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Building Information Modeling Applications in Energy-Efficient Refurbishment of Existing Building Stock: A Case Study

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Abstract: The built environment contributes to 35% of the global energy consumption and 38% of energy-related carbon emissions. The exponential population growth, coupled with the inability of the existing building stock to meet demands or reach the end of its lifespan, has precipitated the proliferation of new constructions worldwide. However, it has been proven well that retrofitting existing buildings might impact the environment less, save resources, and reduce the carbon footprint while extending their lifecycle. Various techniques are available to assess the performance of existing buildings and quantify the energy-saving potential of renovation measures. Building information modeling (BIM) technology serves as a virtual laboratory for buildings and can be used to model building stocks and measure how building performance changes with alternative envelope and system proposals. This research study explores the potential of BIM-based energy modeling to evaluate the effectiveness of refurbishment scenarios on a residential building. A total of 192 alternative scenarios were developed by considering six variables (wall, roofing, insulation, glazing, lighting power density, and photovoltaic panels). The results were analyzed across annual energy consumption (fuel and electric), annual/lifecycle energy costs, energy use intensity, annual CO_2 emissions, and initial investment costs. The optimum alternative scenario decreased the annual fuel and electricity consumption of the sample building by 61% and 64%, respectively. The payback period was calculated as 12 years. This study demonstrates the impact of BIM in enhancing the energy efficiency of the existing building stock, presenting results within the context of a residential building.

Keywords: building information modeling; retrofit; residential buildings; sustainability; energy performance; simulation

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1. Introduction

The construction industry, along with its constituent subsystems, accounted for approximately 13% of the global economy in 2020, with a value of 11 trillion dollars [1]. In Turkey, the market size of the construction sector hovers around 200 billion dollars, constituting approximately 5% of the gross domestic product (GDP), while, in conjunction with its associated 250 subsidiary and ancillary sectors, it contributes 35% of the GDP [2]. Undoubtedly, residential buildings constitute the largest share of the construction industry. Initially meeting the fundamental purpose of providing shelter and safety in the early ages, residential buildings have evolved to become significant contributors to non-renewable energy consumption (e.g., lighting, heating, cooling, household appliances, electronic devices) in recent centuries with the advancements in electricity and technology [3–6]. In fact, the global construction sector is responsible for approximately 35% of the total energy consumption worldwide [3–7]. Nowadays, both globally and in Turkey, there is a consensus on the development of high-performance, environmentally friendly, sustainable, and energy-efficient buildings, leading to a century characterized by intense discussions of alternative solutions [8,9]. As a result, during the last two decades, various organizations and institutions have developed green building certification systems (e.g., BREEAM (UK), LEED (USA), Green Star (Australia), WELL (USA), DGNB (Germany)), which set standards, ratings, and benchmarks to assess the environmental performance of buildings, and thereby to minimize the impact of buildings on the natural environment through sustainable design strategies [10–14]. While some of these systems have been developed with a global application in mind, others have been tailored or adapted to the environmental, economic, and socio-cultural characteristics of particular regions [10]. On the other hand, there is currently no national green building certification system in Turkey, although some legal regulations, such as the "Energy Efficiency Law", "Energy Performance Regulation for Buildings", and "Energy Performance Certificates", exist to promote sustainable design principles within the construction sector [15]. It is crucial to apply energy-efficient and sustainable design concepts not only to newly constructed buildings but also to the existing building stock. This is because the number of newly constructed buildings (especially residential buildings) is significantly low compared to the existing stock. Therefore, optimizing the energy performance of existing residential buildings through retrofit scenarios is of great importance in reducing the global and national energy share of the construction sector.

The construction sector does not have a dedicated laboratory facility. The only environment where construction and its outcomes are tested and evaluated is the physical state in which the product already emerges, leaving no room for reversals or modifications once it is realized. In recent years, in response to this challenge, building information modeling (BIM) technology has emerged to potentially simulate and analyze buildings in a virtual environment prior to actual construction [16]. BIM, in a way, is the digital expression of both the physical and functional characteristics of buildings that can be used throughout their lifecycle [17]. BIM is centered around the creation of object-based parametric and smart models and, when combined with add-on software tools, it facilitates the energy performance analysis of buildings and allows for the evaluation of different scenarios [17–20]. In this research, the potential of BIM technology in conjunction with building performance simulation tools to test the energy performance of existing housing stock and assess the effectiveness of refurbishment scenarios has been investigated. A sample residential building located in Elazig, Turkey was selected since it fits the broad focus of the study. The BIM model of the building was developed using Autodesk Revit and then transferred to Green Building Studio (GBS) to run the performance simulations. A total of 192 alternative scenarios were developed, each varying across six parameters: wall, roof, insulation, glazing, lighting power density (LPD), and photovoltaic panels. The energy performance of each scenario was then compared to the current state of the building. The results were presented across six metrics: annual energy consumption (fuel and electric), annual/lifecycle energy costs, energy use intensity, and annual CO_2 emissions. Furthermore, payback periods of alternative scenarios were calculated based on the national construction cost index.

This paper is structured as follows. The aims and objectives are discussed in Section 2. In Section 3, a brief overview of the literature is provided. Section 4 describes the methodology in detail. In Section 5, the results are presented. Section 6 extends the results, and the contributions of the research, limitations, and future work are discussed. The paper concludes with Section 7.

2. Aims and Objectives

The main aim of this study is to investigate the impact of refurbishment scenarios on the energy performance of a residential building using emerging BIM technology. The research objectives are as follows:

- To explore the potential of BIM-based energy performance analysis;
- To compare the effectiveness of different retrofit scenarios for existing housing stock;
- To use BIM in conjunction with simulation tools;
- To analyze the cost efficiency and financial feasibility of different retrofit strategies.

3. Literature Review

There is a significant body of research exploiting BIM in building performance analysis. For example, Taha et al. [21] explored the impact of the building orientation on energy consumption in the context of a three-story residential building using Revit and GBS software. It was concluded that a proper building orientation might lead to significant energy savings throughout the lifecycle. Abhinaya et al. [22] found significant improvements in the energy performance of a two-story residential building by implementing green material options in the walls, roof, flooring, and windows, highlighting the effectiveness of BIM tools in building performance simulations. In another study, Ahsan et al. [23] investigated the impact of passive cooling techniques on the annual energy consumption of an existing university building using t Autodesk Ecotect software. Modifications were proposed of various parameters, such as insulation, glazing, window-to-wall ratio, and lighting. The results indicated up to a 35% reduction in energy consumption over a span of 38 months. The results revealed that the window-to-wall ratio of the facade was directly proportional to the energy consumption, and when the windows were located at mid-height in all directions, the building's energy consumption was minimized. Ahmed and Asif [17] explored the potential of techno-economic solutions for the renovation of existing housing stock, focusing on two sample buildings in the eastern province of Saudi Arabia. They proposed a three-stage energy improvement plan including changes in eight different parameters. The first, second, and third energy improvement levels decreased the annual energy consumption of villa-type residences by 13.79%, 19.27%, and 56.9%, respectively. As for apartment-type residences, 22.84%, 28.85%, and 58.5% reductions in annual energy consumption were observed.

Kim et al. [24] conducted a study on a two-story residential building to investigate the impact of the position and size of windows, as well as the orientation of the building, on the total energy consumption. They developed 65 different scenarios using Revit in conjunction with GBS. Habibi et al. [25] investigated the impact of retrofitting roofing systems on building energy consumption. The proposed roofing alternative consisted of the following layers: photovoltaic panels, an EPDM membrane, and thermal insulation. The results demonstrated an approximately 15% improvement in building energy performance compared to the existing condition. Egwunatum et al. [26] demonstrated that exploiting BIM in conjunction with building energy simulation tools helped them to achieve a multistorey residential building with 103% positive energy. In another study, Abanda and Byers [27] investigated the impact of the building orientation on energy consumption in a three-story house located in the UK using Revit and GBS. The results showed considerable energy cost savings when the building was well oriented. He et al. [28] examined how window retrofitting with 20 glazing alternatives affected the energy performance of a 20-story residential building located in three different climate zones in China using Revit and Design Builder. The results showed that an adequate window system can save a substantial amount of energy. Jeon et al. [29] explored the potential of BIM-based simulations to evaluate the impact of the building envelope on energy consumption. The results demonstrated around a 20% reduction in energy use in a one-story house through the changes applied to the thermal–physical properties of building envelope elements, including the walls, windows, and roof.

4. Materials and Methods

The methodology of this research consisted of eight main steps, as displayed in Figure 1. In the first step, a comprehensive literature review was conducted to identify building parameters affecting overall energy consumption. Furthermore, widely used BIM and energy simulation tools were reviewed. Secondly, a residential building with well-known characteristics was selected for the case study application, followed by collecting all the required data (e.g., drawings, contextual information) to develop the digital model of the building. In the third step, a BIM model of the building was created using Revit and exported in Green Building XML (gbXML) format to ensure interoperability with GBS.

After this, an energy analysis of the existing building was carried out. Next, an energy simulation was run for each of the 192 scenarios and results were analyzed across six metrics. In the seventh step, the payback period of the best alternative was calculated using cost data. Finally, conclusions were provided. Each of these eight steps is further described in detail in the following sections.

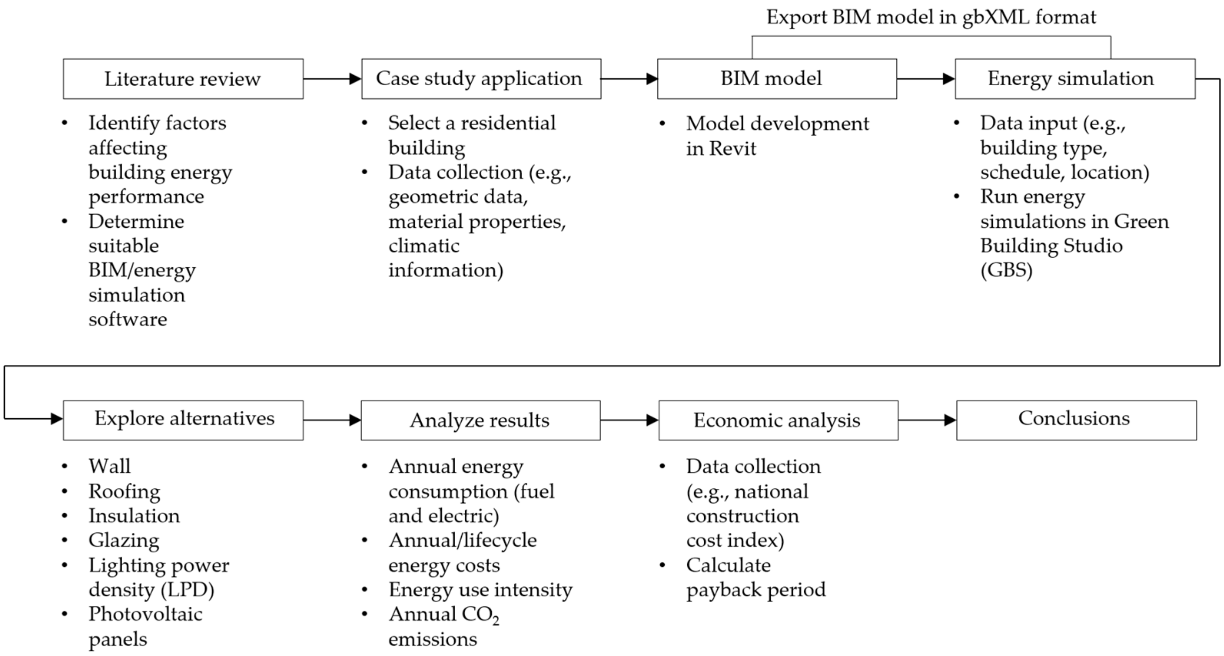


Figure 1. Methodology flowchart.

4.1. A Case Study

The case study building is a three-story house currently being occupied by nine members of three different families. While the case study building may not perfectly align with the average characteristics (e.g., building type, layout, age, size) of the larger population of houses within Turkey or globally, it holds significant potential for refurbishment opportunities, primarily attributable to its current condition. The house was built around 30 years ago and is located in the eastern part of Turkey, in the Kovancılar district of Elazığ Province, which is associated with cold and harsh winters, as well as hot and dry summers. The house includes three floors with a total area of 254 m^2. Each floor consists of an independent residential unit, comprising a living space, three bedrooms, a kitchen, a bathroom, and a WC (Figure 2). The attic is used as storage. The building is oriented in the north–south direction and has four unblocked facades. The transparency ratios of the facades are 15% for the south, 11% for the north, 15% for the east, and 25% for the west (Figure 3). The house has a load-bearing structure. The external walls of the house are made up of bricks with a plaster and paint finish, without thermal insulation. The total thickness of the wall section is 36 cm and the U-value (thermal transmittance) is calculated to be 1.58 W/m^2-K. The roof of the house has a timber structure with corrugated iron sheets and there is no thermal insulation and waterproofing in place. Furthermore, the iron sheets are in a deformative state, causing water leakage during rainy weather. The U-value of the roof is computed to be 0.70 W/m^2-K. The glazing system consists of double glass on the upper floors and single glass on the ground floor, with U-values of 3.13 W/m^2-K and 6.70 W/m^2-K, respectively. There is no shading placed outside the window. The list of all the details of the case study building can be seen in Table 1.

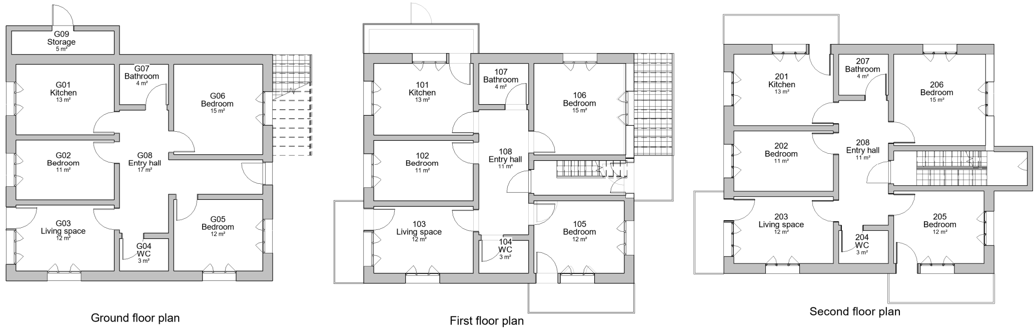


Figure 2. Floor plans of the case study building.

Figure 3. Elevations of the case study building.

Table 1. Characteristics of the case study building.

Element		Description
Typology		House
Location		Kovancilar, Elazig, Turkey
Occupants		9
Total area		254 m^2
Total floors		3
Orientation		North–south
Floor height		2.8 m
Window-to-wall ratio	South	15%
	North	11%
	East	15%
	West	25%
Exterior walls	Layers	Paint, 1.5 cm plaster, 30 cm brick, 1.5 cm plaster, paint
	U-value	1.58 W/m^2-K
Interior walls	Layers	Paint, 1.5 cm plaster, 15 cm brick, 1.5 cm plaster, paint
	U-value	2.33 W/m^2-K
Roof	Layers	Timber structure, corrugated iron roofing
	U-value	0.70 W/m^2-K
Ground floor	Layers	2 cm timber flooring, 5 cm concrete slab topping, concrete slab 30 cm
	U-value	1.82 W/m^2-K
Interior floors	Layers	2 cm timber flooring, 5 cm concrete slab topping, concrete slab 15 cm, 1.5 cm plaster, paint
	U-value	2.48 W/m^2-K

Table 1. *Cont.*

Element		Description
Glazing	Single glass Double glass	U-value: 3.13 W/m^2-K U-value: 6.70 W/m^2-K
Shading		None
Lighting	Type Power density	Light-emitting diodes (LED) 10.76 W/m^2
Heating		Natural gas hydronic heating
Air conditioning		None

4.2. Identification of Retrofit Scenarios

The energy performance of buildings is influenced by many aspects, mainly divided into two categories: environmental factors (e.g., topography, climatic conditions) and building-related factors (e.g., location, orientation, building form, building envelope). In this study, six building-related retrofit scenarios were identified to be effective and practical in enhancing the energy performance of the case study building. These retrofit scenarios include replacing exterior/interior brick walls with pumice and aerated concrete walls; replacing corrugate iron roof sheets with slate, tile, shingle, and wood shake sheets; adding envelope insulation of stone wool, glass wool, expanded polystrene (EPS), and extruded polystrene (XPS) in 6 cm and 8 cm; improving glazing types from single and double glazing to low E double glazing, uncoated double glazing, and triple glazing; increasing the lighting power density (LPD) values by 20%, 40%, 60%, 80%, 100%, 150%, 200%, 300%, and 400% and decreasing the LPD values by 20%, 40%, 60%, 80%, and 100%; and installing single crystalline photovoltaic panels with 13.8% efficiency on the roof of the case study building. These retrofit scenarios have been selected based on the current conditions of the case study building (Table 2). In order to ensure that all possible combinations of the six parameters were considered, a total of 192 scenarios were developed, as shown in Figure 4. The LPD was excluded from these combinations to reduce the workload caused by the large number of possibilities.

Table 2. Selected retrofit scenarios for the case study building.

Retrofit Element	Existing	Proposed
Wall	Brick (exterior U-value: 1.58 W/m^2-K; interior U-value: 2.33 W/m^2-K)	Pumice (exterior U-value: 0.66 W/m^2-K; interior U-value: 0.98 W/m^2-K); Aerated concrete (exterior U-value: 0.36 W/m^2-K; interior U-value: 0.53 W/m^2-K)
Roofing	Corrugated iron (U-value: 0.70 W/m^2-K)	Slate (U-value: 0.69 W/m^2-K); Tile (U-value: 0.67 W/m^2-K); Shingle (U-value: 0.65 W/m^2-K); Wood shake (U-value: 0.54 W/m^2-K)
Insulation	None	Stone wool (6 cm U-value: 0.43 W/m^2-K, 8 cm U-value: 0.34 W/m^2-K); Glass wool (6 cm U-value: 0.41 W/m^2-K, 8 cm U-value: 0.33 W/m^2-K); Expanded polystyrene (EPS) (6 cm U-value: 0.38 W/m^2-K, 8 cm U-value: 0.30 W/m^2-K); Extruded polystyrene (XPS) (6 cm U-value: 0.35 W/m^2-K, 8 cm U-value: 0.28 W/m^2-K)
Glazing	Single glazing (U-value: 6.70 W/m^2-K; SHGC: 0.19) Double glazing (U-value: 3.13 W/m^2-K; SHGC: 0.21)	Low E double glazing (U-value: 2.10 W/m^2-K; SHGC: 0.24); Uncoated double glazing (U-value: 1.99 W/m^2-K; SHGC: 0.62); Triple glazing (U-value: 1.53 W/m^2-K; SHGC: 0.68)
Lighting power density (LPD)	10.76 W/m^2	0 W/m^2; 2.15 W/m^2; 4.31 W/m^2; 6.46 W/m^2; 8.61 W/m^2; 12.92 W/m^2; 15.07 W/m^2; 17.22 W/m^2; 19.38 W/m^2; 21.53 W/m^2; 26.91 W/m^2; 32.29 W/m^2; 43.06 W/m^2; 53.82 W/m^2
Photovoltaic panels	None	Single crystalline—13.8% efficient

Figure 4. Formation of 192 retrofit scenarios.

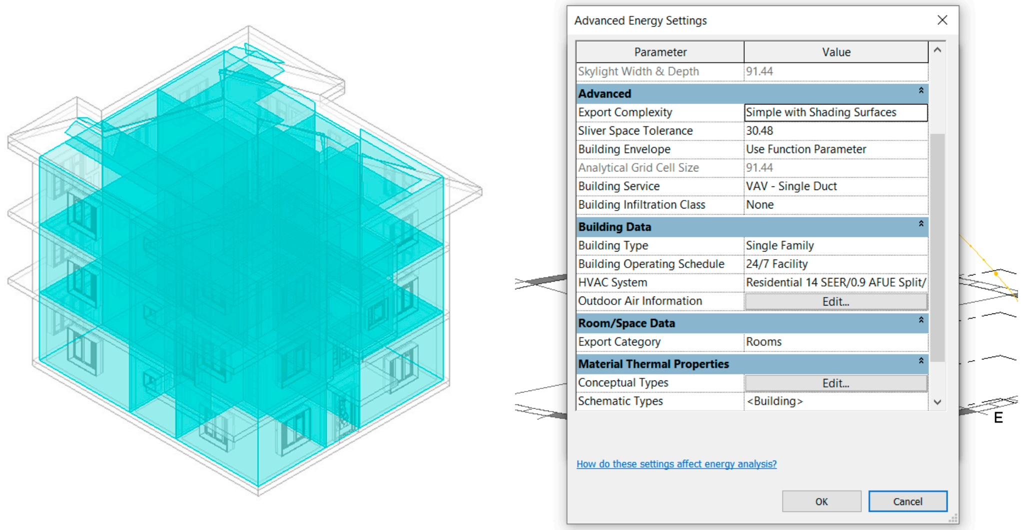
4.3. Development of the BIM Model

The authors conducted geometric surveys on the building using measurement equipment to produce drawings, including floor plans, elevations, and sections. Reconstituted drawings along with other building-specific data, such as the building orientation, building elements, building materials, location, and climatic conditions, were fed into Revit to develop the BIM model of the case study building, as seen in Figure 5. The BIM model of the base case was used to design and visualize the proposed 192 retrofit scenarios across six parameters, expected for changes in the LPD values and applying photovoltaic panels, which were realized in the energy simulation tool, GBS.

Figure 5. BIM model of the case study building.

4.4. Energy Simulation in Green Building Studio

After developing the BIM model(s) in Revit, the energy analytical model(s) of the building was created using advanced energy settings (e.g., building type, building operation schedule, heating, ventilation, and air conditioning (HVAC) system, building service), as shown in in Figure 6. Next, the energy analytical model(s) was exported in gbXML format for energy simulation in GBS. To create a new project in GBS, some details are required to be entered, including the project name, building type, schedule, project type, project location, time zone, and currency (Figure 7). GBS allocates the nearest weather station based on the project location. After the gbXML file(s) was imported, the energy simulation was first conducted for the base case. In order to compare and observe the impact of the retrofit scenarios, simulations were run for each of the 192 scenarios.



(**a**) (**b**)

Figure 6. (**a**) Energy analytical model; (**b**) advanced energy settings.

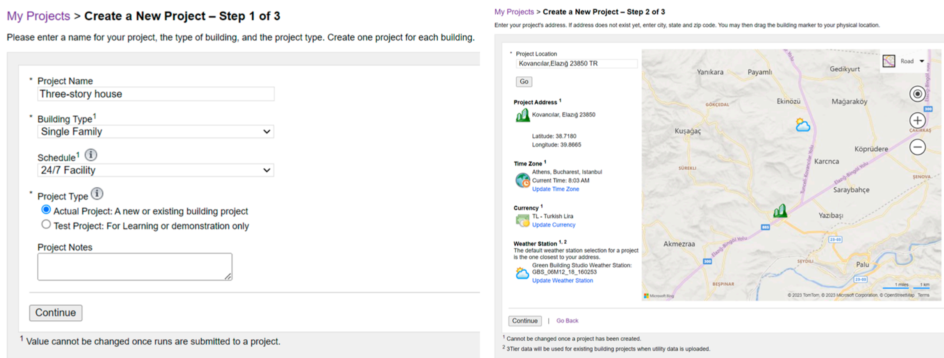


Figure 7. Creating a new project in GBS.

5. Results

This section provides the results of the energy simulation in GBS. The results are presented across six metrics: annual energy consumption (fuel and electric), annual/lifecycle energy costs, energy use intensity, and annual CO_2 emissions. While GBS refers to gas and hot water as "fuel", the electricity consumption consists of HVAC, lighting, and other utilities. The lifecycle cost represents the estimated cost of electricity and fuel consumption calculated over 30 years with a 6.1% discount rate. The utility rates that are representative of the location were inputted as 0.04 TL for 1 kWh electricity and 0.91 TL for 1 MJ fuel. Energy use intensity refers to the quantity of electricity and fuel used per square meter.

5.1. Analysis of the Existing Case

Figure 8 illustrates the distribution of the annual fuel and electricity use of the base run. Heating and hot water account for 80.1% and 19.9% of fuel consumption, respectively. As for electricity, 37.6% is used for lighting, 28.1% for HVAC, and 34.3% for other purposes (cooling, fans, etc.). The annual fuel and electricity consumption are 241,021 MJ and

26,147 kWh, costing 34,210 TL in total (Table 3). Electricity use constitutes around 70% of the annual energy cost.

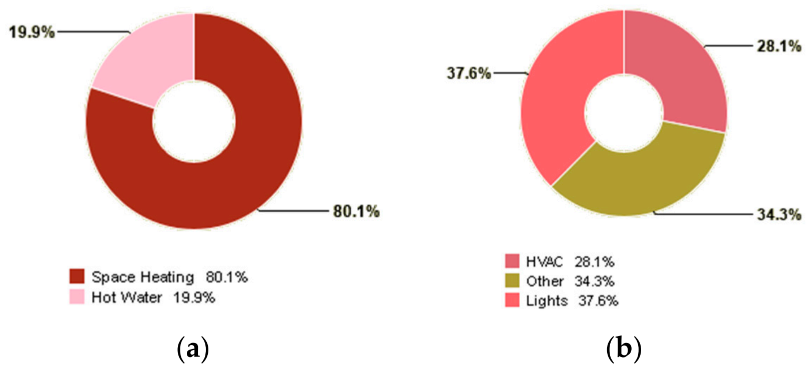


Figure 8. (**a**) Annual fuel consumption; (**b**) annual electricity consumption (right).

Table 3. Simulation results of the existing case.

Scenario	Annual Fuel Consumption (MJ)	Annual Electricity Consumption (kWh)	Annual Energy Cost (TL)	Lifecycle Energy Cost (TL)	Energy Use Intensity (MJ/m^2/Year)	Annual Carbon Emissions (mg)
Existing case	241,021	26,147	34,210	465,974	1320.7	12.0

5.2. Analysis of the Retrofit Scenarios

5.2.1. The Impact of the Wall Material on Energy Performance

Table 4 displays the simulation results pertaining to different wall materials. It has been observed that replacing the wall material of the case study building exerts a significant impact on the annual fuel consumption. Specifically, annual fuel consumption for aerated concrete is measured at 173,529 MJ, while, for pumice and brick, the corresponding values stand at 194,947 MJ and 241,021 MJ, respectively. Regarding annual electricity consumption, aerated concrete performs the best, with a value of 25,184 kWh. Overall, aerated concrete has outperformed pumice and brick in all aspects, thereby exhibiting the best thermal performance as a wall material. Consequently, considerable reductions have been observed in lifecycle energy costs, with the lifecycle energy cost estimated at 414,307 TL for aerated concrete, in comparison to 430,629 TL for pumice and 465,974 TL for brick. In light of the abovementioned data, aerated concrete has been selected as the optimal wall material for the retrofit of the case study building.

Table 4. Simulation results for wall materials.

Scenario	Annual Fuel Consumption (MJ)	Annual Electricity Consumption (kWh)	Annual Energy Cost (TL)	Lifecycle Energy Cost (TL)	Energy Use Intensity (MJ/m^2/Year)	Annual Carbon Emissions (mg)
Brick	241,021	26,147	34,210	465,974	1320.7	12.0
Pumice	194,947	25,484	31,616	430,629	1129.7	9.7
Aerated concrete	173,529	25,184	30,417	414,307	1041.1	8.7

5.2.2. The Impact of Roofing Material on Energy Performance

Table 5 shows the simulation results pertaining to different roofing materials. The results reveal that alternative roofing materials have not yielded significant changes in the building's energy performance. Among the options considered, wood shake and slate exhibit the highest and lowest performance, respectively. Shingle and tile rank second and third, with their values showing close proximity. The annual fuel consumption for the case study building with a corrugated iron roof sheet is calculated at 241,021 MJ, whereas it slightly decreases to 239,693 MJ for wood shake. Conversely, the electricity use values for all scenarios are so similar that they can be deemed virtually equal. Furthermore, the influence of roofing materials on the building's annual and lifecycle energy costs appears negligible, as does their impact on energy use intensity and CO_2 emissions. As a consequence, notwithstanding the marginal discrepancy, wood shake has been identified as the optimal roofing material for the retrofit of the case study building.

Table 5. Simulation results for roofing materials.

Scenario	Annual Fuel Consumption (MJ)	Annual Electricity Consumption (kWh)	Annual Energy Cost (TL)	Lifecycle Energy Cost (TL)	Energy Use Intensity (MJ/m^2/Year)	Annual Carbon Emissions (mg)
Corrugated iron	241,021	26,147	34,210	465,974	1320.7	12.0
Slate	240,924	26,144	34,203	465,879	1320.3	12.0
Tile	240,850	26,137	34,194	465,755	1319.9	12.0
Shingle	240,674	26,136	34,186	465,638	1319.2	12.0
Wood shake	239,693	26,110	34,120	464,739	1314.9	12.0

5.2.3. The Impact of Insulation Material/Thickness on Energy Performance

Table 6 illustrates the simulation results pertaining to different roofing materials and thicknesses. Applying insulation on the building's external walls has been observed to yield a substantial reduction in fuel consumption, leading to a notable decrease in the lifecycle energy costs, while no significant impact on electricity use has been noted. It has been found that XPS and EPS, each with an 8 cm thickness, significantly enhance the building's energy performance, outperforming the other materials. The increase in insulation thickness demonstrates a positive correlation with performance improvements. For instance, increasing the insulation thickness from 6 cm to 8 cm results in respective fuel consumption reductions of 5089 MJ for XPS, 5397 MJ for EPS, 5590 MJ for glass wool, and 5700 MJ for stone wool. Despite minimal performance differences among the insulation materials, XPS and EPS, in particular, exhibit closely comparable values. Notably, for XPS 8 cm, the annual electricity consumption is 24,968 kWh, while, for EPS 8 cm, it is 24,987 kWh, and the corresponding annual energy costs amount to 30,237 TL and 30,330 TL, respectively. Similarly, both stone wool and glass wool demonstrate very close values across all evaluated parameters. Consequently, XPS with an 8 cm thickness has been identified as the best-performing insulation material for the retrofit of the case study building.

Table 6. Simulation results for insulation materials.

Scenario	Annual Fuel Consumption (MJ)	Annual Electricity Consumption (kWh)	Annual Energy Cost (TL)	Lifecycle Energy Cost (TL)	Energy Use Intensity (MJ/m^2/Year)	Annual Carbon Emissions (mg)
No insulation	241,021	26,147	34,210	465,974	1320.7	12.0
Stone wool—6 cm	184,021	25,152	30,842	420,086	1088.2	9.2
Stone wool—8 cm	178,321	25,016	30,472	415,045	1067.5	8.9
Glass wool—6 cm	182.877	25,139	30,780	419,251	1083.5	9.1
Glass wool—8 cm	177,287	25,005	30,416	414,294	1063.2	8.8
EPS—6 cm	181,051	25,118	30,683	417,921	1075.9	9.0
EPS—8 cm	175,654	24,987	30,330	413,111	1056.5	8.8
XPS—6 cm	179,000	25,097	30,579	416,502	1067.9	8.9
XPS—8 cm	173,911	24,968	30,237	411,850	1049.3	8.7

5.2.4. The Impact of Glazing on Energy Performance

Table 7 shows the simulation results pertaining to different glazing materials. The influence of window glazing on the building's fuel consumption, energy use intensity, and CO_2 emissions has been observed to be of significant importance. On the contrary, there have been no considerable changes seen in electricity consumption and annual/lifecycle energy costs. The results reveal that triple glazing offers the most substantial enhancement to the building's energy performance, followed by uncoated double glazing and low E double glazing, respectively. Specifically, triple window glazing results in annual fuel consumption of 172,557 MJ, leading to a commendable fuel saving of 68,464 MJ. However, it should be noted that triple glazing also triggers an increase of 2527 kWh in annual electricity consumption, failing to yield significant reductions in both the annual and lifecycle energy costs. This pattern holds true for the other window glazing types as well, with none of the evaluated glazing options demonstrating the capability to reduce the building's electricity consumption. Notably, low E window glazing exhibits the most efficient performance concerning electricity consumption, and it ranks first in both the annual and lifecycle energy costs, albeit by a slight margin. As a consequence, triple glazing, characterized by its notable reduction in fuel consumption and substantial enhancement in the building's energy performance, has been identified as the optimal glazing material for the retrofit of the case study building.

Table 7. Simulation results for glazing.

Scenario	Annual Fuel Consumption (MJ)	Annual Electricity Consumption (kWh)	Annual Energy Cost (TL)	Lifecycle Energy Cost (TL)	Energy Use Intensity (MJ/m^2/Year)	Annual Carbon Emissions (mg)
Single glazing + double glazing	241,021	26,147	34,210	465,974	1320.7	12.0
Low E double glazing	217,711	26,309	33,551	454,266	1231.1	10.9
Uncoated double glazing	182,694	28,212	33,568	457,225	1120.1	9.1
Triple glazing	172,557	28,674	33,551	456,991	1086.8	8.6

5.2.5. The Impact of Lighting Power Density on Energy Performance

Table 8 displays the simulation results pertaining to different LPDs. Reducing the LPD has been observed to result in a decrease in electricity consumption, energy costs, and energy use intensity, but an increase in fuel consumption and CO_2 emissions. Conversely, an increase in the LPD yields the opposite trends. While a slight increase in fuel consumption is observed with a reduced LPD value, elevating the LPD value leads to significant rises in costs, energy use intensity, and electricity consumption. Consequently, considering both the abovementioned outcomes and the objective of reducing electricity consumption, alternatives with LPD values lower than that of the existing building have shown superior performance. The lowest LPD (0 W/m^2) representing a 100% reduction from the current value offers the most favorable performance. Notably, despite causing a 30,279 MJ increase in annual fuel consumption, this alternative remarkably enables a reduction of 10,695 kWh in electricity consumption, resulting in substantial cost savings and a significant decrease in energy use intensity over the 30-year lifecycle. As a result, the LPD of 0 W/m^2 has selected as the optimal scenario for the retrofit of the case study building.

Table 8. Simulation results for lighting power density (LPD).

Scenario	Annual Fuel Consumption (MJ)	Annual Electricity Consumption (kWh)	Annual Energy Cost (TL)	Lifecycle Energy Cost (TL)	Energy Use Intensity (MJ/m^2/Year)	Annual Carbon Emissions (Mg)
10.76 W/m^2	241,021	26,147	34,210	465,974	1320.7	12.0
8.61 W/m^2	246,960	24,021	32,532	443,121	1313.9	12.3
6.46 W/m^2	252,968	21,897	30,860	420,341	1307.5	12.6
4.31 W/m^2	259,042	19,737	29,156	397,138	1300.8	12.9
2.15 W/m^2	265,150	17,622	27,495	374,521	1294.8	13.2
0 W/m^2	271,300	15,452	25,787	351,255	1288.3	13.5
12.92 W/m^2	235,123	28,279	35,896	488,928	1327.7	11.7
15.07 W/m^2	229,301	30,413	37,586	511,952	1335.0	11.4
17.22 W/m^2	223,569	32,551	39,284	535,077	1342.8	11.1
19.38 W/m^2	217,882	34,692	40,987	558,266	1350.7	10.9
21.53 W/m^2	212,238	36,838	42,695	581,533	1358.9	10.6
26.91 W/m^2	198,273	42,217	46,987	639,987	1380.2	9.9
32.29 W/m^2	184,768	47,613	51,313	698,910	1403.5	9.2
43.06 W/m^2	159,498	58,457	60,089	818,437	1457.8	8.0
53.82 W/m^2	136,434	69,428	69,076	940,832	1522.6	6.8

5.2.6. The Impact of Photovoltaic Panels on Energy Performance

This part presents an analysis of the potential energy savings, costs, and payback period associated with the implementation of photovoltaic panels on the existing building's roof. GBS's built-in feature has been utilized as the primary data source to explore the photovoltaic potential of the case study building, as shown in Figure 9. A situation where 88 m^2 of single crystalline photovoltaic panels with efficiency of 13.8% are installed on 153 m^2 of roof area was designed. The panel cost was determined through thorough market research, yielding a rate of 1 m^2 = 1104.62 TL/1 Watt = 8 TL. As a result, the total cost of installing 88 m^2 of photovoltaic panels amounts to 97,136.89 TL. The installed photovoltaic panels are projected to produce 16,936 kWh electricity annually. It is estimated that the system will achieve a return on investment within a reasonable period of 6 years. In conclusion, the installation of single crystalline photovoltaic panels with 13.8% efficiency on the existing building's roof is deemed as the optimal scenario for the retrofit of the case study building, supported by its potential for substantial energy savings and a favorable payback period of 6 years.

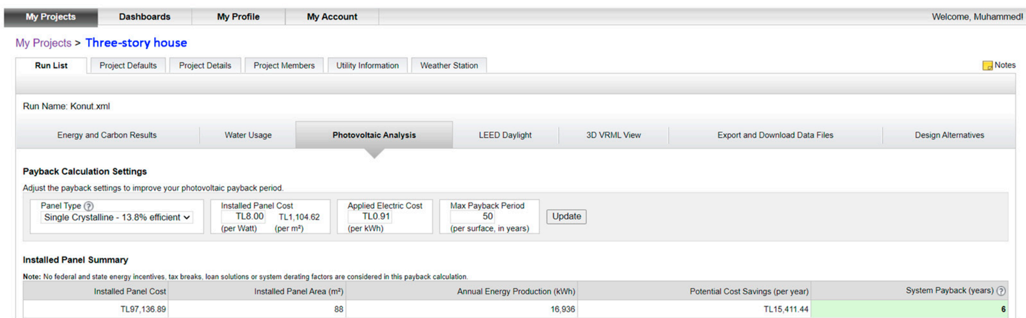


Figure 9. Photovoltaic analysis in GBS.

5.3. Analysis of 192 Alternative Scenarios

This section presents the energy performance results of 192 alternative scenarios designed based on all possible combinations of four parameters. The primary objective was to identify the most efficient option for each building element while considering the probabilities of various parameter combinations to ensure the accuracy and reliability of the optimal retrofit scenario. The LPD has not been included in this analysis owing to the numerous potential combinations. As demonstrated in Table 9, the scenario comprising aerated concrete walls, wood shake roofing, 8 cm XPS insulation, and triple window glazing offered the best energy performance. This particular configuration displayed the highest reduction in fuel consumption (92,287 MJ) and the lowest energy use intensity (767.3 MJ/m^2/year) and CO_2 emissions (4.6 mg). However, a similar scenario involving low E double-glazed windows instead of triple glazing resulted in lower electricity consumption (24,912 kWh) and energy costs (annual: 28,229 TL, lifecycle: 384,500 TL). The findings from the energy analysis of the 192 alternative scenarios underscored the accuracy of the optimal choices made for each parameter in the previous section. Specifically, scenarios with aerated concrete walls consistently outperformed those featuring pumice or brick walls within the same combinations. Similarly, wood shake roofing demonstrated superior performance compared to other options. The 8 cm XPS insulation exhibited the most efficient performance among the various insulation options. Finally, triple-glazed windows outperformed other glazing alternatives. In conclusion, the combination of aerated concrete wall material, wood shake roofing material, 8 cm XPS insulation material, and triple window glazing has been selected as the optimal alternative scenario for the retrofit of the case study building based on its superior energy performance across various parameters.

Table 9. Simulation results for the best two scenarios.

Scenario	Annual Fuel Consumption (MJ)	Annual Electricity Consumption (kWh)	Annual Energy Cost (TL)	Lifecycle Energy Cost (TL)	Energy Use Intensity (MJ/m^2/Year)	Annual Carbon Emissions (mg)
Aerated concrete + Wood shake + XPS 8 cm + Triple glazing	92,287	27,952	29,425	400,775	767.3	4.6
Aerated concrete + Wood shake + XPS 8 cm + Low E glazing	128,632	24,912	28,229	384,500	868.4	6.4

6. Discussion

In this section, first, the energy performance of the optimal scenario combining the best-performing retrofitting strategies, namely aerated concrete walls, wood shake roofing, 8 cm XPS insulation, triple window glazing, an LPD of 0 W/m^2, and photovoltaic panels, is compared to the existing situation of the case study building. As demonstrated in Table 10, the results of energy performance analysis have indicated that retrofitting existing homes could lead to substantial energy and cost savings. Specifically, the annual fuel consumption witnessed a substantial reduction of 61%, while the electricity consumption achieved an impressive 64% reduction. The existing building's annual fuel consumption stood at 241,021 MJ, whereas the alternative scenario showcased a remarkable decrease to 92,287 MJ. Likewise, the electricity use for the current building and the alternative scenario amounted to 26,147 kWh and 11,016 kWh, respectively. Moreover, a 59% decrease in both annual and lifecycle energy expenses has been observed. This translates into a significant reduction of 279,176 TL in the building's lifecycle energy cost. Notably, similar substantial reductions have been observed in energy use intensity and CO_2 emissions.

As shown in Figure 10, triple-glazed windows, aerated concrete walls, and 8 cm XPS insulation contributed to reducing the building's fuel consumption the most, respectively. The implementation of triple-glazed windows resulted in a noteworthy decrease in fuel consumption from 241,021 MJ to 172,557 MJ. Conversely, in terms of electricity consumption, photovoltaic panels and an LPD of 0 W/m^2 were found to have substantial effects, while the impact of other parameters remained limited (Figure 11). Installing photovoltaic panels on the building's roof yielded an impressive annual electricity saving of 16,936 kWh. Additionally, by reducing the LPD value of the lighting fixtures by 100%, a decrease of 10,695 kWh in annual electricity consumption was achieved. Consequently, the most significant reductions in annual and lifecycle energy costs were attributed to parameters associated with electricity consumption, primarily the photovoltaic panel and lighting system, driven mainly by the substantial disparity in unit prices between electricity and fuel (Figure 12). It is noteworthy that while implementing photovoltaic panels resulted in low energy costs, the initial high investment may delay its tangible impact for users in the long run. This underscores the need for careful consideration of both short-term and long-term implications when adopting energy-efficient measures for sustainable building practices.

Table 10. Simulation results for all scenarios.

Scenario	Annual Fuel Consumption (MJ)	Annual Electricity Consumption (kWh)	Annual Energy Cost (TL)	Lifecycle Energy Cost (TL)	Energy Use Intensity (MJ/m2/Year)	Annual Carbon Emissions (mg)
Existing case	241,021	26,147	34,210	465,974	1320.7	12.0
Aerated concrete	173,529	25,184	30,417	414,307	1041.1	8.7
Wood shake	239,693	26,110	34,120	464,739	1314.9	12.0
XPS—8 cm	173,911	24,968	30,237	411,850	1049.3	8.7
Triple glazing	172,557	28,674	33,551	456,991	1086.8	8.6
LPD—0 W/m^2	271,300	15,452	25,787	351,255	1288.3	13.5
Photovoltaic panels	241,021	9211	18,022	245,459	1079.4	12.0
Optimal scenario	92,287	11,016	13,715	186,798	519.4	4.6

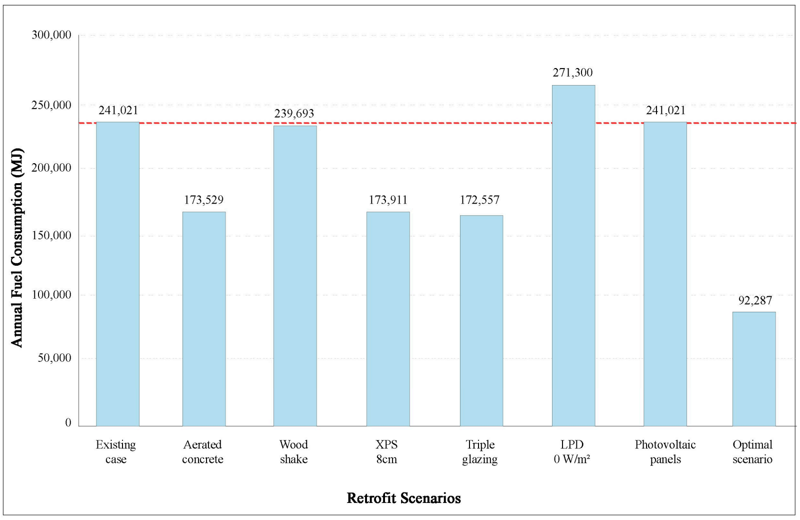


Figure 10. Annual fuel consumption of retrofit scenarios.

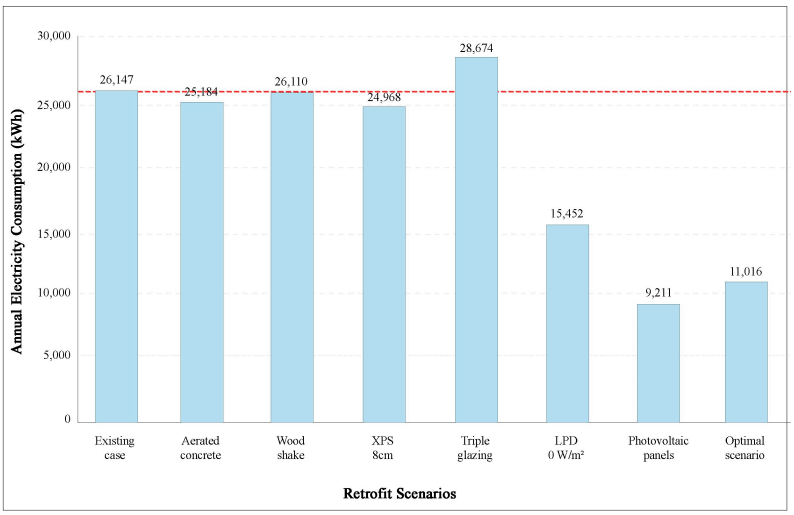


Figure 11. Annual electricity consumption of retrofit scenarios.

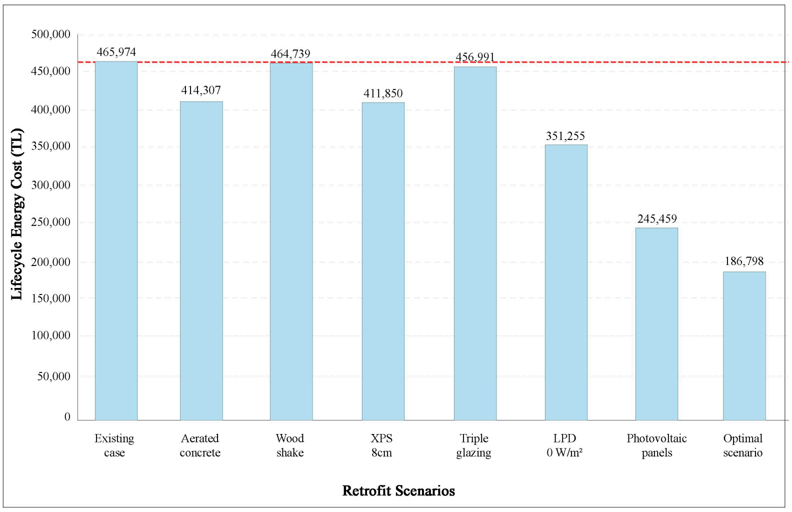


Figure 12. Lifecycle energy cost of retrofit scenarios.

6.1. Economic Analysis of Retrofit Scenarios

In this study, the payback periods of the retrofit scenarios were calculated based on their capital costs and promised savings. Related cost data were sourced from the unit price list of the Ministry of Environment, Urbanization and Climate Change in Turkey, and manufacturers' online resources [30–32]. The quantity, material and labor costs, and total costs of the retrofit scenarios are presented in Table 11. The total cost of implementing all retrofit strategies was computed at 275,050 TL. Comparatively, the existing building incurred an annual energy cost of 34,210 TL, whereas the alternative scenario resulted in a significantly reduced annual energy cost of 11,016 TL. As a result, substantial savings of 23,194 TL per year were achieved. Consequently, the calculated payback period, considering the initial investment costs and annual savings, was approximately 12 years. Remarkably, the retrofitting measure with the highest initial investment cost (99,980 TL) involved replacing brick walls with aerated concrete walls. Due to the necessity of demolishing existing walls and constructing new walls, along with associated plastering and painting costs, this retrofitting approach incurred a considerably high total cost. Nonetheless, despite its substantial capital cost, this scenario only yielded a modest annual saving of 3793 TL, making it an inefficient retrofitting method for future efforts. The second most expensive retrofitting strategy (97,130 TL) was the installation of photovoltaic panels on the building's roof. In contrast, this strategy resulted in a notable 64% reduction in annual electricity consumption, exemplifying its effectiveness as a viable retrofitting technique. Conversely, the removal of corrugated iron roof sheets and installing of wood shake roofing exhibited remarkably high costs in relation to the achieved savings. On the other hand, the implementation of triple-glazed windows, with a relatively modest initial investment cost of 17,850 TL, substantially reduced the building's fuel consumption, proving to be an economically and environmentally sound retrofitting option. A similar case was observed for the addition of 8 cm XPS insulation to the building's envelope. With a reasonable capital cost of 29,940 TL, this retrofitting measure significantly decreased the fuel consumption and enhanced the building's overall performance. Lastly, replacing the current lighting system, with an investment cost of only 2800 TL, significantly contributed to electricity consumption savings, positioning it as another cost-effective retrofitting strategy.

Table 11. Economic analysis of retrofit scenarios.

	Retrofit Scenario	Quantity	Cost of Material and Labor (TL)	Total Cost (TL)
Aerated concrete walls	Demolition of the brick walls	558 m^2	20	11,160
	Building aerated concrete walls	558 m^2	80	44,640
	Gypsum plaster + paint	690 m^2	26	17,940
	Cement plaster + paint	320 m^2	82	26,240
	Total			99,980
Wood shake roofing	Removing the corrugated iron roof sheet	153 m^2	32	4900
	Installing wood shake roofing	153 m^2	150	22,950
	Total			27,850
Triple window glazing	Removing the existing windows	55 m^2	14.5	800
	Installing the new windows with triple glazing	55 m^2	310	17,050
	Total			17,850
8 cm XPS insulation	Insulating the exterior walls	320 m^2	92	29,440
LPD—0 W/m^2	Replacing lighting fixtures	56 items	50	2800
Photovoltaic panels	Installing photovoltaic panels	88 m^2	1104	97,130
	Total			**275,050 TL**

6.2. Validation of Results

The aim of this part was to compare the computational results of GBS with real energy bills to validate the accuracy of the simulation results [33]. The monthly utility bills of the case study building were provided by the homeowners. Table 12 shows the simulation results and the measured data for the actual building. The percentage error (PE) between the simulated results and the measured data was calculated by employing the following formula:

$$\text{PE} = [(\text{Simulated Results} - \text{Measured Data})/\text{Measured Data}] \times 100$$

Table 12. Validation of computational results.

	Annual Fuel Consumption (MJ)	Annual Fuel Cost (TL)	Annual Electricity Consumption (kWh)	Annual Electricity Cost (TL)
GBS	241,021	10,417	26,147	23,793
Utility bills	216,496	9360	6593	6000

It is important to note that a positive PE value indicates that GBS overestimates the results compared to the measured data, while a negative PE value suggests underestimation by the software. According to previous research [34,35], an acceptable PE should be in the range of ±15%. The PE values for annual fuel and electricity consumption are computed as follows: annual fuel consumption: PE = [(241,021 − 216,496)/216,496] × 100 = 11%, annual electricity consumption: PE = [(26,147 − 6593)/6593] × 100 = 296%. The PE value for annual fuel consumption is 11%, which is clearly within the accepted range and indicates a reasonably close match between GBS and the actual data, thereby confirming the reliability of the results. However, for annual electricity consumption, the PE value is 296%, which is significantly higher than the 15% threshold, suggesting that GBS might have failed to accurately compute the electricity consumption. One possible explanation for this discrepancy could be the software's limitations, as GBS made misassumptions concerning occupancy, lighting, and equipment use. For instance, the actual number of occupants in the building is 9, while GBS erroneously processed these data as 21, with no provision for manual data input. The observed non-compliance of the electricity consumption/cost data within an acceptable range in this study may have implications for the proper assessment of the environmental and economic impacts of retrofitting activities. Furthermore, the notably higher GBS results for electricity consumption/cost might lead to misinterpretations of the retrofit methods' efficiency and applicability, erroneous calculation of the payback period for the retrofit measures, and an overestimation of the building's energy performance improvement.

6.3. Contribution of the Research, Limitations, and Future Work

This paper aimed to assess the effectiveness of BIM technologies in the context of retrofitting existing buildings. The findings revealed that BIM-based energy performance analysis offers valuable and efficient resources for the performance of in-depth analyses of existing buildings, as well as accurately simulating retrofitting scenarios and evaluating various alternative design options. The comprehensive capabilities of BIM technologies have shown significant potential in enhancing the efficiency and effectiveness of retrofitting practices, thus contributing to the decarbonization of existing building stock. The thorough analysis of alternative scenarios has shed light on the key factors influencing the building's energy efficiency and provided valuable insights for the optimization of its overall performance. This research also assessed the economic viability of different retrofit practices, highlighting the significance of cost-effectiveness in the refurbishment of existing buildings. This study overall provides valuable insights for environmental, economic, and technological aspects of retrofitting existing building stock using a BIM-based framework. However, despite this, there are still some limitations in this research that need to be addressed.

- One of the main obstacles to upgrading existing buildings in Turkey relates to the lack of available documentation as the building regulations were not enforced properly. In this research, the data were manually captured using measurement equipment, which requires considerable time investments. Therefore, further research is needed to explore the effectiveness of other techniques, such as laser scanning.
- The cumbersome interoperability between BIM and energy simulation tools leads to significant time investments. In this study, after the development of each retrofit scenario in BIM, the model had to be re-exported in gbXML format, resulting in numerous files. There is a crucial need for seamless and real-time connection between BIM and energy simulation tools
- A significant disparity between the computational results of GBS and real utility bills has been identified for electricity consumption. Further research is needed to evaluate the reliability of the results generated from GBS and compare them with other energy simulation software.
- In this study, a case study was conducted on a low-rise residential building to test the BIM-based retrofitting approach. Future studies can be carried out on different contexts, typologies, scales, user groups, and climate zones.

7. Conclusions

The decarbonization of existing building stock is an important step in the pursuit of a net-zero construction industry. In order to meet the requirements of a carbon-neutral building sector, the current performance of existing buildings and the effectiveness of various retrofit strategies need to be properly investigated. This study explored the feasibility of a BIM-based retrofitting framework on a three-story house located in Elazig, Turkey. The results showed that a systematic retrofitting approach might significantly improve the energy performance of an existing house, with more than a 60% reduction in annual fuel and electricity consumption. The findings indicate that BIM is a powerful tool to design, visualize, and assess various retrofit strategies from environmental, economic, and technological perspectives. Future recommendations regarding data acquisition techniques, the interoperability between BIM and energy simulation tools, and the validation of computational results are made to improve the BIM-based retrofitting approach.

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