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Martina Caruso, Vitor Silva, Karim Aljawhari, Al Mouayed Bellah Nafeh & Carmine Galasso

Unveiling the Environmental Impact of Earthquakes in Europe

Martina Caruso[1,*], Vitor Silva[1,2], Karim Aljawhari[1,3], Al Mouayed Bellah Nafeh[1], Carmine Galasso[3]

[1] Global Earthquake Model (GEM) Foundation, Pavia, Italy
[2] CERIS, Department of Civil Engineering, University of Aveiro, Aveiro, Portugal
[3] Department of Civil, Environmental and Geomatic Engineering, University College London (UCL), London, United Kingdom
[*] Corresponding author's e-mail: martina.caruso@globalquakemodel.org

ABSTRACT

Earthquakes represent a significant but often overlooked environmental burden in the construction sector. Post-disaster repairs and reconstruction generate substantial carbon emissions. Here, we unveil the environmental toll of earthquakes in Europe by presenting a seismic risk map of embodied carbon associated with damage across residential, commercial, and industrial buildings. We develop a harmonised database of material quantities and carbon factors covering diverse construction materials and building types, which we integrate into a continental-scale probabilistic seismic risk model. Our analysis reveals that Europe's building stock embodies nearly 14 billion tonnes of CO_2e, with seismic damage, based on over three million earthquake scenarios, contributing an average of 6.6 million tonnes annually. These values are comparable to the yearly emissions of millions of cars or tens of thousands of transatlantic flights. Our models and datasets offer a scalable, transferable tool to incorporate sustainability into disaster risk reduction and advance climate-resilient development.

KEYWORDS

Embodied carbon; environmental impact assessment; exposure; seismic hazard; seismic risk.

INTRODUCTION

The construction sector stands as one of the largest contributors to environmental impacts, including greenhouse gas (GHG) emissions, raw material depletion, and waste generation[1]. Yet, in regions exposed to natural hazards, its impact extends beyond routine construction and operations. Earthquakes can generate millions of tonnes of emissions during the post-event recovery due to the vast volumes of debris, repairs of damaged components, and reconstruction of collapsed buildings. Despite the growing global efforts to decarbonise the construction sector, life-cycle assessments (LCAs) have predominantly focused on planned construction impacts and operational energy consumption, rarely accounting for any disaster-induced consequences. As a result, post-earthquake emissions remain largely unquantified, limiting the integration of climate considerations into current disaster risk and resilience frameworks.

Several past disasters have underscored the severe environmental toll of earthquakes, typically quantified through embodied carbon, a globally recognised indicator of global warming potential. This metric captures the total GHG emissions, expressed as carbon dioxide equivalents (CO_2e), arising from material production, construction, use (excluding operational energy/water use), and end-of-life phases. For instance, the 2023 Türkiye-Syria earthquakes generated up to 210 million tonnes of debris, resulting in over 60 million tonnes of CO_2e from waste management[2]. Gonzalez et al.[3] reported that the demolition and reconstruction of reinforced concrete buildings following the

New Zealand's 2010-2011 Canterbury earthquake sequence produced 300 thousand tonnes of CO_2e. Similarly, Pan et al.[4] estimated that the reconstruction, debris removal, and land conversion following the 2011 Great East Japan earthquake and tsunami released about 26 million tonnes of CO_2e, equal to 2.1% of Japan's total GHG emissions in 2010. These alarming impacts, coupled with the rising sustainability awareness in hazard-prone regions, have prompted research[5–8] to incorporate earthquake impacts in LCA frameworks[5–7]. Some studies have further proposed integrating these impacts among conventional risk metrics, such as economic losses and fatalities, to inform the design of rehabilitation strategies enhancing both structural resilience and environmental performance[9–15]. To build on these efforts, it is essential to consider environmental metrics like embodied carbon within the broader framework of seismic risk assessment.

Seismic risk assessment generally integrates three key components[16]: (i) a probabilistic seismic hazard model that defines the frequency of exceeding a range of ground-shaking intensity levels; (ii) a set of fragility and vulnerability models probabilistically characterising seismic damage and loss at different intensity levels; and (iii) an exposure model detailing the assets at risk, including their location, replacement value, quantity, and physical characteristics. Risk can be communicated to stakeholders and decision-makers in terms of average annual loss (AAL), which reflects the expected yearly loss from seismic damage and subsequent repairs, considering all potential earthquake scenarios derived probabilistically. To allow consistent comparisons across assets or regions, the AAL incurred by each asset is typically normalised by its replacement value, leading to average annual loss ratios (AALRs). Compared to traditional scenario-based assessments, which evaluate losses from single events with fixed magnitude, location, and rupture parameters, the AAL approach offers a more robust, holistic representation of long-term seismic risk.

While major progress has been achieved in seismic risk assessments for conventional loss types (e.g., repair costs, fatalities), quantification of embodied carbon related to earthquake damage remains limited, which hinders integrating sustainability criteria into disaster-resilience frameworks. This is particularly evident at regional scales, where the diversity of construction types complicates the development of robust consequence models that translate various seismic damage levels (also called damage states) into embodied carbon. Most existing studies have derived such models for individual structural and non-structural building components, which are more suited for assessing single structures[11,17–19]. Only a few studies have extended these models to entire buildings[18,20], with the goal of supporting portfolio-level risk assessments[21]. However, these efforts typically tackle a narrow range of building types and have not yet scaled to regional or national applications.

To address this research challenge, we estimate the embodied carbon associated with earthquake-induced damage across Europe's residential, commercial, and industrial building stock. This begins with developing an embodied carbon dataset that complements the latest European building exposure model[22], facilitating environmental impact assessments of building portfolios at national or regional scales. The dataset is applicable to both earthquakes and other hazards, and it offers a foundation for characterising the carbon footprint of Europe's construction sector. To assemble this dataset, we collect, compile, and harmonise environmental-impact information from various European sources, creating an open-access database of embodied carbon values for different construction materials, structural/non-structural components, and building types. Using these data, we conduct a pan-European seismic risk assessment and produce a continental-scale map that conveys seismic risk in terms of the average annual embodied carbon (AAEC) associated with earthquake damage. All datasets and maps are publicly available via a GitHub repository[23], with an additional interactive platform provided via the EPOS Built Environmental Data (BED) service at https://embodiedcarbon.builtenvdata.eu.

RESULTS

European Embodied Carbon Data for Building Materials and Components

Embodied carbon generated by seismic damage is usually expressed as a fraction of the emissions from complete building replacement, as outlined in the "Methods" section. Reliable estimates of replacement carbon for different building types are therefore essential to perform risk assessments. Such estimates must capture emissions across multiple building life-cycle stages, including material production (modules A1-A3), construction (modules A4-A5), and end-of-life processes linked to the demolition of the damaged building (each module corresponds to a specific activity within one of the life-cycle stages, as described in the "Methods" section).

To address the material production stage (modules A1-A3), we derive embodied carbon factors (ECFs) for a range of construction materials and for structural and non-structural components prevalent in new constructions. This is based on an extensive collection and compilation of representative European environmental-impact data from published sources[24–27]. Table 1 lists the ECFs, expressed as average CO_2e per material or component unit. The full dataset, which is included on the GitHub repository[23], includes both individual materials (e.g., steel rebar, ready-mix concrete) and their typical assemblies in structural or non-structural components (e.g., reinforced concrete beams, brick partitions). We acknowledge that this dataset is not exhaustive, but it covers key components most likely to incur earthquake damage. For emissions from the construction stage (modules A4-A5) and end-of-life activities for damaged buildings, we adopt simplified approaches recommended by existing guidelines[28–30], as explained in the "Methods" section.

We note that the ECFs in Table 1 are average values. Coefficients of variation, also provided in the repository, range from 0.17 to 0.80, depending on the variability and consistency of the underlying data. For widely used materials like ready-mix concrete, sand, cement, and hollow clay bricks, the coefficient is below 0.35, implying similar levels of uncertainty for building replacement.

Table 1. Embodied carbon factors (ECFs) of different materials and components (modules A1-A3: production stage).

Material/Component	Average A1-A3 ECF (kg CO_2e/unit)	Unit	Data source
Bituminous roof membrane	5.32	m^2	EC3 database[27]
Cement	789.00	tonne	EC3 database[27]
Ceramic tiles	12.10	m^2	EC3 database[27]
Clay bricks	0.20	kg	Asdrubali et al.[81]
Cold formed steel sections	2.52	kg	EC3 database[27]
Electrical system	9.98	m^2 of built area	Manual collection
Elevators (commercial/industrial)	56,468.18	unit	Manual collection

Elevators (residential)	10,046.48	unit	Manual collection
Fire protection system	4.99	m^2 of built area	Manual collection
Gypsum boards	2.24	m^2	EC3 database[27]
Granite (cladding)	0.09	kg	Crishna et al.[82]
Hot-rolled steel sections	0.69	kg	EC3 database[27]
HVAC system	35.12	m^2 of built area	Manual collection
Metal ceilings	20.11	m^2	Manual collection
Mineral wool boards	3.51	m^2	EC3 database[27]
Non-structural timber	175.00	m^3	EC3 database[27]
Plastic pipes	2.73	kg	Manual collection
PVC window frame, double glazing	68.40	m^2	Asdrubali et al.[83]
Raised access floor	21.60	m^2	Manual collection
Ready-mix concrete	271.00	m^3	EC3 database[27]
Sand	63.32	tonne	Manual collection
Steel decking	2.99	kg	EC3 database[27]
Steel rebars	0.87	kg	EC3 database[27]
Structural mass timber	162.00	m^3	EC3 database[27]

Open-access Database of Embodied Carbon for Building Replacement in Europe

We develop an open-access database providing detailed embodied carbon data on various building types, designed to serve as input for seismic risk assessments. The selected replacements reflect Europe's contemporary engineering practices, thus assuming that vulnerable structural systems (e.g., adobe, stone structures) are no longer viable for new construction. This approach aligns with the "Build Back Better" strategy[31,32], aimed at enhancing community sustainability and resilience by integrating risk reduction measures into the post-disaster restoration of infrastructure and societal systems[33].

In this context, applying the "Build Back Better" principle means that the embodied carbon of seismic damage is expressed as a fraction of the emissions associated with a modern replacement rather than the original building, particularly when the latter is constructed with obsolete or seismically deficient materials. To streamline the modelling process, we assume that replacements retain the same material category as the buildings they substitute, but with improved structural systems and construction quality. For instance, adobe or stone buildings are assumed to be replaced with reinforced masonry structures, while older reinforced concrete buildings are rebuilt with concrete complying with current standards (see the "Methods" section).

To calculate the embodied carbon of building replacement, we derive average quantities of structural and non-structural components for each building type and occupancy category, based on simulated designs of archetype buildings. We then multiply these quantities by the corresponding ECFs described in the previous section, capturing emissions from material production (modules A1-A3). Contributions from the construction stage (modules A4-A5), including pre-construction works, are subsequently added as per the procedure in the "Methods" section. The resulting estimates represent average values; embedding the ECF uncertainty yields an overall coefficient of variation close to 0.35. The full dataset, featuring material quantities and replacement embodied carbon per unit floor area of relevant building types and occupancies, disaggregated by life-cycle stages and structural versus non-structural contributions, is available via the GitHub repository[23].

Figure 1a shows the replacement embodied carbon for different building types and occupancy categories in Europe, measured in kg CO_2e per square metre of floor area (see the “Methods” section for the definition of each building type). The individual shares of life-cycle phases in these estimates are consistent, irrespective of the construction material, lateral load-resisting system, or occupancy. As expected, material/component production (modules A1-A3) consistently dominates the total amount of embodied carbon, accounting for at least 85% of embodied carbon. Construction processes (modules A4-A5), including pre-construction demolition and disposal activities, contribute the remaining 15%, with negligible variations.

Our analysis reveals that the primary construction material is the most influential attribute in the replacement embodied carbon, underscoring the key role of material selection in reducing environmental impacts. Considering A1-A3 modules only, we estimate the average embodied carbon of building replacement of 430 kg CO_2e/m² for reinforced masonry (MR), 375 kg $CO2_e$/m² for reinforced concrete (CR), 270 kg CO_2e/m² for steel (S), and 155 kg CO_2e/m² for timber (W) buildings. These variations stem from differences in quantities and ECFs of construction materials and building components. For example, reinforced masonry buildings feature thick walls constructed from high-impact clay brick units (0.20 kg CO_2e/kg), along with steel rebars and mortar, resulting in higher emissions than ready-mix concrete (0.11 kg CO_2e/kg). Conversely, hot-rolled steel and timber have larger ECFs (0.69 and 0.25 kg CO_2e/kg, respectively). However, their use in structural components tends to be more material-efficient, requiring smaller cross-sectional dimensions than those used in concrete or masonry systems.

Beyond material choice, Figure 1a indicates that the lateral load-resisting system can affect the replacement embodied carbon. For instance, reinforced masonry buildings with concrete hollow blocks and ribbed concrete floors (MR+CBH/LWAL) exhibit up to 33% higher replacement embodied carbon than similar buildings with hollow clay bricks and timber composite floors (MR+CLBRH/LWAL/RWO/FW). Replacement embodied carbon is also influenced by the occupancy category, which introduces significant variations in the type and quantity of construction materials and building components. Commercial and industrial buildings have the highest embodied carbon (Figure 1a), up to 24% greater than residential buildings, due to their design requirements for supporting heavier loads and wider spans that lead to larger structural components or increased reinforcement. We observe an exception in steel residential buildings, which exhibit larger embodied carbon due to their thicker external infill walls, compared to their commercial and industrial counterparts.

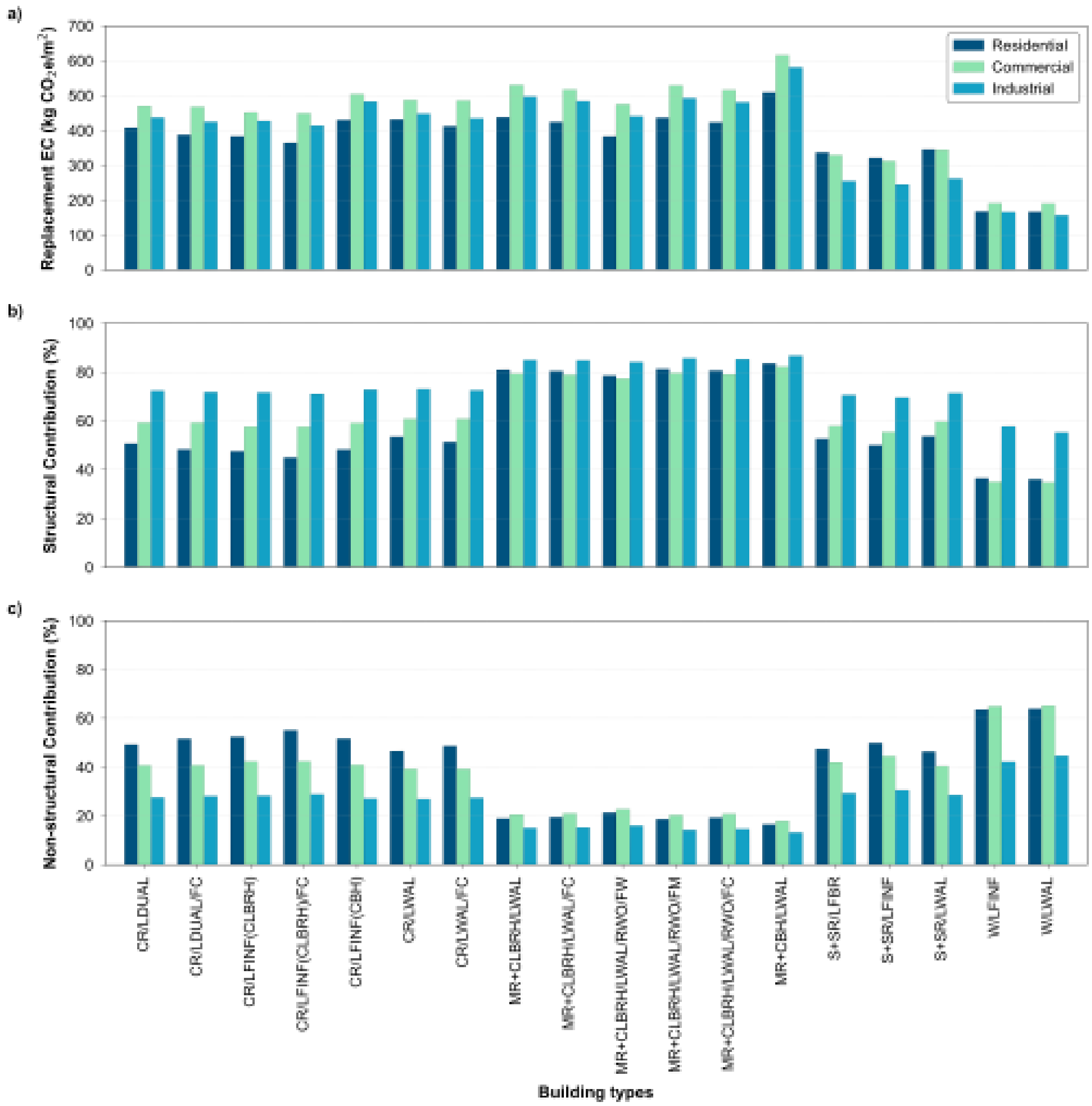

Figure 1. **Replacement embodied carbon by building type and occupancy. a** Replacement embodied carbon (EC) per built area of different building types and occupancy categories (residential, commercial, industrial). **b** Contribution of structural components. **c** Contribution of non-structural components. For the building types, CR: reinforced concrete, MR: reinforced masonry, S: steel, W: timber. The full description of the strings representing each building type is available in the "Methods" section.

Figures 1b and 1c disaggregate the contributions of structural and non-structural components. In most residential building types, non-structural components dominate the carbon footprint due to the relatively smaller structural components. Reinforced masonry buildings break this trend, with structural components representing up to 87% of the replacement embodied carbon due to the presence of thick, reinforced walls. In contrast, timber buildings show structural contributions as low as 35%. This shifts drastically in non-residential occupancies, especially industrial buildings, where structural components become the prevalent emission contributors, reflecting their enlargement to support heavier loads and wider spans.

For comparison and verification, we look at the findings of existing studies, acknowledging potential differences in methodological assumptions and scope. The Embodied Carbon of European Buildings Database (EU-ECB-DB)[34,35] reports mean A1-A3 embodied carbon values of 439 kg CO_2e/m^2 for masonry, 416 kg CO_2e/m^2 for reinforced concrete, and 264 kg CO_2e/m^2 for timber buildings. Our values align well with those for masonry and reinforced concrete, but are notably lower for timber due to different data sources, ECF boundaries, and structural/non-structural component selection. For steel residential buildings, the database of embodied Quantity outputs (deQo)[36] suggests a median value of 399 kg CO_2e/m^2, which exceeds our estimates because it covers the contribution of the use stage in building life cycle. Other studies computed lower embodied carbon values[37–40], likely due to the exclusion of foundations and some non-structural components, and the use of different ECFs. We recognise other global efforts to collect both synthetic and real-world data on embodied carbon[35] and material use intensities[41], but note that only a few provide both material quantities and embodied carbon data (e.g., Benke et al.[42]).

Overall, our study delivers a harmonised database of material quantities and embodied carbon values of building replacement with consistent life-cycle stages, spanning over a range of building types, structural systems, and occupancies. We acknowledge some limitations, such as the representativeness of building types, the scope of LCA modules, and the averaging of ECFs across multiple countries. Nevertheless, the dataset offers a coherent, meaningful basis for cross-comparisons among building types, occupancies, and regions, particularly where detailed building-level data are unavailable or fragmented. It also enhances exposure models of building portfolios, supporting applications like integrating sustainability into regional-scale disaster risk management and informing the prioritisation of risk mitigation strategies, and policy development. Unlike detailed building-specific LCA studies, our work should be viewed as complementary, offering a scalable, portfolio-level framework aiding risk mitigation, resilience planning, and adaptation strategy at the territorial scale.

Embodied-carbon Exposure Data for European Buildings

The latest European exposure model[22], developed as part of the global exposure model of the Global Earthquake Model (GEM) Foundation[32], provides information about the residential, industrial, and commercial building stock at the smallest available administrative level. It comprises data on building counts, locations, built-up area, replacement cost, number of occupants, and key vulnerability attributes, such as construction material, load-resisting systems, number of storeys, and design code level. These attributes are assigned based on nationally reported datasets, including housing census and surveys of commercial and industrial facilities, which offer valuable insights into building types, number of storeys, construction materials, and eras. The European exposure model covers approximately 157 million buildings and over 35 billion m^2 of built-up area, with a total replacement cost estimated at \$60 trillion. Figure 2 depicts the spatial distribution of building counts within Europe, aggregated on a uniform 0.20° hexagonal grid.

Leveraging our embodied carbon database for various building types, we extend the European exposure model by integrating the environmental dimension, facilitating spatial estimates of embodied carbon associated with earthquake damage, repair, and reconstruction. To estimate the total building replacement embodied carbon, we multiply the per-building-type values (Figure 1) by the respective built-up area of each asset in the exposure model. This evaluation helps understanding the fundamental role of the construction sector in regional carbon budgets and identifying opportunities to mitigate its environmental impacts. Accordingly, we present the first version of the exposure map in Figure 3, showing the replacement embodied carbon of the European building stock. Our analysis estimates a total value of 14 billion tonnes of CO_2e; more than double Europe's total CO_2e emissions in 2023 (7 billion tonnes of CO_2e)[43]. Notably, Germany, France, Italy, Türkiye, the United Kingdom, and Spain collectively account for over 60% of the total, with individual contributions ranging from 1.1 to 1.8 billion tonnes CO_2e (see Table *2*). Disaggregated values of replacement embodied carbon, separating structural (e.g., foundations, frames, floors, walls) and non-structural (e.g., partition walls, finishings, plumbing, heating, ventilation, air conditioning, lifts, ceilings) contributions are available in our GitHub repository[23] at the first subnational administrative level of each European country.

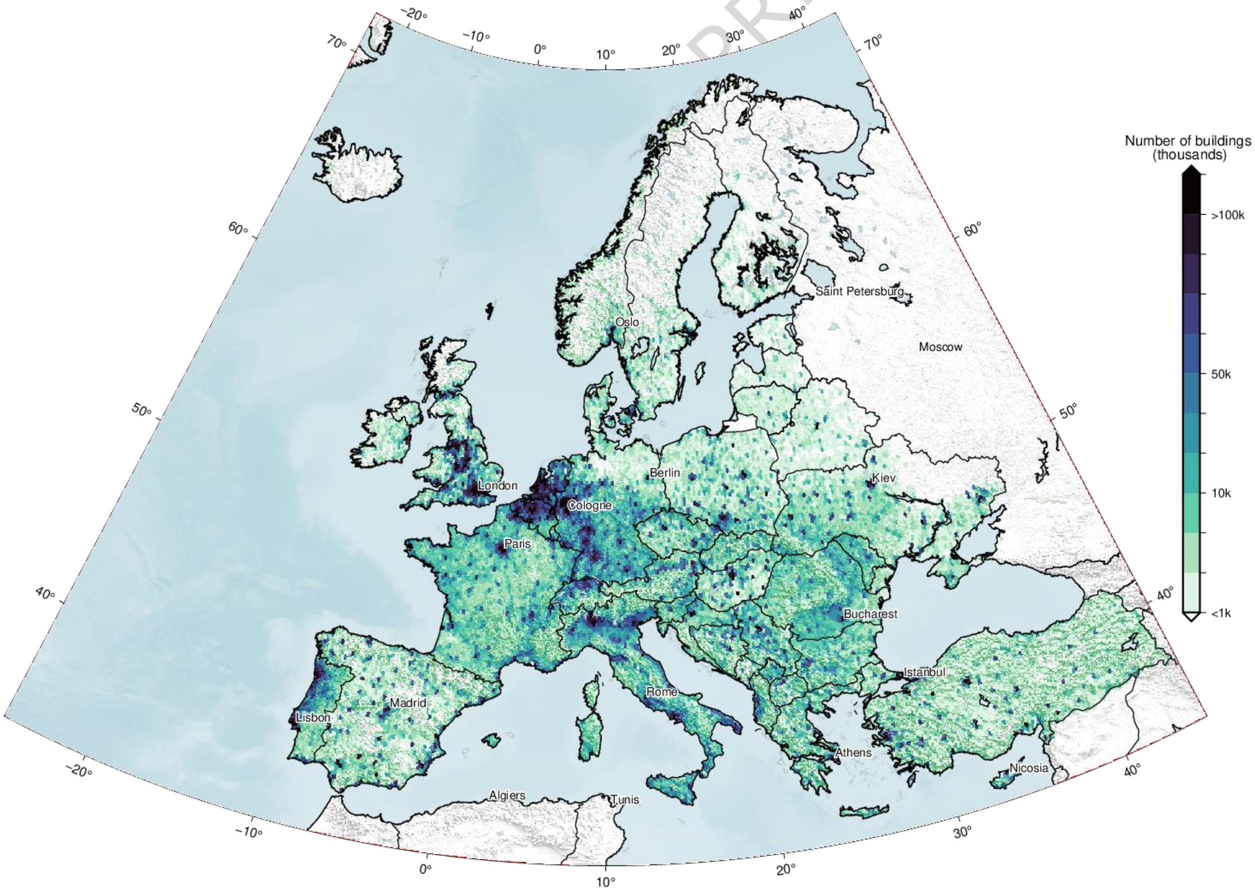

Figure 2. **European building exposure.** Spatial distribution of the number of residential, commercial, industrial buildings on a hexagonal grid with a spatial resolution of 0.20 decimal degrees in GEM's European exposure model. The base maps are derived from the Explorer Base Map (from NASA Earth Observatory), using data from NASA's MODIS Land Cover, the Shuttle Radar Topography Mission (SRTM), the General Bathymetric Chart of the Oceans

(GEBCO 2025 Grid, GEBCO Compilation Group, 2025; doi:10.5285/37c52e96-24ea-67ce-e063-7086abc05f29), and Natural Earth boundaries.

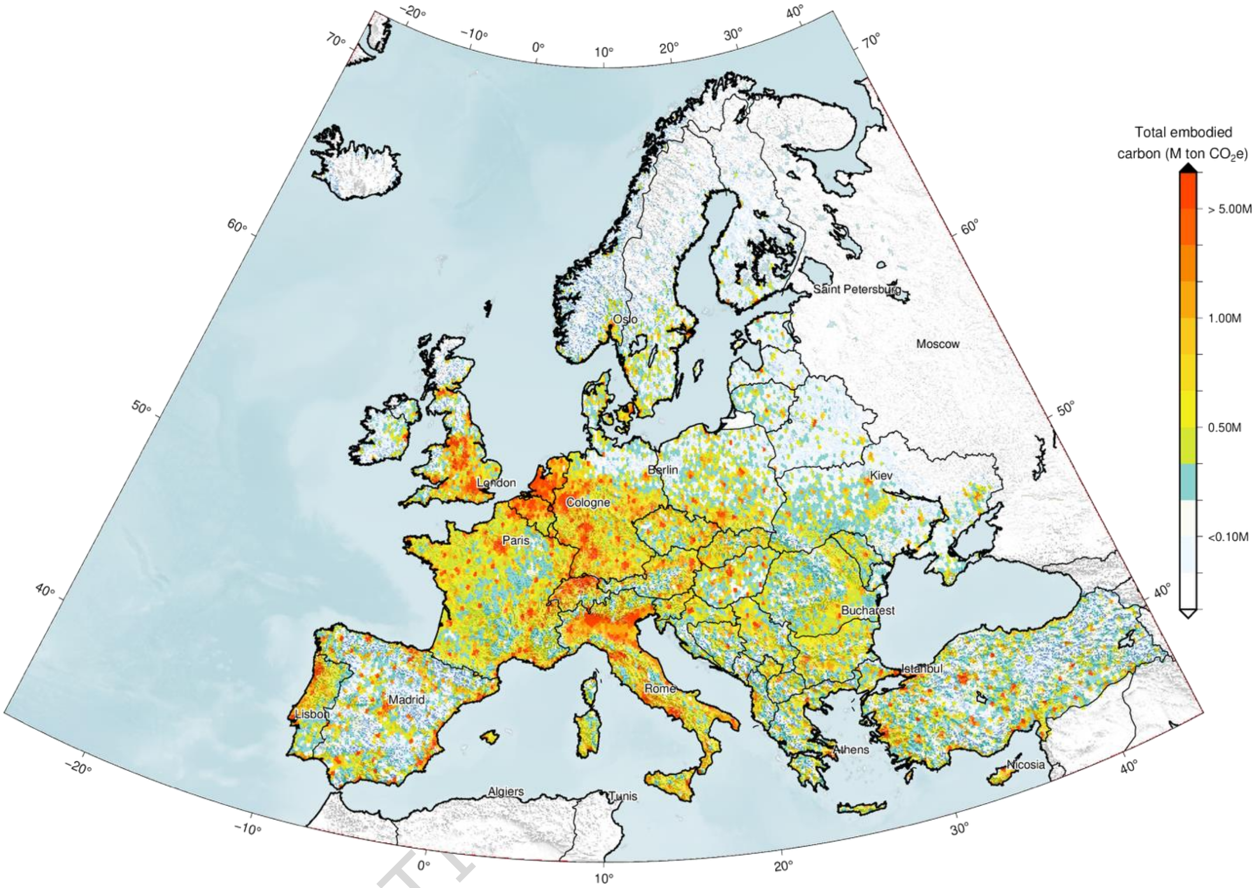

Figure 3. **Embodied-carbon exposure in Europe.** Replacement embodied carbon of the European building stock mapped on a hexagonal grid with a spatial resolution of 0.20 decimal degrees. The base maps are derived from the Explorer Base Map (from NASA Earth Observatory), using data from NASA's MODIS Land Cover, the Shuttle Radar Topography Mission (SRTM), the General Bathymetric Chart of the Oceans (GEBCO 2025 Grid, GEBCO Compilation Group, 2025; doi:10.5285/37c52e96-24ea-67ce-e063-7086abc05f29), and Natural Earth boundaries.

Embodied-carbon Seismic Risk Model for European Buildings

In this study, we address the environmental impact of earthquakes by introducing the concept of AAEC. To streamline comparisons across different building types and regions, regardless of their size or material composition, we express AAEC as a fraction of the building's replacement embodied carbon (average annual embodied carbon ratio, AAECR). This metric is conceptually analogous to the AALR, used in economic risk assessments.

Computing AAECR entails a comprehensive seismic risk assessment that integrates three key components: seismic hazard models, exposure information, and vulnerability functions. We derive the seismic hazard component from GEM's global hazard mosaic[44], which features a harmonised compilation of national and regional probabilistic seismic hazard models developed by various institutions in collaboration with the GEM Foundation. Vulnerability functions estimate seismic losses as a function of ground-shaking intensity and are typically derived by combining fragility curves with damage-to-loss (or consequence) models. Fragility curves characterise the probability of exceeding specific damage states given the shaking intensity, while damage-to-loss models translate these damage states to losses, expressed as ratios of the building's replacement value. For conventional metrics such as economic losses (repair costs) or disruption time, these models are well established[45–49].

In contrast, deriving carbon vulnerability functions is more challenging due to the scarcity of damage-to-carbon models. Existing studies have focused on a limited range of building types, mainly reinforced concrete and steel frames in a few geographic regions[18,20,50]. Despite this limitation, Aljawhari et al.[18] revealed an almost one-to-one correlation between embodied carbon and repair cost ratios of seismic damage[45] in a component-level risk assessment of nine reinforced concrete buildings in Italy. The authors developed both damage-to-carbon[18] and damage-to-cost[45] models for these buildings, confirming their close alignment. Similar correlations have been reported for comparable building types[51,52], and steel frames in China[53]. However, this correlation is not exact because economic losses involve labour costs, which are deemed irrelevant for carbon emissions. Hence, discrepancies might emerge, especially at lower damage levels, where labour constitutes a considerable fraction of repair costs. The correlation improves at large damage levels, where material replacement drives both repair cost and emissions. Further discussion on the applicability and limitations of this assumption, in addition to illustrative case studies, is provided in the Supplementary Discussion.

We adopt the above simplification by assuming that the AALR values, computed via vulnerability functions for economic losses, serve as a proxy for AAECR. We acquire the AALR values for all European building assets by running the event-based probabilistic risk calculator of the OpenQuake Engine[54], an open-source platform for seismic hazard/risk analyses. This calculator generates large sets of stochastic earthquake events over a specified time span, based on regional seismic hazard models. For each simulated event, ground-motion fields are computed using ground-motion models, capturing the spatial distribution of shaking intensity. Losses incurred by each building asset are computed through the relevant vulnerability function. The AAL for each building asset is obtained by dividing the sum of losses from the whole event set by its time span, which is then normalised by the asset's replacement cost to generate the AALR. The complete AALR values for the entire globe, disaggregated by component type (e.g., structural, non-structural) and occupancy (e.g., residential, industrial), are available as part of GEM's global seismic risk model[55].

Finally, we evaluate the AAEC by multiplying the AAECR (assumed equal to the AALR) for each building asset in Europe by its replacement embodied carbon, as further described in the "Methods" section. We emphasise that the resulting AAEC is a probabilistic estimate derived from event-based risk analyses and averaged across millions of simulated earthquake scenarios over a long time span. This allows for capturing the full spectrum of damage outcomes, from slight damage to total collapse, rather than focusing on the consequences of a single deterministic event, where losses are unevenly distributed. This makes the AAEC a more useful metric for decision-making on long-term risk mitigation and resilience planning.

Figure 4 presents the risk map of AAEC due to seismic damage for Europe, measured in tonnes of CO_2e. The map offers a spatially resolved visualisation of the environmental toll of earthquakes, pinpointing the regions where building sustainability is most challenged by seismic activity. When aggregated at the continental level, the total European AAEC exceeds 6.6 million tonnes of CO_2e, a figure equivalent to the overall 2021 carbon footprint of Norway's manufacturing and construction sector, or Serbia's entire transportation network in the same year[43]. To contextualise this further, this total AAEC is comparable to the emissions from 33,000 one-way flights from Paris to New York carrying 200 passengers each, or the annual emissions of approximately 3.9 million diesel cars.

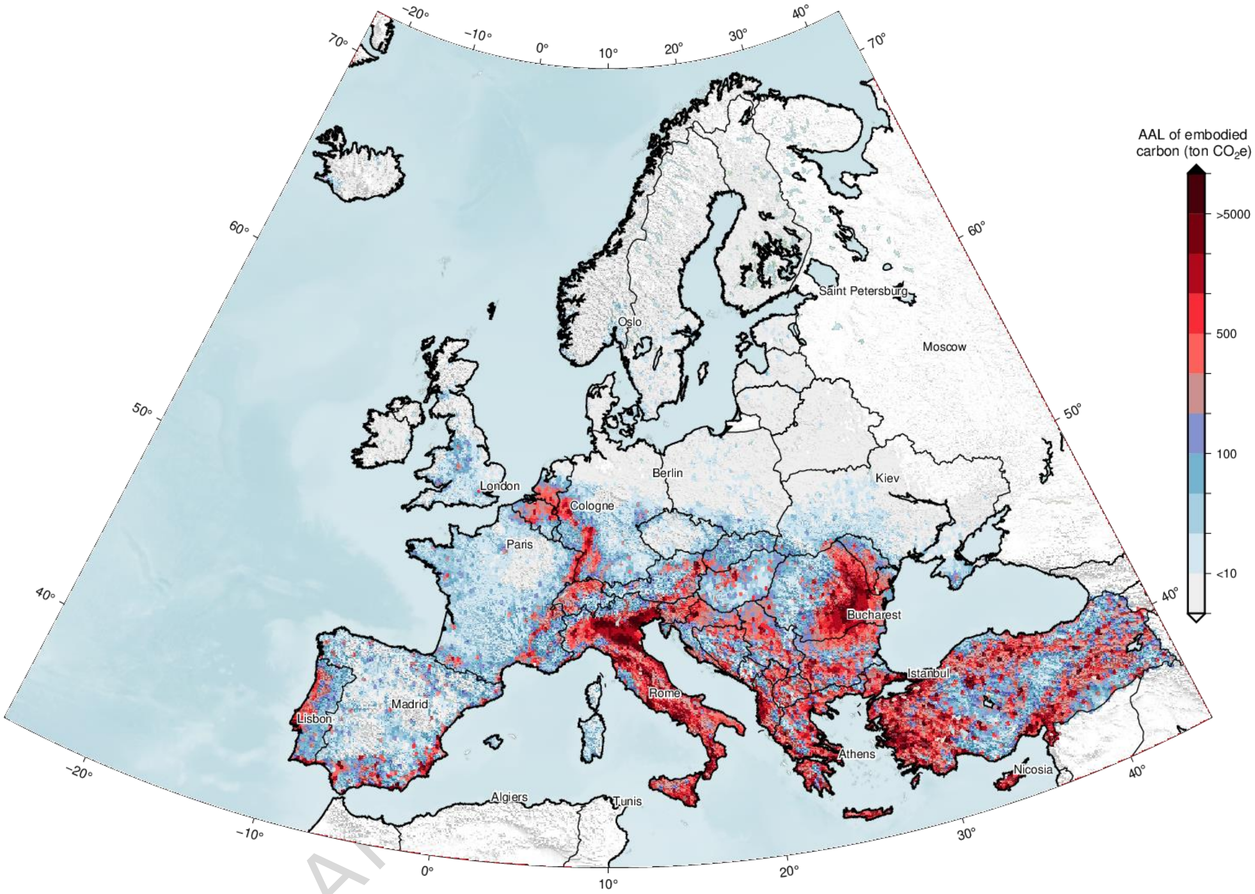

Figure 4. **Embodied-carbon seismic risk in Europe.** Embodied-carbon seismic risk map of the European building stock mapped on a hexagonal grid with a spatial resolution of 0.20 decimal degrees. The base maps are derived from the Explorer Base Map (from NASA Earth Observatory), using data from NASA's MODIS Land Cover, the Shuttle Radar Topography Mission (SRTM), the General Bathymetric Chart of the Oceans (GEBCO 2025 Grid, GEBCO Compilation Group, 2025; doi:10.5285/37c52e96-24ea-67ce-e063-7086abc05f29), and Natural Earth boundaries.

Figure 5 shows the AAEC values aggregated at the national level for 46 European countries, ranked in descending order. Six countries, Türkiye, Italy, Romania, Greece, Spain, and Bulgaria, represent almost 90% of Europe's total AAEC. Türkiye leads by a significant margin, with an estimated 3.5 million tonnes of CO_2e per year, nearly triple of Italy's total, the second largest contributor. This reflects Türkiye's combination of high seismic hazard and large stock of vulnerable buildings. The majority of AAEC in Türkiye, Cyprus, and Greece stems from damage to reinforced concrete buildings (60-80%), while in Italy, Romania, Spain, Bulgaria, and Albania, masonry buildings account for over 60% of the total AAEC. Figure 5 also reports country-level AAECR values. Türkiye is again at the forefront, followed by Cyprus, Albania, and Romania. Despite having smaller building portfolios, Romania and Greece rank fourth and fifth in terms of AAECR due to their high seismic hazard. All AAEC values with structural and non-structural contributions are available in the GitHub repository[23], aggregated at the first subnational administrative division for all European counties.

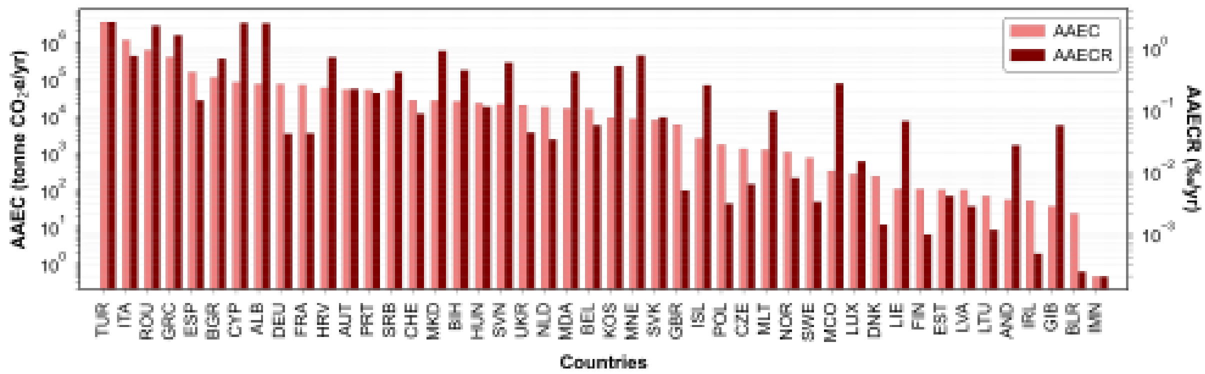

Figure 5. **Average annual embodied carbon per country.** Average annual embodied carbon (AAEC) and average annual embodied carbon ratio (AAECR) of 46 European countries, ranked in descending order of AAEC.

Table 2 offers a detailed breakdown of our analysis, including the total number of buildings, their replacement embodied carbon, and the AAEC with the respective contributions of structural components for the 46 European countries. In countries like Italy, Spain, Albania, and Bulgaria, structural components account for a larger share of the replacement embodied carbon compared to non-structural components. This is due to the prevalence of masonry buildings, where the embodied carbon is driven by structural walls (see Figure 1). Greece and Türkiye, on the other hand, exhibit a more balanced distribution for the two shares because of the substantial number of residential reinforced concrete buildings, where non-structural components like infill walls and partitions have a larger share of the total embodied carbon.

The AAEC values in Table 2 might seem modest in relative terms, but when viewed over a 100-year building lifespan, they become a critical share of the carbon footprint in regions with high seismic risk. In Romania, for example, the embodied carbon induced by earthquake damage and related repairs amounts to nearly 20% of that required for new construction. For countries like Türkiye, Greece, and Romania, this translates into millions of tonnes of CO_2e. As these emissions accumulate across wider geographies and longer time horizons, their significance grows, highlighting the need to incorporate seismic risk into decarbonisation strategies and long-term sustainability planning.

Table 2. Number of buildings (M: million), replacement embodied carbon (REC), share of structural components in REC, average annual embodied carbon (AAEC), and share of structural components in AAEC for 46 European countries, ranked by descending AAEC.

Country	No. of buildings (M)	REC (M tonne CO_2e)	Structural contribution to REC (%)	AAEC (M tonne CO_2e/yr)	Structural contribution to AAEC (%)
Türkiye	9.3225	1,345.9712	57	3.4975	59
Italy	12.1877	1,557.7035	64	1.1375	69
Romania	5.5070	269.6813	59	0.6148	65

Greece	3.3521	244.4031	56	0.3895	62
Spain	10.0126	1,120.9705	66	0.1561	75
Bulgaria	2.1933	168.3821	62	0.1108	68
Cyprus	0.2866	32.3712	59	0.0814	60
Albania	0.6436	29.3087	61	0.0727	69
Germany	19.9348	1,783.2893	58	0.0723	63
France	15.3468	1,669.1501	64	0.0687	69
Croatia	1.6700	83.1179	64	0.0577	70
Austria	2.3156	240.9976	65	0.0518	68
Portugal	3.6289	274.8915	61	0.0508	68
Serbia	2.3408	123.3377	70	0.0500	77
Switzerland	1.9019	304.3378	58	0.0261	65
North Macedonia	0.4938	28.9350	59	0.0257	63
Bosnia and Herzegovina	1.0990	56.7400	63	0.0245	72
Hungary	2.8241	199.1839	69	0.0219	79
Slovenia	0.5121	35.2765	59	0.0201	62
Ukraine	12.6537	458.3304	72	0.0195	75
Netherlands	5.4087	530.4883	71	0.0172	82
Moldova	0.8126	38.9953	64	0.0161	75
Belgium	3.8465	285.0451	71	0.0158	80
Kosovo	0.2923	17.8908	62	0.0090	70
Montenegro	0.1649	11.1517	60	0.0083	64
Slovakia	0.9964	101.2617	66	0.0076	76
United Kingdom	15.4752	1,176.4447	71	0.0057	81
Iceland	0.0741	9.9344	58	0.0024	54
Poland	7.0247	555.5725	66	0.0016	76
Czechia	2.3732	206.2363	62	0.0013	72
Malta	0.1173	12.7761	69	0.0012	73
Norway	1.7614	133.3609	60	0.0010	68
Sweden	2.3787	230.5446	62	0.0007	69
Monaco	0.0101	1.2086	68	0.0003	75
Luxembourg	0.1309	18.6110	74	0.0003	84
Denmark	1.6868	170.1498	63	0.0002	70
Finland	0.0142	1.6100	64	0.0001	62
Liechtenstein	1.3385	108.5020	62	0.0001	68
Estonia	0.2349	24.5469	62	0.0001	71
Latvia	0.3833	36.0490	60	0.0001	66
Lithuania	0.5992	60.1894	63	0.0001	70
Andorra	0.0181	2.0096	71	0.0001	73
Ireland	1.9288	108.7612	69	0.0001	80
Gibraltar	0.0055	0.6300	66	0.0000	66
Belarus	1.7160	95.8271	63	0.0000	75
Isle of Man	0.0199	2.2011	78	0.0000	82

DISCUSSION

Traditional environmental-impact analyses often fail to account for the role of natural hazards, particularly earthquakes, which can inflict severe damage on buildings, triggering repairs and reconstruction activities that generate substantial emissions. Recent advances have begun integrating these impacts into seismic risk frameworks, fostering a more holistic view of resilience in hazard-prone regions. Yet, scalable and reliable models for quantifying the embodied carbon of seismic damage remain scarce, especially at regional and national levels, where building stocks are highly diverse. This challenge also extends to global climate objectives: while major strides have been made in reducing operational carbon through improved building energy efficiency, achieving net-zero goals requires equal attention to emissions embedded in materials, construction methods, and structural systems. This demands datasets that capture the environmental burden of the construction sector, which remain limited.

Our work responds to these needs with a multifaceted approach. We develop a harmonised database of replacement embodied carbon values for a wide range of building types and occupancy categories, incorporating key life-cycle phases (i.e., material production and construction). Guided by the "Build Back Better" strategy, our selected building types reflect current European construction practices, with a variety of materials and structural systems (see Figure 1). This database extends the building exposure model of Europe by introducing the environmental dimension essential for assessing the carbon impacts of earthquakes. The exposure maps and datasets developed here (Figure 3) show that Europe's building stock embodies around 14 billion tonnes of CO_2e, with Germany, France, Italy, Türkiye, the United Kingdom, and Spain jointly accounting for 60% of this total. Beyond seismic risk, the proposed database can be used for forecasting the carbon footprint of future exposure scenarios and evaluating the environmental impacts of other natural hazards, since the replacement embodied carbon depends solely on building types rather than on hazard characteristics.

We also extend seismic risk analysis in Europe by adopting the embodied carbon from seismic damage as a loss metric. Specifically, we compute the AAEC for each building asset in the exposure model, assuming a one-to-one relationship[18] between AAECRs and their AALR counterparts from the latest GEM's global seismic risk model[55]. Accordingly, we introduce a continental-scale seismic risk map depicting the environmental toll of earthquakes in terms of embodied carbon (Figure 4). Our findings reveal that earthquake-induced repair and reconstruction generate nearly 6.6 million tonnes of CO_2e annually, with Türkiye, Italy, Romania, Greece, Spain, and Bulgaria accounting for up to 90% of this total (Figure 5). Our results support the integration of sustainability into disaster risk management by guiding the adoption of lower-carbon construction materials, structural retrofitting, and other risk mitigation strategies to reduce replacement carbon and AAEC[56,57]. Finally, as our methodology relies on AALRs as a proxy for AAECRs, it is broadly applicable to other hazards as long as damage states are clearly defined and economic loss correlate well with embodied carbon.

The accuracy of our results is bounded by several assumptions, which are aligned with the standards of large-scale regional assessments. First, we consider a "Build Back Better" strategy for estimating replacement carbon, reflecting policy-driven resilience goals. Alternative post-earthquake scenarios, such as repairing old buildings to re-instate existing conditions or retrofitting, would yield different environmental outcomes. Second, the exposure model draws primarily from available surveys and national housing censuses, which provide core attributes like construction material and height class. Although misclassifications are possible (e.g., between unreinforced clay and adobe masonry), these tend to occur between building types within similar vulnerability classes[58], thus leading to comparable risk estimates (i.e., law of large numbers). Inherent uncertainties exist as well among the components of seismic risk: hazard, vulnerability, and exposure. These arise from data limitations and modelling assumptions and have been widely discussed in the literature[16,55]. Lastly, our analyses assume that building-component quantities are independent of location and they largely rely on data-rich nations (e.g., the United Kingdom, Spain, France, Italy). We do not explicitly model uncertainties in component quantity, yet our use of carbon factors specific for each building type and structural system provides greater fidelity than generic averages commonly found in the literature (e.g., for single- or multi-family houses, offices).

Future work will broaden the environmental scope of this work by incorporating additional metrics, such as net freshwater use and non-renewable energy consumption, which will provide a more comprehensive view of sustainability challenges linked to construction and post-disaster interventions. A major advancement will involve the derivation of structure-specific damage-to-carbon models, allowing for more refined estimates of embodied carbon caused by different levels of seismic damage. Finally, the framework will be extended beyond Europe, laying the ground for a globally harmonised dataset on the environmental impacts of earthquakes.

METHODS

Replacement Embodied Carbon vs Average Annual Embodied Carbon

The European standard EN-15978[59] divides a building's life cycle into four primary phases, each comprising several modules, as illustrated in Figure 6: (i) the production stage (modules A1-A3); (ii) the construction stage (modules A4-A5); (iii) the operational stage (B1-B7); and (iv) the end-of-life stage (C1-C4). An additional stage, known as "beyond life" (module D) may be considered to capture environmental benefits beyond the building's life-cycle boundaries (e.g., reuse, recycling, recovery of salvaged materials). The environmental impacts emitted at different stages can be expressed here in terms of carbon dioxide equivalent, CO_2e, a widely used indicator for global warming potential. For simplicity, we refer to CO_2e as "carbon" throughout the manuscript. Buildings generate both embodied and operational carbon during their life cycle. Embodied carbon comprises emissions associated with production, construction, use, and end-of-life (i.e., modules A1-A5, B1-B5, and C1-C4), while operational carbon refers exclusively to energy and water use (modules B6-B7). Emissions from the production stage alone can account for up to 50% of a building's total life cycle[60] and nearly 85% of the total embodied portion[61].

Earthquake-induced damage introduces an additional, often overlooked source of embodied carbon, linked to repair and reconstruction activities that might occur during the building's service life. These emissions affect the use stage (mainly modules B3-B5) and can be treated analogously to routine maintenance, where the AAEC is simply multiplied by the building's life span. As outlined earlier, our estimates of AAEC are derived from a probabilistic risk assessment framework, integrating millions of earthquake scenarios over a long period of time, capturing diverse seismic damage levels, from minor repairs to building collapse. Earthquake effects expressed as AAEC can therefore be treated as recurring use-stage emissions rather than end-of-life processes.

Our primary aim is to extend conventional seismic risk analyses by incorporating the embodied carbon associated with earthquake damage and repairs, reflected via the AAEC metric (see the "Results" section). While this approach does not capture the entire life cycle of buildings, it follows established approaches for estimating seismic risk in terms of economic losses. To enable consistent comparisons across building types and regions, we express AAEC as a fraction of the building's replacement embodied carbon (the emissions associated with constructing a modern substitute for a heavily damaged building). Thus, AAEC pertains to existing structures, whereas replacement embodied carbon refers to hypothetical new buildings constructed after a destructive event.

We compute the replacement embodied carbon for a wide range of building types and occupancies, accounting for modules A1-A5 (cradle-to-practical-completion activities). Pre-construction demolition activities are included as part of module A5. The use stage (B modules) is excluded from this metric, as the building replacement is limited to reconstruction works only.

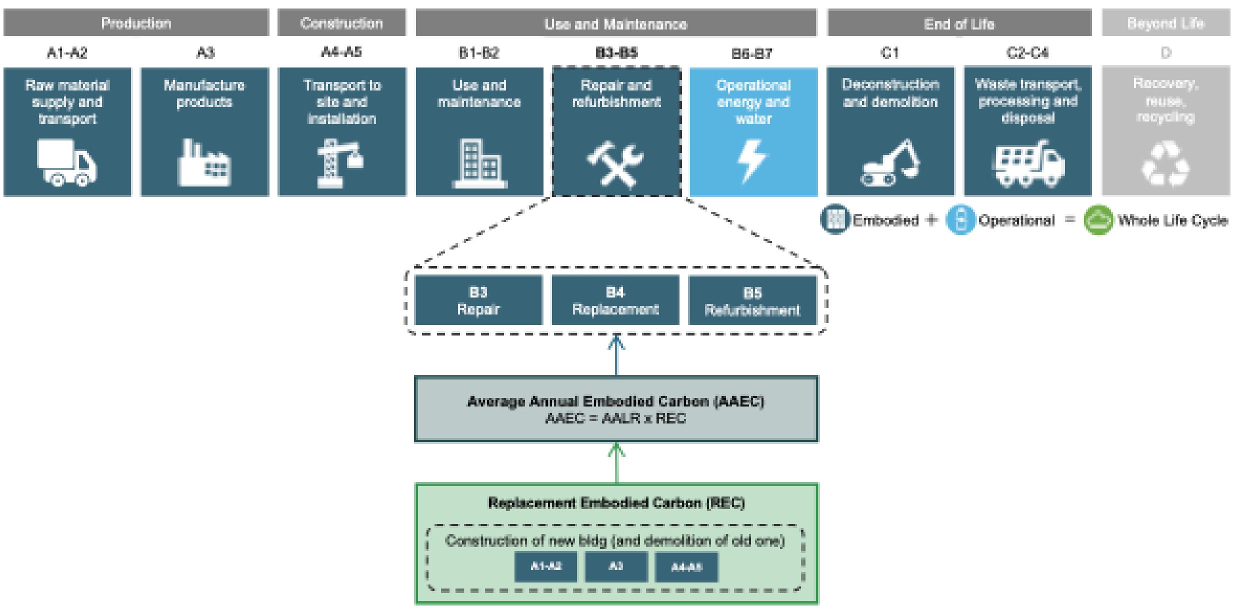

Figure 6. **Extending the building life cycle to include the average annual embodied carbon.** Integration of the embodied emissions from seismic damage repair and reconstruction into conventional building life cycle stages. Figure adapted from Magwood and Huynh[61], The Hidden Climate Impact of Residential Construction (2023), released under a Creative Commons Attribution-ShareAlike 4.0 International (CC BY-SA 4.0), https://creativecommons.org/licenses/by-sa/4.0/.

Identification of Building Types

Europe's building stock is vast and heterogeneous, containing many construction types that are no longer used in new developments due to their reliance on obsolete materials or high seismic vulnerability. Accordingly, when estimating replacement embodied carbon, we focus exclusively on building types compliant with current European engineering practices, following the "Build Back Better" strategy. A similar principle is adopted in GEM's current exposure model[32], which assumes that post-disaster reconstruction meets the minimum affordable housing standards of each country.

This assumption is appropriate for European countries, where national building codes (e.g., Eurocode annexes), are legally enforced. For simplicity, we consider that replacement buildings retain the same material category as those they substitute, but with improved structural systems and modern materials (see "Results"). This reflects typical post-disaster reconstruction, where upgrades involve seismic detailing rather than complete re-designs to meet architectural integration or urban regulatory constraints.

However, we recognise some limitations: (i) reconstruction does not always result in improved seismic performance; (ii) different structural systems can achieve similar seismic performance, yet produce varying carbon footprints; (iii) post-disaster reconstruction may be driven by factors like supply chain disruption or budget constraints, leading to the use of completely different materials (e.g., widespread use of prefabricated concrete upon Romania's 1977 earthquake[62]). As such, our AAEC estimates should be interpreted as representative of plausible scenarios rather than precise forecasts. Nevertheless, the framework is flexible as users may refine results by selecting alternative building replacement types (see Figure 1) or deriving more building-specific component take-offs and multiplying them by the corresponding ECFs.

Each building type in our analysis (both existing and replacement) is classified via unique strings according to GEM's building taxonomy v3.3[63], which encodes the primary structural attributes relevant to seismic performance. These include, among others: (i) main construction material(s); (ii) lateral load-resisting system; (iii) height, expressed as the number of stories; and (iv) occupancy type. Table 3 outlines the building types used within Europe's exposure model and their potential replacements.

Table 3. Existing building types and their potential replacements, including descriptions of materials and systems.

Existing building type*	Potential replacement*	Description of potential replacement
CR/LDUAL	CR/LDUAL	CR dual system with ribbed floors/roof (with hollow clay blocks)
CR/LDUAL/FC	CR/LDUAL/FC	CR dual system with concrete solid floors/roof
CR/LFINF CR/LPB UNK/LFM MATO/LFM SRC/LFM MCF/LWAL MIX/(MUR+CR)/LWAL MIX/LH	CR/LFINF(CLBRH)	CR frame infilled with hollow clay bricks, with ribbed floors/roof (with hollow clay blocks)
CR/LFLS CR/LFINF/FC	CR/LFINF(CLBRH)/FC	CR frame infilled with hollow clay bricks, with concrete solid floors/roof
CR/LFINF(MUR+CBH) CR/LFINF(MUR+CBS)	CR/LFINF(CBH)	CR frame infilled with hollow concrete bricks, with ribbed floors/roof (with hollow concrete blocks)
CR/LWAL UNK	CR/LWAL	CR wall system with ribbed floors/roof (with hollow clay blocks)
CR/LWAL/FC	CR/LWAL/FC	CR wall system with concrete solid floors/roof
MR/LWAL MIX(MUR+W)/LWAL	MR+CLBRH/LWAL	Reinforced masonry system with hollow clay bricks, with ribbed floors/roof (with hollow clay

MUR/LWAL UNK/LWAL MATO/LWAL EU/LWAL		blocks)
MUR/LWAL/FC	MR+CLBRH/LWAL/FC	Reinforced masonry system with hollow clay bricks, with concrete solid floors/roof
MUR/LWAL/FW	MR+CLBRH/LWAL/RWO/FW	Reinforced masonry system with hollow clay bricks, with timber composite floors/roof
MUR/LWAL/RWO/FM	MR+CLBRH/LWAL/RWO/FM	Reinforced masonry system with hollow clay bricks, with ribbed floors (with hollow clay blocks) and timber composite roof
MUR/LWAL/RWO/FC MCF/LWAL/RWO/FC	MR+CLBRH/LWAL/RWO/FC	Reinforced masonry system with hollow clay bricks, with concrete solid floors and timber composite roof
MUR+CB/LWAL MUR+CBH/LWAL	MR+CBH/LWAL	Reinforced masonry system with hollow concrete blocks, with ribbed floors/roof (with hollow concrete blocks)
S/LFBR	S+SR/LFBR	Steel braced frame with hot-rolled steel members, with composite concrete-steel floors/roof
S/LFINF S/LFM	S+SR/LFINF	Steel infilled frame with hot-rolled steel members, with composite concrete-steel floors/roof
S/LWAL	S+SR/LWAL	Steel wall system, with composite concrete-steel floors/roof
W/LFINF W/LFM W/LPB	W/LFINF	Timber infilled frame, with composite concrete-timber floors/roof
W/LWAL	W/LWAL	Timber wall system, with composite concrete-timber floors/roof

* **Material of the lateral load-resisting system**: CR (reinforced concrete), SRC (composite concrete with steel section), S (steel), SR (hot-rolled steel), MUR (unreinforced masonry), MCF (confined masonry), MR (reinforced masonry), CLBRH (fired clay hollow bricks), CBS (solid concrete blocks), CBH (hollow concrete blocks), EU (unreinforced earth), W (timber), MATO (other material), MIX (mixed), UNK (unknown material).
Lateral load-resisting system: LFM (moment frame), LFINF (infilled frame), LFBR (braced frame), LPB (post and beam), LWAL (wall system), LDUAL (dual frame-wall system), LFLS (flat slab/plate or waffle slab), LH (hybrid).
Other features: RWO (timber roof), FC (concrete floor), FW (timber floor), FM (masonry floor).

Quantity Estimation of Structural and Non-structural Components

Calculating the replacement embodied carbon warrants a quantification of all construction materials and individual components[36,40,41,64], particularly those prone to earthquake damage. This becomes more difficult at the portfolio level, where building stock exhibits high variability in structural materials, geometric properties, and occupancy categories. In this context, we perform a simplified, practice-oriented quantity take-off approach consistent with a preliminary design stage. While this does not resolve the full complexity of portfolios, it offers reasonable accuracy appropriate for regional-scale risk assessments[30].

For structural components (i.e., frames, floors, foundations, and walls) of the building types listed in Table 3, we develop spreadsheets that perform tributary load distribution and simulated design using current building codes[65,66]. These calculations are based on simplified archetype geometries and consider only gravity loads. We do not consider seismic design as the associated increase in structural material quantities is unlikely to heavily impact building-level embodied carbon. The resulting quantities vary by material, structural system, number of storeys, and occupancy (i.e., residential, commercial, industrial). For cases where a simulated design is infeasible, we extract quantities from available construction drawings.

Non-structural components are grouped into four drift-sensitive categories (i.e., light partitions and finishings, heavy partitions and finishings, windows/glazing/doors, stairs) and four acceleration-sensitive categories (i.e., heating, ventilation, and air conditioning systems, electrical components, pipes, ceilings). We obtain their quantities from GEM's building-specific inventory, which offers relevant estimates per square meter of built area based on geographic region, primary construction material, and occupancy. These estimates were developed through FEMA's "Normative Quantity Estimation Tool"[17], in conjunction with building surveys, blueprints, and expert judgement. All our quantity estimates, distinguished by individual component category, building type, and occupancy, are publicly available in our GitHub repository[23].

Collection, Compilation, and Assembly of Embodied Carbon Data

The replacement embodied carbon combines emissions from the construction of new buildings (modules A1-A5) with the end-of-life activities related to demolishing damaged structures, which are considered under module A5.

For the production stage (A1-A3), we obtain embodied carbon data from environmental product declarations (EPDs). These are voluntary manufacturer-issued documents reporting product-specific environmental impacts at several life-cycle stages[67]. However, EPDs can involve substantial variability, even for identical products, due to differences in manufacturing processes, regional context, and data consistency (e.g., CO_2 versus CO_2e). To tackle this, we collect and compile an extensive dataset of European EPDs from multiple sources, assuming similarity in products and related processes[56,64,68]. We prioritise the sources outlined below:

- The Embodied Carbon in Construction Calculator (EC3) Tool[27]: a global database reporting environmental-impact data, categorised by material/component type, geographic extent, and other relevant characteristics. The EC3 tool offers the required impacts as average values (with standard deviations), incorporating all EPD records in its database, along with access to individual EPDs from manufacturers;

- Recent peer-reviewed publications that compile multiple EPDs, offering averaged or distributional values for environmental impacts. We use these sources for materials and components not available in the EC3 tool at the time of writing;

- Manually collected EPDs, supplied by European manufacturers. For materials and components not covered by the above sources, we rely on additional EPDs. Overall, we compiled a dataset of more than 370 EPDs obtained from online databases like Eco Platform[24], EPD-Hub[25], and Ökobaudat[26];

- Additional databases, such as the Inventory of Carbon and Energy (ICE)[69].

We aggregate the collected data to derive average ECFs (see Table 1 in the "Results" section), depicting the embodied carbon per unit quantity of materials or components. Most of the embodied carbon data address exclusively the material production stage (A1-A3), as it is the largest emission contributor. For consistency, we only extract A1-A3 data from each EPD, even when some include other modules. We then multiply ECFs by the corresponding material or component quantities to generate the A1-A3 portion of replacement embodied carbon. We note that EPDs have a 5-year validity[67] to adequately reflect prevalent manufacturing and construction practices. Manufacturers are expected to update EPDs upon expiration, which could change environmental-impact profiles, especially with better decarbonisation measures and cleaner production technologies. Thus, our ECF estimates are constrained by the temporal scope of the underlying data.

Comparison with previous studies shows reasonable variations. Pomponi and Moncaster[70] analysed several EPDs worldwide from 2012 to 2016 and reported an average ECF for ready-mix concrete of 0.145 kg CO_2e/kg, while our estimate is 0.11 kg CO_2e/kg (assuming a concrete density of 2,400 kg/m^3). For structural timber, their estimate (0.438 kg CO_2e/kg) exceeds our value (0.25 kg CO_2e/kg; 640 kg/m^3), while our ECF for clay bricks (0.20 kg CO_2e/kg) aligns closely with both Pomponi and Moncaster's[70] (0.223 kg CO_2e/kg) and ICE[69] (0.213 kg CO_2e/kg).

Estimating the contribution of module A4, which covers the transportation of components and materials to sites, is more challenging due to the high variability and lack of standardised data, especially for large-scale assessments. Therefore, we implement a simplified approach that multiplies the transported mass and distance (including empty returns) by a suitable transport carbon factor. Considering national manufacturers only, we assume that trucks (i.e., heavy-duty vehicles, HDVs) travel an average distance of 120 km from factory to site[30], with a 70%[71] increase to account for empty returns. We use a transport carbon factor of 0.053 kg CO_2/t·km, based on the European Environment Agency (EEA)[28] estimates of 2019-2021 HDV emissions. Although this factor reflects CO_2 only, it is broadly representative of CO_2e for HDVs, where CO_2 is the dominant GHG[72].

Module A5 reflects the embodied carbon associated with the construction stage, including pre-construction demolition (A5.1), construction activities (A5.2), and waste management (A5.3). Worker transport (A5.4) is excluded as it is typically considered as responsibility of individual employees[30].

Pre-construction demolition (A5.1) corresponds to the end-of-life stage of the building being replaced (C1-C4). We compute the embodied carbon of demolition (C1) as 25% of the construction activities (A5.2), assuming standard demolition practices with limited deconstruction and recovery[30]. We treat waste transport (C2) similarly to module A4, but with a shorter travel distance of 50 km, given landfill sites are most likely local[40]. We increase this distance by 50% for empty returns[2971]. For waste processing and disposal (C3-C4), we adopt an embodied carbon rate of 0.013 kg CO_2e/kg of waste[29,73], considering a European-average scenario in which 90% of materials are recovered and 10% are landfilled[74]. We note that our end-of-life assumptions may not fully represent post-disaster demolition practices. In the aftermath of major earthquakes, for example, damaged materials are often unsuitable for reuse or recycling, leading to increased landfilling and unsustainable emergency waste disposal, as observed after the 2023 Türkiye-Syria earthquakes[2].

For construction activities (A5.2), we compute on-site diesel machinery emissions from lifting building components to the building's mid height by cranes. We first obtain the fuel consumption in litres (l) via the empirical relation[75–77]: fuel (l) = 0.000037 Mh + M/500 + 0.83, where M is the component mass (kg) and h is the lift height (m). Using a diesel energy content of 38 MJ/L and a carbon factor of 0.073 kg CO_2e/MJ, we convert fuel consumption to embodied carbon. This method only covers equipment fuel use and excludes other site activities (e.g., formwork). In module A5.3 (waste management), construction waste is estimated using component- and material-specific waste rates[30]. The resulting waste quantities are then multiplied by the embodied carbon factors from the applicable modules, depending on the disposal route. For landfill or incineration scenarios, only modules A1-A4 and C2-C4 are considered.

Data Sources and Integration

This study combines multiple datasets to estimate the embodied carbon associated with seismic damage across Europe. As per Figure 7, our analysis relies on two primary data sources: (i) building exposure and seismic risk models developed by GEM; and (ii) embodied carbon data derived from EPDs and scientific literature.

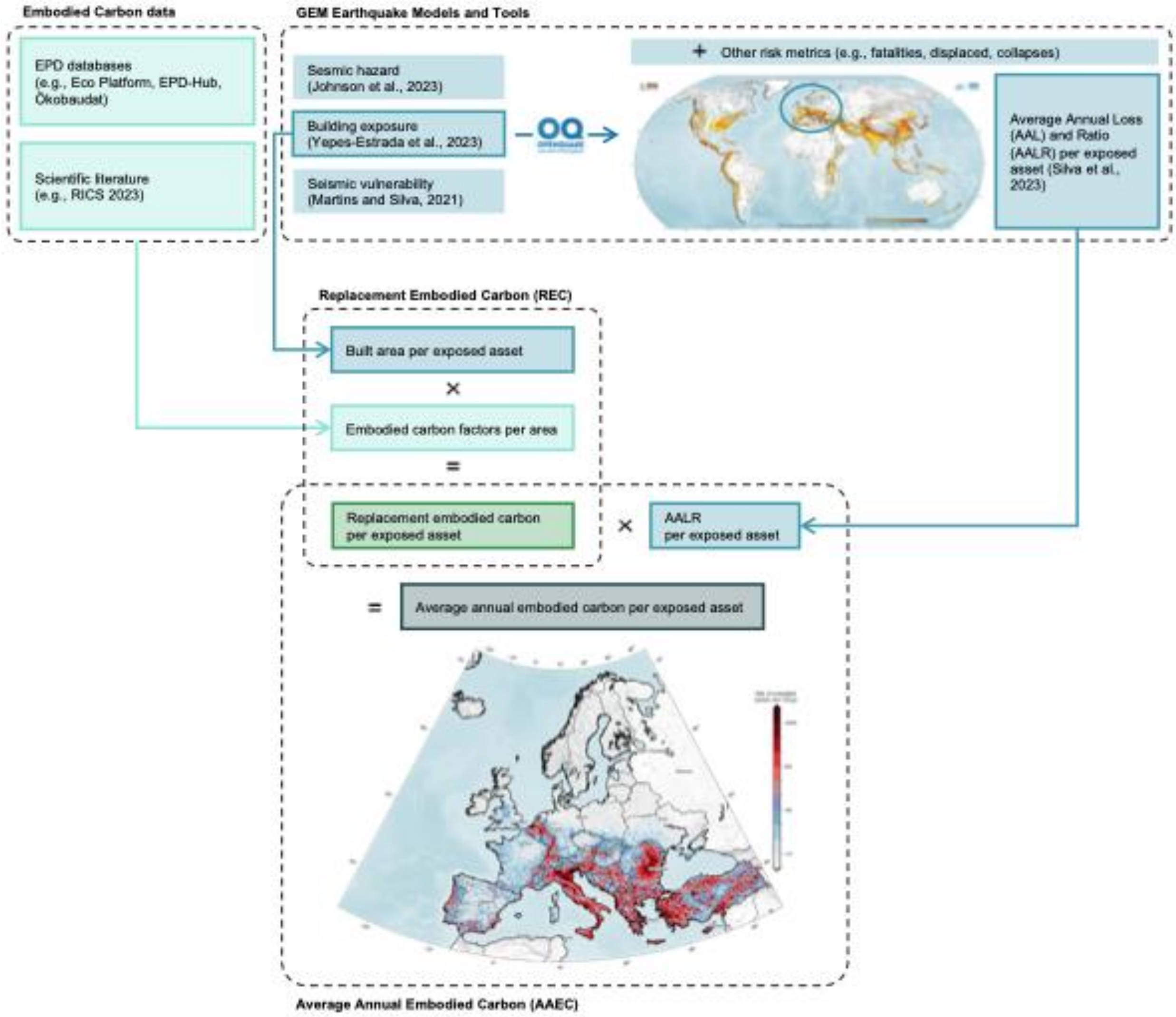

Figure 7. **Data sources and integration overview.** Overview of the data sources and the integration process used in the embodied carbon and seismic risk assessment framework. The base maps are derived from the Explorer Base Map (from NASA Earth Observatory), using data from NASA's MODIS Land Cover, the Shuttle Radar Topography Mission (SRTM), the General Bathymetric Chart of the Oceans (GEBCO 2025 Grid, GEBCO Compilation Group, 2025; doi:10.5285/37c52e96-24ea-67ce-e063-7086abc05f29), and Natural Earth boundaries.

The GEM models for Europe (v2023.1) form a part of a global initiative to develop comprehensive seismic hazard[44], building exposure[32], and vulnerability models[78]. The European component is based on the 2020 European Seismic Hazard Model (ESHM20) and the European Seismic Risk Model (ESRM20)[79]. These datasets are integrated by running probabilistic seismic risk analyses[55] via the OpenQuake Engine[54,80], an open-source platform for seismic hazard/risk assessments. The resulting risk metrics include AALs expected fatalities, displaced populations, and collapsed buildings. GEM's global exposure model is publicly available via GitHub (https://github.com/gem/global_exposure_model/), aggregated at the first subnational administrative division for each country. GEM's vulnerability functions are accessible through https://github.com/gem/global_vulnerability_model/, and the hazard model is hosted on the EFEHR portal (http://www.hazard.efehr.org/en/home/). Country-level summaries and risk metrics are also available through GEM's risk profiles (https://github.com/gem/risk-profiles/). All data layers of GEM's risk model can be downloaded as shapefiles for research and public-good, and can be explored as well via the interactive geoviewer (https://maps.openquake.org/map/grm-2023-1/#3/32.00/-2.00).

To shed more light on our calculations, we use GEM's exposure model to retrieve building assets and their built area at the finest available administrative level. Each asset constitutes a group of buildings with similar structural and occupancy attributes. From these attributes, we estimate component quantities based on building type and occupancy and then multiply them by suitable ECFs, which results in replacement embodied carbon. The AALRs incurred by building assets are derived from GEM's risk model and used as proxies for the AAECRs. The absolute AAEC values of each asset are finally computed by multiplying the AAECRs by the corresponding replacement embodied carbon. The results are then aggregated at the country level. The complete process is depicted in Figure 8 (also see Figure 5 and Table 2).

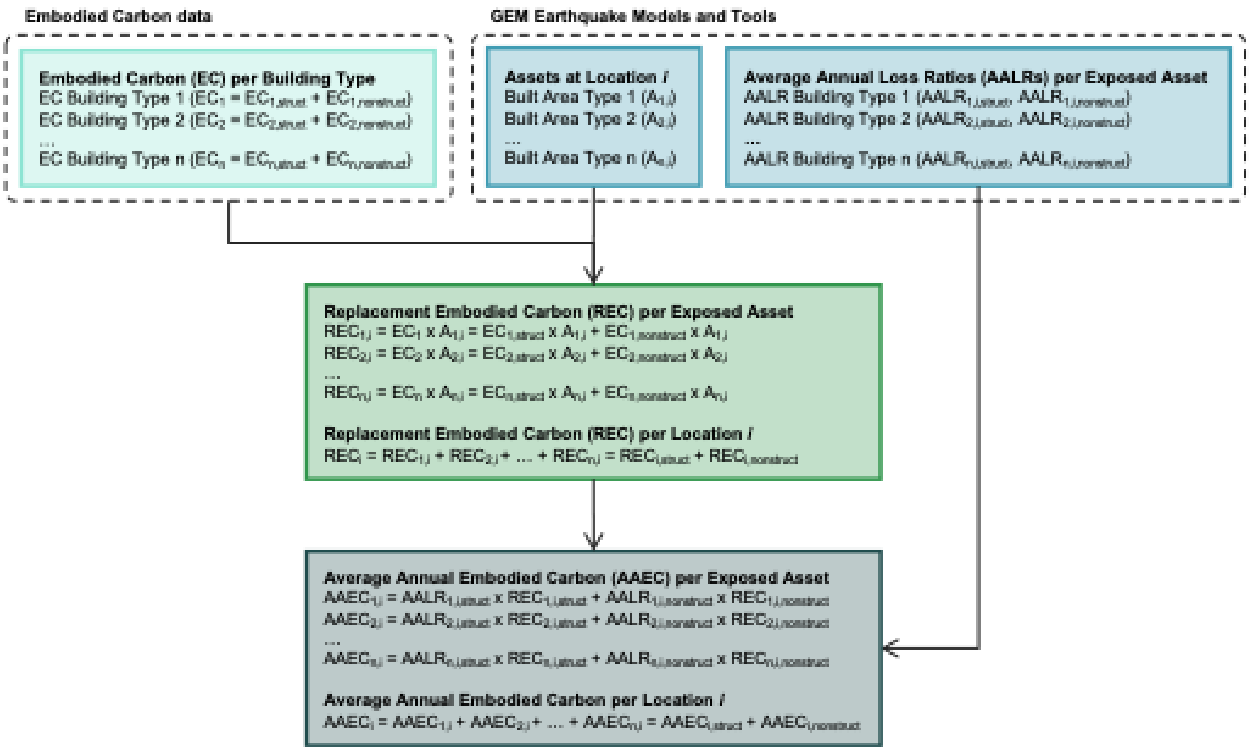

Figure 8. **Workflow for the assessment of replacement embodied carbon and average annual embodied carbon per building asset.** Calculation workflow for estimating replacement embodied carbon (REC) and average annual embodied carbon (AAEC) of a given building asset, with a given occupancy type, exposed to seismic risk.

DATA AVAILABILITY

The datasets generated during the study are available in the GitHub repository, https://github.com/gem/global_embodied_carbon_model. Higher-resolution embodied carbon exposure and risk models are available upon request. Source Data are provided in this paper.

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AUTHORS CONTRIBUTION

M.C. and V.S. conceived the study and designed the methodology workflow. M.C. and K.A. gathered and harmonised all the embodied carbon data and calculated the replacement embodied carbon and the average annual embodied carbon across Europe. A.M.N. estimated quantities of non-structural components. V.S. prepared all the maps. V.S. and C.G. supervised the work. All authors contributed to and revised the writing of the manuscript.

COMPETING INTERESTS

The authors declare no competing interests.

TABLES

Table 1. Embodied carbon factors (ECFs) of different materials and components (modules A1-A3: production stage).

Table 2. Number of buildings (M = million), replacement embodied carbon (REC), share of structural components in REC, average annual embodied carbon (AAEC), and share of structural components in AAEC for 46 European countries, ranked by descending AAEC.

Table 3. Existing building types and their potential replacements, including descriptions of materials and systems.

FIGURES

Figure 1. **Replacement embodied carbon by building type and occupancy. a** Replacement embodied carbon (EC) per built area of different building types and occupancy categories (residential, commercial, industrial). **b** Contribution of structural components. **c** Contribution of non-structural components. For the building types, CR: reinforced concrete, MR: reinforced masonry, S: steel, W: timber. The full description of the strings representing each building type is available in the "Methods" section.

Figure 2. **European building exposure.** Spatial distribution of the number of residential, commercial, industrial buildings on a hexagonal grid with a spatial resolution of 0.20 decimal degrees in GEM's European exposure model. The base maps are derived from the Explorer Base Map (from NASA Earth Observatory), using data from NASA's MODIS Land Cover, the Shuttle Radar Topography Mission (SRTM), the General Bathymetric Chart of the Oceans (GEBCO 2025 Grid, GEBCO Compilation Group, 2025; doi:10.5285/37c52e96-24ea-67ce-e063-7086abc05f29), and Natural Earth boundaries.

Figure 3. **Embodied-carbon exposure in Europe.** Replacement embodied carbon of the European building stock mapped on a hexagonal grid with a spatial resolution of 0.20 decimal degrees. The base maps are derived from the Explorer Base Map (from NASA Earth Observatory), using data from NASA's MODIS Land Cover, the Shuttle Radar Topography Mission (SRTM), the General Bathymetric Chart of the Oceans (GEBCO 2025 Grid, GEBCO Compilation Group, 2025; doi:10.5285/37c52e96-24ea-67ce-e063-7086abc05f29), and Natural Earth boundaries.

Figure 4. **Embodied-carbon seismic risk in Europe.** Embodied-carbon seismic risk map of the European building stock mapped on a hexagonal grid with a spatial resolution of 0.20 decimal degrees. The base maps are derived from the Explorer Base Map (from NASA Earth Observatory), using data from NASA's MODIS Land Cover, the Shuttle Radar Topography Mission (SRTM), the General Bathymetric Chart of the Oceans (GEBCO 2025 Grid, GEBCO Compilation Group, 2025; doi:10.5285/37c52e96-24ea-67ce-e063-7086abc05f29), and Natural Earth boundaries.

Figure 5. **Average annual embodied carbon per country.** Average annual embodied carbon (AAEC) and average annual embodied carbon ratio (AAECR) of 46 European countries, ranked in descending order of AAEC.

Figure 6. **Extending the building life cycle to include the average annual embodied carbon.** Integration of the embodied emissions from seismic damage repair and reconstruction into conventional building life cycle stages. Figure adapted from Magwood and Huynh[61], The Hidden Climate Impact of Residential Construction (2023), released under a Creative Commons Attribution-ShareAlike 4.0 International (CC BY-SA 4.0), https://creativecommons.org/licenses/by-sa/4.0/.

Figure 7. **Data sources and integration overview.** Overview of the data sources and the integration process used in the embodied carbon and seismic risk assessment framework. The base maps are derived from the Explorer Base Map (from NASA Earth Observatory), using data from NASA's MODIS Land Cover, the Shuttle Radar Topography Mission (SRTM), the General Bathymetric Chart of the Oceans (GEBCO 2025 Grid, GEBCO Compilation Group, 2025; doi:10.5285/37c52e96-24ea-67ce-e063-7086abc05f29), and Natural Earth boundaries.

Figure 8. **Workflow for the assessment of replacement embodied carbon and average annual embodied carbon per building asset.** Calculation workflow for estimating replacement embodied carbon (REC) and average annual embodied carbon (AAEC) of a given building asset, with a given occupancy type, exposed to seismic risk.

Editor Summary

Earthquakes generate substantial carbon emissions from building damage repair and reconstruction. The study maps Europe's seismic carbon risk, showing annual losses of 6.6 Mt CO_2e and providing tools for sustainable disaster planning.

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