Insights and experiences from using VERIFY
A life-cycle-based tool for sustainable buildings renovation

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Abstract

This study investigates the application of the VERIFY tool in assessing the sustainability of building renovation projects through a life-cycle-based approach. VERIFY is an advanced life-cycle assessment (LCA) and life-cycle costing (LCC) tool designed to provide a comprehensive evaluation of both environmental and economic impacts in renovation decision-making. By analysing two distinct case studies in Greece and Hungary, this research presents key insights into the practical use of VERIFY, highlighting its role in integrating real-time operational data with dynamic modelling. The study explores the challenges associated with the adoption of LCA tools, including data availability, alignment with regulatory frameworks, and methodological consistency. Additionally, it examines discrepancies between LCA-based and traditional energy performance assessments, complexities in inventory creation, and the evolving nature of sustainability metrics. By addressing these challenges and aligning with EU frameworks such as LEVEL(S), VERIFY enhances the accuracy and applicability of life-cycle-based assessments, contributing to more effective sustainability strategies in building renovations.

1. Introduction

The building sector is a critical contributor to energy consumption and greenhouse gas (GHG) emissions, accounting for roughly 40% of EU energy use, with 85% of buildings constructed before 2000 and 75% exhibiting poor energy performance[1]. Recognizing the urgency, the European Union launched the Renovation Wave initiative, aiming to at least double the current annual renovation rate (around 1%) and reduce building energy consumption by at least 60% by 2030[2]. To support this transition, regulatory frameworks and policies have evolved significantly. The Energy Performance of Buildings Directive (EPBD) was recently recast in 2024 to bolster energy independence, lower bills, and accelerate renovation of poorly performing non-residential buildings by 2030 and 2033. These policies, embedded within the broader European Green Deal and the Fit for 55 packages, envision a net-zero building stock by 2050 and unlock substantial financing and research investment through Horizon Europe funding programmes[3]. To support decision-making in renovation, integrated methodologies like Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) have risen to prominence. Unlike traditional energy audits, LCA and LCC analyses assess both embodied and operational impacts across a building's lifespan, enabling more sustainable and cost-effective renovation choices. However, their real-world application remains limited due to data scarcity, methodological complexity, and challenges in modeling dynamic energy systems and occupancy patterns[4]. Addressing these issues, advanced tools like VERIFY have been developed to integrate dynamic LCA and LCC with time-series of operational data. VERIFY supports holistic evaluation of building retrofits by accounting for temporal energy profiles and environmental, as well as economic impacts[5]. The REHOUSE project, under Horizon Europe, responds to these needs by developing prefabricated, multifunctional, and bio-based renovation packages. These packages combine modular façade elements, renewable energy systems, bio-sourced insulation, phase-change thermal storage in HVAC, and smart window solutions. REHOUSE aims to make deep, scalable, and cost-effective renovations more accessible and replicable across Europe. This paper presents the application of the VERIFY tool within REHOUSE, focusing on two demonstration sites in Greece and Hungary. Through dynamic LCA and LCC assessments, we explore how innovative renovation packages improve energy performance, reduce life cycle GHG emissions, and enhance cost-effectiveness, providing robust evidence for clinical replication and policy support.

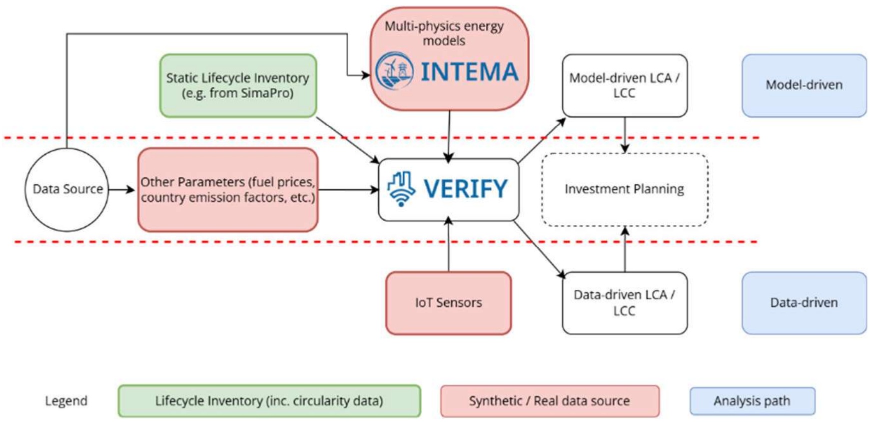
2. Methodology

2.1 VERIFY background

Over the past few years, VERIFY has seen steady growth and refinement, evolving in response to the specific requirements of various Horizon Europe projects (as detailed in Table 1). Its ongoing development includes the integration of new functionalities designed to address the operational and analytical demands encountered in real-world case studies. These field applications provide valuable insights that help fine-tune the platform and enrich its underlying data structure. Created by the Centre for Research and Technology Hellas (CERTH), the tool was designed to support advanced evaluations of innovative energy systems and to enable well-informed, data-supported decision-making in sustainable building renovation projects. As depicted in Figure 1, VERIFY complies with ISO 14044 standards and uses quantitative methodologies to evaluate life cycle assessment (LCA) and life cycle cost (LCC) indicators across a wide range of energy-related technologies in buildings. The platform also features real-time data capabilities, scenario modelling, and end-to-end project evaluations, making it suitable for various renovation and investment planning use cases. Its core focus is on climate and energy performance metrics—such as Global Warming Potential (GWP) and Primary Energy Demand (PED)—while also providing financial metrics like Payback Time (PBT) and the Levelized Cost of Electricity (LCoE). Furthermore, VERIFY is designed in alignment with the Level(s) framework [6,7,8], addressing key sustainability goals: reducing greenhouse gas emissions throughout the building lifecycle, encouraging circular and resource-efficient material use, and optimizing costs and value over time.

VERIFY expands its analytical reach by drawing from diverse data inputs, including bills of quantities that are translated into life cycle inventories, projected costs, and the durability of specific building components. Its implementation across a variety of projects has led to the continuous expansion of a rich database containing life cycle information on both traditional and novel building technologies. To accommodate the variability inherent in standard construction systems, the tool uses a scaling method based on empirical data from reliable sources. This includes internal LCA studies performed using commercial tools like SimaPro, along with authoritative datasets such as EcoInvent, environmental product declarations, academic research, and technical reports. Through this approach, VERIFY models standard components using generalized representations that quantify environmental impact in terms of carbon dioxide equivalents ($CO_{2\text{-eq}}$) and energy usage in megajoules. This method ensures both high analytical accuracy and adaptability for scenario analysis and modelling.

Figure 1: Overview of VERIFY's methodological framework



Project Name	VERIFY Application
POCITYF	LCA/LCC of interventions for positive energy buildings and districts in two EU cities. Systems assessed include among others: hybrid wind / solar power generation, V2G solar charging, aquifer thermal energy, hydrogen-based mobility, residential PV panels and building-integrated PVs.

IANOS	VERIFY upgraded with new functionalities and applied for LCA/LCC of RES, energy efficiency, decarbonization and smartification investments in two islands. Systems assessed include among others: flywheels, biobased saline batteries, heat batteries, tidal kites, auto-generative high-pressure digester.
InCUBE	VERIFY upgraded with new functionalities and applied for LCA/LCC in three use cases.
REHOUSE	LCA/LCC of four residential renovation projects (two of which are presented in section 3). Systems assessed include among others: prefabricated multi-functional panels for building envelopes, HVAC with bio-based PCM thermal storage system, prefabricated façade with bio-source material, bio-sourced – reused and fully recyclable insulation, low-cost smart window renovation system.
REN+HOMES	VERIFY applied for LCA/LCC of four demo sites: two existing buildings for renovation and two new constructions, towards PEB. Innovative systems assessed: prefabricated wall facades with BIPV, BAPVs, insulation panels, geothermal wall system, hydrogen storage system, PVs with recycled cells.

Table 1: VERIFY's application in different research and innovation projects[4].

VERIFY is equipped to conduct life cycle assessments for energy-related technologies and systems across all standard life cycle phases: the product stage (which includes embodied energy and raw material processing), the construction phase (covering transportation and installation), the use phase (factoring in energy use, system efficiency, and maintenance), and the end-of-life (EoL) phase (encompassing disposal and recycling prospects). The platform evaluates both embodied and operational energy consumption across all components, while continuously updating key datasets such as weather conditions, national energy mixes, and pricing data for 27 EU member states. Energy data can be fed into VERIFY using three main approaches: historical data sources, real-time data collection via IoT sensors, or the creation of synthetic data through simulation. For the latter, VERIFY integrates with INTEMA.building[9,10], a dynamic simulation engine that generates realistic operational energy profiles in cases where empirical data is scarce or unavailable. Developed using Modelica[11] and Dymola[12], INTEMA.building conducts detailed simulations of thermal dynamics in buildings alongside their active energy systems. It relies on white-box modelling and open-source libraries like Buildings[13] and BuildingSystems[14], and accurately represents both passive (e.g., windows, walls) and active systems (e.g., photovoltaic panels, heat pumps, energy storage units). It also supports the import of building geometry from BIM files in .ifc format and utilizes EU climate data from PVGIS[15]. Validated in accordance with EN 15265–2007[16], INTEMA.building has shown strong accuracy in simulating passive elements and thermal performance, confirming its effectiveness for building energy modelling.

2.2 VERIFY analysis

VERIFY conducts life cycle assessments to produce key performance indicators (KPIs) and visual performance outputs, allowing for the comparison of scenarios before and after renovation. The main types of input data needed to operate VERIFY are summarized in Table 2. In cases where a particular building or energy system is not already included in VERIFY's database, users must provide supplementary information detailing the materials, energy use, and waste generated over the system's entire life cycle. This ensures that a comprehensive life cycle inventory can be developed for accurate analysis.

System	Category
General building information	Geographical information
	Envelope information
	Usage information
HVAC systems	Component information
	Operational characteristics
	Economic parameters

Insulation & Glazing	Component type
	Dimensions and placement
	Economic parameters
DHW systems	System type
	Tank characteristics
	Economic parameters
RES / ESS	System characteristics
	Installation information
	Economic parameters
Grid connections	Connection information
	Billing information
Investment information	Financial indicators
	Additional information

Table 2: Indicative VERIFY key input categories and data required[4].

VERIFY generates a detailed report featuring key performance indicators (KPIs) that reflect essential life cycle processes. Table 3 presents the main indicators used for both life cycle assessment (LCA) and life cycle costing (LCC), including metrics like Lifetime Primary Energy Demand (PED), Life Cycle Global Warming Potential (GWP), and total Life Cycle Costs (LCC). These KPIs can be computed as one-time values, annual averages, or over the full duration of a project, based on their specific applicability. In demonstration cases, VERIFY's integration with sensor networks enables real-time data collection, allowing for dynamic KPI updates. This capability enhances accuracy and facilitates timely adjustments to improve the performance of assets or buildings. An indicative summary of the formulas, and input variables used for the key VERIFY KPIs is provided in Table 3.

KPI Name (Units)	**Equation**	**Description**
Global Warming Potential (GWP) (kg CO_2-eq/m²)	$L_{GWP} = \frac{L_{GHG}}{Useful\ area}\ with\ L_{GHG} = I_{GHG} + \sum_{i=1}^{N}\left(O_{GHG}^{[i]}\right)$	L_{GHG}: Total greenhouse gas emissions over the lifecycle $Useful\ Area$: Building area with heating/cooling access $O_{GHG}^{[i]}$: Operational GHG emissions of the building's components in year i; I_{GHG}: Infrastructure (embodied) GHG emissions.
Primary Energy Demand (PED) (kWh)	$L_{PE} = I_{PE} + \sum_{i=1}^{N}\left(O_{PE}^{[i]}\right)$	I_{PE}: Energy demand during infrastructure/construction phases $O_{PE}^{[i]}$: Operational/ maintenance energy demand during building's use stage
Lifecycle Costs (LCC) (€)	$LCC = I_C + \sum_{i=1}^{N}\left(O_{NC}^{[i]}\right) - V_R$	I_C: Infrastructure costs (CAPEX) $O_{NC}^{[i]}$: Operational net costs including energy consumption and maintenance V_R: Residual value of components at end of lifecyle
Whole Life Cost (WLC) (€)	$WLC = I_C + \sum_{i=1}^{N}\left(O_{C}^{[i]}\right) - V_R$	I_C: Infrastructure costs (CAPEX) $O_{C}^{[i]}$: Operational costs (energy consumption / maintenance and operational revenues due to electricity exports from RES V_R: Residual value of components at end of lifecyle

Renewable Energy System (RES) Payback Period (Years)	$T_P = T_L + t_r$	T_L: Last year before cumulative savings meet or exceed RES investment t_r: Remaining fraction of the year required for full payback of RES investment
Levelized Cost of Electricity (LCOE) (€/kWh)	$LCOE = \frac{\sum_{i=1}^{N} \frac{I_{C,GEN}^{[i]} + O_{C,GEN,MN}^{[i]} + O_{C,GEN,NEL}^{[i]}}{(1+r)^i}}{\sum_{i=1}^{N} \frac{SC^{[i]} + EX^{[i]}}{(1+r)^i}}$	$I_{C,GEN}^{[i]}$: Generator infrastructure costs $O_{C,GEN,MN}^{[i]}$: Annual generator maintenance costs (which include replacement costs, if the analysis period exceeds the generators' lifetime) $O_{C,GEN,NEL}^{[i]}$: Costs of fuel used for electricity generation (applicable only in the case of electricity generators using other fuel) $SC^{[i]}$ and $EX^{[i]}$: Total energy self-consumed and exported by the building r: project discount rate

Table 3: Indicative key performance indicators (KPIs) calculated by VERIFY (2025 version)[4].

3. Use cases

VERIFY was applied and tested in two distinct renovation projects, serving as use cases (UCs) in Greece (UC#1) and Hungary (UC#3). These UCs are demonstrated as part of the Horizon Europe (HEU) project REHOUSE (Grant Agreement no. No 101079951). REHOUSE brings together 25 partners from several European countries to increase in the scope and productivity of the renovation process, the improvement of comfort and satisfaction of the building inhabitants and users, and the increased use of integrated solutions for the decentralized generation of renewable energy. The selection of the renovation projects aimed to reflect residential buildings ensuring the most adequate coverage of climatic, as well as regulatory and socioeconomic conditions. These use cases provided the opportunity to evaluate innovative renovation strategies combining prefabricated, bio-based, and smart building envelope solutions with advanced energy systems.

The key characteristics of these UCs, including gross floor area, construction year, occupant profiles and climatic zone are summarized in Table 4. Further details are outlined in the following paragraphs, providing the rationale for the selection of the specific two UCs and a concise overview of the renovation actions planned for each.

Photographic documentation of the two UCs on the right → **Key characteristics of the two UCs below ↓**	**UC#1 (GR)** 	**UC#2 (HU)** 
Building Usage	Dormitory	Dormitory
Gross Floor Area (m^2)	1371	1027
Floors (#)	3	3
Construction Date (yyyy)	1997	19^{th} century
Occupants/Users (#)	62	78
Climatic Zone	Warm Mediterranean	Semi-continental (Dfa)
EPC	E	C

Table 4: Key characteristics of the two (2) use cases—renovation projects.

The Greek use case (UC#1) refers to a student dormitory building (Building C2) within the campus of the Democritus University of Thrace, located in Kimmeria, near the city of Xanthi. Heating needs are covered by radiators operating on a fixed schedule (6 hours/day in winter), supplied by a hybrid system combining solar thermal collectors and a biomass boiler, with supplementary hot water provided by a PV-powered resistance system.

The Hungarian use case (UC#2) is a former industrial facility converted into a student dormitory for Saint Paul University students, located in the Kőbánya district of Budapest. The building, with a conditioned floor area of 1,027 m² (net), accommodates 78 students across 37 rooms. The current heating and DHW needs are covered by two natural gas boilers (2 × 45 kW) with 90% efficiency, while no cooling system or renewable energy technologies are installed.

4. Results

The application of VERIFY across the two UCs has provided a comprehensive overview of the energy, environmental and economic benefits associated with deep renovation interventions. The assessment was conducted over a 50-year study period, as defined by the EU Level(s) framework for life cycle evaluation in buildings. The analysis covers the operational stage of the building and its components, as well as the construction and end-of-life (EoL) stages of the relevant systems. This section presents the key findings, structured around the comparative analysis between baseline and post-renovation scenarios.

A cross-pilot comparison (Table 5) reveals significant variability in performance improvements across the two UCs, reflecting differences in initial building conditions, renovation strategies and contextual constraints. Note that the table refers only to energy behaviour-related components and the renovation activities, not the existing buildings themselves.

	UC#1 (GR)			UC#2 (HU)		
	Pre-	**Post-**	**Diff.**	**Pre-**	**Post-**	**Diff.**
Lifetime PED (MWh/y)	452	331	-27%	511	336	-34%
Lifetime PED (kWh/y/m^2)	330	241	-27%	497	327	-34%
Life Cycle GWP (kg$CO_{2\text{-eq}}$/y)	38,365	31,539	-18%	93,429	56,139	-40%
Life Cycle GWP (kg$CO_{2\text{-eq}}$/m^2/y)	28	23	-18%	90.98	54.67	-40%
Life Cycle Costs (kEUR/y)	36,992	27,120	-27%	7,687	5,792	-25%
Whole Life Costs (kEUR/y)	36,528	26,538	-27%	7,661	5,740	-25%
Payback Period (years)	4.4			4.8		

Table 5: Key results extracted for the three UCs.

The UC#1 (GR) exhibited a 27% reduction in primary energy demand (PED), with values decreasing from 452 MWh/y to 331 MWh/y. This improvement reflects the effectiveness of the implemented facade retrofitting, insulation upgrades and the integration of renewable energy systems in enhancing the building's operational efficiency. From an environmental perspective, the intervention led to an 18% reduction in Global Warming Potential (GWP), corresponding to a decrease from 38,365 to 31,539 kg$CO_{2\text{-eq}}$ per year. When normalised by area, emissions dropped from 28 to 23 kg$CO_{2\text{-eq}}$/m²/y. The economic analysis further supports the viability of the renovation strategy. Life cycle costs decreased by 27% (from 36,992 kEUR/y to 27,120 kEUR/y), while whole life costs dropped from 36,528 kEUR/y to 26,538 kEUR/y. The calculated payback period was 4.4 years, indicating a strong balance between upfront investment and operational savings.

The UC#2 (HU) achieved even higher relative performance improvements due to its more energy-intensive baseline. PED decreased by 34%, from 511 MWh/y to 336 MWh/y, reflecting the significant potential of REHOUSE interventions in buildings with poor initial insulation and reliance on conventional heating systems. The environmental benefits were even more striking. The GWP analysis shows a 40% reduction in yearly emissions, with values falling from 93,429 to 56,139 kg$CO_{2\text{-eq}}$. On a per-square-meter basis, this translates to a reduction from 90.98 to 54.67 kg$CO_{2\text{-eq}}$/m²/y. The major gains are linked to the replacement of fossil-based heating (natural gas boilers) with more efficient and renewable-oriented systems, alongside the integration of advanced façade elements and bio-based materials. Economic performance also improved considerably. Life cycle costs dropped by 25%, from 7,687 kEUR/y to 5,792 kEUR/y, while whole life costs fell from 7,661 kEUR/y to 5,740 kEUR/y. The payback period was estimated at 4.8 years, only marginally higher than in the Greek demo, but still highly competitive given the scale of intervention.

UC#1 (GR)

Figure 2: Annual Primary Energy Demand – UC#1

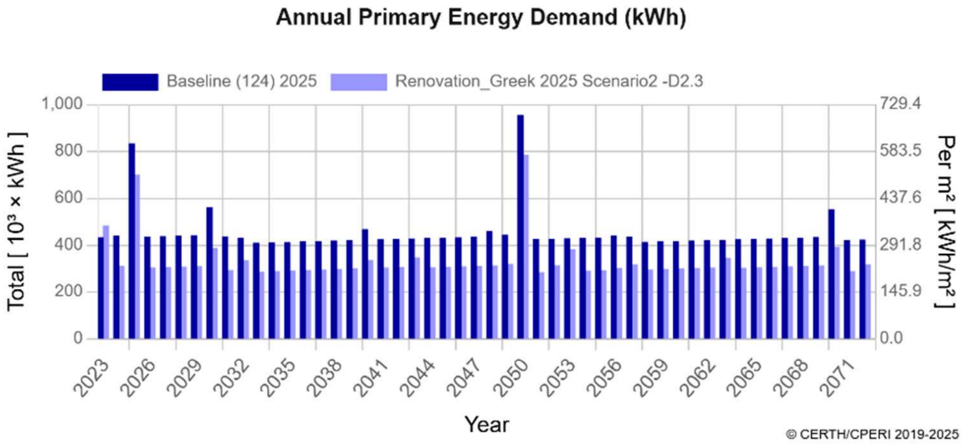


Figure 3: Annual GHG Emissions – UC#1

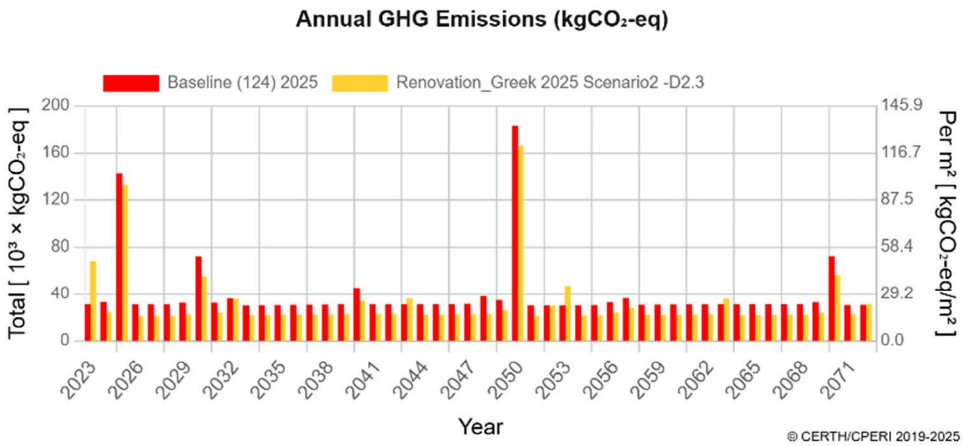


Figure 4: Annual Costs – UC#1

UC#2 (HU)

Figure 5: Annual Primary Energy Demand – UC#2

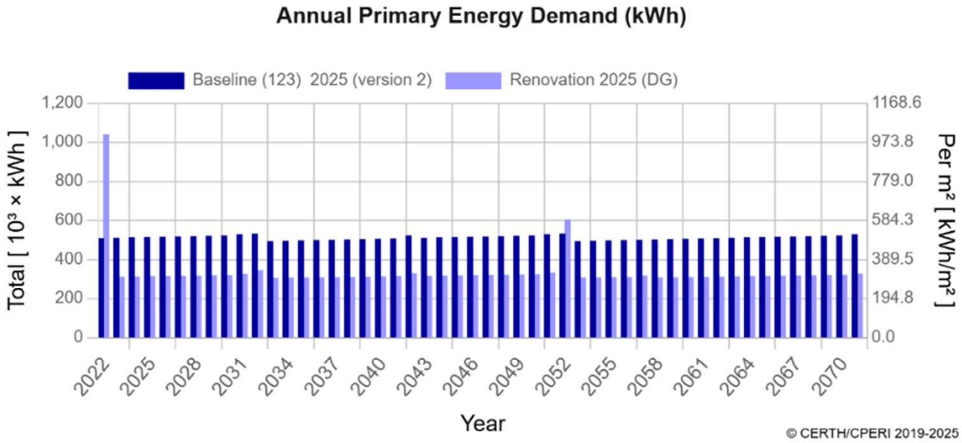


Figure 6: Annual GHG Emissions – UC#2

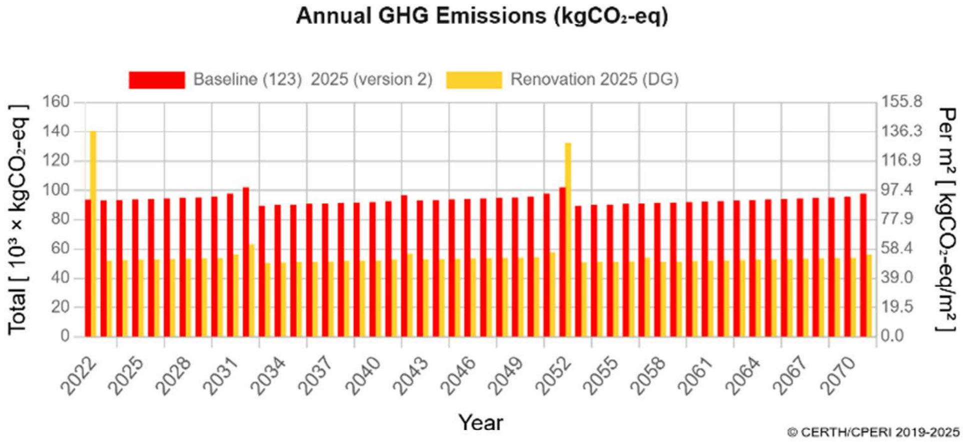
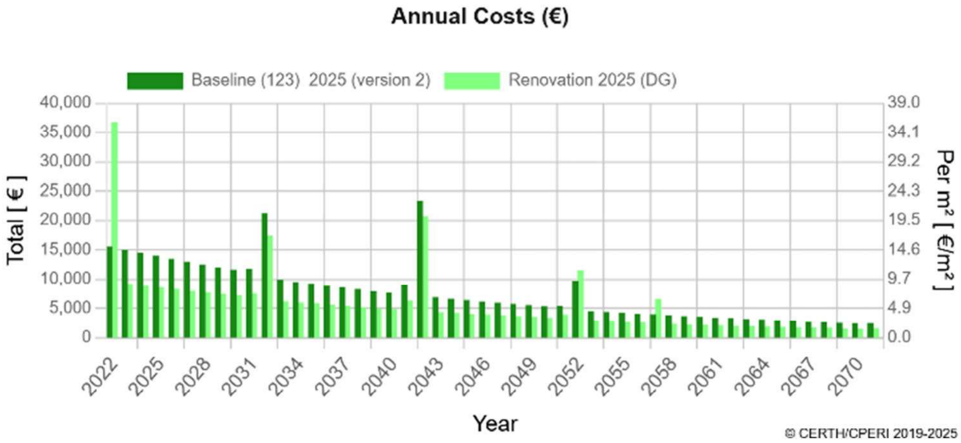


Figure 7: Annual Costs – UC#2



The comparative results (Figures 2-7) confirm that both use cases achieved substantial improvements across energy, environmental and cost dimensions, with short payback periods below five years. The Hungarian demo achieved higher relative reductions in both PED and GWP (34% and 40% respectively), reflecting its inefficient baseline and reliance on fossil fuels. The Greek demo, although starting from a better baseline, still delivered notable reductions of 27% in PED and 18% in GWP, proving the value of REHOUSE's solutions even in partially modernised buildings. In both cases, the cost savings are substantial, with life cycle cost reductions of 25–27%. These figures highlight not only the economic attractiveness of prefabricated renovation solutions, but also the lower operational costs achieved through the integration of RES. The results underline the replicability of REHOUSE technologies across diverse European contexts, supporting EU climate neutrality and Renovation Wave objectives.

5. Conclusions

The application of the VERIFY tool within the REHOUSE project has demonstrated the value of life-cycle-based assessments in evaluating deep renovation strategies. By systematically integrating environmental, energy and economic indicators, VERIFY provided a holistic overview of the two UCs examined in Greece and Hungary. The results confirm that prefabricated, bio-based and technologically advanced renovation packages can substantially reduce primary energy demand, greenhouse gas emissions and life-cycle costs, while maintaining short payback periods that strengthen their economic feasibility.

From a technical perspective, the outcomes underline the effectiveness of deep renovation interventions. In UC#1, primary energy demand fell by 27% and global warming potential (GWP) by 18%, reflecting the contribution of façade retrofitting and renewable energy integration in a building with moderately inefficient baseline conditions. In contrast, the UC#2, which relied heavily on fossil fuels and had poor initial insulation, achieved reductions of 34% in energy demand and 40% in emissions. These findings highlight how the baseline condition strongly influences the relative gains of renovation interventions: buildings starting from lower efficiency levels have greater potential for improvements. Nevertheless, both UCs demonstrated that advanced renovation packages yield tangible and measurable benefits across diverse contexts.

Economically, the results reinforce the cost-effectiveness of the solutions. Both UCs achieved significant life-cycle cost reductions (27% in UC#1 and 25% in UC#2) demonstrating the ability of prefabricated, modular renovation systems to combine technical performance with financial viability. Payback periods of less than five years further strengthen the business case for such interventions, supporting their market uptake and scalability. This is particularly relevant in the context of the EU Renovation Wave initiative, which calls for accelerated renovation rates and stresses the importance of affordable solutions to drive large-scale deployment.

The study also underscores the importance of adopting a life-cycle perspective rather than focusing solely on operational energy. VERIFY enabled a detailed consideration of embodied energy, end-of-life processes and economic trade-offs, in line with EU frameworks such as Level(s). This approach ensures that renovation strategies do not merely shift impacts from one phase to another but instead optimise performance across the full building life cycle. By embedding such methodologies into decision-making, projects can better align with long-term sustainability and circular economy objectives. At the same time, several challenges emerged. Data availability and consistency remain limiting factors, especially for older buildings or innovative materials where detailed life-cycle inventories are scarce. Aligning different regulatory and methodological frameworks also poses practical difficulties, requiring continuous updates to databases. Furthermore, while tools like VERIFY advance the integration of LCA and LCC in practice, their wider adoption still depends on greater awareness, training and simplification for non-expert users. Addressing these barriers is crucial to mainstream life-cycle thinking in the construction sector.

Overall, the findings of this study confirm that holistic renovation strategies, supported by dynamic tools such as VERIFY, can deliver significant energy, environmental and economic benefits while remaining financially attractive. The evidence from the two UCs demonstrates the replicability of REHOUSE's prefabricated and bio-based solutions across diverse European contexts, contributing directly to EU climate neutrality goals and the Renovation Wave targets. Looking ahead, further work is needed to expand the scope of analyses to additional building typologies, integrate more granular socio-economic indicators and explore synergies with digitalisation and smart building technologies. Such advancements will not only enhance the precision and applicability of life-cycle-based assessments but also strengthen the overall resilience and sustainability of the European building stock.

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