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Research article

Affordability assessment of passive retrofitting measures for residential buildings using life cycle assessment

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A R T I C L E I N F O

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A B S T R A C T

Climate change impacts have been increasingly noticeable worldwide, especially as energy concerns have increased. Because buildings consume significant amounts of energy, sustainably retrofitting existing buildings has become essential. However, several countries are pretty concerned about the affordability of retrofitting and energy conservation measures. Therefore, this research assesses the affordability of selected passive heating and cooling retrofitting strategies using the residual approach methodology. Specifically, this work studies the effects and efficiency of retrofitting the residential buildings in Irbid, Jordan, through life cycle analysis, where dynamic thermal simulation (IES-VE) is employed. This strategy determines the required heating and cooling loads, the life cycle carbon dioxide emissions, and the economic feasibility of retrofitting using the Net Present Value methodology. The results show that passive building retrofitting can generate considerable economic and environmental benefits. Additionally, the affordability assessment reveals that retrofitting measures are affordable for 73–78% of Jordanian households. Furthermore, retrofitting makes the energy required for building conditioning affordable for 82.8–85.8% of households. This affordability assessment proved that the initial investment cost of retrofitting is the major obstacle to implementing it, especially for low-income households, despite the long-term economic and environmental benefits of this process. Thus, governmental financial support for the retrofitting projects would support achieving the sustainable development goals and mitigating climate change impacts.

1. Introduction

The energy concerns in the developing countries are increasingly noticeable, besides other global problems related to climate change and global warming [1]. Additionally, the globe's dependence on fossil fuels for energy has increased environmental concerns [2]. Buildings consume about 40% of the total energy generated globally, whereas the replacement rate of the existing buildings with new ones is only about 1–3% annually [3,4]. Thus, making buildings more energy efficient is essential to achieving sustainability, so retrofitting could significantly decrease global energy consumption and greenhouse gas emissions. However, the initial cost of retrofitting is a hindrance to implementing such projects for residential buildings, especially in low- and middle-income countries [5]. Furthermore, affordability and life cycles are crucial for bridging the gap between retrofitting benefits and costs and enhancing and

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expanding retrofitting projects.

2. Literature review

2.1. Retrofitting definition and performance assessment

According to ASHRAE [6], retrofitting is the modification of existing equipment, systems, or buildings to improve performance, update operations, enhance energy performance, or do all three. In the same vein, Vilches, Garcia-Martinez, and Sanchez-Montañes [7] defined retrofitting as building improvements that include new elements or materials to increase energy efficiency or structural integrity. However, the energy efficiency of many existing buildings has been neglected and thus requires energy retrofitting and refurbishment [8]. Energy retrofitting strategies could significantly decrease global energy consumption and greenhouse gas emissions [9,10], improving and maintaining comfortable indoor environments [11,12].

For space-conditioning accounts, which consume the most energy in residential buildings, heating and cooling are responsible for 38–55% of the total energy consumption [13]. Beyond this, a passive system is considered an excellent alternative strategy for enhancing thermal comfort within a building [14]. This is one of the most fundamental and effective energy efficiency measures [15] because passive building retrofitting decreases the energy demand of building operations. Additionally, this process is crucial in reducing the energy requirements of active systems, such as HVAC and lighting systems [16]. Passive building retrofitting includes reducing the energy demand by enhancing the natural energy embedded in the passive methods. The latter include strategies such as light shelves and light pipes, reducing ventilation and heating loads building energy demand for space conditioning, mainly through envelope retrofitting [17].

A building envelope is "the boundary between the conditioned interior of [a] building and the outdoor environment," which is critical in determining building energy consumption and performance [18]. Thus, one must first optimise the building envelope for energy conservation and then address the active mechanical systems to decrease required system loads [19]. Building envelope retrofitting aims to reduce a building's heating and cooling demands, which are mainly affected by the building envelope characteristics: walls, roof, floors, windows, and doors [20]. Many studies have revealed that proper optimisation of building envelope elements could decrease heat loss and gain, improve buildings' thermal performance and enhance energy efficiency [21–23].

The performance assessment of retrofitting evaluates the benefits of retrofitting alternatives, depending on the selected performance indicators. This process is used to benchmark building performance, which includes energy consumption; to identify operational problems and energy conservation opportunities; and to determine the effectiveness of various retrofitting measures, and optimise proper alternatives [24]. According to Ma et al. [9], building energy performance is widely used as a leading indicator of retrofitting effectiveness. This team summarised methods used to evaluate energy performance, including energy simulation and modelling, experimental and mathematical models, and the real measurement approach. Energy assessment tools estimate building energy needs and can be categorised into three categories based on the method of calculations, including dynamic simulations, normative calculations, and statistical methods [11]. Additionally, the economic and environmental impacts of retrofitting are important indicators to consider in the performance assessment of retrofitting.

Life Cycle Cost (LCC) consider an important financial approach to evaluate and compare different products in terms of initial cost against operational cost benefits during the life of the product or the service [25]. On the other hand, Life Cycle Assessment (LCA) measures the total environmental effects of the product or the services, starting from acquiring raw materials to the end-of-life phases [26]. According to ISO 14040 (2006), Life Cycle Assessment (LCA) is defined as the "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle." This method is used to assess possible environmental and economic performances of building fabrics and products throughout their life cycles [7,27]. The LCA method is crucial for sustainability analysis and provides a comprehensive framework for looking at energy in terms of timeframe and criterion. It drives us to consider all prospective energy, economic, social, and environmental effects from cradle to grave [2]. This process facilitates the estimation of the cumulative environmental impacts resulting from product LCA, including impacts not considered in the traditional analysis [2]. Additionally, LCA is used widely to assess the environmental and economic benefits of retrofitting and compare retrofitting alternatives, demonstrating the relationship between the materials' embodied and operational impacts [28].

2.2. Affordability

According to Niens et al. [29], the concept of affordability refers to securing a level of living at a price that does not impose an unreasonable burden on household finances. The chosen affordability perspective determines the affordability definition. The focus is on customer affordability as the significant perspective, indicating that the product or service is inexpensive and that the buyer is willing and able to pay for it [30]. Customer affordability was described by Redman and Stratton [31] as the ability of a product or service to be bought when it is needed at a reasonable cost according to the customer's budget and whether that product or service can meet the customer's performance requirements during its expected life cycle.

Many researchers believe that an affordability definition should consider various elements, including the maintenance and operation of the product over its expected life cycle [32]. Others added the cost of the entire project or product, and its relation to the customer's long-term investment capability [33]. These factors identify the relationship between life cycle costing and customer affordability.

Customer affordability is affected by both quantitative and qualitative factors. The two main quantitative factors are customer budget which is the financial ability or willingness of the customer to buy the product or service, and the whole life-cycle costs (WLCC) of the product or service [30]. On the other hand, qualitative factors affecting customer affordability differ according to the industry or field. Nogal [34] said these factors include world economic climate, competition, quality, performance, customer requirements, legislations, risk, the value of money, and uncertainties. Furthermore, the time value of money is essential in affordability assessment because payments involve long time periods or high discount rates; otherwise, ignoring the time value of money is not a problem [2].

Generally, affordability measurements are linked either to average expenditure as a percentage of income or to a fixed threshold. Two main approaches are commonly used to assess affordability. The first approach depends on the expenditure ratio to the total household income and is called the catastrophic payment method, widely used to determine the affordability of transportation, education, and healthcare. Additionally, Lapsa, Brown [35] have used this method to assess energy affordability, arguing that an energy bill is affordable if it does not exceed 6% of household income. This assessment assumes that utility costs should not exceed 20% of housing costs and that housing costs should not exceed 30% of household income. Lapsa, Brown, and Soni's measure of energy affordability is based on the U.S. Department of Housing and Urban Development's (HUD) ratio of housing affordability [35]. However, this method has been criticised because the ratio does not consider the housing quality or differences in household size and location [36–38].

The second approach is the impoverishment or residual income approach, which depends on the residual income for the household after the expenditure used for assessing housing affordability and health care [29,39]. This method is based on the idea that a household must make certain purchases beyond utilities, which are generally employed in the middle- and low-income communities [40–42].

2.3. Residential Buildings and economic situation in Jordan

Residential buildings in Jordan consist of three main types: villa, Dar, and apartments. Single-family house type (Dar) accounts for 61.5% of residential buildings in Jordan, with an average area of 155.4 m^2. Additionally, the highest growth rate of single-family houses in Jordan is found in Irbid, a rate of 3.75% per year [43,44]. Building construction and materials consume copious amounts of energy; although 64.3% of residential buildings are built from reinforced concrete and block, 88.1% of the total residential buildings are not thermally insulated [44]. Thus, buildings constructed in Jordan during the last decade are "not well adapted to the climate" because they require high heating and cooling loads [45].

The Jordanian code of thermal insulation requires specific characteristics for the building envelope components to ensure energy efficiency. However, only 2% of buildings in Jordan meet the requirements of this code. There are no established programs in Jordan that contribute to the implementation of NetZero Buildings and the improvement of existing buildings' performance. Specific energy efficiency programs serve as a foundation for implementing NetZero Buildings, including the nonprofit Jordan GBC. This nongovernmental organisation offers internationally accredited training programs and works to make green buildings a widespread reality [46].

From 1990–to 2017, Jordan's total greenhouse gas (GHG) emissions increased by 188% [18]. The energy sector contributes to about 72% of the country's total GHG emissions, whereas building operations are responsible for 28%. Additionally, the residential sector accounts for approximately 45.4% of total electricity consumption and 22% of the total energy consumption, mainly improving indoor environment quality with heating, cooling, or lighting [44,47].

According to the World Bank report, Jordan is an upper-middle-income country [48]. However, according to a recent report released by the Jordanian Department of Statistics [44], about 37.6% of Jordanian households' annual income does not exceed 7500 JOD (equivalent to 10,578.41 USD) (625 JD per month), as shown in Fig. 1, and the absolute poverty line for a household is 5760 JD annually (4,80 JD per month; [44]. As the poverty line and poverty rates rise, the economic aspect of any retrofitting project for Jordanian households becomes increasingly essential.

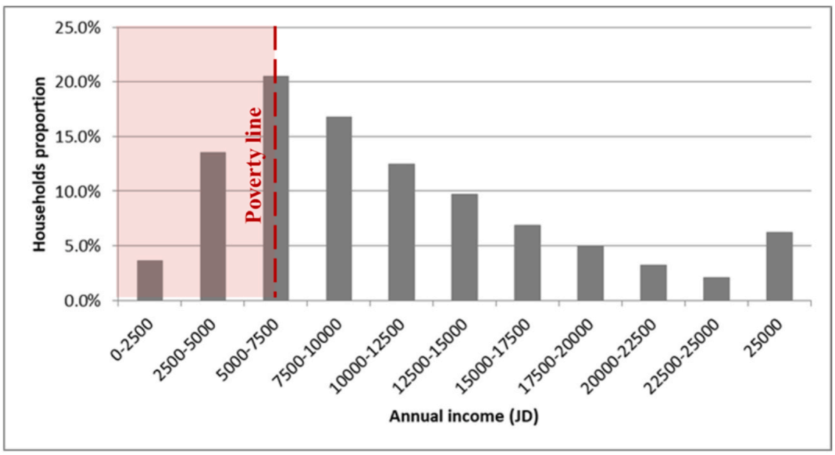

Fig. 1. Percentage distribution of Jordanian households by current income groups (2017–2018) [44].

Therefore, this research is dedicated to assessing the affordability of selected passive heating and cooling retrofitting strategies depending on a broad framework using life cycle assessment methodology by considering energy, economic, environmental impacts, and annual household residual income. This work examines the effects of retrofitting residential buildings in Irbid, Jordan, through life cycle analysis for the required heating and cooling loads, carbon dioxide emissions, and the economic feasibility of retrofitting. To achieve this goal, the energy performance of each retrofitting case is analysed regarding the annual heating and cooling loads required for building conditioning to reach the comfort zone. Beyond this, affordability and energy affordability are assessed only for retrofitting cases achieving annual load reduction. Next, the economic and environmental performances are assessed over the life cycle of the building.

3. Methodology

This research methodology includes four main stages to fulfil the research objectives. The first stage involves selecting and investigating the base case representing the largest sector and the most common type of residential buildings in Jordan. The second stage is the determination of the passive retrofitting measures that are suitable for residential buildings. Third, the study examines the implementation of the identified retrofit measures on the base case model to investigate its efficiency and impact on the annual heating and cooling loads using dynamic thermal simulation using (IES-VE) software. The affordability of the retrofitting project is assessed, as is the affordability of the energy required for building conditioning after the retrofitting implementation. Finally, the fourth stage employs life cycle assessment to evaluate the economic and environmental impacts of retrofitting.

3.1. Base case determination

The study's base case was selected to represent Jordan's most common residential building type and characteristics. As a result, the base case is a one-story, single-family house with a total floor area of 155 m^2. The building's total window-to-wall ratio is 15%, with windows measuring 1 m in height and 2 m in width. The envelope's air infiltration rate is 2 ach, which is the average infiltration rate for concrete block constructions [49]. Lastly, the envelope's reflectance is 10%, and the emissivity is 0.6. Fig. 2 and Table 1 show the prototype and construction parameters of this example.

The base case is in Irbid city, which is located in the Mediterranean climate region, and the city represents the most populated region in Jordan. Additionally, Irbid city shows the highest growth rate of a single-family house prototype in Jordan at 3.75% per year, according to the Department of Statistics reports. Irbid is located in the northern region of Jordan, situated at 32.5° N and 35.8° E, the most densely populated city in the country [50]. The city's mild Mediterranean climate is characterised by a warm, sunny summer with a highest average temperature of 31.3 °C in August, and cool, rainy winter with a lowest average temperature of 4.9 °C in January. The average monthly temperatures are displayed in Fig. 3 [51].

The thermal template and occupancy profiles of a household are crucial because they affect the accuracy of energy demand predictions. In this study, the occupancy patterns were used to determine the running periods of heating and cooling systems, and each was assumed to represent a working family consisting of five people, two adults and three kids, which is the average Jordanian family size [44]. The building rooms were categorised into three zones, as presented in Fig. 2: the living zone, sleeping zone, and guest zone. This categorisation sets the occupancy profiles of the house occupants, reflecting the heating and cooling systems' operation profiles as presented in Table 2.

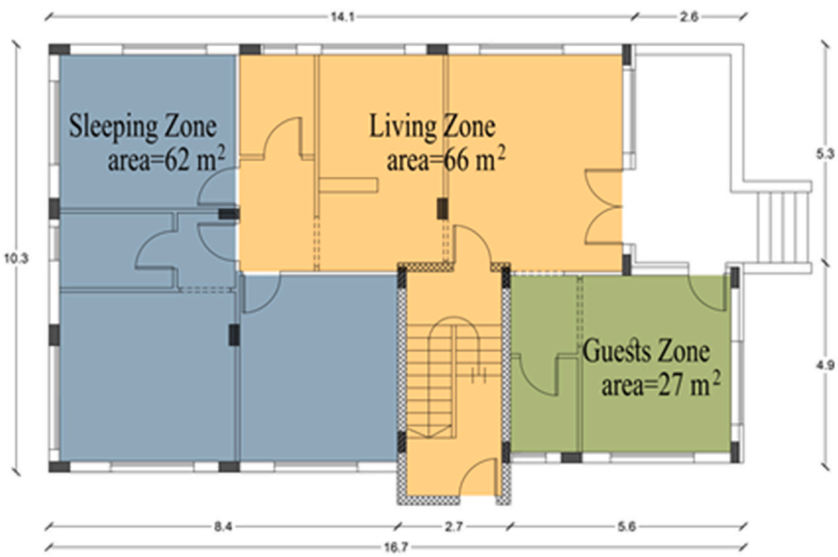

Fig. 2. The studied base case layout and occupancy zones].

Table 1
Base case construction parameters.

Element	Layers	Layer Thickness (cm)	Thickness (cm)	U-value (W/m^2.K)
External walls	Cement plaster	3	26	1.55
	Hollow concrete block	20		
	Cement plaster	3		
Roof	Screed	5	33	2.46
	Reinforced concrete	7		
	Concrete block	18		
	Cement plaster	3		
Floor	Tiling	2.5	50	1.69
	Mortar	2.5		
	Sand	10		
	Reinforced concrete	15		
	Gravel-hardcore	20		
Windows	Single pane glazing	0.3	–	6.44
	Aluminium frame	0.3		

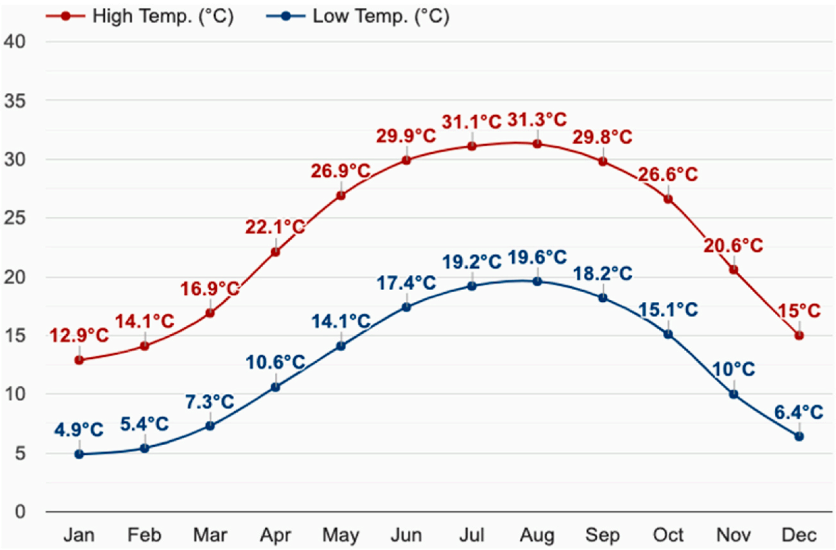

Fig. 3. Average monthly temperature in Irbid, Jordan.

3.2. *Verification of base case model*

Real-site measurements of the indoor air temperatures were used to validate and check the accuracy of the simulation results for the indoor air temperatures of the base case model. The site measurements were taken while the building was occupied in two typical weeks during the summer and winter seasons. In the living room, one data logger (Extech SD800) was put in place. The data logger was mounted 1.2 m above the floor level in the middle of the living room, and measurements were taken every 15 min. The recorded measurements agreed with the simulation results, with an average of 2–3% error for the whole recorded weeks.

3.3. *Determination of retrofitting measures*

This study involved the adoption of passive heating and cooling retrofitting measures, which are effective in decreasing energy consumption while having a low environmental impact and reasonable costs. In this work, the passive heating and cooling retrofitting measures that can be implemented on residential buildings were separated into two groups. The latter was determined as the study's

Table 2
Building occupancy pattern.

Zone	Occupancy period	Occupancy duration	Occupants No.
Living	17:00–22:00	5 h/day	5
Sleeping	14:00–16:00 and 23:00–7:00	10 h/day	2 per room
Guests	18:00–20:00	2 h/week	8

independent variables: wall insulation, roof insulation, window retrofitting, solar shading, infiltration rate, and finishing colours. The first group of retrofitting measures was established in accordance with the Jordanian code of thermal insulation requirements. That is, the Jordanian code of thermal insulation specifies precise characteristics for building envelope components to ensure energy efficiency, as shown below in Table 3. The second group of measures was determined to achieve the Jordan Green Buildings Guide (JGBG) requirements. This research involved the passive heating and cooling at both the obligatory and voluntary requirements levels, depending on which was higher. Table 3 displays the determined retrofitting measures and their groups.

3.4. *Retrofitting assessment*

3.4.1. *Annual loads assessment method*

Conducting a building loads analysis is the first stage in determining and comparing the benefits of building passive heating and cooling retrofitting techniques. In this study, computer simulation software (IES-VE/ApacheSim) was used to calculate the annual and monthly loads required for building heating and cooling using a building performance simulation engine and measuring heat transfer based on the thermal characteristics of the envelope. The difference between the annual loads required for the base case and the building after retrofitting implementation was used to evaluate the performance of retrofitting measures regarding annual loads. This research used dynamic thermal simulation to analyse energy requirements, as they depend on the physical characteristics of the building envelope; the occupancy patterns of the building; and the thermal conditions of the building, including daily heating and cooling periods.

3.4.2. *Validation of base case annual loads*

Another step was conducted to verify the simulation results as in the following: The annual heating and cooling loads of this study were compared to similar studies (Single-family house, located in Irbid, Jordan, and having similar construction materials and envelope specifications). The findings of this study were in good agreement with these studies, as presented in Table 4.

Table 4 shows that annual loads of similar studies using simulation software range between 61.8 and 136 kWh/m^2. However, the annual load for the Base Case is 85.1 kWh/m^2, which falls within the range of the similar cases. Generally, annual building loads show a difference of less than 1.6% between actual and simulation results, which is considered acceptable for energy simulation validation, according to Fathalian and Kargarsharifabad [55]. The difference in the annual loads between the cases can be due to several reasons, including the difference in occupancy patterns, running periods of the heating and cooling systems, and the difference in heating and cooling systems set points.

3.4.3. *Affordability assessment*

Considering the affordability of retrofitting measures is especially important in low-income communities to enhance the acceptance and distribution of such measures. In this research, the researchers studied the affordability of different retrofitting cases to be implemented on the chosen single-family house. Additionally, the affordability of energy after the retrofit implementation is studied to form a solid basis to assess the affordability of a retrofitting project, using the methodology defined in the following sections.

3.4.4. *Affordability of measures*

Customer affordability was studied to determine affordability from the building owner's perspective. Retrofitting affordability was examined regarding initial costs, rewards from energy-saving, and household income categories in Jordan following the impoverishing effect method. The latter is also called the residual income approach.

The impoverishing effect of retrofitting is defined according to the percentage of households that would drop below the poverty line (5760 JD per year) after implementing the retrofit, which is the minimum amount of income needed to fulfil basic household needs and

Table 3
Retrofitting cases parameters and categorisation.

Building Components		Group I Cases		Group II Cases	
External Walls	Insulation	Case No. 1	4 cm of extruded polystyrene	Case No. 6	5 cm of extruded polystyrene
	U-value (W/m^2.K)		0.57		0.45
Roof	Insulation	Case No. 2	5 cm of extruded polystyrene	Case No. 7	6 cm of extruded polystyrene
	U- value (W/m^2.K)		0.55		0.43
Windows	Thickness	Case No. 3	6 mm double pane with an air gap	Case No. 8	6 mm double pane with argon filling
	SHGC		0.237		0.189
	Shading Co.		0.27		0.21
	Net U-value (W/m^2.K)		2.03		1.68
Solar shading	Case No. 4	Fixed external shading devices	–		
Infiltration	Case No. 5	1 ach	–		
External Finishing	Emissivity	–	Case No. 9	0.76	
	Reflectance	–		0.71	

Table 4
Annual heating and cooling loads for the Base Case and similar studies (Simulation values).

Model (reference)	Building type	Study location	Annual load (kWh/m^2) (Simulation)	Error (actual to simulation)
Base Case (This research)	Single-family house	Irbid, Jordan	85.13	–
Ma'bdeh, Ali [52]	Single-family house	Irbid, Jordan	61.8	1.37%
Shariah, Tashtoush [53]	Single-family house	Irbid, Jordan	136	1.59%
El Hanandeh [54]	Single-family house	Irbid, Jordan	134	1.57%

is estimated by the National Aid Fund Department [44]. All income levels of Jordanian households, presented in Fig. 1, were included in the study, and each income category was divided into nine minor groups to produce more accurate results. Additionally, linearity was assumed in the population distribution for the new minor income categories for simplification following the methodology of [29]. This approach compares a household's annual income before and after the retrofit, a method used to generate "impoverishment rates." The latter indicates the percentage of the population that would become impoverished, generating the population rates whose income levels (category) would lower (be negatively affected).

To conduct affordability analysis, four types of data were required: Jordanian households' Income data, population, and household distribution per income wages, retrofit investment cost, and the price of the energy saved. Investment costs were obtained from local manufacturers and distributors, whereas the income-related data were obtained from the department of statistics reports [44]. In this research, the cost of payment for the retrofitting investment was assumed to be completed during the first year, as the minimum allowed bank loan amount in Jordan is above 1000 JD, more than the studied retrofitting cases initial investment costs.

Retrofitting was considered affordable for households that would remain above the poverty line (5706 JD/year) after implementing the retrofitting measure, following the condition explained in Eq. (1). Additionally, the affordability of measures was compared depending on the percentage of the affected households the impoverished households and the households whose income categories have been reduced.

$$Ai - (RIcost - EPs) > 5706 \quad (1)$$

Where Ai is the annual household income in JD, RI cost is the initial investment cost required to implement the retrofitting measure, and EPs is the annual saved energy price resulting from retrofitting in JD.

3.4.5. Affordability of energy

Making energy systems affordable means ensuring that costs and needs are balanced with the ability of users to pay. In this research, the affordability of energy for building conditioning was studied before and after the implementation of retrofitting following the fixed ratio approach. The affordability of energy was studied for households below the poverty line to determine if retrofitting would increase the energy affordability for that household. Building conditioning (heating and cooling) energy is considered affordable if its cost does not exceed 6% of a household's annual income, following Colton's [56] methodology for measuring energy affordability according, as displayed below in Eq. (2). This methodology is based on the U.S. Department of Housing and Urban Development's (HUD) ratio for housing affordability, which assumes that a household's spending should not exceed 30% of its gross annual income on total housing costs. The latter include principal and interest payments; taxes; and services such as electricity, gas, water, and waste management.

$$EP/Ai < 0.06 \quad (2)$$

where EP is the price of energy required annually for building conditioning in (JD), and Ai is the annual household income in (JD).

3.4.6. Life cycle assessment of retrofitting cases

Generally, building life cycle assessment (LCA) goals are multifaceted. This study evaluated the environmental and economic benefits of retrofitting situations using a simplified LCA technique incorporating life cycle carbon emissions assessment (LCCO2) and life cycle costs assessment (LCC). Social aspect assessment is not considered in this life cycle assessment.

The first stage in LCA is to identify a study's goal and scope. According to the simplified LCA method, the system boundary for carbon emissions includes product stages (A1–A3) and operational stage B6, but this step includes operational stage impacts only for cost assessment. Additionally, building lifespan has an important impact on LCA study results because it affects the total energy consumption during the building operation phase. In this study, the building lifespan is defined as 50 years, and the LCA functional unit is the entire building space. The life cycle inventory stage involves defining the total embodied and operational CO_2 emissions and life cycle costs. The operational CO_2 emissions are calculated by simulation using (IES-VE), and the embodied CO_2 per unit value for retrofitting materials is derived from the literature. The life cycle costs include retrofitting costs obtained from local contractors and the consumed energy costs.

3.4.7. Life-cycle carbon emissions

In this research, environmental assessment was conducted only for retrofitting cases that achieved annual load reductions compared with the base case. It includes the embodied CO_2 and the operational CO_2 emissions related to building conditioning during the building's life cycle. Next, CO_2 emissions were analysed as the main environmental indicator of the building before and after the retrofit implementation; other greenhouse gases were neglected.

The operational carbon dioxide emissions, those resulting from heating and cooling energy consumption related to the base case and each retrofitting case over the building's lifespan, were calculated by simulation in terms of CO_2 amount in kilograms. The simulation program calculated the CO_2 emission amount resulting from heating and cooling systems depending on the CO_2 emissions factor related to the fuel type, which is 0.241 $kgCO_2/kWh$ for a heating system using LPG and 0.581 $kgCO_2/kWh$ for cooling using system electricity [57].

Additionally, the retrofitting process includes the installation of new material to the existing building, so this operation increases the structure's embodied carbon. Embodied carbon related to each retrofitting measure was obtained from the Inventory of Carbon and Energy (ICE) database. Next, these data were interpolated and calculated using the amount of retrofitting material used in each case. The base case was assumed to contain no embodied carbon. Life-cycle CO_2 emissions for each case were determined according to Eq. (3) below.

$$\mathrm{LCCO_2}\ (\mathrm{kgCO_2}) = \text{Annual carbon emissions x building lifespan} + \text{embodied carbon} \tag{3}$$

3.4.8. *Life-cycle cost*

The economic feasibility of the retrofitting project was crucial. Thus, life-cycle costs assessment was conducted for each retrofitting measure, so this research considered two main economic variables to calculate LCC. The first variable was the initial investment cost, comprising the cost of the measure itself, installation costs, and labour, measures obtained from local contractors. For the second variable, the annual economic savings resulted from energy savings after retrofitting implementation, which was the saved energy price with respect to the base case. Therefore, the life cycle cost of the retrofit measure for a one-year operation can be calculated in Eq. (4):

$$\text{LCC (JD)} = \text{Investment cost} + \text{annual Energy costs} \tag{4}$$

The economic assessment conducted in this research employed the net present value method (NPV) explained in Eq. (5), which sums the initial capital investment and the present cash inflow and outflow over the lifespan of the retrofitting project considering the time value of money expressed in the form of a discount rate. The total cash flow of each retrofitting case included the initial investment cost of the retrofitting implementation and any maintenance or replacement costs over the building's lifespan. The latter were determined based on local contractors' and suppliers' prices, which were considered cash outflows. Additionally, this amount included the income generated by energy savings, considered a cash inflow. In this study, the discount rate is defined as the risk-free rate of return, where money can be expected to be made on a project with no risk. According to World Government Bonds (2020), the risk-free rate of return is commonly equated to the interest paid on a three-month government Treasury bill, which in Jordan is 2.44%.

NPV formula can be written as follows:

$$\mathrm{NPV} = \sum_{t=0}^{n} F^t (1+i)^{-t} \tag{5}$$

where t is the time in years, n the number of years, Ft the net cash flow in year t, and i the interest rate per period. The acceptance rule of NPV is the project is accepted when NPV is positive (NPV $>$ 0) and rejected when NPV is negative (NPV $<$ 0), and it may be accepted when NPV is zero (NPV = 0), where a higher NPV value represents the most feasible project.

4. Results and discussion

4.1. *Energy performance*

The total annual loads required for building conditioning for the base case and all retrofitting cases are presented in Table 5 and Fig. 4. The results show that not all the retrofitting cases were effective in reducing heating and cooling loads. Five cases achieved load reduction and improved building performance: Case Nos. 1, 2, 5, 6, and 7, cases that have reduced the building annual loads by 6.1%,

Table 5
Annual heating and cooling loads for base and retrofitting cases.

Case	Heating loads kWh	Cooling loads kWh	Total loads kWh	Total saving %
Base case	12424.02	770.56	13,195	–
Case No. 1	11646.46	745.78	12,392	6.1%
Case No. 2	11213.44	265.58	11,479	13%
Case No. 3	12624.5	621.46	13,246	−0.4%
Case No. 4	12592.3	660.24	13,253	−0.4%
Case No. 5	10519.32	740.0179	11,383	14.7%
Case No. 6	11572.96	746.2	12,319	6.6%
Case No. 7	11152.82	250.46	11,403	13.6%
Case No. 8	12684.42	587.58	13,272	−0.6%
Case No. 9	14377.3	254.52	14,632	−10.9%

13%, 14.7%, 6.6%, and 13.6%, respectively. Building retrofitting by increasing envelope airtightness (case No. 5) produced the best results for building conditioning load reduction compared with other retrofitting cases. In this case, the air change rate effectively reduced both heating and cooling loads. Next, roof retrofitting cases (Nos. 2 and 7) displayed the second-best performance in reducing the annual heating and cooling loads, and lastly wall retrofitting cases (Nos. 1 and 6). These cases, which produced the best results as retrofitting cases, depended mainly on reducing the heat transfer between indoor and outdoor environments by increasing the thermal resistance and air tightness of the building envelope.

On the other hand, the results proved that not all passive retrofitting measures would be suitable for energy conservation in the study area. More specifically, four cases were ineffective as retrofitting measures and increased the total building loads for window retrofitting cases (Nos. 3 and 8), fixed non-movable solar shading (No. 4), and finishing retrofitting (No. 9). However, these cases were not efficient in reducing the total building loads. That is, these cases reduced the buildings' cooling loads by 19.3%, 23.7%, 14.3%, and 67%, respectively, indicating these measures could efficiently reduce total building loads in hotter regions, where cooling needs are dominant. These results were similar to those of Košir et al. [58] and Tsikra and Andreou [59]. In the same, Case Nos. 3, 4, and 8 would be effective as retrofitting measures in the study area if they were modified to increase the solar heat gain to enhance building performance in the heating season. That is, this measure caused a slight increase in the annual heating loads for the aforementioned cases by 1.6%, 1.4%, and 2.1%, respectively.

The retrofitting measures that efficiently decreased total building conditioning loads (Case Nos. 1, 2, 5, 6, and 7) were assessed for affordability and economic and environmental performance. Other cases were inefficient as retrofitting measures for this type of building in similar locations and were thus excluded from the environmental and economic assessments.

4.2. Affordability assessment

The retrofitting initial investment was crucial in the economic assessment of retrofitting. The initial investment for each retrofitting case was determined depending on the lowest price proposed from three certified local contractors for retrofit material and implementation costs. Additionally, retrofitting economic benefits such as the price of saved energy were important in the economic assessment. Table 6 displays the energy prices related to different fuels in Jordan, which were used in calculating the saved energy prices. The price of energy used for heating was calculated in terms of LPG cylinder, whereas energy consumed for cooling was calculated based on electricity strips prices in Jordan. The initial investment of each retrofitting case and the prices of the saved heating and cooling energy are presented in Table 7.

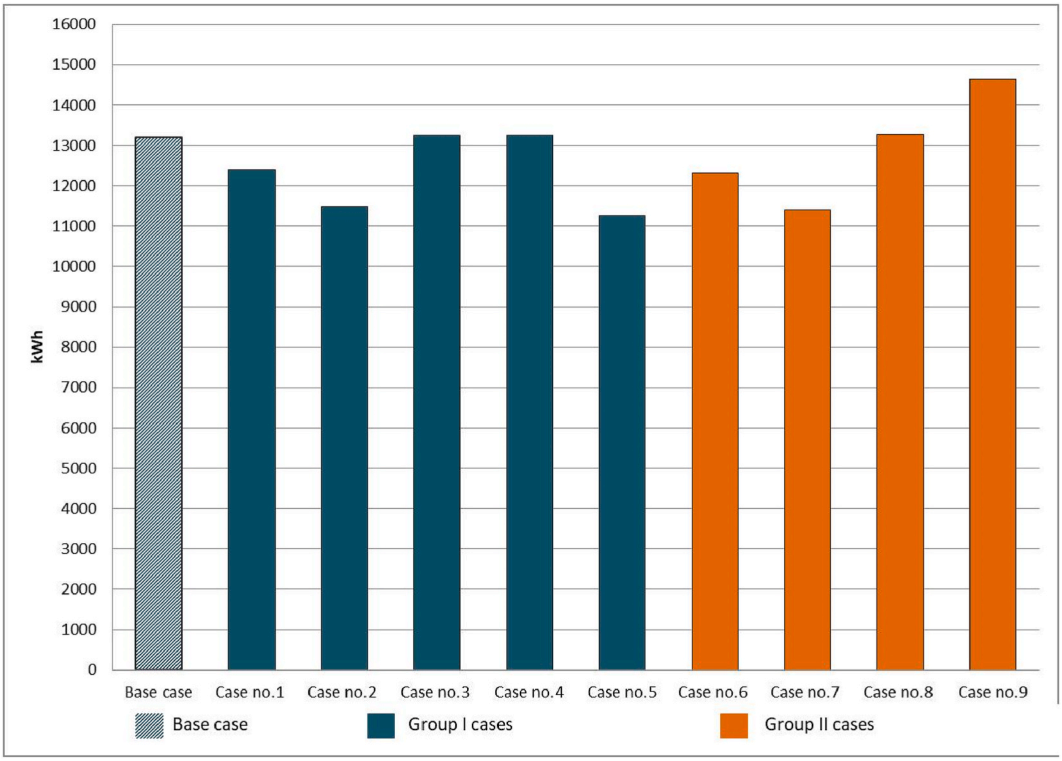

Fig. 4. Annual building loads for the base and retrofitting cases.

4.3. Retrofitting case affordability

Because Jordan is a middle-income country where the affordability of any project is critical, the impoverishing effect method was used to investigate retrofitting affordability. This method compares the proportion of the population below the poverty line (PL) before (Ipre) and after (Ipost) retrofitting. In this study, the affordability of retrofitting cases was analysed depending on the percentage of negatively affected households. This equation involved adding impoverished households to households whose income categories had been reduced after retrofitting purchasing (this affected household proportions).

Fig. 5 demonstrates that all the retrofitting cases analysed would be affordable to a high number of Jordanian households, ranging from 73 to 78%. Because of its low initial cost, Case No. 5 had not impoverished or pushed any proportion of Jordanian households below the poverty line, implying that it would be affordable for all Jordanian households above the poverty line (78.3%). Additionally, Case No. 1 was affordable to 76.03% of households, and Case Nos. 2, 6, and 7 were affordable to 73.75% of households. On the other hand, the results in Table 8 show the total proportion of affected households (impoverished plus lowered category). Furthermore, Case No. 5 had the least negative effect and was the most affordable case because the saved energy price in the first year was higher than the initial cost of the retrofit implementation (total cost is negative). Thus, retrofitting increases household income and functions as a new income source, making it affordable for all households.

On the other hand, the total cost (initial cost – saved energy price) of Case No. 7, which the least affordable case, was relatively high and could cause financial difficulties on 26.7% for the households. Thus, the case would be affordable for fewer households, especially those with an annual income above 6400 JD, as presented in Fig. 6. This figure demonstrates the affordability of the retrofitting cases and the minimum annual income of households for whom retrofitting was considered affordable. Notably, retrofitting benefits and energy savings price are crucial in determining the practice's affordability, consistent with the findings of Riley [60], who studied the affordability of clean cookstoves, considered sustainable energy development products. This study revealed that product affordability is highly dependent on the income that can be derived from carbon credits.

4.4. Energy affordability

Energy prices provide a large share of household income, especially for low-income households. This study examined the affordability of energy needed for building conditioning before and after the retrofitting implementation for the household poverty line. The results revealed that the energy bill in the base case would not be affordable for the households below the poverty line (5760 JD/year; 22.2%), because it would account for more than 6% of their annual income. However, energy affordability increased after implementing the retrofitting cases to become affordable for a higher proportion of the Jordanian households. The energy bill become affordable for 82.8% of the households after Case No. 1 retrofitting; for 84.3% of households after the retrofitting in Case No. 6; and for 85.8% of households after implementing Case Nos. 2, 5, and 7, as presented in Fig. 7 and Table 9. Energy affordability increased because building retrofitting reduced the energy needed for building conditioning, which reduced the energy bill to make it reasonable for low-income households.

Although the studied retrofitting cases were not affordable for poor households, implementing retrofitting would make their energy bills affordable. Building retrofitting could have a positive impact even for the low-income households because less spending on energy bills means more spending on other necessities, improving the household economy and living standards. However, the aim of this affordability analysis was to define and propose a simple assessment method that could help in retrofitting alternatives comparison. Beyond this, life cycle environmental and economic assessments conducted to facilitate a more comprehensive comparison process.

4.5. Life cycle Environmental and economic assessment

This study assessed the life cycle environmental and economic impacts and performance of the retrofitting cases that achieved annual loads reduction. In this research, life-cycle environmental assessment considered the life cycle carbon dioxide emissions related to building retrofitting process, materials, and operations regarding embodied and operational CO_2 emissions. Although life cycle economic performance is assessed using NPV methodology, it considers all the money in- and outflows related to the retrofit application during the defined building lifetime (50 years).

Life-cycle carbon ($LCCO_2$) of retrofitting is the amount of carbon dioxide emitted during the building life cycle including materials embodied CO_2 and operational CO_2. In this research, $LCCO_2$ included the retrofitting material embodied carbon and building operations (heating and cooling) carbon emissions after the retrofit implementation during the remaining lifetime of the building, determined to be 50 years. The reduction in the life cycle carbon dioxide emissions, which included the embodied and the operational

Table 6
Energy prices in Jordan as of 2021.

Energy source	JD/kWh	
LPG	0.024	
Electricity	1–160 kWh	0.033
	161–300 kWh	0.072
	301–500 kWh	0.086
	501–600 kWh	0.114

Table 7
Retrofitting initial cost and saved energy prices.

Case	Investment cost (JD)	Heating energy savings (LPG) (JD/year)	Cooling energy savings (Electricity) (JD/year)	Annual energy-saving cost (JD/Year)
Case No. 1	389.6	22.40	0.80	23.20
Case No. 2	534.75	34.90	16.70	51.50
Case No. 5	40.3	54.90	1.00	55.80
Case No. 6	487	24.50	0.80	25.30
Case No. 7	641.7	36.60	17.20	53.70

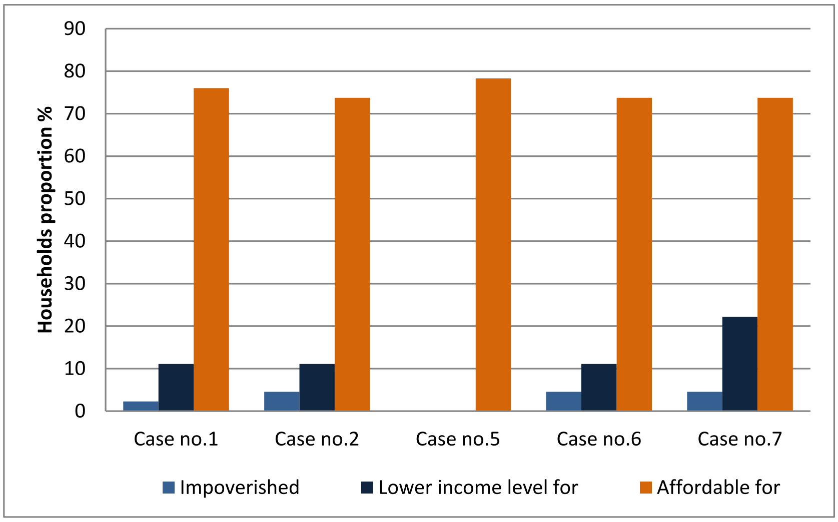

Fig. 5. Affordability and impoverishment effect of retrofitting cases on the Jordanian households.

carbon emissions related to each retrofitting case, was calculated and presented in Table 10. Case No. 5 demonstrated the highest rate of $LCCO_2$ reduction (11.93%), followed by Case Nos. 7 (10.23%), 2 (9.83%), 6 (4.67%), and 1 (4.30%). Additionally, $LCCO_2$ reductions results were determined and affected by the annual load reduction related to each retrofitting case, and the amount of emissions reduction was related to the amount of the annual load reduction. However, these figures were not proportional; a slight difference between CO_2 savings and load-saving proportions was observed, a difference resulting from the heating and cooling system efficiencies and the fuel emissions factors.

Reducing the life cycle carbon emissions is one of the main objectives of any retrofitting project. In this study, the results revealed that retrofitting cases had increased the embodied carbon emissions of the building. That is, the retrofitting process included installing new materials to a building, but the operational CO_2 emissions had lowered significantly due to the reduction in heating and cooling demands, as presented in Fig. 8. For example, the implementation of Case No.7 increased the building embodied CO_2 by 937.71 kg, but this same measure reduced the operational CO_2 emissions by 4943 kg in the first year only. Thus, life-cycle carbon emissions were calculated to facilitate the comparison between the retrofitting cases' environmental impacts and benefits. Ana [61] stated that retrofitting decreases operational CO_2 emissions but increases the embodied CO_2 of a building due to the installation of carbon-intensive materials. Thus, the selection of the best energy retrofit must consider this issue.

Case No. 5 produced the highest rate of $LCCO_2$ reduction, followed by Case Nos. 7, 2, 6, and 1. Additionally, $LCCO_2$ reductions results were determined and affected by the annual loads reduction related to each retrofitting case. These cases showed significant reductions in $LCCO_2$ emissions compared with the base case, results similar to those of Ardente, Beccali [24], who found that this retrofitting could reduce carbon dioxide emissions over these developments' expected lifetime. In the same vein, Gangolells et al. [62] discovered that nearly all of the energy-efficient retrofitting measures reduced building $LCCO_2$ emissions.

The embodied carbon of retrofitting accounted for less than 1% of the entire life cycle emissions, whereas the operational emissions produced the largest share. That is, the heating and cooling operating systems depend mainly on fossil fuel, which has a high CO_2 emissions factor, making the embodied CO_2 amount negligible. However, if the heating and cooling systems depend on renewable energy, the operational CO_2 amount would become negligible, and the embodied carbon would account for a considerable share of the $LCCO_2$ emissions. These conditions make selecting the retrofitting material selection and considering its embodied impacts crucial for

Table 8
Affordability and impoverishment effect of retrofitting cases on the Jordanian households.

Case	Initial cost (JD)	I pre	I post	Impoverished households (%)	Lower income level for (% of households)	Percentage of Negatively Affected households %	Affordable for (% of households)	Energy affordable for (% of households)
Case No. 1	389.6	22.2%	24.478%	2.278	11.107	13.385	82.8	73.24
Case No. 2	534.75	22.2%	26.756%	4.556	11.107	15.663	85.8	70.244
Case No. 5	40.3	22.2%	22.2%	0	0	0	84.4	70.244
Case No. 6	487	22.2%	26.756%	4.556	11.107	15.663	85.8	71.744
Case No. 7	641.7	22.2%	26.756%	4.556	22.214	26.77	85.8	70.244

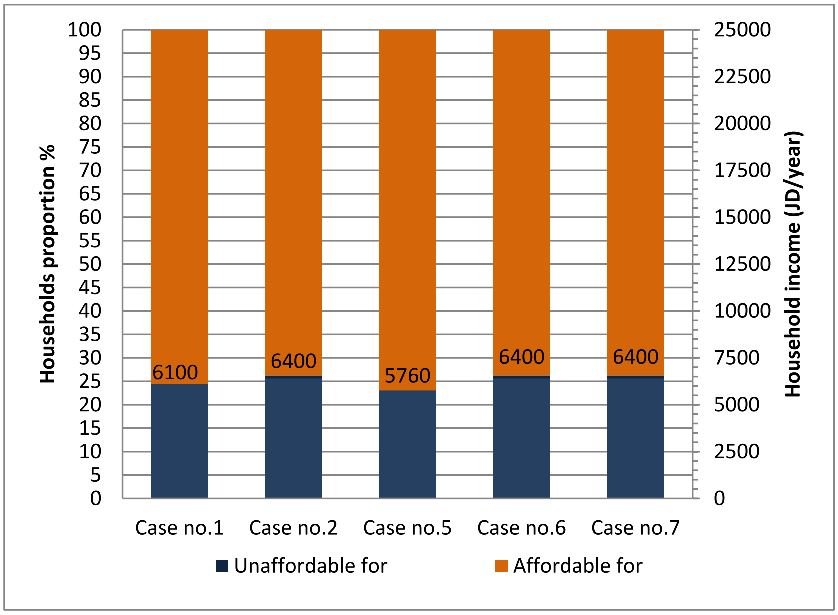

Fig. 6. Affordability of retrofitting cases and minimum household income required to make retrofitting cases affordable.

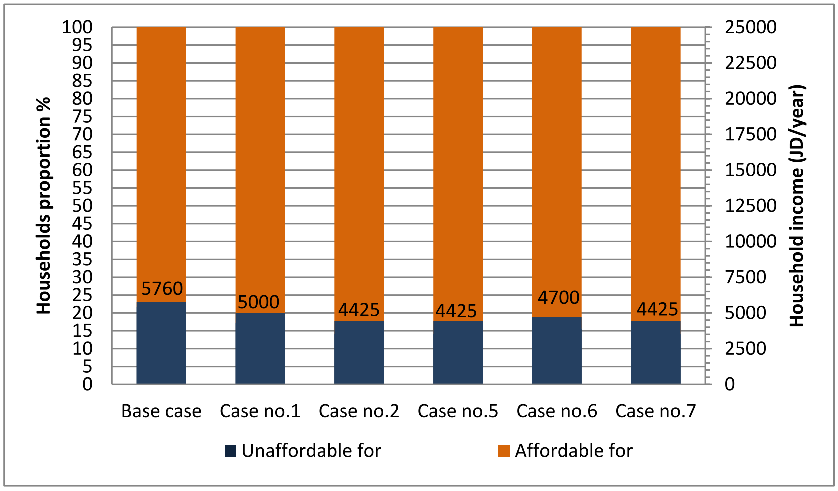

Fig. 7. Energy affordability before and after retrofitting.

reducing the life cycle emissions and achieving the intended environmental benefits.

The economic feasibility of each retrofitting case was studied in terms of life-cycle cost analysis using the NPV method, accounting for initial retrofitting costs, maintenance costs, and energy-saving prices. As presented in Table 10, the NPV of Case No. 5 was the highest among all the retrofitting cases, revealing that this case was the most feasible retrofitting choice from an economic perspective. Additionally, the environmental and energy aspects produced a high load reduction with a low initial cost. On the other hand, retrofitting cases can be ordered according to their NPV values from high to low, as follows: Case Nos. 5, 2, 7, 1, and 6. Similar results were obtained by Shen, Braham, and Yi [63] who studied the economic feasibility of several retrofitting alternatives, revealing that higher annual savings did not necessarily produce more feasible measures. Thus, it is important to use economic effectiveness measures, such as NPV, to evaluate the economic feasibility of retrofitting projects.

Although the economic aspect is the major obstacle for any retrofitting project, the results of this study proved that many retrofitting alternatives are suitable for residential buildings and are affordable for a wide range of households without imposing an unreasonable burden on each household's economy. Thus, supporting retrofitting projects financially and morally is crucial from environmental, and economic point of view at the domestic and national levels, combating climate change and achieving the sustainable development goals.

Table 9
Energy share of poor households' annual income.

Income categories (JD/year)	Base case	Case No. 1	Case No. 2	Case No. 5	Case No. 6	Case No. 7
0–275	117.8%	109.5%	99.3%	97.7%	108.7%	98.5%
275–550	58.9%	54.7%	49.6%	48.9%	54.4%	49.2%
550–825	39.3%	36.5%	33.1%	32.6%	36.2%	32.8%
825–1100	29.5%	27.4%	24.8%	24.4%	27.2%	24.6%
1100–1375	23.6%	21.9%	19.9%	19.5%	21.7%	19.7%
1375–1650	19.6%	18.2%	16.5%	16.3%	18.1%	16.4%
1650–1925	16.8%	15.6%	14.2%	14.0%	15.5%	14.1%
1925–2200	14.7%	13.7%	12.4%	12.2%	13.6%	12.3%
2200–2500	13.1%	12.2%	11.0%	10.9%	12.1%	10.9%
2500–2775	11.8%	10.9%	9.9%	9.8%	10.9%	9.8%
2775–3050	10.7%	10.0%	9.0%	8.9%	9.9%	9.0%
3050–3325	9.8%	9.1%	8.3%	8.1%	9.1%	8.2%
3325–3600	9.1%	8.4%	7.6%	7.5%	8.4%	7.6%
3600–3875	8.4%	7.8%	7.1%	7.0%	7.8%	7.0%
3875–4150	7.9%	7.3%	6.6%	6.5%	7.2%	6.6%
4150–4425	7.4%	6.8%	6.2%	6.1%	6.8%	6.2%
4425–4700	6.9%	6.4%	5.8%	5.7%	6.4%	5.8%
4700–5000	6.5%	6.1%	5.5%	5.4%	6.0%	5.5%
5000–5275	6.2%	5.8%	5.2%	5.1%	5.7%	5.2%
5275–5760	6.0%	5.5%	5.0%	4.9%	5.4%	4.9%

5. Conclusion

The affordability assessment of retrofitting projects is essential to increase the social spread of retrofitting, especially in low- and middle-income countries. In this study, the affordability of passive heating and cooling retrofitting alternatives were assessed, and the results proved that many retrofitting measures suitable for residential buildings would be affordable for a large portion of the Jordanian community. However, the affordability assessment proved that the initial investment cost of retrofitting is the major obstacle to implementing this measure, especially for low-income households, despite the long-term economic and environmental benefits of the process. Thus, micro-finance programs for retrofitting projects can provide financial services and increase the affordability of retrofitting for households. Furthermore, supporting and facilitating retrofitting projects would support the sustainable development goals and mitigate climate change impacts, the Jordanian government's main goals.

This study provided a simple methodology to evaluate selected passive heating and cooling retrofitting measures, considering varied impact categories, such as energy, environmental, and economic performance. This methodology forms a good and easy basis for selecting the suitable retrofit measure that achieves the maximum benefits according to the decision maker's priorities. This study provided a methodology to assess the affordability of retrofitting cases considering household income levels, retrofitting costs, and economic revenues. Additionally, this work could be expanded to consider the qualitative factors in affordability assessment, such as world economic climate, competition, performance, legislations, and risk. Beyond this, such research could include a wider range of retrofitting alternatives. Finally, this investigation could examine life cycle impact categories for retrofitting assessment, such as acidification potential, eutrophication potential, ozone depletion potential, and photochemical ozone creation potential.

Author contribution statement

Shouib Nouh Mabdeh & Yasmeen Abdull Ghani: Conceived and designed the experiments; Performed the experiments; Analysed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper. Laith Obiedat: Performed the experiments; Analysed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper. Mohammed Aloshan: Performed the experiments; Analysed and interpreted the data.

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Additional information

No additional information is available for this paper.

Declaration of competing interest

The authors declare no conflict of interest.

Table 10
Life cycle assessment of retrofitting cases.

Case	Environmental				Economic			
	Embodied CO_2 (kg)	Operation CO_2 (kg/year)	Avoided annual CO_2 (%)	Avoided $LCCO_2$ (%)	Initial cost (JD)	Saved energy price (JD/Year)	Saved energy price (%/Year)	NPV (JD)
Base case	–	5476.8	–	–	–	–	–	–
Case No. 1	625.14	5234.6	4.65%	4.30%	389.6	23.2	9.2	286
Case No. 2	781.42	4965.8	10.32%	9.83%	534.75	51.5	17.4	956
Case No. 5	2.57	4932.2	11.93%	11.93%	40.3	55.8	18.1	1538
Case No. 6	781.42	5212.2	5.10%	4.66%	487	25.3	9.3	251
Case No. 7	937.71	4943.4	10.82%	10.23%	641.7	53.7	17.6	915

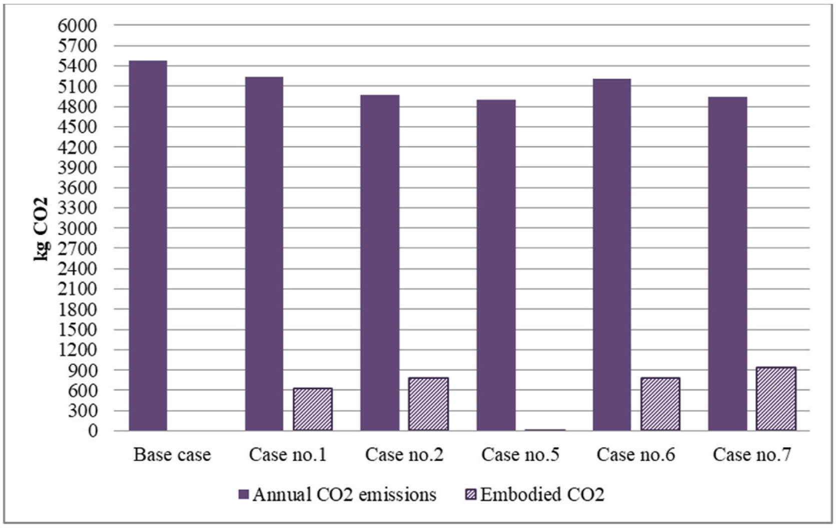

Fig. 8. Embodied and annual CO2 emissions for retrofitting cases.

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