Sādhanā (2022)47:131
https://doi.org/10.1007/s12046-022-01896-1

Sustainable energy retrofit plan for enhancing energy efficiency of residential apartments in arid climate: case of Afghanistan

SHAMBALID AHADY*, NIRENDRA DEV and ANUBHA MANDAL

Civil Engineering Department, Delhi Technological University, New Delhi, Delhi 110042, India
e-mail: shambalidahady_phd2k18@dtu.ac.in

MS received 31 January 2022; revised 22 April 2022; accepted 11 May 2022

Abstract. Building energy retrofitting provides a sustainable solution to enhance the thermal performance of existing structures. Building energy retrofitting has proven to be beneficial in alleviating the pressure of energy shortages in developed countries. However, an economic analysis is necessary to determine technically feasible and economically viable measures in a particular region. Furthermore, residential buildings in developing countries tend to have lower-performance construction and energy systems than modern commercial buildings. Building energy retrofitting is more cost-effective for improving energy efficiency than reconstruction. This study proposes a cost-effective approach for retrofitting existing residential buildings. A well-known dynamic algorithm was used to examine several retrofitting assumptions. Hence, this work examines the importance of thermal retrofitting in the case study of Afghanistan. Based on the quantitative findings of energy modeling, a priority guide was created for the most viable and practical retrofitting solutions for residential buildings, and financial analysis of initial investment versus return was done. This comprehensive approach was applied to the reference building, a typical mid-rise apartment complex in Afghanistan. The findings show that retrofitting existing buildings has substantial advantages and can increase the energy efficiency of buildings. These findings will aid in the energy efficiency of Afghanistan's residential sector and provide valuable references for future thermal retrofit research and innovation in local and global contexts. Moreover, the findings of this research could be used to assist stakeholders in determining the most efficient and suitable thermal retrofit solution for a particular set of targeted buildings and allow Afghan residents to weigh the benefits of improved energy performance from envelope retrofit and the associated capital outlay.

Keywords. Energy efficiency; building energy analysis; existing building; thermal retrofit; payback period.

1. Introduction

Energy conservation has become a subject for national policymakers worldwide and a general requirement in developing countries due to environmental and domestic energy demands. The construction industry's approach to energy efficiency must alter significantly to shift to a more sustainable environment. Enhancing the energy efficiency of buildings is critical to the lower energy use of existing structures and the associated emissions [1]. Existing buildings can be retrofitted to decrease global energy use and greenhouse gas emissions significantly. This is having considered one of the primary strategies to achieve sustainability in the built environment at a low cost and high adoption rate. Building energy retrofits dramatically reduces greenhouse gas emissions at a lower cost and shorter time frames than any other approach [2].

Furthermore, building energy retrofit to increase energy efficiency is more cost-effective than reconstruction, especially in developing nations. Designing and implementing decarbonization strategies for refurbishment and retrofitting increases renovation rates, and encouraging investment should be considered to strengthen the culture of retrofitting buildings in developing countries [3]. Residential buildings should be prioritized for retrofitting because, since urbanization is on the rise, the construction of residential buildings is increasing. This contributes to a significant increase in CO_2 levels, as the residential buildings consume considerable amounts of energy from non-renewable sources to maintain thermal comfort in the interior spaces [4]. As a result, thermal retrofitting of existing buildings would be an alternative to achieve the various energy efficiency standards set by many countries to mitigate the environmental impact of buildings [5].

Afghanistan, a landlocked country, relies considerably on imported energy from neighboring countries [6]. With 71% of total building energy use, residential buildings are the largest energy consumers in Afghanistan, and the bulk of this consumption is related to heating, cooling, and ventilation [7]. Although per capita energy consumption in

*For correspondence
Published online: 05 July 2022

Afghanistan is lower than in many other developing countries, the energy availability and construction practices differ from those of the rest of the world. Therefore, other countries' experiences or results cannot be applied simply and directly in Afghanistan. However, building energy retrofitting is an excellent way to address these problems economically. Some preliminary studies in Afghanistan have also demonstrated the benefits of energy-saving upgrades to existing residences [8], although these only involved traditional and poorly constructed mud houses and conventional practices rather than thermal simulation theories.

The energy retrofit associated with a renovation involves using energy solutions to restore the original functioning of a specific building element or improve the energy performance of either a single element or the entire structure. Various metrics could be investigated depending on the designer's expertise and the most common local practices. Thereafter, to incorporate such energy-saving measures, a detailed energy modeling of a building is necessary, considering the dynamics of the structure and the behavior of the occupants [9]. Thousands of residential buildings, particularly apartments, were built across the country during Afghanistan's rebuilding in 2002. At that time, the relevance of building codes, efficiency, and control became apparent due to the construction of several residential and commercial structures. However, due to the late adoption of the energy code (adopted in 2015), its imperfect content, and a lack of execution, the majority of the buildings in the country are energy inefficient and have excessive energy requirements for heating and cooling the indoor environment. Afghanistan has remained unconcerned about the energy crisis, and none of the commercially motivated efficiency techniques adopted in developing nations were implemented there. This partially explains the lack of awareness and the late introduction of energy-related codes, which have not yet been applied. Therefore, it has become increasingly critical to improve the energy performance of housing across the country through retrofitting. This research aims to propose a methodology to evaluate the viability and applicability of potential energy-saving retrofit measures in residential buildings in Afghanistan. To construct a compelling case for the implementation of these measures, a cost comparison for each measure is performed.

This study uses an example of a seven-story multi-apartment building builtin 2017 in Mazar-I-Sharif city. The household area on every floor is approximately 157 m^2. There are no vacancies in the building, which has 14 residential units. The building has been selected as it represents the bulk of the residential apartment buildings constructed in the last two decades in urban Afghanistan [10], and such conventional buildings with similar envelope materials require energy upgrades. After all, these structures will be in use for many years. These residential structures aid in determining rational energy-saving strategies while improving social and financial values. As a result, the information presented in this study is intended to provide a basic notion of residential energy savings in urban Afghanistan and provide some suggestions for the country as a whole and developing countries with similar economies.

Furthermore, the research describes the methods utilized to execute a comprehensive, quantitative, and verifiable building energy retrofit in terms of economic viability, with consideration of the weather conditions in two of the major cities of Afghanistan, namely, the hot and dry climate in Mazar-I-Sharif, which requires intense air-conditioning, and the mixed dry climate in Kabul city. Cost-effective residential building retrofitting will benefit the country regarding lower buildings' electricity needs. Given the necessity to retrofit a significant number of residential homes in Afghanistan and appropriately assess the cost-benefit of various energy-efficient retrofits, approaches that consider the thermal behavior of homes are required for various retrofit scenarios. Furthermore, to determine a retrofit plan based on Afghanistan's particular economic, technological, infrastructural, and regional climatic patterns, it is necessary to study its climatic condition to identify the best solution accordingly.

2. Literature review

Building energy efficiency has become increasingly important due to a growing interest in lowering energy consumption and decreasing the associated environmental implications [11]. A considerable amount of research on the energy efficiency of buildings is available in the literature worldwide, with residential structures being the most prevalent. Many researchers have examined the energy-saving and CO_2-reduction potential of existing housing. A study on Danish buildings has revealed a potential for a 50% saving in primary energy consumption in apartment buildings [12]; however, there are still several obstacles to the renovation process of residential buildings, such as selecting measures for various climatic and economic levels. AlFaris *et al* [13] have confirmed the efficacy of energy retrofit measures in dry regions and reported savings ranging from 14.4% to 47.6%, based on the combination of conservation practices used. However, the authors do not provide quantitative data on specific indicators or their methodology. Their findings revealed that increasing thermal insulation may not always be the best option. Increasing the wall and roof thermal resistance may be detrimental to high internal heat gains, including in office buildings. This anti-insulation impact could retain excess heat within the structure, necessitating more powerful equipment to eliminate the additional thermal load. However, this phenomenon occurs only in high-internal-gain structures and under particular structural and environmental conditions [14].

In the same context, a study investigated retrofit measures by simulating two residential homes that reflect a high proportion of households in Portugal. The findings revealed that the measures associated with implementing active systems yield rapid results. Moreover, Evangelisti *et al* [15] studied an early 1950s Italian residential structure through the dynamic simulation software TRNSYS (Transient System Simulation Tool) to propose strategies for the building envelope. The study found that while increased thermal insulation reduces heating demand, the window solar gain factor is crucial during summer. Indeed, solar control glazing may reduce cooling energy use by half while also being effective in the winter.

Regarding the expanded polystyrene exterior insulating layer, the researchers indicated that higher thermal insulation reduces wintry heat dissipation but increases cooling energy demand by 45%. The majority of Afghanistan's new housing stock comprises multi-apartment buildings that are mostly energy inefficient. With the climate in Mazar-I-sharif, mechanical cooling in the summer is essential for comfort; the hot and dry environment, combined with poorly constructed homes, results in significant cooling demands.

3. Aim and objectives of the study

Almost all housing units (single-family homes, apartment units) in urban Afghanistan are energy inefficient. In recent decades, an increasing number of buildings in urban Afghanistan have been constructed with reinforced cement concrete (RCC), disregarding the local climate and context, following the prototypes of neighboring countries. Eventually, these constructions require high energy consumption, as evidenced by the significant increase in air conditioners in residential buildings in recent years. The repercussions of this high energy use are alarming for an energy-scarce country such as Afghanistan. This study evaluates the most efficient building energy retrofit packages to decrease the energy demand in conventional residential apartment buildings in urban Afghanistan. The most cost-effective retrofit design package is proposed based on energy-saving, availability, and economically viable indicators.

4. Methodology

This research used modeling and simulation to examine how to reduce energy consumption through energy retrofit techniques and to analyze the technology choices in built environments. Figure 1 depicts the approach that was employed. At the outset, the energy modeling of the mid-rise residential building was performed with DesignBuilder, an EnergyPlus-based simulation program [16], using the original drawing and in-situ measurements. Prior to the energy retrofit, a comprehensive energy simulation of the structure was performed, using the thermal transmittance of building materials acquired from experimental work and temperature and relative humidity measurements. With the use of the in-situ measurement data and the calibrated simulated energy consumption, the energy technologies suited for the purpose were then selected—an energy simulation program assessed and evaluated the various energy technology packages. Finally, the most cost-effective package option was identified, and the energy savings were determined.

4.1 *Climatic and environmental characteristics of selected regions*

Köppen's classification is a widely used climate classification system that classifies climate zones across the world based on local vegetation. Temperature and precipitation, two essential climatic elements, influence the vegetation

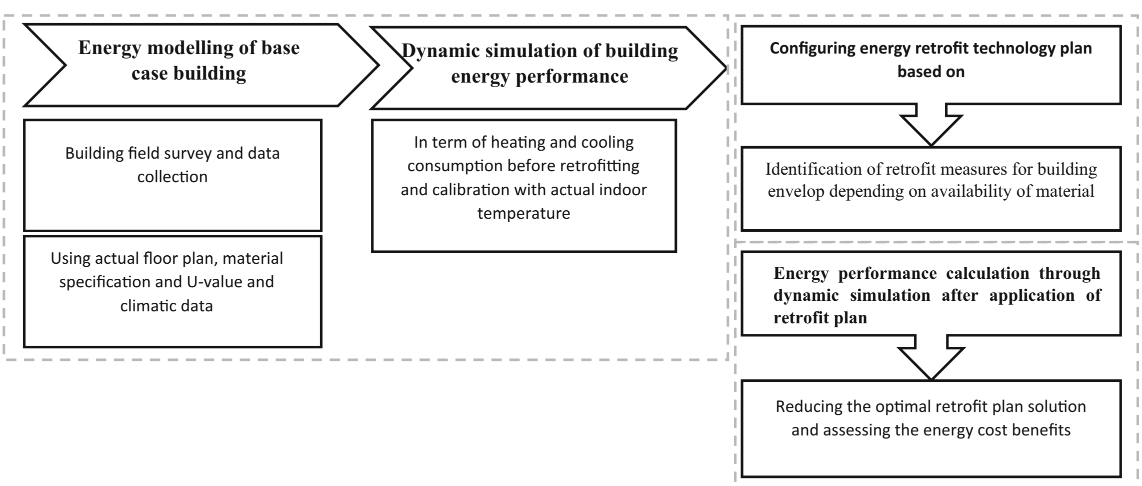


Figure 1. Applied methodology.

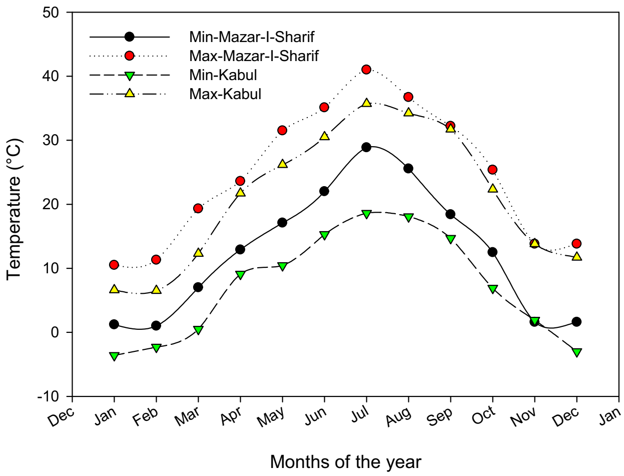


Figure 2. Average minimum and maximum temperature in Mazar-I-Sharif and Kabul city during the year [21].

Figure 3. Residential building, Mazar-I-Sharif, Afghanistan.

that grows in a given place. Köppen's classification map defines the climate of Mazar-I-Sharif as "arid steppe cold" and Kabul as "Cold (Continental), dry, warm summer." [17]. Moreover, the ANSI/ASHRAE (American Society for Heating, Refrigeration and Air-Conditioning Engineers) Standard 169-2020 climate data for building design defines Mazar-I-Sharif as a hot-dry (2B) and Kabul as a mixed-dry climate (4B) [18]. Mazar-I-Sharif, the northern Afghanistan regional hub, located at 36 42' 32.54 N, 67 06' 39.13 E, and 391 m above sea level, is one of the country's most densely populated cities [19]. July is the hottest month of the year, with an average temperature of 40.2°C. Kabul, at latitude 34° 32' 38.0256" N, longitude 69° 9' 38.3472" E, and 1,791m above sea level, is at the center of Afghanistan [20]. The city's average annual temperature is 15 °C. July is the warmest month, with an average temperature of 27°C, while the coldest month is January, with an average dry bulb temperature of 1°C. Figure 2 compares yearly average minimum and maximum temperatures in Mazar-I-Sharif and Kabul.

5. Analysis approach

Building energy consumption is primarily determined by the characteristics and operating schedule of the building and the weather conditions. Therefore, prototypes that mimic actual residential buildings were created in the initial stage. For this purpose, a literature study [10, 22] was done, and a case study was employed to represent the typical characteristics of buildings in urban Afghanistan.

A prototype dwelling was defined to evaluate the most efficient thermal retrofit measures in a harsh climate with scorching summers and freezing winters. The residential building considered in this study is a multi-apartment residential building situated in Mazar-I-Sharif, Afghanistan (figure 3). According to the literature, most recently constructed multi-apartment residential buildings contain similar materials. In other words, the case study building can serve as an example for many more newly designed structures in Mazar-i-Sharif and other major cities across the country. Moreover, available local material, which is typically utilized for constructing envelop (wall) material in Afghanistan, was used in the selected building.

Furthermore, the building was chosen because it was constructed with the standard code of conventional building practices. Therefore, more accurate results are possible by imitating standardized construction in software. Additionally, the building is located in an arid region of the country, characterized by hot summers and harsh winters, similar to most neighboring cities in the country. Consequently, improving the energy efficiency of these residential units may significantly lower overall energy consumption in the building sector in the region. The construction involved RCC and a single layer of burnt clay bricks in the vertical walls. Both sides of the walls are covered with plaster, the interior with GS (Gypsum Soil) plaster made from locally available material, and the exterior with cement plaster. The windows consist of Polyvinyl Chloride (PVC) frames with 3 mm glazing. The apartments have been planned to employ a split air conditioning system for cooling and a gas heating system for heating. Each apartment has a floor space of approximately 334 m^2, with two residential units on each storey. The building comprises a central stairwell with apartments on either side.

The elements of the building construction for the base-case energy model are summarised in table 1. The properties of the energy model were determined with a material experiment and a field survey. The data for the study were derived from three sources, namely, (i) a review of the construction company's building blueprints, (ii) site visits to the building, and (iii) interviews with the clients and contractors. Climate zone, glazing area, and building materials were all considered. The cooling and heating setpoint temperatures, building façade composition; occupancy density; type and schedule of lighting; and heating, ventilation, and air-conditioning (HVAC) systems were all

Table 1. Building location specification.

Location	Afghanistan, Mazar-i-Sharif, longitude: 67° 06’ 39.13 E, latitude: 36° 42’ 32.54” N
Usage	Multi apartment residential building
Construction	Reinforcement concrete (RCC) structure with brick wall
Building size	Number for floor: 1 basement level + 7 ground level
Window to wall ratio	0.35
Building ground floor area	360.15 m^2
Floor height	3 m
Residential plan form	Square
Number of apartments per floor	2

entered into the simulation program. Figure 4 represents the photographs of the interior of a residential unit.

A field investigation was conducted to calibrate the input parameters. The model was calibrated with comparing the measured and simulated data. The measured and simulated free-running indoor air temperature for the peak summer months of 1st July to 12th August 2019 were compared. Apresys (TH 18000436) portable data logger measured the interior air temperature. Two dimensionless error indices, cumulative variation of root mean square error (CVRMSE) and mean bias error (MBE), were employed to measure the difference between the simulated and measured values, respectively, using equations (1) and (2) [19].

$$CV(RMSE) = \frac{\sqrt{\sum_{i=1}^{N_i}\left[\frac{[(M_i-S_i)]^2}{N_i}\right]}}{\frac{1}{N_i}\sum_{i=1}^{N_i} M_i} \quad (1)$$

$$MBE = \frac{\sum_{i=1}^{N_i}(M_i - S_i)}{\sum_{i=1}^{N_i} M_i} \quad (2)$$

M_i and S_i are the measured and simulated data at instance *i*, respectively, and M_i Is the total number of values used in the computation. In conclusion, these explain the discrepancies between EnergyPlus space temperature projections and actual measurements. The MBE and (CVRMSE) values achieved were 4.48% and 9.81%, respectively, within the ASHRAE-14 Guide acceptability level for energy model calibration [23].

The exterior façade has a u-value of 1.52568 w/m2 k and comprises brick walls and RCC structures with a 30% window-to-wall ratio. Each residential unit is cooled and heated with electricity and Liquefied Petroleum Gas (LPG). Floor plans for the study buildings were prepared in AutoCAD at the initial stage of the modeling process. The DesignBuilder model was then generated with scaled AutoCAD floor plans, imported via the user interface. As a result, the software can precisely read and comprehend geometric elements of floor designs. The floor blueprints for each room were then traced to create a 2D representation. Thereafter, the model was enhanced with doors, windows, and other interior and external openings. Table 2 lists the parameters used to model the building.

A rendering of the base-case building simulated model plan is presented in figure 5.

Moreover, the climate data, building orientation, and shading were added. Afterward, multiple zone classifications were introduced to the algorithm and assigned to every building zone, considering occupancy, internal heat generation, and ventilation. Finally, the building’s construction data were included in the model for accurate energy use prediction, and the external and partition walls and the floor and roof materials were all entered. The same

Table 2. Applied parameters for the building modelling.

Parameters	Value
The occupancy density (person/ m^2)	0.018 person/m2
HVAC system	HVAC 2.7 seasonal cop
Metabolic rate	1 met
Infiltration rate	1.71 ac/hr @ 50pa (measured) / 6.02 m3 /hr/ m2

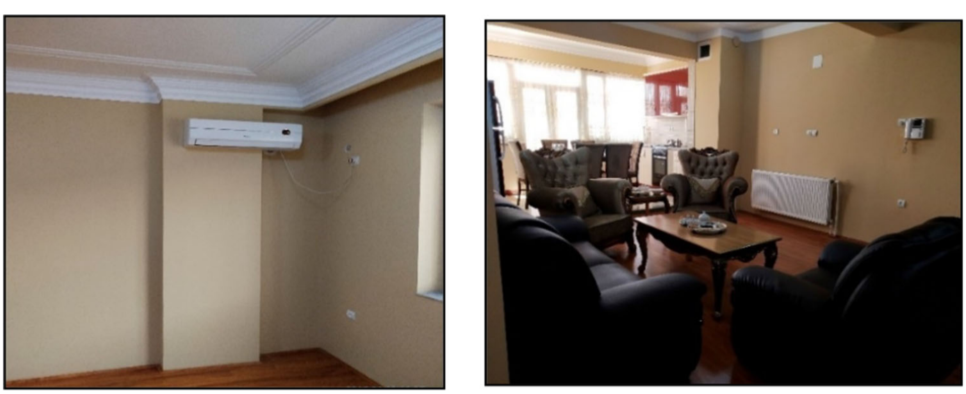


Figure 4. Photographs of the interior of a residential unit.

Figure 5. Floor and zoning plan.

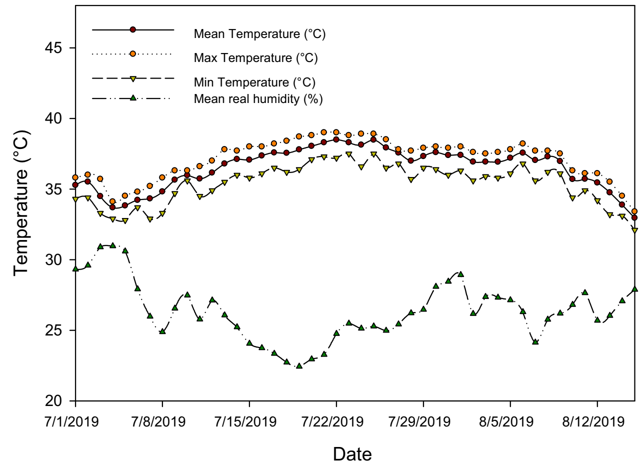


Figure 6. Monitored indoor temperature and relative humidity.

wall construction features were used to ensure that the models were consistent. Table 3 represents the characteristics of the building base model.

5.1 *Weather conditions*

The energy balance of the buildings is always affected by weather conditions. The weather file contains data that includes altitude, latitude, and longitude, as well as hourly series of temperature, humidity, wind speed, solar radiation, precipitation, and other essential climatic characteristics. Figure 6 represents daily indoor air temperatures and the relative humidity of apartment rooms, recorded in the peak summer month (from 1/7/2019 to 12/8/2019) without using an air-conditioning system. Using Apresys portable data logger (TH 18000436), the temperature and relative humidity of the indoor air were recorded at 10-minute intervals. The average indoor temperature on the sixth floor, according to the monitoring, was 37.2^{0}C in July. Furthermore, since the top floor is more exposed to solar radiation and remains unshaded during the day, as opposed to the first floor, which is partially shaded by neighboring structures, the daily temperature is higher. The Monitored indoor temperature and relative humidity are presented in figure 6.

It was confirmed that the average difference between indoor and outdoor temperatures in the summer season is 3.8 ^{0}C, as shown in figure 7. The outdoor temperature impacts the indoor temperature, so as the outdoor temperature decreases, the indoor temperature of the non-AC rooms also decreases [24].

6. Employed retrofit measures in the studied climatic conditions

The application of energy measures aimed at either restoring the original functioning of a particular building feature or improving the energy performance of a specific component or the entire building is incorporated in the energy retrofit linked with renovation [9]. Several metrics that depend on the designer's expertise and the most typical local practices could be investigated. Significant building energy modeling that considers the structure's dynamics and occupants' behavior is necessary to implement energy-

Table 3. Characteristics of the building base-model.

Parameter	Specification
External walls (U-value: 1.52 W/m^2*k)	0.025 m Cement plaster (outer side), 0.3 m burnt mud brick, 0.025 m Gypsum-Soil plaster (inner side)
Roof (U-value: 3.710 W/m^2*k)	0.02 m Cement mortar, 0.005 m waterproofing (bitumen), 0.12 m Concrete slab, 0.025 m Cement plaster
Internal walls (U-value: 1.93 W/m^2*k)	0.025 m Cement plaster (outer side), 0.2 m burnt mud brick, 0.025 m Gypsum-Soil plaster (inner side)
Floor (U-value: 2.135 W/m^2*k)	0.003 m PVC flooring, 0.02 m Cement plaster, 0.12 m Concrete slab, 0.025 m Cement plaster
Glazing SHGC-0.703 (2.68 W/m^2*k)	0.006 Clear-Double glazed with PVC frame, 0.013-Air

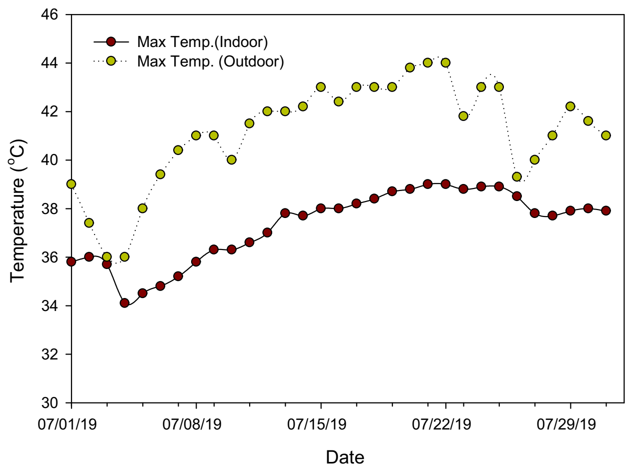


Figure 7. Comparison of indoor and outdoor temperature and relative humidity.

saving measures. The renovated building's energy performance can be compared with a reference building to assess the efficacy of the energy-related solutions. This comparison aims to assess whether primary energy consumption has decreased through the appropriate measurements. The simple payback (SPB) must be assessed to estimate the viability of retrofitting measures in Afghanistan.

The intervention, a standard energy retrofit strategy, may influence the building's primary components, namely the envelope and the systems. The degree of commitment in terms of predefined performance objectives and an initial budget, particularly in emerging countries such as Afghanistan, will determine to what extent energy retrofit technologies will affect these two levels. Since the walls, windows, and roof account for 90% of the energy loss, the subject of this study involves the energy-saving retrofit of these specifically. The conditioned thermal zones in the buildings contain separate HVAC terminals in each unit. The primary heating system in the reference residential unit building is LPG. Electric split air-conditioners are conventional cooling systems and are installed in all the thermal zones in the building.

Windows (double-glazed) with PVC frames constitute the transparent envelope. Existing RCC structures have low energy performance in building walls and roofs. The U-value of opaque envelope elements, for instance, varies from 1.52 to 1.93 W/m2 K, and thermal inertia is high due to the materials utilized (such as burnt bricks). Similarly, double-glazed, air-filled windows with PVC frames with a U-value of 2.68 W/m2 K result in significant energy requirements (per square meter) for cooling and heating.

The study was conducted in two steps. First, the energy effect of each of the individual measures was calculated using the energy simulation of the building model, then the cost of each retrofit measure was calculated with a simple payback period. These findings result in a possible retrofit combination option. A blend of opaque and transparent components characterizes all building envelopes. Polyurethane, expanded polystyrene (EPS), extruded polystyrene (XPS), rock wool, eco-friendly insulation, and other materials can be used to insulate building roofs and walls. However, insufflating insulation materials such as EPS can insulate a structure's walls. In addition, the availability, primary market pricing, and dependability of the technology applied for insulation should all be considered in the choice of material. External or internal insulation can be done, and the latter option could be a good fit for Afghan RCC structure buildings, known for having thicker exterior walls than interior partition walls. Typically, exterior insulation and finishing systems are ideal, particularly for residential properties, as, first, it produces higher internal surface temperatures, which improves thermal comfort, and, second, it generates higher thermal inertia of the envelope and eliminates heat transfer. Depending on the defined energy performance targets and the availability of construction materials and technology in the region, the interventions at the basis of building systems can be summarised as follows.

- In this instance, U-values of approximately 0.5 W/m^2 K could be obtained with wall insulation, which significantly impacts heating demand.
- Roof insulation obtains U-values of less than 0.5 W/m^2 K, especially for the climate zone. Since during the summer season, solar radiation is concentrated on roofs, and solar heat gain may be reduced by insulating these flat roofs.
- Window glass replacement with coated reflective glass can be selected. Double-glazed windows filled with argon or air can be employed, and reflective coatings could be utilized to lower the window's SHGC (solar heat gain coefficient). To achieve appropriate thermal resistance PVC frame window can be used.
- The exterior wall coated with 100mm thick polystyrene insulation and the inner surface with 50 mm, can lower the wall's steady-state u-value without affecting the structure's original form. In theory, the thermal transmittance value should be decreased by almost three times; however, the actual u-values before and after the retrofitting solution were 1.52 w/m2 k and 0.513 w/m2 k, respectively.

Table 4 illustrate the employed retrofit Packages.

The thermal properties of the suggested measures for the building elements were calculated through DesignBuilder software by adding the thermal property values of each layer. The thermal properties of each layer of material were obtained from three sources. Namely, an experiment on primary envelop material, country code [25], and ASHRAE standards. The thermal characteristics of Afghanistan's

Table 4. Employed retrofit Packages.

Cases	Details
I. Reduce the SHGC of glass (U-Value=2.82, and SHGC=0.188)	Replacement of baseline clear glass with reflective glass
II. Reduce the U-Value of the External walls Total: (U-Value 0.513)	Original wall+5 cm EPS (outer side)+25mm cement plaster
III. Reduce the U-Value of the External walls Total: (U-Value= 0.313)	Original External wall+10 cm EPS (outer side) +2.5 cm cement plaster
IV. Reduce the SHGC of glass and U-Value of the external wall (SHGC=0.188, and U-Value =0.513)	Original External wall + 5cm EPS (outer side) +2.5 cm cement plaster, and Replacement of clear window glass with Reflective glass
V. Reduce the U-Value of roof, wall and SHGC of glass (U-Value =0.351, U-Value= 0.513, SHGC=0.188	Original Roof +5 cm XPS+ 0.4 cm bitumen sheet + 2.5 cm cement plaster; Original External wall + 5 cm EPS+2.5 cm cement plaster' Replacement of clear window glass with Reflective glass
VI. Reduce the U-Value of External) U-Value= 0.313, and partition wall.) U-Value=0.533)	Original External wall+10 cm EPS (outer side) +2.5 cm cement plaster. Original partition wall +5cm EPS (Inner side) +2.5 cm SG (Soil gypsum) plaster.

traditional brick and GS interior plaster were identified as critical components for the building envelope. As a result, a separate experiment was conducted to determine the thermal properties of these local materials. The ASHRAE guidelines were used for other standard materials. The thermal properties of brick and GS plaster, which were utilized for the interior plastering of the case study building, were tested with the MTCoE/SOP (Standard Operating Procedure – ISO:22007-2:2015) technique. The samples were tested using a thermal constants analyzer with a scanning rate of 406.184 ms.

7. Results and discussion

Before analyzing the energy-saving impacts of the chosen measures, the base-case (i.e., before energy retrofit) cooling and heating loads of the subject building were calculated with the EnergyPlus simulation engine and DesignBuilder interface as a benchmark [16]. The heating and cooling loads of the measures were computed with the same approach (i.e., after energy retrofit).

The annual cooling and heating energy consumption for the entire building was simulated. Figure 8 summarises and graphs the computer modeling and analysis findings to visually present the changes in the building's heating, cooling, and total energy use. Table 5 contains tabulated findings obtained directly from the DesignBuilder program after the base-case simulation. The annual cooling and heating energy is expressed in kilowatt-hours (kWh). As expected, space cooling accounts for the bulk of the electrical energy use for the baseline in Mazar-I-Sharif. As indicated in figure 9, space cooling accounts for 57.11% of the building's total annual energy use. Heating is required during the winter months (primarily in November, December, and January), accounting for approximately 31.66% of annual energy use.

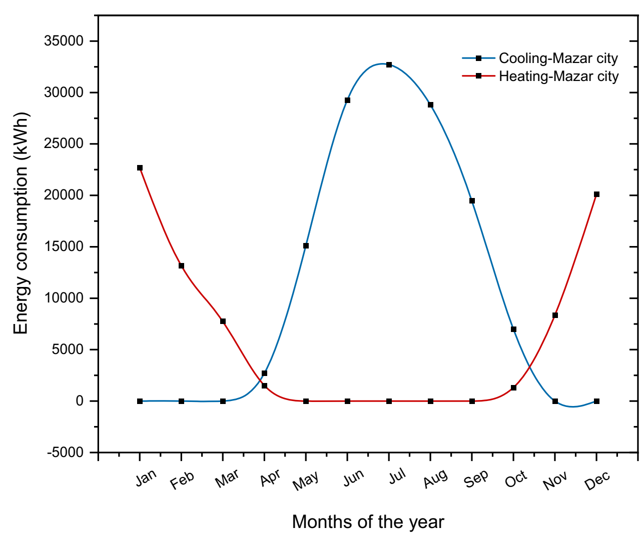


Figure 8. Base case-building annual energy consumption for Mazar-I-Sharif city.

Table 5. Base case Scenario annual total energy required (Mazar-I-Sharif City).

Cooling	135086.50 (kWh)
Heating	74902.11 (kWh)
Lighting	7641.48 (kWh)
Domestic Hot Water	18896.19 (kWh)

Since this research examined two regions that require both heating and cooling, it is critical to consider ways to improve the efficiency of the envelope to reduce cooling and heating loads through insulation, window glazing, and other specific approaches. The simulation for the climate of Kabul is presented in figure 9, and it illustrates that the heating demand is higher than the cooling energy requirement.

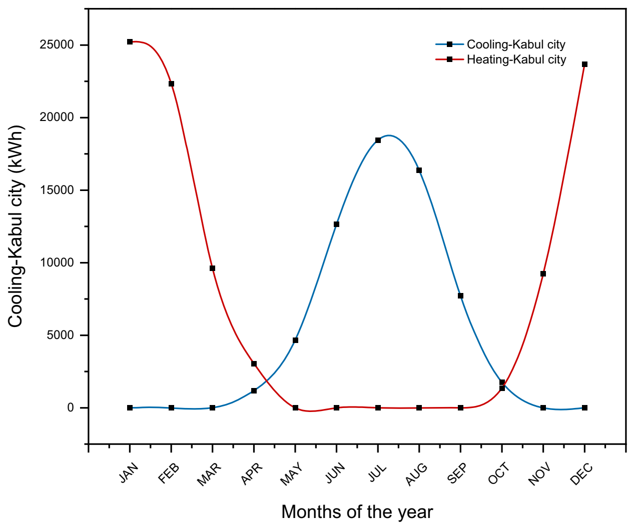


Figure 9. Base case-building annual energy consumption for Kabul city.

Table 6. Base case Scenario annual total energy required (Kabul City).

Cooling	62825.13 (kWh)
Heating	94543.36 (kWh)
Lighting	7641.48 (kWh)
Domestic Hot Water	18896.19 (kWh)

The energy demand for heating, cooling, lighting, and DHW for the base-case scenario that considers the climate of Kabul is presented in table 6.

Table 7. Case 1- Total energy demand annually.

Category	Energy demand kWh (Mazar-I-Sharif city)	Energy demand kWh (Kabul city)
Cooling	92641.92	29989.90
Heating	107455.58	131755.06
Lighting	7641.48	7641.48
DHW	18896.19	18896.19

a. Result for case 1

The results indicate that replacing the reflective glass with baseline clear glass increases the heating energy requirements by 43.46% and 39.35% in Mazar-I-Sharif and Kabul, respectively. However, it positively impacts cooling demand, which decreased by 4.18 % in the Mazar-I-Sharif scenario; conversely, it caused an increase in overall energy demand in the Kabul scenario. Figure 10 represents building energy demands for both the selected cities after applying case 1, aggregated annually.

The energy demand for heating, cooling, lighting, and DHW for the reference building after applying the retrofit package (case 1) is presented in table 7 for the Mazar-I-Sharif and Kabul climates, respectively.

b. Result for case 2

Different climatic conditions demand varied ideal thicknesses of EPS for wall insulation to regulate energy consumption for heating and cooling. Fifty mm of EPS and exterior plaster were applied to the original wall to determine the effect of such insulation on the exterior wall of buildings in two different regions. The results indicate that it has a significant effect on the cooling energy demand in the hot climate of Mazar-I-Sharif. However, it does not

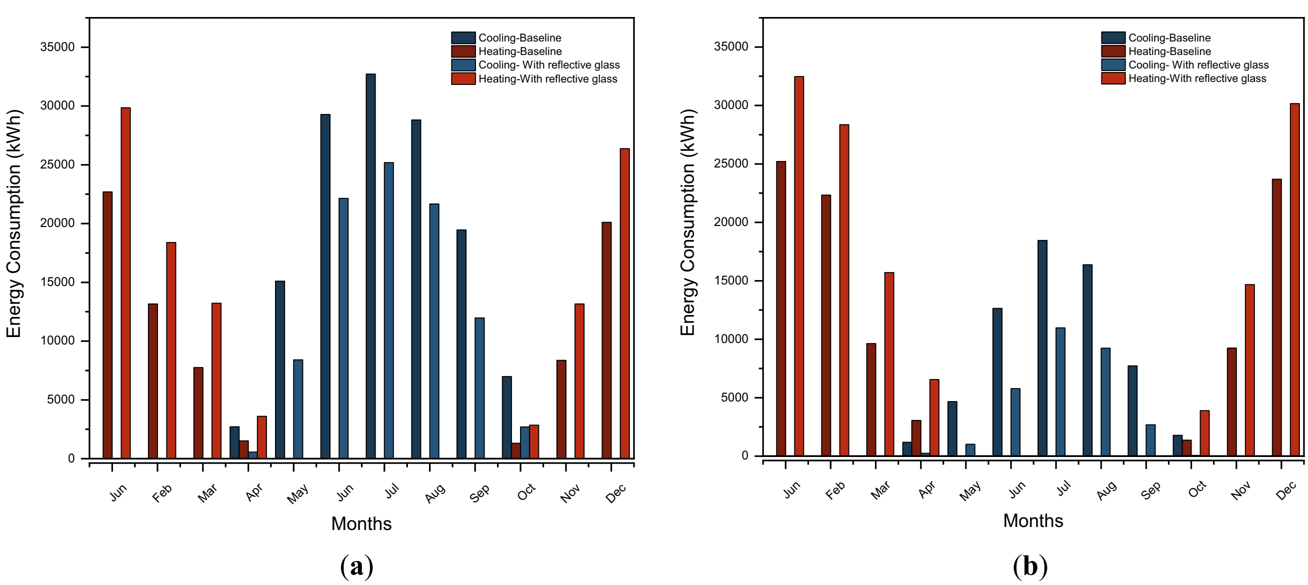


Figure 10. Baseline building vs. Case 1. a) Mazar-i-Sharif city and b) Kabul city.

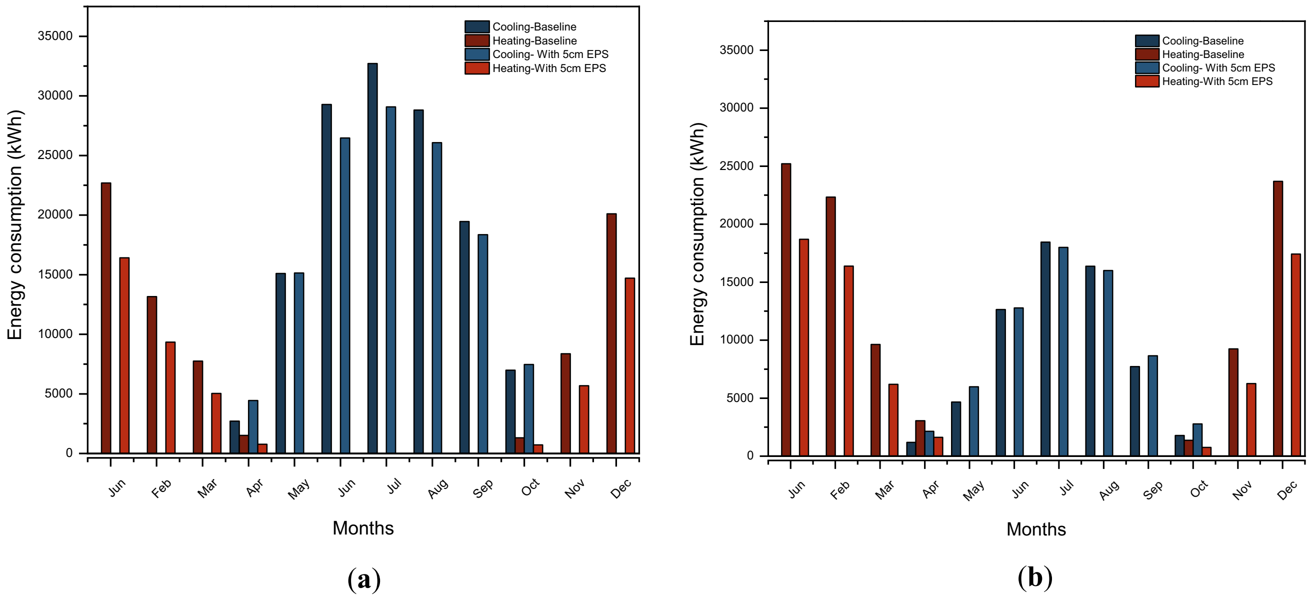


Figure 11. Baseline vs. Case 2. a) Mazar-I-Sharif city and b) Kabul city.

considerably affect the cooling energy demand in Kabul. Moreover, the insulation on the exterior walls decreased heating energy demand in both climates by 29.6% and 28.7%, respectively. Figure 11 displays annual building energy demands after applying case 2, considering Mazar-I-Sharif and Kabul city weather conditions.

The energy demand for heating, cooling, lighting, and DHW for the selected buildings after applying the retrofit package (case 2) is presented in table 8 for the Mazar-I-Sharif and Kabul climates, respectively.

c. Result for case 3

The energy-saving retrofit for the external wall of the building was accomplished by applying an external insulating layer of EPS (100 mm) to minimize the heat transfer coefficient. The exterior wall insulation is beneficial in Mazar-I-Sharif in summer and winter, decreasing heating and cooling energy consumption by 35.8% and 7.8%, respectively. However, the result indicates that the added EPS layer does not significantly affect the cooling energy demand for Kabul housing but can decrease the consumption of energy for heating by 35.18 % during the winter season. Figure 12 demonstrates annual building energy demands for case 3, considering Mazar-I-Sharif and Kabul city weather condition.

The energy demand for heating, cooling, lighting, and DHW for the reference building after applying the retrofit package (case 3) is presented in table 9 for the Mazar-I-Sharif and Kabul climates, respectively.

d. Result for case 4

Figure 13 presents the effect of applying reflective glass and wall insulation (5 cm EPS) on the energy demand for heating and cooling in both climates. The result indicates an overall reduction in energy consumption of 22.48% and 13.9 % for Mazar-I-Sharif and Kabul, respectively, but the energy demand for heating is not appreciably affected. This is due to the reflective glass that blocks the sun from warming the indoor environment, negatively affecting energy consumption in both climates. The energy demand for heating, cooling, lighting, and DHW for the reference building after applying the retrofit package (case 4) is presented in table 10.

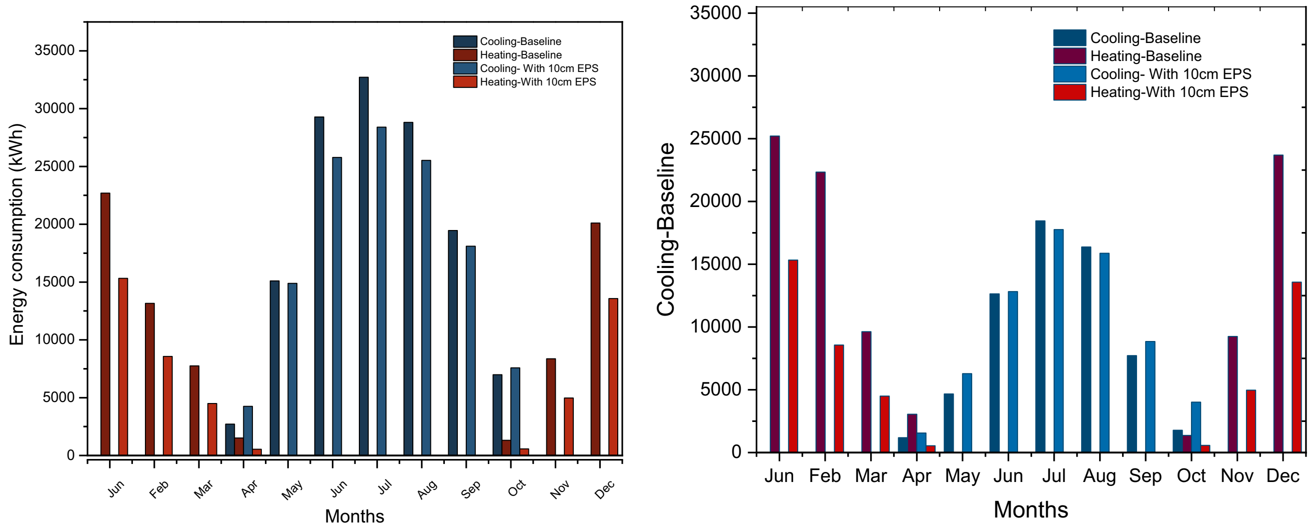
e. Result for case 5

This scenario shows that Mazar-I-Sharif and Kabul's overall reduction in energy consumption is 34.11% and 26.9%, respectively. The residential buildings in Afghanistan mainly have flat roofs. Therefore, the XPS board applied to the flat roof and bituminous sheet as an external insulation layer has considerably affected the energy consumption. Figure 14 illustrates the energy demand of the reference building after considering the retrofit package for the climates of Mazar-I-Sharif and Kabul, respectively.

The energy demand for heating, cooling, lighting, and DHW for the reference building after applying the retrofit package (case 5) is presented in table 11 for Mazar-I-Sharif and Kabul climates.

Table 8. Case 2- Total energy demand annually.

Category	Energy demand kWh (Mazar-I-Sharif city)	Energy demand kWh (Kabul city)
Cooling	127050.94	66327.34
Heating	52687.19	67330.60
Lighting	7487.33	7487.33
Domestic Hot Water	18515.00	18515.00

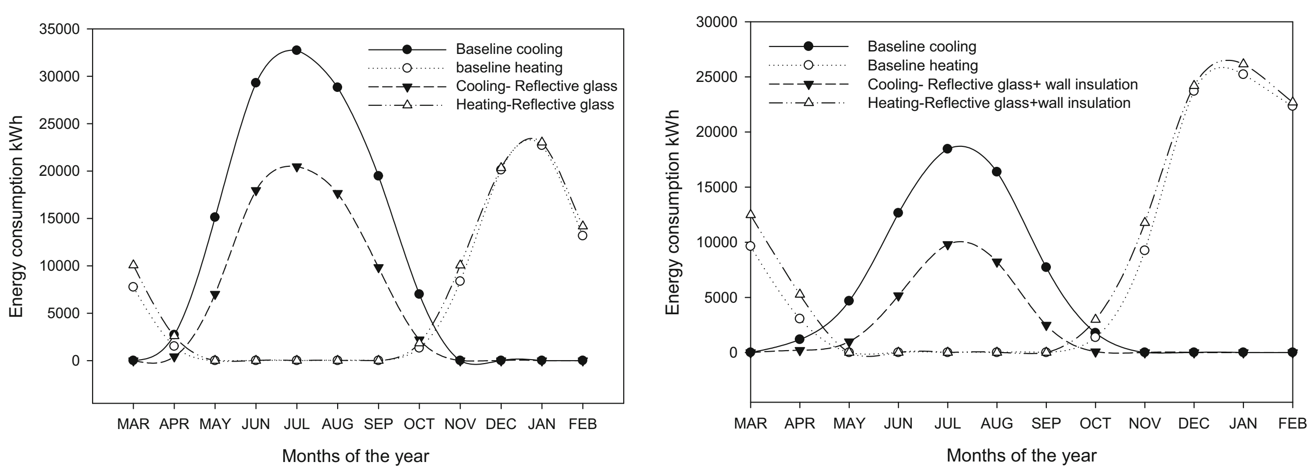


(a) (b)

Figure 12. Baseline vs. Case 3. a) Mazar-I-Sharif city and b) Kabul city.

Table 9. Annual total energy demand considering case 3.

Category	Energy demand kWh (Mazar-I-Sharif city)	Energy demand kWh (Kabul city)
Cooling	124534.75 (kWh)	67153.97 (kWh)
Heating	48035.68 (kWh)	61277.94 (kWh)
Lighting	7397.14 (kWh)	7397.14 (kWh)
Domestic Hot Water	18291.98 (kWh)	18291.98 (kWh)



(a) (b)

Figure 13. Baseline vs Case 4. a) Mazar-I-Sharif city and b) Kabul city.

f. Result for case 6

The addition of an external insulating layer, consisting of an EXP coating on the partition and exterior walls, was simulated to study the impact of opaque surfaces on annual energy consumption. With a 17.5% reduction in overall and 37.53% reduction in heating energy consumption, case 6 represents the unique approach to mitigating heat dispersion in winter. Figure 15(a) and (b) present the energy consumption for case 6 for the Mazar-I-Sharif and Kabul climates during the year, respectively.

Table 10. Building annual total energy demand- case 4.

Category	Energy demand kWh (Mazar-I-Sharif city)	Energy demand kWh (Kabul city)
Cooling	75585.56	26984.89
Heating	82068.84	105321.19
Lighting	7397.14	7487.33
Domestic Hot Water	18291.98	18515.00

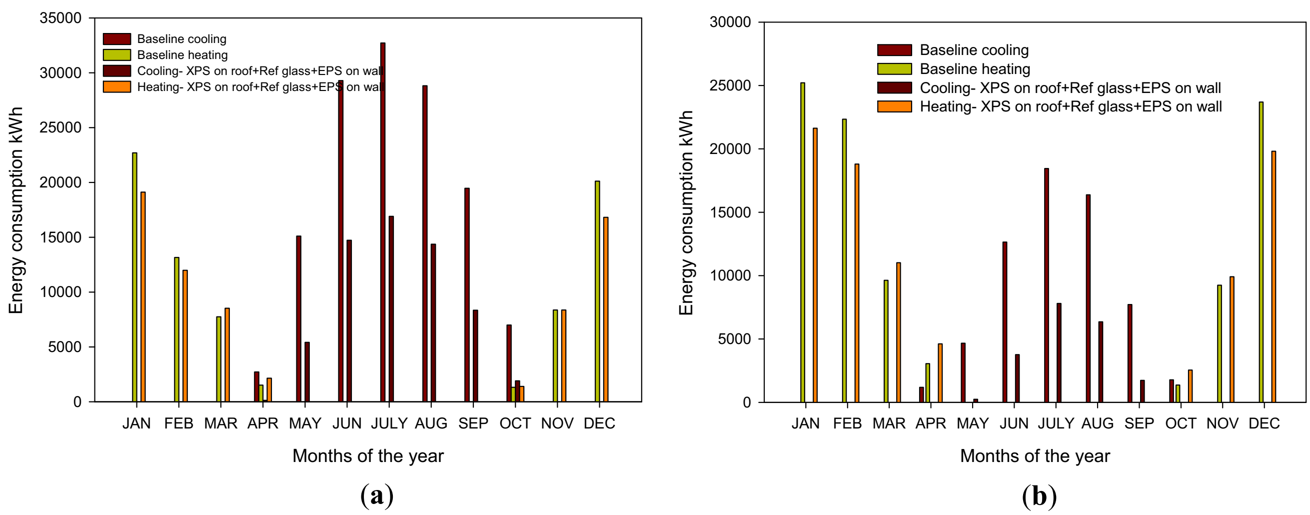


Figure 14. Base-case vs. Case 5. a) Mazar-I-Sharif and b)Kabul city.

Table 11. Building annual total energy demand- case 5.

Category	Energy demand kWh (Mazar-I-Sharif city)	Energy demand kWh (Kabul city)
Cooling	61789.70	19926.18
Heating	68354.58	88332.61
Lighting	7397.14	7487.33
Domestic Hot Water	18291.98	18515.00

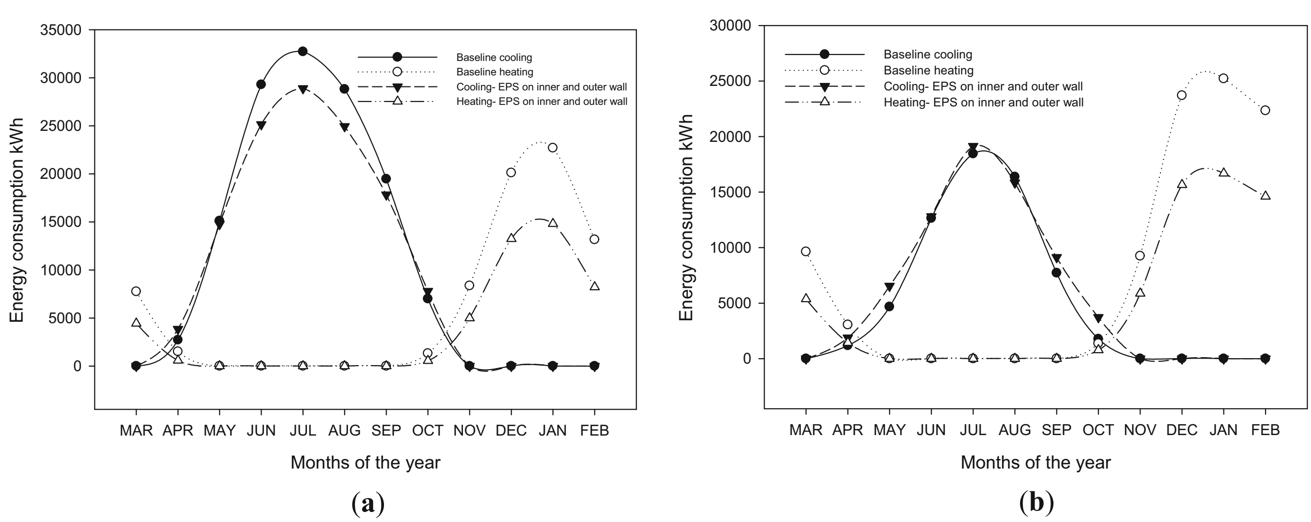


Figure 15. Base-case vs. Case 6. a) Mazar-I-Sharif and b) Kabul city.

Table 12. Building annual total energy demand- case 6.

Category	Energy demand kWh (Mazar-I-Sharif city)	Energy demand kWh (Kabul city)
Cooling	123195.27	69049.40
Heating	46790.78	60400.97
Lighting	7207.69	7207.69
Domestic Hot Water	17823.48	17823.48

Table 13. Energy savings chart for all the envelope parameters.

Retrofit packages	City	Peak Energy month	Peak energy kWh	Annual total heating and cooling energy kWh	Percentage of Savings
Baseline	Mazar-I-Sharif	JULY	32717.270	209988.6039	0 %
	Kabul	JAN	26787.610	157368.49	0 %
Case 1 - reflective glass	Mazar-I-Sharif	JAN	29853.962	200097.4981	4.7 %
	Kabul	JAN	33919.680	161744.96	−2.78 %
Case 2 – 5 cm EPS on external wall (Inner side)	Mazar-I-Sharif	JULY	29078.53	179738.1	14.4 %
	Kabul	JAN	20243.056	133657.94	15.06 %
Case 3 – 10 cm EPS on external (Outer side)	Mazar-I-Sharif	JULY	28395.79	172570.4	17.81 %
	Kabul	JAN	18655.607	128431.91	18.38 %
Case 4- Reflective glass+ 5 cm EPS on external wall (outer side)	Mazar-I-Sharif	JAN	23021.73	157654.4	24.92 %
	Kabul	JAN	27679.010	132306.08	15.92 %
Case 5 – 5 cm XPS on roof+ Reflective glass+ 5 cm EPS on external wall	Mazar-I-Sharif	JAN	19116.1	130144.3	38.02 %
	Kabul	JAN	23171.112	108258.79	31.2 %
Case 6 – 5 cm EPS on internal wall + 10 cm EPS on external wall (outer side)	Mazar-I-Sharif	JULY	28883.260	169986.0442	19.04 %
	Kabul	JAN	18171.364	129450.37	17.74 %

The energy demand for heating, cooling, lighting, and DHW for the reference building after applying the retrofit package (case 6) is presented in table 12, considering the cities' weather conditions.

7.1 *Comparison of the best retrofit packages for various energy-saving targets*

Table 13 demonstrates that regardless of the energy-saving goal, retrofitting the walls constantly improves a building's energy efficiency. The results shown in figure 16 demonstrate that when insulation is applied to both the walls and the roof, more energy savings are achieved than when only one of the building envelope components is insulated. Moreover, the result indicates that reflective glass is not feasible in the Kabul climate as it increases energy consumption.

Figure 17 compares the baseline and each case energy requirement considering Kabul and Mazar-I-Sharif city weather conditions.

7.2 *Estimating the benefits*

There are different benefits from building energy efficiency retrofit measures based on the building and the economic status of households. Furthermore, electricity prices and implementation costs significantly influence the cost-effectiveness of residential buildings' energy-efficient retrofit techniques. Since Afghanistan relies mainly on imported energy from neighboring countries [6], energy prices are high and vary depending on the region. However, building retrofits can provide direct and indirect economic benefits (e.g., increased property value or rental level of existing structures, improved living comfort) [26]. Indirect effects are difficult to define and translate into monetary terms, so the current study focused on direct economic advantages. However, improving the thermal performance of dwellings also provides noneconomic benefits to residents, such as the comfort given by energy-efficient homes. It enhances various areas of everyday living, including well-being, productivity, health, and mood (resulting in improved family relations) [27]. This study presents the benefit of decreasing energy use through any alternative measure while maintaining the same degree of comfort. Ten local suppliers (retailers, contractors, construction companies, and real estate developers) were engaged for cost advice and to ensure that the suggested features were doable and financially feasible in local practice. External variables may influence the energy demand of buildings. A heat island effect that increases cooling requirements in hot climates is often found in densely populated metropolitan areas [28].

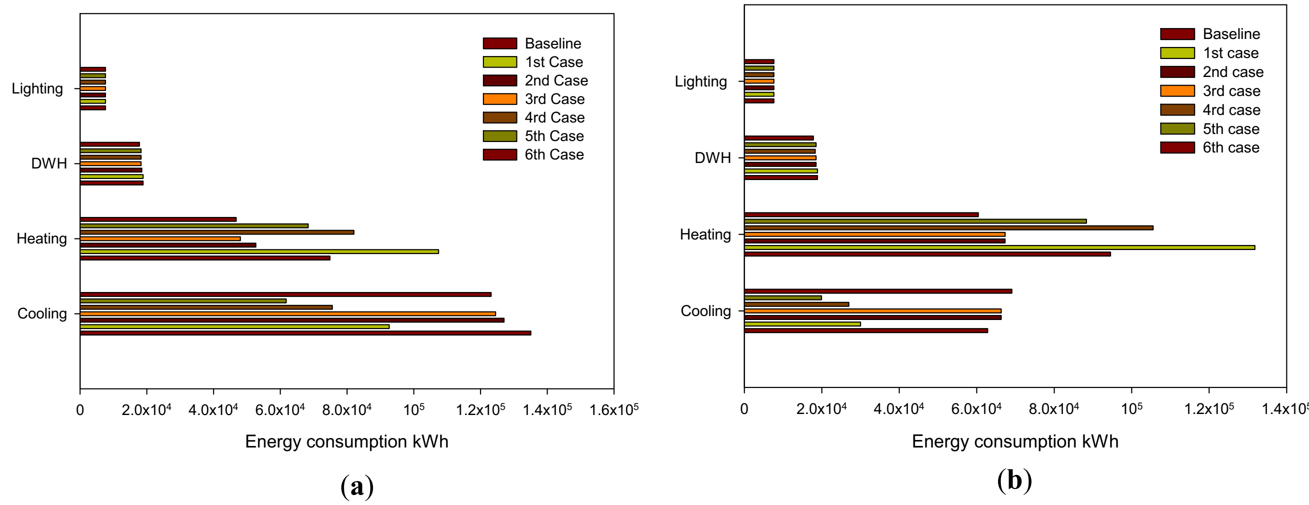


Figure 16. Building energy consumption baseline building vs. each case a) Mazar-I-Sharif and b) Kabul.

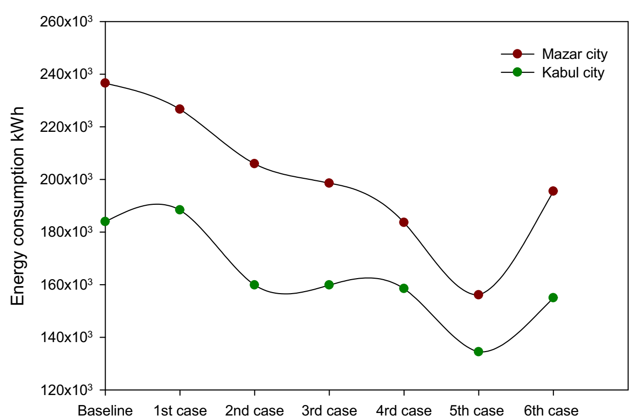


Figure 17. Comparison between baseline and each case building energy requirement.

7.3 *Payback time*

Although upgrading energy efficiency is always beneficial in terms of decreasing energy use, the payback times vary depending on the form and source of funding [27]. Allocating resources necessitates relying on the future to reap the rewards, and the future is, by definition, unpredictable. Understandably, consumers want to receive and enjoy products and services sooner rather than later, so they are prepared to pay interest on money (purchase of fuel) in exchange for earlier purchases of products and services [29].

A simple payback method for an operating year was used to choose the best retrofit solutions. Da Afghanistan Breshna Sherkat (DABS) services determined the electrical unit cost in each region. The average energy consumption for both locations was then assessed, and the annual energy savings were determined and used to establish the simple payback. The payback period was calculated by dividing the cost of any retrofit measure by the savings realized for the specific retrofit in a year. The costs of energy efficiency measures were computed in both US dollars ($) and Afghani (AFN) and were based on market rates. The exchange rate that was determined at the end of 2021 was used. Therefore $/AFN is equal to 1/96.

Every investment was evaluated from a financial standpoint, considering the price of supplies and installation.

The difference between the energy requirement of the current building (EC_{Existing}) and the energy requirement after the retrofit solution ($EC_{\text{Retrofitting}}$) is known as energy savings (ES). The energy savings were computed using equation (3) [30].

$$ES = EC_{Existing} - EC_{Retrofitting} \tag{3}$$

The payback period is defined as the ratio between the initial investment and the annual savings due to the thermal insulation. The payback time was calculated using equation (4) [31].

$$\textit{Payback period} = \frac{\text{Initial investment} + \text{maintainance cost}}{\text{The total cost of the energy saved (annually)}} \tag{4}$$

It should be noted that the payback period for the retrofitting of the building, considering the Kabul climate, is comparatively high; however, in Mazar-I-Sharif, which has scorching summers and cold winters, most of the retrofit packages are economically viable with a short payback period. Moreover, the electricity price in the two regions also affects the economic viability of retrofit packages. Table 14 presents the top minimum retrofit scenarios considering a simple payback period.

Table 14. Retrofit packages considering minimum simple payback period.

Region	Packages	Payback period (years)	Investment cost ($)	Return of investment (%)	Annual total energy saving ($)
Mazar-I-Sharif Hot-dry (2B)	II	1.84	3,842	54%	2,084
	III	1.54	3,991	64%	2,590
	IV	8	28,884	12.4%	3,600
	V	5.7	31,128	17.5%	5,463
	VI	3.7	10,477	26.8%	2,810
Kabul Mixed-dry (4B)	II	6	3,842	16.4%	631
	III	5	3,991	19.4%	775
	VI	13.6	10,477	7.3%	766

8. Conclusion and recommendations

There are direct and indirect benefits to building retrofits, especially in residential buildings in developing countries. The essential direct benefits include cost savings for heating and cooling in the winter and summer. Due to the large number of newly constructed uncomfortable and power-hungry residential buildings that do not meet the energy efficiency standards in the country and region, it is necessary to assess the financial viability of an energy retrofit plan and the suggested feasible retrofit measures. One of the critical goals of the energy performance of buildings in Afghanistan should be to promote cost-effective improvements to the overall energy performance.

The primary goal of this study was to develop a technique to accurately select and evaluate intervention packages consisting of several retrofit solutions that can be applied to an existing building to lower energy consumption. A case study was done on a residential apartment complex in Mazar-I-Sharif in Afghanistan to evaluate the technique. The approach is based on dynamic simulations of the thermal behavior of the building, which were performed with the DesignBuilder program and the EnergyPlus simulation engine. The simulations consider a base-case scenario and a succession of retrofit intervention packages, and the results were compared from energy and a cost perspective. Since it is impractical to examine all possible combinations of the measures, appropriate retrofit options for the building envelope, such as thermal insulation and retrofitting of the glazing, were selected.

On one hand, the results show that applying relatively low-cost wall and roof insulation may be the most cost-effective. On the other hand, replacing windows glass is not feasible in the Kabul climate; however, it has a relatively positive impact on cooling energy demand in the dry and hot climate of Mazar-I-Sharif.

Wall insulation is beneficial at every level. Thermal bridges are eliminated by insulating the entire perimeter of the building with EPS, which can save up to 18% of the building's energy consumption. This measure is the most effective retrofit option for the building envelope. Although window glass replacement is a frequent retrofit option in hot climate regions, it is not the most effective option in Afghanistan for a low payback time.

Furthermore, the analysis shows that the cost of enhancing the thermal performance of Afghan houses is recouped in a reasonable timeframe because the cost of modifying building requirements is compensated by the energy savings associated with a decreased demand for mechanical cooling. The study has shown that there are various advantages to enhancing the energy efficiency of Afghanistan's building stock, including reduced power consumption. Moreover, retrofitting existing buildings is highly cost-efficient, considering the economic advantages of decreased fuel consumption and a decreased demand for electricity production capacity. Besides, given the high cost and scarcity of electricity, households and other private entities should consider energy efficiency retrofit measures that are less expensive and enable property owners and/or users to invest in energy conservation at a reasonable cost. Establishing an institutional solid labor force capability is necessary for any energy efficiency initiatives for existing and newly constructed buildings in Afghanistan.

Acknowledgements

The authors are thankful to the Delhi Technological University for supporting this research work.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

References

[1] Wei Y, Zhang X, Shi Y, Xia L, Pan S, Wu J, Han M and Zhao X 2018 A review of data-driven approaches for prediction and classification of building energy consumption. *Renew. Sustain. Energy Rev.* 82: 1027–1047. https://doi.org/10.1016/j.rser.2017.09.108

[2] Christina E H and Runa D 2021 Ambitious deep energy retrofits of buildings to accelerate the 1.5°C energy transition

in Canada. *Can. Geogr.* 65: 116–127. https://doi.org/10.1111/cag.12637

[3] IEA 2020 GlobalABC/IEA/UNEP GlobalABC Roadmap for Buildings and Construction: Towards a zero-emission, efficient and resilient buildings, *Intrenaitonal Energy Agency*, Paris. https://www.iea.org/reports/globalabc-roadmap-for-buildings-and-construction-2020-2050 (accessed January 2, 2021)

[4] Abdulrahman Haruna, Nasir Shafiq and Montasir Osman Ahmad Ali 2021 Building information modelling application for developing sustainable building (Multi criteria decision making approach , *Ain Shams Eng. J*. 12: 293–302. https://doi.org/10.1016/j.asej.2020.06.006

[5] Rehmaashini J, Mat Naim-Abdullah M A, Abdul-Hakim M, Mohmmad-Nazir J, Janice Lee Y M and Maizan B 2017 Green retrofitting – A review of current status, implementations and challenges. *Renew. Sustain. Energy Rev.* 67: 1360–1368. https://doi.org/10.1016/j.rser.2016.09.091

[6] Shambalid Ahady, Nirendra Dev and Anubha Mandal 2020 An overview of the opportunities and challenges in sustaining the energy industry in Afghanistan", in: *E3S Web Conf.* https://doi.org/10.1051/e3sconf/202017303006

[7] Mohammad Omar Temori 2017 Energy Efficiency Guidbook for Buildings, kabul. http://catalog.acku.edu.af/cgi-bin/koha/opac-detail.pl?biblionumber=44454&fbclid=IwAR0O3HdXFaipXGTamHwKGQ3byQwC3oCUsV51btv3Gmc0axMhYctX16UEliE

[8] GERES 2015 Live comfortably: Lower heating costs Clean indoor air, *GERES* , Kabul

[9] Menna Costantino, Del Vecchino Ciro, Di Ludovico Marco, Mauro Gerardo Maria, Ascione Fabrizio and Prota Andrea 2021 Conceptual design of integrated seismic and energy retrofit interventions. *J. Build. Eng.* 38: 102190. https://doi.org/10.1016/j.jobe.2021.102190.

[10] Shambalid Ahady, Nirendra Dev and Anubha Mandal 2022 Urban Residential Buildings' Energy Consumption Pattern and Efciency , *Iran. J. Sci. Technol. Trans. Civ. Eng*. https://doi.org/10.1007/s40996-022-00848-3

[11] Jami Shady, Forouzandeh Nima, Zahra Sadat Z, Tahsildoost Mohammad and Khoshbakht Maryam 2021 The effect of occupant behaviors on energy retrofit: A case study of student dormitories in Tehran. *J. Clean. Prod.* 278: 123556. https://doi.org/10.1016/j.jclepro.2020.123556

[12] Rose Jorgen, Kirsten Engelund T, Mørck Ove C, Miriam Sanchez M G and Jensen Soren Østergaard 2019 Refurbishing blocks of flats to very low or nearly zero energy level–technical and financial results plus co-benefits. *Energy Build.* 184: 1–7. https://doi.org/10.1016/j.enbuild.2018.11.051

[13] AlFaris Fadi, Juaidi Adel and Manzano-Agugliaro Francisco 2016 Energy retrofit strategies for housing sector in the arid climate. *Energy Build.* 131: 158–171. https://doi.org/10.1016/j.enbuild.2016.09.016

[14] Gomes Ricardo, Ferreira Ana, Azevedo Luis, Neto Rui Costa, Aelenei Laura and Silva Crlos 2021 Retrofit measures evaluation considering thermal comfort using building energy simulation: two Lisbon households. *Adv. Build. Energy Res.* 15: 291–314. https://doi.org/10.1080/17512549.2018.1520646

[15] Evangelisti Luca, Guattari Claudia and Gori Paola 2015 Energy retrofit strategies for residential building envelopes: An Italian case study of an early-50s building. *Sustain.* 7: 10445–10460. https://doi.org/10.3390/su70810445

[16] DesigBuilder 2021 DesigBuilder version 7.0.0.096, *Designbuilder*. UK https://designbuilder.co.uk/

[17] Köppen-Geiger 2022 Köppen-Geiger climate classifcation. (access 2 January 2022) http://koeppen-geiger.vu-wien.ac.at/present.htm

[18] ANSI/ASHRAE Standard 169-2020, 2021 Climatic Data for Building Design Standards, *American Society of Heating Refrigerating and Air-Condationing Engineers*

[19] Ahady Shambalid, Dev Nirendra and Mandal Anubha 2021 Solar radiation control passive strategy for reduction of heating and cooling energy use in arid climate: Case of Afghanistan. *Indoor Built Environ.* 31(4): 955–971. https://doi.org/10.1177/1420326X211050114

[20] ASHRAE 2021 KABUL WEATHER-ASHRAE handbook-Fundamentals, *American Society of Heating Refrigerating and Air-Condationing Engineers*

[21] Afghanistan Metrological Department 2021Afghanistan Weather data, *Afghanistan Metrological Department*, Kabul

[22] Municipality Office 2021 Construction Department, *Municipality office*, Mazar-I-Sharif

[23] Royapoor Mohammad and Roskilly Tony 2015 Building model calibration using energy and environmental data. *Energy Build.* 94: 109–120. https://doi.org/10.1016/j.enbuild.2015.02.050

[24] Wakili Karim Ghazi, Binder B, Zimmermann M and Tanner Ch 2014 Efficiency verification of a combination of high performance and conventional insulation layers in retrofitting a 130-year old building. *Energy Build.* 82: 237–242. https://doi.org/10.1016/j.enbuild.2014.06.050

[25] ANSA 2015 Afghanistan Energy Efficiency code for Building (AEEC), *Afghanistan National Sandard Authority,* Kabul

[26] Liu Yuming, Liu Tingting, Ye Sudong and Liu Yisheng 2018 Cost-benefit analysis for Energy Efficiency Retrofit of existing buildings: A case study in China. *J. Clean. Prod.* 177: 493–506. https://doi.org/10.1016/j.jclepro.2017.12.225

[27] Preciado-pérez Oscar A and Fotios Steve 2017 Comprehensive cost-benefit analysis of energy efficiency in social housing. Case study: Northwest Mexico. *Energy Build.* 152: 279–289. https://doi.org/10.1016/j.enbuild.2017.07.014

[28] Yang Jun, Ren Jiayi, Sun Dongqi, Xiao Xiangming, Xia Jianhong Cecilia, Jin Cui and Li Xueming 2021 Understanding land surface temperature impact factors based on local climate zones. *Sustain. Cities Soc.* 69: 102818. https://doi.org/10.1016/j.scs.2021.102818

[29] Morrissey John and Horne Ralph E 2011 Life cycle cost implications of energy efficiency measures in new residential buildings. *Energy Build.* 43: 915–924. https://doi.org/10.1016/j.enbuild.2010.12.013

[30] Mahlia T M I, Abdul Razak H and Nursahida M A 2011 Life cycle cost analysis and payback period of lighting retrofit at the University of Malaya. *Renew. Sustain. Energy Rev.* 15: 1125–1132. https://doi.org/10.1016/j.rser.2010.10.014

[31] Wong Ingliang, Eames Philip C and Perera Srinath 2007 A review of transparent insulation systems and the evaluation of payback period for building applications, *Solar Energy.* 81:1058–1071. https://doi.org/10.1016/j.solener.2007.04.004