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Research paper

Comparative environmental assessment of construction materials in climate action projects

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ABSTRACT

Climate action projects increasingly depend on construction materials whose embodied impacts strongly influence sustainability performance, yet cross-comparison between different types of infrastructure remains limited. This study evaluates the material related environmental impacts of representative European climate interventions using a unified life cycle impact framework focused on production and delivery stages. A structured workflow was applied, including project selection, inventory extraction from public technical reports, material quantification, and impact modeling using Global Warming Potential (GWP), Ozone Depletion Potential (ODP), and Human Toxicity (HT). To allow a consistent comparison between heterogeneous interventions, results were normalized using category-specific functional units: floor area for buildings, surface area for parks, and length for flood defenses. Ten projects spanning building renovation, insulation upgrades, green infrastructure, and flood prevention systems were analyzed. The results show that environmental performance is governed primarily by material intensity rather than project size alone. Flood prevention infrastructure exhibits the highest absolute impacts due to heavy mineral material requirements, whereas green infrastructure projects demonstrate low normalized impact intensity relative to spatial scale. Renovation and insulation projects show wide variability depending on envelope material strategies, showing embodied exchanges that are not visible in total impact values. By integrating material inventories with category-based normalization, the framework transforms conventional material LCA into a comparative engineering tool capable of evaluating several climate actions on a common basis. This approach supports evidence-based material selection, exposes efficiency differences between intervention strategies, and advances the practical integration of embodied impact metrics into climate infrastructure planning.

1. Introduction

The increasing global awareness of climate change and its impacts on the environment and human societies has accelerated the need for innovative and effective strategies to mitigate and adapt to these changes [1]. These strategies often involve investments in infrastructure, materials, and technologies [2]. Recent global assessments indicate that the building and construction sector continues to be one of the largest contributors to climate change. According to the 2024 Global Status Report for Buildings and Construction, the sector accounted for 34% of global energy related greenhouse gas emissions, with buildings responsible for approximately one-third of global energy demand and associated CO_2 emissions in 2022 and 2023 [3]. This high share reflects both operational energy use and embodied impacts of construction materials, underscoring the importance of addressing material selection and structural interventions in urban sustainability strategies. The continued prominence of this sector in global emissions trends highlights the urgency of integrating embodied impact considerations into climate action planning for sustainable urban development [4]. Consequently, there is a growing interest in sustainable construction practices and climate action strategies [5], which include but are not limited to building renovation, development of green urban areas, flood prevention, and improved insulation of buildings [6]. Following the Paris Agreement on climate action, the building industry received significant attention in achieving an ambitious level of building performance that led to efficient consideration of forward-thinking, highly efficient architecture, and engineering with renewable energy sources, such as solar panels and geothermal energy [7].

To ensure the efficiency of infrastructure targeting strategies, it is essential to assess the impacts associated with the construction

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materials they require. Based on Life Cycle Assessment (LCA) principles, this approach enables the identification of major impact contributors and supports evidence-based choices for more sustainable project implementation. Life cycle assessment is a helpful tool to assess the environmental impacts of products and processes throughout their entire life cycle, from the extraction of raw materials to the disposal [8]. It is a widely used methodology to evaluate the environmental impacts of systems throughout their entire life cycle [9]. By integrating this approach into the analysis of climate action projects, it becomes possible to highlight environmental hotspots, compare alternative design or material choices, and support more sustainable decision making in future implementations [10]. Recent studies have also emphasized the importance of material-oriented environmental evaluations in construction and infrastructure projects [11]. These works highlight how life cycle-based methods can support sustainability-oriented decision making in real engineering applications, reinforcing the need for detailed material assessments within climate action contexts [12]. The fight against climate change intensifies the planning and implementation of climate actions, for which a comprehensive environmental assessment methodology is lacking. Existing frameworks, such as those based on standardized Life Cycle Assessment (LCA) or Life Cycle Inventory (LCI) procedures, were developed primarily for conventional construction projects with well-defined system boundaries and data availability. However, climate action projects cover a much broader range of interventions, such as building retrofits, green infrastructure, and flood prevention systems, each characterized by distinct material compositions, functional goals, and spatial scales. Applying a full LCA to such heterogeneous cases is often constrained by the absence of detailed operational data, long-term performance information, and standardized functional units across sectors. On the other hand, relying solely on LCI data without translating them into impact categories limits the ability to compare projects and identify the most environmentally demanding materials. To address these methodological gaps, this study introduces a material-centered cradle-to-gate analytical framework that integrates LCI data with Life Cycle Impact Assessment (LCIA) indicators. This approach enables a consistent comparison of material-related environmental effects throughout different types of climate action while maintaining a level of methodological rigor suitable for early-stage evaluation and decision making. By bridging the gap between traditional LCA and LCI methods, the proposed framework contributes a more adaptable and comparative tool for assessing the environmental implications of climate action projects.

To operationalize the proposed framework, this study applies it to several climate action categories characterized by the intensive use of construction materials. This application highlights both the environmental importance of these interventions and the methodological value of a material centered life cycle analysis. Building renovation has been identified as one of the most effective climate actions to reduce energy consumption and greenhouse gas emissions in the built environment [13]. Retrofitting existing buildings not only enhances energy efficiency, but also substantially reduces GHG emissions, thus playing a pivotal role in global decarbonization efforts [14]. By retrofitting existing buildings, significant improvements in energy efficiency can be achieved, which in turn leads to reduced operational costs and carbon footprints [15]. The evaluation of the impacts of construction materials offers a practical means of capturing the environmental importance of building renovation activities [16]. Beyond the renovation of existing buildings, the creation and expansion of green spaces within urban environments. Parks and green areas not only enhance the esthetic appeal and livability of cities [17], but also provide other environmental benefits, such as improving air quality, reducing urban heat island effects, and promoting biodiversity [18]. Nature-based solutions, such as the implementation of extensive green roofs, have demonstrated positive effects on various aspects of urban settings, including building energy savings, particularly during extreme seasons like summer and winter [19]. In addition, these green areas are important in mitigating the impacts of extreme weather events, such as floods and heatwaves, by improving the infiltration of natural water and providing cooling effects [20]. In addition, flood prevention and management are becoming increasingly important as the frequency and intensity of extreme weather events increase due to climate change [21]. Urban areas are more exposed to flooding [22], and the integration of flood prevention measures into urban planning and construction is essential to protect infrastructure and human lives [23]. This includes the use of permeable materials, rain gardens [24], green roofs [25], and other natural solutions that help manage stormwater and reduce the risk of flooding [26]. Lastly, improving the thermal performance of buildings through insulation is a key component of climate action [27]. Using better insulation materials for buildings reduces the need for heating and cooling, thereby reducing energy consumption and associated emissions [28]. The selection of insulation materials plays a decisive role in the environmental performance of energy efficiency measures. Evaluating the impacts associated with material production allows for a clearer understanding of the balance between operational energy savings and the embodied impacts of the materials themselves [29].

Previous studies have utilized LCA and LCI data to determine the environmental impacts of climate action measures, including building construction [30], renewable energy systems [31], and transportation infrastructure [32]. These studies have highlighted the importance of considering multiple stages in the life cycle of products and processes, as significant environmental impacts can occur at different phases [33]. For example, a study shows that material recycling significantly influences energy consumption and greenhouse gas emissions, emphasizing the importance of a comprehensive life cycle approach [34]. However, most existing research remains focused on specific sectors or technologies, with limited attention to the different categories of climate action projects that rely on construction materials [35]. Consequently, more targeted assessments are needed that examine the environmental implications of materials used through different types of climate action. Conducting material-level analyzes based on life cycle data can provide a clear understanding of the environmental performance of these initiatives and help identify opportunities for improvement before project implementation [36]. Climate actions related to the built environment include a wide range of interventions such as building renovation, the creation of green and open spaces, improvement of thermal insulation systems, and flood-prevention infrastructure. While LCA and LCI approaches are well established and supported by international standards and numerous studies on conventional construction practices and renewable energy systems, these methods often focus on single-sector applications. What remains insufficiently addressed is the integration of material-level analysis in relation with the climate action categories that rely on construction materials. Existing frameworks rarely account for the variability in material composition, function, and scale among such interventions, which limits cross-category comparisons and the identification of shared environmental hotspots. This study addresses this gap by applying a unified approach based on a material-centered life cycle that combines inventory data with impact assessment metrics, thereby enabling consistent evaluation of the environmental implications of materials used in different climate action categories. In addition, recent studies such as [37] and [38] provide detailed assessments of environmental impacts in construction materials, their scope is limited to residential building systems. In contrast, climate action planning involves a broader spectrum of infrastructure types beyond buildings alone. The present study addresses this gap by extending material impact analysis throughout multiple categories of climate interventions. Instead of focusing solely on residential buildings, the framework evaluates several infrastructure types, including renovation projects, insulation upgrades, urban parks that require construction materials for elements such as seating and landscape structures, and flood prevention systems involving embankments and heavy mineral works. This scope captures the material demands of real climate action projects beyond the building sector. By linking material inventories to functional outputs across these heterogeneous interventions, the study provides a unified basis

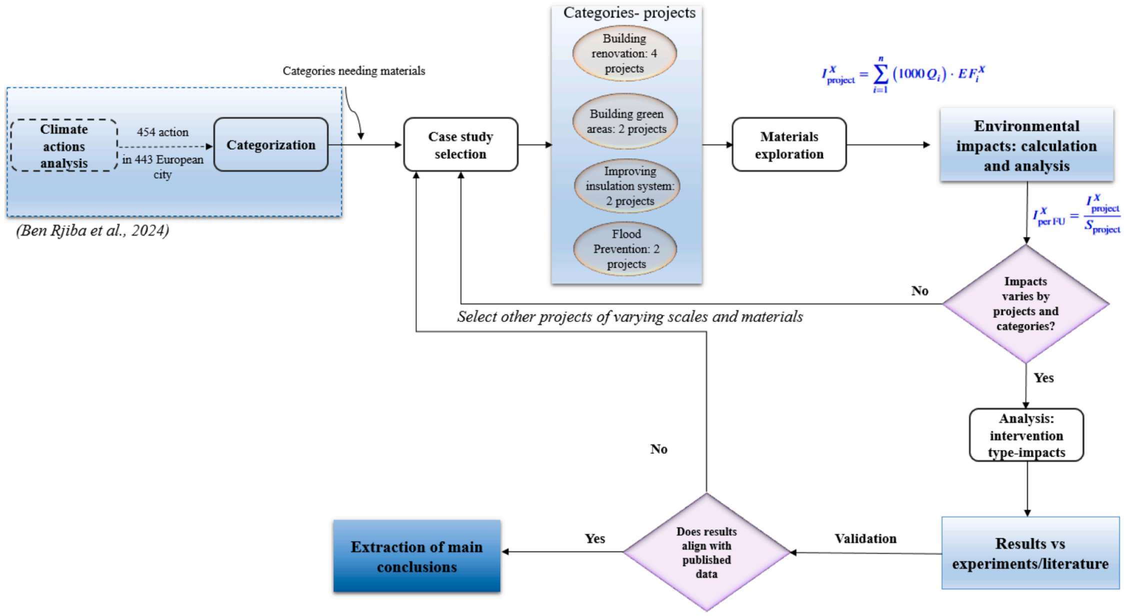


Fig. 1. Workflow of the life cycle impact assessment methodology for climate action projects.

for comparing how material choices shape environmental performance. Another important contribution is the way environmental impacts are compared throughout the different climate action interventions. Instead of applying a single generic reference basis, which can distort comparisons between heterogeneous systems, the framework adopts a category consistent normalization logic aligned with the functional purpose of each intervention. This allows impact intensities to be interpreted within meaningful contexts while avoiding artificial aggregation across incompatible infrastructures, addressing a methodological gap in existing assessments that often rely on uniform comparison metrics or focus on a single infrastructure type.

This paper introduces a novel approach by focusing on 10 projects that belong to four categories of climate actions, quantifies the construction materials used in each project and evaluates their environmental impacts. This focused and comparative analysis provides an understanding of how specific material choices influence environmental outcomes across different types of climate action, offering recommendations to optimize sustainability in future urban planning initiatives. It aims to quantify the materials used in various climate action projects, specifically focusing on building renovation, the development of green urban areas, flood prevention, and insulation improvement. Using a material-centered life cycle-based analysis, this study will evaluate the environmental impacts of these materials and projects, providing information on the most sustainable practices and materials for future climate-resilient construction.

2. Methods

The diversity of climate actions requires an environmental impact assessment method suitable for identifying and comparing the impacts of fundamentally different processes. The proposed workflow introduces a climate action specific, material centered analytical framework based on Life Cycle Assessment principles. Its applicability is demonstrated through selected projects from European cities, illustrating how established LCA methods can be adapted to assess the material related impacts of several climate action interventions. The process of the proposed methodological framework is presented in detail in Fig. 1.

Fig. 1 illustrates the process and key steps involved in assessing the environmental impacts of commonly used construction materials in climate action projects. Rjiba et al. grouped climate actions by analyzing and studying 443 already implemented action plans, which is the input climate action pool for the development of the material centered life cycle based analytical framework [39]. From the different categories identified previously, this study will specifically focus on climate action initiatives that require significant quantities of construction materials, as these are expected to have more significant environmental impacts. These categories have been prioritized to ensure that the analysis remains centered on projects where construction materials play an important role. In addition, it helps identify the specific areas where construction materials play an important role, providing a foundation for deeper investigation of their environmental impacts. Within the categories selected, multiple case studies of climate action projects will be chosen to ensure a diverse and representative sample. In order to widely demonstrate the applicability of the proposed framework, case studies will be selected to include a range of project scales, from small to large, as well as a variety of construction materials used. This approach aims to provide an understanding of the usage of materials in different project contexts, highlighting variations in environmental impacts based on the scale and type of materials used. After selecting the case studies, the next phase focuses on quantifying the quantities of construction materials used in each project. This quantification process will be conducted with great precision, ensuring that the material data is accurately recorded to serve as a reliable foundation for further analysis. Once the material quantities have been documented, the data will undergo a detailed life cycle based analysis (Fig. 1). This methodological approach will assess the environmental impacts associated with each project, increasing awareness of the sustainability and ecological implications of materials used in varying project contexts. This analytical approach provides a comprehensive framework for measuring and analyzing the environmental impacts of each project [40]. This study will employ three critical indices to evaluate these impacts: Global Warming Potential (GWP), Ozone Depletion Potential (ODP), and Human Toxicity (HT), described as follows:

- **GWP** will be the primary environmental indicator of this study, estimating the potential contribution of each project to global warming over the next 100 years. This metric shows the long-term climate implications of the materials and processes used in the projects [41].
- **ODP** will measure the extent to which each project may contribute to the depletion of the ozone layer, an essential factor in evaluating its effects on atmospheric protection and stability [42].

- **HT** will focus on evaluating the potential risks to human health posed by materials and processes used throughout the project life cycle, highlighting the broader implications of construction choices [43].

Several environmental indicators are available within life cycle impact assessment frameworks. However, the selection of indicators in this study was guided by their relevance to material production processes, data consistency, and their direct link to the objectives of climate action projects. The Global Warming Potential was selected as the primary indicator because greenhouse gas emissions from construction material production are a dominant contributor to climate change and represent the main target of mitigation-oriented climate actions. Ozone Depletion Potential was included to account for the possible influence of specific substances related to materials on stratospheric ozone, particularly in industrial production chains, where ozone-depleting emissions, although reduced, remain relevant. Human Toxicity was selected to capture the potential risks to human health associated with material extraction and manufacturing, which are increasingly considered in sustainability-oriented infrastructure planning. Other impact categories, such as acidification and eutrophication, were not included because their effects are highly location-dependent and primarily driven by site-specific emissions and environmental conditions that cannot be assessed within the defined system boundary and data availability of this study. In addition, these categories are less directly influenced by material production alone and are more strongly associated with operational or local-scale environmental processes. Focusing on GWP, ODP, and HT, therefore, enables a scientifically consistent and comparable assessment of material-related impacts while avoiding uncertainties associated with indicators that require spatially explicit modeling beyond the scope of this work.

Together, these indices provide a detailed understanding of the environmental and human health impacts associated with the selected case studies. To perform these evaluations, the total potential influence of each project will be calculated for each environmental impact. This analysis includes the aggregation and comparison of data, allowing to identify trends and patterns in the environmental performance of various construction materials and types of project. By comparing these impacts, the analysis provides valuable results showing how different materials and construction practices influence environmental outcomes, offering a deeper understanding of their ecological implications and sustainability profiles. This process requires drawing conclusions about the most suitable construction materials by evaluating a combination of key factors, such as construction quality, project lifespan, and environmental sustainability. Through this integrated approach, the analysis aims to identify materials that provide an optimal balance between durability and environmental impacts, offering an actionable vision to advance future climate action initiatives and promoting sustainable construction practices. This methodology ensures an evaluation of construction materials in the context of climate action, thereby supporting more informed and strategic decision-making in the pursuit of sustainable urban development.

2.1. Selection of material-intensive climate actions

A total of 454 climate actions, implemented and planned by 443 European cities, were identified and subjected to an in-depth analysis. This evaluation aimed to classify the range of climate initiatives into different categories based on their objectives and implementation strategies. As a result, the actions were grouped into ten primary categories [39], of which the categories with significant construction material needs and used to demonstrate the applicability of the proposed framework are highlighted in bold:

- **Buildings retrofit and renovations (Br).**
- **Heat control and improvement of heating systems (Hi).**
- Seeking financial investments, and joining projects (Fi).
- Involving the community in decision-making phase (Ci).
- Optimizing transportation (To).
- Street light replacement (Str).
- Transition to renewable energy (Re).
- **Adding green areas, parks and planting trees (Tp).**
- **Flood avoidance (Fa).**
- Enhance monitoring systems and data analysis (Da).

These categories, due to their dependance on various construction materials, were considered most relevant for further study. The categorization process not only provided a clear framework for understanding the various approaches taken by cities in their efforts to combat climate change, but also served as an important foundation for the next phase of the study. This phase involves selecting specific climate action projects from the identified categories to allow a focused analysis of the environmental impacts associated with the construction materials used. This structured method guaranties a focused assessment, that enables the extraction of valuable discoveries and trends.

2.2. Case studies selection

Ten climate action projects were selected from the initiatives listed on the Covenant of Mayors website [44]. These projects were carefully chosen to represent a wide range of categories and objectives (Fig. 2). Four of the selected projects focus on building renovation and retrofitting, which is the highest number of projects selected, as this category involves the largest variety and quantities of construction materials. These projects are the following:

- The renovation of **Fondazione Prada** in Milan, Italy
- The retrofit of the **Stedelijk Museum** in Amsterdam, Netherlands
- The restoration of **Fondaco dei Tedeschi** in Venice, Italy
- The **Restoration of the Vieux Lyon Renaissance Houses** in Lyon, France

Two projects fall under the category of "Expanding green spaces and parks," emphasizing the creation and enhancement of urban green areas. The associated projects are:

- **Parque Madrid Rio** in Madrid, Spain
- **Superkilen Park** in Copenhagen, Denmark

Another two projects belong to the category of "Enhancing heat control," highlighting efforts to improve heating systems in residential settings. These initiatives are as follows:

- Improvement of heat systems in a multi-family residential building in Feldkirch, Austria
- Improvement of heat systems in a multi-family residential building in Frankfurt, Germany

Lastly, two projects address "Flood prevention," focusing on safeguarding urban areas from flooding risks:

- The **'Room for the River'** project in Nijmegen, Netherlands
- The **Thames Estuary 2100 (TE2100) Plan** in London, United Kingdom

This selection of projects provides a well-rounded representation of climate actions, enabling a detailed study of the environmental impacts associated with the construction materials used in various contexts.

Fig. 2 highlights the geographic distribution of the 10 selected climate projects in various European regions and countries. These projects were deliberately chosen from different locations to reflect the wide range of climatic, economic, and social conditions that exist throughout Europe.

Fig. 2 provides also an overview of the general information for each selected project. Notably, the starting dates of projects within the same category are relatively close to each other. This alignment was intentionally designed to ensure that all the cases reflect the same period's

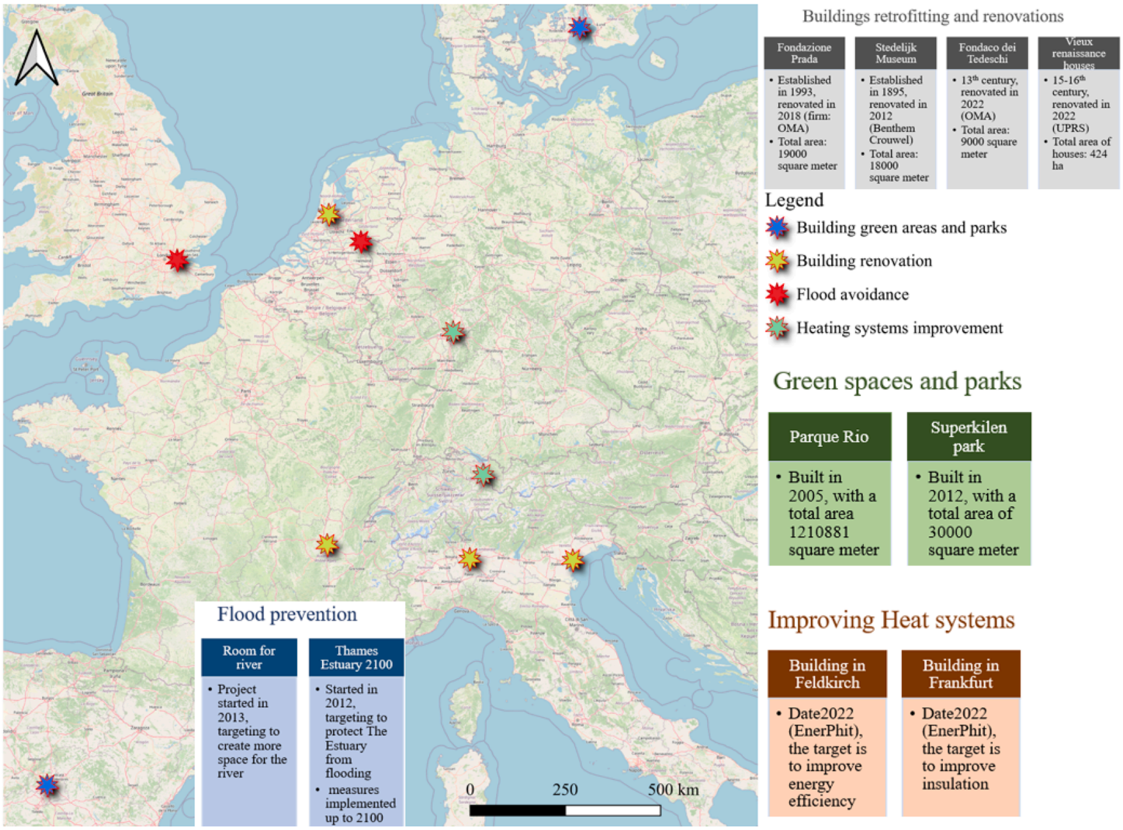


Fig. 2. Map of the case studies location and their basic properties.

availability and advancements in commonly used construction materials.

By selecting projects initiated within a similar time frame, analysis can focus on comparing materials under consistent market and technological conditions. Furthermore, the projects within each climate action category were chosen to be of comparable scale. This alignment was purposefully created to ensure that each case represents the availability and developments of widely used building materials throughout the same time period. By reporting both total impacts and normalized material intensities, the framework distinguishes infrastructure scale from design efficiency. This allows engineering performance to be interpreted in terms of material strategy rather than project size alone.

2.3. Construction materials quantification

Once the projects selected for the study have been finalized, the next step involves collecting detailed data on the types and quantities of construction materials utilized in each project. This data collection process is essential for understanding the composition of the material and the scale of resource usage in the chosen initiatives. The projects analyzed are available in the Covenant of Mayors library as official reports, which provided the necessary information to identify the main materials used in each case. The quantities of these materials were estimated primarily based on the dimensions of the buildings associated with each climate action project. In this study, functional units were defined in a category-specific manner to ensure meaningful comparison of material-related environmental impacts across heterogeneous climate action projects. Rather than applying a single functional unit to all interventions, the analysis adopts reference metrics that reflect the primary function and scale of each climate action category. For building renovation and heating or insulation improvement projects, the functional unit is defined as one square meter of treated floor area, representing the service provided by the intervention. For urban green space projects, impacts are normalized per square meter of park or green area developed, while for flood prevention measures, the functional unit is defined per kilometer of flood defense or riverfront intervention. These functional units were selected to align with established practices in infrastructure and building assessment and to enable comparison within each category while preserving physical relevance. Material quantities for each project were normalized using the corresponding reference metric, based on available project documentation and dimensional characteristics, with explicit assumptions applied where detailed information was unavailable. The environmental assessment focuses on the production and delivery stages of construction materials. This functional unit framework allows consistent evaluation of material-related impacts within each climate action category while avoiding inappropriate cross-category aggregation based on a single, non-representative unit (Fig. 1).

In addition to defining functional units, Table 1 further documents the reference metric values and quantity units used to normalize material quantities for each project. The reference metric value specifies the physical scale of the intervention and serves as the basis for converting absolute material quantities into comparable intensities, while the quantity unit indicates whether normalization is expressed per square meter or per kilometer. For projects where material data or dimensional information were incomplete, explicit assumptions were applied, which may introduce a degree of uncertainty in the estimated values. In the Fondazione Prada renovation, wood quantities initially reported in square meters were converted to mass using an assumed thickness of 2 cm and a density of 500 kg/m^3, corresponding to 0.01 tonnes per m^2. For the multi-family residential building in Feldkirch and the Vieux Lyon Renaissance Houses, reference floor areas of 1800 m^2 and 600 m^2, respectively, were assumed based on typical scales of comparable residential and historic renovation projects. These specifications ensure

Table 1
Project metadata and functional unit definition.

Project & Action category	Functional unit type	Ref metric value	Ref metric unit	Quantity unit
Fondazione Prada (Br)	floor area (m^2)	19,000	m^2	tonnes/m^2
Stedelijk Museum (Br)	floor area (m^2)	8000	m^2	tonnes/m^2
Fondaco dei Tedeschi (Br)	floor area (m^2)	9000	m^2	tonnes/m^2
Vieux Lyon Renaissance Houses (Br)	floor area (m^2)	600	m^2	tonnes/m^2
Parque Madrid Rio (Tp)	park area (m^2)	1,210,881	m^2	tonnes/m^2
Superkilen Park (Tp)	park area (m^2)	30,000	m^2	tonnes/m^2
Multi-family residential building in Feldkirch (Hi)	floor area (m^2)	1800	m^2	tonnes/m^2
Multi-family residential building in Frankfurt (Hi)	floor area (m^2)	1500	m^2	tonnes/m^2
'Room for the river' Nimejen (Fa)	flood defence length (km)	0.8	km	tonnes/km
Thames Estuary plan (Fa)	flood defence length (km)	330	km	tonnes/km

dimensional consistency and transparency in the normalization of material flows across projects.

Following the definition of reference metrics and normalization assumptions, Table 2 presents the distribution of construction materials normalized per category-specific functional unit, allowing comparison of material intensities across climate action projects. Within the building renovation category, significant variability in material use per square meter is observed, reflecting differences in the function of the building, the structural requirements and the scope of the renovation. Large cultural buildings such as the Stedelijk Museum exhibit high concrete intensities, indicating the structural reinforcement demands associated with large-scale renovations, while historic renovation projects, such as the Fondaco dei Tedeschi and the Vieux Lyon Renaissance Houses, show lower concrete use but higher relative contributions from masonry-related materials and stones, consistent with preservation-oriented interventions. Urban green space projects show markedly lower material intensities per square meter compared to building-related actions. Parque Madrid Río and Superkilen Park are characterized by very small normalized quantities of steel, liners and wood-related materials, reflecting the spatially extensive but materially light nature of landscape and surface-level interventions. Despite their low per-unit material intensity, the large surface areas involved imply that these projects may still generate considerable absolute material demands, highlighting the importance of normalization when comparing across categories. Heating and insulation improvement projects demonstrate a distinct material profile, dominated by insulation materials such as wool and foam, along with glass-related components. The Feldkirch residential building shows higher normalized values for glass and insulation materials, consistent with envelope-focused retrofitting strategies, while the Frankfurt case exhibits a more limited material palette, reflecting differences in intervention depth and building typology. Flood prevention projects stand out due to their exceptionally high material intensities per kilometer, particularly for concrete and stones. The 'Room for the River' project demonstrates the dominance of heavy mineral materials required for large-scale hydraulic and earthwork interventions, while the Thames Estuary Plan highlights the use of linear structural elements and protective layers over long distances. These results underline the fundamentally different material demands of flood

Table 2
Construction materials distribution normalized per category functional unit (tonnes/m^2 for **Br**, **Tp**, **Hi**; tonnes/km for **Fa**). (**Br**: Building renovation, **Tp**: Extending green areas and parks, **Hi**: Improvement of the heating and insulation system, **Fa**: Flood prevention).

Project & Action category	Concrete	Brick	Steel	Terrazzo/gypsum	Stones	Bamboo/Timber/liners	Glass/Aluminum	Wool	Foam	Wood/Hardwood
Fondazione Prada (Br)	1.01053	0	0.05263	0	0	0	0.00105	0	0	0.03158
Stedelijk Museum (Br)	4.5	0	0	0.03125	0	0.025	0.00656	0	0	0
Fondaco dei Tedeschi (Br)	0	0.00972	0.00111	0.00444	0.01333	0	0.0005	0	0	0.00042
Vieux Lyon Renaissance Houses (Br)	0	0.05	0.00833	0.03333	0.25	0	0.00383	0	0	0.005
Parque Madrid Rio (Tp)	0	0	0.00002	0	0	0.00002	0	0	0	0.00017
Superkilen Park (Tp)	0.00667	0	0	0	0.005	0	0	0	0	0.014
Multi-family residential building in Feldkirch (Hi)	0	0	0	0	0	0.00333	0.08333	0.0125	0.00161	0
Multi-family residential building in Frankfurt (Hi)	0	0	0	0	0	0	0	0.006	0	0.002
'Room for the river' Nimejen (Fa)	90,000	0	6250	0	650,000	0	0	0	0	0
Thames Estuary plan (Fa)	0	0	0	0	0	14.54545	0	3.0303	0	0

Table 3
Environmental impacts per 1 kg of construction materials across projects.

Materials	GWP ($kgCO_{2eq.}/kg$)	ODP ($kgR_{11eq.}/kg$)	HT ($CTUh/kg$)
Concrete	0.1	2 E-5	65 E-5
Brick	0.5	35 E-6	45 E-5
Steel	2	3 E-6	15 E-4
Terrazzo	0.7	2 E-5	65 E-5
Gypsum	0.2	2 E-5	25 E-5
Stones	0.3	3 E-5	13 E-5
Bamboo	0.2	2 E-5	12 E-5
Timber	0.21	22 E-6	25 E-5
Liners	0	3 E-5	3 E-3
Glass	1.5	2 E-5	55 E-5
Aluminum	8.8	25 E-6	2 E-3
Wool	3	3 E-5	75 E-5
Foam	4.4	2 E-5	2.4 E-3
Wood	0	15 E-6	2 E-4
Hardwood	0	1 E-5	25 E-5

prevention infrastructure compared to building and area-based climate actions, reinforcing the need for category-specific normalization when assessing material-related environmental impacts.

2.4. Environmental impacts of the construction materials used in the climate action projects

Table 3 presents the environmental impacts of 1 kg of the different construction materials selected for the various projects, assessed using three key indices: GWP (Global Warming Potential), ODP (Ozone Depletion Potential), and HT (Human Toxicity). Each construction material listed in the table includes several types depending on its intended use. For example, wool can appear as natural sheep wool, glass wool, or rock wool, each with distinct environmental characteristics. However, in this study, and considering that the differences in environmental impact between types of the same material are relatively minor, the average environmental impact for each material type was used.

Table 3 summarizes the environmental impact factors used to evaluate material-related contributions in climate action projects. Clear differences are observed among construction materials, particularly in terms of GWP, reflecting the energy intensity and emission profiles of their respective production processes. Aluminum exhibits the highest GWP value at 8.8 $kgCO_{2eq.}/kg$, highlighting the carbon-intensive nature of primary aluminum production. Similarly, foam and steel display relatively high GWP values, consistent with their reliance on energy-intensive and chemically driven manufacturing processes. In contrast, materials such as concrete, gypsum, bamboo, and stones show lower GWP values, indicating comparatively lower climate impacts per unit mass. Originally, negative GWP values were associated with certain bio-based materials, including wood, hardwood, and liners, reflecting temporary biogenic carbon storage assumptions embedded in some life cycle databases. However, in the context of this study, these negative values were conservatively set to zero. This adjustment was made to avoid overstating climate benefits that depend on long-term carbon storage assumptions, end of life scenarios, and temporal system boundaries that are not explicitly modeled within the defined cradle-to-gate scope. By assigning a neutral GWP value, the analysis ensures consistency with the selected system boundary and avoids introducing methodological bias when comparing material-related impacts across heterogeneous climate action projects. The values of Ozone Depletion Potential remain uniformly low in all materials, generally within the range of 10^{-5} to 10^{-6} $kgR_{11eq.}/kg$, indicating a limited influence on stratospheric ozone depletion. Brick shows a comparatively higher ODP value, likely linked to emissions associated with high-temperature kiln processes. Other materials, such as concrete, gypsum, glass, bamboo, and stones, present similar magnitudes of ODP, suggesting that ozone depletion is a secondary concern relative to other impact categories for material production. Human Toxicity indicators show pronounced variability among materials. Steel, foam, aluminum, and liners exhibit higher toxicity values, reflecting the presence of heavy metals, solvents, and chemical additives in their production chains. However, mineral- and bio-based materials, such as stones, bamboo, gypsum, and timber, demonstrate lower HT values, suggesting comparatively lower risks to human health per unit mass. Materials such as concrete and terrazzo occupy an intermediate position, with moderate impacts across all three indicators.

The table underscores the need for strategic material selection in climate action projects. While high-performance materials like aluminum or foam offer structural or thermal benefits, their elevated environmental burdens (especially in GWP and HT) require careful assessment. In contrast, renewable or natural materials such as wood, bamboo, and stones demonstrate a more favorable environmental profile.

All of these findings suggest that the type of material has a significant influence on the environmental impacts. However, it is worth highlighting that there are significant efforts to reduce these impacts in the development of different construction materials. For example, in the case of concrete, the majority of carbon dioxide emissions come from the manufacturing process of Portland cement, as direct emissions ([45]). The greatest potential for reducing emissions lies in the substitution of Portland cement clinker with suitable supplementary cementitious materials. But there is also considerable promise in the use of waste concrete, available worldwide, as recycled aggregates, supplementary cementitious materials, filler, and feedstocks for clinker production ([46]). It is also important to note that the global construction sector is a major producer of waste, using only half of the waste materials. The principles of the circular economy are therefore increasingly important here, as the reuse of materials minimizes waste and avoids the extraction and production of new raw materials, reducing the environmental footprint ([47]). This is also true for ceramic bricks, where reuse can lead to an environmental improvement of around 85% compared to new bricks.

Building on the material-specific impact factors discussed previously, the next step consists of quantifying the total environmental impacts associated with the construction materials used in each climate action project. For each project, material quantities were first harmonized in mass units to ensure consistency with the characterization factors, which are expressed per kilogram of material. Quantities originally reported in tonnes were therefore converted to kilograms prior to calculation. The total impact for each environmental indicator was then obtained by multiplying the mass of each material by its corresponding characterization factor and summing the contributions of all materials included in the project inventory. This calculation was performed separately for Global Warming Potential (GWP), Ozone Depletion Potential (ODP), and Human Toxicity (HT), using the impact factors reported in Table 3 and within the defined system boundary covering material production and delivery stages.

$$I^X_{\text{project}} = \sum_{i=1}^{n} \left(1000\, Q_i\right) \cdot EF_i^X \tag{1}$$

In this expression, I^X_{project} represents the total impact of a given project for impact category X (GWP, ODP, or HT), Q_i is the quantity of material i expressed in tonnes, EF_i^X is the corresponding characterization factor per kilogram of material and n denotes the number of material types considered in the project. This approach ensures dimensional consistency between material quantities and impact factors and provides an absolute measure of the environmental burden associated with each project. In addition to total project impacts, environmental indicators were also normalized using category-specific functional units to allow comparison among projects of different sizes within the same climate action category. Normalization was performed by dividing the total project impact by the reference metric value associated with each project, such as the treated floor area, developed park area, or flood defense length, depending on the intervention type. This step yields an intensity-based indicator that expresses environmental impacts per unit of delivered service, rather than per project.

Table 4
Project-level impact results (total) and normalized impacts per category functional unit (FU). Total impacts are reported for the full project, while normalized impacts divide totals by the category reference metric (m^2 for Br/Tp/Hi; km for Fa).

Project & Action category	Total GWP	Total ODP	Total HT	GWP/FU	ODP/FU	HT/FU
Fondazione Prada (Br)	4,096,000	396.5	1 558	215.57894	0.02087	0.082
Stedelijk Museum (Br)	3,768,750	730.05	2 455.375	471.09375	0.09126	0.30692
Fondaco dei Tedeschi (Br)	134,500	7.6395	50.2725	14.94444	0.00085	0.00558
Vieux Lyon Renaissance Houses (Br)	87,450	6.056	36.465	145.75	0.01009	0.06078
Parque Madrid Rio (Tp)	60,000	4.068	129.3	0.04955	0.000003	0.00011
Superkilen Park (Tp)	65,000	12.7	137.5	2.16667	0.00042	0.00458
Multi-family residential building in Feldkirch (Hi)	305,260	3.913	124.335	169.58889	0.00217	0.06908
Multi-family residential building in Frankfurt (Hi)	27,000	0.315	7.35	18	0.00021	0.0049
‘Room for the river’ Nimejen (Fa)	173,200,000	17,055	73,030	216,500 000	21318.75	91 287.5
Thames Estuary plan (Fa)	3,960,000	135.6	1 950	12,000	0.41091	5.90909

$$I^X_{\text{per FU}} = \frac{I^X_{\text{project}}}{S_{\text{project}}} \tag{2}$$

$I^X_{\text{per FU}}$ denotes the normalized impact per category functional unit, and S_{project} corresponds to the reference size of the project expressed in square meters or kilometers, as defined in Table 1. This normalization enables consistent comparison of material-related impact intensities across projects within the same climate action category, independent of overall project scale. Reporting both total and normalized indicators provides complementary information. Total impacts reflect the absolute environmental burden associated with material use and are relevant for understanding the contribution of individual projects to city- or program-level emissions and impacts. Normalized impacts, in contrast, reveal the environmental intensity of material use per unit of intervention and support comparative evaluation across projects with differing dimensions. Together, these indicators offer a more complete and robust basis for interpreting material-related environmental performance in climate action projects.

3. Results and discussion

Table 4 synthesizes the results of the life cycle based analytical framework by reporting both absolute project impacts and impacts normalized per category functional unit (FU). Across all projects, the results show pronounced variability in GWP, ODP and HT, driven by two main factors: (i) the total quantity and type of materials used, which determine the absolute impacts, and (ii) the material intensity per unit of intervention, which is captured by the FU-normalized indicators. This dual reporting is essential for interpreting climate action projects because the interventions differ significantly in scale and physical configuration; therefore, absolute impacts alone would primarily reflect project size, whereas normalized results show the environmental intensity of delivering a unit of service within each climate action category. Flood prevention interventions exhibit the highest absolute impacts, dominated by the ‘Room for the River’ project, which reaches 173.2 million $kg\,CO_{2eq.}$ and 73,030 $CTUh$, reflecting the heavy reliance on concrete and stones required for large-scale earthworks and hydraulic protection. Normalization by the category FU (km of flood defense) further highlights the exceptional material intensity of this intervention, yielding 216.5 million $kg\,CO_{2eq.}/km$ and 91287.5 $CTUh/km$. In contrast, the Thames Estuary Plan shows lower total impacts than ‘Room for the River’, but the FU-normalized values remain substantial (12000 $kg\,CO_{2eq.}/km$ and 5.91 $CTUh/km$), illustrating that flood-prevention measures can differ strongly in environmental intensity depending on design approach, scale of structural works and protective layers. These findings emphasize that flood prevention climate actions constitute a distinct class of material intensive infrastructure compared to building and area-based interventions. Within the building renovation category, large cultural buildings exhibit the highest absolute impacts, with the Fondazione Prada and Stedelijk Museum projects reaching 4.10 million and 3.77 million $kg\,CO_{2eq.}$, respectively. However, the FU normalized results show that the Stedelijk Museum has a markedly higher GWP intensity (471.09 $kg\,CO_{2eq.}/m^2$) than Fondazione Prada (215.58 $kg\,CO_{2eq.}/m^2$), indicating that the environmental burden per unit renovated area is more strongly influenced by the material mix and intervention depth than by total project scale alone. The relatively low normalized values for the Fondaco dei Tedeschi (14.94 $kg\,CO_{2eq.}/m^2$) suggest a lower material intensity per unit area, whereas the Vieux Lyon Renaissance Houses show intermediate intensities (145.75 $kg\,CO_{2eq.}/m^2$), consistent with renovation strategies where stone and finishing materials contribute more strongly relative to structural concrete. Similar patterns are observed across ODP and HT, where the Stedelijk Museum also presents the highest intensities (0.0913 $kg\,R_{11eq.}/m^2$ and 0.3069 $CTUh/m^2$), pointing to both higher material demand per m^2 and the use of materials with higher characterization factors. Heating and insulation improvement projects present lower absolute impacts than major renovations, yet FU normalized results indicate that these interventions can still be environmentally intensive per treated area, depending on the retrofit package. Feldkirch exhibits 169.59 $kg\,CO_{2eq.}/m^2$ and 0.0691 $CTUh/m^2$, while Frankfurt shows much lower intensities (18 $kg\,CO_{2eq.}/m^2$ and 0.0049 $CTUh/m^2$). This contrast reflects differences in material composition, particularly the relative contribution of insulation and envelope related materials, and demonstrates the value of FU normalized indicators for distinguishing between shallow and deep retrofit strategies when evaluating climate action measures that target operational energy savings but require additional embodied impacts. Green space projects show comparatively small absolute impacts (60000–65000 $kg\,CO_{2eq.}$), and their FU normalized intensities are also low, especially for Parque Madrid Rio (0.0496 $kg\,CO_{2eq.}/m^2$). Superkilen Park presents a higher normalized intensity (2.17 $kg\,CO_{2eq.}/m^2$), indicating a more material intensive landscape design relative to its area. Although these values are lower than those of building and flood prevention interventions, their interpretation is important because green space climate actions can cover very large areas. Therefore, small per unit intensities may still translate into significant absolute material demands at the city scale. Overall, the FU normalized results provide category consistent intensity metrics that make it possible to compare projects within the same climate action category on an equal basis and to identify projects where material choices or intervention depth drive disproportionately high impacts per unit of delivered service. This category based normalization is particularly relevant for climate action portfolios, where decision makers must prioritize among heterogeneous interventions (buildings, green infrastructure, and flood prevention) that cannot be compared meaningfully using a single universal functional unit. By linking material inventories and impact indicators to climate action typologies through category specific functional units, the results support a more interpretable and action-oriented assessment of material-related environmental performance than reporting total impacts alone.

3.1. Environmental impact comparison of project categories

As demonstrated in the previous section, comparing all selected projects provides a general comparison depending on their scale. To make this comparison more specific, it should be assessed across project categories, because the materials used vary significantly between projects, depending on their respective climate action categories. Therefore, this section focuses on comparing the environmental impact indices of projects within the same climate action category.

3.1.1. Building renovation projects

The comparison between the Fondazione Prada and Stedelijk Museum projects illustrates how differences in material composition translate directly into both absolute and normalized environmental impactsThe comparison between the Fondazione Prada and Stedelijk Museum projects illustrates how differences in material composition translate directly into both absolute and normalized environmental impacts. The plot of the intensity of the stacked material shows that the Stedelijk Museum requires more concrete and steel per square meter than the Fondazione Prada renovation, resulting in a total intensity of the material more than four times higher (Fig. 3). Because concrete dominates the mass profile of both projects, even moderate increases in concrete use produce large differences in total embodied impacts. This relationship is reflected in the total GWP results, where Fondazione Prada reaches 4.10 million $kg\,CO_{2eq.}$ while the Stedelijk Museum records 3.77 million $kg\,CO_{2eq.}$, despite the latter having a smaller reference floor area. When normalized by functional unit, the contrast becomes more pronounced: the Stedelijk Museum exhibits a GWP intensity of 471 $kg\,CO_{2eq.}/m^2$ compared to 216 $kg\,CO_{2eq.}/m^2$ for Fondazione Prada. This indicates that the environmental burden per renovated square meter is driven more by structural reinforcement and material choice than by project size alone. The toxicity and ozone depletion indicators follow a similar pattern. The Stedelijk Museum shows higher HT and ODP values, consistent with its greater reliance on steel and processed materials that carry higher characterization factors. Importantly, the normalized indicators show that the difference between projects is not simply a scale effect, but reflects a fundamentally different material strategy. While both projects fall within the same climate action category (building renovation), the figure demonstrates that renovation depth, structural intervention, and finishing materials can shift the environmental profile significantly. This result highlights the analytical value of combining absolute impacts with functional unit normalization: total values capture city scale burden, whereas normalized metrics expose material efficiency. Together, they provide a more varied understanding of how design decisions influence the environmental performance of climate action projects.

The comparison between the Fondaco dei Tedeschi and the Vieux Lyon Renaissance Houses shows how historic renovation strategies can produce markedly different material and environmental profiles. The stacked material plot indicates that the Vieux Lyon project relies more heavily on mineral materials, particularly stones and terrazzo-related components, resulting in higher material intensity per square meter. In contrast, Fondaco dei Tedeschi uses a lighter material palette, leading to lower normalized material demand (Fig. 4). These differences are reflected in the impact results. Although Fondaco dei Tedeschi records a higher total GWP (134500 $kg\,CO_{2eq.}$) than Vieux Lyon (87450 $kg\,CO_{2eq.}$), normalization reverses the interpretation: Vieux Lyon reaches 145.75 $kg\,CO_{2eq.}/m^2$ compared to 14.94 $kg\,CO_{2eq.}/m^2$ for Fondaco. Similar trends are observed for ODP and HT. This demonstrates that environmental performance is governed more by material intensity and intervention depth than by absolute project scale. Reporting both total and normalized indicators, therefore, shows differences in renovation efficiency that would not be visible from project totals alone.

3.1.2. Park and green space development projects

The two projects selected for this category involve the creation of two parks: Parque Río in Madrid and Superkilen Park in Copenhagen. This category of climate actions does not rely on a large variety or quantity of construction materials but instead focuses on the extensive use of trees and grass.

The comparison between Parque Madrid Río and Superkilen Park highlights how urban green space projects can differ in environmental performance despite belonging to the same climate action category. In absolute terms, Parque Madrid Río exhibits the higher total GWP (134500 $kg\,CO_{2eq.}$) compared to Superkilen Park (87450 $kg\,CO_{2eq.}$), reflecting its larger spatial extent and total material demand. However, normalization per functional unit shows the opposite trend. Superkilen Park reaches a GWP intensity of 2.17 $kg\,CO_{2eq.}/m^2$, whereas Parque Madrid Río records only 0.0496 $kg\,CO_{2eq.}/m^2$. This indicates that Superkilen relies on a more material intensive design relative to its developed area (Fig. 5). A similar pattern is observed for ODP and HT, where Parque Madrid Río shows higher absolute values due to scale, but Superkilen presents greater environmental intensity per square meter. These results demonstrate that, for green infrastructure projects, absolute impacts are primarily driven by total area, while normalized indicators capture differences in design strategy and material density. The figure therefore emphasizes the importance of functional unit normalization in distinguishing between large area, low intensity landscape interventions and smaller but more material intensive urban park developments.

3.1.3. Improving building insulation and heating efficiency

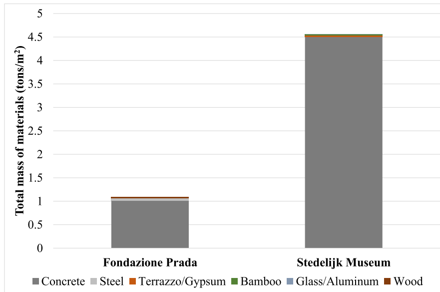
The two projects selected for this category are small-scale initiatives aimed at enhancing the insulation of two multi-family residential buildings, one located in Feldkirch and the other in Frankfurt. This type of actions do not require a wide variety of materials (Table 2).

The comparison between the residential buildings in Feldkirch and Frankfurt illustrates how differences in insulation strategies and façade systems translate into large variations in environmental performance. In absolute terms, the Feldkirch building shows higher total GWP (305260 $kg\,CO_{2eq.}$) than the Frankfurt case (27000 $kg\,CO_{2eq.}$), reflecting a greater reliance on glass, aluminum, and insulation materials. These material choices also drive the higher ODP and HT values observed for Feldkirch, particularly in relation to synthetic insulation components . Normalization per functional unit confirms that the difference is not only a matter of project size. Feldkirch reaches a GWP intensity of 169.59 $kg\,CO_{2eq.}/m^2$, compared to 18 $kg\,CO_{2eq.}/m^2$ for Frankfurt. Similar proportional gaps are visible for ODP and HT, indicating that the environmental burden per unit of floor area is consistently higher in Feldkirch. The figure therefore demonstrates that heating and insulation interventions can vary widely in material efficiency, and that high performance envelope solutions may introduce significant embodied impacts. Evaluating results per functional unit is essential to visualize these trade-offs and to support balanced design decisions in building energy retrofits (Fig. 6).

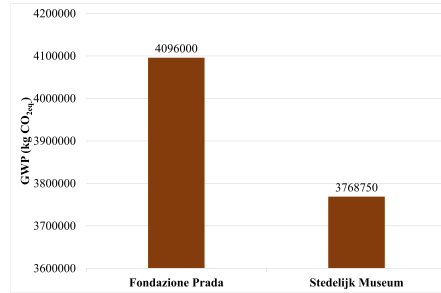
3.1.4. Implementing flood prevention measures

The two projects selected for this climate action category are 'Room for the River' in Nijmegen (Netherlands), and the Thames Estuary 2100 (TE2100) Plan in London, the capital of the United Kingdom.

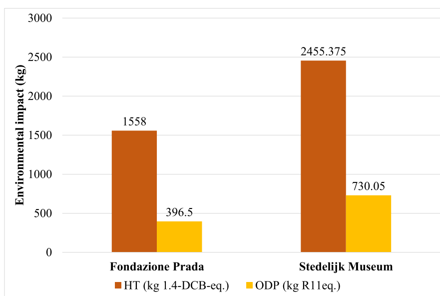
The comparison between the 'Room for the River' project and the Thames Estuary plan illustrates the extreme scale sensitivity of flood prevention infrastructure. In absolute terms, the Room for the River intervention exhibits a total GWP of 173.2 million $kg\,CO_{2eq.}$, far exceeding the 3.96 million $kg\,CO_{2eq.}$ associated with the Thames Estuary plan. This difference reflects the massive quantities of concrete and stone required for large hydraulic earthworks. The same trend is observed for ODP and HT, where the Room for the River project records higher totals due to the material intensity of structural flood defenses. Normalization per functional unit reinforces this contrast. The Room for the River project reaches 21.65 million $kg\,CO_{2eq.}/km$, compared to 12,000 $kg\,CO_{2eq.}/km$ for the Thames Estuary plan. Such a disparity indicates that the environmental burden is not only driven by project length but by the



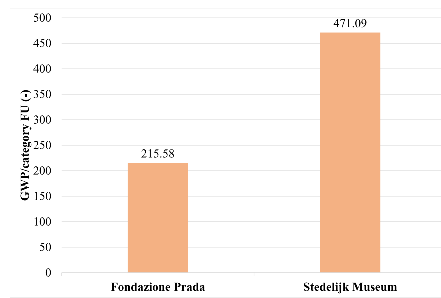
(a) Material distribution (tons)



(b) Global Warming Potential (GWP)

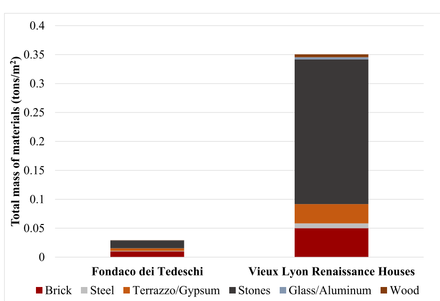


(c) HT and ODP of the projects

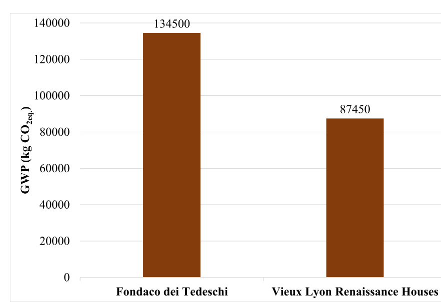


(d) GWP/functional unit of the category

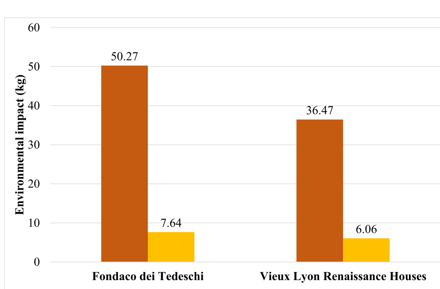
Fig. 3. Comparison of GWP, ODP, HT, and material distribution between Fondazione Prada and Stedelijk Museum projects.



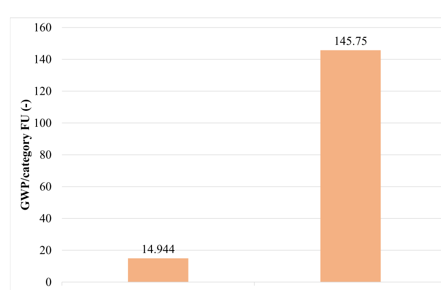
(a) Material distribution (tons)



(b) Global Warming Potential (GWP)

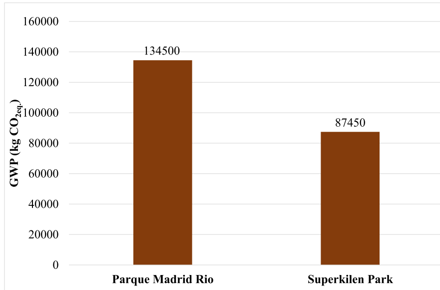


(c) HT and ODP of the projects

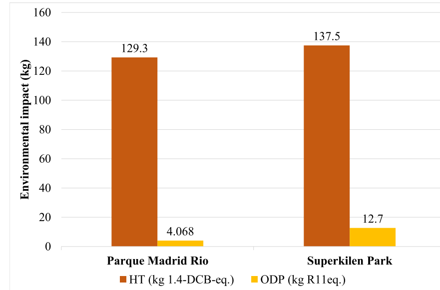


(d) GWP/functional unit of the category

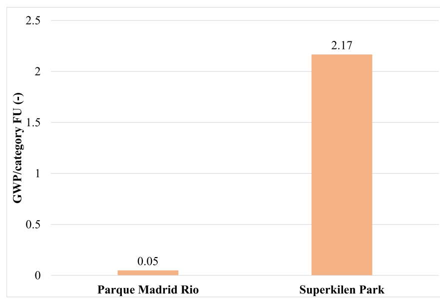
Fig. 4. Comparison of GWP, ODP, HT, and material distribution between Fondaco dei Tedeschi and Vieux Lyon Renaissance Houses projects.



(a) Global Warming Potential (GWP)

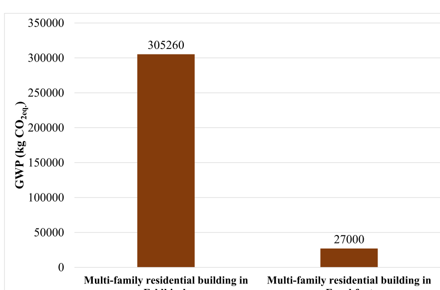


(b) HT and ODP of the projects

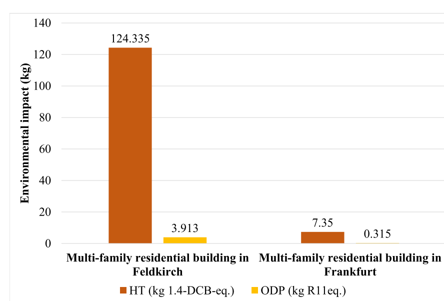


(c) GWP/functional unit of the category

Fig. 5. Comparison of GWP, ODP and HT between Parque Rio and Superkilen Park projects.



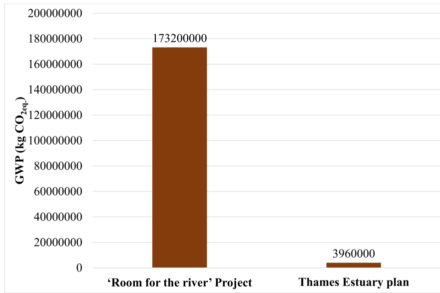
(a) Global Warming Potential (GWP)



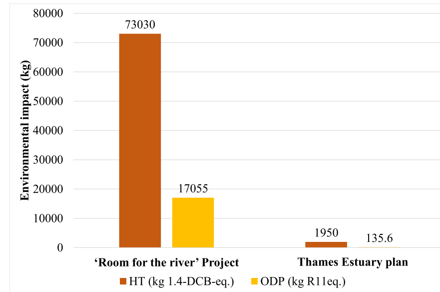
(b) HT and ODP of the projects

(c) GWP/functional unit of the category

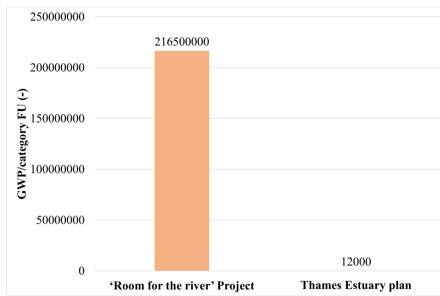
Fig. 6. Comparison of GWP, ODP and HT between the insulation of the multi-family residential buildings in Feldkirch and Frankfurt.



(a) Global Warming Potential (GWP)



(b) HT and ODP of the projects



(c) GWP/functional unit of the category

Fig. 7. Comparison of GWP, ODP and HT between the 'Room for the River' and the TE2100 projects.

construction approach itself, particularly the reliance on heavy mineral materials. The figure demonstrates that flood prevention strategies can differ by several orders of magnitude in embodied impacts. Reporting normalized indicators is therefore essential to distinguish between infrastructural efficiency and total system scale, providing a clearer basis for evaluating alternative hydraulic engineering solutions (Fig. 7).

3.1.5. Material impacts validation: Modelled results vs experiments

In order to contextualize and validate the calculated material impacts, the modelled life cycle results were compared qualitatively and quantitatively with experimentally derived LCA data reported in the literature. The validation exercise focuses on GWP because greenhouse gas emissions are the dominant driver of embodied environmental impact in construction materials and represent the most consistently measured and experimentally reported indicator in industrial LCA datasets.Previous life cycle assessment studies provide measured emission intensities for construction materials that allow benchmarking of the calculated factors used in this work. For example, published experimental LCA results report that the upstream and core production of rock wool insulation generates approximately 1.01 $kg\,CO_{2eq.}/kg$ of product, with manufacturing energy use dominating the impact. This value falls within the range typically observed in measured industrial LCA datasets and aligns with the magnitude of the insulation related emission factors applied in the present analysis. The agreement supports the plausibility of the modelled GWP intensities for mineral based insulation materials. Comparative experimental studies of construction materials consistently show that structural materials such as concrete and steel contribute the largest share of embodied impacts when normalized per kilogram of product, while insulation materials exhibit lower GWP intensities. This general hierarchy of impacts is reproduced in the calculated results of the current study, confirming that the modelling approach reflects experimentally observed material behavior. Beyond validating emission factors, the comparison provides an application oriented interpretation of life cycle data. Whereas most LCA studies discuss experimental results at the level of individual materials, the present work interprets these benchmarks within distinct climate action categories, including building renovation, insulation improvement, urban green space development, and flood prevention infrastructure. This linkage enables material level impact data to be understood in terms of their influence on real project outcomes. As a result, experimentally observed material performance is translated into a project scale perspective, offering practical insight into how material choices shape the environmental profile of different climate interventions implemented by cities (Table 5).

Table 5
Comparison of modelled material GWP factors with experimentally reported values.

Material	Modelled GWP ($kgCO_{2eq.}/kg$)	Experimental /literature GWP ($kgCO_{2eq.}/kg$)	Reference
Concrete	0.09 – 0.13	0.08 – 0.15	[48,49]
Glass	0.85 – 1.10	0.80 – 1.20	[49]
Steel	1.80 – 2.20	1.70 – 2.30	[48]
Mineral wool insulation	0.90 – 1.10	0.95 – 1.05	[50]
Polymer foam insulation	2.50 – 3.20	2.30 – 3.50	[48]
Wood (production stage)	0.00 – 0.05	0.00 – 0.10	[48]

3.2. Research implications and limitations

This paper presents a material centered analytical framework based on life cycle assessment principles to evaluate construction materials used in climate action projects, offering a novel contribution to the field by linking the quantification of materials with their environmental impacts. Unlike traditional studies, that focus on general construction practices, this research provides a more specific and targeted analysis of materials used in climate action initiatives. Many existing studies emphasize the structural performance and durability of materials without integrating environmental considerations in full. For example, studies such as those by Michael et al. (2018) and Lee et al. (2020) focus on optimizing material strength and cost in construction projects but lack an in-depth evaluation of the environmental implications involved ([51][52];). Additionally, Kumar et al. (2020) examined material selection for infrastructure projects but focused primarily on economic feasibility rather than environmental impact [53].

In contrast, this paper emphasizes the balance between the functional performance of materials and their environmental implications, introducing a dual lens for material evaluation. By quantifying construction materials and correlating their quantities with metrics such as Global Warming Potential (GWP), Ozone Depletion Potential (ODP), and Human Toxicity (HT), this study highlights the importance of choosing materials that perform well structurally while minimizing ecological harm. For example, it underscores that while materials such as concrete offer durability, their high GWP necessitates careful consideration and potential substitution with lower impact alternatives such as bamboo or stones.

As a future research task to complement the proposed analytical framework based on life cycle assessment principles, it is essential to explore tools that provide a broader perspective on sustainability in construction, like Building Information Modeling (BIM), which has been a transformative tool in enhancing the sustainability of building projects through its capabilities in design, visualization, and analysis [54]. BIM allows for the integration of energy analysis and sustainability assessments into the design process [55], enabling project teams to minimize environmental impacts while optimizing energy use [56]. However, the implementation of BIM faces challenges such as high initial costs, the need for specialized training, and potential interoperability issues among stakeholders [57]. Despite these limitations, BIM's ability to reduce construction waste and improve overall project sustainability is widely recognized, making it a valuable asset in contemporary construction practices [58].

Although BIM excels in optimizing design and managing projects, our proposed framework provides a complementary perspective by focusing on the granular analysis of environmental impacts associated with specific materials. Unlike BIM, which offers a macro-level view of sustainability, this study explores the life-cycle impacts of materials used in climate action projects, providing a level of detail that is important for understanding material-specific environmental concerns. Together, these approaches can offer a better understanding of how to improve sustainability in construction. It should be added that BIM applications and the associated IFC files are still mostly in an introduction status.

However, the analysis relies on available data, which may not fully capture regional variations in construction practices or reflect the latest advancements in material technologies. Additionally, the scope of this research is confined to a specific set of climate action projects, primarily focusing on construction materials used in building renovation, green space expansion, heat control, and flood prevention initiatives. While these categories are important for sustainable urban development, the other significant climate action areas mentionned in Section 2.1 remain unexplored in this study. It is recommended to extend the proposed framework to additional action categories. In addition, the aim of this study is to evaluate the environmental impacts associated with construction materials up to their production and delivery stages. Consequently, A deeper exploration into material sciencefield, particularly by assessing environmental impacts beyond additional Life Cycle Assessment (LCA) phases such as deconstruction and material circularity, can enhance the accuracy and completeness of the analysis.

Future research could address these limitations by expanding the range of climate action categories analysed. For example, transportation projects, which play a pivotal role in reducing greenhouse gas emissions, could benefit from an integrated assessment of materials used in infrastructure such as roads, bridges, and rail systems. Quantifying the materials used in these projects and evaluating their environmental impacts would be interesting to ensure a sustainable transportation development. Additionally, incorporating dynamic factors such as vehicle energy efficiency and emissions reductions achieved through optimized transport systems could further enhance the analysis. Another avenue for future work involves the integration of lifecycle inventory data into Building Information Modeling (BIM) platforms. This integration could bridge the gap between material-specific environmental assessments and project-level sustainability optimization. For example, BIM could be used to model transportation networks alongside their environmental footprints, allowing planners to compare various design scenarios. Such an approach would offer a clear view of sustainability, extending beyond construction materials to include operational and lifecycle impacts of entire infrastructure systems. Future studies could provide more comprehensive strategies to achieve climate action goals through several project categories.

4. Conclusions

This study developed and applied a material centered life cycle impact framework to evaluate construction materials used in representative climate action projects throughout Europe. By combining project level inventories with category specific functional units, the analysis enables consistent comparison between heterogeneous interventions such as building renovation, insulation upgrades, urban green spaces, and flood prevention infrastructure. The results extend material LCA from isolated product assessment toward a project scale decision framework relevant to climate engineering practice. The main findings can be summarized as follows:

- Environmental impacts are driven primarily by material intensity rather than project function alone. Projects within the same climate action category can differ by an order of magnitude in normalized impacts due to differences in structural and material strategies.
- Structural materials such as concrete, steel, and mineral aggregates dominate total embodied impacts, especially in flood prevention infrastructure, where scale effects amplify environmental burdens.
- Renovation and insulation projects show high variability in impact efficiency, demonstrating that energy performance improvements can introduce significant embodied exchanges depending on envelope material selection.
- Green infrastructure projects generally exhibit low normalized impacts, indicating that landscape based interventions can deliver climate benefits with relatively low material intensity when compared to heavy structural works.
- Normalization per category functional unit shows environmental efficiency that is not visible in total project impacts, enabling fair comparison between interventions of different size and typology.

From an engineering and planning perspective, the framework provides important guidance related to material selection in climate action design. Policymakers and infrastructure planners can use normalized impact indicators to prioritize low intensity material strategies, especially in large scale hydraulic and renovation projects where embodied impacts dominate early lifecycle stages. Integrating such indicators into project evaluation criteria can support climate action planning that balances operational performance with embodied environmental costs. The principal contribution of this work is the integration of material level impact data with climate action typologies through a unified normalization approach. This shifts life cycle assessment from product centric evaluation toward a comparative engineering tool capable of informing cross-sector climate decisions. Future research should extend the framework to include use-phase performance, maintenance cycles, and end of life scenarios, enabling full life cycle optimization of climate infrastructure systems.

CRediT authorship contribution statement

Iskander Ben Rjiba: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization;

Georgina Tóth-Nagy: Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Investigation, Conceptualization; **Éva Makó Kristófné:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Investigation, Conceptualization; **Viktor Sebestyén:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization.

Data availability

No data was used for the research described in the article.

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.

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