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Assessment of Building Materials in the European Residential Building Stock: An Analysis at EU27 Level

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Abstract: Reducing greenhouse gas (GHG) emissions and energy consumption in the building sector requires not only improving the energy efficiency of buildings but also minimising material requirements, embodied emissions, and waste generation. Circular Economy (CE) principles can be applied to minimize resource extraction and waste generation in the building industry. However, to implement effective CE strategies, quantification and evaluation of materials accumulated in buildings are required. This study aims to provide accurate data and a detailed analysis of the materials available in the EU27 residential building sector. By elaborating the data provided by the H2020 European projects Hotmaps and AmBIENCe, the different materials used for floors, roofs, walls, windows, and insulation layers in single-family houses, multifamily houses, and apartment blocks in the different construction periods were quantified for each EU27 country. Considering results at the EU27 level, concrete and brick characterize the largest part of the European residential building stock, whereas materials such as wood and different types of rock are used in much more limited amounts. These results form the basis for policymakers to monitor the status 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.

Keywords: circular economy; urban mining; residential building stock; European building stock; building materials; construction and demolition waste

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1. Introduction

With the announcement of the Green Deal [1], the European Commission established a comprehensive set of policy initiatives aimed at making the European Union (EU) climate-neutral by 2050. The Green Deal defines a collection of measures to address climate change by reducing greenhouse gas (GHG) emissions, promoting sustainable energy use, and improving energy efficiency. Achieving these goals requires important transformations in all sectors of the economy, including the building sector.

According to the United Nations Environment Programme [2], the building sector represents 36% of global energy use and 37% of energy-related GHG emissions. These figures make the building sector the highest energy-consuming sector and one of the largest global emitters of carbon dioxide among all economy sectors [3]. In light of the important role of the building sector in achieving the goal of climate neutrality by 2050, different Green Deal measures focus on the clean energy transition of the building stock. For example, the Renovation Wave strategy aims to improve building energy efficiency and to promote the use of renewable energy sources by doubling the rate of renovation in the building sector [4]. Similarly, the Energy Performance of Buildings Directive (EPBD) [5] aims to improve the energy efficiency of buildings by defining the minimum energy performance standards. Finally, the New European Bauhaus [6] aims to create a framework for designing and building sustainable, inclusive, and aesthetically pleasing environments while promoting social and economic development. Overall, these directives aim to reduce the energy consumption of the building sector by setting new energy efficiency standards and promoting the reconstruction and renovation of the existing building stock.

However, GHG emissions and energy consumption in the building sector are determined not only by the operational requirements (e.g., heating and cooling, lighting, ventilation, etc.) of already existing buildings, but also by the carbon footprint of the materials and the emissions produced in the construction of new buildings. In fact, a large share of GHG emissions associated with the building sector is caused by the production of building materials and building operation [2,3].

The construction industry is the biggest global user of raw materials [3], and the amount of material used in the building stock accounts for almost 60% of all materials used by humanity [7]. The energy required during the extraction, transportation, manufacturing, and assembly of materials for building construction contributes to a large part of GHG emissions [8–10]. Considering the GHG emissions associated with the building sector, around 11% are attributed to the manufacturing of building materials and products, and around 28% are attributed to operation of buildings [2,3]. Moreover, in addition to GHG emissions and material consumption, the building sector is responsible for the generation of large amounts of construction and demolition waste (CDW) [11]. In the EU, CDW constitutes about 25–30% of total generated solid waste [12].

To summarize, the manufacturing of building materials and other operations related to building construction (e.g., CDW generation) account for almost 40% of the GHG emissions associated with the building sector. Therefore, reducing GHG emissions and energy consumption in the building sector requires not only focusing on the energy efficiency of buildings, but also taking into account GHG emissions related to material consumption and CDW generation in the building industry. In the coming decades, population growth and urbanization are expected to continue to increase [13]. The construction of new buildings, together with the increment of renovation rates of existing buildings promoted for improving energy efficiency, will increase material consumption and amplify these environmental challenges [14,15]. For these reasons, the evaluation of embodied GHG emissions in the building materials [16,17] and the quantification of CDW [18,19] have received growing attention in recent years.

In addition to the increase in energy efficiency, the transition towards a climate-neutral building stock requires a reduction in material consumption and CDW generation. To minimize unnecessary resource extraction and waste generation, it is crucial to keep building materials in use for as long as possible and to recycle them when needed. In this way, fewer primary materials are required, limiting energy use and GHG emissions across the product lifecycle [20]. These are among the key principles of circular economy (CE) [21].

In contrast to the traditional linear economy, where materials are extracted, used, and discarded, CE aims to minimize waste production and promote sustainability by maximizing the re-use of resources [22,23]. The main concept of CE is to maintain materials in the socio-economic system for as long as possible at their highest value [24]. To prevent the production of waste and limit the extraction of new raw materials, products should be designed to maintain their use at their highest possible value across multiple lifecycles. Ideally, when waste is generated, products should be reused without alteration or modification to their original state or shape. Alternatively, materials can be recycled into a new substance or product. Finally, if this is not possible, waste recovery processes should allow the extraction of other materials or energy from waste or, as the least valuable down-cycling hierarchy option, waste disposal (e.g., landfilling) can be considered.

In applying CE principles to the building sector, the primary goal is to extend the use of buildings for as long as possible and to promote building retrofitting. When retrofitting is not an option, buildings should be deconstructed and the components directly reused or remanufactured. Another option is to dismantle buildings to their component parts and recycle or reuse the individual materials [25,26]. In current practices, however, CDW is usually utilized for low-value applications that make further reuse impossible, such as road construction or backfilling [19,27,28]. Therefore, in order to limit the consumption of primary resources and reduce GHG emissions, it is crucial to shift from downcycling to high-quality recycling of CDW with the aim of maintaining material use at the highest possible value across multiple lifecycles [29].

A new perspective is emerging in the scientific literature that highlights the important role of buildings as resource banks. This approach is defined as "*urban mining*" [30,31]. Buildings are an extensive repository of secondary resources which can be easily accessed and recovered. These resources encompass a wide range of materials, components, and systems present within the building stock. The materials contained within buildings, such as metals, concrete, wood, glass, and plastics, can be extracted, processed, and recycled. For these reasons, urban mining is considered an excellent opportunity for resource recovery through CE strategies. The need for new material extraction is minimized by exploiting the anthropogenic material stock in the built environment, leading to a reduction in the associated energy consumption and GHG emissions [25]. Apart from being a means of reducing the environmental impact of the construction industry, urban mining is gaining increasing attention as an opportunity for the creation of new markets and industries. For all these reasons, CE and urban mining are crucial elements of EU policy design and play a key role in the European Green Deal [1]. The European Commission introduced a CE action plan defining the "EU Strategy for a Sustainable Built Environment" [32]. This strategy introduces CE principles throughout the lifecycle of buildings. For example, it establishes innovative strategies for urban mining and building material reuse, promotes the idea of "waste as a resource", and encourages a shift towards more sustainable construction practices. Furthermore, the H2020 Building As Materials Banks (BAMB) project has been funded to enhance the value of building materials and prolong their durability [33]. However, despite these initiatives, buildings are a material reservoir that, to date, remains mainly untapped [34].

Several challenges hinder the re-use of building materials [25]. The main limit is that building materials are mainly large in volume and low in unit value. Therefore, to be economically feasible, supply and demand have to be close to each other in order to limit transportation costs [35,36]. Moreover, the absence of data regarding material availability and the unclear market demand for secondary resources do not allow for the implementation of effective CE strategies [37].

To better understand possible opportunities for building material recovery and implement effective CE strategies, quantification of the materials accumulated in buildings and infrastructure is required [38–40]. Furthermore, accurately characterizing and accounting for the available building materials is fundamental to enhancing awareness and assisting policymakers and planners in making decisions that can increase city circularity [30,41]. Currently, there are two main methods used for characterizing and accounting for building materials:

- *Bottom-Up Approach*: This approach involves collecting data at the individual building or material level and aggregating it to estimate the total material stock of a region or city. The focus is on the detailed characterization of individual buildings and materials to create a comprehensive picture of the available resources.
- *Top-Down Approach*: This approach uses statistical and modeling techniques to estimate the material stock of a region or city based on macro-level data, such as the age, size, and occupancy rate of buildings. The focus is on creating estimates that are accurate at the regional or city level, rather than at the individual building or material level.

Detailed information on material quantity and quality with high spatial definition (ideally at the building level) is crucial for informing CE strategies. In these cases, bottom-up approaches are used and data on single building elements (e.g., number of windows) are preferred compared to material mass values characterization to favour building component reuse instead of material recycling [42]. In the literature, there are several studies proposing bottom-up approaches to characterizing the available building materials in specific regions and cities [26,34].

On the contrary, top-down approaches are preferred to study building stock dynamics and general patterns on a larger scale. These studies are crucial to informing policymakers and monitoring environmental performance at the national level. However, the studies available in the literature focus mainly on individual countries [31,43], and only a limited number of studies have provided data regarding the entire EU.

To the best of our knowledge, only Landolfo et al. [44] have provided an overview of the main building construction technologies that characterize the largest parts of the EU27 residential building stock. In their study, however, quantitative analysis was conducted only for a limited number of countries (i.e., Bulgaria, Greece, Italy, Portugal, and Romania), whereas for the other countries only qualitative data were available. Moreover, the results were provided in a highly aggregated form without differentiating materials according to different residential building types and construction periods. Complete and more detailed information is required by policymakers in order to understand the current state of the building stock, identify areas for improvement, and develop strategies to promote more sustainable and circular practices in the construction industry.

The present study aims to address these limits by providing accurate data and 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 to differentiate among different residential building types (i.e., single-family houses, multifamily houses, and apartment blocks) and construction periods.

2. Materials and Methods

In this section, the data sources used in the analysis are listed and the steps followed during the process of data elaboration are described.

2.1. Data Collection

Complete and high-quality datasets that cover the entire EU27 building stock and differentiate among countries, building types, and construction periods are difficult to find. Fortunately, two Horizon 2020 European projects have provided all of the data required for this study. Relying on the data provided by these European projects allows us to be confident in the quality of the provided information, as these values went through several validation processes before being approved by the European Commission. The two Horizon 2020 European projects used in this study are:

- *H2020 Hotmaps: The open source mapping and planning tool for heating and cooling* [45]. The H2020 Hotmaps project developed a toolbox that supports local, regional, and national heating and cooling planning processes. Among other results, they provided a dataset [46] 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 [47].
- *H2020 AmBIENCe: Active Managed Buildings with Energy Performance Contracting* [48]. The H2020 AmBIENCe project aimed to extend the concept of energy performance contracting for active buildings and make the model available and attractive for use with a wider range of building typologies. Among other results, they provided a dataset [49] regarding the dynamic thermal behaviour of building stock segments' reference buildings 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 [50].

These datasets each provide complete values for all EU27 countries and differentiate among different building types and construction periods. Moreover, both datasets are publicly available online. Summary information for each dataset is provided in Table 1.

Table 1. Dataset summary information.

Dataset	Reference Year	Spatial Coverage	Description
H2020 Hotmaps	2016	EU27	Pysical characteristics of the building stock (i.e., number of buildings, floor area, energy consumption, etc.)
H2020 AmBIENCe	2021	EU27	Dynamic thermal behaviour of building stock segments' reference buildings (i.e., materials and volumes of building elements)

2.2. Data Elaboration

All the required information for the analysis was obtained by combining the values available in the Hotmaps and AmBIENCe datasets. From Hotmaps, the number of buildings for each EU27 country according to the different building types and construction periods was considered. 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 included the type of material and the volume of the different building elements (i.e., floors, roofs, walls, windows, and insulation layers). Note that the AmBIENCe dataset is based on reference buildings which are representative of their respective building stock segments [50]. Therefore, although these values may not be applicable for individual buildings, reliable results can be obtained at the national level for the respective segments.

Considering the different residential building types, both Hotmaps and AmBIENCe datasets use the same three categories:

- *Single-family houses (SFHs)*
- *Multifamily houses (MFHs)*
- *Apartment blocks (ABs)*, i.e., high-rise buildings that contain several dwellings and have more than four storeys.

Regarding the different construction periods, the Hotmaps and AmBIENCe datasets use different year intervals. In particular, while Hotmaps uses the same year intervals for all countries and building types, in AmBIENCe the intervals change among countries and building types. To facilitate comparison of results among countries and building types, and because the numbers of building types were obtained from Hotmaps, the following construction periods defined in Hotmaps were considered [47]:

- *Before 1945*. Buildings constructed before 1945 are generally classified as historic buildings. The historic building stock is highly inhomogeneous, making it difficult to apply a standardized assessment. Nevertheless, certain characteristics may be generalized, such as the use of massive construction methodologies for residential buildings.
- *1945–1969*. Buildings erected after World War II and before 1969 are generally characterized by nearly missing insulation and inefficient energy systems caused by the choice of cheap construction materials and short construction times. These result in higher specific useful energy demand.
- *1970–1979*. Buildings built between 1970 and 1979 present the first insulation applications (a consequence of the world energy crises of the 1970s).
- *1980–1989* and *1990–1999*. Buildings constructed during these two periods reflect the introduction of the first national thermal efficiency ordinances, which occurred 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 [51]).
- *Post 2010*. Recently constructed buildings are analysed to understand the impact of the economic crisis on Europe's construction branch. The present analysis contains data updated until the year 2016.

A summary of the different residential building types and construction periods considered is presented in Table 2.

Table 2. Residential building types and construction periods.

Residential Building Types	Construction Periods
Single-family houses (SFHs)	Before 1945
Multi-family houses (MFHs)	1945–1969
Apartment blocks (ABs)	1970–1979
	1980–1989
	2000–2010
	Post-2010

To compute the available materials according to the Hotmaps construction periods, the values of each AmBIENCe reference building were weighted according to the number of overlapping years. Thus, for example, if AmBIENCe provided two reference buildings with year ranges 1965–1973 and 1974–1981, the materials for the Hotmaps construction period 1970–1979 were obtained by weighting the two reference buildings at 40% and 60%, respectively. Note that in multiple cases AmBIENCe provides more than one reference building spanning the same year range. When this occurs, the reference buildings were weighted according to their respective prevalence as indicated by AmBIENCe.

To compute the material volumes for the different building elements, the following approach was adopted:

- *Floors*. For each reference building, AmBIENCe provides the values for the floor area, floor thickness, and the number of storeys. Using these values, the floor volume was computed according to Equation (1).

$$Floor\ Volume\left[m^3\right] = Ground\ Floor\ Area\left[m^2\right] \times Floor\ Thickness[m] \times Number\ of\ Storeys \quad (1)$$

  Note that AmBIENCe provides only single values for floor thickness and area, without considering potential variations between different floors. This means that any distinctions between floors, such as the first floor connected to the foundation compared to other floors, are not taken into account in the dataset.
- *Roofs*. For each reference building, AmBIENCe provides the values for the roof area and thickness. Using these values, the floor volume was computed according to Equation (2).

$$Roof\ Volume\left[m^3\right] = Roof\ Area\left[m^2\right] \times Roof\ Thickness[m] \quad (2)$$

- *Walls*. For each reference building, AmBIENCe provides the values for the wall area and thickness. Using these values, the floor volume was computed according to Equation (3).

$$Wall\ Volume\left[m^3\right] = Wall\ Area\left[m^2\right] \times Wall\ Thickness[m] \quad (3)$$

- *Windows*. For each reference building, AmBIENCe provides the values for the window glazing and window frame thickness. However, a single value for the window area is provided without differentiating between the glazing and the frame area. To overcome this issue, 70% of the total window area was considered as made of glass and 30% as made of frame material. Using these values, the window glazing and frame volumes were computed according to Equation (4).

$$\begin{aligned} Glazing\ Volume\left[m^3\right] &= .7 \times Window\ Area\left[m^2\right] \times Glazing\ Thickness[m] \\ Frame\ Volume\left[m^3\right] &= .3 \times Window\ Area\left[m^2\right] \times Frame\ Thickness[m] \end{aligned} \quad (4)$$

Note that the AmBIENCe values regarding glaze thickness already take into account the different types of windows (i.e., single- and double-glazed). However, for a limited number of reference buildings, AmBIENCe does not provide the thickness for single-glazed windows or the thickness of window frames made of plastic or steel. In these cases, the thickness for single-glazed windows was set to 6 mm and window frames in plastic and steel were set to 24 mm and 20 mm, respectively.

- *Insulation layers*. For each reference building, AmBIENCe provides the values for the insulation layer area and thickness. Using these values, the insulation layer volume was computed according to Equation (5).

$$Insulation\ Volume\left[m^3\right] = Insulation\ Area\left[m^2\right] \times Insulation\ Thickness[m] \quad (5)$$

Note that AmBIENCe distinguishes between roof insulation, floor insulation, and wall insulation. In this study, however, the volume of each individual insulation element was first computed separately and then the results were aggregated to obtain a single value. This approach allowed more reliable results to be obtained and provided a comprehensive overview of insulation across the building elements in the analysis.

Moreover, for each building element, AmBIENCe specifies the material and its density. In Table 3, the list of materials used in AmBIENCe and the respective labels used in the current study are presented. Note that window material is not specified in AmBIENCe, though is expected to be glass. Additionally, the materials utilized for the insulation layers were categorized into three distinct groups: *"Fossil"*, *"Mineral"*, and *"Composite"* [52].

Table 3. 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	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	Fossil
Polyurethane foam	
Urea formaldehyde resin foam	
Mineral wool	Mineral
Rock wool	
Perlite board expanded	
Asbestos fibre	
Cement fiber slabs shredded wood	Composite

To characterize each building element in terms of its material composition, the material mass was calculated using the already obtained volumes of the building elements and the material densities provided by AmBIENCe, according to Equation (6).

$$Mass\ Element_i[kg] = Volume\ Element_i\left[m^3\right] \times Density\ Element_i\left[kg/m^3\right] \quad (6)$$

The AmBIENCe data provide values for all material densities with the exception of the values for the window glazing and window frame materials. For these elements, the reference values reported in Table 4 were used.

Table 4. Density values for window glass and window frame materials.

Material	Density [kg/m^3]
Wood	500
Aluminium	2800
Plastic	1500
Steel	7850
Glass	2500

All data manipulations and statistical analyses were performed using R Programming Language (V4.2.1) [53]. All scripts are available at https://doi.org/10.5281/zenodo.7984727 (accessed on 10 April 2023).

3. Results

The resulting dataset is contains 3242 rows. Each row provides information regarding the quantity of a material used for each specific building element according to the different building types, construction periods, and EU27 countries. The dataset structure (i.e., column names and variable information) is presented in Table 5.

Table 5. Dataset column summary information.

Column Name	Variable Type	Description
`country_code`	Factor (27 levels)	Three letters country code for each EU27 country
`country`	Factor (27 levels)	Full name of each EU27 country
`sector`	Factor (1 level)	Specify the data refers to the `"Residential sector"`
`subsector`	Factor (3 levels)	Specify building type (`"Single-family houses"`, `"Multifamily houses"`, and `"Apartment blocks"`)
`bage`	Factor (7 levels)	Specify the construction period (`"Before 1945"`, `"1945-1969"`, `"1970-1979"`, `"1980-1989"`, `"1990-1999"`, `"2000-2010"`, and `"Post 2010"`)
`element`	Factor (6 levels)	Specify the building element (`"floor"`, `"roof"`, `"wall"`, `"window"`, `"frame"`, and `"insulation"`)
`material`	Factor (13 levels)	Specify the building element material (`"aluminum"`, `"brick"`, `"concrete"`, `"glass"`, `"granite"`, `"limestone"`, `"plastic"`, `"sandstone"`, `"steel"`, `"wood"`, `"composite"`, `"fossil"`, and `"mineral"`)
`area_m2`	Numerical	Value of the area [m^2] of each specific building element
`thickness_m`	Numerical	Value of the thickness [m] of each specific building element

Table 5. *Cont.*

Column Name	Variable Type	Description
volume_m3	Numerical	Value of the volume [m^3] of each specific building element
density_kg_m3	Numerical	Value of the density [kg/m^3] of each specific building element
material_kg	Numerical	Value of the material mass [kg] of each specific building element
build_M	Numerical	Value of the number of buildings [Millions] that present each specific element. This value can be used for weighting row values when computing aggregated results

The dataset is available at https://doi.org/10.5281/zenodo.7984727 (accessed on 10 April 2023). In the following sections, the results obtained for each different building element are summarized presenting aggregated values at the EU27 level.

3.1. Floor Materials

Quantification of materials used in the construction of floors according to the different building types and construction periods is reported in Table 6, whereas percentages are presented in Figure 1.

Table 6. Quantification of floor materials, expressed in 1000 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	7226	11,947	9179	9743	12,961	16,482	12,189
Granite	1062						
Limestone	2116	2174	1742	2071	2071	2071	
Wood	622	406	59			103	69
Multifamily houses							
Brick	5189						
Concrete	28,538	81,579	69,161	32,315	47,472	65,481	55,552
Limestone	4161	4161					
Wood	1414	1417	1185	1706	2579	2503	1386
Apartment blocks							
Brick	18,826	2350					
Concrete	64,160	156,818	213,071	191,060	260,955	395,688	274,309
Wood	475	411	330	688	1275	5618	3583

These results clearly indicate that concrete is by far the most widely 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. Bricks are present mainly in the *"before 1945"* construction period, in particular for ABs, where they represent almost 25% of the floor materials. Limestone is present mainly in SFHs, and its share declines over the construction periods, starting from almost 20% and decreasing to around 10%. Wood, on the contrary, is consistently present in all building types and construction periods, although in a smaller percentage (around 2–3%). Finally, granite is present only to a limited extent (around 10%) in SFHs in the *"before 1945"* construction period.

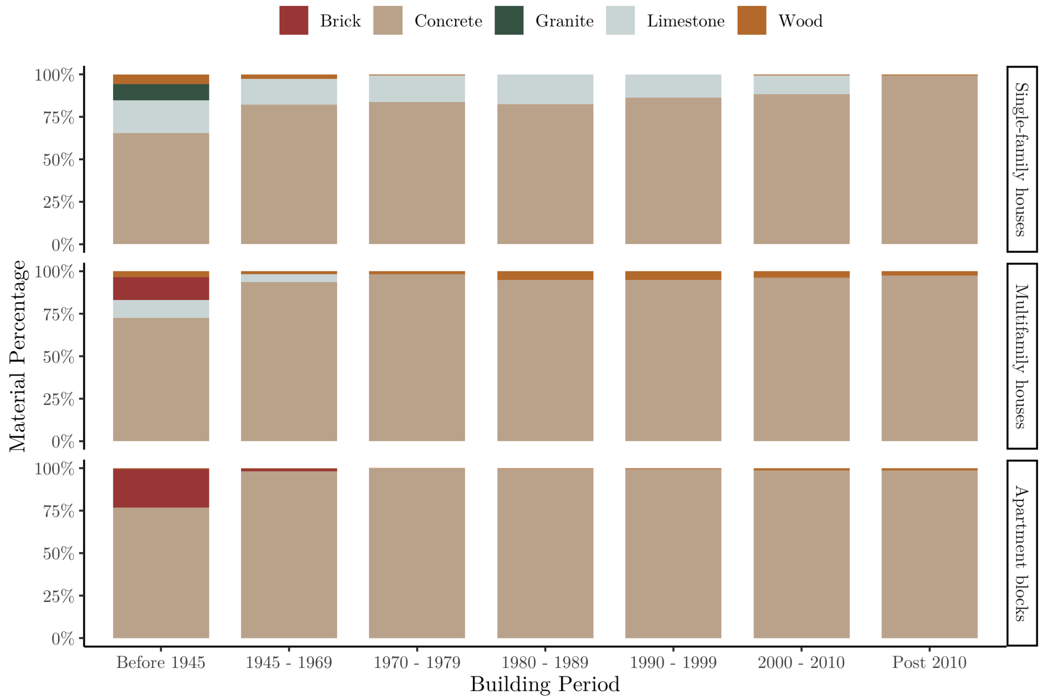

Figure 1. Percentages of floor materials at EU27 level according to building types and construction periods.

3.2. Roof Materials

Quantification of materials used in the construction of roofs according to the different building types and construction periods is reported in Table 7, whereas percentages are presented in Figure 2.

Table 7. Quantification of roof materials, expressed in 1000 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	2643	3126	2375	2799	2172	3531	2457
Wood	460	925	966	909	1251	1162	772
Multifamily houses							
Brick	561						
Concrete	5257	12,961	10,245	8862	10,717	16,989	12,434
Wood	1272	2711	3222	3457	4066	3185	3099
Apartment blocks							
Brick	581	198					
Concrete	6016	17,088	17,794	12,040	17,702	47,400	27,969
Wood	462	394	271	535	837	1224	786

Again, the results clearly indicate that 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 a very limited amount is composed of brick (less than 1%). Wood is consistently present for all building types and construction periods; however, its presence is greater in SFHs and ABs, where it covers up to 25–30% of the roof materials. On the contrary, brick is present only to a limited extent (around 8%) in MFHs and ABs in the *"before 1945"* construction period.

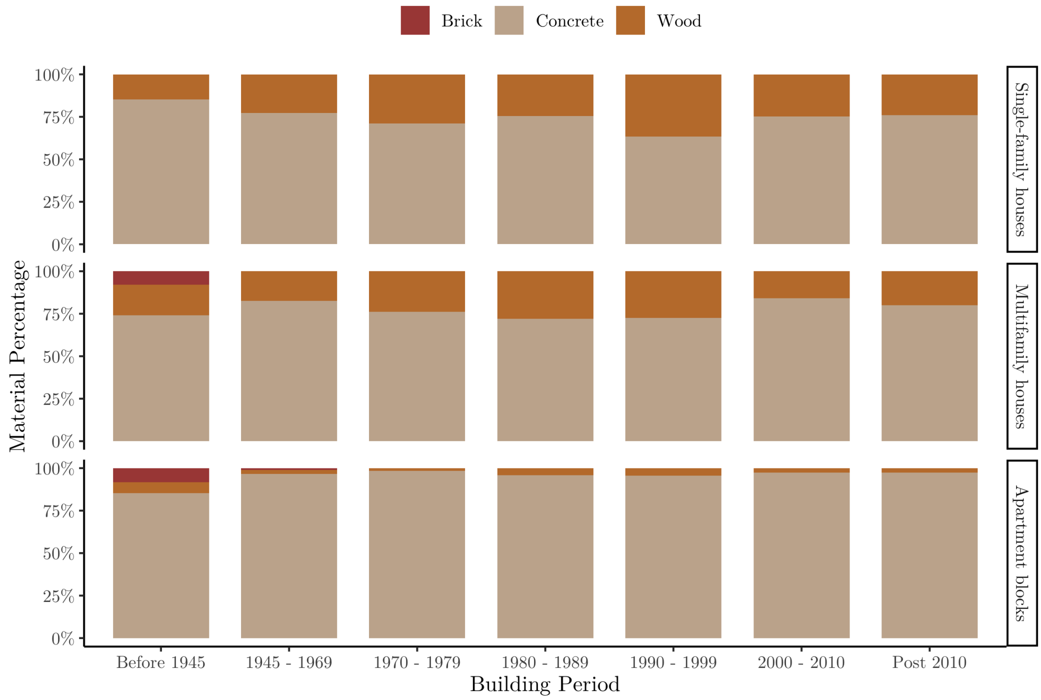

Figure 2. Percentages of roof materials at EU27 level according to building types and construction periods.

3.3. Wall Materials

Quantification of materials used in the construction of walls according to the different building types and construction periods is reported in Table 8, whereas percentages are presented in Figure 3.

Table 8. Quantification of wall materials, expressed in 1000 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	4325	8507	7833	7003	6381	10,368	6863
Concrete	111	264	420	2697	2334	589	487
Granite	3102	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		5313	8627	19,740	21,343	24,918	8209
Granite	4006						
Limestone	1487						
Sandstone	2439						
Wood	106				527	890	908
Apartment blocks							
Brick	21,072	28,738	19,230	14,811	27,638	47,139	37,103
Concrete	7425	24,586	33,255	50,407	50,284	78,785	41,392
Limestone	1671						
Sandstone	3322						
Wood		66	244	179	755	1139	1628

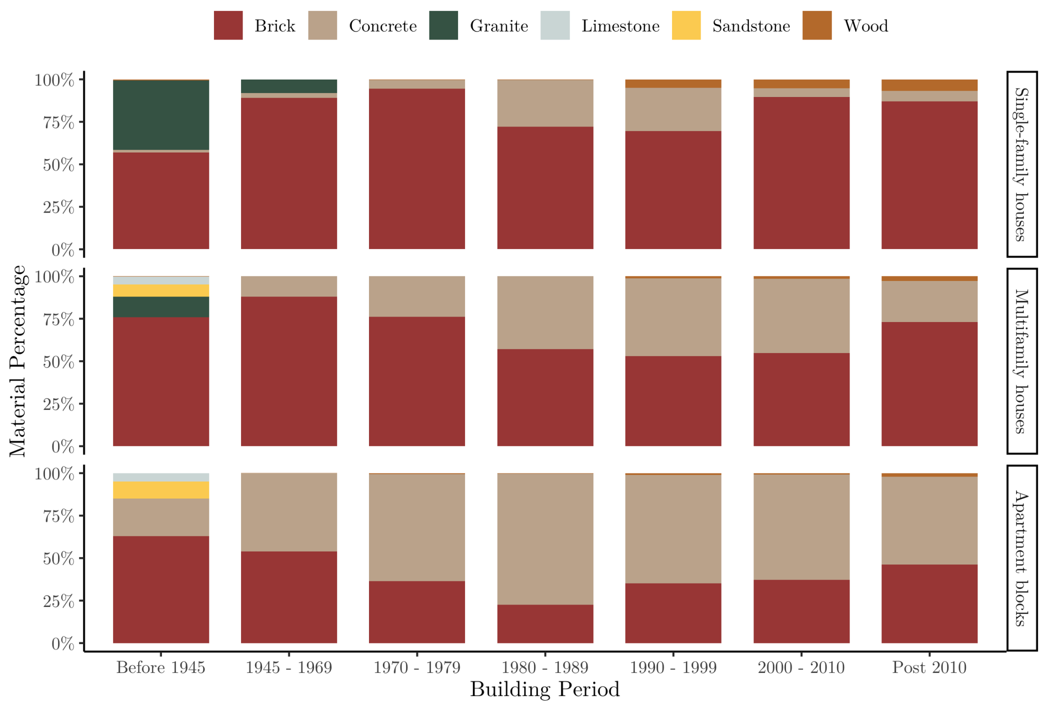

Figure 3. Percentages of wall materials at EU27 level according to building types and construction periods.

In this case, concrete is preferred to brick, being the most commonly used material. Overall, brick and concrete represent almost all of the materials used in the construction of walls, at 52% and 45%, respectively. However, their share varies considerably across building types and construction periods. In SFHs and MFHs, brick is always the most used material. On the contrary, concrete tends to be the preferred material in ABs. Considering the variations among construction periods, the same pattern can be observed for all building types; during the construction period covering the 1970–1999 range, there is an increase in the use of concrete; however, in more recent construction periods the opposite trend occurs, with an increase in the use of brick. Considering the other materials, each one covers less than 1% of the total wall materials. Granite, limestone, and sandstone are mainly present in the older construction periods. Granite is especially found in SFHs, where it covers up to 40%. On the contrary, sandstone is especially found in ABs, where it covers up to 10%. Finally, wood is consistently present in all building types and construction periods, although in smaller portions (around 1–2%).

3.4. Window Materials

Quantification of materials used in the construction of window glazing and frames according to the different building types and construction periods is reported in Table 9. Percentages of materials are presented in Figure 4 for window frames only, as window glazings are always made of glass.

Table 9. Quantification of window materials, expressed in 1000 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

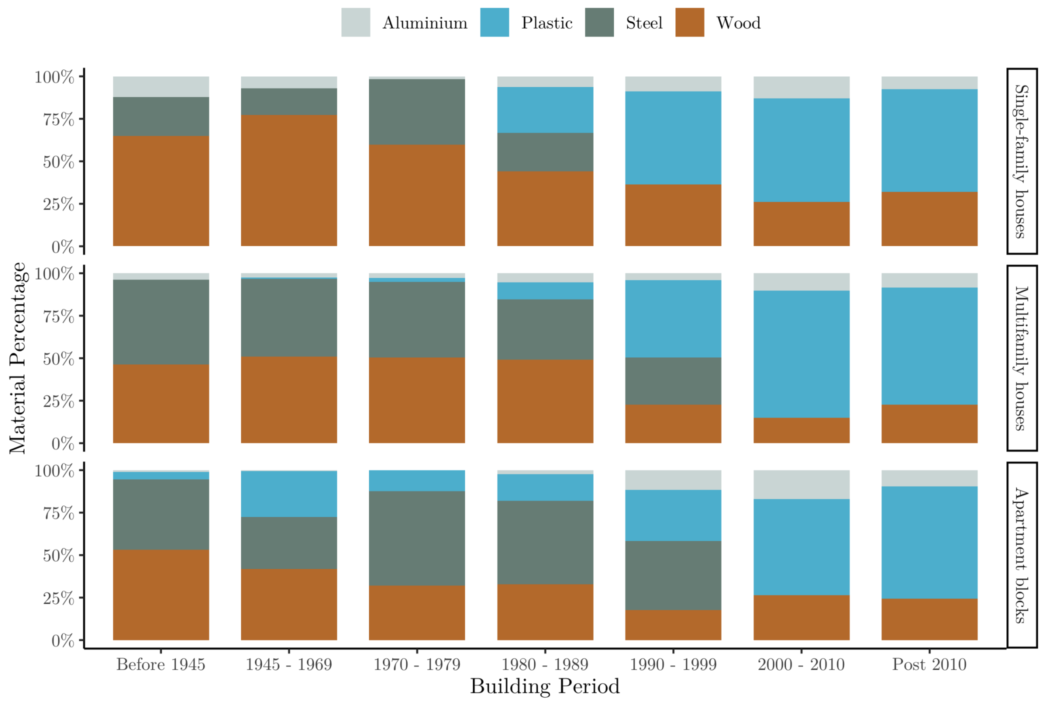

Figure 4. Percentages of window frame materials at EU27 level according to building types and construction periods.

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. However, their respective shares vary considerably across construction periods, following a similar pattern in all building types. In older construction periods, wood and steel are the main materials used for window frames, and have similar proportions. As the construction periods progress, the introduction and gradual increase in the use of plastic can be observed, with a consequent decrease in the use of steel and wood. Plastic is a cost-effective material as it offers a thermal transmittance similar to wood (and significantly lower than materials such as aluminium and steel) while requiring much less maintenance, reducing long-term costs [54]. In the most recent construction periods, plastic is the most diffuse material (up to 70%) and wood maintains 25–30% coverage, whereas steel is no longer used. In contrast to these materials, the presence of aluminium is limited, though a progressive increase in the most recent construction periods can be observed.

3.5. Insulation Materials

Quantification of materials used for insulation layers according to the different building types and construction periods is reported in Table 10, whereas percentages are presented in Figure 5.

Table 10. Quantification of insulation materials, expressed in 1000 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

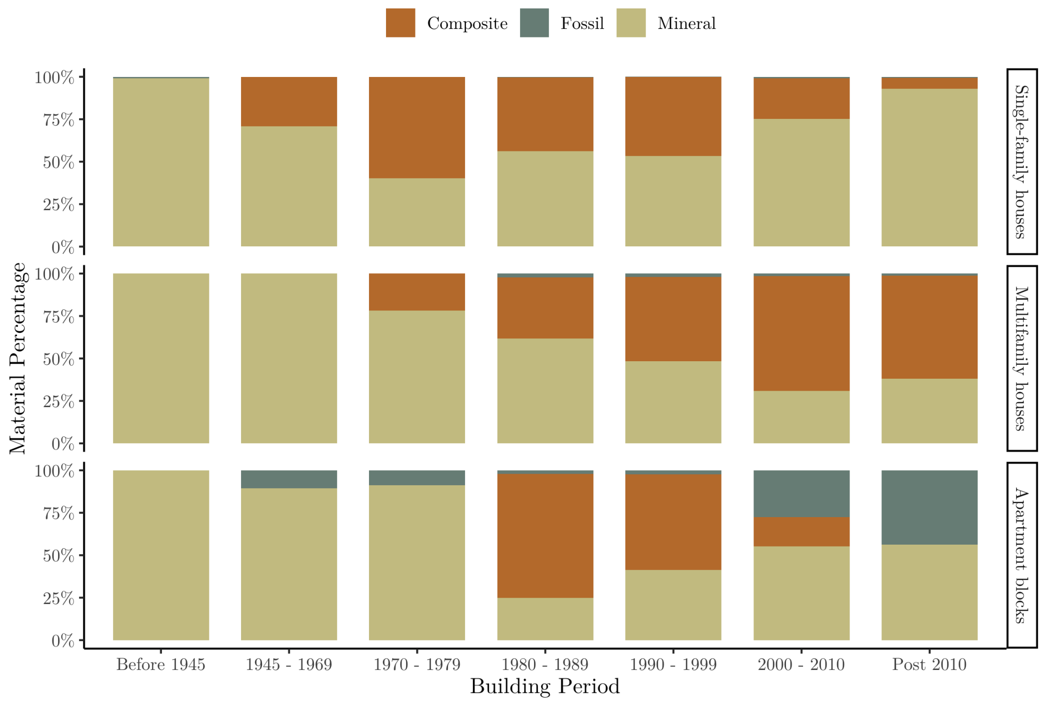

Figure 5. Percentages of insulation materials at EU27 level according to building types and construction periods.

These results clearly indicate an increase in the use of insulation materials, particularly starting from the construction period of 1980–1989, which further is intensified in the subsequent construction periods. Considering the different types of insulation materials, mineral insulation materials are the most commonly used. However, their prevalence varies across different building types and construction periods. The use of composite insulation materials increases after the 1980–1989 construction period, although the respective shares vary depending on the type of construction. Finally, fossil insulation materials display the lowest presence among the different types.

4. Discussion

The present analysis provides aggregated values at the EU27 level regarding the quantities of different materials used for each specific building element. The results differentiate among different residential building types (i.e., single-family houses, multifamily houses, and apartment blocks) and specific construction periods. These results offer a detailed overview of the materials available in the EU27 residential building stock, and are in line with those provided by Landolfo et al. [44]. In fact, both studies reported similar use of materials for the different building elements in the EU27 residential building stock. Concrete and brick are the main materials used for the construction of walls and floors, whereas materials such as wood or different types of rock (e.g., granite, limestone, sandstone, etc.) are used in much smaller quantities. Considering the materials used for the construction of roofs, concrete is the main material, though in this case wood is present with a significant share as well.

Comparing the obtained results with studies that have assessed material presence in the building stock of other regions of the world presents challenges due to variations in the methodologies and taxonomies employed. For instance, Marinova et al. [55] provided a global analysis of materials in the residential sector. Their findings highlight concrete as the most commonly used material, with wood, steel, and glass being employed to a lesser extent. However, their results lack differentiation among different building elements and construction periods. Furthermore, the different classifications of residential building types do not allow direct comparisons between the two studies, limiting the possibility of identifying differences and similarities in the findings.

The current results at the EU27 level are useful to monitor the current state of the European residential building sector. However, the most valuable result of this study consists of the data providing values for each EU27 country, available at https://doi.org/10.5281/zenodo.7984727 (accessed on 10 April 2023). This dataset contains disaggregated values at the national level. For each country, the 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 and can inform decision-making processes.

However, the main limitation of this study is that the data at the country level are 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 technologies adopted (e.g., glass with smart films), installed heating and cooling systems, and installed renewable solutions (e.g., photovoltaic or thermal panels) are needed in order 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 [56]. For this purpose, information at the individual building level is needed, which can only be obtained through a bottom-up data collection approach.

5. Conclusions

The building sector plays a major role in GHG emissions and energy consumption. To effectively reduce its impacts, it is necessary to consider both the energy efficiency of buildings and the GHG emissions associated with material consumption and generation of CDW in the building industry. Therefore, adopting CE strategies is crucial to minimizing the environmental impact of the building sector. CE strategies aim to decrease energy usage and GHG emissions throughout the entire lifecycle of buildings by maximizing the utilization of building materials and promoting recycling whenever possible. However, the successful implementation of CE strategies relies on accurate and detailed data about the building stock.

In this 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 current analysis offers aggregated data at the EU27 level, presenting the quantities of different materials used for each specific building element. Additionally, detailed information is provided for each EU27 country, which can be accessed at https://doi.org/10.5281/zenodo.7984727 (accessed on 10 April 2023). This includes the quantities of different materials used for each specific building element based on different building types and construction periods within each country.

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 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 can 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.

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Abbreviations

The following abbreviations are used in this manuscript:

ABs	Apartment blocks
BAMB	Building as materials banks
CDW	Construction and demolition waste
CE	Circular economy
EPDB	Energy performance of buildings directive

EU	European Union
GHG	Greenhouse gas
MFHs	Multi-family houses
SFHs	Single-family houses

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