D3.5: Circular economy approach to building stock decarbonization

The role of construction and demolition waste

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AB	Apartment Blocks
C&DW	Construction and Demolition Waste
CE	Circular Economy
EPBD	Energy Performance of Buildings Directive
EU	European Union
EWC	European Waste Catalogue
GWP	Global Warming Potential
GHG	Greenhouse gas
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
MFH	Multifamily House
SFH	Single-Family House

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Executive Summary

BuiltHub H2020 European project aims to create a dynamic EU building stock knowledge hub. By linking the potential data sources and the building-related policy and business, the project explores the benefits of developing community-enhanced data-driven applications.

The aim of Task 3.5 was to review available data and information that can inform and support circular economy strategies (CE) and practices in the construction sector to be included in the data hub. In particular, the work focus on material recovery and recycling of Construction and Demolition Waste (C&DW).

Estimating the material flows and material recovery rates associated with the EU building sector is fundamental to analyse the environmental impact of the building industry. By understanding the potential environmental and economic implications of recovering and recycling C&DW from the EU building stock, it is possible to support the development and implementation of new eco-design tools based on life-cycle approaches like life-cycle assessment (LCA) and life-cycle costing (LCC). According to the obtained data and information, valuable insights can be gained for assessing the environmental and economic impacts related to current and future material flows in the EU building stock. Moreover, this knowledge can aid in the effective prevention and management of C&DW, contributing to sustainable practices within the construction industry.

Two case studies are presented to show how the data collected can be used to support sustainable practices:

- Case Study I quantifies the C&DW volumes per member state and evaluates the potential for recovery of waste and potential savings (benefits) of such recovery in terms of environmental impacts and costs. Lastly, potential opportunities and challenges of CE practices in the EU building stock are discussed.
- Case Study II provides a comprehensive analysis of the construction materials utilized in various building components, such as floors, roofs, walls, windows, and insulation layers, within the residential building stock of the EU27 countries. These results enable policymakers to assess the current status of the residential building sector, evaluate the potential of CE strategies, and facilitate the identification of new opportunities.

Overall, the application of LCA and LCC methodologies to assess and compare the performances of recycled materials demonstrated the feasibility of achieving both environmental benefits and economic profitability. However, to fully capitalize on these advantages, it is crucial to improve material recovery and minimize the use of virgin resources by implementing dedicated Circular Economy (CE) strategies. By following this approach, a more sustainable building industry can be achieved.

1. Introduction

This report summarizes the work carried out within Task 3.5 of the project, entitled “Circular economy for contributing to building stock decarbonization”. The objective of this task was to provide relevant data and information that can inform and support circular economy strategies and practices in the construction sector, to include in the BuiltHub database. Such data and insight have a focus on material recovery and recycling of Construction and Demolition Waste (C&DW).

In this context, technical and economic data related to C&DW and its potential use have been included in the data hub. Such data, described here, include estimates of material flows associated with the EU building stock, material recovery rates, and potential environmental and economic costs and benefits of recovering and recycling C&DW from the EU building stock. The data provided aims at supporting further analyses, as well as the development and application of new eco-design tools based on life-cycle approaches, such as life-cycle assessment (LCA) and life-cycle costing (LCC). Ultimately, the data and information can contribute with valuable insight for the assessment of environmental and economic impacts of current and future material flows associated with the EU building stock, and the prevention and management of C&DW.

The report discusses possible circular economy strategies and measures for reducing carbon emissions associated with the EU building stock; it reviews existing datasets, describing the data and indicator selection to be integrated in the BuiltHub dataset; and it provides two case studies.

The first case study illustrates an application of the data to estimate and characterize: (i) C&DW volumes per member state, (ii) potential for recovery of waste (through re-use, re-manufacturing, and recycling), and (iii) potential savings (benefits) of such recovery in terms of environmental impacts and costs. Lastly, it briefly discusses potential business model innovations within a CE perspective, and challenges and opportunities for improving monitoring and evaluation of CE practices in the EU building stock.

The second case study provide a comprehensive analysis regarding the construction materials utilized in various building components, such as floors, roofs, walls, windows, and insulation layers within the residential building stock of the EU27 countries. The obtained data enables policymakers to assess the status of the residential building sector, evaluate the potential of CE strategies at the national level, and conduct lifecycle assessments (LCAs) to measure the environmental impact of building practices. Ideally, these data can facilitate the identification of new opportunities and encourage further research to explore the potential of specific CE strategies, ultimately fostering the adoption of less environmentally impactful building practices and contributing to a more sustainable future for the building industry.

In Chapter 2, a review of the concept of Circular Economy in the building sector is provided. In Chapter 3, datasets and indicators that can support CE in the EU building stock are reviewed and analysed. In Chapter 4, the two case studies are presented. Finally, in Chapter 5, conclusions are summarized.

2. Circular economy in the built environment

Waste, as defined by the Article 3(1) of the Directive 2008/98/EC on Waste [1], is composed by “any substance or object which the holder discards or intends or is required to discard”. In 2018 all the economic activities and households within the European Member States produced about 2337 million tons of waste [2]. Construction and demolition waste represent a significant part of the total that was quantified in about 36% in 2018 [2].

The management of this amount of waste can generate a significant pollution and can be characterized by serious environmental impacts. The EU policies therefore aim at reducing the environmental and health impacts of waste and improving the EU resource efficiency.

The EU principles about waste management are based on a hierarchy that establishes which are the preferred program priorities based on sustainability. This hierarchy is usually presented graphically in the form of a pyramid where the most favoured options are located on the top and the least favourable ones are positioned on the base.

The first solution indicated by the pyramid regards waste prevention and after that waste minimization. In practice, it implies sharing, leasing, reusing, repairing, and refurbishing existing materials and products as long as possible giving them a second life. When it is not possible, recycling is considered as the first alternative. Energy recovery follows in case of materials or products that can be incinerated for energy production purposes and that upgrade the less inefficient incinerators. Disposal or landfill is the last preferable option of the pyramid.

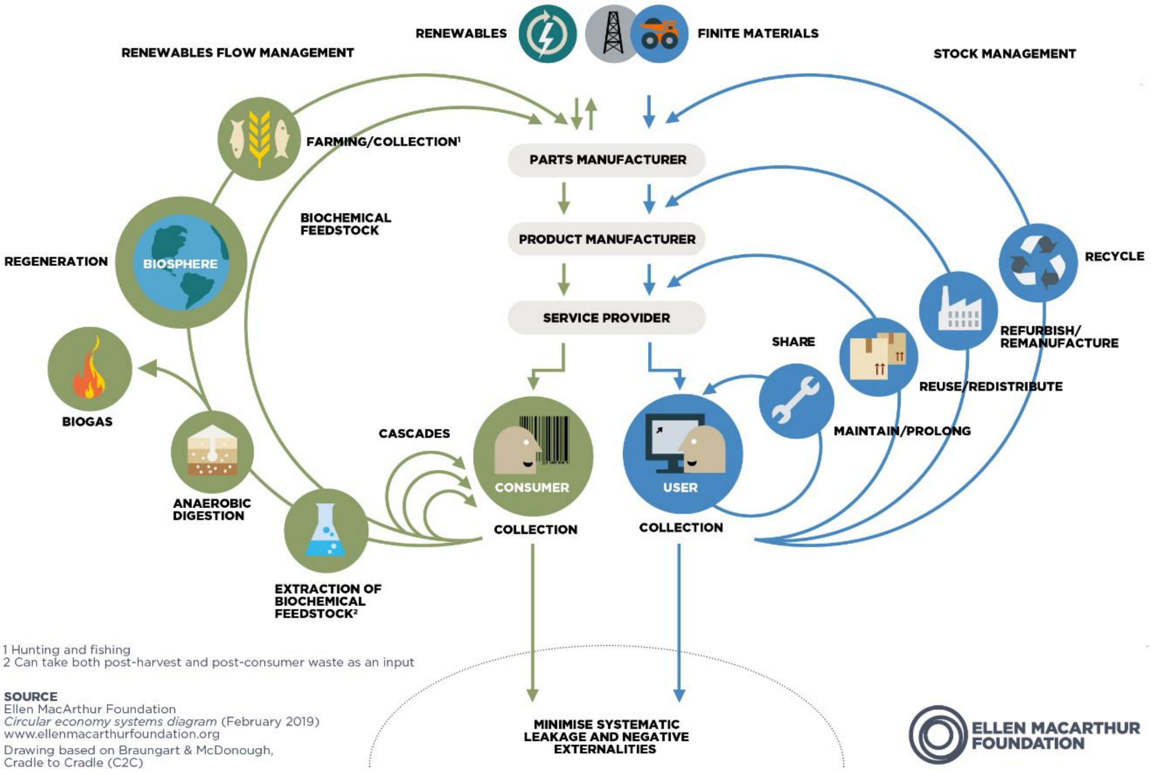
The EU waste management scheme is centred on the concept of the “circular economy” of technical cycles that is based on the central principle of maintaining the value of products, materials, and resources in the economy for as long as possible, by returning them into product cycles at the end of use, thus minimizing waste generation. In the last couple of decades, the Circular Economy (CE) emerged as a quite new paradigm in opposition to the current Linear Economy cantered, instead, on a unidirectional economic model where the waste was considered an output of the system. The definitions given about CE are quite various on the basis of official bodies, nongovernmental organisms, as well as scientists and professionals that have already proposed them. The Box displays the definition of CE given by the European Commission in its first action plan towards the adoption of circular economy strategies.

Circular Economy: EU definition

“a production and consumption model which involves reusing, repairing, refurbishing, and recycling existing materials and products to keep materials within the economy wherever possible. Waste will itself become a resource, consequently minimizing the actual amount of waste. It is generally opposed to a traditional, linear economic model, which is based on a ‘take-make-consume-throw away’ pattern.”

Box 1: Definition of Circular Economy given by the European Commission in 2015 [3].

In order to describe better the concept of CE the Ellen McArthur foundation proposed a butterfly diagram (see Figure 1) that illustrates the continuous flow of technical and biological materials through the 'value circle'. The diagram shows on the left side the biological cycle and on the right side the technical cycle. The technical cycle is characterized by different sub-cycles that represent the already cited waste management alternatives: sharing to increase costumers' utilization, reuse, refurbish/maintain, recycle. The biological cycle reports all the streams of biological materials (such as food, textiles and clothing) that can return to a natural system in regenerating circles restoring the natural capital. With anaerobic digestion, for example, we can obtain fertilizers, that can return to a natural agricultural system, as well as energy. As regards high quality clothing, instead, the waste can be reused for different purposes in a sort of cascade after the extraction of their biological feedstock: cleaning products, wipes, stuffing of car seat and insulation materials.



1 Hunting and fishing
2 Can take both post-harvest and post-consumer waste as an input

SOURCE
Ellen MacArthur Foundation
Circular economy systems diagram (February 2019)
www.ellenmacarthurfoundation.org
Drawing based on Braungart & McDonough,
Cradle to Cradle (C2C)

Figure 1: Butterfly diagram of Ellen MacArthur foundation [4].

To achieve this, integrated measures and actions are required, not only at the end-of-life, but across all the stages of the products' lifecycle. Indeed, early stages can play a significant role in the transition to a circular economy: improved design and production processes are essential to increasing resource efficiency and to reduce inefficient waste management practices.

The adoption of circular economy opens up new avenues for business such as waste recycling and resource recovery, and alternatives for products and services that have a higher ecological footprint. Moreover, they can create new job opportunities that can lead to enhanced productivity. Many companies and startups are realizing the potential of these opportunities and are coming forward with new business models to suit the requirements of the future market trends.

C&DW are defined by the European Directive 2018/851 [5] as waste that derive from activities of construction and demolition including works on the private residential sector, educational buildings, hospitals, commercial and industrial sectors, and public procurements (included the project and maintenance of infrastructures). In general, the C&DW is composed by a mixture of different materials such as concrete, bricks, glass, wood, metals, gypsum, and plastic but also hazardous substances such as asbestos and lead.

The application of CE in the construction sector follows the EU management scheme represented by the pyramid of waste (see **Figure 2**) through the minimization of rubble and the recycle of the materials that can be separated.

Figure 2: The pyramid of waste (Waste Framework Directive).

2.1 CE initiatives and policies in the EU

The Circular Economy is within key EU policy priorities in order to address sustainable development [6] with a particular focus on high resource-intensive and high-impacts sectors such as the construction one. The effort in the promotion of circular economy is strongly linked with the EU objectives on climate change and energy efficiency and with the Commission package on 'Clean Energy for all Europeans' [7]. This is particularly the case of biomass by products that can be converted efficiently into energy or used in place of energy intensive materials.

The circular economy is also instrumental in supporting the EU commitments on sustainability, as outlined in the Communication ‘Next steps for a sustainable European future’ [8]. In particular, the principles of CE are evoked to reach the Sustainable Development Goal 12 'Responsible consumption and production': reducing waste generation through prevention, reduction, recycling, and reuse; achieving the environmentally sound management of all wastes throughout their life cycle. The Ecodesign directive [9] furthermore reinforces the focus of policy on products realized within a circular economy framework that employs secondary materials, by-products, and wastes. These “sustainable practices” are promoted in the market through the adoption of green labels and labelled products should also be supported in public procurement practices.

In 2015, the European Commission (EC) adopted the “Circular Economy Package”, including an ambitious EU Action plan [3] for the CE, which established measures covering the whole life-cycle of products: from production and consumption to end-of-life, and a market for secondary raw materials, together with a new legislative proposal on waste management. The plan aimed at enabling the EU transition to a CE, boost competitiveness, foster sustainable economic development and generating new jobs. The “Circular Economy Package” is a sort of watershed in the management of waste: what was previously considered as an “output” is transformed into a valuable resource that should remain into the economy as long as possible.

A series of product specific waste management measures is detailed for five priority sectors: plastics, food waste, critical raw materials, construction and demolition, and biomass and bio-based products.

C&DW is one of them and its management is considered a priority by the CE package and three potential measures are indicated to guarantee adequate level of resources recovery:

- Guidelines for pre-demolition and deconstruction,
- Development of a voluntary protocol for recycling,
- Design of a framework of key indicators for the environmental assessment of buildings and development of incentives for their diffusion.

The pre-construction phase is considered important as well since the design should be focused on durability and disassembly. Disassembly, in fact, can facilitate the separation of the materials during the demolition stage avoiding less-efficient processes of differentializing of the rubble.

In 2016 the European Commission, with the involvement of the Demolition Association, published the EU Construction and Demolition Waste Management Protocol [10] that represents the first guideline for C&DW management. The protocol is part of the CE Package, and its main aim is to increase confidence in the C&DW management process and the trust in the quality of Construction and Demolition recycled materials. This goal can be achieved by:

- Improved waste identification, source separation, and collection
- Improved waste logistics
- Improved waste processing
- Quality management
- Appropriate policy and framework conditions

The recovery target that was set by the Commission to be reached by 2020 is equal to 70%. Currently, most EU countries have reached this target and, in some cases, by more than 20 percentage points [11]. However, different factors (e.g., non-unified methods of data collection, different waste coding systems and misinterpretations of the term ‘backfilling’, etc.) could have significantly influenced the outcomes; a more standardized methodology should be considered for the next years to improve datasets and enhance comparability at the EU level [12].

Starting from 2015 and then with the 2019 Action Plan [13], the European Commission proposed a comprehensive body of legislative and non-legislative actions which aimed at the transition of the European economy from a linear one to a circular model.

Recently the new Circular Economy Action Plan [14] is a cornerstone of the EU Green Deal, the EU's most recent commitment toward sustainable development. The new action plan will promote circularity principles throughout the lifecycle of buildings by:

- introducing some recycled content requirements for certain construction products,
- promoting measures to improve the durability and adaptability of built assets,
- considering a revision of material recovery targets,
- promoting the use of Level(s) tool to assess the environmental performance of the built environment,
- promoting initiatives to reduce soil sealing, rehabilitate abandoned or contaminated brownfields.

Different projects about CE in the construction sector have already been promoted and financed by the EU. The H2020 project *Building As Materials Banks* (BAMB) [15], for example, joined 15 partners from 7 countries of the EU that worked together with one mission: enabling a systemic shift in the building sector by creating circular solutions. The project focused on how to increase the value of construction materials and how to extend their durability in time. The vision was to transform the building stock in "materials banks", thus a stock of valuable materials in place of potential generator of waste. BAMB developed electronic *Material Passports,* as a set of data that describe the relevant characteristics of materials giving them a higher potential and value favouring their recovery and reuse. The BAMB *Material Passports* aimed at:

- Increasing (or maintaining) the values of materials, products, and components in time,
- Incentivizing the producers to manufacture building products that are sustainable and circular,
- Favouring the choice of construction materials in case of high circularity production chains,
- Improving the logistics and distribution of circular products.

Another interesting database that develops material passports is Madster [16]. This online library entails information about the materials and products that are part of the buildings and infrastructure objects that are registered on the platform. The information provided includes mass quantities, circularity indexes, embodied carbon and presence of toxic substances.

2.2 Monitoring and evaluating CE practices

Almost all the European countries reached the target established by the Union in 2020 with percentages of C&DW recovery that, sometimes, highly exceeds the 70% (see Figure 5).

This may suggest that the European construction sector is highly circular, as it reintroduces large percentages of its waste into the economy by avoiding disposal options such as incineration and landfilling. Nevertheless, due to historical building practices and the absence of high-purity material generation during demolition, the material flows resulting from demolition and requalification activities are currently not appropriate for immediate reuse or closed-loop recycling. This hampers the full implementation of circular economy in the construction sector.

Moreover, the high recovery results are often met with low-grade utilization of waste materials. Backfilling is the most diffused scenario for the end-of-life of rubble and it reduces the potential of a management of C&DW that is really circular. The real challenge regards the maintenance of the economic value and of the intrinsic quality of the waste materials as long as possible. A particular attention should be paid to the difference between the economic values during the use phase and the re-use one. An efficient recovery, reuse or recycle of C&DWs consists, for example, in the transformation of them into virgin secondary materials that can be reused in construction products.

Monitoring the C&DW management practices provides insight on ongoing trends, and it is important to keep track of the progress made and of the effectiveness of implemented strategies and policies. Therefore, it can be useful for a range of economic actors.

The European Commission is going to revise the target about C&DW recovery within the end of 2024 by setting reuse and recycling targets for C&DW and its material-specific fractions [5]. The EU is also incentivizing the diffusion of platforms for the reuse and recycle with the objective of sustaining an internal market of secondary materials.

2.3 CE for building stock decarbonization

The construction sector is responsible for approximately 40% of EU energy consumption and 36% of the greenhouse gas emissions within the European Union [17]. Buildings are therefore the single largest energy consumers in Europe.

The effort in reducing the environmental impacts of the building sector is manly focused on the containment of the operational energy requirement of the constructions: different authors, in fact, have already demonstrated that, in traditional constructions, the operational impacts are dominant in the entire life cycle [18]. The building stock realized before the advent of legislation about energy efficiency is characterized by high energy intensities, low renewable energy coverage and, consequently, high carbon emissions.

This impulse push towards energy efficiency, together with the increase in renewable energy coverage, has recently brought to a stringent legislation about the energy performance of the new constructions: the EPBD recast [17], for example, imposed that all new buildings realized after 2021 should guarantee a “nearly Zero” balance between the energy exported and imported from the external distribution grids.

The minimization of the operational components, however, may cause a burden shifting of the environmental impacts on other life cycle stages, such as the ones regarding the production of building components and the extraction of raw materials they are composed of. In order to verify the overall environmental benefit considering all the rebound effects, the adoption of a life cycle approach is strongly recommended.

If the buildings’ life span is considered equal to 50 years, new constructions may be characterized by embodied impacts that represent the 45-50% of the total [18]. The reduction of the embodied components of the overall life cycle environmental impact of constructions becomes very important and the adoption of CE strategies to achieve this goal is surely one of the pathways to go through.

Currently, the adoption of a life cycle approach is recommended by a lot of EU funded projects which aim at extending the Energy Performance Certificates (EPCs) of buildings with new indicators encompassing different life cycle stages [19]. The European framework for sustainable buildings (LEVELs [20]) encourages the adoption of a life cycle approach providing a set of indicators and common metrics for measuring the sustainability performance of buildings. The adoption of reused or recycled materials is also awarded by a lot of buildings building certification schemes (LEED, BREAM, ITACA Protocol, CasaClima Nature, …). CasaClima Nature, for example, attributes scores for the use of materials that have a low content of non-renewable energy, low acidification, and greenhouse gas potential. Moreover, bonus scores are provided if the materials employed are regional produced or achieved a third-party ecological certification. The use of recycled or secondary materials is both able to reduce the environmental footprint of virgin products and to guarantee local resources as input for the production system. Their diffusion in the design of new buildings would generate a further reduction of the embodied impacts connected to the constructions, facilitating the achievement of higher scores in the protocols aiming at evaluating the sustainability of the building sector.

Bearing in mind the importance of considering a cradle-to-cradle life cycle approach, this task aims at offering access to pertinent data for policy makers and other stakeholders in relation to the materials stored in the building stock, their recovery potential and the related environmental benefits. This information can support the decision-making and progress monitoring of CE strategies and practices in the EU building stock.

3. Materials and methods

This section reviews and analyses existing datasets and indicators that can support CE in the EU building stock. In particular, it describes the materials and methods used to analyse the EU building stock including:

1. estimating and characterizing C&DW across EU member states;
2. estimating potential for the recovery of waste (re-use, re-manufacture, recycle);
3. estimating potential savings (benefits) of recovery in terms of environmental impacts, based on life-cycle assessment and cost analysis.

3.1 Data sources and indication selection

This section reports the databases containing data about waste statistics in Europe that were considered for the development of the Task 3.5 of the BuiltHub project. In particular, relevant data and indicators about C&DW were reviewed and integrated in the project contents. The selection was based on the publicly available data shared by governmental or scientific institutions and is not intended to be exhaustive.

- **Eurostat EW MFA accounts**

Economy-wide material flow accounts (EW-MFA) [21] provide an aggregate overview, in thousand tons per year, of the material flows into and out of an economy (see Figure 3).

Material inputs into national economies include domestic extraction of materials originating from the domestic environment and physical imports originating from other economies. Material outputs from national economies include materials released into the domestic environment (e.g., emissions into air, water, and soil) and physical exports to other economies. EW-MFA cover solid, gaseous, and liquid materials, except for bulk flows of water and air while material flows within the economy are not considered in EW-MFA.

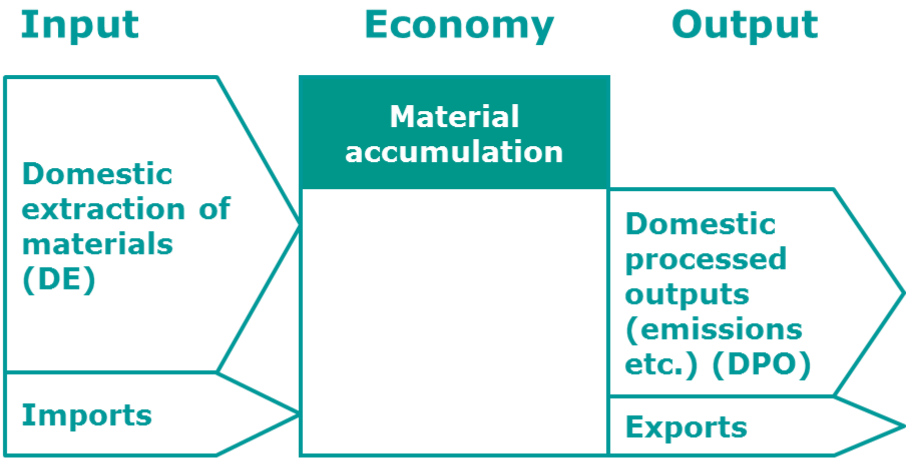


Figure 3: Economy-wide material flow accounts (EW-MFA) balance [21].

The EW MFA statistics also provide some indicators about CE in the EU.

The circular material use rate (CMU), also called 'Circularity rate', measures in percentage the share of material recycled and fed back into the economy in the overall material use. The Circularity rate is defined as the ratio of the circular use of materials (U) to the overall material use (M). The U is calculated from the sum of the amount of waste recycled in domestic recovery plants (RCV_R), minus imported waste destined for recycling (IMPw), plus exported waste destined for recycling abroad (EXPw). The M, instead, is equal to the sum of the domestic material consumption (DMS) and U.

$$CMU = \frac{U}{M} = \frac{(RCV\_R - IMP_w + EXP_w)}{DMC + (RCV\_R - IMP_w + EXP_w)}$$

Figure 4 shows the CMU rates for Italy, for Netherland (that is the best performing country in Europe) and the average values for the EU countries. Table 1 displays the CMU rate by material type (biomass, metal ores, non-metallic minerals, fossil energy materials/carriers).

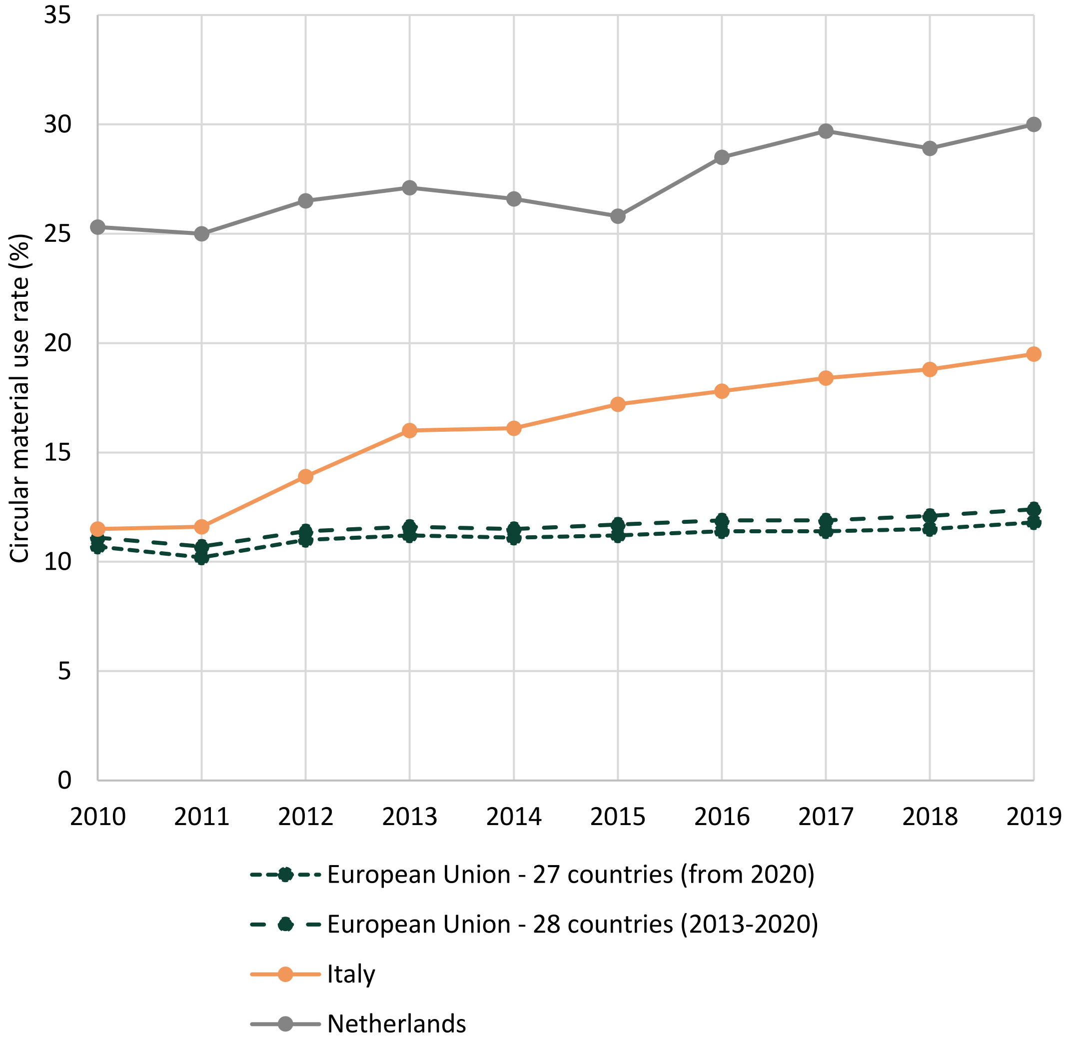


Figure 4: Circular material use rates for EU countries, Italy, and Netherlands [21].

Table 1: Circular material use rate (%) by material type and year - average data EU 28.

MATERIAL/TIME	2017	2018	2019
Total	11.9	12.1	12.4
Biomass	8.8	9.0	9.2
Metal ores (gross ores)	26.2	25.9	27.1
Non-metallic minerals	15.8	15.6	15.7
Fossil energy materials/carriers	2.5	2.5	2.7

- **Eurostat Waste statistics**

The Eurostat Dissemination Database is regularly updated with the most recent data on the generation and treatment of waste in Europe. It provides statistics collected under the Waste Statistics Regulation as well as data collected for key waste streams under thematic reporting obligations on waste [22].

The total amount of mineral waste from construction and demolition activities in 2018 in EU 27 was equal to 303 170 000 tons; in Italy, in the same year, the total amount of mineral C&DW was equal to 41 265 790 tons of which 242 747 (0.59%) tons were hazardous waste.

Eurostat also published some waste-related indicators about material prices for recycles since understanding how the price of recycled materials changes over time is an important aspect of waste management. The prices are based on the data provided by the Foreign Trade Statistics (FTS) that publish monthly, with a delay of approximately 3.5 months and since 2004, reliable information about the volumes (tons) and values (€) of some waste materials such as glass, paper, and plastics. The waste materials considered, aggregated by FTS codes, range from lower value post-consumer to higher priced and well-defined residues from manufacturing processes.

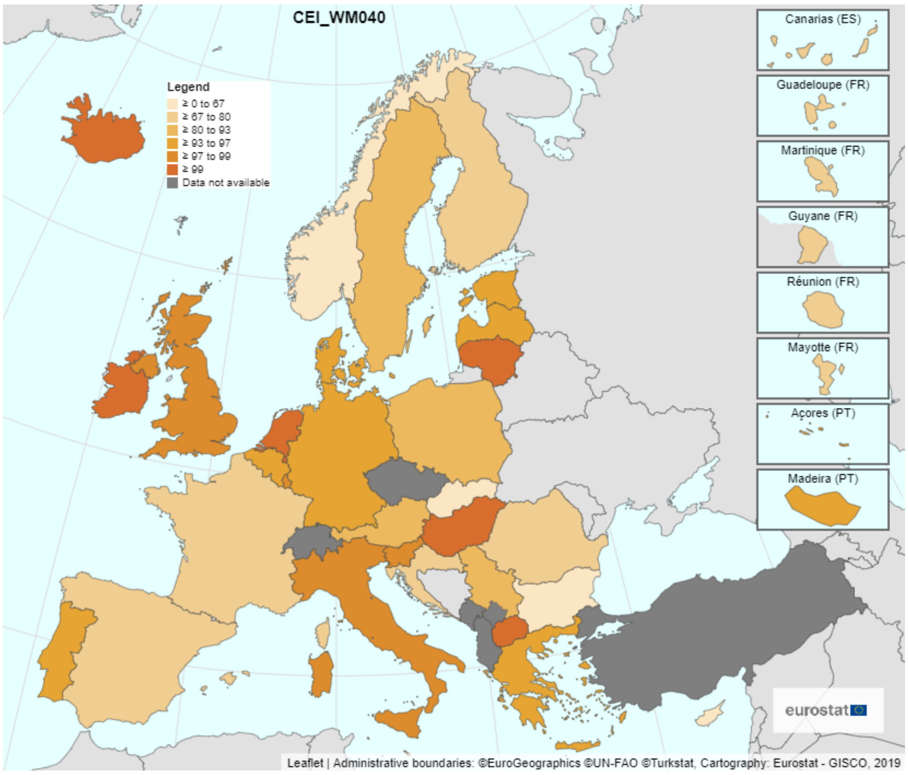
The primary indicator is the specific price per ton of traded volume (€/ton). The average values of monthly prices for 2019 were 52.3 €/ton (glass), 114.1 €/ton (paper) and 316.0 €/ton (plastics). An additional indicator is the total volume (import and export) of the 3 traded waste materials reported in (tons/month). It shows the activity of the market and covers intra- and extra-trade in EU-28.

- **Eurostat: Recovery rate of construction and demolition waste**

Eurostat provides some statistic data about the recovery rate of C&DW in all EU countries [23]. This indicator is determined as the ratio between construction and demolition waste, which is prepared for re-use, recycling or subject to material recovery, including backfilling operations, and the construction and demolition waste treated as defined in Regulation (EC) No 2150/2002 on waste statistics. The indicator covers the waste category 'Mineral waste from construction and demolition' (EWC-Stat 12.1). Only non-hazardous waste is taken into account.

As already stated in the previous sections, the values reported for each member state are sometimes much over the target of 70% recovery rate that represented the goal for 2020. Italy, for example, showed a recovery rate of 98% in 2018.

At the same time, also average values are very high in comparison with the 2020 target: in 2018 they were equal to 88% for EU 27 and 90% for EU 28. Figure 5 shows the C&DW recovery rates in EU countries in 2018.



Leaflet | Administrative boundaries: ©EuroGeographics ©UN-FAO ©Turkstat, Cartography: Eurostat - GISCO, 2019

Figure 5: C&DW recovery rates in EU countries in 2018.

- **International resource panel (IRP) report and database on resource efficiency**

The International Resource Panel (IRP) produced a report on resource efficiency in 2020 [24]. The report discusses the reuse potential rates of a range of construction components indicating, after a literature review, what are the materials with no potential (0%), low potential (<50%), medium potential (~ 50%) and high recovery potential (>50%).

- No potential: clay bricks (cement-based mortar), steel rebars and connections, structural concrete, asphalt, plastic pipes (water and sewage), plastic roof sheets, plastic floor mats, electric-cable insulation, plastic windows, concrete (pipes and drainage, water treatment and storage tanks and sea and river defence units), non-ferrous metal components (aluminium window frames, curtain walling, cladding, copper pipes, zinc sheets for roof cladding).
- Low potential: mineral wool, gypsum wallboard, steel rebar in pre-cast concrete, structural steel, timber trusses, concrete in-situ, concrete (fencing, cladding, staircases, and stair units), glass components (windows).
- Medium potential: steel cladding, steel cold formed sections, steel pipes, pre-cast concrete, slate tiles, timber floorboards,
- High potential: clay bricks (lime-based mortar), steel rebar, structural steel, concrete building blocks, concrete paving slabs and crash barriers, clay roof tiles, concrete (fencing, cladding, staircases, and stair units), stone paving, stone walling.

The report shows how the establishment of stringent policies about the management of C&DW can generate high recovery rates: eight years after enacting the Japanese Construction Material Recycling Law, recycling rates of 99.5% for asphalt concrete, 99.3% for concrete and 99.4% for wood were reached in the country largely through the usage of the recycled concrete as aggregate for road-building. Similarly, high recovery rates were detected in the Netherlands, Denmark and Germany following the institution of landfill bans on recyclable material and high landfill taxes.

- **Scientific literature on waste recovery factors**

Scientific literature has already studied extensively the circularity level of the materials that can be separated from C&DW. After the revision of some works [20–21], the most common utilization of C&DW that were detected are the following:

- Concrete: the rubble is crushed and the resulting material is used as backfilling in roads foundations. The percentage of materials that can be separated from rubble is between the 79-84% and the recovery rate is over 90%. Carbon benefits of recycling concrete are often small and are sensitive to the distance to the site of use.
- Brick and mineral materials: the waste material is crushed and used in lower-grade filling applications. The recycling percentages in Italy are equal to 97.4% (the remaining part is mainly landfilled – 2.2%- and backfilled – 0.4% [27]).
- Wood: wooden waste material is usually burned with energy recovery. Alternatively, if the quality of the source is high, it can be used to manufacture different kinds of wooden panels: particle boards, wooden fibreboards, or strand boards.
- Insulation materials: the percentages of recovery of these kinds of products are very low (1.5% for Wiprächtiger et al. [25]). The materials of organic fossil origin can be incinerated with energy recovery.
- Plastic materials: high levels of recovery are possible in case of materials that contain polyethylene, polypropylene, polystyrene, and PVC. These materials must, however, be adequately separated and cleaned-up because the recycle is very complex in presence of contaminants. The presence of pure materials in the rubble is not common. A certain quantity of virgin materials must be added in the recycling process to obtain adequate performances of the final recycled products. Their content of recycled is generally equal to 70% or higher.
- Metals: the main metals that can be recovered from construction and demolition activities are steel and aluminium. Both steel and aluminium can be characterized by high percentages of material recycling that can arrive at 95-99% and that guarantee high environmental benefits.
- Glass: the glass elements can be recycled with percentages of efficiency of about 70-85%. If windows are disassembled without damaging the glass parts, they can be directly reused. Otherwise, the glass can be recovered for the production of insulation panels (in glass fibres) and, if reduced in fine elements, as a filling material in concrete production. Coarser elements can be used as an aggregate for concretes and asphalts.
- Photovoltaic panels: waste material from photovoltaic systems is expected to rise during the following years. Significant quantities of glass, silicon and aluminium can be

recovered from dismantled panels. Furthermore, mono-crystalline, and polycrystalline cells can be recovered to produce new recycled photovoltaic material.

- Asphalt: 50% of asphalt waste can be used for the production of new asphalt, containing 10–15% recycled asphalt added to new asphalt. The remaining broken part can be bonded with cement and used in place of sand in recycled asphalt paving.

- **C&DW characterization**

The European Waste Catalogue (EWC) is the official classification of wastes adopted by the European Commission with the decision 2000/532/EC2. It is divided into twenty main chapters, each one described by a two-digit code between 01 and 20. Most of the chapters are industry-based but there are some of them which are based on materials and processes. Within these, there are codes for individual wastes that are characterized by a six-figure number. Hazardous wastes are signified by entries where the code is followed by an asterisk. Chapter 17 includes C&DW flows that are described in the different sub-chapters.

Even if this is the official classification, literature works sometimes adopt their own customized classification to provide information about the composition of C&DW. The data that were declared in the literature studies analysed are displayed in Table 2.

Table 2: C&DW composition based on scientific literature [23–26].

	[32]	[33]	[34]	[35]	[29]	[30]	[31]
Minerals	58.3%	84.3%	85.0%	67.24%	-	58.0%	86.24%
Concrete	-	-	-	-	58.86%	17.0%	-
Bricks	-	-	-	-	29.26%	8.0%	-
Mortar	-	-	-	-	9.83%	-	-
Metals	8.3%	0.08%	1.8%	3.63%	2.05%	0.5%	13.0%
Timber	8.3%	-	11.2%	14.58%	-	8.0%	0.5%
Plastic	0.83%	-	0.2%	-	-	-	0.05%
Asphalt	10.0%	6.9%	-	-	-	-	-
Insulation	-	-	-	-	-	8%	-
Glass	-	-	-	-	-	0.5%	0.21%
Other	14.2%	8.8%	1.8%	14.55%	-	-	-

As it can be noted, the C&DW is mainly composed of mineral materials (concrete, bricks, tiles and ceramics, stones, mortars, gypsum boards); sometimes the amount of concrete and bricks is distinguished from the overall mineral waste since the mechanical performance of the recycled material derived can be of a higher grade. The amounts of metals and timber that can be derived strongly depend on the typology of the load bearing structure and on the construction techniques that are diffused in a specific geographic area.

Asphalt is another material that can be separated in significant quantities from C&DW. The amount that is derivable is higher in case of demolition of infrastructures (roads, streets, parking area, airports, …) than in the case of buildings where it is sometimes used in roofs and floorings.

Finally, few quantities of glass, plastics, insulation materials and other materials can be obtained from demolition rubble.

- **Evaluating climate change benefits**

The environmental benefits deriving from the recycle of C&DW materials were determined using LCA methodologies. The LCA is a technique that allows to assess environmental impacts associated with all the life cycle stages of a product, which range from raw material extraction through materials processing, manufacturing, distribution, use and end-of-life. The application of LCA in the building sector has already been standardized by the EN 15978 of 2011: in particular, the standard defines which are the life cycle stages that should be included in a comprehensive LCA study of a building (see Table 3). This study, instead, focuses only on the end-of-life phase (stage C1-C4) and on the benefits that are achievable through the reuse, recovery and recycling of the materials that can be obtained from C&DW.

Table 3: Buildings LCA stages.

LCA Phases																				
Product Stage			**Const. Stage**		**Use Stage**							**End of Life Stage**				**Benefits and Loads beyond the System Boundary**			
Raw Materials Supply	Transport	Manufacturing	Transport	Construction	Use	Maintenance	Repair	Replacement	Refurbishment	Operational Energy	Operational Water	Demolition	Transport	Waste Processing	Disposal	Reuse	Recovery	Recycling	Exported Energy
A1	**A2**	**A3**	**A4**	**A5**	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**	**C1**	**C2**	**C3**	**C4**	**D**			

Some robust life cycle databases were considered in this study as the sources of the background data. Since the interest of the projects is in climate change impacts and GHG emissions reduction, we considered the Inventory of Carbon and Energy database [36] at first. The ICE Database is a cradle to gate data resource (module A1 to A3) and the benefits linked to future life cycles (such as recycling ones) are beyond the scope of the database. However, some important information about recovery rates and recycling benefits is provided by the entries in ICE database, in particular for those materials that have a high GWP benefit from recycling. The information gathered is reported in Table 4.

Table 5 shows the same contents but derived from alternative sources such as literature studies and other LCA databases. One of them is Ecoinvent [37] that is one of the most robust, transparent, and widely used background database for life cycle inventory all over the world. It contains a lot of information about the different environmental impacts that can characterize a production process or the provision of a service.

The benefits obtainable from the recovery of C&DW materials are rather small because of the non or low recyclability of some materials (e.g., insulation materials, gypsum boards), or because of the low/negligible benefits related to the recycling process of mineral materials (e.g., concrete, bricks).

High potential benefits can instead be reached for metals, particularly in case of aluminium and steel. However, the amount of metals that can be separated from C&DW is quite low.

Table 4: Recovery rates and related carbon benefits, ICE database [36].

	EOL scenario	Recovery rate	Recovery benefit
Aluminium General, EU Mix, Inc Imports	Recycled	95%	-3.13 kg CO_2eq/kg
Aluminium General, Worldwide	Recycled	83%	-8.69 kg CO_2eq/kg
Aluminium, produced in Europe	Recycled	83%	-3.64 kg CO_2eq/kg
Steel, Wire rod	Recycled	85%	-1.15 kg CO_2eq/kg
Steel, Section	Recycled	85%	-0.34 kg CO_2eq/kg
Steel, Rebar	Recycled	85%	-0.79 kg CO_2eq/kg
Steel, Engineering steel	Recycled	85%	+0.31 kg CO_2eq/kg
Timber - Average	Energy recovery	100%	~ 0 kg CO_2eq/kg
Timber - Average	Reuse	100%	-1.52 kg CO_2eq/kg
Glass	Downcycled	0%	-

Table 5: Recovery rates and related carbon benefits, literature data.

Reference	Material	EOL scenario	Recovery rate	Recovery benefit
[28] ecoinvent	Concrete	Recycling	100%	+0.00591 kg CO_2eq/kg
[24] Wang	Steel	Recycling	-	-1.811 kg CO_2eq/kg
[24] Wang	Concrete	Recycling	-	+0.00483 kg CO_2eq/kg
[24] Wang	Bricks	Recycling	-	+0.03222 kg CO_2eq/kg

The recycling of hard wood for panels fabrication is interesting as well for the benefits deriving from the avoided deforestation. The data collected do not permit a correct modelling of the end-of-life scenarios because the characteristics of wooden material that is part of the rubble are not detailed. A distinction between pure or treated wood and between virgin or already-recycled wood in the C&DW should be provided for a more comprehensive analysis of the environmental benefits that can be obtained from the recycling scenarios that can be supposed.

4. Case studies

4.1. Case study I: Assessing the economic and environmental benefits of C&DW recycling

In this first case study, we evaluated the aggregated economic and environmental benefits that might be achieved in each EU member state by using recycled C&DW for backfilling in place of virgin material. A more detailed evaluation will be performed in the next case studies, where more specific data on the EU building stock will be considered in order to provide a deeper estimation of the different material flows characterizing C&DW. The topic is recently acquiring a significant interest because of the huge amount of C&DW that is generated annually in developed countries and because of the intense turnover that the European building stock is experiencing as a result of the “renovation wave” that aims at increasing energy efficiency while facilitating the transition to clean energy.

The study then combines the Eurostat data about C&DW generation across EU member states with their recovery rate and provides an estimation of the potential savings in terms of GHG emissions and costs that can be obtained from the recycling.

The case study focuses only on the 'Mineral waste from construction and demolition’ as defined by the European Waste Classification for Statistics (EWC-Stat 12.1). It includes materials such as concrete, bricks, tiles and ceramics, gypsum, insulations, track ballast deriving from construction and demolition activities. Only non-hazardous waste is considered: the material does not contain oil, heavy metals, coal tar, organic pollutants, or asbestos. The origin of the material is both from building and civil engineering works. On the contrary, it excludes solid waste from soil remediation, soils and stones, insulation and construction materials containing asbestos, waste containing PCB, pure and sorted fractions of glass. The C&DW mineral material is mainly recovered for backfilling operations.

4.1.1. Materials and methods

In the proposed study, a combination of different methodologies was applied to evaluate the GHG and economic performances of the C&DW recycling systems: in particular, life cycle assessment (LCA) was used to evaluate climate change impacts, and life cycle costing (LCC) was used for measuring the costs. The methodology applied is structured as follows:

- Estimating the C&DW generation across EU member states;
- Estimating the recovery rate of C&DW across EU member states;
- Estimating the potential savings (benefits) of the recovery of C&DW in terms of climate change impacts and costs, applying life-cycle assessment methodologies and cost analyses.

The background data concerning the amount of C&DW produced in European countries as well as its recovery rate (Rr) were derived from the Eurostat Dissemination Database. The case study is based on the most recent year-to-date data available, therefore referred to 2018.

Concerning the climate change impact, the evaluation is based on the application of the LCA methodology that makes use of the single-issue indicator IPCC GWP 100y. No other impact categories were taken into consideration for the scopes of the analysis. Ecoinvent v3.8 was used as the background database. The functional unit that was chosen is equal to 1 ton of generated C&DW. The transportations were not included in the calculations. The boundaries of the analysis are displayed in Figure 6. Following the 'polluter pays' principle, the impacts linked to the demolition phase are not allocated to the recycled material. The 'polluter pays' principle is the commonly accepted practice that attributes to the producer of the waste the environmental costs of managing it to prevent damage to human health or to the environment. By that way, in this study, the C&DW material is considered burden free.

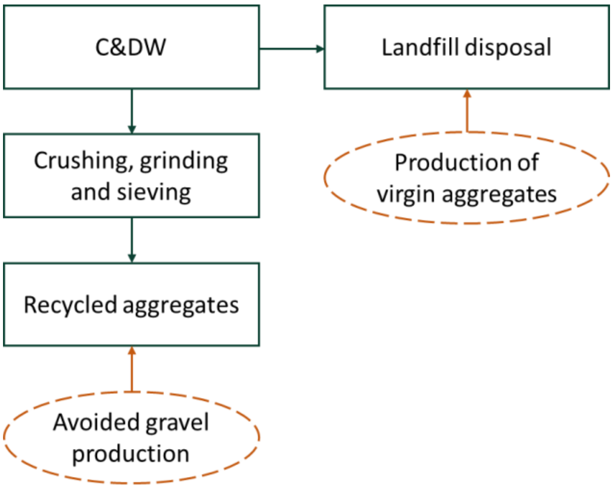


Figure 6: Processes included in the analysis.

The following equation was employed for the calculation of the total GHG savings (GWP_{sav} in kg CO_2eq/ton) due to the use of recycled material in place of the virgin one:

$$GWP_{sav} = \sum_i m_{C\&DW,i} \; Rr_i \, Rf \, (GWP_{rec} - GWP_{nat})$$

where GWP_{nat} (kg CO_2eq/ton) is the Global Warming Potential of 1 ton of natural virgin aggregates, GWP_{rec} (kg CO_2eq/ton) is the Global Warming Potential of 1 ton of recycled material, $m_{C\&DW}$ is the mass (in tons) of C&DW produced in the member state I, Rr (%) is the recovery rate of C&DW in the country i and Rf is the recovery factor of the recycling process, that is supposed to be equal to 90%. Ecoinvent v3.8 [37] is the main source of data to model the GWP of natural and recycled aggregates.

The costs are instead derived from national price lists [38] or from literature works [29–31]. The following equation was used for the calculation of the total cost savings ($Cost_{sav}$ in €/ton) due to the use of recycled material in place of the virgin one:

$$Cost_{sav} = \sum_i m_{C\&DW,i} \; Rr_i \, Rf \, (Cost_{rec} - Cost_{nat} - Tax_{disp,i})$$

where Tax_{disp} (€/ton) is the disposal tax applied by the European country (i).

The resulting recycled aggregates, produced starting from 1 ton of mineral C&DW, are composed by inerts with different granular size (sand, gravel, clay, other sediments, …). In particular, for the calculation of the CO_2 and costs savings, average values were calculated for the following typologies of aggregates:

- Sand: rock fragments or mineral particles that range in diameter from about 1/16 to 2 mm;
- Gravel: chipped or rounded rock fragments that typically range in diameter from about 3 to 75 mm;

The packaging of the material was not considered in the calculations while bulk material is accounted.

4.1.2. Results

The Eurostat dissemination database reported a production of about 364 million of tons of mineral non-hazardous waste from construction and demolition. Considering the recovery rate of the different countries and the efficiency of the recycling facilities about 295 million of tons of recycled aggregates can be produced starting from the C&DW generated by all the member states.

The application of LCA provided the amount of CO_2 (in kg) that is saved in the case of using recycled material in place of virgin aggregates in backfilling operations. The calculated saving was equal to 2.10 kg CO_2eq/ton of C&DW: this value is quite similar to the one that is provided by other literature works [39]. The total saving is mainly related to the avoided production of natural aggregates and to the un-subsistence of the related mining activities: the C&DW material is, in fact, considered as a burden free input since the impacts of the demolition phase are allocated outside the waste management process to the producer of waste.

The total GHG savings for each member state are shown in Figure 7: they strongly depend on the amount of C&DW generated in each country (see secondary axis on the right of the plot) and on their recovery rate for C&DW. Due to their substantial amount of C&DW and high recovery rate, countries such as Germany, UK, France and Italy display the highest savings. This result is definitely correlated with the amount of built assets (buildings and infrastructures) that are present in each country and with the construction or renovation activities that are in place. The total savings that are obtainable in Europe consist of about 644 million of kg CO_2eq (512 million of kg CO_2eq excluding the UK).

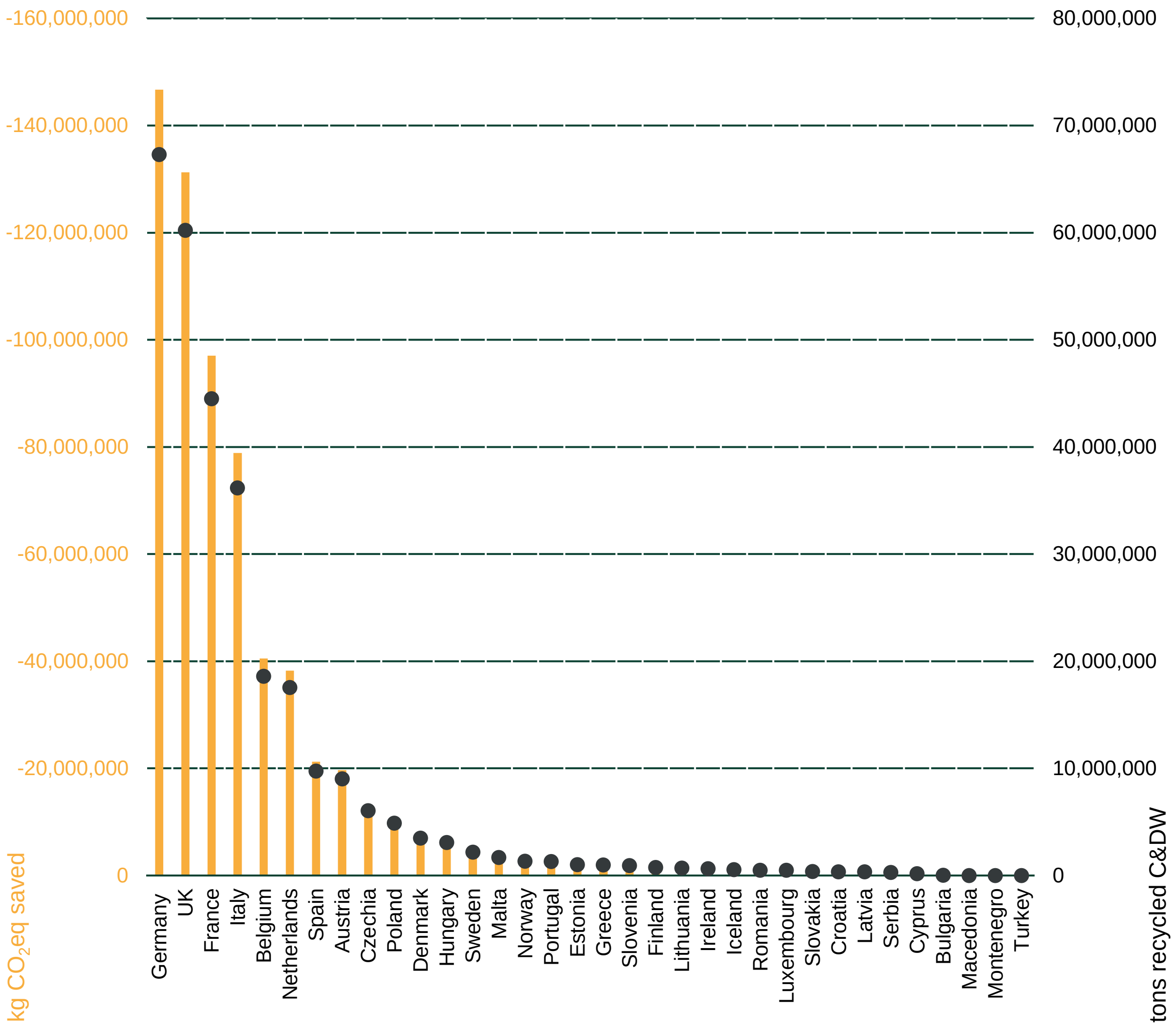


Figure 7: Total GHG emissions saving from the recycling of C&DW.

Considering the economic aspects, Dahlbo et al. [39] reported a saving of 1.50 €/ton due to the use of recycled material and the avoided production of quarry aggregates. This value is quite low if we consider that Giorgi et al. [40] reported the prices shown in Table 6 for natural and secondary materials. Moreover, the consultation of the Italian national price list permitted to calculate an average value of 1.90 €/ton; to adopt a reliable value, that remains in favour of security, we considered the lowest value found that was equal to 1.50 €/ton.

Generally, the recycling is hindered by the cost of C&DW disposal that is quite cheap: in Italy, for example, according to the Italian law 549/1995 the landfill cost ranges from about 1€/ton to 10€/ton, based on the different Regions. That is why some European countries set up a taxation scheme for the disposal of C&DW material: the tax applied in each country for ton of C&DW material is reported in Table 7 and it was derived from the work of Osmani and Villoria-Sáez [41].

Table 6: Selling prices for natural and recycled inert material in Italy [40].

Activity	Price €/ton
Selling of secondary material	3-7 €/ton secondary inert aggregate for road substratum
Selling of natural sand	15 €/ton
Selling of natural gravel	10 €/ton
Transportation until 50 km	6 €/ton
Cost of disposal	1-10 €/ton

Table 7: Tax for C&DW disposal in some EU member states [41].

Country	Tax for C&DW €/ton
Austria	9.20
Belgium	56.05 – 113.01
France	30.00
Germany	-
Lithuania	3.00
Netherlands	13.11
Poland	33.00
Portugal	4.27
Slovakia	0.33
Slovenia	2.2
Spain	0.5 - 4

The total cost saving that is obtainable without considering landfill taxation is equal to 443 million of Euros (352 million of Euros excluding the UK). The total cost savings for each member state are reported in Figure 8. As it can be noted, some countries show a very low total cost savings due to the limited amount of produced and recycled C&DW while Turkey and Montenegro are characterized by a null value because they do not report any amount of C&DW in 2018. If taxation is excluded, the cost savings are proportional to the CO_2 savings reported in the previous plot. The taxation makes the difference being able to hugely influence the savings achievable through recycling: France, Belgium, Netherland and Poland, that are characterized by a high landfilling taxation, become the countries where recycling generates the highest economic benefits.

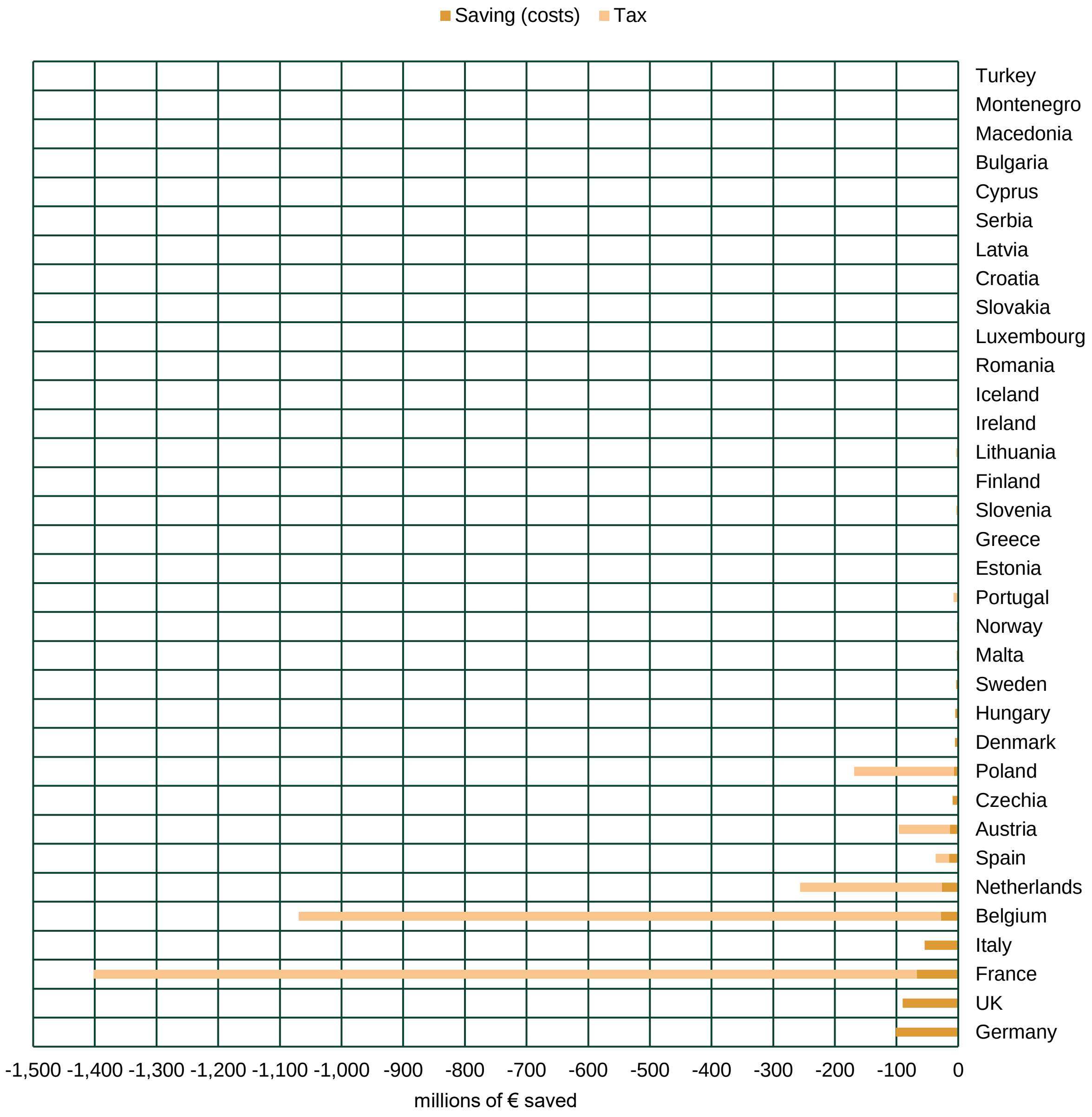


Figure 8: Total cost saving from the recycling of C&DW.

Since both carbon and cost savings are correlated with the amount of built assets that are part of the building stock of a country, we employed BuiltHub data about the total surface of residential and service buildings to normalize the Eurostat data on C&DW production. The results are displayed in Figure 9, and referred only to EU27 countries. Looking at the carbon savings, some countries show values that are above the EU27 average. This result can be linked to the higher renovation and demolition rate that characterizes the building stock in these countries: for instance, France and the Netherlands have already been identified by other sources [42] as the EU countries with the most prominent rates of building stock renovation. However, the data used in this case study are referred only to 2018 and should not be generalized. Concerning cost savings, landfilling taxation plays a crucial role in determining the economic competitiveness of recycling: countries such as Belgium, Austria, Poland, France are, in fact, characterized by values that are sensibly over the EU27 average.

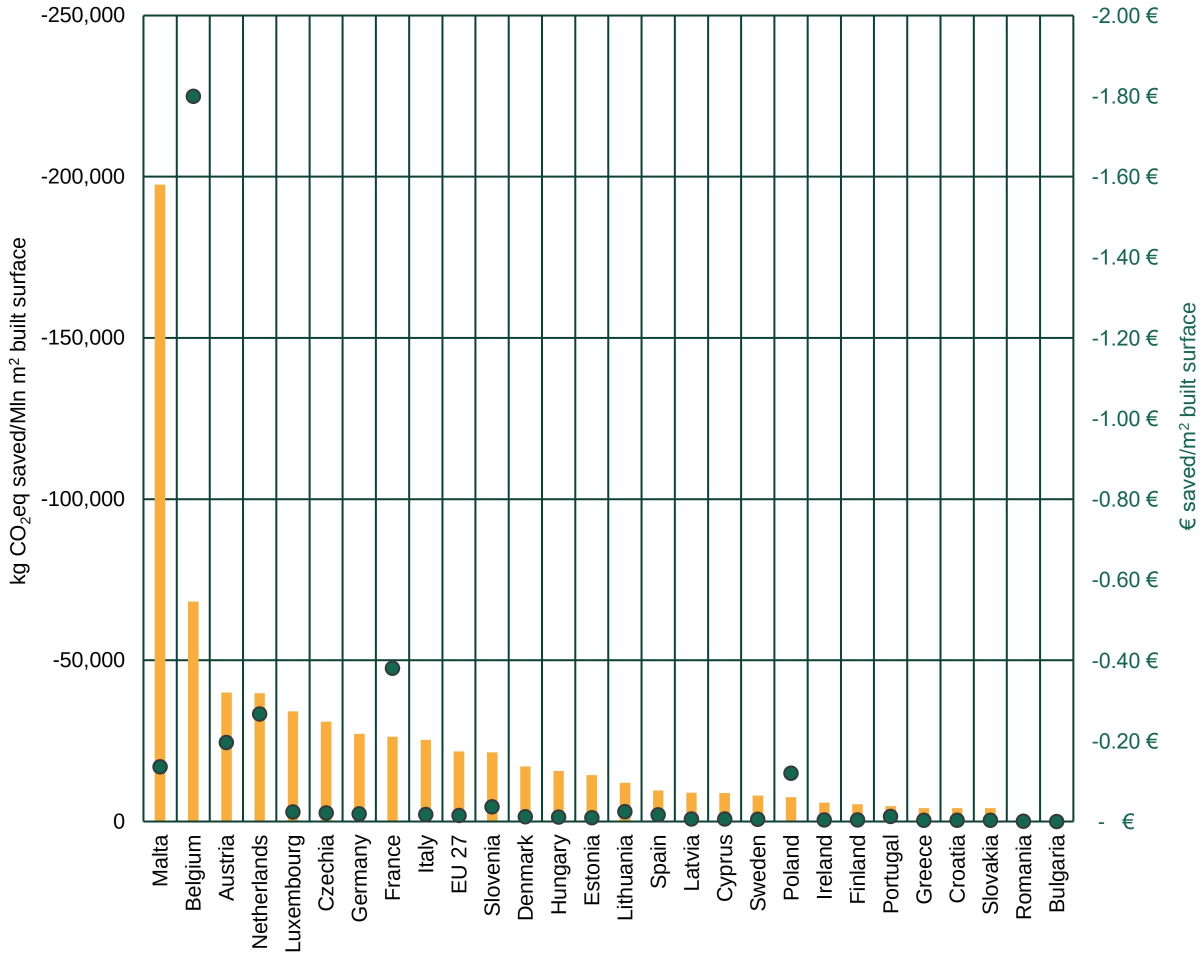


Figure 9: CO_2 (left axis) and cost savings (right axis) normalized per built surface.

4.1.3. Conclusions

This first case study aimed at evaluating the GHG emissions and cost savings due to the use of recycled aggregates in place of virgin ones in backfilling operations. LCA and LCC methodologies were applied to accomplish the objectives of the evaluation and to compare the performances of recycled and virgin aggregates.

According to the results, the recycling of C&DW produced environmental benefits and was economically profitable. The recycling, in fact, can avoid the production of virgin aggregates with the related quarrying and mining activities that represent a significant source of environmental impact and economic expenses in the whole life cycle of natural inerts. Remaining in favour of security, the economic and environmental benefits were quantified respectively in about 1.5-1.9 €/ton and 2.10 kg CO_2eq/ton.

The competitiveness of the recycling is however hindered by the low price of raw materials that are not so expensive to stimulate the secondary aggregates request (about 10-15€/ton depending on the granularity). The competitiveness of recycling could be increased by raising the price of primary raw materials or through landfill taxation. Addressing this issue, different EU countries have already introduced a taxation scheme for landfilling of C&DW making recycling much more attractive.

Given the small benefits obtainable through C&DW recycling, the increase in the transportation distances can lead to the neutralization of the economic and environment gains of recycling: longer transportation distances, in fact, mean higher environmental impacts and higher costs for bringing C&DW to recycling facilities. Moreover, in particular for medium or small demolition works that generate a little amount of waste, a long distance to a treatment plant leads to prefer landfill in case of closer landfilling sites.

Further analysis should be performed if recycled aggregates are employed for the production of other building materials, such as concrete, or for the other C&DW material flows such as wood, metals, plastics, and paper. The recovery of metals to avoid virgin material consumption, for example, can generate more important benefits in terms of GHG emissions and costs per ton of recycled material. The energy valorisation of the wooden material that has not a commercial value can be very interesting as well. Finally, the direct reuse of some C&DW materials (old bricks, tiles, wooden elements,) in new buildings or in refurbishments can be a very competitive solution from both the economic and the environmental perspectives.

Even if it provides a valuable general overview of the potential environmental and economic savings achievable through the recycling of the mineral C&DW, this case study suffers from several limitations. The definition of an averaged cost saving coefficient for all the EU countries, for example, does not take into account the different local market conditions that contribute to define the price of C&DW debris. Since transportation distance plays a crucial role in determining the recycling potential of C&DW, more specific local data are needed to provide the right spatial granularity to analyse the economic and environmental savings of building aggregates recycling.

4.2. Case study II: Assessment of building materials in the European residential building stock[1]

In this second case study, we provide a detailed analysis of the available materials in the residential building sector for all 27 European Union countries. The analysis quantifies the usage of various materials for the following building elements: floors, roofs, walls, windows, and insulation layers. Moreover, detailed results are provided differentiating among different residential building types (i.e., single-family houses, multifamily houses, and apartment blocks) and construction periods. These results form the basis for policymakers to monitor the current state of the residential building sector, evaluate the potential of CE policies at a national level, and assess the environmental impact of building practices through lifecycle assessment.

4.2.1. Materials and methods

This study combined and elaborated the data coming from H2020 Hotmaps [43] and H2020 AmBIENCe [44] EU projects:

- H2020 Hotmaps provides data [45] regarding the characteristics of the entire EU27 building stock (i.e., number of buildings, floor area, energy consumption, etc.). The reference year of the Hotmaps dataset is 2016 and all the details about data collection and elaboration are provided in the deliverable available online [46]. From Hotmaps, the number of buildings for each EU27 country according to the different building types and construction periods was considered.
- H2020 AmBIENCe provides data [47] regarding the dynamic thermal behaviour of building stock segments' reference building for the entire EU27 building stock. The reference year of the AmBIENCe dataset is 2021 and all the details about data collection and elaboration are provided in the deliverable available online [48]. From AmBIENCe, the values regarding the reference building characteristics for each EU27 country according to the different building types and construction periods were considered. These include the type of material and the volume of the different building elements (i.e., floors, roofs, walls, windows, and insulation layers).

The EU27 residential building sector was analysed considering three different building types: Single-family houses (SFHs), Multifamily houses (MFHs), and Apartment blocks (Abs - high-rise buildings that contain several dwellings and have more than four storeys). Moreover, seven different construction periods were defined:

- Before 1945. Buildings constructed before 1945 are generally classified as historic buildings;

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[1] This case study is adapted from the scientific paper Zandonella et al. (2023) funded by the H2020 BuiltHub EU project. This scientific paper was published as part of the activities of WP3. Full reference:

Zandonella Callegher, C.; Grazieschi, G.; Wilczynski , E.; Oberegger, U.F.; Pezzutto, S. Assessment of Building Materials in the European Residential Building Stock: An Analysis at EU27 Level. Sustainability 2023, 15, 8840. https://doi.org/10.3390/su15118840

- 1945-1969. Buildings erected after World War II and before 1969 are generally characterized by nearly missing insulation and inefficient energy systems;
- 1970-1979. Buildings built between 1970 and 1979 present the first insulation applications;
- 1980-1989 and 1990-1999. Buildings constructed during these two periods reflect the introduction of the first national thermal efficiency ordinances (around 1990);
- 2000-2010. Buildings considered to be influenced by the impact of the EU Energy Performance of Buildings Directive (2002/91/EC and following recasts [49]);
- Post 2010. The present analysis contains data updated until the year 2016.

The material volumes for the different building elements were computed according to the following equation:

$$Element\ Volume\ [m^3] = Element\ Area\ [m^2] \times\ Element\ Thicknes\ [m].$$

Note that in the case of floors volume, the total floor area was obtained by multiplying the ground floor area by the number of storeys. Moreover, in the case of windows, two values were computed considering window glazing and window frame separately.

Subsequently, to characterize each building element in terms of its material composition, material mass was calculated according to the following equation:

$$Element\ Mass\ [kg] = Element\ Volume\ [m^3] \times\ Density\ Element\ [kg/m^3].$$

In Table 8, the materials available in the AmBIENCe dataset are listed together with the respective labels used in the present study. Note that window material is not specified in AmBIENCe but is expected to be glass. Moreover, the materials utilized for the insulation layers were categorized into three distinct groups: “Fossil”, “Mineral”, and “Composite” [50].

Table 8: Material labels conversion

AmBIENCe	Present Study
Element materials	
Precast concrete (dense - exposed)	Concrete
Precast concrete (dense - protected)	
Cast concrete 2000	
Concrete block (dense - protected)	
Brick, fired clay	Brick
Limestone Granite	Limestone
Granite, red	Granite
Sandstone	Sandstone
Oak, beech, ash, walnut	Wood
Maple, oak, and similar hardwoods	
Wood	
Aluminium	Aluminium
Plastic	Plastic
Steel	Steel
	Glass

Insulation materials	
Polystyrene expanded Polyurethane foam Urea formaldehyde resin foam	Fossil
Mineral wool Rock wool Perlite board expanded Asbestos fibre	Mineral
Cement fibre slabs shredded wood	Composite

All data manipulations and statistical analyses were performed using R Programming Language (V4.2.1) [51]. All scripts are available at https://doi.org/10.5281/zenodo.7984727.

4.2.2. Results

Aggregated results at the EU27 level are presented separately for each different building element. Quantification of materials used in the construction of floors according to the different building types and construction periods are reported in Table 9, whereas percentages are presented in Figure 10.

Table 9: Quantification of floor materials, expressed in 1,000 kg, at EU27 level according to building types and construction periods.

Material	Before 1945	1945 – 1969	1970 – 1979	1980 – 1989	1990 – 1999	2000 – 2010	Post 2010
Single-family houses							
Concrete	7,226	11,947	9,179	9,743	12,961	16,482	12,189
Granite	1,062						
Limestone	2,116	2,174	1,742	2,071	2,071	2,071	
Wood	622	406	59			103	69
Multifamily houses							
Brick	5,189						
Concrete	28,538	81,579	69,161	32,315	47,472	65,481	55,552
Limestone	4,161	4,161					
Wood	1,414	1,417	1,185	1,706	2,579	2,503	1,386
Apartment blocks							
Brick	18,826	2,350					
Concrete	64,160	156,818	213,071	191,060	260,955	395,688	274,309
Wood	475	411	330	688	1,275	5,618	3,583

Results clearly indicate how concrete is by far the most used material for all building types and construction periods. Overall, concrete represents more than 95% of all materials used in the construction of floors. Considering other materials, each one covers around 1% of the total floor materials.

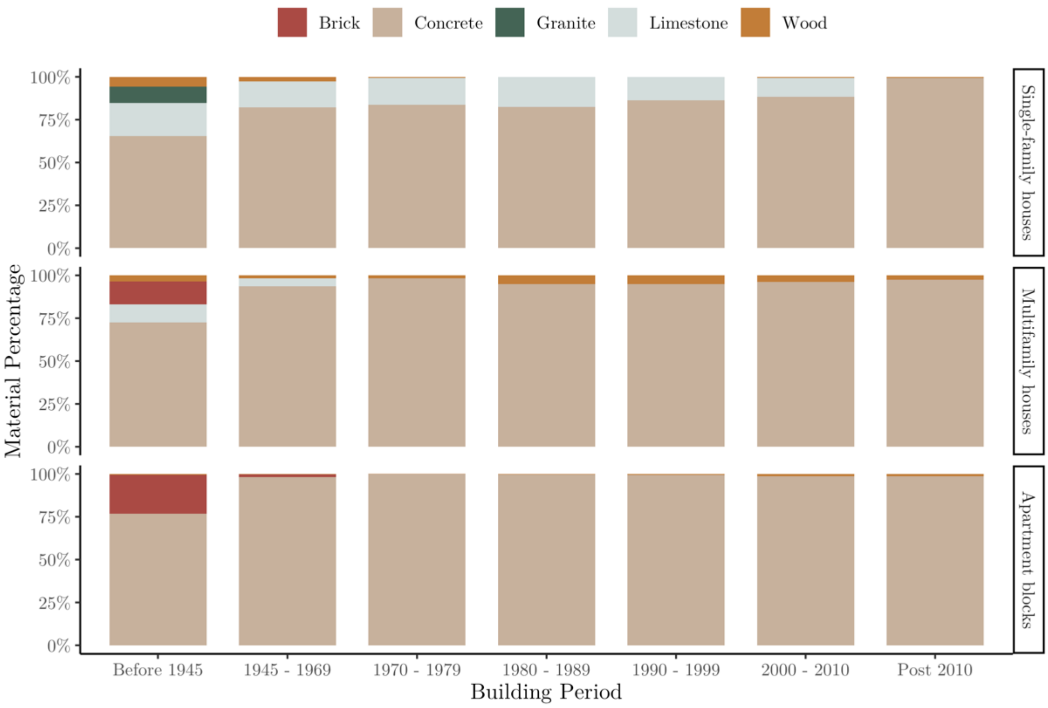

Figure 10: Percentages of floor materials at EU27 level according to building types and construction periods.

Quantification of materials used in the construction of roofs according to the different building types and construction periods are reported in Table 10, whereas percentages are presented in Figure 11.

Table 10: Quantification of roof materials, expressed in 1,000 kg, at EU27 level according to building types and construction periods.

Material	Before 1945	1945 – 1969	1970 – 1979	1980 – 1989	1990 – 1999	2000 – 2010	Post 2010
Single-family houses							
Concrete	2,643	3,126	2,375	2,799	2,172	3,531	2,457
Wood	460	925	966	909	1,251	1,162	772
Multifamily houses							
Brick	561						
Concrete	5,257	12,961	10,245	8,862	10,717	16,989	12,434
Wood	1,272	2,711	3,222	3,457	4,066	3,185	3,099
Apartment blocks							
Brick	581	198					
Concrete	6,016	17,088	17,794	12,040	17,702	47,400	27,969
Wood	462	394	271	535	873	1,224	786

Again, results clearly indicate how concrete is by far the most used material for all building types and construction periods. Overall, concrete represents almost 90% of all materials used in the construction of roofs. The remaining part is composed of wood (around 10%) and, only in a very limited amount, of bricks (less than 1%).

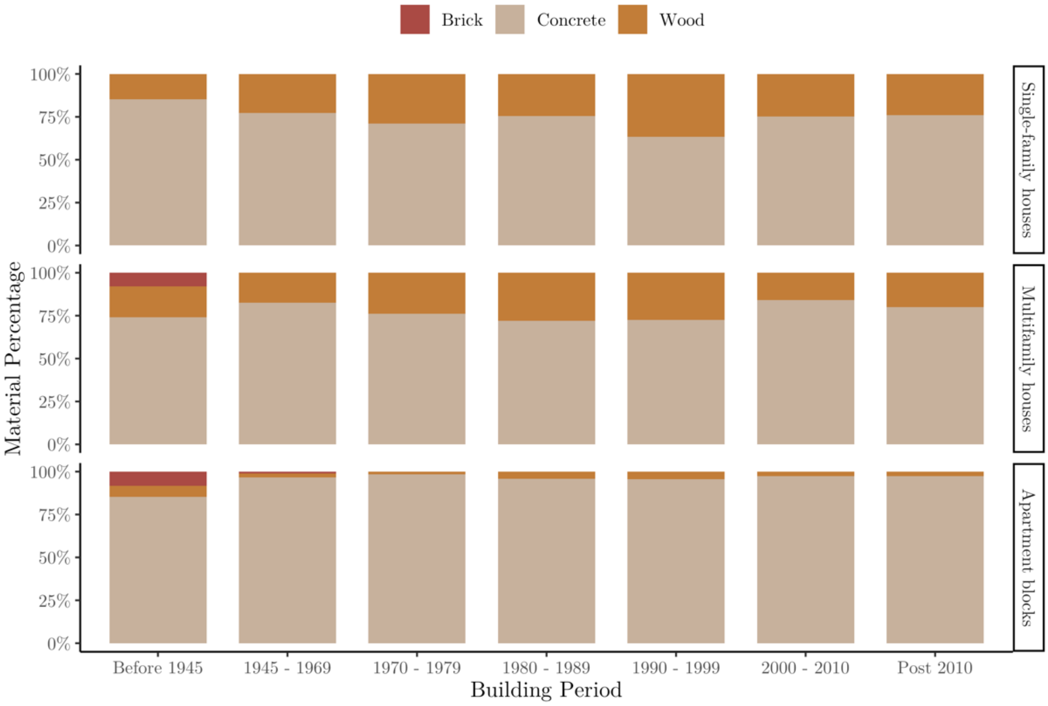

Figure 11: Percentages of roof materials at EU27 level according to building types and construction periods.

Quantification of materials used in the construction of walls according to the different building types and construction periods are reported in Table 11, whereas percentages are presented in Figure 12.

Table 11: Quantification of wall materials, expressed in 1,000 kg, at EU27 level according to building types and construction periods.

Material	Before 1945	1945 – 1969	1970 – 1979	1980 – 1989	1990 – 1999	2000 – 2010	Post 2010
Single-family houses							
Brick	4,325	8,507	7,833	7,003	6,381	10,368	6,863
Concrete	111	264	420	2,697	2,334	589	487
Granite	3,102	772					
Wood	54		26	26	456	611	533
Multifamily houses							
Brick	25,249	39,174	27,606	26,161	24,652	31,287	24,863
Concrete		5,313	8,627	19,740	21,343	24,918	8,209
Granite	4,006						
Limestone	1,487						
Sandstone	2,439						
Wood	106				527	890	908

Apartment blocks							
Brick	21,072	28,738	19,230	14,811	27,638	47,139	37,103
Concrete	7,425	24,586	33,255	50,407	50,284	78,785	41,392
Limestone	1,671						
Sandstone	3,322						
Wood		66	244	179	755	1,139	1,628

This time, concrete is preferred to bricks, becoming the most commonly used material. Overall, bricks and concrete represent almost the total of all materials used in the construction of walls with 52% and 45%, respectively. Considering the other materials, each one covers less than 1% of the total wall materials.

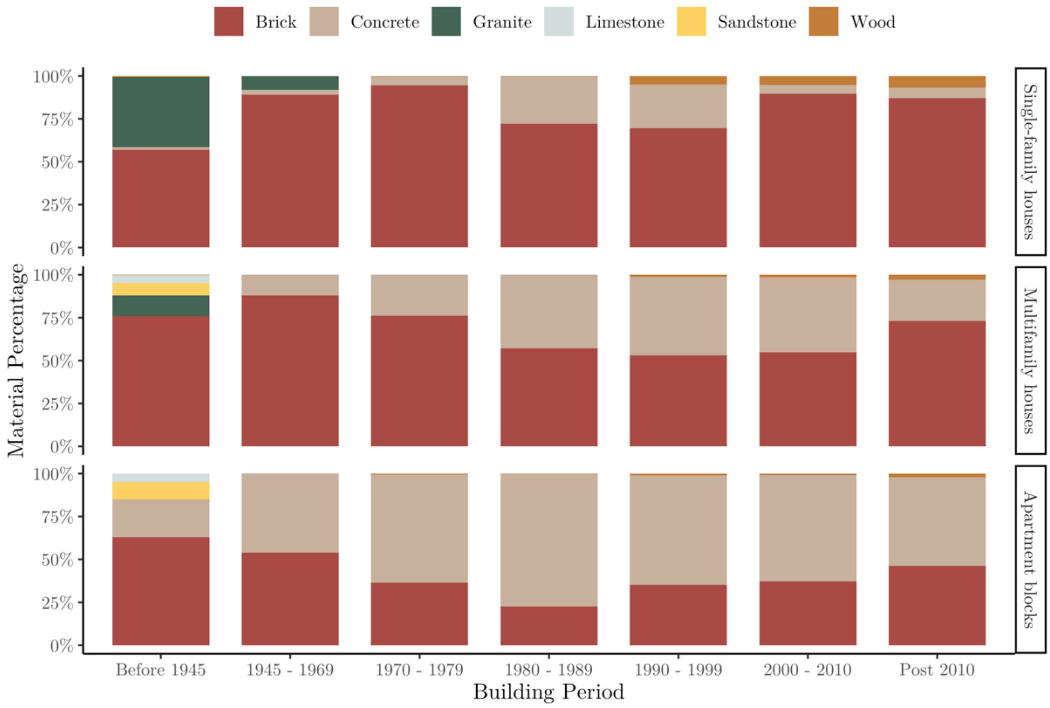

Figure 12: Percentages of wall materials at EU27 level according to building types and construction periods.

Quantification of materials used in the construction of window glazing and frames according to the different building types and construction periods are reported in Table 12. Percentages of materials are presented in Figure 13 only for window frames as window glazings are always made of glass.

Table 12: Quantification of window materials, expressed in 1,000 kg, at EU27 level according to building types and construction periods.

Material	Before 1945	1945 – 1969	1970 – 1979	1980 – 1989	1990 – 1999	2000 – 2010	Post 2010
Single-family houses							
Glass	14.99	21.25	15.72	17.97	24.30	34.39	22.28
Aluminium	0.78	0.61	0.17	0.65	0.87	1.76	0.66

Plastic				2.83	5.34	8.33	5.21
Steel	1.46	1.37	3.72	2.36			
Wood	4.14	6.69	5.77	4.61	3.56	3.57	2.76
Multifamily houses							
Glass	80.55	159.36	134.14	99.58	116.20	193.19	150.50
Aluminium	1.89	2.35	2.35	3.19	3.05	8.69	5.62
Plastic		0.87	1.94	5.90	34.18	64.11	45.57
Steel	25.43	43.61	37.30	20.91	20.91		
Wood	23.57	48.79	42.47	28.86	16.96	12.74	14.94
Apartment blocks							
Glass	101.42	188.32	196.69	182.43	295.96	605.87	482.83
Aluminium	0.72	0.72		3.77	23.16	37.14	16.41
Plastic	3.01	38.08	24.46	26.37	60.79	124.49	112.62
Steel	28.12	42.67	110.07	81.48	81.48		
Wood	35.99	58.77	63.59	54.36	35.51	57.82	41.43

Considering the different materials used for window frames, wood, steel, and plastic are almost equally distributed. Overall, wood, steel, and plastic cover 32%, 29%, and 32% of all materials respectively.

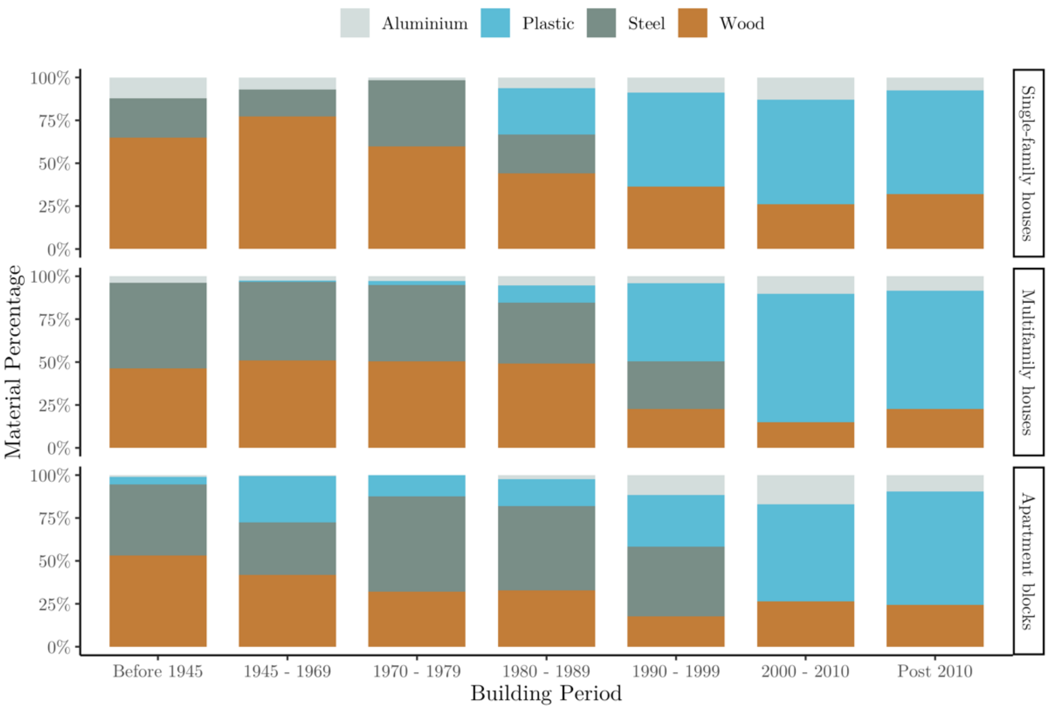

Figure 13: Percentages of window frame materials at EU27 level according to building types and construction periods.

Quantification of materials used for the insulation layers according to the different building types and construction periods are reported in Table 13, whereas percentages are presented in Figure 14.

Table 13: Quantification of insulation materials, expressed in 1,000 kg, at EU27 level according to building types and construction periods.

Material	Before 1945	1945 – 1969	1970 – 1979	1980 – 1989	1990 – 1999	2000 – 2010	Post 2010
Single-family houses							
Composite		4.36	7.38	12.43	19.76	19.59	7.38
Fossil	0.08			0.08	0.08	0.74	0.80
Mineral	9.58	10.54	4.96	16.11	22.80	61.68	108.91
Multifamily houses							
Composite			4.41	13.65	19.33	203.64	193.55
Fossil				0.83	0.83	4.17	4.11
Mineral	0.23	20.11	15.89	23.30	18.89	92.61	121.44
Apartment blocks							
Composite				131.97	131.97	118.58	
Fossil		0.89	4.70	3.82	5.32	188.63	212.26
Mineral	1.18	7.50	48.26	44.90	96.70	378.31	272.04

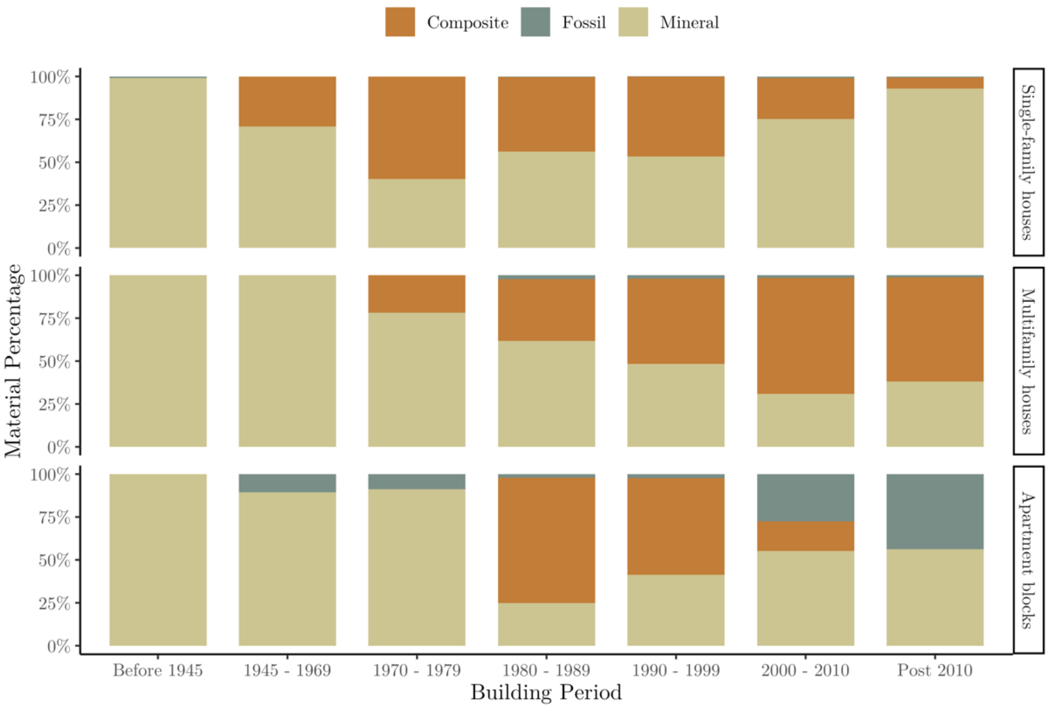

Figure 14: Percentages of insulation materials at EU27 level according to building types and construction periods.

Results clearly indicate an increase in the use of insulation materials, particularly starting from the construction period of 1980-1989, which further intensifies in the subsequent construction periods.

4.2.3. Conclusions

In the present case study, a comprehensive analysis was conducted regarding the construction materials utilized in various building components, such as floors, roofs, walls, windows, and insulation layers within the residential building stock of the EU27 countries. The results differentiate among different residential building types (i.e., single-family houses, multifamily houses, and apartment blocks) and specific construction periods. Overall, concrete and bricks are the main materials used for the construction of walls and floors (98%), whereas materials such as wood or different types of rocks (e.g., granite, limestone, sandstone, etc.) are used in much smaller quantities (2%). Considering the materials used for the construction of roofs, concrete is still the main material (88%) but, in this case, wood is also present with a significant share (12%).

Additionally, detailed data providing values for each EU27 country are available at https://doi.org/10.5281/zenodo.7984727. This dataset contains disaggregated values at a national level. For each country, quantities of different materials used for each specific building element according to the different building types and construction periods are provided. Such a detailed and complete dataset covering all EU27 countries is extremely valuable for policymakers to inform their decisions.

However, the main limitation of this study is that data at the country level are still not detailed enough to actually implement ad hoc CE strategies. In fact, although the provided data represent an improvement compared to the previous results available in the literature, defining and applying effective CE strategies requires detailed information on material quantity and quality with higher spatial resolution. Moreover, information on single building elements (e.g., number of windows), specific technology adopted (e.g., glass with smart films), installed heating and cooling systems, and installed renewable solutions (e.g., photovoltaic or thermal panels) are also needed to implement effective CE strategies. The limited availability of data on these elements is a known problem in the scientific literature and the collection of more granular data is advocated [52]. For this purpose, information at the individual building level is needed, which can only be obtained through a bottom-up data collection approach.

Although the provided data may not offer the specific spatial granularity and level of detail required for the definition of ad hoc CE strategies, these initial findings regarding the available materials in the residential sector at the country level still hold valuable insights for policymakers. The EU27-level data are beneficial for monitoring the current state of the residential building sector across the EU27 countries. On the other hand, the disaggregated values for each EU27 country are particularly valuable to policymakers as they inform decision-making processes. By gaining an understanding of the current conditions of the building stock in each country, policymakers can develop tailored measures aimed at promoting sustainable practices in the building sector.

This approach enables policymakers to assess the status of the residential building sector, evaluate the potential of CE strategies at the national level, and conduct lifecycle assessments

(LCAs) to measure the environmental impact of building practices. Ideally, these data can facilitate the identification of new opportunities and encourage further research to explore the potential of specific CE strategies, ultimately fostering the adoption of less environmentally impactful building practices and contributing to a more sustainable future for the building industry.

5. Conclusions

The building sector plays a major role in GHG emissions and energy consumption. To effectively reduce its impacts, it is important to address not only the energy efficiency of buildings but also the GHG emissions associated with material consumption and generation of C&DW in the construction industry. Therefore, promoting CE strategies is fundamental to minimize the environmental impact of the building sector.

In this report, available data and information regarding the material flows and material recovery rates associated with the EU building sector were reviewed. Moreover, two case studies were conducted to understand the environmental and economic potential of recovering and recycling C&DW from the EU building stock. The obtained results offer valuable insights that allow to monitor the current state of the European building sector and inform the design of dedicated directives aimed at promoting sustainable practices in the building sector. In particular:

- Case Study I showed the potential savings (benefits) achievable through the recycling of the mineral component of C&DW. The environmental and economic savings were determined applying LCA and LCC methodologies. The results obtained demonstrated that recycling competitiveness is hindered by the low price of raw materials that are not so expensive to stimulate the secondary aggregates request. Landfilling taxation can surely facilitate CE practices while the increase of transportation distances to collection facilities represents a detrimental aspect. The location of these facilities become very important from a policy perspective as well as the collection of specific georeferenced data on C&DW materials flows.

- Case Study II tried to respond to the necessities emerged in the first case study, providing a comprehensive analysis of the construction materials in residential building stocks. These data could enable policymakers to assess the materials flows characterizing the building stock of a country or a region and to evaluate the localization of C&DW collection and treatment facilities, the potential of CE strategies or the necessity of the implementation of new policy regulations.

Overall, LCA and LCC methodologies applied to evaluate and compare the performances of recycled materials indicated that environmental benefits and economically profitable solutions are feasible. However, to fully capitalize on these advantages, it is important to enhance the recovery of materials and avoid the consumption of virgin material. This requires the development of dedicated CE strategies that encourage the adoption of less environmentally impactful building practices leading to a more environmentally sustainable building industry.

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