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Advancing Sustainability in a Residential Building in Europe: A Case Study on LCA and LCC across Different Scenarios

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Abstract

This study evaluates the environmental and economic performance of the "ESTIA of Athens" residential building considering its energy consumption and greenhouse gas (GHG) emissions. It also explores the potential for improvements in these areas. The European Union's strategy to reduce GHG emissions from buildings by 55% compared to 1990 levels by 2030, as part of its broader aim for climate neutrality by 2050 is a background for the study. The methodology involves a Life Cycle Assessment (LCA) using SimaPro software, monitoring energy consumption, temperature and humidity of the building. The thirteen impact categories and damage impact assessment that include human health, ecosystem and resources were examined. The study compares various scenarios, including historical data from 2018 to 2022 and two hypothetical scenarios to assess environmental impacts across different categories. Additionally, Life Cycle Costings (LCC) are performed to evaluate the economic aspects of the building's performance. The results highlight substantial differences in energy consumption, GHG emissions and economic costs among the scenarios. The findings suggest that a hypothetical scenario, referred to as Case 3, demonstrates lower environmental impacts and economic costs compared to other scenarios, indicating its potential as an optimal renovation strategy for the building. This includes reductions of 32%, 40% and 58% in the human health, ecosystems, and resources categories, respectively. A similar trend is observed across the impact categories, with reductions ranging from 4% in the Mineral Resource category to 47% in the Global Warming category. The study underscores the importance of holistic assessments in informing energy policy and renovation strategies for achieving both environmental sustainability and economic viability in buildings.

Keywords: greenhouse gas emissions, buildings, life cycle assessment

1. Introduction

The majority of greenhouse gas (GHG) emissions in buildings are created from energy consumption, particularly in space heating accounting for around 70% of the total consumption, of which 37% is attributed to fossil fuel energy sources (D'Agostino & Mazzarella, 2019). The European Union has implemented several regulations to reduce energy consumption in buildings, improve energy efficiency and achieve significant savings. These savings can be achieved through regular examinations of heating and air conditioning systems and using of renewable energy sources, such as solar panels and biomass heating systems [EU, Directive, 2012/27/EU; Renewable Energy Directive, 2023/28/EU). The strategy of EU is to achieve a 55% reduction in GHG emissions from buildings compared to 1990 levels by 2030 in order to achieve climate neutrality by 2050 [European Green Deal, 2019]. A growing number of research studies have been conducted on building energy performance and the reduction of GHG emissions using Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) (Chen et al, 2016, Schmidt & Crawford, 2018; Nwodo & Anumba, 2019; Schneider-Marin et al., 2022). This is driven by growing sustainability concerns in the building sector with a primary focus on identifying environmental and economic factors. This approach offers opportunities to adopt broader perspectives such as life cycle thinking and circular economy (Schneider-Marin et al., 2022). Schmidt & Crawford (2018) developed an integrated framework to help building design professionals optimize GHG emissions and LCC for glazing options in residential buildings emphasizing the need to balance these factors in decision-making and recognize the uncertainties in developing the most effective design solutions. Nwodo & Anumba (2019) examined a dynamic LCA as an improvement to traditional static LCA incorporating time-sensitive factors like technological progress, occupancy behavior, impact characterization and weighting factors. Although Dynamic LCA is still in its early stages, some studies have created frameworks for applying in buildings using real-world scenarios. A number of tools have been considered in those studies for assessing the overall sustainability impact and energy performance like SimaPro, Gabi and EnergyPlus. The majority of studies are conducted on the entire life cycle phases including production, construction, transport, use and the end-of-life of building while only a few focus on using LCA to assess energy efficiency for improving existing buildings. The main aim of this study is to evaluate the environmental and economic performance of a residential building named as "ESTIA of Athens" based on energy consumption and explore the possibilities for improvements using two different hypothetical scenarios. It has been reported that energy and water consumption are the primary contributors to GHG emissions, followed by maintenance and replacement of the materials (Lavagna et al., 2018).

2. Methodology

A LCA using SimaPro software (PRé Sustainability, Netherlands) of the "ESTIA of Athens" building (Figure 1), monitored for energy consumption, temperature and humidity, has been evaluated. Figure 2 shows the system boundaries of the building that include: (i) the conditions of the building with input energy consumption data for heating and electricity (B1 - 2018, B2 - 2019, B3 - 2020, B4 – 2021, B5-2022); (ii) predicted energy consumption outcomes obtained from the two simulated/hypothetical scenarios: (a) Case 3, involving heating and cooling without mechanical ventilation and (b) Case 5A, involving heating with mechanical ventilation. The environmental impact results were compared across various scenarios: B1- B5, Case 3- B1, Case 3 – B5, Case 5A – B1, Case 5A – B5. Assessment of damage impact on human health, ecosystems and resources was conducted across all scenarios and categories.

Figure 1. Images of Athens building

2.1 Goal and Scope Definition

The **goal** of this study is to carry out an LCA considering substantial amount of monitoring (energy consumption, temperature, humidity) and assess environmental impact during 2018-2020, B1 - 2018, B2 - 2019, B3 - 2020, B4 – 2021, B5-2022, and two hypothetical scenarios, Case 3 and Case 5A. Case 3 involves heating and cooling without mechanical ventilation (MV) while Case 5A involves heating and cooling with mechanical ventilation. This approach is adopted because mechanical ventilation has been shown to be effective in high-performance buildings where energy losses are minimized (Tronchin et al, 2018). The "ESTIA of Athens" constructed in the 1960s was selected as a pilot because it needed upgrades to reduce energy consumption.It is also located in a dense urban area in the centre of Athens next to a busy road where external pollution is high. Mechanical ventilation would allow filtration of external pollutants.

The **scope** of the study, having specified the functional unit (kWh) involved defining the system boundaries and carryout the LCA simulations. The overall data used for SimaPro simulations are presented in Tables 1-2. They include energy consumption for heating and electricity based on the historical data; predicted energy consumption results based on the renovation scenarios and predicted energy consumption data based on simulation results. Based on all the data presented in Tables 1-2 the system boundaries for the building were established and are presented in Figure 2.

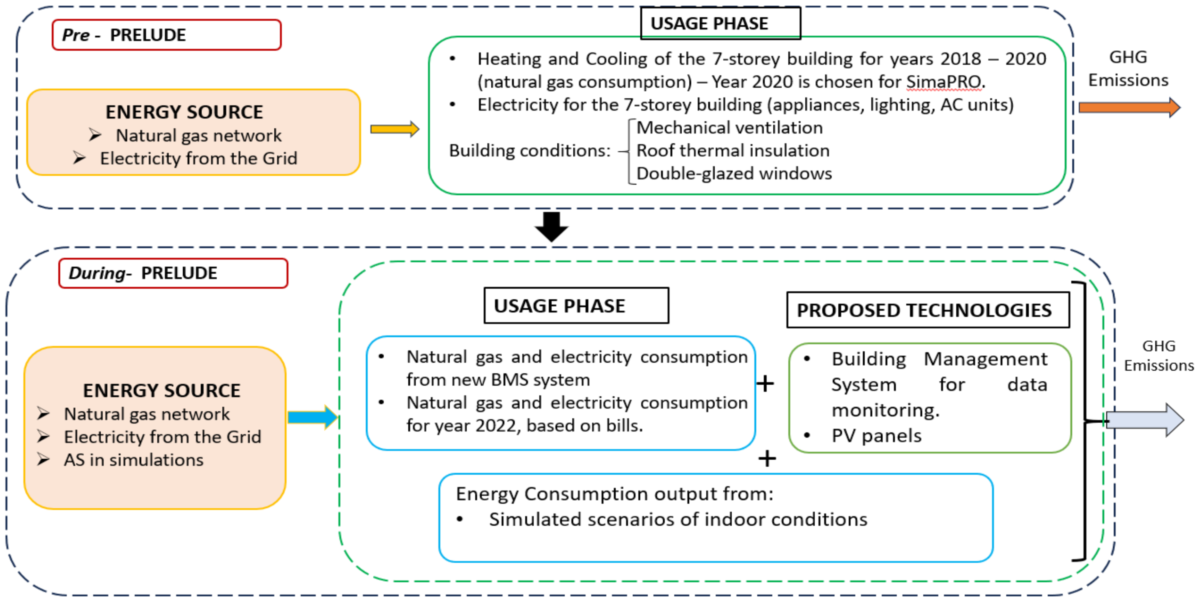

Figure 2. The system boundaries for the LCA

The environmental impact results are compared across various scenarios: B1- B5, Case 3-B1, Case 3 – B5, Case 5A – B1 and Case 5A – B5. The assessment of damage impact on human health, ecosystems and resources are conducted across all scenarios and categories are also considered. Their corresponding costs are calculated based on the obtained cost from the GlobalPetrolPrices and presented in Tables 1-2. The annual GHG emissions data were obtained from SimaPro calculations and are also presented in Tables 1-2.

Table 1. LCI data used for SimaPro simulations for the historical period from 2018-2022

Scenario	**Year**	**Energy source**	**Annual Energy Consumption (kWh)**	**Annual GHG emissions (kg CO2-eq)**	**Annual Energy Costs (€)**
B1	2018	Heating	249,755	58,903	39,961
		Electricity	38,760	38,430	10,116
B2	2019	Heating	200,505	47,287	32,081
		Electricity	43,360	42,991	11,317
B3	2020	Heating	243,387	57,401	38,942
		Electricity	43,840	43,467	11,441
B4	2021	Heating	212,127	50,028	33,940
		Electricity	40,640	40,294	10,607
B5	2022	Heating	249,696	58,889	39,951
		Electricity	51,640	51,201	13,478

Table 2. LCI data used for SimaPro simulations for hypothetical building scenarios

Scenarios	Energy source	Annual Energy Consumption (kWh)	Annual GHG emissions (kg CO2-eq)	Annual Energy Costs (€)
Case 3 (Heating & Cooling)	Heating	84,240	19,867	13,478
	Electricity	43,840	43,467	11,442
Case 5A (Heating + Mechanical Ventilation + Electricity (Cooling)	Heating	85,320	19,650	13,651
	Electricity	66,640	19,867	17,393

2.2 Life Cycle Costings (LCC)

The **goal** of the LCC is to determine cost characterization for a building condition using electricity and heating consumption data as employed in the environmental LCA analysis. The same system LCA boundaries presented in Figure 2 were considered with input energies consistent with those used in the LCA studies. (Tables 1-2).

The **scope** of the LCC involved specifying the costs of electricity and heating in € /kWh. The price for heating is 0.160 € /kWh and electricity is 0.261 € /kWh.

3. Results and Discussion

3.1 Life Cycle Costings

The total amount of the energy-related GHG emissions for various scenarios considered for Athens building are presented in Figure 3. It includes period from 2018 to 2022 marked as B1-B5 and two simulated/ hypothetical scenarios, Case 3 and Case 5A as presented at Tables 1-2. The GHG emissions varied from 63,334 kg CO2-eq for scenario Case 3 to110,089 kg CO2-eq for scenario B.

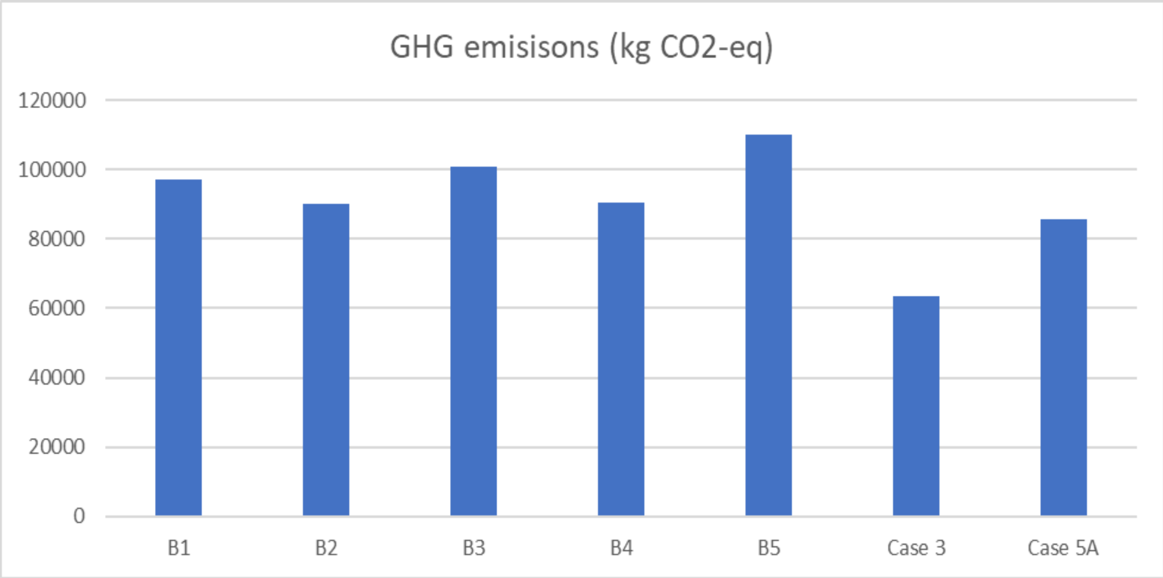

Figure 3. The variations of GHG emissions between different scenarios

Figure 4 presents the contribution of thirteen environmental impact categories to the overall environmental impact. It is evident that there are some variations between all categories in each period. For the simulated scenarios, Case 3 demonstrated similar results or reduced environmental impact for all categories of interest related to the B1- B5 scenarios. In contrast, the simulated Case 5A demonstrated higher environmental impact which may be as a result of the additional electricity consumption used for mechanical ventilation. Each simulated/ hypothetical scenario was compared against scenarios B1 (2018) and B5 (2022).

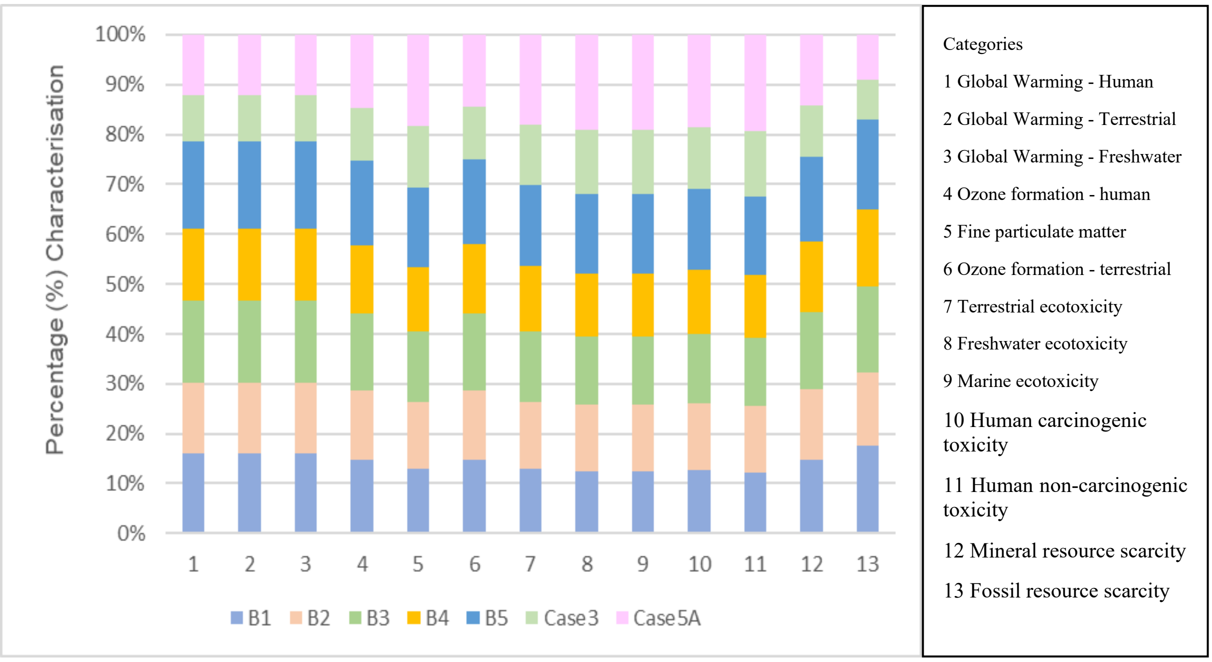

Figure 4. Environmental impact assessment (%) for all scenarios for 13 different categories

Figure 5 provides a more detailed breakdown of the differences between the scenarios presented in Figure 28, as follows:

(i) B5 vs B1 scenarios assess the environmental effects between 2022 and 2018. It shows a consistent 21% rise in the characterization across all categories that are presented in Figure 3.

This is perhaps because the heating consumption remains largely unchanged between the two years, with the primary difference being the slightly higher electricity consumption in 2022.

(ii) Case 3 vs B1 scenarios showed that the hypothetical Case 3 scenario demonstrated significantly lower heating consumption with a reduction of 66% compared to 2018 and a slightly higher electricity consumption of 12%. This resulted in the following variations: a 42% reduction in the *Global Warming* categories (1-3); a 29% reduction in ozone – related categories (4 and 6); a 4% reduction in the Fine Particulates category (5); a 5% reduction in the *Ecotoxicity* categories (7 -9); a 2% reduction in the *Human Toxicity* categories (10 and 11), a slight 6% increase in non-carcinogenic categories; a 31% reduction in Mineral categories (12); a 56% reductions in Fossil Fuel categories (13); a slight 4% decrease in the Mineral Resources category (12) and a substantial 48% decrease in the *Fossil Fuels* category.

(iii) Case 3 vs B5 showed similar trend to B1 scenario with the following variations: a 47% reduction in the *Global Warming* categories (1-3); a 38% reduction for the *Ozone Production* and *Fine Particulate Production* categories (4 and 6); a 42% reduction in the *Fine Particulates* category (5); above 39% increase of in the *Ecotoxicity* categories (7, 8, 9); 46% and 59% increase respectively in the *Human Toxicity* categories (10 and 11); a 4% reduction in *Mineral resources* categories (12).

(iv) Case 5A vs B1 revealed comparable heating consumption with a slight compared to Case 3. However, due to the utilization of mechanical ventilation in Case 5, there was a significant increase in electricity consumption compared to Case 3 and B1. This resulted in the following variations: a 24% reduction in the *Global Warming* categories (1-3); no change in the *Ozone Production* and *Fine Particulate Production* categories (4 and 6) but a significant increase of 42% in the *Fine Particulates category* (5); a 39% increase in the *Ecotoxicity categories* (7, 8, 9); 46% and 59% increase in the *Human Toxicity categories* (10 and 11); reductions in *Mineral and Fossil Fuel categories* (12 and 13) with a slight 4% decrease in the *Mineral Resources category* (12) and a substantial 48% decrease in the *Fossil Fuels* category (13).

(v) Case 5A vs B5 showed that Case 5A heating consumption is only 1% higher than Case 3 and 66% lower than scenario B5 while electricity consumption is 29% higher than scenario B5. This resulted in the following variations: a 31% reduction in the *Global Warming categories* (1-3); a 13% reduction in the *Ozone Production* (4 and 6) but an increase of 13% in the *Fine Particulates* category (5); 11% increase in the Ecotoxicity categories (7, 8, 9); 10% and 21% increase in the *Human Toxicity* categories (10 and 11); 17% reduction in *Mineral and Fossil Fuel categories* (12 and 13) and a substantial 50% decrease in the *Fossil Fuels* category (13).

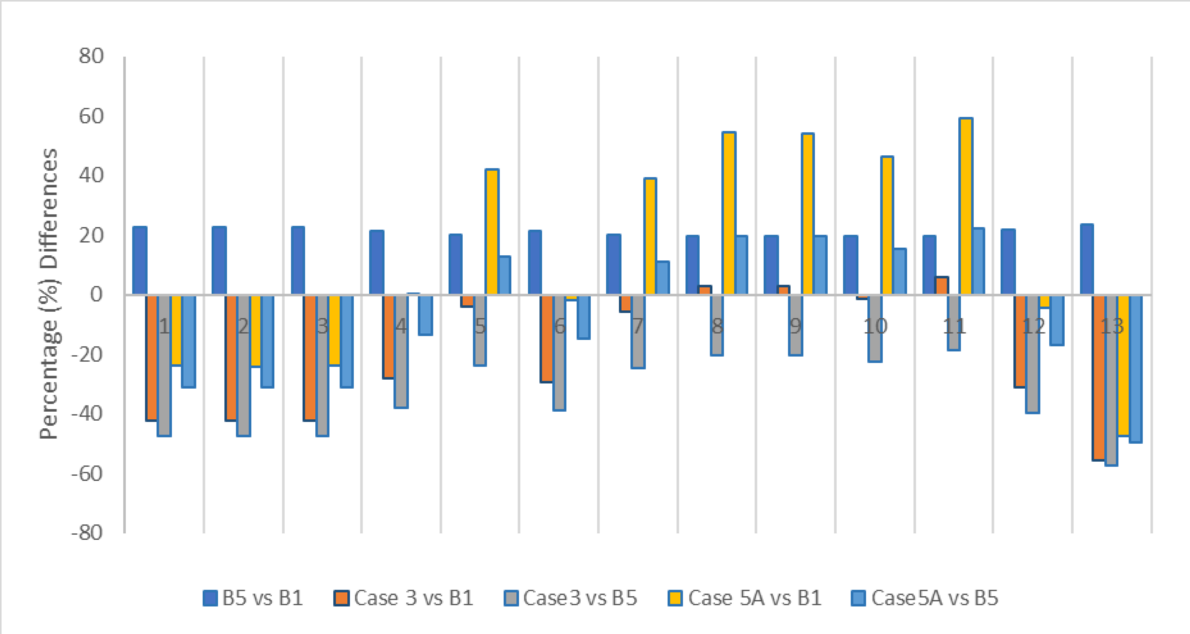

Figure 5. Variations in the environmental impact across different scenarios within 13 different categories

The damage impact assessment for all the scenarios (B1, B2, B3 B4 and B5) and simulated/hypothetical scenarios of Case 3 and Case 5A that include the following groups: 1 - human health; 2- ecosystem; and 3- resources are presented in Figure 6. The findings indicated a higher damage impact on the health category in a simulated Case 5A compared to Case 3, which agrees with the increase of human health categories (10 and 11) as shown in Figure 4. Additionally, Scenario B5 exhibited higher results, which is consistent with increased electricity and heating consumption in 2022 compared to previous years.

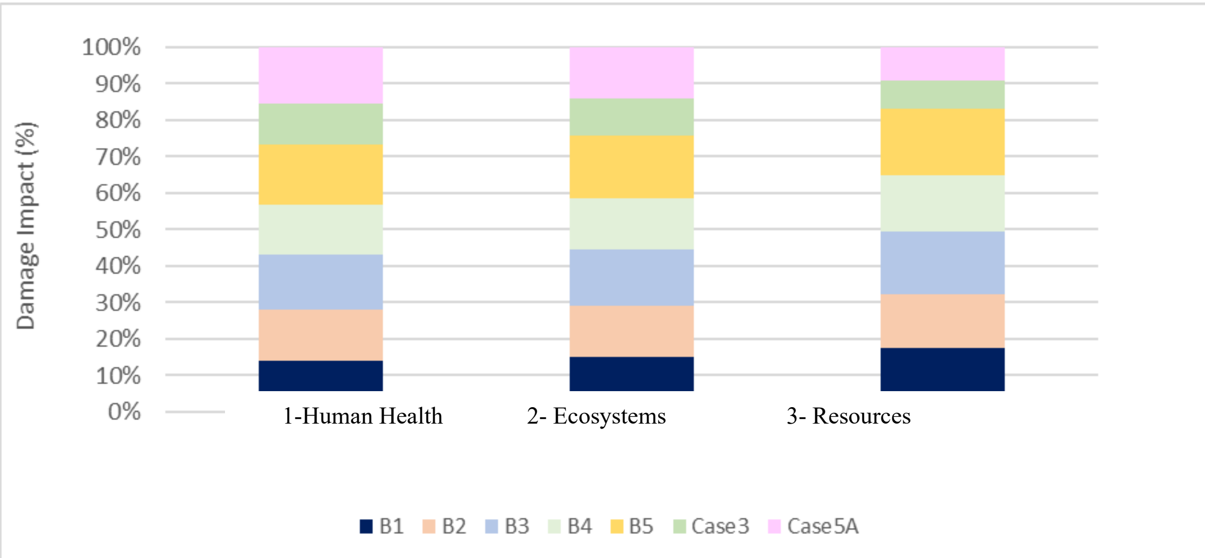

Figure 6. Damage impact assessment for the three main categories: 1 - Human health; 2 - Ecosystem; and 3 – Resources of all scenarios

Figure 7 presents the differences between the different scenarios for the damage impact assessment. The two hypothetical cases Case 3 and Case 5A are compared to scenarios B1 and B5. The largest differences of 32% have been observed between Case 3 and B5 for the human health group while 40 % and 58% reduction for the ecosystems and resources groups.

These percentage (%) reductions could be attributed to the nearly significant reduction in heating for Case 3 compared to year 2022 (scenario B5) – and the lower 17% in electricity consumption. The second most significant variances were observed between Case 3 and Scenario B1 while Case 5A showed a lower decrease, which agrees with the other observations presented in Figures 3-5. Once more, it appears that the building conditions assumed for the hypothetical Case 3 might represent the most favourable conditions among the two hypothetical scenarios in this work.

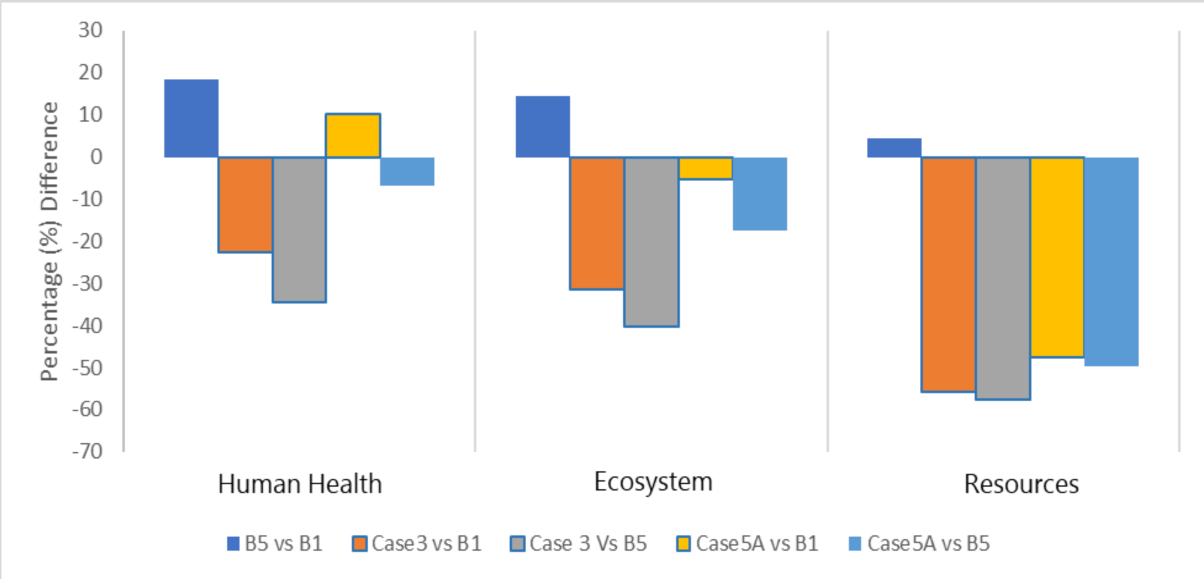

Figure 7. Variations in damage impact assessment across different scenarios within the three primary categories: 1 - Human health; 2 - Ecosystem; and 3 – Resources

3.2 Life Cycle Costings

The LCC results for the building across all scenarios, including five basic scenarios and two hypothetical scenarios are presented in Figure 8, based on the system boundary presented in Figure 2 and data in Tables 1-2. The findings demonstrated the greatest economic impact in scenarios B1 and B5 while the hypothetical scenarios of Case 2 and Case 5A the lowest economic impact. This agrees with the environmental assessment results where the Case 3 scenario indicates the least environmental impact. Furthermore, the cost assessment reveals that the Case 5A scenario displays a lower economic impact compared to Case 3, which is also in agreement with the environmental assessment results.

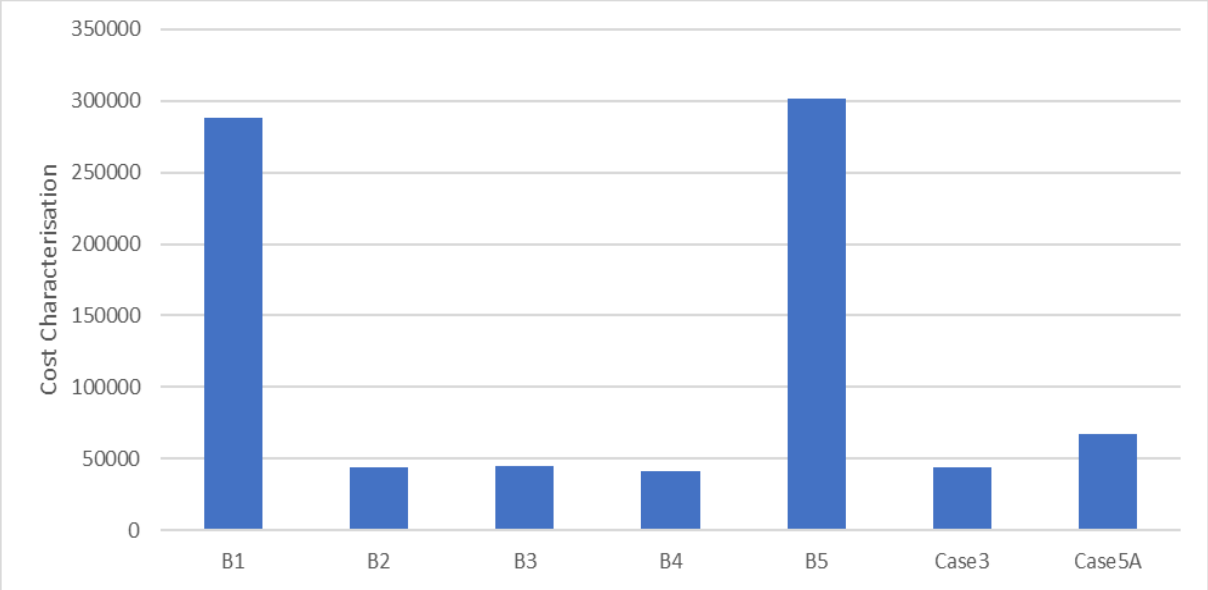

Figure 8. Economic impact of all scenarios

The comparison of economic impact across various scenarios showed that there is an 80% reduction in economic costs between Case 3 and B1 and B5 scenarios while no visible difference is observed with the B2 scenario and only a marginal economic increase is seen in comparison to B3 and B4 scenarios. Similarly, a comparison between scenario Case 5A and the five historical scenarios demonstrated the most significant differences between Case 5A and scenarios B1 and B5, with reductions of the costs of up to 80%. On the other hand, significant increases exceeding 40% are observed when compared to scenarios B2, B3 and B4. The comparison between Case 3 and Case 5A demonstrated higher economic costs for Case 5A, which is in line with the results concerning environmental impact, where Case 5A demonstrates a greater environmental footprint.

Although previous studies reported the benefits of using mechanical ventilation in residential buildings to reduce energy losses (Tronchin et al., 2018), this study found that the use of mechanical ventilation actually increased energy consumption and consequently the environmental impacts across all categories. In a study of Chen et al. (2016), an EnergyPlus simulation model was used to evaluate the energy performance of buildings and found that the optimal energy savings were achieved with an air temperature of 20°C and ambient temperature of 26°C. The study reported that the use of mechanical ventilation did not reduce energy consumption, which agrees with the findings of this research. Laverna et al (2018) explored the environmental impacts of buildings across different climatic zones and found that there were different effects of space heating requirements. The electricity use and space heating were primary contributors to overall environmental impacts because their reliance on fossil fuels for heating and electricity generation.

4. Conclusion

A comprehensive evaluation of LCA and LCC for the "ESTIA of Athens" municipal building was performed on the historical data from 2018 to 2022 and two hypothetical scenarios—Case 3 (heating and cooling without mechanical ventilation) and Case 5A (heating with mechanical ventilation). The findings indicated significant differences in energy consumption, greenhouse gas emissions and overall environmental impact between these scenarios. It was found that Case 3 showed lower environmental impact across most categories compared to historical scenarios and Case 5A. While demonstrating improved heating efficiency, Case 5A showed higher electricity consumption due to mechanical ventilation and consequently increased its environmental impact. The LCC analysis demonstrated similar trend with Case 3 and Case 5A offering more economic benefits compared to the historical scenarios with significant cost reductions. Case 3 demonstrated lowest economic impact. When comparing the hypothetical scenarios with historical data, Case 3 showed the most favorable results in terms of both environmental and economic performance. The increased costs and environmental impacts associated with Case 5A highlight the need for a careful and detailed approach when incorporating new technologies like mechanical ventilation.

The current study primarily considers energy consumption and GHG emissions. It highlights the importance of a holistic approach to building renovation that considers both environmental and economic factors. Future research should expand the scope to include other environmental impacts such as resource depletion and ecological effects, to provide a more holistic view of building renovation strategies.

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