Energy & Buildings 372 (2026) 118194

Contents lists available at ScienceDirect

Energy & Buildings

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

National energy and material flows along the building supply chain in the EU

Juliana Barbosa [a,*], Sofia G. Simoes [a], Cristine Jordão [a], Ruichang Mao [b], Davide Aloini [c], Pierluigi Zerbino [c], Safaa Mabroum [c], Giammarco Montalbano [c], Husam Sameer [d], Hans H. Dürr [c], Bernardo Jerónimo [e], Ana T. Lima [b]

[a] *Resource Economics Unit, LNEG – National Energy and Geology Laboratory, 2720-999 Amadora, Portugal*
[b] *DTU Sustain, Department of Environmental and Resource Engineering, Technical University of Denmark, Kgs Lyngby, Denmark*
[c] *Department of Energy, Systems, Territory and Construction Engineering, Largo Lucio Lazzarino 1, University of Pisa, Pisa, Italy*
[d] *Engineering Hydrology and Water Resources Management, Faculty of Civil and Environmental Engineering, Ruhr-University Bochum, Bochum, Germany*
[e] *NOVA University Lisbon, Lisbon, Portugal*

ARTICLE INFO

Keywords:
Steel
Glass
Cement
Bricks
Construction stage
Raw material
CO_2 emissions
Construction
Supply chain

ABSTRACT

Construction activity is responsible for substantial greenhouse gas (GHG) emissions, but most of these reflect only a single stage of the building construction supply chain. Closing the gap, this work presents a cross-supply-chain perspective on annual material and energy consumption and GHG emissions for the sector on the European scale. These are estimated at the country level, disaggregated for raw material extraction, material manufacturing, demolition, and several intermediary transport stages. The study underscores cement, steel, flat glass, and ceramic bricks as manufactured materials; and sand, limestone, clay, iron ore, and coal as raw materials. Estimates consider both new construction and renovation, across varied typologies of residential and non-residential buildings. The results show that new construction & renovation of the building stock emits 235.31 Mt of CO_2 annually, excluding energy consumption for building operations. These are associated with the consumption of circa 1 994.29 Mt raw and construction materials, and circa 1 990.27 PJ of final energy per year. These figures correspond to 4.33% of the total EU values (45 923 PJ). New building construction and renovation account for 63% of the materials used, while the material manufacturing stage accounts for 74% of the final energy consumption. By adopting a full supply chain perspective at the European level, we can support the development of holistic and more targeted public policies to decarbonize the sector.

1. Introduction

The construction sector plays a significant role in global resource consumption and environmental impact because buildings require large quantities of materials throughout their construction, renovation, and end-of-life stages [1,2]. The extraction of raw materials, their transformation into construction products, transportation, and their incorporation into buildings generate substantial material flows, energy demand, and greenhouse gas (GHG) emissions [3]. The construction industry accounts for approximately 30% of global raw material use, including sand, timber, gravel, steel, cement, and plastics [3,4]. This extensive demand for materials is a major driver of resource depletion and environmental degradation [1,2,4].

The International Energy Agency highlights that the building and construction sector is accountable for nearly 40% of energy-related CO_2 emissions and 38% of total greenhouse gas emissions [5]. A significant share of these impacts originates not only from construction activities themselves but also from upstream supply-chain processes, particularly the extraction, processing, and transport of construction materials [6]. Consequently, understanding how environmental burdens are distributed across supply-chain stages and material types is essential for identifying effective mitigation opportunities.

The construction sector's reliance on non-renewable materials and energy resources further exacerbates its environmental impact. It is estimated that this industry consumes over 50% of the world's produced energy [4] and is a leading consumer of non-renewable materials [1]. The push towards sustainable construction practices is critical to mitigating these impacts, with strategies focusing on reducing material flows

* Corresponding author.
E-mail address: juliana.barbosa@lneg.pt (J. Barbosa).

https://doi.org/10.1016/j.enbuild.2026.118194
Received 30 January 2026; Received in revised form 31 August 2026; Accepted 2 September 2026
Available online 10 September 2026

[7], enhancing resource efficiency ([8]; [7]), and adopting circular-economy principles [9,10].

While previous studies have provided valuable insights into embodied carbon at the building level, they are typically based on individual case studies or specific building typologies and often adopt a whole-life-cycle perspective. In contrast, climate policies, GHG inventories, industrial decarbonization strategies, and resource-efficiency targets are primarily designed and implemented at the national level and on an annual basis. Therefore, there is a need for methodologies capable of translating building-related material demand into annual country-level estimates of raw material use, energy consumption, and GHG emissions across the construction supply chain. Such an approach requires the explicit allocation of impacts by material and supply-chain stage, allowing the identification of the industrial processes and economic sectors most directly associated with building activity. This level of disaggregation remains largely absent from the literature and is essential for supporting evidence-based policy design and monitoring progress towards climate and circular-economy objectives.

Accordingly, the objective of this paper is to quantify the annual primary raw materials, energy, and CO_2 emissions along the buildings supply chain in each EU country, including raw material extraction, material manufacture, construction (including maintenance and refurbishment), demolition, and waste transport/management and transport stages. Note that we do not consider the use phase of buildings because of their minimal material use and their focus on energy consumption (a widely studied topic annually for each EU country). The analysis focuses on four pervasive, carbon-intensive construction materials - cement, glass, steel, and ceramic bricks - and evaluates their contribution to the overall material, energy, and emissions footprint of the European building supply chain. By linking building activity to upstream resource extraction and manufacturing processes, the proposed framework provides a level of supply-chain and material-specific resolution that is particularly relevant for national policy assessment and intervention.

2. Methods

The flows of materials, energy, and CO_2 emissions in the supply chain for building construction consider seven stages: extraction of raw materials (i.e., mining and quarrying), transportation from extraction sites to manufacturers, construction materials manufacturing (steel, cement, flat glass and ceramic bricks), transportation from manufacturers to construction sites, building construction, and transportation from construction and demolition (CDW) sites to final waste disposal. The overall developed methodological approach is depicted in Fig. 1.

Herein, three flows are quantified: i. materials, ii. energy consumption and iii. CO_2 emissions, allocated to building construction and renovation along its supply chain, for each considered stage and per country. The analysis is disaggregated for each of the following carbon-intensive construction materials: flat glass, cement, steel, and ceramic bricks (hereafter, bricks). Supply chain mapping includes the description of explicit manufacturing processes, as described in [11]. The study also includes its associated raw materials, namely silica sand, common sand, limestone, clay, dolomite, gypsum, salt, and iron ore, as well as iron scrap, soda ash, fly ash, ammonia, coal (non-energy use), lime, and cullet.

The considered geographical scope comprises all countries of the European Union (EU27) plus the United Kingdom (UK), Switzerland, Iceland, and Norway, hereafter referred to as EU+ (see the completed list of countries and its abbreviations in Supplementary material a. The work is carried out for the current situation and for an average annual year, derived from annual values from 2017 to 2022 (excluding 2020; an atypical year due to the pandemic).

Embodied emissions associated with the import of construction materials and raw materials were not considered. Therefore, for those countries that do not manufacture one or more of the four studied construction materials, it is assumed that there is no corresponding raw material extraction, nor transport of manufactured products. It is

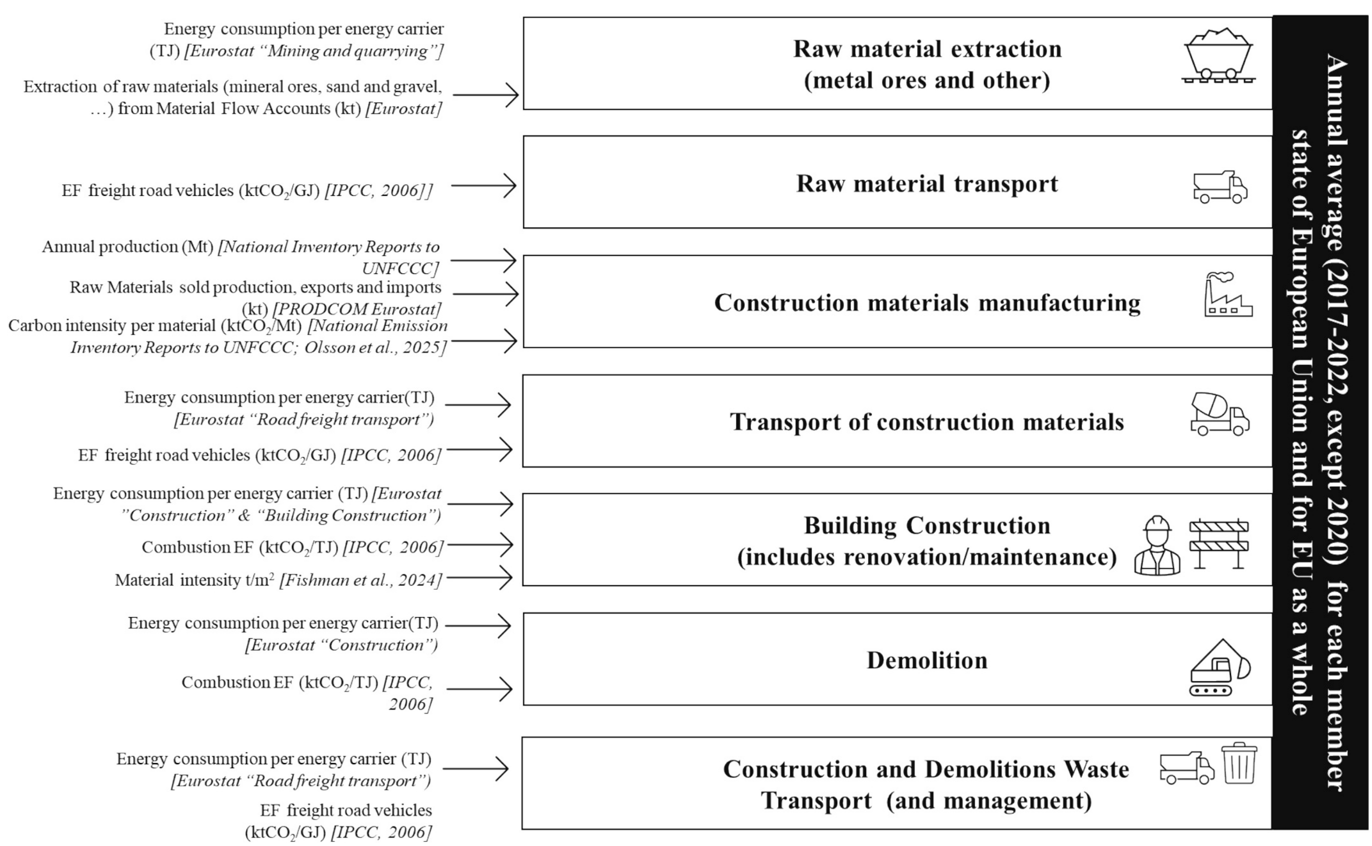

Fig. 1. General overview of the adopted methodology across the construction supply chain as considered for this study. EF stands for Emission Factors.

assumed that in these cases the construction materials are imported and thus are not modelled in this study.

Both new construction and renovation of residential and non-residential buildings are considered. Residential buildings are disaggregated into detached houses (SFH), semi-detached houses (MFH), and flats (ABL). Non-residential (or commercial) buildings are disaggregated into offices, hotels & restaurants, hospitals, small shops, large shops/shopping malls, and sports & recreation buildings.

Different types of renovation are considered, but only for residential buildings: deep, medium, and light renovation, which, in practice, differ in the types of interventions performed and thus in the materials and energy consumption involved. A light renovation is considered a relatively quick process (less than a week) that does not imply breaking down walls (e.g., replacing windows, roof tiles, or doors). A medium renovation is assumed to involve some masonry work and should last between 1 and 2 months (e.g., insulating windows, roofs, and/or floors). A deep renovation is assumed to be a more complex and lengthy endeavor, closer to building a new dwelling. It lasts more than two months and entails breaking down walls, changing the building/residence configuration (e.g., adding new rooms, walls), installing insulation on walls/roof/floors, installing new walls, and/or installing a new roof or new heating systems.

2.1. Building construction and renovation activity data in Mm^2

Although there are official national statistics on residential building stock, including the number of dwellings [12], and an indication of the average dwelling area (grouped by class [13], there is no data on built area per year. For non-residential buildings, there are no official national statistics on current building stock levels, current occupied areas, or built areas per year. Therefore, it was necessary to estimate these values in Mm^2, since this is the unit of measure required to estimate material use for new construction and renovation. The departing point was the existing building stock which is presented in Table 1. The area of residential buildings for EU+ is circa 16 154.04 Mm^2 according to official statistics. The stock of non-residential buildings was obtained from the JRC-EU-TIMES energy system model [14] and is estimated to be of 6 819.52 Mm^2. This is several times smaller than the stock of residential buildings, which represented 70% of the total European building stock.

JRC-EU-TIMES is a model that represents the entire EU+ energy system, including buildings (residential and non-residential), with high-level detail. It was developed by the Joint Research Centre of the European Commission and models the evolution of the energy building stock for each EU+ country from 2010 to 2050. The JRC-EU-TIMES model has been widely used to study climate and energy policies in the EU [15–18]. Residential buildings are modelled by number of dwellings, and non-residential buildings are modelled in Mm^2 using the same disaggregation of building typologies as in this study [19]: three types of residential buildings and six types of non-residential buildings. In this study, the number of dwellings was converted to Mm^2 by using an average dwelling area per country, based on ENTRANZE and IDEES data (summary in Table 3 of Supplementary material a.i) [20]. The detailed dataset with 2010 and 2050 building data considered in JRC-EU-TIMES is freely available [14,21].

To estimate built areas per year, new buildings' annual construction rate was derived from the assumptions in the JRC-EU-TIMES energy system model [14] for 2010 and 2050. The model considers the 2010 existing dwellings and non-residential buildings area per country and projects its evolution until 2050. In [14] study, it was assumed that there was a linear trend in building evolution between 2010 and 2050 and based on this it was derived the annual construction rate per country per building typology in Mm^2 (detailed values per country in Supplementary material Annex a.i).

Regarding renovation activity (only considered for residential buildings), annual average renovation rates of the total residential building stock per country were retrieved from European Commission [22]. This study covers residential building energy-related renovation activities and the uptake of nearly zero-energy buildings in the EU28 from 2012 to 2016, based on desk research and three surveys (targeting consumers, architects, and contractors/installers). Renovation activities are disaggregated by the potential primary energy savings achievable: "below threshold", "light", "medium", and "deep". The detailed country-level assumptions on renovation rates considered only the last three renovation categories and can be found in the Supplementary material ii.

Given the high uncertainty in the approach to construction and renovation activity data, the dataset was validated using the number of issued residential building construction permits, disaggregated by number of dwellings and residential building type. This information was available from the construction industry [23,24]. When not available for some countries, it was complemented with building permits per dwelling from Eurostat [12,25], including data from Census 2021[1] [26]. Building permits in Mm^2 for new buildings were translated into newly built areas per country. The allocation of this built area across the considered building typologies followed the allocation from the ENTRANZE project, available in [14] with data from [27–36]. More details on the approach used for validation of residential and non-residential construction and renovation activity data are presented in Table 4 of the Supplementary material i.

The considered annual construction and renovation activity in Mm^2 is presented in Table 1 for the whole of EU+. Values are presented by building type and disaggregated by new construction and type of renovation. Details of the residential buildings by country are described in Supplementary material a. i.

A total value of 1,185.84 Mm^2/yr is considered, including both new construction and renovation for the whole of EU+. The main activity, in terms of m^2 of floor area, is light renovation (67% of all construction and renovation activity in Mm^2), especially in flats (25% of all construction and renovation), followed by detached houses (23%). New construction accounts for only 11% of all construction and renovation activity in Mm^2 (i.e., 133.81 Mm^2/yr).

Construction and renovation in residential buildings are substantially larger than in non-residential buildings, especially given that renovation of the latter was disregarded due to a lack of data. Residential building construction and renovation account for 97% of the total Mm^2/yr considered. If only new construction is considered, residential buildings still account for circa 77% of the total Mm^2/yr.

In non-residential buildings, the main construction activity is new office buildings, with 12.34 Mm^2/yr. According to our calculations, the least significant activity in terms of Mm^2/yr is the deep renovation of semi-detached houses.

In the EU+, renovation accounts for 89% of total construction and renovation-impacted floors if it were being considered non-residential renovation, the total renovation would represent 91% albeit mainly light renovation. In terms of newly built areas, semi-detached houses are the most relevant, with 35.40 Mm^2/yr, followed by apartments with 34.84 Mm^2/yr, detached houses with 32.52 Mm^2/yr, and office buildings. The construction of new hospitals is the least relevant, with only 2.03 Mm^2/yr.

2.2. Material flows

The material flow approach comprises three stages: the extraction of raw materials (metal and non-metallic minerals); the manufacturing of materials (flat glass, cement, steel, and bricks); and the final construction of new buildings and the renovation of various types of buildings. Although there are transport stages between the stages, raw material

[1] In the case of Germany, Poland, Romania and UK, there is no information in the EUROSTAT Census 2021, and thus data from Census 2011 was used.

Table 1
Considered existing building stock, annual total average evolution in building construction and renovation per type of building in Mm^2 for EU+ and EU27

Type of buildings	Considered existing building stock EU+	% of total EU+	Type of Building Construction	EU+	EU27	% of total EU+	% of total EU27
Detached houses	5354.298	23.3%		32.52	25.70	3%	2%
Semi-detached houses	6251.166	27.2%		35.40	19.54	3%	2%
Flats	4548.573	19.8%		34.48	29.69	3%	3%
Hospitals	418.61	1.8%		2.03	1.82	0%	0%
Sport & recreation	973.98	4.2%		4.50	3.67	0%	0%
Hotels & restaurants	870.76	3.8%		3.83	3.26	0%	0%
Shopping malls	1,080.94	4.7%		5.01	3.95	0%	0%
Small shops	794.46	3.5%		3.70	3.24	0%	0%
Offices	2,680.77	11.7%	**New completed annual building**	12.34	10.64	1%	1%
Total	**22,973.56**	**100%**	**floor area**	**133.81**	**101.51**	**11%**	**10%**
Renovation for residential buildings							
Detached houses				270.12	252.51	23%	24%
Semi-detached houses				224.24	201.77	19%	19%
Flats			**Light renovation of the annual**	302.15	258.17	25%	25%
Total light renovation	n.a.		**building floor area**	**796.51**	**712.45**	**67%**	**69%**
Detached houses				67.29	61.75	6%	6%
Semi-detached houses				56.61	48.74	5%	5%
Flats			**Medium renovation annual building**	101.03	84.31	9%	8%
Total medium renovation	n.a.		**floor area**	**224.93**	**194.8**	**19%**	**19%**
Detached houses				8.40	7.82	1%	1%
Semi-detached houses				6.87	6.10	1%	1%
Flats			**Deep renovation of the annual**	15.31	13.73	1%	1%
Total deep renovation	n.a.		**building floor area**	**30.58**	**27.65**	**3%**	**3%**
Total renovation	n.a.			**1052.02**	**934.9**	**89%**	**90%**
Total construction & renovation	n.a.		**Total**	**1,185.84**	**1,036.39**	**100%**	**100%**

extraction, construction material manufacturing, and construction, they do not have an impact on material flows, and thus, they are not considered here.

To calculate the raw material flow from mining and quarrying into the construction sector, a mass balance and the total production of each manufactured product (cement, steel, flat glass, and bricks) were used Tables 1 and 2. To assess the required manufactured products, the total area of building construction (Table 1) was multiplied by the material intensity for each type of building and construction [37–39].

Table 2
Considered mass balances (t input/t produced material).

Raw Material	Cement	Steel	Flat glass	Bricks
Limestone	1.199	–	0.255	
Clay	0.202	–		1.35
Gypsum	0.053	–	–	–
Dolomite	–	–	0.17	–
Salt	–	–	0.257	–
Iron scrap	–	0.125	-	–
Silica sand	0.049	-	0.576	–
Common Sand	7			
Cullet	–	–	0.108	–
Ammonia	–	–	0.158	–
Lime	–	0.27	–	–
Fly ash	–	-	–	0.06
Iron ore	–	1.37	–	–
Soda ash	–	–	0.158	–
Coke (non energetic use)	–	0.78	0.014	–

For sand, it was considered two types, besides the silica sand used in flat glass production, common sand was also used in concrete preparation on construction sites.[2] (i.e., seven times the total mass of cement used). According to [40] the most common type of concrete in the European market has the proportion of 1:2:4 referring to: cement, fine aggregates and coarse aggregates. Please note that coarse and fine aggregates are both considered as “common sand” for the purpose of this paper. Therefore, considering both fine and coarse aggregates, we have a factor of 6 of sand for concrete only. However, if we consider the weighted average between mortar and concrete consumed in European residential buildings, this factor becomes 1 to 7. This is because the ratio of sand in mortar composition according to the European mortar standard EN 998-2 (mortar designation type iv) is of 1:8 cement: sand. Considering the RASMI database [37] mortar has a weight of circa 30% on what we assume to be “cement” in this paper (i.e. 30% of the of sum of mortar, cement and concrete).

Tables 23 and 24 in Supplementary material lists the manufactured products and the calculation of raw materials. Mass balances were assessed across all countries [41]; we set a threshold of 4% of the final product's mass, so we include only materials that exceed it.

[2] The total amount of sand in the construction sector was considered to be the sum of the total amount of silica sand used in the flat glass industry plus the total sand used in concrete. This approach has two problems: first, the purity levels of these two types of sand are completely different, meaning that the process losses in the silica sand preparation for flat glass production are not accounted for. The second problem involves some inconsistencies in cement production and sand extraction, which are detailed in Table 1 in the annex.

The second stage—product manufacturing—was based on required products for building construction, considering the construction area and material intensity as described before. For flat glass, raw material consumption was based only on original glass producers in 11 countries (DE, IT, FR, CZ, UK, BE, ES, HU, PL, RO, BG). Therefore, all the flat glass required in the EU+ countries was assigned to eleven producers adopted from [42].

In the third stage, construction of buildings (residential and non-residential). For residential buildings, both new construction and renovation were included. For non-residential buildings, only new buildings were included due to data limitations. Renovation was categorized into deep, medium, and light renovation. Non-residential building types considered were hospitals, sports & recreation facilities, hotels & restaurants, shopping malls, small shops, and offices. Residential building types considered were flats, detached houses, and semi-detached houses. The building classification is based on the Entranze project, [14].

For material intensity, the dataset RASMI [37] includes glass, cement[3], bricks and steel represent a literature review of 106 published papers and have 909 datapoints. For the missing countries, data are determined using climate-zone averages as proxies, except for Switzerland and Norway, for which the average is for residential buildings. For this dataset, when material intensity was specified in terms of concrete or mortar rather than cement, conversions were applied using a 0.13 ratio for concrete and a 0.21 ratio for mortar. In Norway, only concrete and wood were recorded. For non-residential buildings, material intensity is derived from the RASMI dataset and other data sources.

2.3. Energy consumption

Energy consumption was estimated for all seven stages of the supply chain, including the three transportation stages. One challenge in designing an energy consumption model for the building construction & renovation supply chain is isolating the energy used in this sector at each stage. For example, regarding raw materials, we know that Germany used an average of 4.32 TJ of electricity for metal ore mining between 2017 and 2022, excluding 2020 [43]. However, we do not know how much of this metal ore was converted into steel used in German building construction annually during this period.

To identify the energy that could be allocated to the extraction of raw materials used in building construction, the energy consumption data by economic activity is analyzed [4](or NACE) from the Eurostat dataset [33,43] was calculated energy intensity of mining metal ores and non-metallic minerals (Tables 11 and 12 in Supplementary material) in each country, and then it was multiplied by the required raw material calculated previously, considering the area of construction, building material intensity, and mass balances.

For Iceland, the UK, and Switzerland, disaggregated energy consumption by NACE is not available. For Iceland, national statistics were used. [44]. However, these are aggregated into total mining, without differentiating between per-metal, other, or support activities. All values were considered as non-metallic minerals mining, as there is no metal production on MFA [45] in Iceland and in the GHG emission inventories [46], they declared that they have no steel production. As the most recent data is for 2021, the average was calculated for 2017, 2018, 2019, and 2021.

For mining non-metallic minerals in the UK, it was used in the 2022 report ECUK [47]. There is no data on support services for mining, nor for metallic minerals mining, so this was considered zero. For Switzerland, even in the most disaggregated tables and reports, it was not possible to identify the amount of energy used in mining in any category [48]. To solve the problem, we calculate the average energy intensity for non-metal minerals (considering the average energy intensity of all other countries with data).

To calculate energy use for transporting raw materials from extraction sites to manufacturing locations, we considered the total raw material used in each country to estimate the total load to be transported. The average transportation distance in each country was obtained from national statistics [49] multiplied by two to reflect the assumption that transportation is by road and that trucks travel both ways — full on the way to the manufacturing site and empty on the return journey. The load per truck is assumed to be the maximum allowed according to the International Transport Forum [50]. Efficiency is assumed to be the same across all countries and products. For glass, only raw material transportation for original flat-glass producers was considered.

In the manufacturing step, it was considered the energy intensity for glass, cement and steel (Tables 15-17 in Supplementary material) calculated using the final energy consumption disaggregated by economic activity [43] divided by the annual production informed in the national inventories [46,51–53]. After having energy intensity, it was multiplied by the required manufactured products Table 3 to calculate the energy used attributable to the manufacturing of the main construction products.

In the case of bricks, the energy consumption cannot be calculated using this method because the energy consumption data [43] for ceramics is aggregated in "*Manufacture of other non-metallic mineral products except glass, glass products, cement, lime and plaster*" that includes all the activities of NACE 23 except glass (231) and cement (235). This set contains materials with very different energy requirements. For the production of refractory products (232), for example, the average temperature of the oven is above 1000°C [54] and the concrete products (236) are around 200°C [55], so it means that we cannot use, in this case, the assumption that energy use is proportional to mass. For ceramics, we used the average energy intensity of 1.50 GJ/t [56] for bricks and multiply it by the total production in kt (Table 3). To allocate the consumed energy by energy vector, the share of 2022 in the NACE 23, except glass (231) and cement (235) [43].

To allocate energy used in raw-material extraction by material type, we considered each material's relative mass. We multiplied the mass balances by total production to estimate the raw material required for each country. Then, we calculated the relative importance of cement, glass, ceramics, and steel in the total material mix. This helped estimate the raw material extraction energy consumption that could be allocated to each material (cement, glass, ceramics, and steel), as shown in Table 20 in Supplementary material

The energy used for manufacturing is not available for all 31 countries. For example, the Netherlands did not report the natural gas used for glass, cement, and ceramics production in Eurostat; the missing data were obtained from national statistics [57]. For Switzerland and the United Kingdom, these three products were aggregated into a single category in the national statistics. To disaggregate them, we used the total production (in kt) reported in the UNFCCC GHG emission inventories for 2019 [46,48,58].

For cement production in Denmark, this method could not be applied because the total energy for the "nonmetallic minerals" category is not disaggregated in the national statistics. For this country and sector, we used the average of the other countries for each energy vector.

In the transportation stage from manufacturing sites to construction sites, the total load is the mass of the specific products. The efficiency is assumed to be the same as in the previous transportation stage, and the distance is based on values from several Environmental Product Declarations, as listed in the Supplementary material c.iii, Table 19. It was assumed that one-third of the trucks returned empty.

[3] In the Rasmi dataset, cement and mortar were considered as cement and ceramics and bricks were considered as bricks.

[4] Disaggregated final energy consumption in industry by NACE Rev. 2 activity – quantities [nrg_d_indq_n_custom_12832660] EUROSTAT– "Mining of metal ores except mining of uranium and thorium ores [B07_X_B0721]", "Other mining and quarrying except extraction of peat [B08_X_B0892]" and "Mining support service activities [B09]".

Table 3
Annual estimated production of manufactured materials consumed in building construction & renovation in Mt.

Country	Estimated production of manufactured materials (Mt)					Difference from total production in UNFCCC (%)		
	Cement	Steel	Flat Glass	Bricks[a]	Total	Cement	Steel	Glass
AT	4.64	3.14	0.00	2.41	**10.19**	−26%	119%	
BE	6.60	5.99	0.49	2.39	**15.46**	−24%	29%	188%
BG	1.25	0.71	0.43	0.87	**3.26**	70%	−18%	41%
CH	4.57	4.74	0.00	2.26	**11.56**	−29%	−76%	
CY	0.44	0.00	0.00	0.32	**0.77**	240%		
CZ	0.39	3.07	0.43	2.77	**6.67**	847%	50%	172%
DE	9.39	3.80	1.94	8.03	**23.16**	167%	943%	279%
DK	2.24	0.00	0.00	1.64	**3.88**	−4%		
EE	0.09	0.00	0.00	0.05	**0.14**	462%		
EL	3.01	1.37	0.00	1.39	**5.77**	114%	−1%	
ES	17.49	5.75	0.73	6.73	**30.70**	0%	137%	555%
FI	1.15	1.13	0.00	0.58	**2.87**	−1%	204%	
FR	19.83	12.64	0.97	9.40	**42.85**	−35%	15%	250%
HR	0.98	0.46	0.00	0.72	**2.16**	132%	−85%	
HU	0.84	0.24	0.26	0.99	**2.33**	31%	652%	41%
IE	2.33	0.00	0.00	1.65	**3.99**	48%		
IS	0.00	0.00	0.00	0.00	**0.00**	–		
IT	23.29	6.11	0.97	4.56	**34.93**	−35%	279%	521%
LT	0.35	0.00	0.00	0.20	**0.55**	205%		
LU	0.56	0.00	0.00	0.46	**1.02**	44%		
LV	0.12	0.00	0.00	0.09	**0.21**	817%		
MT	0.00	0.00	0.00	0.08	**0.08**	–		
NL	8.09	10.21	0.00	2.40	**20.70**	−100%	−33%	
NO	1.74	1.24	0.00	1.14	**4.12**	−19%	−50%	
PL	5.79	4.47	1.13	4.08	**15.47**	145%	103%	208%
PT	5.65	3.36	0.00	3.75	**12.76**	−24%	−73%	
RO	3.10	2.59	0.25	2.69	**8.63**	136%	40%	41%
SE	3.83	4.02	0.00	1.87	**9.71**	-34%	−53%	
SI	0.47	0.39	0.00	0.41	**1.26**	98%	66%	
SK	1.14	0.99	0.00	0.96	**3.09**	151%	264%	
UK	18.60	33.37	0.49	9.61	**62.07**	−58%	−78%	348%
EU+	**147.96**	**109.79**	**8.10**	**74.51**	**340.37**	**2%**	**41%**	**348%**

[a] There are no national or EU-wide statistics on volumes of bricks manufactured.

In the construction stage, the total energy used in construction [43] was based on the value of building construction [59]. It was assumed that this was the total energy per energy carrier used in the building construction sector. To split this value in terms of building/construction typology, the area of each building/construction typology was used (Table 1). To estimate how this energy could be split by material, a weighted material intensity was used, multiplying each material's intensity by the area of each typology and construction type in each country, Table 20 in Supplementary material.

The total energy used for demolition is the total energy used in construction, multiplied by the relative importance of the demolition subsector within the construction sector, based on the gross added value of demolition [59]. The final transportation after demolition considered the total Construction and Demolition Waste from EUROSTAT [32,60–62], Table 21, in 2022 (the most recent year), in terms of mass. The distance was based on the average freight transportation distance in each country [49]. The share attributed to each material was derived from the same weighted average material intensity, Table 20 in Supplementary material.

2.4. CO2 emissions estimates

To estimate annual CO_2 emissions for each of the seven considered supply chain stages, energy consumption was disaggregated by energy carriers. The emission estimation approach considers the emission factors (EF) for energy combustion activities from the IPCC [63]. For stationary sources, the values considered were 56 CO_2/GJ for Natural Gas, 74 CO_2/GJ for Oil products, and 105 CO_2e/GJ for solid fossil fuels. The EF for consumed electricity varies depending on the power mix of each country, and thus, country-specific EFs were adopted for the year 2023 [64]. To estimate transport emissions, it was assumed that all transport stages were carried out entirely by road and using diesel-fueled trucks. Therefore, the considered EF was 74,1CO_2/GJ diesel [63].

In the manufacturing stage, in addition to emissions from energy consumption, emissions from industrial processes were also considered. Fig. 2 illustrates the adopted approach for CO_2 emissions calculations as the sum of emissions from energy consumption and from industrial processes, calculated with the national GHG emission inventories submissions to UNFCCC [46]. In the case of bricks, the EF was 0.17 kt CO_2/kt [56].

3. Results

This section presents the main results regarding material flows, energy consumption for the building construction supply chain, and subsequent CO_2 emissions. The results are mostly shown for the EU+ countries, but detailed results per country are presented in the Supplementary material.

3.1. Materials' flows

The materials' flows were estimated disaggregated per raw materials and manufactured materials (steel, cement, flat glass and bricks). Although the raw materials stage precedes material's manufacture, in this work annual manufactured materials' flows for buildings construction and renovation were calculated as a preliminary step and thus are shown first in this section (Table 3).

It is estimated that a total of 340.37 Mt of the four construction materials is manufactured per year for EU+ building construction and renovation. Of these, 43% is cement, 32% is steel and 22% bricks. Several countries do not manufacture all these materials (or any, as is the case of IS). As mentioned in the previous section, for these countries, it is assumed that construction materials are imported.

Although domestic and extra-EU trade is out of the scope of the

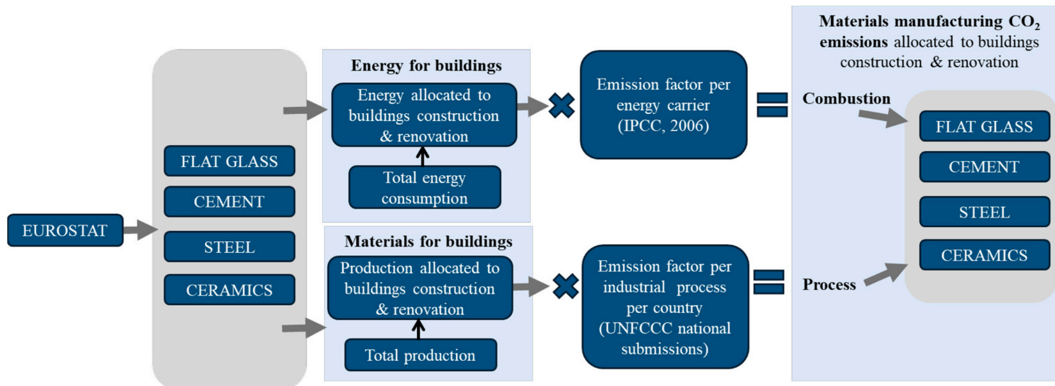

Fig. 2. Approach used for estimating GHG emissions from material manufacturing.

current work, Table 3 shows a comparison between the estimated required manufactured products calculated in the current work and the reported total production to the UNFCCC [46]. Negative values indicate a country with estimated materials for building construction & renovation above the total national production, i.e. they are net importers. On the other hand, the countries with positive differences could indicate net exporters of those materials. Furthermore, it should be noted that cement, steel and glass are destined for other uses besides the construction and renovation of buildings that are also beyond the scope of the current work.

The manufacture of construction materials drives the corresponding raw material extraction as in Fig. 3. 1,653.92 Mt of raw materials are consumed per year in EU+ for building construction and renovation (being 1 605.21 Mt of primary raw materials and 48.71 Mt of secondary raw materials). Common sand is the raw material with the highest consumption (average annual consumption of 1 088 Mt for new building construction & renovation across all EU+ countries). This is followed by limestone (188 Mt), iron ore (158 Mt), and, finally, 112 Mt of clay and non-energetic use of coal (89.8 Mt). The high consumption of common sand is justified by concrete manufacturing, which accounts for 7 times the volume of cement in a standard concrete recipe. Final computation estimates that common sand consumption in building construction accounts for 65% of all raw materials.

When looking at the results from a construction material perspective, steel is the material with the highest raw material consumption, with circa 279 Mt annual average consumption in EU+, followed by cement (222 Mt), bricks (105 Mt), and finally flat glass with only 11 Mt consumption for building construction & renovation.

Raw material flows' results per country are depicted in Fig. 3B and Supplementary material e.i. (Table 23). UK, Italy, Spain, and France are the largest consumers of raw materials for building construction & renovation. In these countries, material consumption is 10 times higher than in other EU+ countries, such as DK, NO, or IE. The disaggregation of raw materials consumption per country aligns with the overall EU+ figure, with common sand as the largest raw material consumed across all countries, followed by iron ore, limestone, and clay. Having said that, there are minor variations in the raw materials' national profiles, as some countries do not manufacture flat glass, iron, steel, cement, or brick products for building construction.

Another way to show the national variation in raw material consumption is calculating a raw material intensity index per country in EU+ by dividing total raw materials consumed per m^2 of newly added/renovated annual built area per country (Fig. 4). Malta is the country that consumes the least material per m^2 of constructed & renovated building (154kg/m^2), with Greece being the most material-intensive country (2447kg/m^2). The estimated raw material production in Malta is 272 times lower than in Greece, and the estimated constructed area is 17 times bigger in Greece than in Malta.

Finally, regarding the overall flows across EU+ Fig. 5 shows the complete annual average material flows for building construction and renovation across the raw material and manufacturing stages, detailed per material, building type, and construction/renovation activity. The construction & renovation of residential buildings uses more materials than the construction of non-residential buildings. Common sand is not represented in Fig. 5. Residential buildings consume most of the construction materials – 7.81 Mt/yr - while non-residential consume only 0.285 Mt/yr. New residential building construction dominates material consumption. The complete tables with the detailed data are in Supplementary material e.i.

3.2. Energy consumption for building construction supply chain

Regarding energy consumption per stage of the supply chain, Table 4 shows values for the whole of EU+. Most of the energy (73.91%) is consumed during the material manufacturing stage, followed by the construction stage (18.63%). It is worth mentioning the type of energy carriers being consumed. In global terms, electricity represents only 26%, and natural gas 30%. Coal accounts for 9%, whereas oil is consumed at all stages, accounting for 31%.

Similarly to materials flows that are allocated to building construction & renovation, the energy consumed for manufacturing the four studied construction materials for buildings is a fraction of all the energy used for these materials production, considering all other uses in both non-building construction and in non-construction uses (Fig. 6).

The fractions vary per country, and detailed results are presented in Supplementary material e.ii, Table 33. At an aggregated EU+ level, the results show that final energy consumption for total steel manufacturing is the highest compared to other construction materials, with 834 PJ/yr versus 581 PJ/yr for total cement, 437 PJ/yr for ceramic[5] products, including bricks, and only 289 PJ/yr for total glass (including flat glass). When zooming in on the four studied construction materials and only on the ones used for building construction & renovation, it is estimated that energy consumption for steel manufacturing is the highest (680 PJ), followed by cement (612 PJ), bricks (112 PJ), and only then by flat glass (68 PJ).

The difference in energy consumption between total material manufacturing and materials used only in building construction and renovation is also visible in Fig. 6. There we can observe that the estimated final energy consumption for cement production for buildings construction in EU+ is above the final energy consumption for total cement production (105%) in EU+. This difference can be explained by international trade, which is beyond the scope of this work, as mentioned in section 2.b. Table 3 showed the disparities in the estimated required cement and the declared national production to UNFCCC. This

[5] Ceramics here is the broad category "Manufacture of other non-metallic mineral products except glass, glass products, cement, lime and plaster".

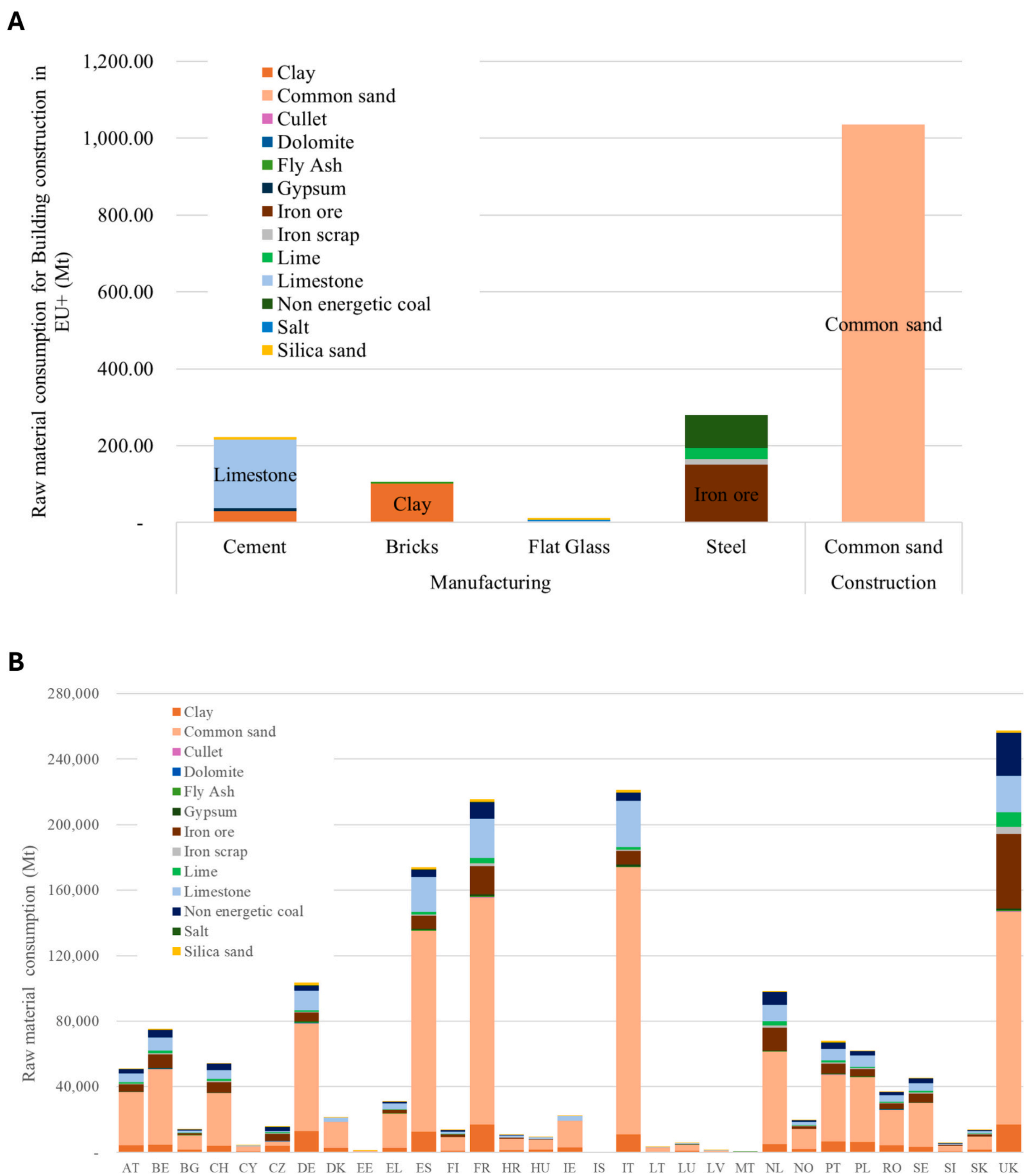

Fig. 3. A) Total annual average raw material consumption for building construction & renovation per material for EU+; B) Annual average consumption of raw materials for building construction & renovation by country, including sand.

could justify the difference in estimated final energy consumption for cement production. For steel manufacturing, 82% of final energy consumed for all steel manufacturing is allocated to steel for building construction and renovation. These shares are 26% for flat glass and 23% for bricks.

3.3. CO2 emissions along the construction supply chain

Fig. 7 shows average annual CO_2 emissions for the whole supply chain per construction material for EU+ countries, disaggregated by supply chain stage and type (i.e., resulting from energy combustion across all stages and from process emissions that occur solely during the material manufacturing stage). The results show that, annually, building & renovating the building stock in the EU+ emits 235.31 Mt of CO_2 (these emissions do not include the buildings' operational stage, i.e., energy consumption for building operation). Clearly, process emissions are the most relevant source of CO_2, and among these, emissions from clinker production within cement production are the most pertinent (78.31Mt CO_2), representing 33% of all annual CO_2 emissions estimated. These are followed by energy emissions from cement (37.86 Mt, or 16.1% of total emissions) and process emissions from steel production (circa 37 Mt CO_2, or 15.7% of total emissions).

Fig. 7 also presents CO_2 emissions associated with each stage of the building construction & renovation supply chain. It shows that

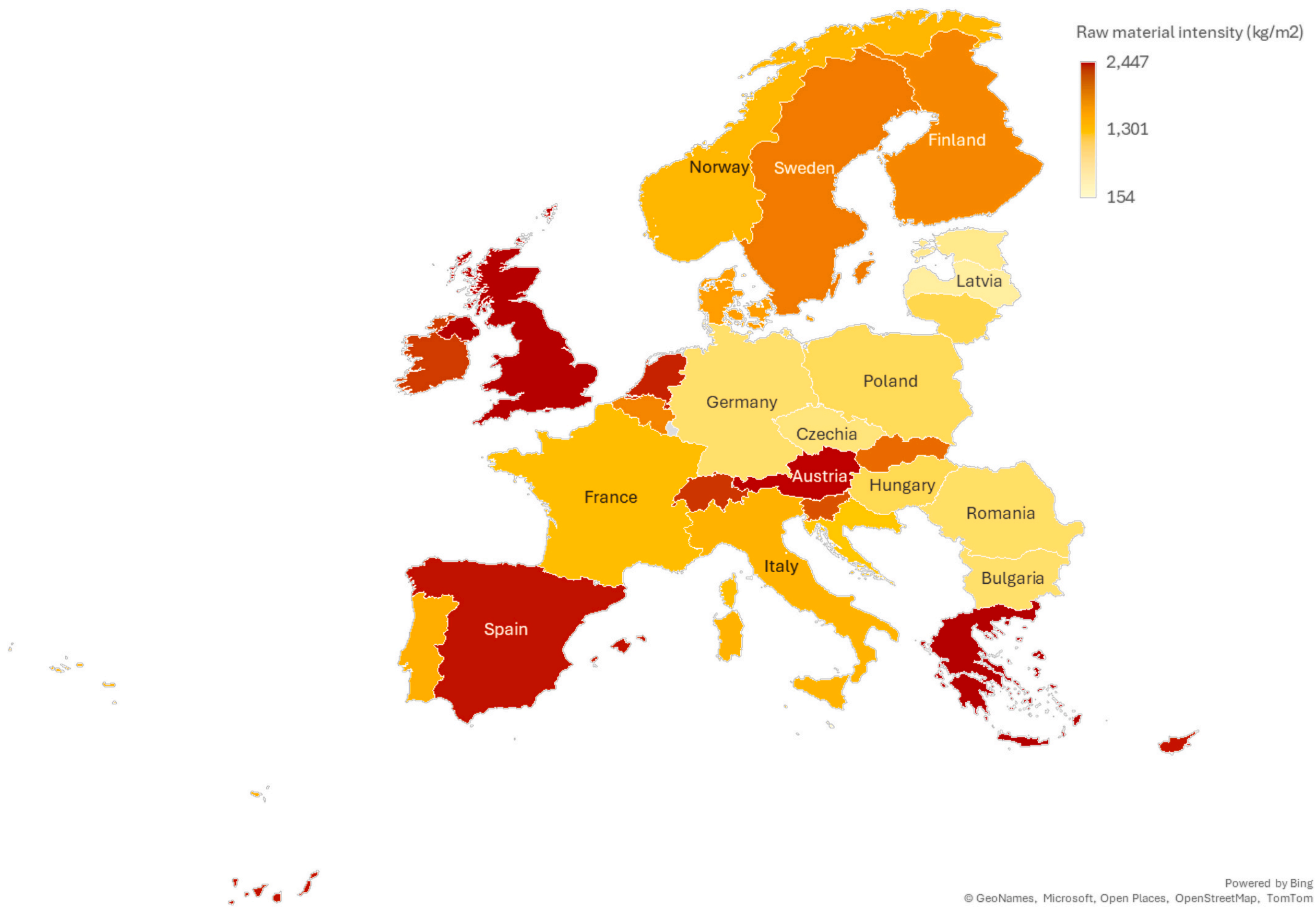

Fig. 4. Total raw material intensity in kt per m^2 of newly built & renovated area per country per year.

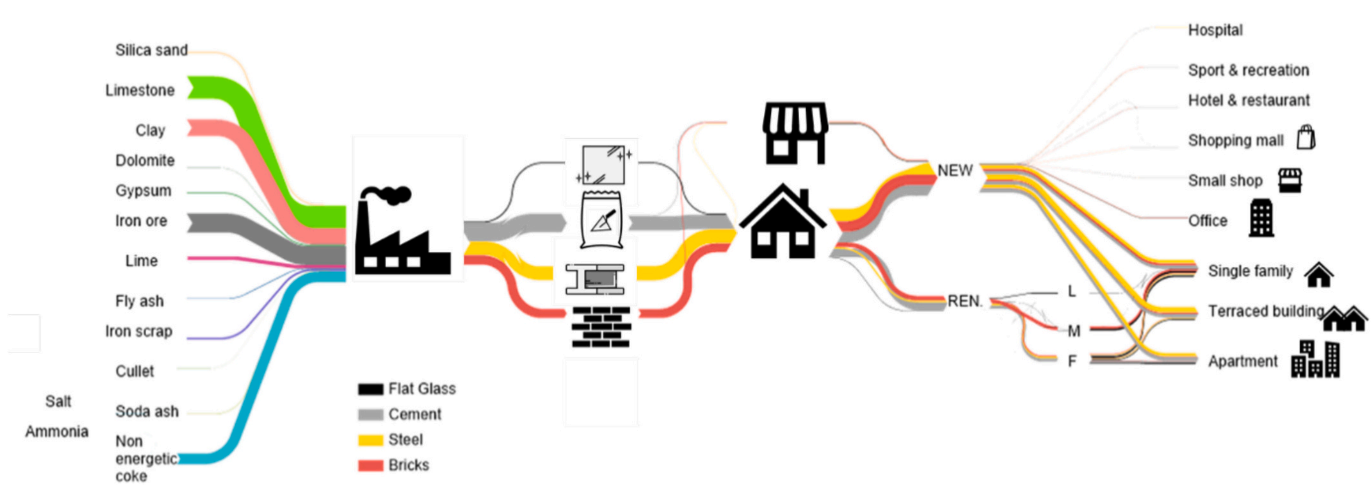

Fig. 5. Annual average material flows for building construction and renovation in the overall EU+. New stand for new construction and REN stand for renovation. L stands for light renovation, M for medium renovation and F stands for Deep renovation. Common sand is not represented.

manufacturing accounts for 86% of the sector's total CO_2 emissions. The construction stage accounts for approximately 10.1% of total emissions, well below the manufacturing stage (Fig. 7A). The transport stage accounts for 1.8 % of the total footprint, with construction and demolition waste transport accounting for 0.34% of total emissions. In turn, the raw materials extraction and demolition stage each account for 1.5% and 0.08% of total emissions, respectively. To split energy by material during the construction stage (and consequently the emissions associated with each material), we used a weighted material intensity based on the specific material intensity for each building type and the area of each type constructed (Table 25).

United Kingdom is the country with the highest CO_2 emissions from building construction, Fig. 7B, at around 34 277 kt CO_2/year. France is the second-highest emitter (32 790 kt CO_2/year, Italy is the third-highest emitter (27 906 kt CO_2/year), followed by Germany, Spain, Austria, Belgium and Poland, with around 20 Mt, 19 Mt, 11.44 Mt, 11.43

Table 4
Average annual energy consumption along the building construction supply chain in EU+ countries in PJ. % of total energy consumed during the manufacturing stage is shown in red and bold.

Supply chain stage	Energy carrier	EU+	
		PJ	%
Extraction of raw materials used in buildings	Solid fossil fuels	1.62	
	Natural gas	37.57	
	Oil products	7.59	
	Renewables	0.35	
	Electricity	13.65	
	Subtotal Extraction	60.78	3.05%
Transport of raw material extracted	Oil products	37.16	1.87%
Manufacturing used in buildings	Solid fossil fuels	172.36	
	Natural gas	471.94	
	Oil products	318.78	
	Renewables	92.30	
	Electricity	415.57	
	Subtotal Manufacturing	1,470.95	**73.91%**
Transport of manufactured products	Oil products	20.38	1.02%
Construction of buildings	Solid fossil fuels	0.52	
	Natural gas	79.31	
	Oil products	199.17	
	Renewables	6.53	
	Electricity	85.36	
	Subtotal Construction	370.88	18.63%
Transport of demolition waste	Oil products	27.32	1.37%
Demolition	Solid fossil fuels	0	
	Natural gas	0.68	
	Oil products	1.44	
	Renewables	0.04	
	Electricity	0.64	
	Subtotal Demolition	2.8	0.14%
TOTAL		**1,990.27**	100%

Mt and 11.18 Mt, respectively. The remaining countries are below 10,000 kt CO_2/year, and some are even below 1,000 kt. Luxembourg, Lithuania, Latvia, Iceland, Cyprus, and Estonia are among the countries with the lowest emissions. Malta stands out as the country with the lowest annual emissions (77.37 kt CO_2/year), possibly due to its smaller size and the lack of data reported to Eurostat.

In almost all countries, the manufacturing stage is responsible for more than half of the CO_2 emissions, and in some countries, even more than 90% of the supply chain emissions, as is the case in BE, IE, EL, SK, SE, AT, PT. BG, CH, and LU. IS is the only country where manufacturing is not the stage of the supply chain with the highest associated emissions; there are no emissions at all, as this country does not manufacture construction materials. The construction stage is, in almost all countries, the second-largest emitter of CO_2, except in Iceland, where it is the largest. Emissions from this stage also stand out in countries such as Hungary, Latvia, Estonia, and Malta, accounting for more than 30% of total emissions. The transport stage of construction materials is the third-largest source of CO_2 emissions. In the UK, PL, and ES, this stage is responsible for more than 2.6% of each country's CO_2 emissions. Emissions from the extraction of raw materials and the demolition of buildings are together responsible for approximately 1.58% of total emissions worldwide, except in IT, the UK, PL, and EL (4.74% in Italy and 3.27%, 2.58% and 1.93% in the others respectively). For the other countries, the emissions are below 1.5%.

4. Discussion

4.1. Discussion of the results

This study highlights the total use of materials, focusing only on cement, steel, bricks, and flat glass. Among the four materials, cement shows the highest consumption in buildings construction compared to the EU-wide average (Table 3). Indeed, cement is almost exclusively used for construction, while the other considered materials (steel, flat glass, and bricks) have multiple uses besides construction. When it comes to new buildings, Europe is indeed an established continent, where new structural projects such as bridges and tunnels are scarce, explaining the high use of cement in buildings construction. Consequently, cement also presents the most carbon-intensive material in the construction of new buildings (Fig. 7A). Steel follows cement closely, exceeding it in material requirements (Fig. 3B) by requiring 279 Mt of raw materials, but falling behind in GHG emissions (Fig. 7A). Brick and flat glass are the least consumed materials – as expected – due to lower demand for new buildings and renovations. The vast existing literature on the use of construction materials in buildings already predicts this,

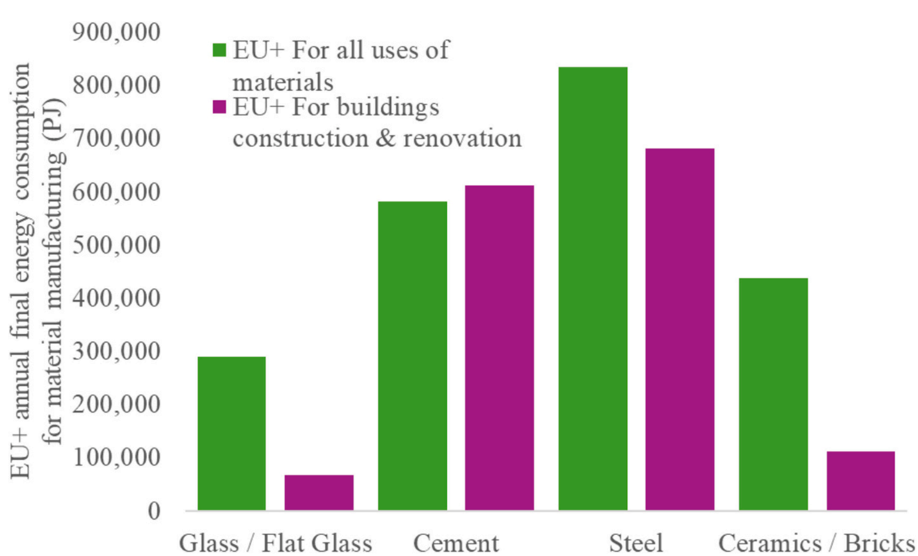

Fig. 6. Annual average energy consumption for construction material manufacturing per construction product for total material manufacturing (in green) and only for construction materials used for building construction and renovation (in purple).

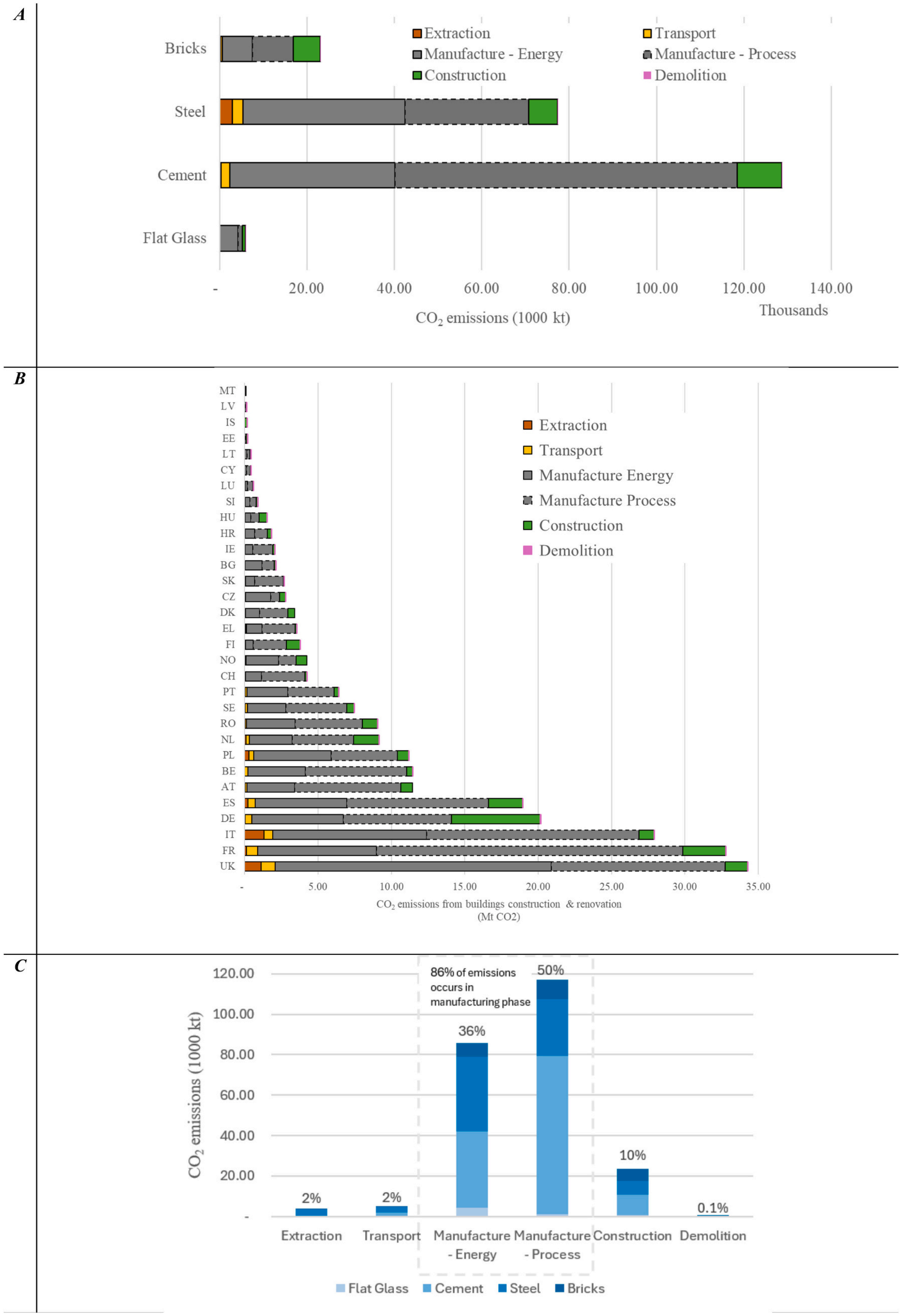

Fig. 7. A) Annual average CO_2 emissions for the overall EU+ countries for the construction supply chain; B Emissions of Buildings construction by stage and country EU+.

for example [37,65,66]

While the RASMI database [37] provides material intensities coefficients differentiated by region, building function, and structural typology, it does not quantify how this material intensities translate into annual material flows, energy consumption, and GHG emissions across the construction supply chain at the national level. In contrast, the present study integrates building activity data, material intensities, industrial production, and supply-chain processes to quantify resource use and emissions from raw material extraction to demolition and waste management across 31 European countries. Furthermore, unlike studies such as Matching Demolition and Construction Material Flows [67], which focus primarily on balancing construction demand and demolition waste flows, this work provides a comprehensive assessment of material flows, energy consumption, and CO_2 emissions across multiple supply-chain stages, enabling the identification of cross-supply-chain decarbonization hotspots and intervention opportunities.

Our analysis estimates, for the first time, that the production of cement, steel, ceramic bricks, and flat glass used annually in building construction and renovation requires 1,654 Mt of raw materials, corresponding to approximately 42% (Table 5) of the total metal ores and non-metallic minerals extracted in the EU+ region. This indicator therefore represents the contribution of building-related demand for these four materials to total economy-wide mineral extraction, rather than a share within the supply chains of the selected materials. Previous studies have allocated over 52% of materials to building construction [68]), based on material footprint estimates (the number of raw materials extracted from nature, both within and outside the EU). It should be mentioned that comparison between the 42% estimated in this study and the 52% reported by the EEA should be interpreted with caution due to differences in system boundaries. While the EEA estimate is based on a consumption-based material footprint approach that includes global supply chains and international trade, this study adopts a bottom-up assessment of four construction materials used in building construction and renovation within the EU+. Therefore, the two indicators are not directly comparable but provide complementary perspectives on the resource demands of the building sector [68,69].

Our bottom-up approach to raw materials accounting across the supply chains of cement, steel, brick, and flat glass represents a step towards a supply chain-based approach to mitigation. To complement this comprehensive approach, we should include aluminum and polymers, among others. Understanding the order of magnitude of the building supply chain's impact on each individual material supply chain is relevant not only to material producers but also to policymakers.

Table 5
Fractions of materials (cement, steel, bricks and flat glass), energy consumed and CO_2 emitted for the (new and renovations) building supply chain in relation to the total consumed in EU+.

	Full (new and renovation) building supply chain	Total EU+	Fraction of (new and renovation) building supply chain compared to the EU+ total consumption
Raw material (Mt)	1 654.18	3 959.65 *	42%
Energy consumption (PJ)	1 990.27	45 923.49 ‡	4.33%
Carbon dioxide emissions (Mt CO_2)	235.31	2 972.67 ǂ	7.92%

ǂ considering 2017 to 2022 average, except 2020. ([70]; [71]).

* considering the average between 2017 and 2022 except 2020 ([45]; [72]) considering the sum of MF2 (Metal ores (gross ores)) and MF3 non-metallic minerals (Non-metallic minerals).

‡ considering the average for 2017-2022 except 2020 [73]. For UK it is the average between 2017 and 2019 and for Switzerland is the 2022 value [74].

After addressing the construction stage – which has so far been underexplored – we focus on the manufacturing stage. Material manufacturing is singled out here as the supply chain stage with the highest energy consumption, accounting for 73.91% of the supply chain's final energy consumption in new building construction and renovation (Table 4). The 73.91% considers only four material supply chains – cement, steel, brick, and flat glass. From the four materials studied, cement and steel manufacturing have the highest representation (Fig. 7). The consumption of 1 654 Mt of raw materials for cement, brick, flat glass, and steel production accounts for 1 990.27 PJ of energy consumption, and 235.31 Mt of CO_2 emissions annually. In relative terms, materials consumed in the building supply chain account for 42% of mineral raw materials, 4.33% of energy consumption and 7.92% of CO_2 emissions of the total EU+ consumption/emissions (Table 5). While the bulk of energy is not so expressive in the total energy consumption, the corresponding fraction of carbon emissions more than doubles this impact. This number underscores the need for the material manufacturer to rely on cleaner energy sources during manufacturing. Understanding the effects of production, consumption, and waste management at the material unit of analysis is considered a key action in several ambitious EU policies impacting the building construction supply chain, including the Critical Raw Material Act [75], and the Circular Economy Act [76]. One example of a full supply chain of materials has been addressed for plastics [77]. For cement, steel, brick, and flat glass, we can conclude that the main gains in CO_2 reductions are in the manufacturing processes of cement and steel.

The main limitations we observed stem from uncertainty regarding primary data on annual building construction and renovation activity. These statistics do not exist, and we estimated them using several assumptions with high levels of uncertainty. The adoption of material intensity coefficients is an uncertain practice to start with, as we assume a single coefficient as representative of a diverse building stock, and is aggravated by the scarce literature for non-residential buildings. We list these assumptions and other limitations in the Supplementary material.

In summary, this study delivers, for the first time, the following figures:

- 42% of all raw materials used in the manufacturing of cement, steel, brick, and flat glass in EU+ come from the construction of new buildings and renovation of the building stock, annually.
- 73.91% of the whole building supply chain energy consumption is allocated to the material manufacturing stage – the number drops to 4.33% of the total annual EU+ energy consumption;
- 235.31 Mt of CO_2 emissions come from new building construction and renovation every year – an amount that represents 7.92% of the total European emissions.

Beyond quantifying impacts, the results provide insights for policy prioritization. The finding that manufacturing accounts for the largest share of supply-chain energy consumption and emissions indicates that the greatest mitigation potential lies in the decarbonization of material production, particularly cement and steel. Therefore, policies promoting low-carbon manufacturing processes, increased recycling rates, material efficiency, and the use of secondary raw materials are likely to achieve larger reductions than interventions focused exclusively on construction activities. Furthermore, the quantification of raw material requirements associated with buildings supports the objectives of European resource-efficiency, circular-economy, and critical raw materials policies by identifying the materials and supply-chain stages where demand-reduction and circularity measures can have the greatest effect. The methodology can therefore contribute to monitoring progress towards both climate and resource-efficiency targets by explicitly linking building activity to upstream material, energy, and emissions flows.

4.2. Uncertainties, assumptions and limitations

The quantification of material flows, energy consumption, and GHG emissions across seven stages of the building construction supply chain and 31 countries necessarily required a number of assumptions due to limitations in the available data. Consequently, the results should be interpreted as indicative estimates of the magnitude and distribution of impacts rather than exact values.

A major source of uncertainty concerns the estimation of construction and renovation activity. Harmonized statistics on annual newly constructed and renovated floor area are not available across all countries considered in this study. Alternative data sources, including Eurostat building permit statistics and data from the European Construction Industry Federation (FIEC), were explored but were found to be incomplete or inconsistent for several countries. Comparisons with alternative datasets revealed differences of up to a factor of three in estimated construction activity for some cases. To improve robustness, the estimates were cross-checked against census data and the building stock representation of the JRC-EU-TIMES model [14]. Nevertheless, uncertainties in construction and renovation activity propagate throughout the assessment and directly affect the estimated material demand, energy consumption, and emissions. Future studies should prioritize the development of harmonized European datasets and perform formal uncertainty propagation analyses, such as Monte Carlo simulations.

Additional uncertainty is associated with the use of representative material and energy intensity coefficients. Construction energy consumption was assumed to scale proportionally with the affected floor area, while material requirements were estimated using average material intensity values differentiated by country and building typology. Although necessary at the European scale, these assumptions simplify the heterogeneity of construction techniques, structural systems, and design solutions observed in practice. Consequently, the framework may not fully capture variations within individual building categories. Although country-specific material intensity coefficients were adopted, these values remain simplifications of highly heterogeneous building stocks. Differences in construction technologies, structural systems, seismic regulations, climatic conditions, and national building codes may lead to substantial variability in material requirements within the same building typology. Consequently, the adopted coefficients should be interpreted as representative averages rather than precise descriptions of all buildings within a country. Future research should seek to develop more spatially resolved material intensity datasets that explicitly account for these factors, thereby improving the accuracy of national and cross-country comparisons.

The material intensity estimates adopted from the RASMI database [37] constitute another important source of uncertainty. Although RASMI currently represents one of the most comprehensive datasets available, substantial differences are observed across countries, particularly for cement and steel use in residential buildings. Extreme values, such as those observed for Greece and Malta, are therefore largely driven by the underlying data source rather than by assumptions introduced in this study. These discrepancies may reflect genuine differences in construction practices, limitations in data availability, or methodological constraints associated with the original database. Accordingly, country-level comparisons involving particularly high or low material intensity values should be interpreted with caution.

A further limitation arises from the adoption of a territorial accounting perspective. International trade flows of construction materials and their associated embodied emissions were not explicitly modelled. As a result, impacts associated with imported materials are not captured within the countries where these materials are ultimately consumed. This limitation is particularly relevant for smaller and highly import-dependent economies, where a substantial fraction of material-related impacts may occur outside national borders. Similar divergences between production-based and consumption-based assessments have been widely documented in the material footprint literature [69,78]. The occurrence of values exceeding 100% in the allocation of final energy consumption to cement production illustrates this limitation and should be interpreted as a consequence of the combined effects of estimated material demand, production statistics, and the exclusion of trade flows rather than as a physical result. To better deal with this limitation, we made alternative calculations for allocation of GHG, energy and raw materials to each country that now correspond only to the construction materials quantities being manufactured nationally. Any additional material demand is met through imports and emissions; energy and materials are not considered. Under this assumption, values above 100% no longer occur and the estimated impacts at EU+ level are reduced by 32% for GHG emissions, by less 34% for raw material consumption and by less 40% for energy consumption compared with the baseline results. However, this approach effectively transfers part of the material demand outside national boundaries and may therefore underestimate the total resources required to support building deployment. By allocating material requirements to the country where buildings are constructed, regardless of where materials are produced, the approach adopted in this study better captures the overall resource demand driven by the transition and is therefore considered more suitable for assessing resource dependencies and potential supply bottlenecks.

The scope of the analysis also introduces limitations. The study focuses on four major construction materials—cement, steel, ceramic bricks, and flat glass—which account for a substantial share of material demand and embodied impacts in buildings. However, additional materials such as aluminum, polymers, insulation products, and timber can also contribute significantly to embodied energy and emissions, particularly in contemporary low-energy buildings. Consequently, the results should be interpreted as a detailed assessment of four major construction-material supply chains rather than a complete accounting of all material flows associated with the built environment. The inclusion of additional materials would likely increase the impacts attributed to manufacturing and could alter the relative contribution of individual materials and supply-chain stages.

Data availability represents an additional challenge. For Switzerland, Iceland, Norway, and the United Kingdom, several datasets were not available through Eurostat and had to be supplemented using national statistics. Potential methodological differences between data sources were not explicitly quantified and may introduce further uncertainty into the analysis.

Despite these limitations, the principal findings of the study are considered robust. While uncertainty affects the absolute magnitude of the reported values, it is unlikely to alter the identification of the major supply-chain hotspots. In particular, the dominant role of material manufacturing and the prominent contribution of cement and steel are consistent with the broader literature on embodied impacts and material demand in buildings [37,79]. Therefore, the results are most appropriately interpreted as identifying strategic intervention points and relative priorities for decarbonization rather than providing precise quantitative estimates. Future work should focus on uncertainty quantification, improved activity datasets, explicit representation of international trade, broader material coverage, and prospective scenario analysis to further enhance the robustness and policy relevance of the framework.

Regarding uncertainty quantification, the results are presented as point estimates and therefore do not explicitly quantify uncertainty ranges. This reflects the limited availability of uncertainty information for several key input datasets, including construction activity, renovation rates, and material intensity coefficients. Consequently, the reported values should be interpreted as indicative estimates rather than precise measurements. Future work should incorporate formal uncertainty quantification methods, such as Monte Carlo simulations and global sensitivity analyses, to derive confidence intervals, assess the robustness of model outputs, and identify the parameters exerting the greatest influence on the results [80]).

Beyond the uncertainty associated with individual assumptions, this work also highlights a broader methodological challenge in the assessment of building-related material, energy, and emissions flows at the national scale. Whereas the literature on buildings is dominated by life-cycle assessments of individual buildings, case studies, and specific building typologies, comparable analyses at the annual country level remain scarce. The main reason is not a lack of methodological frameworks, but rather the absence of consistent and harmonized datasets linking building activity, material intensities, industrial production, energy use, and emissions across the entire supply chain. Addressing this challenge required the integration of multiple heterogeneous data sources, scales, and accounting methodologies, each characterized by different system boundaries and levels of aggregation. Consequently, an important contribution of the present work lies not only in the quantification of impacts but also in the development of a framework capable of connecting building activity to upstream raw-material extraction, manufacturing, transport, construction, and end-of-life processes. This revealed several key knowledge gaps, including the lack of harmonized statistics on annual renovation activity, limited information on material intensities for non-residential buildings, and the absence of detailed trade-adjusted material flow datasets for the construction sector.

These limitations also define the next generation of research in this field. Future work should focus on improving the consistency of construction activity datasets, developing more representative and dynamic material intensity databases, integrating international trade and embodied emissions through consumption-based approaches, and systematically quantifying uncertainty using sensitivity and Monte Carlo analyses. Furthermore, expanding the framework to additional construction materials and linking it with prospective scenarios of technological change would enable the evaluation of decarbonization pathways across the entire construction supply chain. Such developments would transform the framework from a retrospective accounting tool into a forward-looking decision-support model capable of informing both climate mitigation and circular-economy policies.

5. Conclusions

This study quantified, at the EU+ level, the material flows, energy consumption, and CO_2 emissions associated with the building construction supply chain, explicitly considering supply-chain stages, construction and building typologies, materials, and countries. By linking raw material extraction, material manufacturing, construction activities, transport, demolition, and waste management, the analysis provides an integrated cross-supply-chain perspective on the environmental impacts associated with building construction and renovation.

The results show that sand extraction for cement-based construction is the dominant raw material flow, followed by limestone and iron ore. Among the four materials analysed, cement is the largest contributor to supply-chain emissions, primarily because of process emissions associated with clinker production, while steel is the second most important contributor to both energy consumption and CO_2 emissions. Material manufacturing was identified as the dominant supply-chain stage, accounting for the largest share of energy use and emissions, followed by construction activities and transportation. Furthermore, building renovation—particularly light renovation of apartments—represents a substantially larger activity in terms of floor area than new construction, highlighting the increasing importance of the existing building stock in shaping future resource demand.

From a cross-supply-chain perspective, the results indicate that the most effective decarbonization leverage points are concentrated upstream in the production of construction materials, particularly cement and steel. Although improvements in transport, construction, demolition, and waste management remain important, their contribution to overall emissions is substantially lower than that of material manufacturing. Consequently, the largest mitigation potential lies in a combination of industrial decarbonization measures—including low-carbon fuels, renewable electricity, electrification, carbon capture, utilization and storage (CCUS), increased use of secondary materials, and material-efficiency strategies—together with measures that reduce demand for primary materials through renovation, circularity, lightweight design, and material substitution.

The analysis also revealed significant differences among countries in terms of energy intensity, material requirements, and emissions profiles. These findings underline the importance of considering national circumstances when designing policies for the construction sector. Rather than adopting uniform approaches, policies should reflect the specific characteristics of national construction supply chains, energy systems, industrial structures, and building stocks.

The results should nevertheless be interpreted considering several limitations. The most important sources of uncertainty include the limited availability of harmonized statistics on annual construction and renovation activity, the use of material intensity coefficients to represent heterogeneous building stocks, the exclusion of international trade flows and embodied emissions, and the restricted material scope of the analysis, which considered only cement, steel, ceramic bricks, and flat glass. These limitations primarily affect the precision of the absolute values reported and may influence the ranking of countries or impact categories with similar values. However, they do not alter the identification of the principal hotspots across the building supply chain, namely the dominant role of material manufacturing and the importance of cement and steel.

Future research should focus on reducing these uncertainties and expanding the scope of the framework. This includes the development of harmonized European databases on construction and renovation activities, improved country-specific and building-specific material intensity datasets, and the implementation of formal sensitivity and uncertainty analyses, such as Monte Carlo approaches, to assess the robustness of results. Additional value could be generated by explicitly accounting for international trade and embodied emissions through consumption-based accounting approaches, thereby improving cross-country comparisons and better capturing the global dimension of construction supply chains.

The framework could also be expanded by incorporating additional materials such as aluminum, polymers, timber, and other emerging construction products. Finally, future applications should examine prospective transition scenarios, including the deployment of CCUS in cement production, increased use of electric arc furnaces in steelmaking, greater adoption of renewable electricity, hydrogen and biofuels, higher recycling rates, material substitution, lightweight construction strategies, and evolving patterns of construction and renovation. Such developments would transform the present framework from a descriptive assessment tool into a forward-looking decision-support platform capable of evaluating alternative pathways towards climate neutrality, resource efficiency, and circularity in the European construction sector.

CRediT authorship contribution statement

Juliana Barbosa: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sofia G. Simoes:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Cristine Jordão:** Data curation. **Ruichang Mao:** Data curation. **Davide Aloini:** Data curation. **Pierluigi Zerbino:** Data curation. **Safaa Mabroum:** Data curation. **Giammarco Montalbano:** Data curation. **Husam Sameer:** Writing – review & editing, Writing – original draft. **Hans H. Dürr:** Writing – review & editing. **Bernardo Jerónimo:** Methodology, Conceptualization. **Ana T. Lima:** Writing – review & editing, Writing – original draft, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This research has been supported by the European Union's Horizon Europe research and innovation program, under grant agreement No. 101056862, CO2NSTRUCT project. This output reflects only the authors' view, and the European Union cannot be held responsible for any use that may be made of the information contained therein.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enbuild.2026.118194.

Data availability

Data will be made available on request.

References

[1] K.A.M. Kamar, Z.A. Hamid, Sustainable Construction and Green Building: The Case of Malaysia, 2011, pp. 15–22, https://doi.org/10.2495/ST110021.
[2] L. Muhwezi, F. Kiberu, M. Kyakula, A.O. Batambuze, An assessment of the impact of construction activities on the environment in Uganda: a case study of Iganga municipality, J. Constr. Eng. Project Manag. 2 (4) (2012) 20–24, https://doi.org/10.6106/JCEPM.2012.2.4.020.
[3] X. Chuai, X. Huang, Q. Lu, M. Zhang, R. Zhao, J. Lu, Spatiotemporal changes of built-up land expansion and carbon emissions caused by the chinese construction industry, Environ. Sci. Technol. 49 (21) (2015) 13021–13030, https://doi.org/10.1021/acs.est.5b01732.
[4] C. Cobreros, D. Espinosa, F. Hidalgo, A. Manzano-Ramírez, J.L. Reyes, Cereal straw production analysis, availability of materials, and provincial map for manufacturing of sustainable prefabricated panels, BioResources 9 (1) (2013), https://doi.org/10.15376/biores.9.1.786-800.
[5] H. Kloft, C. Gehlen, K. Dörfler, N. Hack, K. Henke, D. Lowke, J. Mainka, A. Raatz, <scp>TRR</scp> 277: additive manufacturing in construction, Civ. Eng. Des. 3 (4) (2021) 113–122, https://doi.org/10.1002/cend.202100026.
[6] H. Yan, Q. Shen, L.C.H. Fan, Y. Wang, L. Zhang, Greenhouse gas emissions in building construction: a case study of One Peking in Hong Kong, Build. Environ. 45 (4) (2010) 949–955, https://doi.org/10.1016/j.buildenv.2009.09.014.
[7] P. Mykytyuk, V. Brych, V. Manzhula, O. Borysiak, A. Sachenko, A. Banasik, W. M. Kempa, Y. Mykytyuk, A. Czupryna-Nowak, I. Lebid, Efficient management of material resources in low-carbon construction, Energies 17 (3) (2024) 575, https://doi.org/10.3390/en17030575.
[8] T. Eddy, A. Agustina, S. Purnomo, Influence of Sustainable Construction for The Environment and Social Community, RSF Conference Series: Business, Management and Social Sciences 3 (3) (2023) 410–417, https://doi.org/10.31098/bmss.v3i3.705.
[9] J. Barbosa, P. Trindade, F. Amorim, D. Aloini, P. Zerbino, S. Karytsas, T. I. Oikonomou, H. Sameer, H.H. Dürr, S. Slabik, M. Flörke, A. Hafner, T.G. Ambaye, A.T. Lima, S.G. Simoes, Synergies and antagonisms between EU circular economy and climate mitigation policies: focusing on construction sector, Circ. Econ. Sustain. 5 (6) (2025) 5171–5194, https://doi.org/10.1007/s43615-025-00673-6.
[10] A.T. Lima, S.G. Simoes, D. Aloini, P. Zerbino, T.I. Oikonomou, S. Karytsas, C. Karytsas, O.S. Calvo, B. Porcar, I. Herrera, S. Slabik, H.H. Dürr, A. Genovese, M. Bimpizas-Pinis, Climate mitigation models need to become circular – let's start with the construction sector, Resour. Conserv. Recycl. 190 (2023) 106808, https://doi.org/10.1016/j.resconrec.2022.106808.
[11] P. Zerbino, S. Mabroum, G. Montalbano, A.T. Lima, D. Aloini, Mapping supply systems in circular settings: a proposal for a new methodology, Comput. Ind. Eng. 201 (2025) 110891, https://doi.org/10.1016/J.CIE.2025.110891.
[12] Eurostat, Conventional Dwellings by Occupancy Status, Type of Building and NUTS 3 Region [cens_21dwob_r3_custom_15670664]. https://ec.europa.eu/eurostat/databrowser/view/cens_21dwob_r3__custom_15670664/default/table, 2025.
[13] Eurostat, Dwellings by Type of Building, Number of Rooms or Useful Floor Space and NUTS 3 Region [cens_21dwbnr_r3]. https://ec.europa.eu/eurostat/databrowser/view/cens_21dwbnr_r3$dv_3140/default/table?lang=en&category=hous.hous_pop.hous_cens.hous_cens_dw, 2025.
[14] W. Nijs, P. Ruiz, 02_JRC-EU-TIMES Building Stock Module, European Commission, Joint Research Centre (JRC) [Dataset] PID, 2019. http://data.europa.eu/89h/c2824007-5e24-4380-ac02-e391fdb1e9de.
[15] S.L. Luxembourg, S.S. Salim, K. Smekens, F.D. Longa, B. van der Zwaan, TIMES-Europe: an integrated energy system model for analyzing Europe's energy and climate challenges, Environ. Model. Assess. 30 (1) (2025) 1–19, https://doi.org/10.1007/s10666-024-09976-8.
[16] A. Sgobbi, W. Nijs, R. De Miglio, A. Chiodi, M. Gargiulo, C. Thiel, How far away is hydrogen? Its role in the medium and long-term decarbonisation of the European energy system, Int. J. Hydrog. Energy 41 (1) (2016) 19–35, https://doi.org/10.1016/j.ijhydene.2015.09.004.
[17] S. Simoes, W. Nijs, P. Ruiz Castello, A. Sgobbi, D. Radu, P. Bolat, C. Thiel, E. Peteves, The JRC-EU-TIMES Model - Assessing the Long-term Role of the SET Plan Energy Technologies, 2013.
[18] C. Thiel, W. Nijs, S. Simoes, J. Schmidt, A. van Zyl, E. Schmid, The impact of the EU car CO2 regulation on the energy system and the role of electro-mobility to achieve transport decarbonisation, Energy Policy 96 (2016) 153–166, https://doi.org/10.1016/j.enpol.2016.05.043.
[19] A. Chiodi, De Miglio Rocco, Gargiulo Maurizio, Kanudia Amit, Nijs Wouter, Politis Savvas, Ruiz Castello Pablo, Zucker Andreas, Upgrade-Buildings and Heating and Cooling Technologies, EUR 29078 EN, Publications Office of the European Union, 2017, https://doi.org/10.2760/602564.
[20] Entranze, Enerdata. https://entranze.enerdata.net/, 2019.
[21] GitHub. (n.d.). KanORS-E4SMA / EU_TIMES_Veda2.0. 2024. Retrieved November 28, 2024, from https://github.com/KanORS-E4SMA/EU_TIMES_Veda2.0?tab=readme-ov-file#readme.
[22] European Commission, Comprehensive Study of Building Energy Renovation Activities and the Uptake of Nearly Zero-Energy Buildings in the EU Final Report. www.navigant.com, 2019.
[23] FIEC - European Construction Industry Federation, Statistical Report N°67 (Edition 2024). https://fiec-statistical-report.eu/, 2025.
[24] Federal Statistical Office, Overview Construction and Housing - Key Figures. 2025. https://www.bfs.admin.ch/bfs/en/home/statistics/construction-housing.html, 2025.
[25] Eurostat, Conventional Dwellings by Occupancy Status, Type of Building and NUTS 3 Region [cens_11dwob_r3_custom_15675042], 2015.
[26] Eurostat, Building Permits - Annual Data - sts_cobp_a, 2024.
[27] Buildings Performance Institute Europe, Building Stock. https://www.bpie.eu/knowledge-hub/, 2019.
[28] Central Statistics Office, Production in Building and Construction Index Archive 2011. https://www.cso.ie/en/statistics/buildingandconstruction/productioninbuildingandconstructionindex/productioninbuildingandconstructionindexarchive2011/, 2012.
[29] Institut Wohnen und Umwelt (IWU), Strategische Entwicklung des Gebäudebestands — Publikationen. https://www.iwu.de/publikationen/, 2019.
[30] Odyssee, Odyssee Database. https://www.odyssee-mure.eu/, 2019.
[31] State Enterprise Centre of Registers, State Enterprise Centre of Registers. https://www.registrucentras.lt/en/, 2019.
[32] Statistics Iceland, Waste Collection and Allocation 2014–2020. https://px.hagstofa.is/pxen/pxweb/en/Umhverfi/Umhverfi__3_efnisflaedi__2_urgangur/UMH04105.px/table/tableViewLayout2/, 2024.
[33] Stefan Hausberger, Monitoring Mechanismen 2013 Verkehr, in: Institute of Thermodynamics and Sustainable Propulsion Systems vol. 3130, 2013.
[34] Tabula, Tabula Project. https://episcope.eu/welcome/, 2019.
[35] The Authority for Spatial Planning and Construction of the Slovak Republic (ASPC SR), Slovak Building Standards. https://uupv.sk/en, 2019.
[36] J. van Oorschot, Housing Typology Assessment More-Connect WP3.1, 2016.
[37] T. Fishman, A. Mastrucci, Y. Peled, S. Saxe, B. van Ruijven, RASMI: global ranges of building material intensities differentiated by region, structure, and function, Sci. Data 11 (1) (2024) 418, https://doi.org/10.1038/s41597-024-03190-7.
[38] E. Hoxha, N. Francart, B. Tozan, E.B. Stapel, S.R.B. Gummidi, H. Birgisdottir, Spatiotemporal tracking of building materials and their related environmental impacts, Sci. Total Environ. 912 (2024) 168853, https://doi.org/10.1016/j.scitotenv.2023.168853.
[39] R. Schinke, J. Hennersdorf, K. Gruhler, U. Grießbach, G. Schiller, Material Cadastre of Buildings in Germany 2022 (matcad2022, adm2022). https://data.fdz.ioer.de/dataset.xhtml?persistentId=doi:10.71830/V2STEU, 2025.
[40] A. Neville, Properties of Concrete, Fifth edition, Prentice Hall, 2012.
[41] G. Montalbano, S. Mabroum, P. Zerbino, D. Aloini, V. Mininno, E. Crisostomi, R. Dulmin, G. Salvadori, Deliverable 3.2 Mapping and Characterisation of Conventional and Circular Supply Chains for Clay-based. www.co2nstruct.eu, 2025.
[42] Glass for Europe, Main Markets. https://glassforeurope.com/the-sector/key-data/, 2025.
[43] Eurostat, Disaggregated Final Energy Consumption in Industry by NACE Rev. 2 Activity – quantitiesnrg_d_indq_n, 2024, https://doi.org/10.2908/NRG_D_INDQ_N.
[44] Statistics Iceland, Energy Consumption by Energy Product and NACE Sector 2014–2021. https://px.hagstofa.is/pxen/pxweb/en/Umhverfi/Umhverfi__4_orkumal__3_orkuflaedireikningar/UMH40100.px/, 2024.
[45] Eurostat, Material Flow Accounts - env_ac_mfa. https://ec.europa.eu/eurostat/databrowser/view/env_ac_mfa/default/table?lang=en&category=env.env_mrp, 2024.
[46] UNFCCC, National Inventory Submissions 2023. https://unfccc.int/ghg-inventories-annex-i-parties/2023, 2024.
[47] UK National Statistics, Energy Consumption in the UK (ECUK): Final Energy Consumption Tables. https://assets.publishing.service.gov.uk/media/657c2346254aaa0010050de6/ECUK_2023_Consumption_tables.xlsx, 2023.
[48] Swiss Federal Office of Energy, Energy Consumption Statistics in the Industry and Services Sectors. https://www.bfe.admin.ch/bfe/en/home/supply/statistics-and-geodata/energy-statistics/sector-statistics.html, 2024.

[49] Eurostat, Road Freight Transport by Type of Operation and Type of Transport - (t, tkm, vehicle-km) - annual data road_go_ta_tott, 2024, https://doi.org/10.2908/ROAD_GO_TA_TOTT.

[50] International Transport Forum/OECD, Permissible Maximum Weights of Lorries in Europe (In Tonnes). https://www.itf-oecd.org/sites/default/files/docs/weights-2021_0.pdf, 2022.

[51] Hungarian Central Statistical Office, 13.1.3.9. Cement Production [Million Tons]*. https://www.ksh.hu/stadat_files/ipa/en/ipa0029.html, 2025.

[52] INE, Estatísticas da Produção Industrial - 2019. https://www.ine.pt/xportal/xmain?xpid=INE&xpgid=ine_publicacoes&PUBLICACOESpub_boui=467890702&PUBLICACOESmodo=2, 2020.

[53] National Statistics UK, Energy Consumption in the UK (ECUK): Final Energy Consumption Tables. https://assets.publishing.service.gov.uk/media/657c2346254aaa0010050de6/ECUK_2023_Consumption_tables.xlsx, 2024.

[54] A. Bigeard, L. Girard, E. Boller, V. Trillaud, C. Mesnager, D. Bouvard, D. Jauffres, Multi-scale in-situ microstructure observation of sintering and thermal damage in a refractory ceramic, Materialia 39 (2025) 102269, https://doi.org/10.1016/j.mtla.2024.102269.

[55] W.P. Zakka, N.H. Abdul Shukor Lim, M. Chau Khun, A scientometric review of geopolymer concrete, J. Clean. Prod. 280 (2021) 124353, https://doi.org/10.1016/j.jclepro.2020.124353.

[56] J.A. Olsson, H. Hafez, S.A. Miller, K.L. Scrivener, greenhouse gas emissions and decarbonization potential of global fired clay brick production, Environ. Sci. Technol. (2025), https://doi.org/10.1021/acs.est.4c08994.

[57] CBS, Energy Balance Sheet; Supply and Consumption, Sector. https://opendata.cbs.nl/statline/portal.html?_la=en&_catalog=CBS&tableId=83989ENG&_theme=1080, 2024.

[58] UK Department-for-energy-security-and-net-zero, Digest of UK Energy Statistics (DUKES): Energy, 2024.

[59] Eurostat, Annual Detailed Enterprise Statistics for Construction (NACE Rev. 2, F - sbs_na_con_r2) (2005-2020). https://ec.europa.eu/eurostat/databrowser/view/sbs_na_con_r2__custom_9509026/default/table, 2024.

[60] Eurostat, Generation of Waste by Waste Category, Hazardousness and NACE Rev. 2 Activity, 2024.

[61] Abteilung Abfall und Rohstoffe, Bundesamt für Umwelt BAFU, 2024.

[62] Department for Environment, F. & R. A, UK Statistics on Waste. https://www.gov.uk/government/statistics/uk-waste-data/uk-statistics-on-waste, 2024.

[63] IPCC, Guidelines for National Greenhouse Gas Inventories. https://www.ipcc-nggip.iges.or.jp/EFDB/main.php, 2006.

[64] European Environment Agency, Greenhouse Gas Emission Intensity of Electricity Generation in EUROPE. https://www.eea.europa.eu/en/analysis/indicators/greenhouse-gas-emission-intensity-of-1, 2023.

[65] M.T. Lotz, A. Herbst, A. Müller, L. Kranzl, J. Rosales Carreon, E. Worrell, A material flow model of steel and concrete in EU buildings: national differences of the service-stock-flow nexus, Clean. Waste Syst. 8 (2024) 100153, https://doi.org/10.1016/J.CLWAS.2024.100153.

[66] B. Sprecher, T.J. Verhagen, M.L. Sauer, M. Baars, J. Heintz, T. Fishman, Material intensity database for the Dutch building stock: towards big data in material stock analysis, J. Ind. Ecol. 26 (1) (2022) 272–280, https://doi.org/10.1111/jiec.13143.

[67] T.J. Verhagen, M.L. Sauer, E. van der Voet, B. Sprecher, Matching demolition and construction material flows, an urban mining case study, Sustainability 13 (2) (2021) 653, https://doi.org/10.3390/su13020653.

[68] European Environment Agency, From Data to Decisions: Material Footprints in European Policy Making. https://www.eea.europa.eu/en/analysis/publications/material-footprints-in-european-policy-making, 2024.

[69] T. Wiedmann, M. Lenzen, Environmental and social footprints of international trade, Nat. Geosci. 11 (5) (2018) 314–321, https://doi.org/10.1038/s41561-018-0113-9.

[70] Department for Energy Security and Net Zero, 2023 UK Greenhouse Gas Emissions: Final Figures - Data Tables. https://www.gov.uk/government/statistics/final-uk-greenhouse-gas-emissions-statistics-1990-to-2023, 2025.

[71] Eurostat, Air Emissions Accounts by NACE Rev. 2 Activity [env_ac_ainah_r2 $defaultview]. https://ec.europa.eu/eurostat/databrowser/view/env_ac_ainah_r2/default/table?lang=en&category=env.env_air.env_air_aa, 2025.

[72] UK Office National Statistics, Material Flow Accounts. https://www.ons.gov.uk/economy/environmentalaccounts/datasets/ukenvironmentalaccountsmaterialflowsaccountunitedkingdom, 2025.

[73] Eurostat, Energy Flow - Sankey Diagram: nrg_bal_sd, Final consumption - energy use, https://ec.europa.eu/eurostat/databrowser/view/nrg_bal_sd/default/table?lang=en&category=nrg.nrg_quant.nrg_quanta.nrg_bal, 2025.

[74] Swiss Federal Office of Energy SFOE, Overall Energy Statistics Schweizerische Gesamenergiestatistik 2024. https://www.bfe.admin.ch/bfe/en/home/supply/statistics-and-geodata/energy-statistics/overall-energy-statistics.html/, 2025.

[75] EC, Critical Raw Materials Act - Internal Market, Industry, Entrepreneurship and SMEs. https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials/critical-raw-materials-act_en, 2026.

[76] EC, Commission Launches Consultation for Upcoming Circular Economy Act - Environment, November 6, https://environment.ec.europa.eu/news/commission-launches-consultation-upcoming-circular-economy-act-2025-08-01_en, 2025.

[77] A.M. Amadei, L. Rigamonti, S. Sala, Exploring the EU plastic value chain: a material flow analysis, Resour. Conserv. Recycl. 197 (2023) 107105, https://doi.org/10.1016/J.RESCONREC.2023.107105.

[78] H. Wang, T. Fujita, A review of research on embodied carbon in international trade, Sustainability 15 (10) (2023) 7879, https://doi.org/10.3390/su15107879.

[79] X. Zhong, S. Deetman, A. Tukker, P. Behrens, Increasing material efficiencies of buildings to address the global sand crisis, Nat. Sustainability 5 (5) (2022) 389–392, https://doi.org/10.1038/s41893-022-00857-0.

[80] J.C. Helton, J.D. Johnson, C.J. Sallaberry, C.B. Storlie, Survey of sampling-based methods for uncertainty and sensitivity analysis, Reliab. Eng. Syst. Saf. 91 (10–11) (2006) 1175–1209, https://doi.org/10.1016/j.ress.2005.11.017.