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Environmental and Economic Assessment of Energy Renovation in Buildings, a Case Study in Greece

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Abstract: The environmental and economic evaluation of energy renovation in buildings plays a crucial role in achieving sustainability goals and the decarbonization of the built environment. This paper presents a case study of a student house in Athens, Greece, to assess the environmental and economic impacts of energy renovation and seismic reinforcement with a steel exoskeleton. This study utilizes a comprehensive approach that combines life cycle assessment (LCA) and life cycle costing (LCC) methodologies using One Click LCA. The LCA assesses the environmental impacts associated with energy consumption and greenhouse gas emissions, while the LCC evaluates the economic aspects, both analyses being conducted for a lifespan of 25 years from now. The results provide an evaluation of what would happen in terms of greenhouse emissions and costs in two scenarios: with and without interventions. ProGETonE strategy results in an environmental impact with a GWP of 26.78 $kgCO_2eq/m^2y$ with a reduction of 30% of the pre-renovation state. Economically, the actualized energy use costs for 25 years are 50% less in the post-renovation state, but the high construction costs make the strategy seem inconvenient. In this context, it is important to consider the non-economic benefits of seismic reinforcement, such as enhanced safety and the potential lives saved, which are critical in high seismic zones. These advantages complement the strategy's environmental and energy use impacts, underscoring the holistic value of integrated seismic and energy retrofitting approaches like ProGETonE. The study underscores the importance of LCA and LCC analyses when evaluating the feasibility of renovation projects and of an evidence-based decision-making process for policymakers, building owners, and stakeholders for energy-efficient retrofitting.

Keywords: environmental impact; economic impact; energy retrofit; seismic retrofit; LCA; LCC

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1. Introduction

The European Union (EU) aims to reach climate neutrality by 2050 [1], meaning that greenhouse emissions should be reduced to zero. This goal must be achieved in all sectors, including buildings that are responsible for a significant share of greenhouse gas (GHG) emissions in the EU. According to data from the European Environment Agency (EEA) and Eurostat, buildings are estimated to contribute around 36% of the EU's total CO_2 emissions. This includes emissions from residential and non-residential buildings [2].

To address the climate emergency, the EU has implemented various policies and initiatives to improve the energy efficiency of buildings. These efforts include the Energy Performance of Buildings Directive (EPBD), the Renovation Wave strategy, and various funding programs that support energy-efficiency interventions and building renovations.

The goal is to significantly reduce buildings' emissions through improvements in energy efficiency, the use of renewable energy sources, and the promotion of sustainable building practices.

As well as energy efficiency, seismic safety is a significant issue in certain regions of the European Union that are prone to seismic activity. While not all EU member states face high seismic hazards, countries such as Italy, Greece, Spain, Portugal, and Romania have notable seismic risks due to their geographical locations. In these areas, recent seismic events have shown the relevance of the issue of seismic vulnerability for existing buildings of reinforced concrete since many of these were designed without any reference to anti-seismic criteria [3].

The H2020 ProGETonE (Proactive synergy of inteGrated Efficient Technologies on buildings' Envelopes) project represents a concerted European research and innovation initiative targeting the dual objectives of enhancing both the energy and seismic performance of buildings. This project is dedicated to the development of pioneering technologies and methodologies for the optimization of building envelopes [4].

About 75% of existing buildings are energy inefficient [5], so their renovation plays an important role in reaching the energy-saving objectives before 2050. On top of this, educational buildings account for the largest share of the oldest stock, so retrofitting existing educational buildings presents a great challenge and offers a great benefit [6].

This paper focuses on the environmental and economic assessment of the strategy proposed by ProGETonE for the renovation and seismic reinforcement of buildings. The results are based on the analysis of one demo case, a student house in Athens, Greece. The aim is to assess the environmental and economic implications of energy renovation and seismic reinforcement using a steel exoskeleton in residential buildings, providing valuable insights into the environmental and economic feasibility and benefits of such interventions by evaluating the entire life cycle of the building in both pre-renovation and post-renovation scenarios.

The outcomes of this research are anticipated to offer critical perspectives for policymakers, property managers, and all parties engaged in energy retrofitting initiatives. One of the primary objectives of this article is to underscore the significance of life cycle assessment (LCA) and life cycle costing (LCC) evaluations in appraising intervention scenarios. This is because interventions with higher initial environmental impacts or costs during the construction phase may prove to be more advantageous over the long term. Ultimately, this research aims to promote sustainable building practices, reduce energy consumption, and lower carbon emissions in the building sector, while also highlighting the economic viability of measures of this type.

2. Methodology and Literature Review

2.1. Methodology

The methodology for evaluating the ProGETonE strategy and its impact on the renovation and construction of a steel exoskeleton for a student house in Athens can be outlined as follows:

1. Initial Analysis: The process starts with an in-depth review of ProGETonE's strategic approach and the outcomes of the deep renovation and steel exoskeleton construction on the Athens student house. This stage sets the foundation for a comprehensive understanding of the project's objectives, strategies, and results, preparing the ground for further technical evaluation.
2. Construction Materials Inventory: Utilizing Autodesk Revit and the BIM method, an inventory of building materials is compiled. This involves a detailed cataloging of the materials used, using the Revit model to accurately identify and quantify the materials. This model ensures that the assessments are based on precise bills of quantity for both pre-renovation and renovated states.
3. Cloud-Based Analysis: This phase connects the BIM model inventory with One Click LCA's extensive database through cloud-based analysis. This integration aligns the

material inventory with environmental and economic impact data from One Click LCA, allowing for precise life cycle assessment (LCA) and life cycle cost (LCC) analyses.

4. LCA and LCC Analyses: Performed in One Click LCA for both the building's pre-renovation and post-renovation phases. This comparative analysis rigorously assesses the environmental and economic impacts of the renovation project, quantifying the benefits and disadvantages of the strategies employed.
5. Results Comparison: The outcomes from the LCA and LCC analyses are then compared, spotlighting the variances in environmental impact and cost-effectiveness for the pre-renovation and post-renovation states. This comparison sheds light on the efficacy of the ProGETonE strategy and the steel exoskeleton's construction.
6. Conclusions: The final phase draws conclusions from the comparative analysis, synthesizing the results. It offers a well-informed viewpoint on the project's success in meeting its sustainability and efficiency goals, highlighting the importance of the life cycle analyses in evaluating the impacts of buildings.

2.2. Literature Review

Several studies have focused on assessing the impacts of buildings and the role of life cycle analyses when evaluating the convenience of renovation interventions. Bragadin et al. analyzed the ProGETonE case study and highlighted that renovating Europe's building stock for better structural and energy performance is crucial, but often hindered by high costs, leading to a preference for demolition. Life cycle analysis (LCA) is essential for evaluating sustainability and impacts, notably global warming potential, which can increase significantly through the design process. Building information modeling (BIM) supports this by facilitating data management in deep renovation projects. Wong, Lindsay, Crameri, and Holdsworth demonstrated in their study the critical importance of both carbon accounting and energy efficiency rating systems in building design and management [7].

Assimakopoulos et al. [8] highlighted that adding volume to existing buildings offers numerous benefits beyond energy efficiency, potentially motivating occupants, tenants, and communities to actively engage in the design process. This approach could significantly hasten the transition of the existing building stock to nearly zero energy standards, marking a critical objective for the sustainable evolution of the building sector.

Apostolopoulos et al. evaluated global warming impact assessments in building renovation using LCA and LCC methodologies through VERIFY, an online tool for dynamic life cycle analysis. They evaluated the environmental and cost impacts of retrofitting a multifamily residential building in Athens to meet the Passive House Standard. The retrofit included envelope improvements, thermal component upgrades, and renewable energy systems, aiming for near-zero energy impact. The results showed a significant reduction in primary energy needs and CO_2eq emissions, with substantial savings over 25 years [9].

3. Evaluation of the Impacts: LCA and LCC Analysis

The evaluation of the impacts of energy renovation measures involves examining both environmental and economic aspects. In this research, the environmental evaluation is performed through life cycle assessment (LCA), which provides an assessment of the environmental impacts associated with the renovation process, including energy consumption, greenhouse gas emissions, and resource depletion throughout the whole lifespan of the building.

In parallel, the economic evaluation is conducted through life cycle costing (LCC), which assesses the costs and benefits associated with energy renovation projects. It considers investment costs, energy savings, maintenance costs, and overall life cycle costs to evaluate the economic viability of the project. Integrating LCA and LCC allows us to achieve a more holistic understanding of the impacts and benefits of energy renovation actions in buildings.

3.1. Life Cycle Assessment

LCA, or life cycle assessment, is "the compilation and evaluation of the inputs, outputs, and the potential environmental impacts of a product system throughout its life cycle." [10]. LCA considers all phases of the life cycle, including raw material extraction, production, use, and end-of-life disposal or recycling. It assesses the environmental burdens and quantifies the inputs of energy, materials, and resources. It serves as a tool for enhancing the environmental aspects of processes and services and is applicable to a broad range of fields, including the building industry.

In the European Union, several regulatory tools provide guidelines and requirements for conducting life cycle assessments:

- ISO 14040 and ISO 14044 are international standards developed by the International Organization for Standardization (ISO) that provide a framework for conducting life cycle assessments. ISO 14040 provides general principles and a framework [10], while ISO 14044 specifies the requirements and guidelines for performing an LCA [11].
- The Product Environmental Footprint (PEF) is a harmonized methodology for assessing the environmental performance of products throughout their life cycles [12].
- Environmental Product Declarations (EPDs) are standardized and verified reports that describe the life cycle environmental impact of a product. EPDs are used as tools for sustainable and environmental labeling [13].
- The Circular Economy Action Plan is a comprehensive strategy to promote a more sustainable and circular economy. It emphasizes the importance of life cycle assessment in enabling the transition to a circular economy [14].

These regulatory tools and frameworks in the EU support the adoption of life cycle thinking and assessment, providing guidelines and requirements for conducting LCAs and promoting sustainability throughout the life cycles of products and processes. LCAs are widely used in the building sector to evaluate the environmental impacts of buildings throughout their life cycles.

LCAs assess the environmental impacts associated with the extraction, processing, and transportation of building materials. LCAs can also compare different materials to determine their environmental performance and guide the selection of more sustainable options for energy consumption and associated environmental impacts during the operational phase of buildings. This includes energy used for heating, cooling, lighting, ventilation, and other building services. LCAs consider the environmental impacts of construction activities, including site preparation, assembly, and installation. They assess factors such as energy use, emissions from construction machinery, waste generation, and transportation impacts. The environmental impacts associated with demolition, disposal, or recycling are also considered.

3.2. Life Cycle Cost

Life cycle costing (LCC) is a methodology used to assess the total costs associated with a product or system throughout its entire life cycle. It considers the upfront investment costs and costs related to acquisition, operation, maintenance, and disposal. LCC can help evaluate the economic viability and cost-effectiveness of different options and support the decision-making process.

The EU has established public procurement directives (2014/24/EU and 2014/25/EU) [15,16] that govern the procedures for the public procurement of goods and services and works. These directives encourage the consideration of life cycle costs and promote the evaluation of economic aspects along with environmental and social factors. The European Committee for Standardization (CEN) has published a series of standards, such as EN 15643 [17], which provide guidelines for the conduct of LCCs in construction projects. In previous relevant studies, the cost-benefit assessments of retrofit actions showed excessive payback times, creating in investors and final users a strong and generalized lack of confidence [18]. Therefore, in this study, the use of LCC plays a key role in studying and evaluating the economic feasibility of energy efficiency measures and in calculating the payback period for investments in order to analytically investigate the benefits and drawbacks of such energy and seismic interventions.

3.3. One Click LCA and Integration with BIM

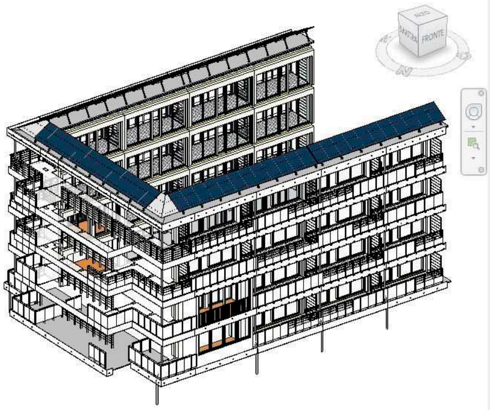
One Click LCA is a cloud-based software tool that enables LCA and LCC analyses for buildings. It is designed to simplify the process and enable users to assess the environmental performance and life cycle costs of buildings. The software integrates various data sources, calculation methodologies, and certification standards to provide accurate results. In fact, One Click LCA supports various building certification schemes, such as LEED, BREEAM, and Level(s). The software integrates several databases of EPDs, providing information on the environmental impacts of building materials [19].

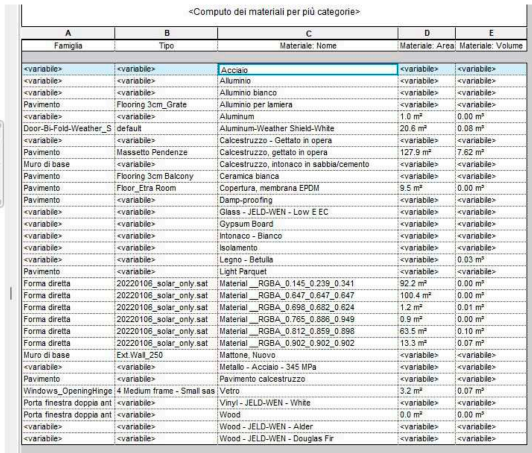
In this research, One Click LCA software was also chosen for integration with the BIM Autodesk Revit software. BIM is very useful for evaluating building performance, energy efficiency, carbon emissions, LCA, and LCC. BIM models capture a wide range of information about buildings, including their design, spatial layout, materials, systems, construction details, and even specifications regarding intended products or suppliers. The BIM process recognizes that both visible geometry and non-visible properties are essential for assessing building performance [20]. Quantifying carbon emissions in buildings typically involves multiplying material quantities with environmental impact profiles (found in EPDs or databases). In the case of One Click LCA, the Adaptive Recognition module can identify and assign suitable environmental impact profiles for most clearly defined materials in the BIM model. However, certain ambiguities may still require manual definition or, if insignificant, may be omitted. Some objects in the model, particularly smaller systems or parts like lock systems or cabling, may not be suitable for automated performance analysis. According to EN 15978 [21], building LCAs can exclude objects comprising less than 1% of the building mass, with total omissions not exceeding 5% of the total mass. In One Click LCA, users have the option to automatically filter out marginally contributing items from the model. Additionally, the Model Checker function allows an assessment of the correctness of a BIM model for LCA purposes, identifying any deficiencies or risks and enabling the user to determine whether corrections are necessary. In the case of this research, for example, structural elements were added manually to ensure better compliance with real known quantities [22].

The methodology involves an integrated workflow between Autodesk Revit and One Click LCA software to conduct a cloud-based life cycle assessment (LCA) for a building renovation project. The process begins with the use of Revit to meticulously compile a comprehensive inventory of construction materials employed within the project like shown in Figure 1. This inventory serves as the foundation for the subsequent phase, where the One Click LCA plugin facilitates the association of Revit-specified materials with their corresponding entries in the One Click LCA database. Subsequently, an LCA and an LCC were conducted.

These analyses were executed in two distinct phases: an initial assessment of the pre-renovation state, followed by an evaluation of the post-renovation one. This phased approach provides a comparative analysis of the environmental impacts before and after the renovation interventions. Such a methodology enables the identification of the carbon footprint and other environmental and economic impacts associated with the construction, operational, and end-of-life phases of the building. By conducting LCA and LCC at specific project phases, stakeholders can pinpoint improvement opportunities and optimize the overall environmental and economic performance of the building.

The research team conducted an LCA using One Click LCA, starting from the BIM model created within the ProGETonE project and using the Revit plugin of One Click LCA. The following is an outline of the process workflow:





<Computo dei materiali per più categorie>

A	B	C	D	E
Famiglia	Tipo	Materiale: Nome	Materiale: Area	Materiale: Volume
<variabile>	<variabile>	Acciaio	<variabile>	<variabile>
<variabile>	<variabile>	Alluminio	<variabile>	<variabile>
<variabile>	<variabile>	Alluminio bianco	<variabile>	<variabile>
Pavimento	Flooring 3cm_Grate	Alluminio per lamiera	<variabile>	<variabile>
<variabile>	<variabile>	Aluminum	1.0 m²	0.00 m³
Door-Bi-Fold-Weather_S	default	Aluminum-Weather Shield-White	20.6 m²	0.08 m³
<variabile>	<variabile>	Calcestruzzo - Gettato in opera	<variabile>	<variabile>
Pavimento	Massetto Pendenze	Calcestruzzo, gettato in opera	127.9 m²	7.62 m³
Muro di base	<variabile>	Calcestruzzo, intonaco in sabbia/cemento	<variabile>	<variabile>
Pavimento	Flooring 3cm Balcony	Ceramica bianca	<variabile>	<variabile>
Pavimento	Floor_Etra Room	Copertura, membrana EPDM	9.5 m²	0.00 m³
Pavimento	<variabile>	Damp-proofing	<variabile>	<variabile>
<variabile>	<variabile>	Glass - JELD-WEN - Low E EC	<variabile>	<variabile>
<variabile>	<variabile>	Gypsum Board	<variabile>	<variabile>
<variabile>	<variabile>	Intonaco - Bianco	<variabile>	<variabile>
<variabile>	<variabile>	Isolamento	<variabile>	<variabile>
<variabile>	<variabile>	Legno - Betulla	<variabile>	0.03 m³
Pavimento	<variabile>	Light Parquet	<variabile>	<variabile>
Forma diretta	20220106_solar_only.sat	Material __RGBA_0.145_0.239_0.341	92.2 m²	0.00 m³
Forma diretta	20220106_solar_only.sat	Material __RGBA_0.647_0.647_0.647	100.4 m²	0.00 m³
Forma diretta	20220106_solar_only.sat	Material __RGBA_0.698_0.682_0.624	1.2 m²	0.01 m³
Forma diretta	20220106_solar_only.sat	Material __RGBA_0.765_0.886_0.949	0.9 m²	0.00 m³
Forma diretta	20220106_solar_only.sat	Material __RGBA_0.812_0.859_0.898	63.5 m²	0.10 m³
Forma diretta	20220106_solar_only.sat	Material __RGBA_0.902_0.902_0.902	13.3 m²	0.07 m³
Muro di base	Ext.Wall_250	Mattone, Nuovo	<variabile>	<variabile>
<variabile>	<variabile>	Metallo - Acciaio - 345 MPa	<variabile>	<variabile>
Pavimento	<variabile>	Pavimento calcestruzzo	<variabile>	<variabile>
Windows_OpeningHinge	4 Medium frame - Small sas	Vetro	3.2 m²	0.07 m³
Porta finestra doppia ant	<variabile>	Vinyl - JELD-WEN - White	<variabile>	<variabile>
Porta finestra doppia ant	<variabile>	Wood	0.0 m²	0.00 m³
<variabile>	<variabile>	Wood - JELD-WEN - Alder	<variabile>	<variabile>
<variabile>	<variabile>	Wood - JELD-WEN - Douglas Fir	<variabile>	<variabile>

Figure 1. Revit model of the case studies with the bill of quantities.

1. Preparation and Setup in Revit
   - Model Preparation: The Revit model must be properly structured and contain all the necessary information, including materials and quantities. The model should be as detailed and accurate as possible to ensure that the LCA results are reliable.
   - Configuration of the Plugin: The plugin settings are configured according to project needs, including the appropriate geographical location, which affects the environmental impact data.
2. Exporting Data from Revit
   - Data Extraction: The plugin extracts relevant data from the Revit model, such as materials, quantities, and other information needed for the LCA.
   - Data Review and Adjustment: After extraction, a review of the data for accuracy and completeness is necessary.
3. Importing Data into One Click LCA
   - Data Import: The extracted data are imported into the One Click LCA platform.
   - Data Mapping: The imported data are mapped to the corresponding materials and processes in the One Click LCA database. This step ensures that the environmental impacts are calculated based on the correct materials and their life cycle stages.
4. Conducting the LCA
   - Analysis Settings: Configuration of the analysis settings in One Click LCA, including the life cycle stages to be included (e.g., production, transportation, use, and end-of-life) and any specific impact categories of interest.
   - Running the Analysis: One Click LCA calculates the environmental impacts of the building design across the selected life cycle stages and impact categories.

4. Case Study

4.1. ProGETonE

ProGETonE is a European Horizon 2020 research project that aims to integrate various technologies to achieve multiple benefits in existing buildings. These include enhancing seismic safety measures to face future earthquakes and achieving near-zero energy performance. Additionally, the project aims to add significant social and architectural value to buildings. In more detail, ProGETone focuses on the following aspects:

- Energy requirements—by adding new prefab and plug-and-play high-energy performing envelopes and HVAC (Heating, Ventilation, Air Conditioning) systems.
- Safety—using appropriate external structures to increase the overall structural capacity of a building.

- Social and economic sustainability—increasing the real estate value of buildings. ProGETonE, which stands for Proactive synergy of inteGrated Efficient Technologies on buildings' Envelopes, has secured a total budget of 5 million Euros, including funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 723747. The project consortium comprises 13 partners from 8 countries, including universities, technical consultants, manufacturers, SMEs, public authorities, and associations. It was coordinated by the University of Bologna. In the project, four different case studies were evaluated in different climatic zones. Simulations and feasibility studies have been performed for three buildings in Reggio Emilia (IT), Brasov (RO), and Athens (GR). In Groningen (NL), a 2D exoskeleton has been implemented in a number of semidetached housing units. The actual live demonstrator of the project, where all studied technologies and systems were implemented, is the student's residence at the National and Kapodistrian University of Athens (NKUA). Its renovation via ProGETone started in May 2021. The whole renovation action of the ProGETone project, including the implementation of the integrated GET system, was finalized in September 2022.

4.2. The Student House

In this paper, a case study of the NKUA's student residence is presented. Athens features a hot-summer Mediterranean climate, characterized by extended periods of hot and dry summers and mild to cool winters with moderate rainfall. Built in 1986, the building known as "B FEPA" was constructed with reinforced concrete and has a rectangular shape (56.6 m $\times$ 15.4 m) consisting of four floors above ground and an additional basement level. The building consisted of 138 single-bed rooms, designated for students, with a gross area of around 3642 square meters. Each floor had 36 single-bed rooms for students, except for the ground floor, which had 30 rooms. Figure 2 shows the facades of the building in the pre renovation state. Prior to renovation, the building's energy demands were 67 kWh/m^{2}year for electricity and 62 kWh/m^{2}year for natural gas. After renovation, they were 39 kWh/m^{2}year for electricity and 10 kWh/m^{2}year for natural gas, these results are shown in Figure 3 [23]. These values were obtained through energy simulation in EnergyPlus.

Figure 2. The student house in its pre-renovation state.

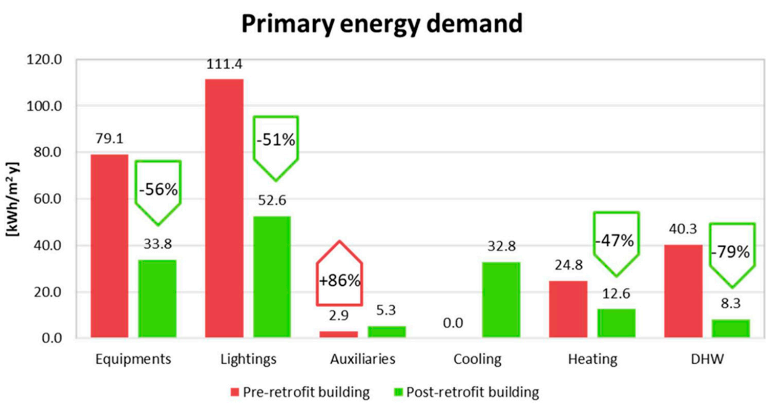


Figure 3. Primary energy demand in pre-renovation state and post-renovation state. Source: [24].

4.3. The Deep Renovation and GET Project

The ProGETonE project proposes a strategy for expanding an existing building by incorporating a seismic-resistant steel framework, known as an exoskeleton, which facilitates the addition of extra spaces on each level. This approach enhances energy efficiency, seismic resilience, and spatial enlargement, and has been collectively termed the "GET system", which refers to the "Integrated Efficient Technologies" included in the ProGETonE project's name. The case study of the students' residence promotes social inclusion and social awareness in issues such as energy efficiency, seismic safety, and environmental performance.

The construction of the exoskeleton allows for the addition of new sunspaces, balconies, and even extra rooms for existing bedrooms. The structure consists of a steel frame for each floor, incorporating bracing elements in the transverse direction. This frame is linked to the pre-existing reinforced concrete frame, specifically at the junctions between beams and columns. In the longitudinal direction, these frames are interconnected using supplementary beams that are hinged, thereby creating an appropriate space for volumetric extensions.

The GET system provides an effective means of enhancing the rigidity of steel structures without adding vertical loads to the current structure while simultaneously bolstering its resistance to horizontal forces, thereby minimizing displacements. This approach can improve seismic safety by up to 40% compared to the original structure. The GET system (shown in Figure 4) has been applied in the student house of NKUA, where seismic safety was doubled through additional topological interventions aimed at reinforcing the existing structure [4]. As shown in Section 5 (Results), the construction cost of the deep renovation (without the cost of the GET exoskeleton) is EUR 1,133,461, while the cost of the GET structure is EUR 1,522,842, making a total of EUR 2,656,303.

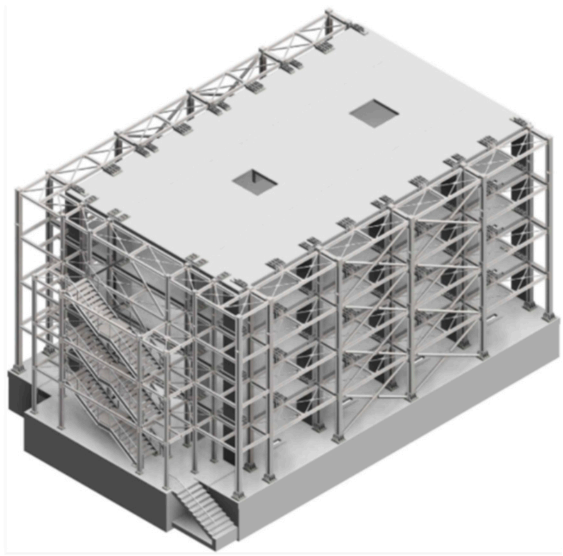


Figure 4. The rendering of the GET system. Source: H2020 ProGETonE.

The GET system, beyond the improvement it offers on seismic aspects, includes a plug-and-play insulated façade system, an HVAC system with heat pumps for heating, cooling, and domestic hot water, controlled mechanical ventilation, and smart building controls. The retrofitted building consists of autonomous heating and cooling systems serving a small part of the building and a mixed air–water centralized system serving the other part of the building.

The bathrooms and other common areas use hot water radiators fueled by a gas heating boiler for heating purposes. Domestic hot water is provided by a gas boiler connected to a solar collector system.

On the roof, a PV and solar panel system producing about 20,000 kWh/year of electricity and 58,000 kWh/year of thermal energy was installed (see also Figure 5). Lastly, each zone of the building is equipped with a decentralized mechanical ventilation system. This system, featuring heat recovery and air filtration capabilities, can deliver five distinct levels of fresh air flow corresponding to five varying fan speeds [23].

Figure 5. The student house in the post-renovation state. **Left**: the rendered image from the software. **Right**: the actual photo after retrofit. Source: H2020 ProGETonE.

The case study is particularly emblematic, as it allows the assessment of costs and benefits of a combined action from both the energy and seismic reinforcement aspects. Despite being a building owned by a university, its typology can be considered similar to a residential building. It also offers students an enhanced awareness of the environmental and seismic aspects. For this reason, the replicability of the strategy can significantly contribute to the decarbonization and seismic reinforcement of European residential stock.

5. Results

The scenarios evaluated in this research are:

- Pre-Renovation: This refers to the hypothesis that the building remains the same as it was before the construction of the GET structure, with no renovation interventions at all.
- Post-Renovation: This refers to the building as it is after the addition of the GET structure and after the deep renovation of the rest of the building.

For both scenarios, the period of evaluation was fixed at 25 years because the student house was built almost 40 years ago, and this is the new reasonable lifespan.

The Level(s) calculation tool of One Click LCA was used for the LCA analysis. Level(s) is a European framework used to assess the sustainability performance of a building throughout its life cycle [25]. The Level(s) tool is in compliance with EN 15978, and for the purpose of this study, the results focus on Global Warming Potential (GWP) or Carbon Footprint, which refers to the alterations in surface temperatures at local, regional, or global scales resulting from heightened concentrations of greenhouse gases in the atmosphere. The increased release of greenhouse gases, primarily from the combustion of fossil fuels, has been closely linked to two additional environmental effects: acidification and smog. These combined impacts are commonly referred to as the "carbon footprint", representing the overall environmental footprint associated with carbon emissions.

The One Click LCA tool, which focuses on life cycle cost analysis, was developed to align with the EN 16627 [26] and ISO 15686-5 [27] standards. The tool generates results based on cost categories that are obligatory, according to the EN standard. At a minimum, the required cost categories for reporting include construction, operation, maintenance, and end-of-life costs.

As for the discount rate used, One Click LCA automatically loads the data for each country based on local economies. For Greece, the value is 7%, meaning that all future costs are actualized and discounted with inflation, all to be compared at time zero.

5.1. Pre-Renovation LCA

For this scenario, all the phases have been evaluated, and the results are shown in the Table 1 below:

Table 1. LCA results of the pre-renovation stage.

Section	Result Category	Global Warming $kgCO_2eq$
A1–A3	Construction Materials	2,144,086.47
A4	Transportation to site	63,678.94
A5	Construction/installation process	109,748.9
B1	Use phase	0
B3	Repair	0
B5	Material replacement and refurbishment	2,574.89
B6	Energy consumption	3,414,642.82
C1–C4	End of life	65,412.62

For the entire life cycle, the emissions are a total of about 5,800,144.64 $kgCO_2eq$ and 63.7 $kgCO_2eq/m^2$year. If considering only the 25 years from the time set as "zero" in this research, the construction phase should not be included in the calculation because it took place before the years considered. The emissions for 25 years for the operational and end-of-life phases of the building are 3,482,630.33 $kgCO_2eq$ and 38.25 $kgCO_2eq/m^2$year.

5.2. Pre-Renovation LCC

For the pre-renovation period, all the phases were evaluated, and the financial results are shown in the Table 2 below:

Table 2. LCC results of the pre-renovation stage.

Section	Result Category	Life-Cycle Cost, Discounted with Inflation
A0–A5	Construction	EUR 4,959,559
B4–B5	Replacement/refurbishment	EUR 12,589
B6	Operational energy use	EUR 1,418,772
C1–C4	End of life	EUR 205,462

For the entire life cycle, the LCC shows a total of EUR 5,885,079 and EUR 64/m^2year. However, as for LCA, if considering only the 25 years from the instant "zero", the construction phase should not be included in the calculation. The total cost for 25 years for the operational and end-of-life phases of the building are EUR 1,636,823 and 18 €/m^2year.

5.3. Post-Renovation LCA

For this scenario, all the phases were evaluated for the GET structure, while for the rest of the building, the materials for deep renovation, new energy demand, and the end-of-life impacts should be considered.

The results are shown in the Tables 3 and 4.

Table 3. LCA results of the post-renovation stage-GET construction.

Section	Result Category	Global Warming $kgCO_2eq$
A1–A3	Construction Materials	916,580.27
A4	Transportation to site	12,341.2
A5	Construction/installation process	23,236.18
B1	Use phase	0
B3	Repair	0
B5	Material replacement and refurbishment	823.56
B6	Energy consumption	12.24
C1–C4	End of life	14,411.94

Table 4. LCA results of deep renovation of the building.

Section	Result Category	Global Warming $kgCO_2eq$
A1–A3	Construction Materials	67,566
B6	Energy consumption	1,639,591.23
C1–C4	End of life	65,412

For the whole life cycle of the GET, the emissions total about 967,393.15 $kgCO_2eq$ and 86 $kgCO_2eq/m^2y$, normalized on the added surface of 450 m^2.

For the renovated building, the emissions total about 1,772,569.23 $kgCO_2eq$.

To assess the environmental impact of this scenario, the values of the GET and the building are summed to give totals of 2,739,963.00 $kgCO_2eq$ and 26.78 $kgCO_2eq/m^2year$, normalized on a surface of 4092 m^2.

5.4. Post-Renovation LCC

For the LCC, as for the LCA, all the phases were evaluated for the GET structure, while for impacts on the rest of the building, only the materials for deep renovation, new energy demand, and the end-of-life phases should be considered. Results are shown in Tables 5 and 6.

Table 5. LCC results of the post-renovation stage -GET construction.

Section	Result Category	Life Cycle Cost, Discounted with Inflation
A0–A5	Construction	EUR 1,522,842
B4–B5	Replacement/refurbishment	EUR 1796
B6	Operational energy use	EUR 0
C1–C4	End of life	EUR 23,205

Table 6. LCC results of the deep renovation of the building.

Section	Result Category	Life Cycle Cost, Discounted with Inflation
A0–A5	Construction	EUR 1,133,461
B4–B5	Replacement/refurbishment	EUR 159,211
B6	Operational energy use	EUR 480,511
C1–C4	End of life	EUR 17,272

For the whole life cycle of the GET structure, the LCC totals EUR 1,547,844.

For the renovated building the LCC is EUR 1,690,455.

To assess the total LCC of this scenario the values of the GET and of the building are summed for totals of EUR 3,236,716 and EUR 31/m^{2}year, normalized on a surface of 4092 m^2.

6. Discussion and Comparison of Results

6.1. Environmental Impact

In this study, both environmental and financial assessments have been undertaken for the pre-renovation and post-renovation stages. Keeping the building in its original state, without any retrofit innovations at all, would have produced a total GWP of 3,482,630.33 kgCO_2eq and 38.25 kgCO_2eq/m^{2}year (excluding the construction phase), while the GET construction and deep renovation proposed by this study reduces emissions by about 30%, to 2,723,541 kgCO_2eq and 26.78 kgCO_2eq/m^{2}year. This means that the construction of the GET and the overall energy retrofit contribute to a reduction of GWP by more than 759 tons of CO_2 over 25 years. These results are shown in Figure 6.

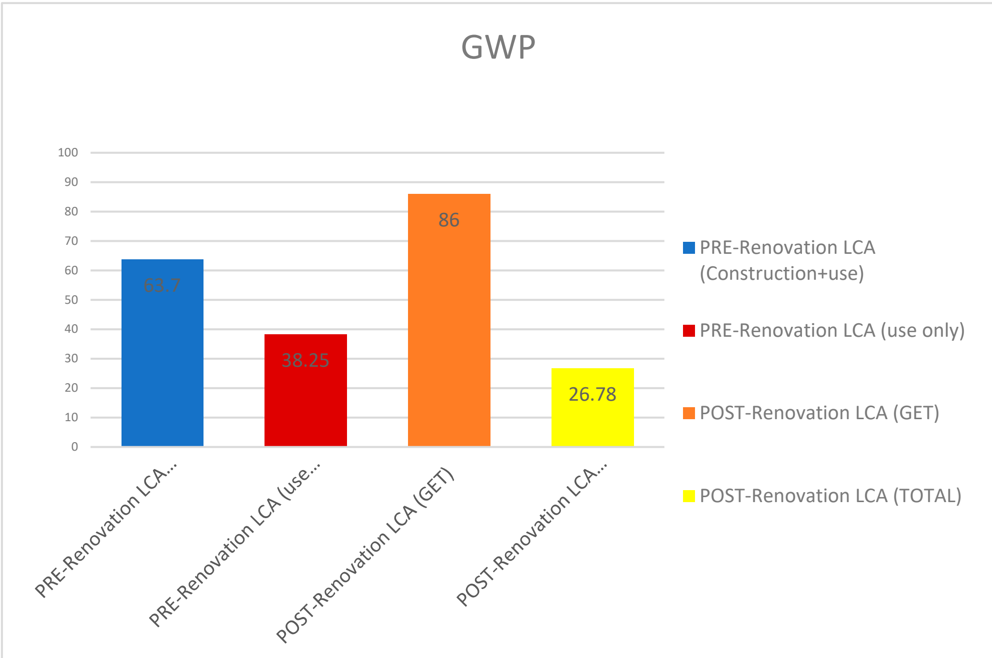


Figure 6. Graph of LCA results for the different scenarios.

Regarding energy use, in particular, the building would have had an impact of 3,414,642.82 kgCO2eq without any retrofit plan, while the post-renovation state has an impact of 1,639,603 kgCO_2eq, resulting in a 50% reduction in energy use.

This result takes into account the construction of the steel exoskeleton (GET) for the enhancement of its seismic performance, which has an increased normalized environmental impact due to its material usage. In fact, considering only the added surface of about 450 m^2, the construction of the GET has an impact of 86 kgCO_2eq/m^{2}year that is higher than that of the original building's entire life cycle (63.70 kgCO_2eq/m^{2}year). This high value is counterbalanced by the great reduction in GWP during the operational phase, thanks also to the deep renovation of the rest of the building, which reduces energy demand.

Nonetheless, the steel exoskeleton system provides a huge advantage for the seismic reinforcement of the building; it is not counted in the calculations, but provides a unique and major social benefit for the students.

6.2. Economic Impact

The pre-renovation state would have produced a total LCC of EUR 1,636,823 and 18/m^{2}year (excluding the construction phase), while with the GET construction and the deep renovation, the LCCs total are EUR 3,236,716 and EUR 31/m^{2}year. This means that the ProGETonE retrofit plan costs EUR 1,599,893 more than the pre-renovation strategy in 25 years and seems not to be economically convenient.

If considering the energy use stage, the original state would have had a cost of EUR 1,418,772, while the post renovation state has a cost of EUR 480,511, with a reduction of about 65%, saving EUR 938,261 in 25 years as seen in Figure 7.

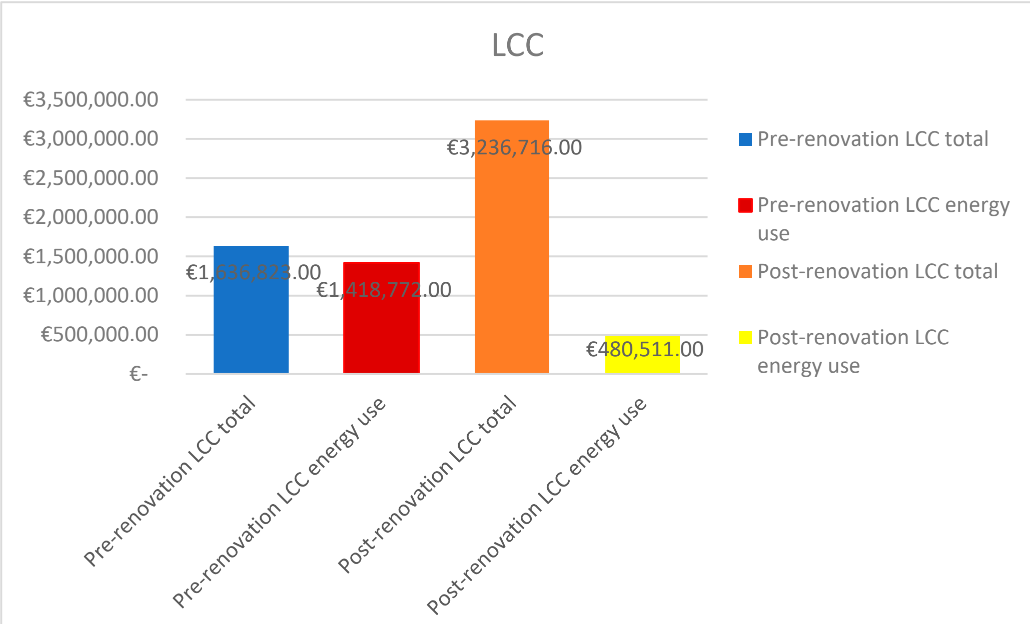


Figure 7. Graph of LCC results for the different scenarios.

This result does not counterbalance the very high cost of the construction of the GET structure, which is due to the need for a massive steel structure and deep foundations to ensure seismic consolidation. Furthermore, the structure has several integrated technologies for energy efficiency and air quality and is designed to be plug-and-play and disassembled according to the principles of circular building.

The need for seismic reinforcement justifies the high cost because it represents saved lives and savings in terms of money in case of earthquake. These costs are not included in the LCC, so just looking at the energy savings may make the investment seem not to be convenient, but the costs must be considered when assessing the value and convenience of the project.

6.3. Discussion

The results demonstrate that although the exoskeleton has high embodied carbon, the ProGETonE strategy allows a reduction in the GWP of the use phase and, consequently, of the entire life cycle of the building. The advantage of a structure like ProGETonE is that it combines energy retrofitting with seismic reinforcement, creating a plug-and-play structure that does not require inhabitants to relocate for long periods. The environmental benefit of maintaining the building as is becomes evident at 25 years and grows with longer simulation study intervals. Economically, while constructing the exoskeleton and plug-and-play façade system is costly, it proves economical when considering only energy-use costs, confirming the strategy's validity in terms of energy retrofitting. Construction costs should be viewed as an investment in seismic consolidation, not immediately reflected in cashflows, leading to a numerical decrease in life cycle costing (LCC) values. The benefits of seismic consolidation are not solely economic but also social, in terms of lives saved and personal safety, to which can be added the social and logistical advantages of reduced construction times with the plug-and-play solution described in the research.

Such significant and invasive projects might be overlooked due to high initial costs, but it is crucial to note the importance not only of energy retrofitting but also of seismic reinforcement in high-seismic zones, considering the devastating outcomes of recent major earthquakes. ProGETonE aims to offer a strategy that merges energy and seismic aspects through integrated technologies and plug-and-play structures. This research seeks to objectively assess the environmental and economic impacts of this strategy across the building's lifecycle. The findings indicate environmental validity at 25 years, while the economic impact shows energy use benefits, although construction cost amortization may exceed 25 years. These costs must be weighed against the previously mentioned non-economic benefits.

7. Conclusions

This research contributes significantly to the understanding of the importance of energy renovation in buildings for achieving environmental sustainability and decarbonization goals, combined with strategies to enhance seismic safety. The case study conducted in Greece provides compelling evidence that implementing Pro-GETonE measures can effectively reduce carbon emissions, improve energy efficiency, and enhance seismic safety in buildings.

The findings of the study highlight the economic viability of such interventions, particularly in terms of the long-term cost savings associated with reduced energy consumption. However, it is noted that the construction cost of the GET structure is considerable, potentially making the strategy less financially attractive unless the benefits of seismic reinforcement, such as saved lives and economic savings in the event of an earthquake, are considered.

Furthermore, the study emphasizes the importance of considering life cycle costing (LCC) and life cycle assessment (LCA) in evaluating the feasibility and overall convenience of a project. This aspect is crucial for policymakers, building owners, and stakeholders in their efforts to achieve energy efficiency and environmental objectives within the building sector. This holistic approach to evaluation ensures that both economic and environmental considerations are considered, ultimately facilitating more sustainable and effective decision-making in the building sector.

Moving forward, future research steps could involve conducting simulations over longer lifespans and comparing different intervention scenarios, such as demolition and reconstruction, to further refine and optimize strategies for achieving sustainability goals in building renovation projects.

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