass timber construction for residential use in Japan: an LCA approach. *Modular and Offsite Construction (MOC) Summit Proceedings*, 157-164.
- [131] Zerbe, J., I., Zhiyong, C., Harpole, G., B. (2015): An evolutionary history of oriented strandboard (OSB). *General Technical Report FPL-GTR-236*. Madison, WI: U. S. Department of Agriculture, Forest Service, Forest Products Laboratory. 6 p.
- [132] ETM Recycling (2024): The ultimate guide to wood recycling: <https://www.recyclingbristol.com/the-ultimate-guide-to-wood-recycling/>; (accessed September 17, 2024)
- [133] Nguyen, D., L., Luedtke, J., Nopens, M., Krause, A. (2023): Production of wood-based panel from recycled wood resource: a literature review. *European Journal of Wood and Wood Products* (2023) 81:557–570
- [134] Jimenez, L., F., et al. (2020): A Review on Recycling Waste Wood for Sustainable Construction Materials, *Sustainability*, 2020
- [135] Case Study 0018 (2023): Timber Development UK, Durley Chine Environmental Hub - Commercial & Leisure, Nov. 2023. [www.timberdevelopment.uk](http://www.timberdevelopment.uk)
- [136] Pickering, S., J. (2019): Recycling Technologies for Wood Waste and Fibreboards, *Journal of Material Cycles and Waste Management*, 2019.
- [137] Pazzaglia, A., Castellani, B. (2023): Wood Waste Valorization in Europe: Policy Framework, Challenges, and Decisional Tools, *SNSIM, Procedia Environmental Science, Engineering and Management* 10 (2023) (2) p.345-352
- [138] Faraca, G., Boldrin, A., Astrup, T. (2019): Resource quality of wood waste: The importance of physical and chemical impurities in wood waste for recycling. *Waste Management*, 87, 135-147.
- [139] Bergsagel, D., Isaac, P., Koeck, A. (2022): Reusing Timber in Construction - Feasibility Study Exploring Turning Reclaimed Timber into Structural Glulam, *Circuit Research Paper MS8*: 109p.
- [140] Rose, C., M., Bergsagel, D., Dufresne, T., Unubreme, E., Lyu, T., Duffour, P., Stegemann, J., A. (2018): Cross-Laminated Secondary Timber: Experimental Testing and Modelling the Effect of Defects and Reduced Feedstock Properties. *Sustainability* 2018, 10, 4118. <https://doi.org/10.3390/su10114118>
- [141] UNILIN (2021): <https://www.unilinpanels.com/en/sustainability/wood-revolutions>
- [142] Elginöz, N., Blokland, J., Safarian, S. Movahedisaveji, Z., Yadeta Wedajo, D., Adamopoulos, S. (2024): Wood Waste Recycling in Sweden—Industrial, Environmental, Social, and Economic Challenges and Benefits. *Sustainability* 2024, 16, 5933. <https://doi.org/10.3390/su16145933>
- [143] Bais-Moleman, A., Sikkema, R., Vis, M., Reumerman, P., Theurl, M., Erb, K. (2018): Assessing wood use efficiency and greenhouse gas emissions of wood product cascading in the European Union. *Journal of Cleaner Production*. 2018; 172:3942-54. doi:<https://doi.org/10.1016/j.jclepro.2017.04.153>
- [144] Jahan, I., Zhang, G., Bhuiyan, M., Navaratnam, S. (2022): Circular Economy of Construction and Demolition Wood Waste—A Theoretical Framework Approach. *Sustainability*, 14, 10478. <https://doi.org/10.3390/su141710478>
- [145] Borzecka, M., Fernando, A., L., Costa, J., Boulday, D., Antoine, P., Cocchi, I., Bern, I., Forsgren, H., Detterfelt, L., Supancic, K. (2020): The European wood waste platform: Wood waste recycling for circular bioeconomy; <http://bioreg.eu/platform/>
- [146] *Waste Wood Assessment Guidance for the UK Waste Wood Industry*, Version 3, February 2024, Wood Recyclers' Association, pp. 54, <https://woodrecyclers.org/wp->

- [content/uploads/WRA-Waste-Wood-Assessment-Guidance-V3-Feb-2024.pdf](https://content/uploads/WRA-Waste-Wood-Assessment-Guidance-V3-Feb-2024.pdf)
- [147] Cakaj, A., Hesse, L., Krause, A., Speth, H., Ludtke, J. (2025): Barriers and Potentials for Circular Use of Waste Wood in Construction and Demolition Sector with Special Focus on Germany. *Urban Sci.* 2025, 9, 367. <https://doi.org/10.3390/urbansci9090367>
- [148] Knauf, M. (2015): Waste hierarchy revisited - an evaluation of waste wood recycling in the context of EU energy policy and the European market, *Forest Policy and Economics* 54 (2015) 58–60, <http://dx.doi.org/10.1016/j.forpol.2014.12.003>
- [149] Korba, A., Lekawska-Andrinopoulou, L., Chatziioannou, K., Tsimiklis, G., Amditis, A. (2025): Wood Waste Valorization and Classification Approaches: a Systematic Review, *Open Research Europe* 2025, <https://doi.org/10.12688/openreseurope.18862.2>
- [150] Gedde, K., B., Lamøy, E., Stenstad, A., Müller, D., Ross, L. (2025): Post-consumer wood in Norway: composition analysis and potential for reuse and recycling, *Journal of Material Cycles and Waste Management* (2025) 27:3905–3918, <https://doi.org/10.1007/s10163-025-02306-4>
- [151] Besserer, A., Troilo, S., Girods, P., Rogaume, Y., Brosse, N. (2021): Cascading Recycling of Wood Waste: A Review. *Polymers* 2021, 13, 1752. <https://doi.org/10.3390/polym13111752>
- [152] Rimkiene, A., Vejelis, S., Vaitkus, S. (2025): Analysis and Use of Wood Waste in Lithuania for the Development of Engineered Wood Composite. *Forests* 2025, 16, 577. <https://doi.org/10.3390/f16040577>
- [153] <https://www.sylvagen.co.uk/materials-we-supply-for-recovery-and-recycling/waste-wood-for-processing/> (accessed January 9, 2026)
- [154] Bioenergy insight, <https://www.bioenergy-news.com/news/uk-waste-wood-market-thrives-in-2024/> (accessed December 10, 2025)
- [155] Maier, D.: A Review of the Environmental Benefits of Using Wood Waste and Magnesium Oxide Cement as a Composite Building Material, *Materials* 2023, 16, 1944. <https://doi.org/10.3390/ma16051944>
- [156] Berger, F., Gauvin, F., Brouwers, H., J., H. (2020): The recycling potential of wood waste into wood-wool/cement composite, *Construction and Building Materials* 260 (2020) 119786, <https://doi.org/10.1016/j.conbuildmat.2020.119786>
- [157] <https://www.nibio.no/en/news/educating-professionals-on-the-reuse-of-woodNorway>, (accessed January 9, 2026)
- [158] PUUWOOD (2024): Towards an economically viable use of recycled wood, <https://puuinfo.fi/2024/06/18/towards-an-economically-viable-use-of-recycled-wood/?lang=en>, (accessed April 17, 2025)
- [159] <https://www.tomra.com/waste-metal-recycling/media-center/news/2022/extending-the-lifecycle-of-wood-from-forest-to-products>, (accessed December 30, 2025)
- [160] Buschalsky, F., Y., B., Mai, C. (2021): Repeated thermo-hydrolytic disintegration of medium density fibreboards (MDF) for the production of new MDF, *European Journal of Wood and Wood Products* (2021) 79:1451–1459. <https://doi.org/10.1007/s00107-021-01739-6>
- [161] Yespayeva, A., S., Altayeva, Z., N., Sarsenbayev, B., K., Karshyga, G., O., Sauganova, G., R. (2020): Lightweight materials based on wood waste, *IOP Conference Series: Materials Science and Engineering* 945 (2020) 012030, doi:10.1088/1757-899X/945/1/012030
- [162] <https://natural-resources.canada.ca/forest-forestry/forest-industry-trade/wood-plastic-composites>, (accessed January 2, 2026)
- [163] MDF recovery London, UK, <https://www.mdfrecovery.co.uk/> (accessed January 2, 2026)
- [164] <https://www.steelconstruct.com/eu-projects/advance/> (accessed June 27, 2024).
- [165] Yu, Y., Yazan, D., M., Junjan, V. Iacob, M., E. (2022): Circular economy in the construction industry: A review of decision support tools based on Information & Communication Technologies, *Volume 349, 2022, Journal of Cleaner Production*, vol. 349, p. 13133, 2022.
- [166] Illankoon, C., Vithanage, S., C. (2023): Closing the loop in the construction industry: A systematic literature review on the development of circular economy, *Journal of Building Engineering*, vol. 76, p. 107362, 2023.
- [167] Historical Changes to Steel Bridge Design (2021): Composition, and Properties, Publication No. FHWA-HRT-21-020. 2021, Federal Highway Administration (FHWA), Research, Development, and Technology Turner-Fairbank Highway Research Center
- [168] Villalobos, J., C., Del-Pozo, A., Campillo, B., Mayen, J., Serna, S. (2018): Microalloyed Steels through History until 2018: Review of Chemical Composition, Processing and Hydrogen Service, *Metals* 2018, 8(5), 351; <https://doi.org/10.3390/met8050351>
- [169] Structural steel reuse (2019): Assessment, testing and design principles, Publication Number: SCI P427, Steel Construction Institute, 2019. ISBN 13: 978-1-85942-243-4
- [170] American Iron and Steel Institute and Steel Manufacturers Association (2021): Technical Report “Determination of Steel Recycling Rates in the United States”, July 27, 2021, (accessed October 31, 2025)
- [171] Agyemang, E., Ofori-Dua, K., Dwumah, P., Forkuor, J., B. (2024): Towards responsible resource utilization: A review of sustainable vs. unsustainable reuse of wood waste, *PLoS ONE* 19(12): e0312527. <https://doi.org/10.1371/journal.pone.0312527>
- [172] EN 1090-2:2024, Execution of steel structures and aluminium structures - Part 2: Technical requirements for steel structures.
- [173] Bartsch, H., Eyben, F., Voelkel, J., Knobloch, M., Feldmann, M. et al., Guidance on establishing European rules for the design of reclaimed steel components for reuse, DENTON, S. (editor), Publications Office of the European Union, Luxembourg, 2025, <https://data.europa.eu/doi/10.2760/9138843>, JRC144410.
- [174] CEN/TC 135 (2024): CEN/TS 1090-201:2024 - Execution of steel structures and aluminium structures - Reuse of structural steel. European Committee for Standardization, Brussels.