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LCA- and nZER-based methodology for identifying optimal low environmental impact interventions for existing buildings

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ABSTRACT

Reducing the energy demand in the building sector appears to be the most important aspect to make them energy efficient. Opting for durable minor interventions results in further reduction of embodied carbon. This paper proposes a method which combines the evaluation of the environmental impact of interventions together with the visual preservation of buildings. A new indicator, the Embodied Impact of Intervention (EII), was defined to evaluate the overall environmental impact considering three indicators within the Life Cycle Assessment: Global Warning Potential (GWP), Primary Energy Non-Renewable (PE-NRe), and net-Fresh Water (FW) offering the stakeholders a holistic view for selecting the most sustainable solutions for interventions in existing buildings. The methodology has been tested to a benchmark, (i.e., masonry wall components), considering low, medium, and high visual impact scenarios, and a lifespan of 100 years. A direct proportionality is shown between GWP and PE-NRe, whereas FW does not have a singular relationship with the other indicators as it is mainly influenced by the material production. High GWP values occur in scenarios in which Nature Based Solutions (236.82 kg_{CO2eq}) and Building-Integrated Photovoltaic panels are implemented (798.09 kg_{CO2eq}), being ≈2.7 and ≈9 higher than the same High Visual Impact scenarios without mitigation solutions. It was found that the visual impact of the interventions may not align with the corresponding EII, resulting in dichotomous scenarios with medium visual impact and low EII, or high visual impact and medium EII. In Low-Income Countries, using recycled materials can minimize the production phase, reducing EII, energy efficiency, energy usage and waste, to accomplish the Sustainable Development Goal in the long-term.

Introduction

In recent years the building sector is at the front line to align with the Sustainability Goals of the 2030 Agenda and the EU Green Deal (European Commission, 2019; Global Sustainable Development Report (GSDR), 2023). EU regulations push to meet high energy standards in the building sector, despite initial economic challenges, for long-term environmental benefits (EU Directive 2023/1791, 2023). (Sartori & Hestnes, 2007) have stated that reducing the demand for operating energy in new and existing buildings appears to be the most important aspect to make them energy efficient throughout their lifespan. In the case of existing buildings, (Papadakis & Katsaprakakis, 2023) have identified three key categories of interventions for promoting energy efficiency: behavioral, technical, and operational. Behavioral interventions focus on the way people use energy, and they require a shift in mindset towards waste reduction and energy conservation through daily practices and conscious efforts, resulting in more challenging implementations but with higher long-term benefits. Operational interventions involve redefining building management practices (e.g., implementing lighting and heating controls based on occupancy patterns, or economic incentives for energy-efficient buildings). Although they require changes to operating procedures, they offer a cost-effective solution by optimizing existing systems and emphasizing the importance of maintenance, that plays a crucial role in creating a healthy and efficient environment for building occupants. Lastly, technical interventions focus on optimizing building envelope (e.g., thermal insulation) and equipment efficiency (e.g., through HVAC system improvements, or indoor lighting enhancements), or on integrating Renewable Energy Sources (RES), or adopting Nature-Based Solutions (NBSs) on buildings (e.g., green roof/walls). Although these require a substantial initial investment, they can result in significant energy

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Abbreviations

A	Assembly
BIPV	Building Integrated Photovoltaics
C	Component
EII	Embodied Impact of the Intervention
EPD	Environmental Product Declaration
FU	Functional Unit
FW	Net Fresh Water consumption (m^3/FU)
GWP	Global Warming Potential (kg_{CO2eq}/FU)
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
LCI	Life Cycle Inventory
NBS	Nature-Based Solutions
PE-NRe	Primary Energy Non-Renewable resources (MJ/FU)
PM	Planned Maintenance
RBM	Risk-Based Maintenance
RES	Renewable Energy Sources
SDG	Sustainable Development Goal
TR	Total Renovated amount (same unit of FU)

savings over time as well as comfort for occupants.

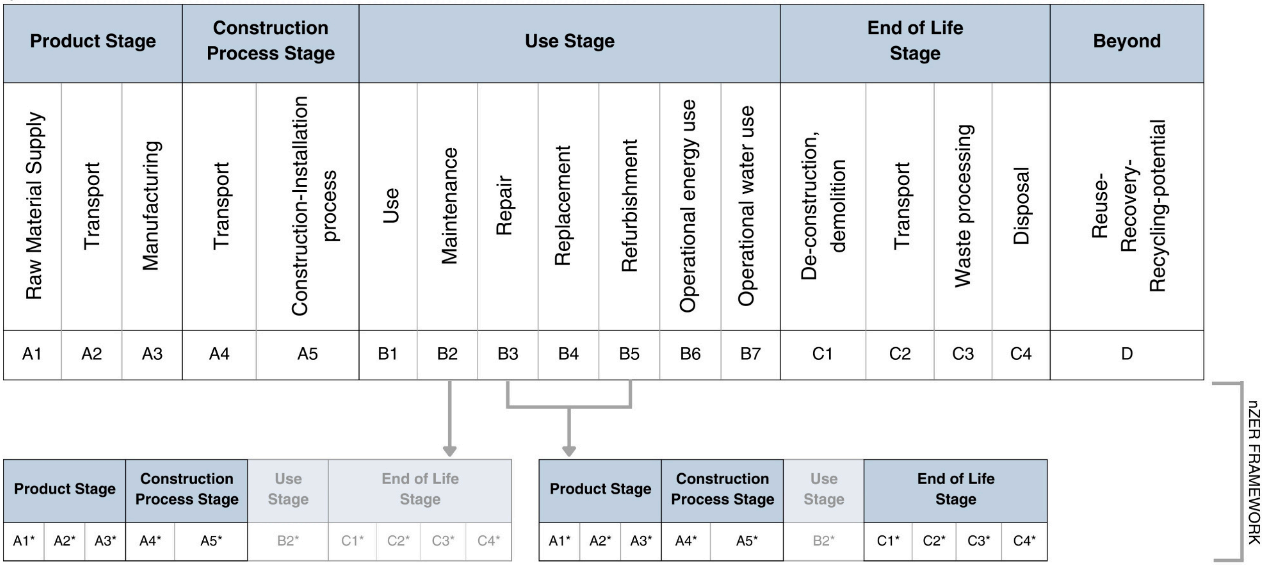
Indeed, the ongoing maintenance should be preferred against heavy refurbishment occurring when an asset breaks, gets damaged, or stops working thus eventually involving partial or total demolition and reconstruction. Opting for durable and repeated minor interventions may result in reduced embodied carbon emissions throughout the whole building's life and may offer a favorable opportunity to maximize carbon benefits (Bui et al., 2022), as it necessitates fewer subsequent interventions (Kayan, 2013). More than 50 % environmental impact reductions can be expected refurbishing rather than constructing a new building (Hasik et al., 2019). In addition, (Fufa et al., 2021) has highlighted that the retrofit and/or refurbishment of existing buildings with the simultaneous installation of insulation materials and use of RES is more beneficial and effective in achieving short- and mid-term environmental goals than constructing new buildings with similar features, as also demonstrated by (Endo & Takamura, 2021; Jerome et al., 2021; Serrano et al., 2022) (Gravagnuolo et al., 2020), thus improving environmental sustainability. Indeed, the time required to offset the greenhouse gas emissions produced by a new construction can vary from 10 to 80 years, which corresponds in turn to the lifetime already overcome in the case of some existing buildings (Fufa et al., 2021). The global community must not underestimate this fact, as a significant portion of its buildings are nowadays over 50 years old, with many in use that are hundreds of years old. Therefore, restoring buildings instead of reconstructing them has a dual benefit of minimizing environmental impact and reducing waste by preserving the original materials and appearance of the buildings.

In this context, the Life Cycle Assessment (LCA) can be used to compute both embodied and operational emissions for newly constructed parts during the refurbishment or for interventions on existing buildings with the aim of estimating their environmental sustainability. The LCA approach can be integrated with the assessment of the economic, energetic, and environmental benefits of interventions throughout a building's life cycle, including calculating payback times, energy, and carbon savings from retrofits (Roncone et al., 2022), comparing refurbishment with extreme scenarios of demolition and reconstruction (Marique & Rossi, 2018). When it comes to designing interventions on existing buildings following the LCA approach (EN 15978:2011, 2011), the nearly Zero Emission Refurbishment (nZER) goals can be integrated in its overall assessment to find suitable and sustainable low-carbon interventions that satisfy the requests of the involved stakeholders (Bertolin & Loli, 2018; Loli & Bertolin, 2021). In this specific case, the nZER refers to the type of interventions and can be hinged upon the "Use stage" of the LCA, in particular on the B2-B5 modules, as in Fig. 1, to comply with EN 15978:2011 (2011), for the estimation of the emissions during an intervention (Bertolin & Loli, 2018; Loli et al., 2019; Loli & Bertolin, 2021). The nZER approach can be used for all the existing buildings, including historic buildings because it allows to recategorize the protection of the buildings with the decay level of the materials.

As highlighted by (Loli & Bertolin, 2018) and recently by (Kyritsi et al., 2023), the major complexity arises when it comes to enhance the energy performance of historic buildings protected as part of a designated environment, or because of their special architectural or historical merit. In such a case the implementation of interventions for the energy efficiency can be less stringent than those laid down for other existing or new buildings (EU Directive 2023/1791, 2023). Historic buildings have the highest limitations within the building sector, thus strongly narrowing the field of possible actions as: (i) recognizing and preserving the historical/cultural significance of the structure together with its aesthetic appearance, (ii) harmonizing attributes and interventions at different scale (from single to multiple buildings) to finally take into account the conservation of a (historic) urban landmark/district, and (iii) performing reversible, non-invasive and non-destructive interventions. These requirements, adding supplementary decision layers, make necessary the development of multi-criteria decision-making processes for evaluating and searching the optimal intervention. Then, although the restoration is highly encouraged, the lack of environmental information on the life cycle of traditional components is a further limitation. Additionally, in the market still few RES are proposed with solutions which aim to enhance the aesthetic integration, compatibility, and non-invasiveness (Ibrahim et al., 2021; Tsoumanis et al., 2021). As an example, PV modules have been developed to harmonize the colors and textures with the existing built environment following the roof frame and ridges, roof inclination, and covering pipes (Polo López et al., 2021), cables and anchoring elements (Akbarinejad et al., 2023; De Medici, 2021). A final and noteworthy observation pertains to the selection of components that may have a low environmental impact but are not compatible with the original materials (Bottino-Leone et al., 2019), or may not be suitable for the climate zone and/or occupancy requirements (Rodrigues & Freire, 2017; Tadeu et al., 2015). In this case, the project design can change accordingly to the extent of the intervention and the scale of sites making difficult the definition of a systematically replicable standardized procedure.

Similar difficulties arise when dealing with existing buildings located in Low-Income Countries, for which limited data on implemented construction materials are available, together with difficulties in characterizing typical lifecycles during retrofit or maintenance interventions due to incomplete, uncertain, and incoherent use of construction materials that often are de-constructed from other building assets or reused and/or upcycled after being disposed by other buildings sites. Despite this, several 'best practices' exist for minimizing carbon emissions in Low-Income Countries providing useful perspectives for developing nations aiming to reduce their carbon emissions and foster sustainable growth. These practices include: (1) greening financial Development Policies (Yan et al., 2023); (2) the elimination of Energy Price Subsidies; (3) Economic Restructuring and Clean Air Laws; (4) Addressing Deforestation and Switching to Natural Gases; (5) Slower Population Growth and Energy Efficiency Improvements (Chandler et al., 2002).

(Hashempour et al., 2020) have reviewed scientific literature on procedures to accomplish energy performance optimization within existing buildings. They highlighted the need of accomplishing with three key aspects: (1) defining a methodology that is not oriented to specific building type, (2) developing a decision-making tool for improving the energy efficiency focused on increasing sustainability and (3) the focus on weather conditions, reference buildings, and human behavior. Their study highlights the importance of considering the



Product Stage			Construction Process Stage		Use Stage							End of Life Stage				Beyond
Raw Material Supply	Transport	Manufacturing	Transport	Construction-Installation process	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	De-construction, demolition	Transport	Waste processing	Disposal	Reuse-Recovery-Recycling-potential
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D

Product Stage			Construction Process Stage		Use Stage	End of Life Stage			
A1*	A2*	A3*	A4*	A5*	B2*	C1*	C2*	C3*	C4*

Product Stage			Construction Process Stage		Use Stage	End of Life Stage			
A1*	A2*	A3*	A4*	A5*	B2*	C1*	C2*	C3*	C4*

Fig. 1. “Building LCA” framework, according to EN 15978:2011 (2011), with a focus on the “Use stage” for the nZER framework.

attributes and sustainable values of a wide range of buildings within a broad spectrum of climate zones and type of use. However, it is evident that beside having lack of data related to construction materials, there is currently no comprehensive methodology which helps in analyzing where these components are used, at what extents and with which impact i.e., specifically tailored to answer the decarbonization needs of developing countries.

The present paper aims to propose a method which combines the evaluation of the environmental impact of interventions together with the visual preservation of the existing buildings, by proposing designing interventions in accordance with the nZER approach, thus extending the methodological approach examined by (Guidetti & Ferrara, 2023). A new indicator, called the Emission Impact of Intervention (EII), was defined to evaluate the environmental impact of the intervention considering three impact categories (climate change, resource use, and consumptive freshwater) in the LCA methodology. The methodology can be used in a dual-stream approach, both for evaluating novel sustainable interventions (forward) and for selecting those aligned with stakeholder objectives (backward). The methodology has been tested to a benchmark considering a lifespan of 100 years. Indeed, when looking at applications, conducting pilot calculations on typical case studies can be beneficial in bridging the gap between theory and practical implementation. This approach can enhance the sustainable management of the current built environment from a more comprehensive and inclusive standpoint. The benchmark has offered the opportunity to discuss scenario in accordance with the pursuit of Sustainable Development Goals (SDGs) also discussing the limitations of applying the method to Low-Income Countries. Finally, the functionality of the method remains regardless the Gross Domestic Product (GDP) income across countries, although some reflections have been highlighted when it comes to its

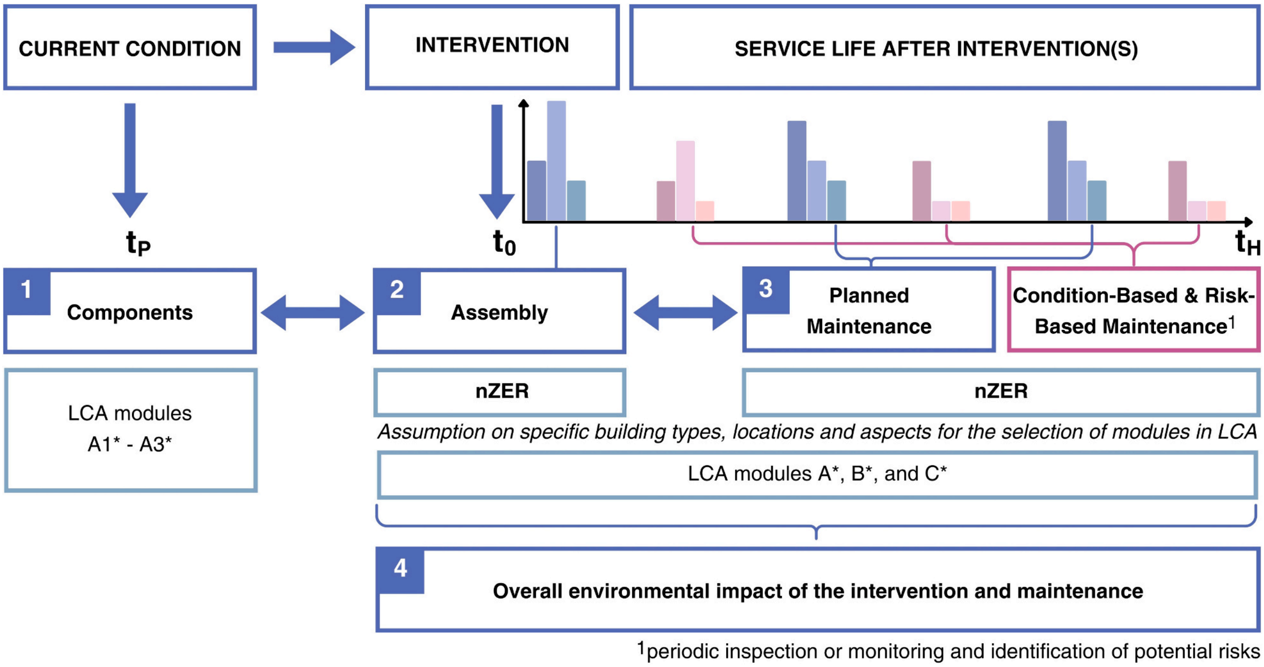


Fig. 2. Schematic workflow of the proposed methodology to evaluate the environmental impact of an intervention on existing buildings.

application in countries with emerging market and developing economies (see Rendering of the methodology in low-income countries section).

Materials & methods

LCA- and nZER-based methodology

Fig. 2 shows the schematic workflow of the proposed incremental methodology, performed through the LCA and based on the principles of the nZER approach for intervention on existing buildings. It starts with the analysis of the current condition of the building or its part (being the result of the past events t_p), that defines our baseline, and proceeds with the design of the intervention, from its implementation (at time t_0) to its maintenance in the future (at time t_H, that can be longer than the expected building service life). The methodology is applicable at any stage of a building's lifecycle. Whether for new constructions or recently built ones, it aids in selecting sustainable materials and it can also be used to design a scenario with minimal environmental impact while meeting the necessary criteria based on the stakeholder requests of maintenance. When dealing with existing buildings, the assumption is that the building has deteriorated and needs renovation or components replacement, or it must be refurbished to comply with regulations. In such a case the approach - while keeping minimal visual impact to enhance social acceptance - focuses on evaluating scenarios which accomplish with the need of reducing embodied energy (EE) over a temporal horizon comparable or exceeding the 30-years typical climate norm to anticipate what might be future frequency of maintenance and refurbishment interventions under the ongoing climate change. In the more stringent case of dealing with historic buildings, interventions with low visual impact address conservation interventions both from the social requirements, looking at non-invasiveness, acceptability, reliability, and safety, and from the stricter technical requirements, which prioritize compatibility, reversibility, and integration of proposed components.

In this paper, the focus is the design of the intervention(s), that comprise(s) the evaluation of the environmental impact of the components (1) that make the assembly (2) and its planned maintenance (3) over the future together with the structural/visual impact of the intervention, resulting in the (4) overall environmental impact, i.e., the summation of the assembly and its planned maintenance. The environmental impact is assessed through the LCA, whereas the structural/visual impact is associated with the nZER approach. The methodology can be employed with a dual streamlined approach, thereby enhancing the stakeholder experience. Following the forward streamline, it enables the implementation of innovative interventions, while the backward streamline facilitates the selection of known interventions and identification of the necessary component(s). The method – used in the Low-Income Countries – can help in mapping what are the new and/or the re-used components constituting the assembly, and it might become crucial in identifying what are component prerequisites for decent living standards and not harmful condition for occupants' health.

Input and output data for the Life Cycle Inventory (LCI) devoted to the environmental impact of materials employed for interventions can be extracted from the Environmental Product Declarations (EPDs), using a predefined functional unit (FU). Since multiple EPDs can be available for the same component (due to several manufactures, technology for production, energy mix, age of data), it is also possible to perform the uncertainty analysis for the Life Cycle Impact Assessment (LCIA). Several are the methods that can be used (Barahmand & Eikeland, 2022; Di Giuseppe et al., 2020). In this article, EPDs are mainly divided into three groups, called "a", "b" and "c", which represent standard materials (a), technological materials (b) and conservative materials (c).

The nZER approach is integrated to LCA in the categorization of the type of intervention and in accordance with the evaluation of the extent of alterations of the current condition of the building or its parts (Bertolin & Loli, 2018; Loli & Bertolin, 2018, 2021), as follows:

- Low-change (L), "maintenance" scenario, associated with module B2 (maintenance). As an example, if the extent of alterations of a building or its parts is evaluated with slight symptoms, the intervention can interest only the maintenance. As this intervention does not include demolition of the existing components, only sub-module A* is used in the computation of B2.
- Medium-change (M), "renovation" scenario, associated with the modules B3 (repair) and B4 (replacement). As an example, if the extent of alterations is macroscopically detectable and is evaluated with medium symptoms, the intervention can change or modify the character or condition of a building. As this intervention can include demolition of small parts of the existing components, sub-modules A* and C* are used in the computation of B3 and B4.
- High-change (H), "retrofit" scenario, associated with module B5 (refurbishment). As an example, if the extent of alterations is macroscopically detectable and is evaluated with high symptoms, the intervention can modify and improve the existing parts to bring it up to an acceptable condition. As this intervention can include demolition of wider parts of the existing components, sub-modules A* and C* are used in the computation of B5.

The environmental impact of the intervention consists of four steps through the evaluation of the following equations, taking the nZER method as reference (Bertolin & Loli, 2018; Loli & Bertolin, 2021):

1. component(s) ("C"): a list of components (including renewable energy sources elements) in which the impact indicators are extracted from modules A1-A3 of the EPDs to compute the environmental impact at the production stage (Impact Component, I_C) according to Eq. (1):

$$I_C = Q\cdot \sum_{k=A1}^{A3} i_k \tag{1}$$

where Q is the quantity of components expressed in FU, and "k" refers to the modules of LCA used and i to the i-th component under analysis.

2. Assembly ("A"): a set of scenarios assembled from the selected components in which the impact indicators are extracted from module B calculated according to the related nZER approach. Here, it is important to well define the "A" to avoid its technical failure at short-term period. We propose a methodology to compute B module as it is normally not included in EPDs (Del Rosario et al., 2021). If it is a low-change intervention (B2), the intervention at t_0 integrates the sub-modules A1*-A5* of components transported and used during the maintenance. This is because maintenance activities typically do not generate waste. If the intervention is classified as medium-change (B3-B4) or high-change (B5), the intervention at t_0 integrates sub-modules A1*-A5* and C1*-C4* to consider deconstruction, demolition, transport, waste, and disposal activities during the intervention (Bertolin & Loli, 2018). In this way, it is possible to cluster the "A" according to the environmental impact of the intervention (Impact Assembly, I_A) computed with Eq. (2).

$$I_A = \sum_{C=1}^{N} Q_C\cdot \left[\left(\sum_{k=A1}^{A5} i_k\right) + \left(\sum_{k=C1}^{C4} i_k\right)\right]_C \tag{2}$$

Where Q is the quantity of components expressed in FU, "C" refers to the components, N refers to the maximum number of components constituting an assembly, and "k" refers to the modules of LCA used.

3. planned (based) maintenance ("PM"): a set of scenarios with the number of interventions (n, computed with Eq. (3)) on the selected "A" scheduled at fixed time intervals depending on the "A" new

service life (Service Life Assembly, SL_A) over a temporal horizon of (t_H) years.

$$n = int\left(\frac{t_H - 1}{SL_A}\right) \tag{3}$$

n can be varied if condition or risk-based maintenance ("RBM") are preferred instead (Toda et al., 2006). While "PM" is implemented after periodic scheduled inspection or monitoring of the building or its part, "RBM" is implemented after having identified (or to address in advance potential) risks that could derive by ageing, climate and natural hazards, or other negative events (e.g., political/market instability, economic crisis). It is worth noticing that the uncertainty in the results could be higher than expected as at t_0 it is challenging to have enough input to predict the technology development in components and their "A" nor the unexpected events in the life of the building (Jerome et al., 2021) unless using probability functions based on the estimation of a specific damage law (Garavaglia et al., 2018). This is not the focus of this paper. Eq. (4) shows the environmental impact of the "PM" (I_{PM}). Finally, it is worth noticing that in the case of the use of renewable energy sources to accomplish with Sustainable Development Goal (SDG 7 - affordable and sustainable energy), it is pivotal to include them as component (pedex with C) and then to include the related emission recovery (ER) in the calculation (Eq. (4)).

$$I_{PM} = n\cdot\left\{\sum_{C=1}^{N} Q_C\cdot\left[\left(\sum_{k=A1}^{A5} i_k\right)+\left(\sum_{k=C1}^{C4} i_k\right)\right]_C\right\} - ER \tag{4}$$

4. Finally, the Overall Environmental Impact consists in the calculation of the Embodied Impact of the Intervention ("EII"), which is the cumulated environmental impacts of the intervention at t_0, i.e., the impact of the assembly (I_A per FU), and over the following temporal horizon t_H, i.e., the impact of the planned maintenance (I_{PM} per FU) multiplied by the total amount of renovated assembly (TR, same unit of FU) according to Eq. (5):

$$EII = (I_A + I_{PM}) \times TR \tag{5}$$

This implies that to assess the environmental impact of a building envelope, we need to multiply the indicator values in FU by the total surface area of the masonry.

Fig. 3 illustrates the lifespan of a building, beginning at time t_P and ending at time t_H after renovation/refurbishment, passing through stage B. This stage includes various interventions (i.e. L/M/H changes, dash line boxes, bottom of Fig. 3) using different components selected according to stakeholders' priorities (e.g., a, b, or c; bottom Left in Fig. 3) including upcycled ones, that can reduce the total EII. In our case, stage B is divided into multiple interventions starting at time t_0 and continuing (refer to Fig. 2 as well), all featuring – being a PM - the same type of interventions. If maintenance interventions follow a "Condition-based" or "Risk-based" approach instead, they would involve more focused maintenance, aiming to reduce material usage through specific and contextual strategies tailored to reduce the risk of decay at the case study. This could lead to a reduction in sub-stages B (e.g., B_0, B_i, B_{i+1} etc. …), impacting less on the environment, in line with SDG 13 Climate Change.

The outcomes from this methodology can feed the environmental perspective in the multi-criteria decision-making tool, called TEnSE (Frasca et al., 2023, 2024), thus providing stakeholders an objective tool to compute step-by-step the performance of the intervention(s). Other Key Performance Indicators (KPI) are provided in (Bartolucci et al., 2024).

Benchmark example: Interventions on façades protected by law

The benchmark example was applied to a historical building as it is the most challenging application. However, it is also indicative for existing buildings that do not have legislative constraints.

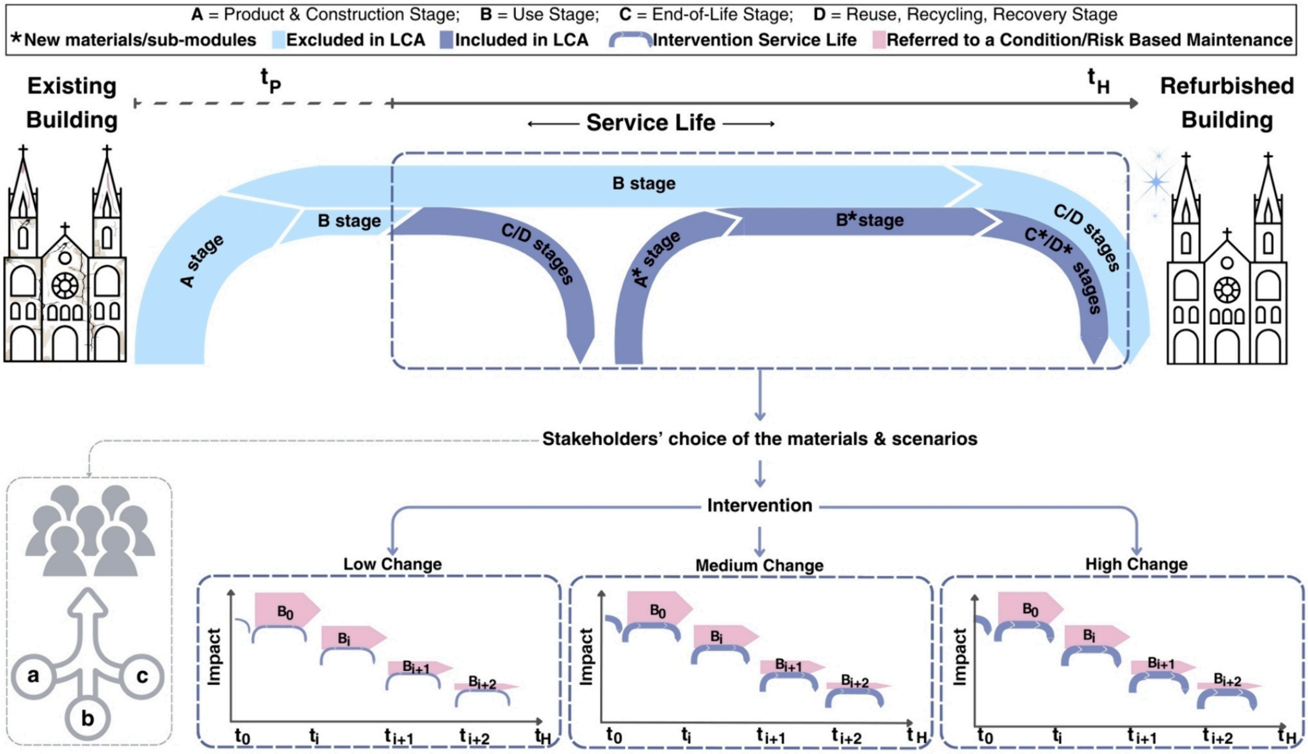


Fig. 3. Life Cycle Stages of existing and retrofitted buildings - adapted from (Hasik et al., 2019) - and detail of the B stage during Low, Medium, and High Change interventions.

This section describes how to apply the methodology when it comes to the intervention on façades of a historical building. All the impact indicators are considered with respect to 1 m^2 FU, which is a common FU for walls, floor, etc. Three EPDs for each component are used: a) EPDs available on Environdec and EPD Italy (EPD); b) EPDs used in a real façade intervention (EPD′); c) EPDs retrieved for products properly manufactured for conservative interventions (EPD_{CH}). The stratigraphy of the baseline wall is schematized in Fig. 4, and it consists of the original wall (visible on the left) made of a reinforced concrete 20 cm thick covered with internal and external plasters layers of 0.01 m each.

In this example, the impact categories considered for the LCIA of the intervention are:

- Climate change through the Global Warming Potential (GWP in $kg_{CO2eq.}$): assessing a building's environmental impact, measuring its contribution to global warming for the entire lifecycle (Dodd & Donatello, 2021). This knowledge contributes to understand how CO_2 emitted by an intervention can be mitigated through minimization during a retrofit, to accomplish with SDG 13 "Climate Change".
- Resource use through the Primary Energy – Non-Renewable (PE-NRe in MJ): computing the consumption of non-renewable energy sources, specifically as energy carriers (Environmental Performance Indicators, 2023). This parameter is significant in determining the material(s) that have the highest energy consumption impact, to minimize it during the retrofit, accomplishing the SDG 7, particularly target 7.3.
- Consumptive freshwater through the Net Fresh Water (FW in m^3): this is not considered as a "water footprint" because it doesn't consider the water uses in different geographical locations (Environmental Performance Indicators, 2023). This indicator contributes to understanding if the intervention accomplishes with the SDG 12, target 12.2 about the sustainable management and efficient use of the natural resources.

Table 1 reports the list of the components possibly employed in the intervention(s), associated with an Identification Numbers ("ID"), the related EPDs and the number of interventions (n) from t_0 until $t_H = 100$ years calculated according to Eq. (3).

The environmental impact of each component (I_C) was calculated with values extracted from modules A1-A3. Since the type of intervention(s) depends on the current condition of the façade at t_p and on the target objective of the refurbishment, forty-four nZER scenarios (6 L, 12 M and 26H scenarios) are defined to encompass three assembly solutions for each: a) commonly used components, b) technologically advanced components, and c) conservation-specific components. L interventions at time t_0 can be implemented if negligible alterations on surfaces have occurred by t_p and no specific requirements of energy retrofit, or clean energy production exist by the user. They can involve repainting and/or cleaning of the surfaces. M and H interventions can be employed if alterations on surfaces or in the wall core, or both, have occurred by t_p, and can involve changing, modifying, or implementing single or multi wall components. In these examples, reinforced concrete was fully restored during "A" step and subsequently re-inserted to fill the degradation of respectively 1 % and 10 % of the total. In particular, in all M scenarios and H.1 and H.2 scenarios degradation is considered to be 1 %, while in H.3, H.4 and H.5 scenarios degradation is considered to be 10 % (Fig. 4). From this moment, the new service life of the proposed "A" starts (t_0), and it is possible to compute the environmental impact of its "PM" in the future over a temporal horizon (t_H) that in this study has been set at 100 years (even though it could open a large uncertainty in the results in the case of maintenance (Jerome et al., 2021)). The number of interventions was estimated according to the number of PM over t_H, as in Eq. (3). As an example, generally 20 interventions are expected in indoor walls for a better indoor air quality (Mathiou Services, 2017) over a century, while 4 in outdoor walls due to the higher durability of components (Credit Suisse, 2017). Each "PM" replicates the initial intervention as a new one. The "EII" of each scenario is computed according to Eq. (5).

To ensure an efficient data visualization, in each stage of the method a "bubble chart" graph has been used. This tool provides a representation of three parameters in a two-dimensional plot, which would be otherwise traditionally displayed in three dimensions. Our chart includes the PE-NRe on the x-axis, the GWP on the y-axis, and the third dimension FW illustrated through the diameter of the bubble. In particular, results from each step are displayed in bubble charts containing multiple plots: all scenarios are depicted on the left, whereas on the right, three sub-plots offer a comprehensive magnification of L/M/H scenarios.

Since the benchmark is not related to any specific location, we will not consider the environmental impact due to buildability and workability (strongly dependent on local energy carriers and market, workers' skills, etc.), this means that EII represents the baseline of any scenario, excluding the operational strategies. Moreover, as shown by (Del Rosario et al., 2021), EPDs fully incorporate the values for A1-A3 modules, but A4-A5 and C1-C4 modules are represented at a lower percentage (60–70 %) and stage B is calculated in only 20 % of the EPDs examined in their research. These aspects, although being limitations in the present method, however they can be partially overcome thanks to semi-quantitatively accuracy estimation by using a reliability index in % as reported below.

Results

The methodology steps have been applied to the benchmark and the results are presented here through bubble charts representing GWP vs PE-NRe and FW. For the developed method, the components study the A1-A3 (Eq. (1)) stages, the "A" and "PM" are regulated by Eq. (2) and Eq. (4), while the "EII" allows to find the total embodied impact of the intervention through the Eq. (5). The benchmark has a unit of $1m^2$, therefore in these scenarios, the "EII" is not multiplied by the TR. This allows for displaying the environmental impact indicators per FU for the "EII" as well. Before applying the methodology, the EPDs were analyzed in terms of reliability of data. The stages A1-A3 are considered in all the EPDs, while stages A4-A5 in 65 %, circa. The stage C is considered for the 70 % of the EPDs, while the stage D in only 30 % of the EPDs. Notwithstanding as the Stage D is not used in Eqs. (1)–(5) (Materials & Methods section), in the overall the EPDs data can be considered at least 65 % complete, making them reliable enough to conduct the analyses using this novel approach.

Environmental impact of the component(s) ("C")

The bubble chart presented in Fig. 5a shows all the components (materials) that could be used in a retrofit intervention and therefore are studied in the LCA product stage, for the indicators GWP, PE-NRe, and FW. The x-axis represents PE-NRe, the y-axis represents GWP, and the bubble size represents the values of FW. For ease of reading, the IDs already listed in Table 1 have been used. The colors in the left-graph legend are blue for components from ID 0 to 8 and 9.2, and orange for ID 9.1. The blue components are then studied in detail in Fig. 5b where the colors are different for each component, as shown in the legend.

The best fit presented in Fig. 5b demonstrates that all elements tend to align from the origin to the opposite angle, following a trajectory that may either be linear or curved based on the chosen EPDs. In these instances, the arrangement of "C" demonstrates an exponential regression pattern. This phenomenon arises due to the rarity of EPDs where either PE-NRe or GWP approaches zero independently, suggesting a correlation where high values of PE-NRe coincide with elevated GWP values, and vice versa.

Also, component ID 9.1 (i.e., BIPV, orange bubble in Fig. 5a) is the highest in terms of environmental impacts, considering all three indicators. Moreover, when focused on Fig. 5b, IDs 5, 6, and 6′ have the

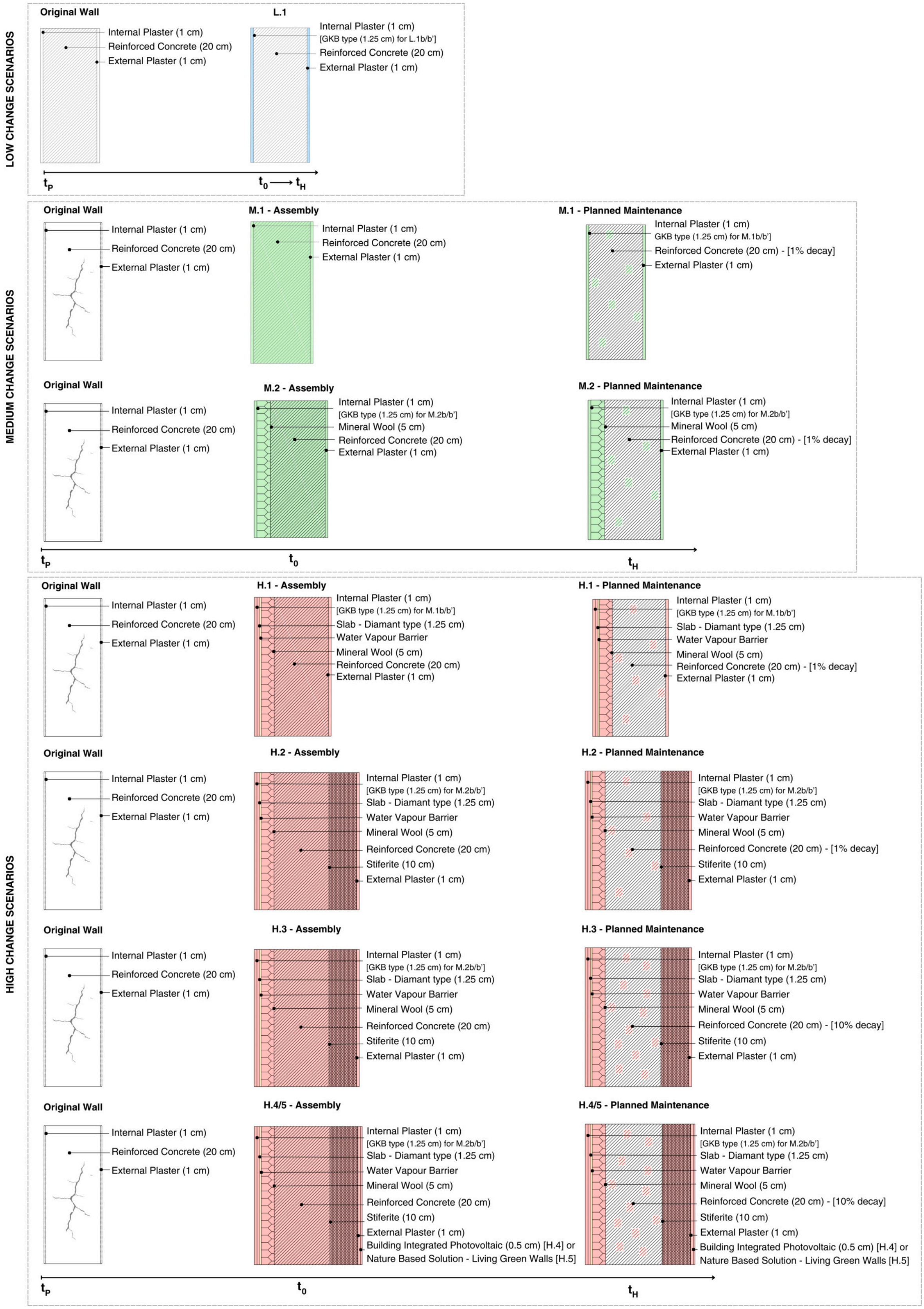


Fig. 4. The original wall section at t_P is situated to the left. The wall section after the intervention at time t_0 is situated in the center. The wall section after the Planned Maintenance is on the right of the figure. Three sub-sections are made for the three types (L. M. H) scenarios.

Table 1

List of components with their “Product Stage” values from the EPDs used (NA = not available) and the number (n) of planned maintenances over $t_H = 100$ years.

ID		Component	EPD			EPD′			EPD$_{CH}$			SL$_A$ [years]	n of PM over t_H [−]
			PE-NRe [MJ/m^2]	GWP [kg$_{CO2eq}$/m^2]	FW [m^3/m^2]	PE-NRe [MJ/m^2]	GWP [kg$_{CO2eq}$/m^2]	FW [m^3/m^2]	PE-NRe [MJ/m^2]	GWP [kg$_{CO2eq}$/m^2]	FW [m^3/m^2]		
0		Internal Paint	(Quarzolite, 2019)[a]			(Prodotti Vernicianti per Interni, 2020)[b]			(Quarzolite, 2019)[a] or (Prodotti Vernicianti per Interni, 2020)[b]			5	20
			6.65	2.80E-01	3.13E-03	2.15E-05	1.35E-01	2.07E-03					
1		Diamant slab	NA			(Plasterboard Knauf DIAMANT, 2020)			NA			50	2
						50.6	3.24	2.02E-2					
2	2.1	Internal Plaster	(Gyproc Igniver, 2020)			(Marino, 2016c)			(Mape-Antique Intonaco NHL, 2021)				
			19.10	1.10	6.10E-03	36.80	2.30	1.00E-02	13.28	1.61	4.15E-03		
	2.2	Internal Plaster (type GKB)	(Plasterboard Knauf GKB®, 2020)			(Marino, 2016b)			NA				
			31.00	2.01	1.20E-02	38.20	2.40	1.27E-02					
3		Vapor barrier	(Air, Wind and Water Barrier Membranes and Vapor Control Layers, 2021)										
			12.80	8.41E-01	3.82E-03	12.80	8.41E-01	3.82E-03	12.80	8.41E-01	3.82E-03		
4[e]		Internal Thermal Insulation	(NaturBoard FORTE, 2019)			(Mineral Wool Insulation ARENA and T without Facing, 2021)			(NaturBoard FORTE, 2019) or (Mineral Wool Insulation ARENA and T without Facing, 2021)				
			75.5	6.35	2.14E-02	31.68	1.82	8.61E-02					
5[f]		Reinforced Concrete	(YTONG Calcestruzzo Aerato Autoclavato, 2016)										
			242.14	32.52	1.12E-01	242.14	32.52	1.12E-01	242.14	32.52	1.12E-01		
6[g]		External Thermal Insulation	(Peters & Grahl, 2023)			(Peters et al., 2023)			(Peters & Grahl, 2023) or (Peters et al., 2023)				
			153	9.77	6.91E-02	153.65	9.51	6.17E-02					
7		External Plaster	(PLANITOP, 2018)			(Marino, 2016a)			(Mape-Antique Intonaco NHL, 2021)				
			5.81	4.97E-01	2.48E-03	54.9	3.4	2.06E-02	13.28	1.61	4.15E-03		
8		External Paint	(Quarzolite, 2019)[c]			(Pettini, 2022)[d]			(Quarzolite, 2019)[c] or (Pettini, 2022)[d]			25	4
			6.4	2.59E-01	2.99E-03	7.25	3.93E-01	8.39E-05					
9[h]	9.1	BIPV	(Building Integrated Photovoltaic Module (BIPV), 2023)						NA				
			2350	173	6.36	2350	173	6.36					
	9.2	NBS	(Urbanscape® Green Roof System, 2021)						NA			50	2
			82.1	3.68	1.57E-01	82.1	3.68	1.57E-01					

[a] “Tonachino Plus”.

[b] “Innencolor”.

[c] “Tonachino”.

[d] “Decorquarz bianco” (retrieved from EPD Italy).

[e] ID 4 is added in scenarios M.2.

[f] ID 5 is considered degraded for 1 % during Planned Maintenance for M scenarios, and for scenarios H.1 and H.2, while it is considered degraded for 10 % for scenarios H.3, H.4 and H.5.

[g] ID 6 is added from scenarios H.2.

[h] ID 9.1 is only for scenarios H.4 and ID 9.2 is only for scenarios H.5.

highest impact concerning GWP and PE-NRe. On the other hand, FW presents a different trend, with the highest FW value belonging to component 9.2 (i.e., NBS, red bubble in Fig. 5b), which is not the component with the highest GWP and PE-NRe values. Overall, it appears that there is no visible correlation between “GWP *vs* PE-NRe” and “FW.” Hence, it is essential to discuss the third dimension (FW) differently, possibly by examining its behavior in connection with each of the other two indicators separately.

Given the diverse number of EPDs, Fig. 6 shows bar graphs about the different components. If there are at least two EPDs considered, each column shows the average values of impact indicators for the same material. When only one EPD is considered, the bar represents the precise value of the A1-A3 for each impact indicators. Error bars are included only for components with a minimum of two EPDs, showing the minimum and maximum values retrieved from the EPDs for the same impact indicators. Components 0, 2, 4, 6, 7, and 8 offer the widest selection of EPDs. Notably, ID 4 exhibits significant variability, particularly concerning FW, indicating a substantial difference in water usage during material production.

Choosing an EPD with the lowest environmental impact values for a particular material is quite challenging because multiple companies worldwide produce the same material, each with varying access to raw materials depending on their production location. Therefore, this analysis tends to have a relatively high margin of error, particularly when it comes to the origin of material production, contributing to the increase in A1-A3 values within the overall LCA.

Environmental impact of the assembly (“A”)

Fig. 7 shows the three visual impact-based intervention types: L, M, and H scenarios. Each intervention specifically contains six L (shades of blue), twelve M (shades of green), and twenty-six H scenarios (shades of red). Fig. 7a provides an overview of all the proposed scenarios without a differentiation on their visual impact. Here, the L scenarios are visibly

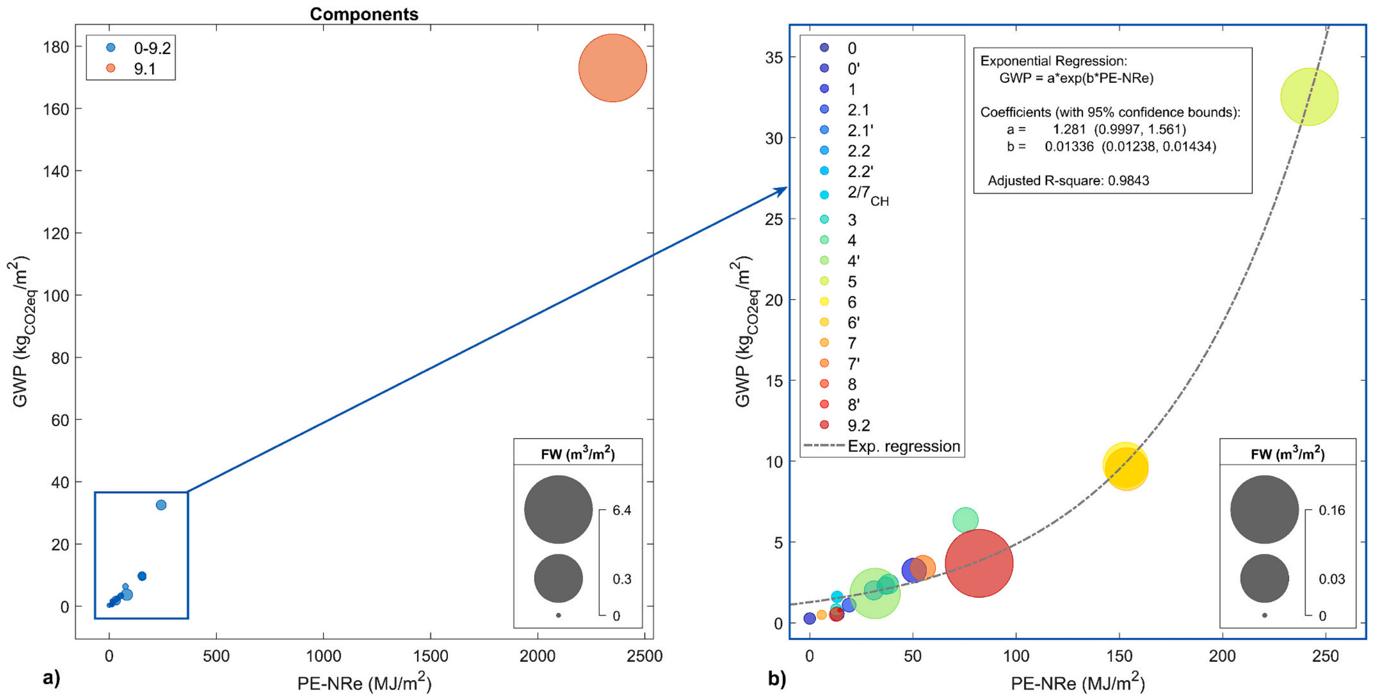


Fig. 5. Left: bubble chart of all the "Components" which can be used in the retrofit; right: zoom of the "0–8" and "9.2" components. In both graphs, the x-axis represents the PE-NRe, the y-axis represents the GWP; the third dimension is the FW. The chart on the right has a separate colour code, different from the chart on the left.

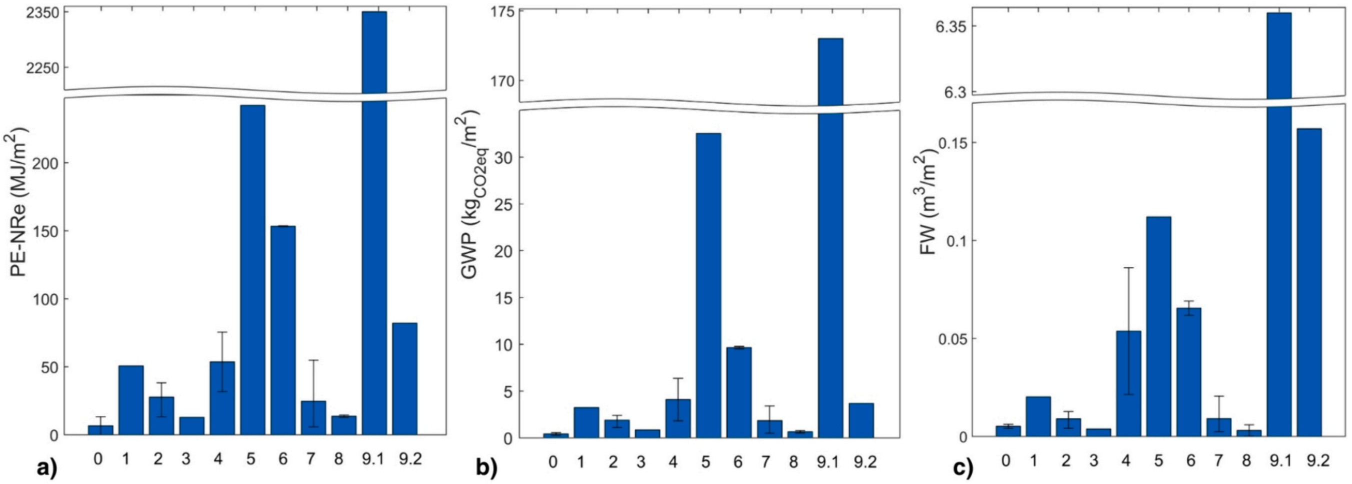


Fig. 6. Bar-plots showing each environmental impact indicator (y-axis), i.e., a) PE-NRe (MJ/m^2), b) GWP (kg_{CO2eq}/m^2), and c) FW (m^3/m^2). On the x-axis the ID numbers of the components are shown (written without differentiation among EPD typologies).

distinct from the M and H scenarios, which share some overlapping. This demonstrates that, while a particular type of intervention can have significant visible impact due to the changes made with consequent social acceptance implications, their impact on the environment may not be as substantial as expected (red circles overlapped to the green ones, Fig. 7a). Fig. 7b/c/d show the different scenarios. It is evident that the scenarios grouped under category "c" (also with apostrophe), which prioritize conservation aspects, have a lower impact concerning both GWP and PE-NRe compared to the other groups of scenarios "a" and "b".

Four distinct groups emerge:

- The first group concerns the L scenarios (Fig. 7b). They are grouped within a range of 40–120 MJ/m^2 (x-axis) and between 2 and 8 kg_{CO2eq}/m^2 (y-axis), while FW values range between 0.01 and 0.04 m^3/m^2- Therefore this first group is the less environmentally impactful regarding the three parameters considered for the study. L.1c and L.1c' have the lowest PE-NRe values, and on average also the lowest GWP and FW.
- The second group concerns the whole M and some of the H scenarios (Fig. 7c). In particular, it comprehends scenarios from H.1a to H.3c' within a range of PE-NRe of approximately 290–830 MJ/m^2 and GWP varying between 35 and 68 kg_{CO2eq}/m^2. Also in this case, it is noticed that the scenarios denoted with the letter c (also with apostrophe) represent those less impacting to the environmental level. The most obvious example is M.2a', 2b' and 2c'. The latter has a value of PE-NRe much lower than the other two, proving that the use of plaster compatible with the historicity of the building requires a smaller amount of PE-NRe in the production of the material itself.

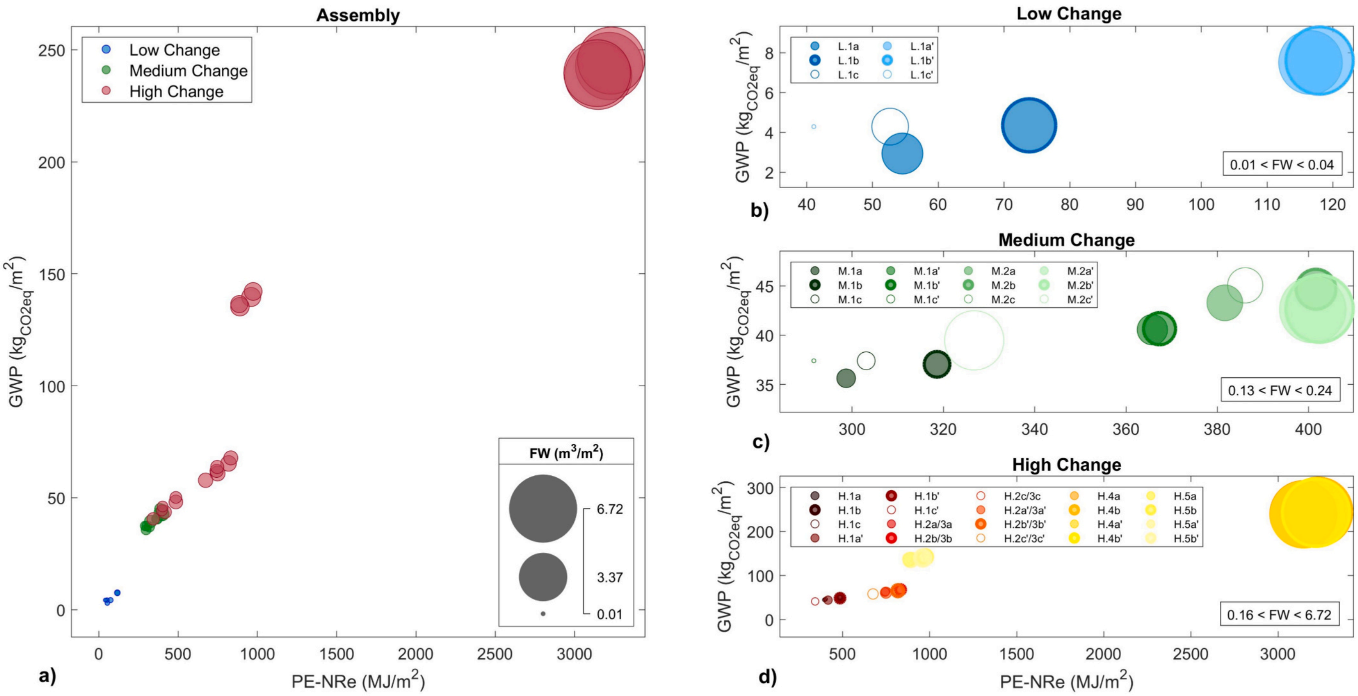


Fig. 7. Left: a) bubble chart of all the scenarios of the “A”; right: details of the b) L (shadows of blue), c) M (shadows of green), and d) H (from red to yellow) scenarios. The x-axis represents the PE-NRe (MJ/m^2), the y-axis represents the GWP (kg$_{CO2eq}$/m^2). The third dimension is the FW (m^3/m^2).

- The third group only considers H.5a/5b/5a’/5b’ scenarios (Fig. 7d, yellow bubbles). These scenarios consider the use of NBSs (e.g., Living Walls) that could be applied on a building façade (Ogut et al., 2022). For this scenario there is actually an underestimation in terms of all the three impact indicators: in fact, due to the lack of choice of NBS for the walls, an EPD regarding the roof was used instead. In the graph only the impact in production and assembly (that is, the intervention itself) is considered and not the potentiality that the use of a NBS might have in reducing GWP being out of the scope of the paper.
- The fourth and last group concerns H.4a/4b/4a’/4b’ scenarios (orange bubbles in Fig. 7d), considering the BIPV on the vertical façade. Again, what is not considered is the payback of GWP and PE-NRe over time. Instead, what is perceived is the high consumption of water used for BIPV, as already seen in the graph in Fig. 5 (for component 9.1).

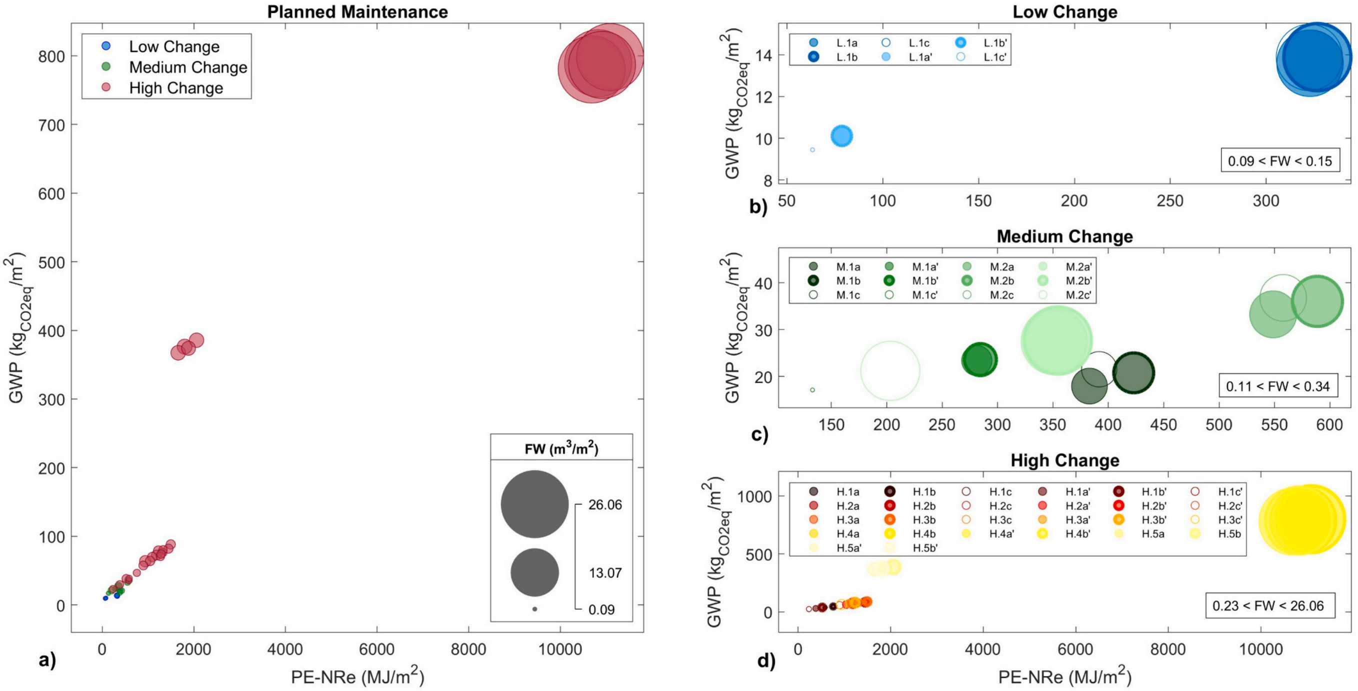


Fig. 8. Left: a) bubble chart of all the scenarios of the “PM”; right: details of the b) L (shadows of blue), c) M (shadows of green), and d) H (from red to yellow) scenarios. The x-axis represents the PE-NRe (MJ/m^2), the y-axis represents the GWP (kg$_{CO2eq}$/m^2). The third dimension is the FW (m^3/m^2).

In general, it seems that all scenarios (except the NBS), align on the same linear regression.

Environmental impact of the planned maintenance ("PM")

Fig. 8 shows the bubble chart of the "PM" scenarios. In these results, the 4 groups identified in the "A" step are consolidated into 3. This alteration could be attributed to the notable influence of the "PM" on L scenarios, aligning them more closely at the cluster of the M scenarios. As for Fig. 7, none of the values fall in the lower-right or upper-left quadrants because the indicators never approach zero. Consequently, the cumulative effect of multiple "PM" activities leads to their simultaneous increase, aligning them around the linear regression of PE-NRe vs GWP. Furthermore, FW values typically stay below an average of 13.07 m^3/m^2, but scenarios in the upper-right quadrant significantly increase FW, deviating from the norm.

Overall environmental impact ("EII")

Fig. 9 shows the whole method application, more details are provided in the Appendix A. This is constituted by "A" (Fig. 9a, intervention at the time t_0) added to the 100 years of "PM" operations (Fig. 9b), resulting in the "EII" (Fig. 9c). PE-NRe tends to exert a more significant impact on GWP.

Discussion and future research directions

The relationship between impact categories

The "EII" of each scenario is shown in Fig. 10. Three linear regressions were fitted to data considering GWP and PE-NRe indicators: Linear Fit 0 including scenarios from L.1 to H.4; Linear Fit 1 including scenarios from L.1 to H.3 and Linear Fit 2 including all intervention scenarios. The R^2 is always higher than 0.9. The PE-NRe value has the most significant influence on the "EII" and on trends of the scenarios. However, in the H.5 scenarios, which encompass the NBS solution, the GWP appears to have a greater influence compared to the other scenarios.

The relationship between GWP and PE-NRe in the semi-logarithmic scale is demonstrated through the use of the linear fit. In particular, the one including the NBS is the one with the lowest R^2 (0.91) which is still a good correlation. A further analysis on the standardized raw data (i.e., average = 0 and standard deviation = 1) has been conducted applying the Principal Component Analysis (PCA). The principal component 1 being the linear combination of the original data represents the definition itself of EII and it is capable to capture the maximum variance in the data equals to 96.7 %. For further details, see Appendix B.

The Energy Recovery (ER) appearing in Eq. (4) is not shown in Fig. 10 and needs to be further analyzed in the future (Ogut, Tzortzi, Cavazzani, & Bertolin, 2024).

Fig. 11 shows the scatter plots of a) FW vs PE-NRe and b) FW vs GWP. Two separate and parallel groups are observed and identified through yellow and blue areas in the boxes. The regression between the two couples of indicators is linear with an R^2 greater than 0.98. The vertical shift between these groups corresponding to a higher FW consumption aligns with the implementation of mineral wool in the "A" implemented in a real case study.

Three macro-areas representing Low, Medium, and High "EII" can be identified:

- Low Impact ranges between 0 and 800 MJ/m^2 for PE-NRe; 0 to 50 kg_{CO2eq}/m^2 for GWP; and around a maximum value of 0.4 m^3/m^2 for FW;
- Medium Impact ranges between approximately 800 and 1700 MJ/m^2 for PE-NRe; 50 and 110 kg_{CO2eq}/m^2 for GWP; around a threshold set at 0.4 m^3/m^2, with a maximum limit of 0.8 m^3/m^2 for FW;
- High Impact is located on the right for both PE-NRe and GWP, with the minimum threshold set at 1700 MJ/m^2 and 110 kg_{CO2eq}/m^2, and in the uppermost section for FW, with a minimum threshold of 0.8 m^3/m^2.

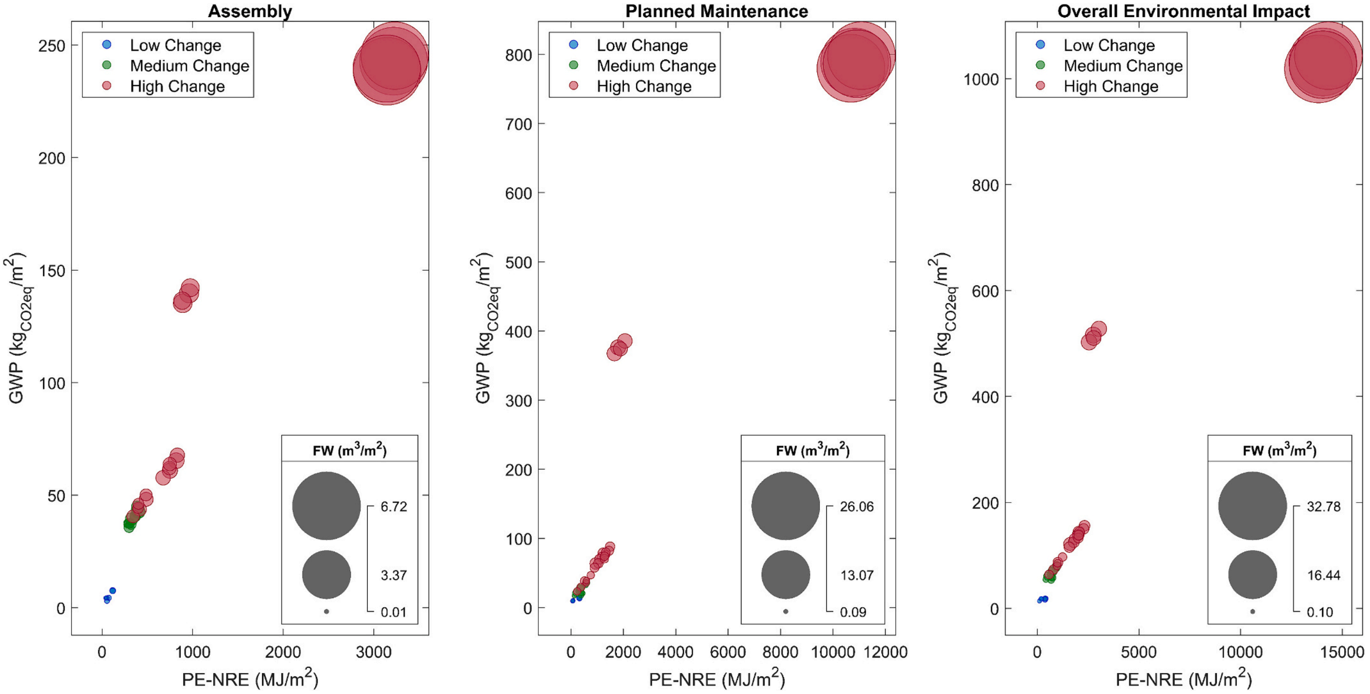


Fig. 9. a): bubble chart of "A" (intervention at time t_0); b): bubble chart of "PM" done over a lifespan of 100 years (after the intervention over a t_H horizon); c): bubble chart of the "EII", i.e., the summation of "A" and "PM".

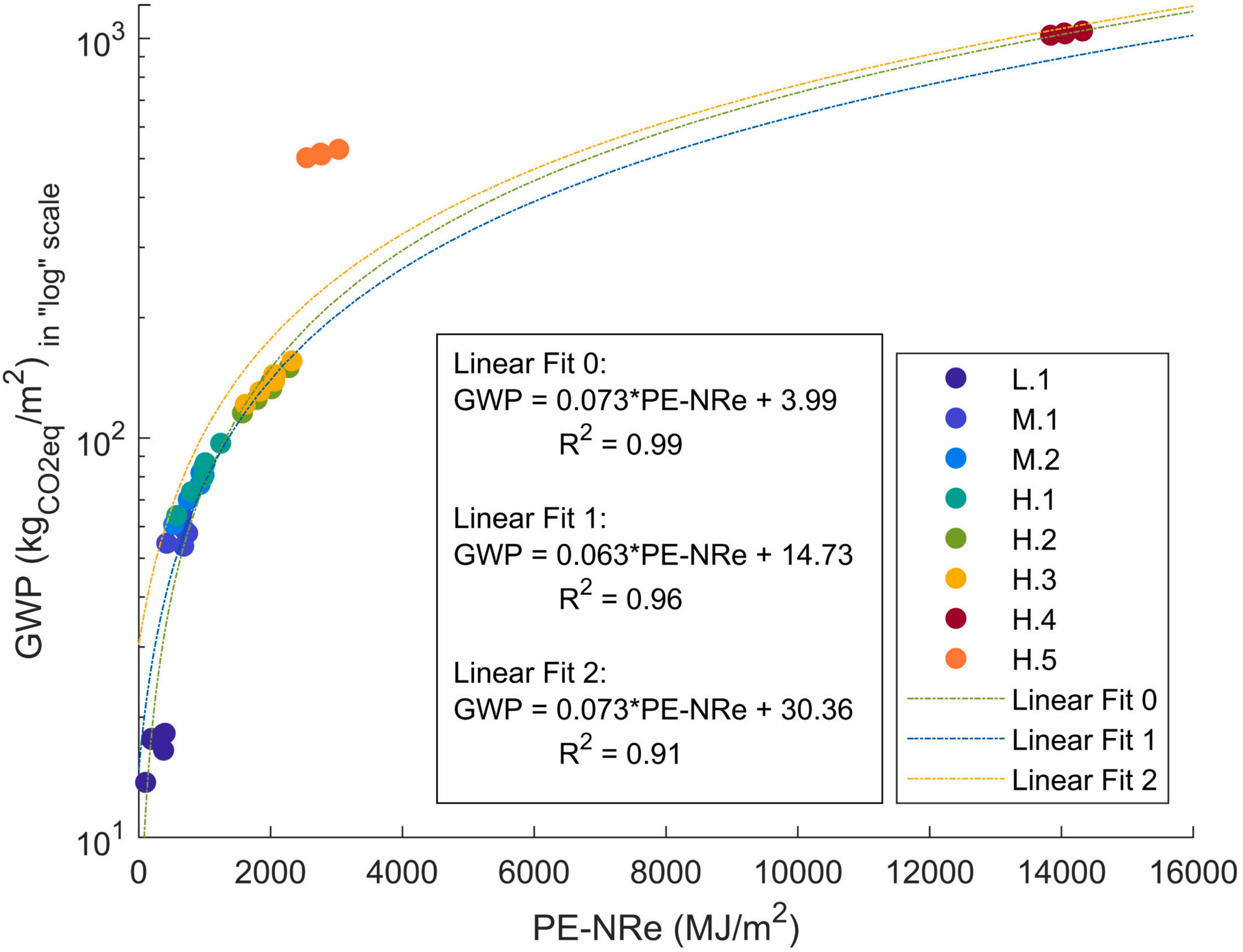


Fig. 10. GWP vs PE-NRe of all scenarios in semi-logarithmic scale. Linear Fit 0 refers to scenarios from L.1 to H.4; Linear Fit 1 refers to scenarios from L.1 to H.3; Linear Fit 2 refers to all scenarios.

The level of visual change defined according to the nZER approach (L, M and H) mostly overlaps to the relative level of EII. Only H.1 scenarios have a medium EII, since they do not implement Stiferite as external thermal insulation component (6) that has high GWP and PE-NRe values.

Fig. 11 has shown that the EII is mainly affected by the selection and implementation of thermal insulation components. This step is one of the most challenging as there is a wide range of available products in the market with a relatively low economic competitiveness and the choice is often influenced by specific preferences of stakeholders, such as raw material availability and buildability (Frasca et al., 2023, 2024).

These results can be advantageously used to:

1. assess in advanced as an example if the transformation of a historic building into at least a nearly zero-energy building (nZEB) throughout the selected temporal horizon can be responsible for high EII.
2. understand the EII in the pre-design and implementation process in a generic building. In this way, starting from a specific level of visual change, it is possible to modify the assembly selecting components at lower environmental impact.
3. address the potential future challenges of the implemented solution according to the local climate challenges. As an example, if a past intervention has been implemented in water-stressed regions, our methodology makes it possible to identify a similar assembly but made of components with lower FW.
4. select a specific intervention balancing both environmental and visual change impacts.

In the proposed methodology, the focus is on environmental impact of materials and maintenance aspects as it serves as a benchmark. The impact due to operational strategies during the realization of interventions have not been evaluated due to its dependency to the specific country i.e., Low-, Middle-, or High-Income Countries and the almost complete lack of data. Differently, the proposed method could easily integrate the phases B6 and B7 of the LCA to broaden its future applicability to post-intervention scenarios to evaluate users' satisfaction. Notwithstanding these aspects fall beyond our current scope.

Rendering of the methodology in low-income countries

The scalability to different scenarios is one of the key points of this methodology. Indeed, its function is the foresee of the roadmap of interventions over the temporal horizon and the likelihood of achieving the energy neutrality through interventions. In addition, it is independent of any social and economic aspects at local level making it applicable regardless of the Gross Domestic Product income within (internal disparities) and across countries. However, some considerations should

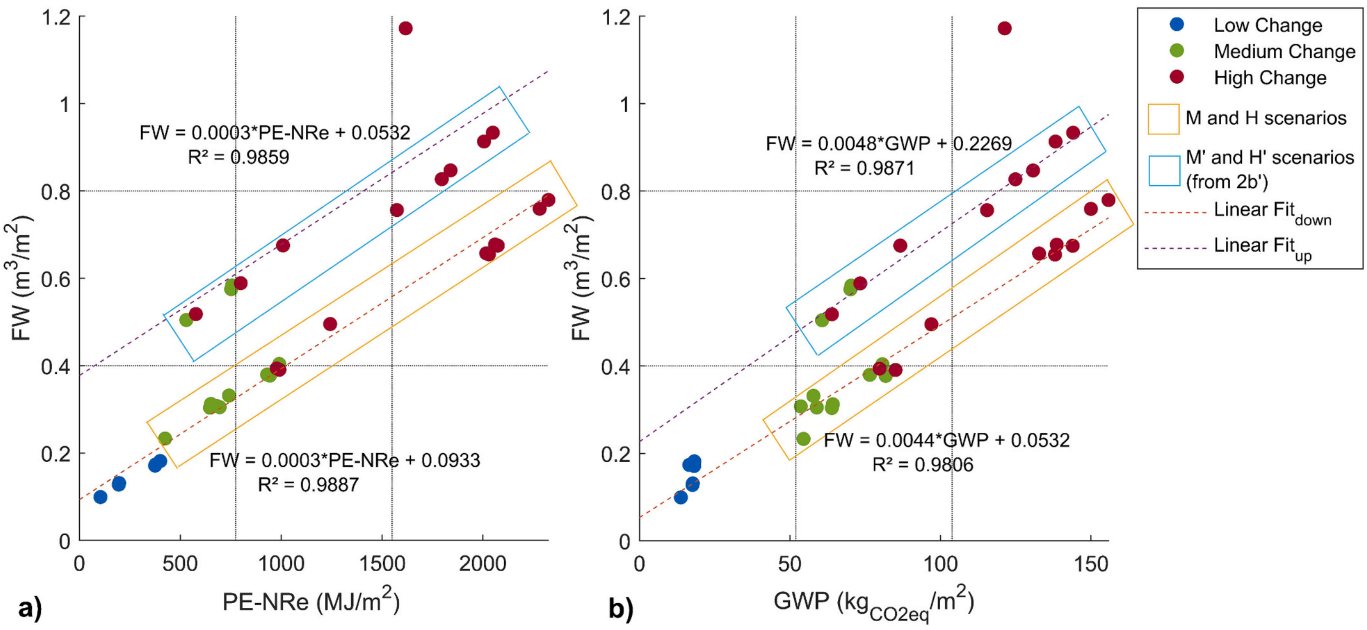


Fig. 11. a) FW vs PE-NRe of all scenarios (excluding High 4 and 5); b) FW vs GWP of all scenarios (excluding High 4 and 5).

be highlighted when it comes to the application of the method in Low-Income Countries, i.e., emerging market and developing economies. Our results have demonstrated that High Change intervention scenarios are usually responsible for the highest EII, especially when the implemented solutions need for high-tech (hence high cost) components and assemblies that usually need to be replaced and disposed at the end of the service life. This would make the implementation of these scenarios unlikelihood in Low-Income Countries due to the lack of local high-tech electric grid infrastructures and due to existing economic constraints e. g., lack of budget, grants, and subsidies available to help landlords and housing associations in funding retrofit projects thus retarding the decarbonization goal. For all these reasons, intervention scenarios in Low-Income Countries are often implemented with upcycled and/or decommissioned components and assemblies (also including high-tech components, e.g., BIPV modules (van der Heide et al., 2022)), also because the primary goal significantly diverges from the aesthetic and historical importance of the building, focusing instead on its functionality. If this inherent approach (based on economic deficiency and availability of more obsolescent technology) is visualized in the bubble chart of our method (Fig. 12) a minimization of the EII due to the absence of the emission of the initial production phase of components, (and eventually assembly) will be visible. It follows that the EII would be

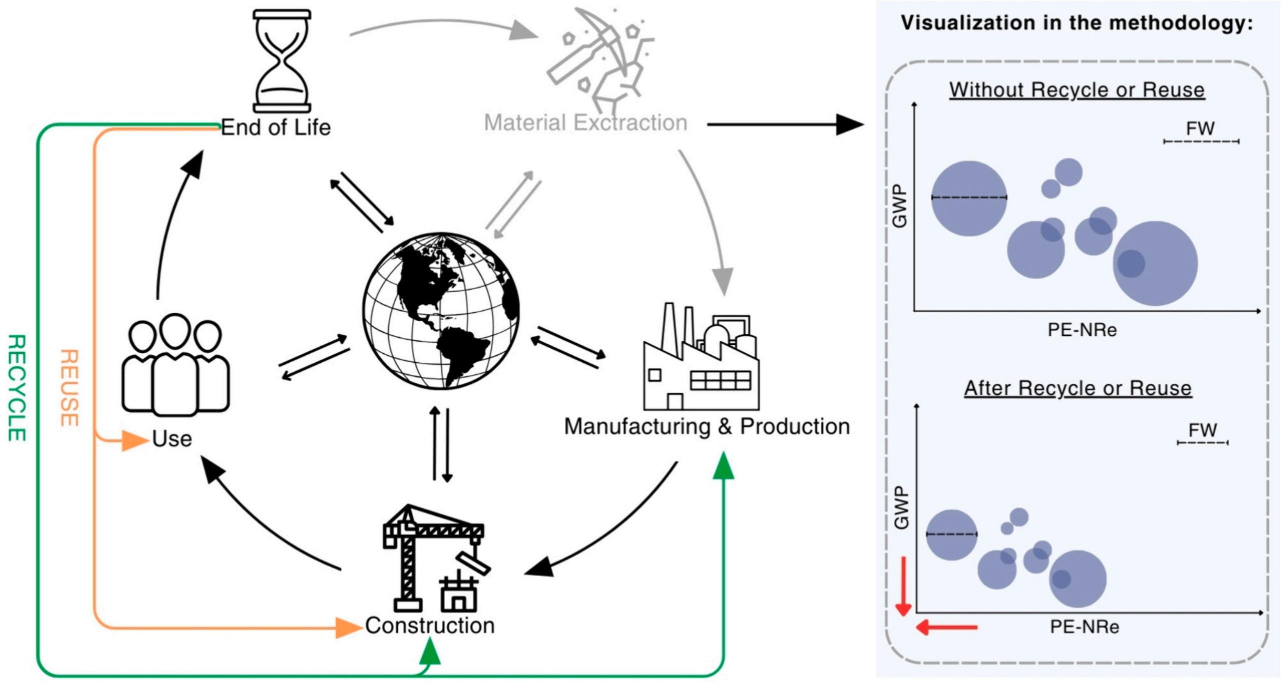


Fig. 12. Minimization in “Components” and “Assembly” steps due to recycle/reuse (green and orange arrows) and use of upcycle materials in Low-Income Countries. This leads to a new visualization in the methodology, i.e., the reduction of the three environmental indicators (red arrows).

mainly ascribed to the planned maintenance (Ogut, Tzortzi, & Bertolin, 2024). This means that the decarbonization of the building sector in Low-Income Countries can be pursued but over longer horizon because of the lower overall emission impact of the intervention and maintenance (EII) restraint by implementation of high-tech components and assemblies (adequately) disposed from High- and Middle-Income Countries or by limited availabilities of resources.

This inherent practice of re-using and upcycling might open interesting perspectives in the establishments of:

- new trades of upcycled components and assemblies from High-Income (or high-tech) to Low-Income Countries;
- new job opportunities focused on optimizing the upcyclability of the intervention in all its phases.

However, the advantage to foster a global circular economy and to create new professionals hides some barriers already underlined in the literature (Adegun et al., 2022; Ogut, Tzortzi, & Bertolin, 2024). These are:

- vandalism due to the illegal/unauthorized removal of upcycled components after the intervention;
- sustainable policy deficiency towards the implementation of strategies for achieving the nZER and nZEB;
- urban policy deficiency towards to the implementation of upcycled components with high pollution impact;
- health policy deficiency towards to the implementation and disposal of upcycled components with high toxicity for human and land (Daniela-Abigail et al., 2022);
- water dependency in water-stressed areas, especially for greening solution (e.g., green walls and roofs).

Some of these barriers (e.g., pollution, toxicity) can be overcome if the trades of the upcycled components and assemblies is ruled by a transnational legislation to avoid that environmental justice of High-Income Countries leads to social injustice in Low-Income Countries. It should aim at coping with the speculative initiatives and the illicit traffic of high-impact waste from country to country, thus accelerating the achievement of sustainable goals at global level. This means that stakeholders or decision-makers have to adopt a Global Life Cycle Thinking to break down these barriers.

In Low- and Middle-Income Countries, the lack of consideration for the minimal visual impact of an intervention may be attributed to the mindset and resources of those professional or users carrying out the intervention. Additionally, cultural preferences may lead to a desire for visible interventions as a demonstration of wealth and technical know-how at the opposite of interventions in High-Income Countries where a low visual impact after an intervention corresponds to a work to the highest standards in preserving the original architecture or significance of the building. This discrepancy highlights the need for conducting further studies in Low- and Middle-Income Countries to assess the post-intervention satisfaction based on the resulting visual impact. Nevertheless, it is important to recognize that in Low- and Middle-Income Countries, reusing materials or available waste material for implementing interventions can be a valuable practice within the optic of circular economy and SDGs. It is crucial to educate and promote the idea that preserving the significance of constructions, both historical and otherwise, involves minimizing visual invasiveness while optimizing materials reuse and recycling. This may be a new concept for Low- and Middle-Income Countries and may challenge the perception that visibility - even in case it distorts original architecture of the buildings - signifies wealth and well-being. The approach can help tackle and combat the “imbalance,” “inadequacy,” and “insufficiency” present in shantytowns (Yuan & Song, 2020) – areas where individuals reside in impoverished and unfavorable conditions, yet with valuable traditions and structures that should be maintained for future relevance.

A new cross indicator for SDGs 6, 7, 9, 11, 12 and 13

Interventions rather than reconstruction of new building stock has the main advantage of pursuing the achievement of different Sustainable Development Goals (SDGs) in the building sector, as shown in Fig. 13. As already discussed in the Introduction section, several studies have demonstrated that interventions on the existing building stock have the main advantage of prolonging the service life of the building while enhancing energy performance and minimizing waste associated with demolition operations. This is particularly crucial in the case of historic buildings, where preserving the original structure and the visual appearance of surfaces is imperative.

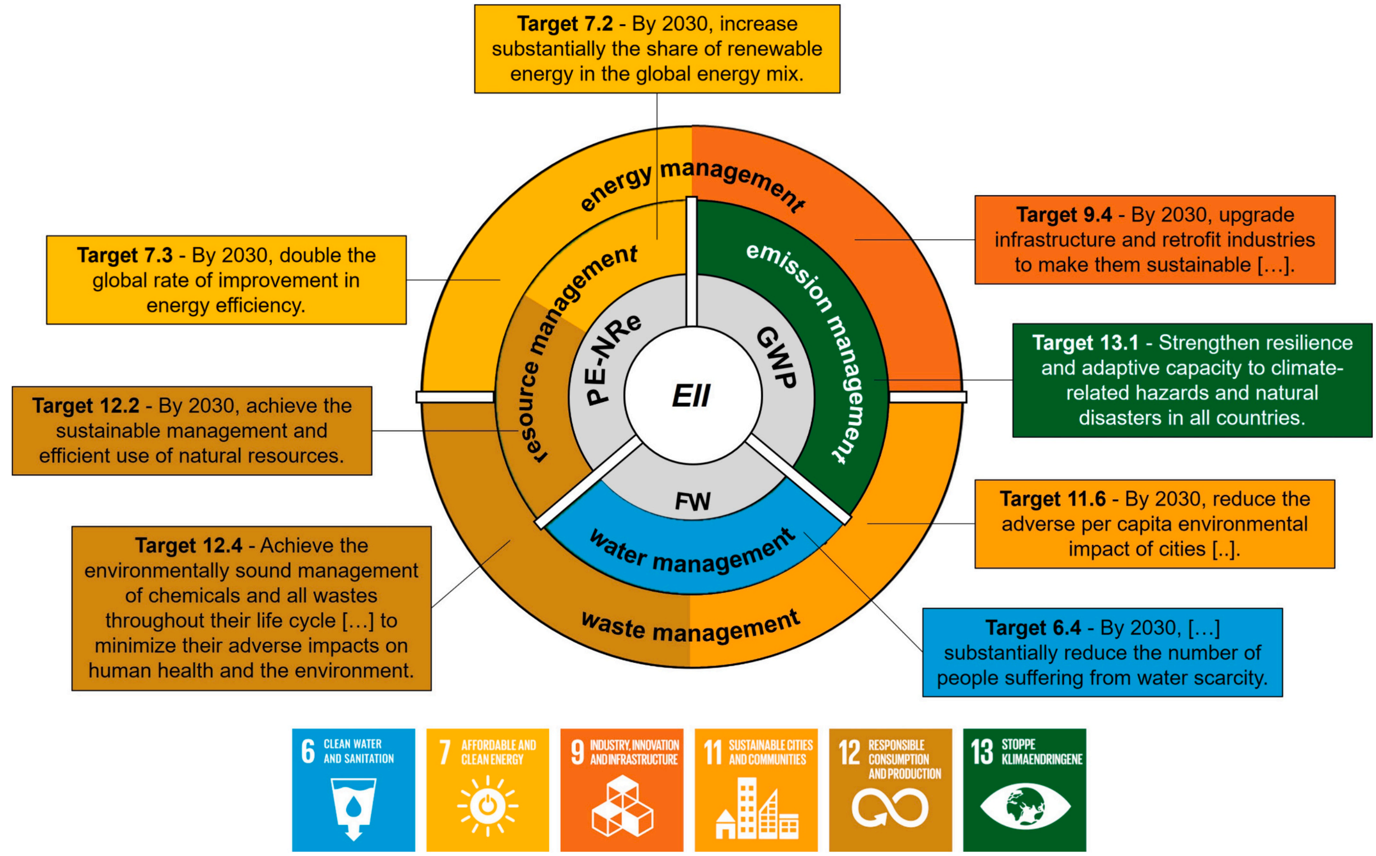
Within the broader framework of interventions, enhancing the energy performance of existing buildings can accelerate the achievement of SDGs 9 (target 9.4) and in the case of implementing natural-based and renewable energy solutions the achievement of SDG 7 (target 7.3); whereas minimizing the waste associated with demolition operations and its management can accelerate the achievement of SDGs 11 (target 11.6) and 12 (target 12.4). In this context, the EII proposed in this study allows to estimate the impact of interventions on existing buildings along their service life. It can be advantageously used in the pre- and post-design/implementation projects as a cross indicator of three environmental impact categories (climate change, resource use, and consumptive freshwater), related to the resource (PE-NRe), emission (GWP) and water (FW) management of the intervention, respectively. Minimizing PE-NRe enables the pursuit of SDGs 7 and 12, as each existing building can contribute to the global energy mix by sharing the produced renewable energy (target 7.2) through the exploitation of natural resources (target 12.2). Reducing GWP has the main advantage of making existing buildings more resilient and adaptive, thus accelerating the achievement of SDG 13 (target 13.1), also in addressing the needs of developing countries (targets 13.a and 13.b). Finally, limiting the use of FW is pivotal to increase the water-use efficiency in accordance with the SDG 6, especially in water-stressed areas (target 6.4). This applies to both high- and Low-Income Countries. Regardless of economic status, global initiatives should prioritize sustainability and fair development. Wealthier nations can use advanced technologies and resources to lead innovative solutions, while less affluent countries offer valuable insights into resilience and community-centered strategies. Through promoting cooperation and mutual assistance, we can build a more inclusive and sustainable future for everyone.

A balance should be found among the minimization of EII and visual impact of the intervention and the achievement of the energy efficiency of the existing building. Indeed, low and medium impact interventions may meet the energy efficiency goal with a very long temporal horizon, that in turn decelerate the achievement of the (EU Directive 2023/1791, 2023).

Conclusions

The key focus of this research is on enhancing buildings service life simultaneously reducing their need for operational energy, thereby improving energy efficiency throughout their lifetime. Our approach lays its foundation in the fact that the continuous maintenance of a building has a lower environmental impact than its demolition and reconstruction. In addition, the reduction in environmental emissions during interventions should prospect the attainment of Sustainable Development Goals (SDGs) or Gold and Platinum rating of environmental certifications such as LEED (Leadership in Energy and Environmental Design) or Very Good, Excellent, and Outstanding classification of BREEAM (Building Research Establishment Environmental Assessment Method).

The method seeks to expand on the existing nZER method, focusing on sustainable solutions, as well as conservative retrofit and energy refurbishment of existing buildings. The innovation of this method is its step-by-step approach that can be implemented through a dual-stream


Target 7.2 - By 2030, increase substantially the share of renewable energy in the global energy mix.

Target 7.3 - By 2030, double the global rate of improvement in energy efficiency.

Target 9.4 - By 2030, upgrade infrastructure and retrofit industries to make them sustainable […].

Target 13.1 - Strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries.

Target 12.2 - By 2030, achieve the sustainable management and efficient use of natural resources.

Target 11.6 - By 2030, reduce the adverse per capita environmental impact of cities [..].

Target 12.4 - Achieve the environmentally sound management of chemicals and all wastes throughout their life cycle […] to minimize their adverse impacts on human health and the environment.

Target 6.4 - By 2030, […] substantially reduce the number of people suffering from water scarcity.

Fig. 13. Sustainable development goals in line with the framework of the proposed methodology.

strategy. In this way, stakeholders can embrace a more systematic and data-driven approach to choose the type of intervention starting from the selection of components and their assembly towards the planned maintenance in the near and far future. The proposed methodology involves analyzing the current state of the building (t_p) and, hence, planning the intervention from the assembly at time t_0 to the future maintenance over a 100-year horizon (t_H). The environmental impact is assessed with the LCA, whereas the visual impact is defined according to the nZER approach.

The application of the method to the benchmark has demonstrated that there is a direct proportionality between the two impact indicators Global Warming Potential (GWP) and Primary Energy-No Renewable (PE-NRe). The Fresh Water (FW) indicator does not have a singular relationship with the other two indicators as it is mainly influenced by the location and method of material production. All these indicators, compressed in the Embodied Impact of Intervention (EII), play a key role in driving to the selection of the interventions that allow to reduce energy and waste management, thus accelerating the achievement of the Sustainable Development Goals in the energy efficiency of existing and historic buildings. Additionally, the EII allows to estimate the transformation of the building into at least a nearly Zero-Energy Building (nZEB) or Zero-Energy Building (ZEB) according to the (EU Directive 2023/1791, 2023), as it considers the embodied impact of the planned maintenance too.

The methodology highlights the importance of reducing both assembly and planned maintenance to achieve a progressively lower overall environmental impact. By analyzing since the beginning all the Low, Medium, and High scenarios, founded on the nZER approach concerning the aesthetic and visual impact of the intervention, it is perceived that this subdivision does not fully align with environmental impact counterpart. In particular the “Medium” and “High” scenarios differ considerably: numerous Medium scenarios exhibit low environmental impact, and several High scenarios report a moderate environmental impact, resulting in a distinct classification. However, thanks to the benchmark application and the possibility to easily compare diverse scenarios, stakeholders can acquire valuable insights on how to decrease their environmental impact based on their specific requirements and preferences in time and scale of climate change. The proposed methodology provides a practical approach for the construction sector within the retrofit framework, focusing on sustainability and minimal environmental impact. It addresses climate change, global warming, and potential future water shortages. Finally, the methodology can be effectively implemented in both high- and Low-Income Countries. Particularly in Low-Income Countries, it can play a significant role in reducing carbon emissions, especially during the production stages (A1-A3), by promoting recycling/upcycling, and embracing circular economy practices. Then, the calculation of EII in benchmarks buildings located in Low-Income Countries has the potentiality to highlight which relationship exists between the environmental impact of interventions and the GDP of that specific Low-Income Country. In Low- and Middle-Income Countries, considerations for the visual impact of interventions may be lacking due to mindset, resources, and cultural preferences. Reusing materials can be a valuable practice, similarly the promotion of the practice of minimizing visual invasiveness to preserve constructions' significance, even in shantytowns areas although such practice could meet some resistance due to the perceptions of visibility that in in Low- and Middle-Income Countries could be equated with wealth and well-being.

In the future, a further development of the proposed method adopting a global Life Cycle Thinking and a global Life Cycle Costing approaches could lead to assess components/assemblies' lifecycle flow and economic aspects among countries. This means, that - at the net of travel emissions - the method could have the potentiality to analyze whether it is still sustainable or not to reuse or upcycle in a Low-Income

Country the components/assemblies that were deconstructed and disposed in the country where the CO_2 was originally emitted (e.g. High income) thus contributing – at global scale - in recovering such emission.

CRediT authorship contribution statement

Beatrice Bartolucci: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Francesca Frasca:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Conceptualization. **Chiara Bertolin:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Francesca Frasca reports financial support was provided by Government of Italy Ministry of Education University and Research.

Data availability

Data will be made available on request.

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Appendix A

The "EII" is shown in Fig. A1: to the left, Fig. A1a displays the three scenarios, distinguished by colors. To the right, the different types of interventions are outlined in detail in three subplots (Fig. A1b/c/d). Although with a less clear distinction compared to the graph representing the Assembly, in Fig. A1a is again visible the subdivision in 4 groups:

- The first one concerns L scenarios, within the range of approximately 100–400 MJ/m^2 and 14–18 kg$_{CO2eq}$/m^2.
- The second group concerns the M and some H scenarios that are overlapping. As in the "A" and in the "PM" steps, this group does not include H.4 and H.5 scenarios. In this group PE-NRe ranges between approximately 400 and 2325 MJ/m^2 and the GWP is approximately between 50 and 160 kg$_{CO2eq}$/m^2.
- The third and fourth groups consider, respectively, the H.5 and H.4. Scenarios 5a/5b/5a'/5b' are located in the most central area (PE-NRe between 2545 and 3035 MJ/m^2 and GWP between 500 and 530 kg$_{CO2eq}$/m^2). Scenarios 4a/4b/4a'/4b' are located in the upper part (PE-NRe between 13,830 and 14,320 MJ/m^2 and GWP between 1018 and 1045 kg$_{CO2eq}$/m^2).

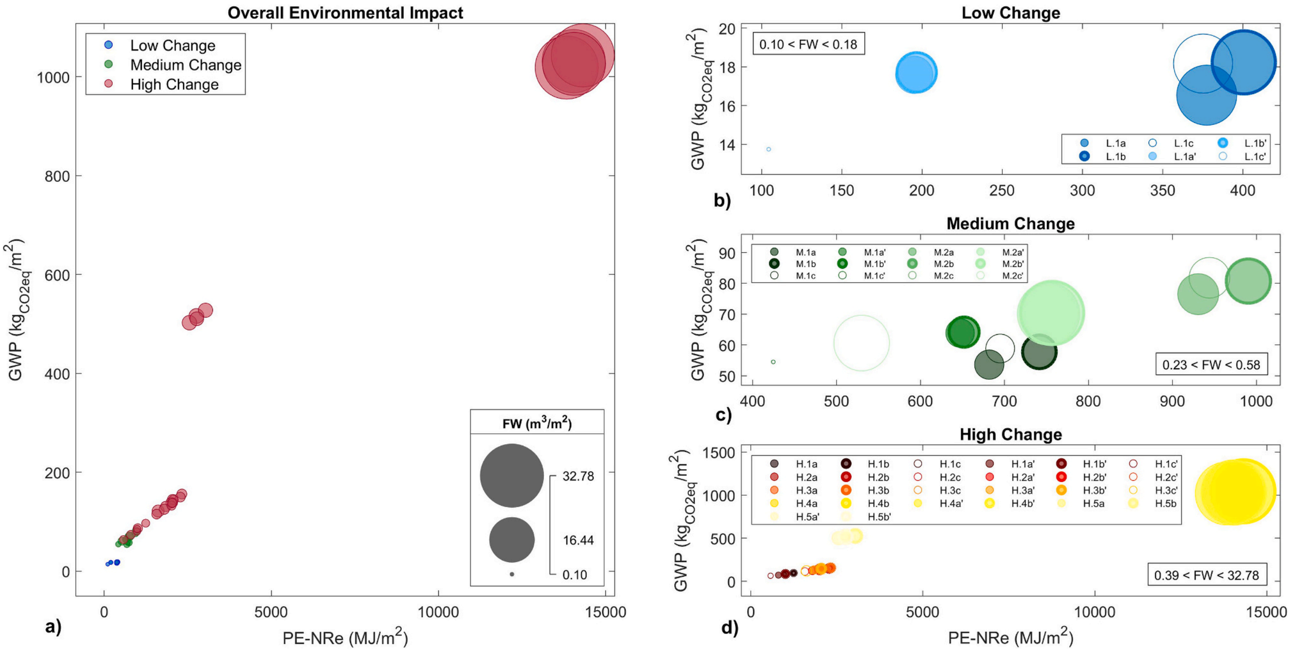

Fig. A1. Left: a) bubble chart of all the scenarios of the "EII"; right: details of the b) L (shadows of blue), c) M (shadows of green), and d) H (from red to yellow) scenarios. The x-axis represents the PE-NRe (MJ/m^2), the y-axis represents the GWP (kg$_{CO2eq}$/m^2). The third dimension is the FW (m^3/m^2). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Appendix B

Results from the Principal Component Analysis on the standardized raw data (i.e., average = 0 and standard deviation = 1) indicate that the percentage of the total variance explained by each principal component, is maximum for the first component (Component 1 = 96.7 %, Component 2 = 3.1 % and Component 3 = 0.2 %). Moreover, the analysis of the PCA scores shows that they change little, however the principal component coefficients (or loadings) of the PCA, represented in Fig. B1 by the blue lines linked to the three variables PE-NRe, GWP, and FW, change depending on the variable. The biplot in Fig. B1 shows that the three variables contribute positively to the first component. Regarding the second component, we observe that only GWP contributes positively, while the PE-NRe contributes positively to the third component (the coefficients are written in Table B1). While the latter has an explained variance of less than 0.5 and therefore a very low significance in this analysis, component 2 has 3.1 % of explained variance, which although low in value, could represent a property in our system, i.e. it could correspond to the extent to which the intervention fails to strengthen resilient and adaptive capacity to climate change (SDG 13).

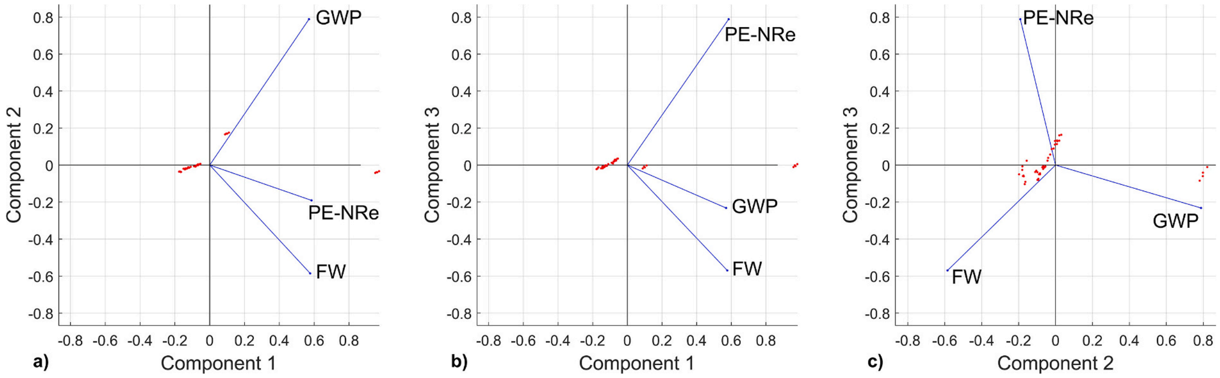

Fig. B1. Biplot constructed from the standardized raw data of PE-NRe, GWP, and FW. a) Component 1 vs Component 2; b) Component 1 vs Component 3; c) Component 2 vs Component 3. In the three subplots it is possible to understand the relationship between the Principal Components with the three variables.

By interpreting Component 1 as EII, it is possible to understand how much the variables (i.e., the three indicators) influence each component.

Table B1
Coefficients (or loadings) of the PCA for each variable, for the three Principal Components.

	Coefficients		
	1	2	3
PE-NRe	0.5848	−0.1908	0.7884
GWP	0.5701	0.7881	−0.2321
FW	0.5771	−0.5852	−0.5696

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