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Research Article

Effectiveness of building envelope parameters and adopting PV panels to reduce reliance on local generators in hot-dry climate

Ahmed Jabar Ibrahim [a,b], Dnya Dlshad Zangana [a,b,*], Laleh Dehghanifarsani [c]

[a] *School of Architecture, Southwest Jiaotong University, Chengdu, China*

[b] *Department of Architecture, Faculty of Engineering, Koya University, Kurdistan Region, Iraq*

[c] *Department of Biomaterials, Saveetha Dental College and Hospitals, SIMATS, Saveetha University, Chennai-600077, India*

Abstract.The growing energy demand, associated with the inability of the current infrastructure to satisfy this demand, has presented numerous challenges in Iraq's electricity sector. As a result, there has been an increased dependence on local diesel generators to mitigate power outages in homes. However, these generators raise environmental concerns and are associated with high operating CO_2 emissions. Here, using the DesignBuilder and EnergyPlus simulation software, the effectiveness of different building envelope modifications and photovoltaic panels as alternative energy sources was examined. Specifically, the impact of wall and roof insulation, window glazing, and shading devices on energy efficiency was analyzed. The results indicated that roof insulation is the most effective in reducing energy consumption by 28.8%, followed by wall insulation by 13.01%, while the effect of windows glazing and shading devices was insignificant. Furthermore, the installation of solar panels led to a significant reduction in energy demand by 53.6%, thereby decreasing operating carbon dioxide emissions and providing a practical alternative to the use of local generators. Our study offers valuable insights into the design of energy-efficient residential buildings in hot and dry climates. It highlights the importance of selecting appropriate building materials and integrating renewable energy sources, presenting a more environmentally effective solution to mitigate energy shortages.

Keywords: Building Envelope; Energy Simulation; Building energy consumption; CO_2 emissions; Erbil City; Electricity Demand

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1. Introduction

The greenhouse effect and the shortage of energy have become increasingly pressing issues. Consequently, the development of the building envelope has emerged as a critical strategy for promoting sustainable development. Buildings account for 40% of the world's energy consumption, with an annual increase of 2.2% (Zhao & Magoulès 2012; Bordbari *et al.* 2018). In the U.S., residential buildings are the largest energy consumers, representing 22% of the total energy usage in 2022 (U.S. Energy Information Administration 2023a). The U.S. EIA predicts a 65% increase in global energy consumption by buildings from 2018 to 2050, escalating from 91 to 139 quadrillion Btu. Specifically, in residential buildings, energy consumption is expected to rise from 192 TWh in 2012 to 1200 TWh in 2050, influenced by factors such as higher incomes, urbanization, and improved access to electricity. However, estimated energy consumption could be reduced by up to 40% through the implementation of energy efficiency measures and policies (U.S. EIA 2023b; Liu *et al.* 2020). The World Watch Institute estimates that buildings are responsible for 40% of global energy consumption, especially in urbanized and industrialized countries (Oldewurtel *et al.* 2010). In Iraq, the building sector accounts for 48% of residential, 29% of industrial, 13% of office, 6% of commercial, and 4% of agricultural energy consumption (Alsammarae 2005). Moreover, cooling and heating are the most significant energy consumers, compared to lighting and other uses, with 69% of annual household energy in Baghdad allocated to cooling and 42% and 26% to heating, respectively (Hasan 2012).

Since the 1990s, energy generation in Iraq has been facing a continuous crisis, with demand exceeding supply. The current political instability and war have contributed to this issue (Alaamery 2008). The economic embargo has caused the existing energy generation to deteriorate, leading to an energy supply shortage in the building sectors (Al-Ali 2013). For example, Basra City, one of Iraq's major cities, has been facing this energy crisis since 2003, with energy demand reaching 750 megawatts during the summer of 2004 and 850 MW in 2005, a 12% increase in one year. Energy supply in Iraq depends entirely on fossil fuel resources, with natural gas and steam power plants accounting for 60-70% of overall power generation. Steam power plants are powered by oil or diesel and are the primary energy providers in the southern Iraqi region (Ministry of Electricity 2014). However, energy generation decreased by 13% in 2010 compared to 1990 due to poor maintenance and sudden shutdowns of some steam power plants (Al-Ali 2013). This highlights the urgent need for comprehensive strategies to address the energy crisis, focusing

* Corresponding author
Email: dunya.dlshad@koyauniversity.org (D.D.Z)

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on possibly diversifying energy sources to meet the growing demand sustainably.

Erbil's prosperity has led to a surge in residential projects, driven by the availability of land for investment. However, the city faces challenges such as a shortage in electricity production and a high and growing demand due to the rapid expansion of the residential building sector (Rudaw 2021; Kurdistan24 2022). In 2015, residential buildings in Erbil city accounted for the highest energy consumption and CO_2 emissions among all other sectors, totaling 7,855,170 MWh and approximately 4,422,846 tCO_2, as reported in the Sustainable Energy Action Plan. The BAU projection for 2030 suggests a significant increase in energy consumption to 12,725,375 MWh and 7,165,010 tCO_2 emissions (KRG of Iraq & LADP 2018).

On average, U.S. households require energy to operate various home devices and equipment. However, over half (51%) of a household's yearly energy usage is allocated to just two purposes: space heating and air conditioning. These uses, typically seasonal and requiring sufficient energy, vary considerably depending on location, home size and structure, and the type of equipment and fuel used (EIA 2015). This high energy consumption rate, combined with rising energy costs, requires prioritizing energy efficiency measures during the design and construction of residential buildings. Similarly, in Iraq, cooling and heating are the two major energy-consuming activities that require a significant amount of energy compared to other uses, such as lighting. A recent study (Abbood *et al.* 2015) conducted in Iraq reveals that cooling alone accounts for 42% of the energy consumption in homes, while heating constitutes 26%. Hence, the combined cooling and heating activities consume up to 69% of the total energy in households, indicating the need for more efficient and sustainable methods to control indoor temperatures.

The usage of air conditioning systems, lighting, and the thermal efficiency of building materials are major contributors to the amount of electricity used in residential buildings in Iraq. Sultan (2019) states that the residential sector in Iraq has the potential to save electrical energy, which currently makes up more than 47% of the total national energy consumption. He also predicted that residential energy usage in Iraq would rise from 64,783 GWh in 2013 to 121,606 GWh in 2023, with household appliances being a key contributor, accounting for 34.95% of this consumption. Baglivo *et al.*, (2023), Mohamed *et al.* (2016) and (2015) have highlighted the importance of roof thermal radiation and the impact of highly reflective roofs on reducing energy consumption. Additionally, Alnuaimi and Mohammed (2021) have proposed using "cool roofs" as an architectural technique to reduce electricity consumption. Improving thermal efficiency for the building envelope and adopting energy-efficient strategies in residential buildings is crucial to reducing energy consumption significantly. Therefore, it is essential to integrate energy-efficient measures during the design and construction of residential buildings for a sustainable future.

The Kurdistan Region government provides 12–16 hours of electricity daily (Rudaw 2021). Sometimes, the daily outages may reach up to 20 hours, forcing residential premises to depend on private neighborhood generators, which are often located in the middle of neighborhoods and produce electricity using fossil fuels (Rudaw 2021). Specifically, this outage represents a major problem for the city of Erbil, which constantly suffers from a major shortage of electricity due to various factors, such as old power plants and overloaded distribution networks. To address the electricity shortage, Erbil has more than 5,000 neighborhood generators, which can contribute significantly to air pollution by emitting thick black smoke (Rudaw 2023). Considering these challenges, conducting an investigation is crucial to identify solutions that can address the growing energy shortage by utilizing clean energy sources and mitigating carbon emissions.

Photovoltaic panels, as a renewable energy source, can reduce energy consumption in buildings by converting sunlight into electricity (U.S. EIA 2022). Different studies indicated the importance of photovoltaic panels (Zhan *et al.*, 2024; Samarasinghalage *et al.* 2022); for instance, studies in China have shown that net-zero energy buildings can be achieved by integrating photovoltaic systems (BIPV) on the rooftops of low-rise residential buildings (Liu *et al.* 2019; Feng *et al.* 2023). Similarly, a study by Sorgato *et al.* (2018) conducted in six Brazilian cities found that these systems could meet the net energy consumption requirements of 4-story office buildings. However, there is a shortage of studies investigating how the photovoltaic system can be used to reduce dependence on neighborhood generators in cities that face shortages of electricity, such as Erbil.

Researchers worldwide have shown growing interest in energy-efficient envelope design strategies over the past few decades (Asfour, 2020; Chen *et al.* 2015; Pérez-Lombard *et al.* 2008). Improving building envelope techniques has become widespread to enhance buildings' energy efficiency (Al-Tamimi, 2022; Mustafa *et al.* 2020; Alkhalidi & Aljolani, 2020;). The building envelope can play an essential role in isolating the indoor environment from the outdoor environment, enhancing indoor conditions, and controlling quality regardless of external conditions (Sadineni *et al.* 2011; Dabaieh *et al.* 2015). For example, Alrashed and Asif (2014) revealed in a study on 115 residential buildings in Dhahran, KSA, that the energy consumption of dwellings with thermal insulation was 32% lower than that of those without insulation. Moreover, Mustafa *et al.* (2020) found that wall insulation notably reduces energy use for cooling requirements in the summer.

Additionally, as another building envelope parameter, the glazing can have a significant effect on reducing energy consumption, as asserted by Taleb (2014) and Allouhi *et al.* (2018), who demonstrated that multi-layer glazing with lower U-values and shading coefficients can significantly reduce energy needs for cooling in summer and heating in winter. Furthermore, Samanta *et al.* (2014) stated that shading devices in hot and dry tropical regions can reduce 8% of the cooling energy load, while Mustafa *et al.* (2020) reported a lower energy savings percentage from shading devices in a similar climate, attributing this to the windows-to-wall ratio. However, further studies are important to assess which part of the building envelope has the most effect on energy consumption in residential buildings in hot-dry climates.

Another challenge to increasing energy consumption in residential buildings is carbon emissions. The energy consumed in heating and cooling homes is considered one of the most significant sources of carbon dioxide emissions, constituting 30–50% of total energy use (IEA 2019). The Energy Performance of Buildings Directive (EPBD) requires all new buildings in the European Union to be nearly zero-energy by 2021, while existing buildings must be renovated to improve their energy efficiency (Gouldson *et al.* 2015). The importance of the building envelope is evident in its impact on energy consumption and CO2 emissions, as energy-efficient buildings require less energy for heating and cooling, which leads to lower CO2 emissions (IEA 2019). Therefore, it is crucial to investigate how modifications to the building envelope can further decrease carbon emissions.

To address the gaps in the study, DesignBuilder and EnergyPlus were used to construct a simulation model and conduct a parametric analysis for a typical house in Erbil City, Iraq, using a case study approach. Erbil has cold winters and hot

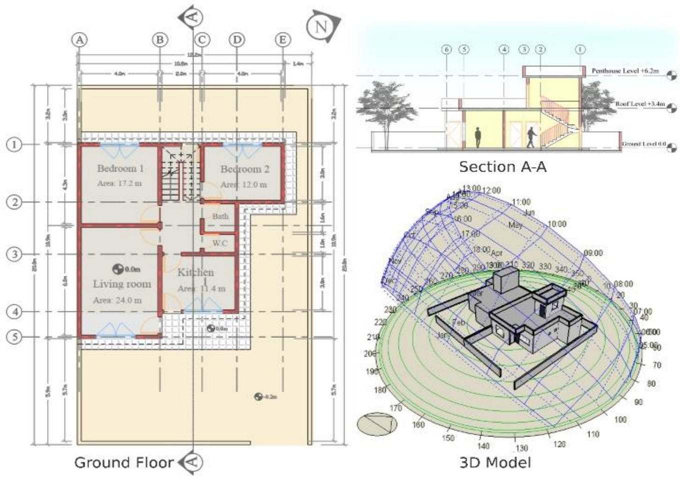


Fig. 1 Architectural drawing of the case study with 3D model to show zones dimensions & orientation.

summers, with July to August, which can exceed 42°C, while January to February can drop below 6°C. Transitional months have moderate temperatures. Our study aims to address the following two questions: (1) What are the parts of a building's envelope that significantly impact energy consumption, and (2) Does the utilization of photovoltaic (PV) panels represent an effective alternative to traditional neighborhood generators in mitigating electricity shortages? The remainder of this paper is organized as follows: Firstly, the paper presents the case study and then explains the simulation model and parameterization. The subsequent section discusses the simulation results and analysis of various parameter combinations. The paper concludes with suggestions for optimal parameters, their implications for regional construction, and potential areas for future research. This paper addresses the energy gaps in residential buildings in hot and dry climates. Our study provides practical recommendations that guide decision-makers in reducing energy usage, lowering CO2 emissions, and promoting the adoption of renewable energy sources over traditional local generators.

2. Methods

2.1 Case study

Erbil City has two main types of residential buildings: houses and apartments. Houses can either be detached or attached to other houses on one, two, or three sides. They typically consist of one or two floors, with a staircase leading to the penthouse. The area of houses in Erbil city ranges from 100 m² to over 300 m². On the other hand, apartments are multi-storey buildings of various sizes. This study focuses on a single-family house as a case study. The house is a typical residential building in Erbil and has seven zones, including a living room, two bedrooms, a kitchen, a connecting corridor, a W.C., and a bathroom, as shown in Fig. 1. The west façade of the house is attached to other buildings and is not directly facing the sun's radiation. The property occupies a land area of 244 m², with a net building area of 94.1 m². The building is designed on a single floor with a height of 3.40 meters and has a penthouse. The construction material details obtained from the site survey are presented in Table 1.

2.2 Methodology

The methodology of this study involves analyzing the energy consumption and the operational CO_2 emission of a typical house in Erbil. To create a detailed simulation model, use DesignBuilder software and gather construction details from a site survey of all building components listed in Table 1.

Our baseline model calculates the energy consumption of a single-family house in Erbil city with a south orientation. Then, the data was transferred to EnergyPlus to assess annual energy consumption and CO2 emission. The evaluation of various building envelope components to improve energy efficiency, including wall materials, external insulation, window glazing, and shading devices, was carried out. Our goal is to determine which envelope parts have the most significant impact on energy consumption. Additionally, the potential of PV solar panels to generate energy and reduce reliance on neighbourhood generators was examined. To evaluate the energy-saving performance of each change made to the building envelope parameters, we simulated annual energy consumption during the building's operational period. This process is illustrated in the flow chart shown in Fig. 2.

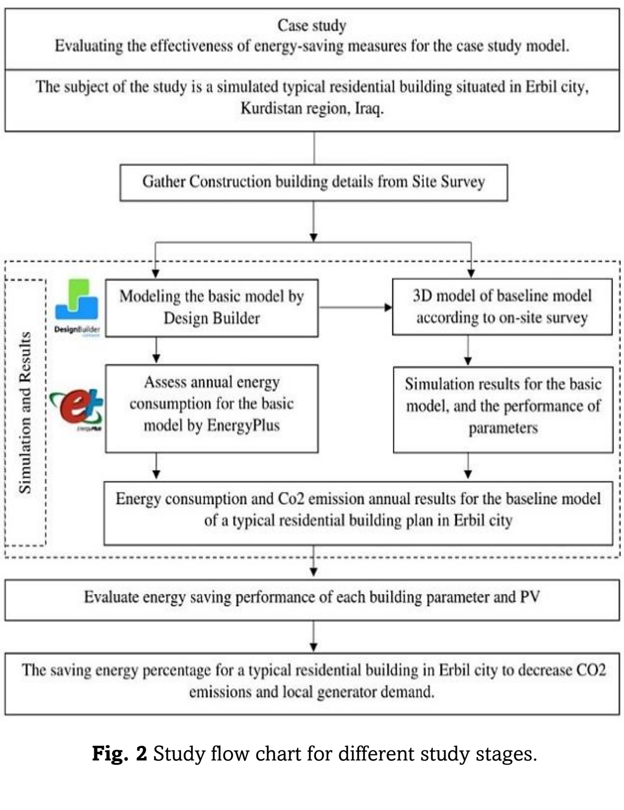
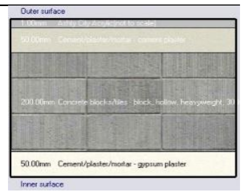
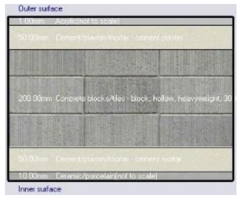
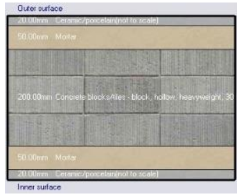
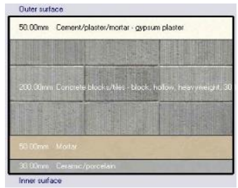
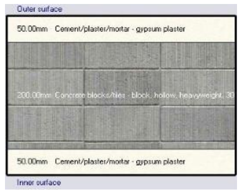


Fig. 2 Study flow chart for different study stages.

Table 1
Construction materials of the case study according site survey.

Building elements	Construction Material from out surface to inner surface	U-Value [W/m^2-K]	Figures
Ext. wall between rooms & ext.	5 cm Cement with paint + 20 cm Concrete hollow block + 5 cm Gypsum	2.038	
Ext. wall between kitchen, bath & ext.	5 cm Cement with paint + 20 cm Concrete hollow block + 5 cm Concrete + 2 cm Ceramic tile	2.129	
Int. walls between bath & kitchen	2 cm Ceramic tile + 5 cm Concrete + 20 cm Concrete hollow block + 5 cm Concrete + 2 cm Ceramic tile	1.810	
Int. walls between bath, kitchen & rooms	2 cm Ceramic tile + 5 cm Concrete + 20 cm Concrete hollow block + 5 cm Gypsum	1.706	
Int. walls between rooms	5 cm Gypsum + 20 cm Concrete hollow block + 5 cm Gypsum	1.655	
Roof	20 cm reinforced concretes (with %2 steel) + 2 cm Gypsum	3.858	
Ground Floor	Soil + 10 reinforced concretes (with %1 steel) + 5 cm Floor screed + 5 cm Concrete + 2 cm 2 cm Ceramic tile	2.263	
Main door	Metal	3.124	
Interior doors between rooms	MDF	2.823	
Interior doors for bath and W.C	PVC (polyvinyl chloride)	2.572	
Windows	PVC (polyvinyl chloride) frame with single clear glass 3mm	5.894	

2.3 Simulation

Simulation technology that utilizes computers accurately models design and usage changes (Muller, 2001). Our research involved creating energy models for a typical house using an hourly building simulation tool called DesignBuilder. This software is based on EnergyPlus, a state-of-the-art building performance simulation software (DesignBuilder, n.d.). DesignBuilder is a unique software tool that enables the creation and evaluation of building projects. It provides a wealth of data on environmental performance, including maximum summer temperatures, comfort conditions, energy consumption, carbon emissions, and dimensions of HVAC components.

Table 2
Area and ratio for windows and walls of the case study.

Building side	Gross wall area [m^2]	Window opening area [m^2]	Window-Wall Ratio [%]	Windows opening Ratio [%]
North	44.94	6.4	14.24	45
East	51.16	2.08	4.07	80
South	44.94	5.82	12.96	37.5
West	14.1	0	0	0

Table 3
Input parameters for simulate the case study by DesignBuilder.

Location	Erbil, Iraq
Latitude/longitude [deg]	36.23/43.97
Elevation [m]	408.7
Local time zone [GMT +/− N hours]	+3 hours
Number of occupants [person]	4
Cooling/Heating setpoint temp.[◦C]	25/24
Cooling and heating system	Split air conditioner
Hours Simulated [hrs.]	8760
Using shading device	No

DesignBuilder employs the latest EnergyPlus simulation engine to calculate building performance, making it suitable for architects, energy consultants, and construction service engineers.

In order to achieve accurate and location-specific results, careful consideration of various building and environmental aspects is required during the simulation stage. Tables 2 and 3 present the critical parameters used in the model simulation. Notably, the ratio of windows to walls varies across different parts of the building (Table 2), with the living room having the highest ratio of 25% and the bath having the lowest ratio of 4.33%. According to the site survey, the Split air conditioning system is used for cooling and heating (Fig. 3), maintaining a consistent temperature of 24°C in winter and 25°C in summer, in accordance with the ASHRAE Standard 55-2020 Adaptive Method (Tartarini *et al.* 2020).

All building spaces are equipped with split-unit air conditioners except for the bath, W.C., and corridor. The hot-dry climate of Erbil City was determined using reliable weather data from the EnergyPlus weather data library, which was employed for the simulation. Maintaining consistency in these parameters across all simulations is crucial to achieving precise and efficient outcomes for the study. In this study, various building envelope parameters, as presented in Table 4, have been investigated to enhance the energy efficiency of the building. These include changes to the building envelope, including wall material, glazing, and insulation, besides using shading devices. Each strategy has been assessed to determine its specific impact on the overall energy efficiency of the building.

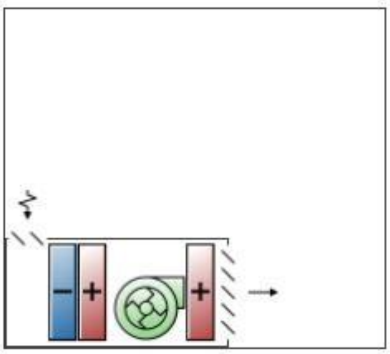


Fig. 3 HVAC system for conditioned zones

2.4 Calculating annual energy and operational carbon

DesignBuilder is a software that calculates the annual energy consumption of buildings using a detailed simulation approach. It models the building's physical and operational characteristics, including its geometry, materials, HVAC systems, and usage patterns, to accurately simulate its energy performance under real-world conditions (Fathalian & Kargarsharifabad, 2018). For HVAC energy consumption, DesignBuilder simplifies the calculation by using the Coefficient of Performance (CoP) data at the building level for boilers, chillers, and domestic hot water (DHW). DesignBuilder supports a wide range of analyses, including heating and cooling loads calculation, daylighting, natural ventilation, and environmental impact assessment, providing detailed breakdowns of energy consumption by fuel and end-use (Alshahrani & Boait, 2018).

To calculate the annual operational carbon emissions in DesignBuilder, the data on the building's energy consumption was collected from the simulation results. This includes heating, cooling, lighting, equipment uses, and any other operational energy uses (DesignBuilder, n.d.). Convert the energy consumption data into CO_2 emissions using conversion factors. Utilize DesignBuilder's reporting tools to generate the Operational Carbon report, which summarises the CO2 emissions associated with the building's operation.

2.5 Determination of building envelope variables

The insulating materials were carefully selected based on various criteria relevant to the Erbil market and construction practices. The selected materials are readily available in Erbil and are commonly used in the region. In the selection process, traditional construction methods suitable for the climate were also considered, such as the use of brick, which is a common element in the buildings of the historic city of Erbil. The aim is to provide a range of materials that reflect traditional and modern building practices and to identify the most effective insulation strategies that are compatible with the climatic conditions of the region and the local construction industry. The simulations used different materials and thicknesses to provide a comprehensive understanding of how each option contributes to the thermal efficiency of the building in the unique environmental context of Erbil (Table 4).

Table 4
The variables used for assessing the energy saving.

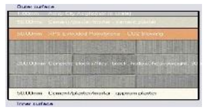
Building envelops elements	U-value [W/m^{2}K]	Figures
Wall material		
5 cm Cement & paint + Double 10 cm concrete hollow blocks with 10 cm air gap + 5 cm Gypsum	1.365	
5 cm Cement & paint + Clay hollow brick 12 cm + 5 cm Gypsum	0.875	
5 cm Cement & paint + Double 12 cm Clay hollow brick with 10 cm air gap + 5 cm Gypsum	0.76	
5 cm Cement & paint + Extruded polystyrene XPS 3 cm + 20 cm Concrete hollow block + 5 cm Gypsum	0.728	
5 cm Cement & paint + Rock wool 5 cm + 20 cm Concrete hollow block + 5 cm Gypsum	0.643	
5 cm Cement & paint + Extruded polystyrene XPS 5 cm + 20 cm Concrete hollow block + 5 cm Gypsum	0.51	
5 cm Cement & paint + Extruded polystyrene EPS 7.5 cm + 20 cm Concrete hollow block + 5 cm Gypsum	0.423	
5 cm Cement & paint + Extruded polystyrene XPS 7 cm + 20 cm Concrete hollow block + 5 cm Gypsum	0.392	
5 cm Cement & paint + Rock wool 10 cm + 20 cm Concrete hollow block + 5 cm Gypsum	0.382	
5 cm Cement & paint + Extruded polystyrene EPS 10 cm + 20 cm Concrete hollow block + 5 cm Gypsum	0.334	
5 cm Cement & paint + Extruded polystyrene XPS 10 cm + 20 cm Concrete hollow block + 5 cm Gypsum	0.291	
5 cm Cement & paint + Extruded polystyrene EPS 15 cm + 20 cm Concrete hollow block + 5 cm Gypsum	0.236	
Roof material		
20 cm reinforced concretes (with %2 steel) + Extruded polystyrene XPS 3 cm + 2 cm Gypsum	0.876	
10 cm reinforced concretes (with %1 steel) + Extruded polystyrene XPS 3 + 20 cm reinforced concretes (with %2 steel) + Extruded polystyrene XPS 3 cm + 2 cm Gypsum	0.844	

Table 4
The variables used for assessing the energy saving *(Cont'd)*

20 cm reinforced concretes (with %2 steel) + Rock wool 5 cm + 2 cm Gypsum	0.756	
20 cm reinforced concretes (with %2 steel) + Extruded polystyrene XPS 5 cm + 2 cm Gypsum	0.578	
10 cm reinforced concretes (with %1 steel) + Extruded polystyrene XPS 5 + 20 cm reinforced concretes (with %2 steel) + Extruded polystyrene XPS 3 cm + 2 cm Gypsum	0.564	
20 cm reinforced concretes (with %2 steel) + Extruded polystyrene XPS 7 cm + 2 cm Gypsum	0.431	
10 cm reinforced concretes (with %1 steel) + Extruded polystyrene XPS 7 + 20 cm reinforced concretes (with %2 steel) + Extruded polystyrene XPS 3 cm + 2 cm Gypsum	0.423	
20 cm reinforced concretes (with %2 steel) + Rock wool 10 cm + 2 cm Gypsum	0.419	
20 cm reinforced concretes (with %2 steel) + Extruded polystyrene XPS 10 cm + 2 cm Gypsum	0.312	
10 cm reinforced concretes (with %1 steel) + Extruded polystyrene XPS 10 + 20 cm reinforced concretes (with %2 steel) + Extruded polystyrene XPS 3 cm + 2 cm Gypsum	0.308	
Glass material		
Singal 6 mm clear glass	5.778	
Double 3 mm clear glass with 13 mm air gap	2.716	
Double 6 mm clear glass with 13 mm air gap	2.665	
Overhang projection	Length [m]	
Overhang projection 1	0.5	
Overhang projection 2	1	
Overhang projection 3	1.5	
Side-fin projection	Length [m]	
Side-fin projection 1	0.5	
Side-fin projection 2	1	
Side-fin projection 3	1.5	

2.6 Adaptive comfort standard

The conventional PMV indicator is unsuitable for assessing thermal comfort in natural ventilation due to individual control and psychological expectations shifts (Goto *et al.* 2007). To solve this problem, ASHRAE Standard 55 proposed the Adaptive Comfort Standard (ACS), which allows for wider acceptable indoor temperature ranges in warmer climate zones (de Dear & Brager 2002). With the ACS model, designers can determine appropriate temperatures for load calculation and cooling plant sizing based on occupants' thermal responses, according to Luo *et al.* in 2015. The ACS model introduces the 80% acceptability of indoor operative temperature, which considers prevailing meteorological conditions and occupants' thermal expectations to address their adapting behaviour as follows:

$$To = xTa + (1 - x)Tr \quad (1)$$

$$To, up80 = 0.31Tao + 21.3 \quad (2)$$

$$To, low80 = 0.31Tao + 14.3 \quad (3)$$

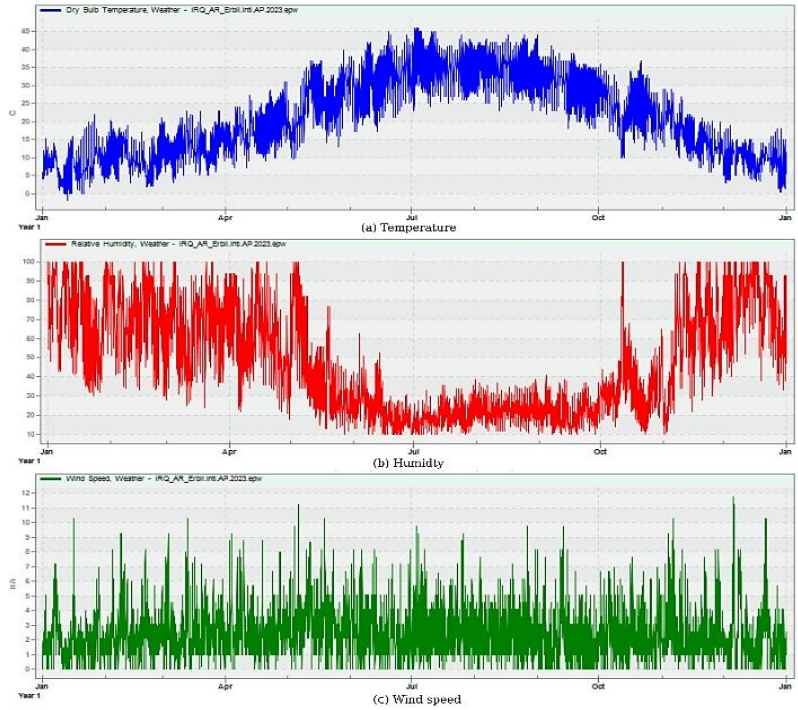


Fig. 4 Weather condition of Erbil city.

where: *To* is the operative temperature, *Ta* is the average air temperature, *Tr* is the mean radiant temperature; *x* is the coefficient depending on the relative air speed according to ASHRAE 55; *To, up*80 is the upper limit of acceptable operative temperature; *To*, low80 is the lower limit of acceptable operative temperature; *Tao* is the prevailing mean outdoor air temperature.

The ACS equations apply to indoor air speeds less than 0.3 m/s and outdoor temperatures ranging from 10 °C to 33.5 °C. These equations are intended for non-mechanically ventilated spaces with occupants' metabolic rates between 1.0 and 1.3 met. It is recommended that occupants adjust their clothing based on outdoor and indoor conditions within a range of 0.5 to 1.0 clo. The simulation calculates the indoor operative temperature using air and radiant temperatures as well as air speed sensors. If the operative temperature exceeds 80%, the windows should be closed and the AC should be turned on. If the AC is off and the indoor temperature exceeds the outdoor temperature, the windows should be opened. The monthly set points are modified based on the limits specified by ACS.

2.7 Weather file

To use Energy Plus, it is necessary to have a weather file in.epw format. This file should contain hourly weather information for a typical year in the chosen location. Aside from weather data, it also contains several parameters that identify the specific location, such as location name, data source, latitude and longitude, time zone, elevation, peak design conditions, holidays, and daylight saving period. In addition, the file includes many meteorological variables, such as dry bulb and dew point temperature, relative humidity, station pressure, solar radiation (global, extraterrestrial, horizontal infrared, direct, and diffuse), illumination, wind direction and speed, and sky cover. Additionally, weather files help accurately model how a typical home will respond to the local climate in terms of energy consumption and heating and cooling needs.

2.8 Weather condition

Iraq's climate varies across its regions. Northern Iraq has a Mediterranean or Dry-Summer Subtropical climate in its mountainous Kurdistan region. Winters are cold and snowy, with hot-dry summers. Temperature data for Erbil (Fig. 4), according to the weather file EPW, shows the lowest temperatures ranging from 6.20°C in January to 7.20°C in December and the highest temperatures ranging from 15.4°C in January to 42.7°C in July. The average temperatures in Erbil range from 10.8°C in January to 35.10°C in July. Temperature patterns show temperatures increase from winter to summer, with the transitional months showing moderate temperatures.

Figure 4, also presents the humidity levels in Erbil city for each month. The average humidity for the year is 51.57. Humidity varies with higher levels at the beginning and end of the year and lower levels during the middle months. This indicates a transition from higher to lower humidity and back again over the year. Furthermore, the average daily wind speed ranges from 2.10 ms in January to 2.69 ms in December. The lowest and highest daily wind speeds range from 0.31 ms to 3.92 ms in January and from 0.42 ms to 6.23 ms in June. Wind speeds remain consistent from April to October but decrease slightly in November to 2.07 ms. When accounted for in energy simulations, these climatic factors can lead to more accurate predictions of energy needs and the performance of energy-saving measures across different seasons.

3. Results

3.1 Annual energy consumption for the baseline module

This study used the DesignBuilder software to simulate the annual energy consumption required to operate a typical house in Erbil. Tables 1, 2, and 3 outline the building parameters, including window structures, exterior walls, floors, roofs, shading methods, and HVAC systems set within the software to create the simulation model. Erbil's temperature rises from April

Table 5
Energy consumption for the basic model in different categories.

Categories	Energy consumption [kWh]	Percentage [%]
Cooling	2950.59	22.8 %
Heating	5132.38	39.6 %
Interior lighting	3573.07	27.6 %
Fans system	879.36	6.7 %
Exterior lighting	403.57	3.12 %
Total end uses kwh	12938.97	100 %

to October, with July being the hottest month, necessitating the use of cooling systems for comfort. Conversely, the temperature decreases from October to April of the following year, requiring heating systems to maintain a comfortable temperature. The annual energy simulation results obtained from DesignBuilder are displayed in Table 5, providing an overview of electricity consumption across various categories, with a total consumption of 12938.97 kWh. Heating represents the largest portion of the building's energy consumption, accounting for 39.6%, or 5132.38 kWh, followed by cooling at 22.8% (2950.59 kWh). These findings offer valuable insights into the distribution of electricity within the building.

The data in Fig. 5 and Fig. 6 presents a clear breakdown of monthly electricity usage for heating and cooling. Upon closer examination, it becomes apparent that there is a distinct seasonal fluctuation in consumption. The winter months of January (1536.187 kWh), February (973.925 kWh), and December (1206.679 kWh) show the highest electricity usage for heating, which is to be expected given the colder ambient temperatures during this time. Conversely, the summer months of July (903.4123 kWh) and August (828.5486 kWh) witness the highest consumption for cooling, reflecting the increased need for air conditioning in response to rising temperatures. April and October, on the other hand, show a more moderate energy usage pattern for heating and cooling, indicating milder weather conditions. This data not only provides insight into the building's thermal energy dynamics but also serves as a valuable tool for assessing the effectiveness of its thermal management systems and identifying opportunities for improving energy efficiency.

Fig. 5 introduces an additional aspect, the amount of CO_2 emissions in kilograms, to complement the previously presented data on electricity usage for heating and cooling. This addition enables a more comprehensive evaluation of the

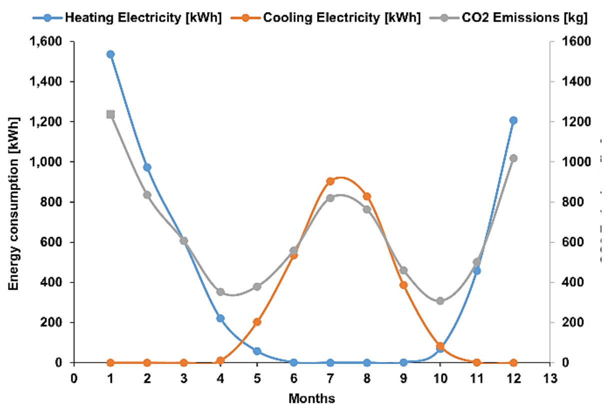


Fig. 5 The heating and cooling energy consumption for case study baseline model by months.

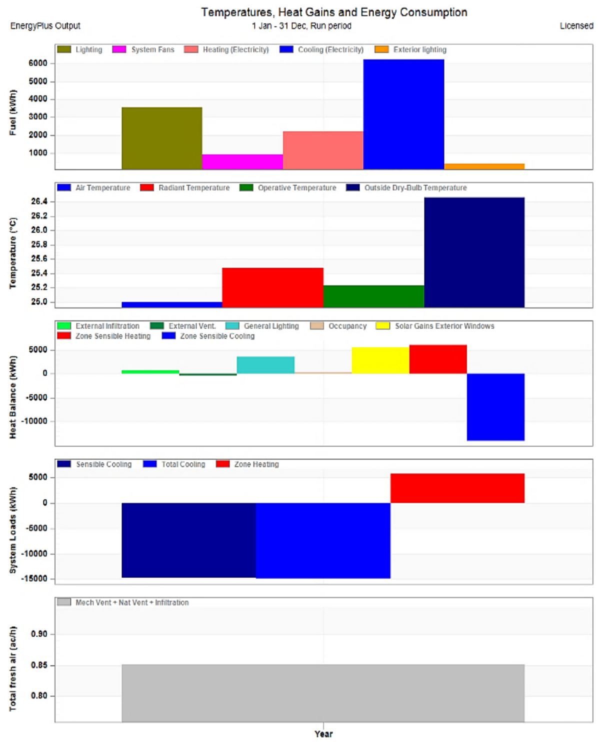


Fig. 6 The results of energy consumption pattern for baseline model by DesignBuilder.

building's environmental impact in terms of energy usage. Notably, during the colder months of January (1237.213 kg), February (835.8834 kg), and December (1018.748 kg), the CO_2 emissions are particularly high, which can be linked to increased heating electricity consumption. This trend indicates that heating not only consumes a significant amount of energy but also contributes significantly to the building's carbon footprint. Conversely, the highest CO2 emissions during the warmer months of July (820.176 kg) and August (762.7454 kg) correspond with the highest cooling electricity consumption, underscoring the environmental impact of air conditioning in response to elevated temperatures.

The discrepancy between energy consumption and CO_2 emissions during the transitional months is an interesting observation. For instance, in April, despite relatively low heating and cooling electricity consumption (220.4764 kWh and 10.7916 kWh, respectively), CO_2 emissions (353.0378 kg) remained significant. This suggests the possibility of high energy consumption in the other category. Similarly, the cooling electricity consumption (202.2234 kWh) in May led to higher CO_2 emissions (379.1635 kg) than expected, given the energy usage. This highlights the need to explore improving the building envelope to reduce energy consumption and transition to a greener energy supply. This analysis emphasizes the importance of considering both direct energy consumption and associated CO_2 emissions when evaluating the environmental impact of building operations. It underscores the need for integrating renewable energy sources and energy-saving measures.

3.2 Simulation of the building envelope variables

By running simulations of the baseline model, the energy saved annually for electricity consumption (kWh) can be determined. Our objective is to identify which part of the building's envelope affects energy consumption the most. To do this, our study conducted several simulations by changing one of the primary variables in Table 4 while keeping all other

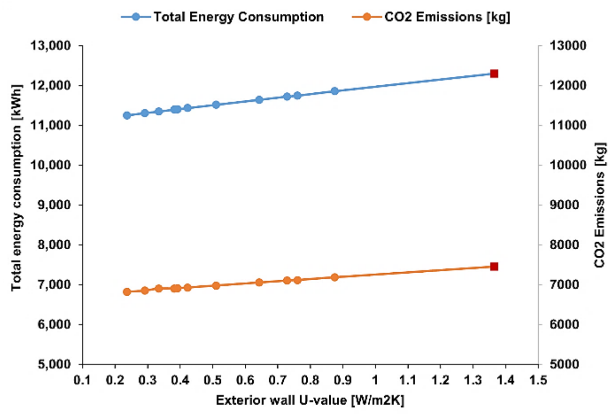


Fig. 7 The impact of changing external wall materials and using different thermal insulation on energy saving percentage and CO2 emission.

parameters consistent. This method enabled us to evaluate the individual influence of each variable on the baseline model without considering the impact of other factors., thereby improving overall energy efficiency.

3.2.1 Changing external wall materials and using thermal insulation

The results showed the effects of replacing concrete hollow blocks with different materials, as illustrated in Table 4. Bricks were traditionally used in Erbil's heritage buildings due to their adaptability to hot and dry climates (Algburi & Beyhan 2019). The results showed that using different exterior wall materials led to a significant decrease in annual energy consumption, resulting in energy savings ranging from 4.9% to 9.2%. On the other hand, using different insulation materials with concrete hollow blocks, the energy savings range from 9.37% to 13.01%.

Figure 7 illustrates the correlation between a building exterior's thermal efficiency, measured by its U-value, and its resulting energy consumption and associated CO_2 emissions. The U-value, expressed in watts per square meter kelvin (W/m^2K), measures the wall's insulating ability, with lower values indicating superior insulation. Upon analyzing the figure, it is evident that energy consumption decreases progressively with an improvement in the wall's U-value. Starting at a U-value of 1.365 W/m^2K, the energy usage is recorded at 12304.73 kWh, consistently decreasing as the U-value improves, reaching its lowest at a U-value of 0.236 W/m^2K with an energy consumption of 11255.98 kWh. This trend highlights the potential for energy savings through enhanced insulation.

Furthermore, the CO_2 emissions align with the energy consumption trends, with a higher U-value resulting in increased emissions. The highest emission figure stands at 7456.66 kg for the highest U-value, followed by a steady decline parallel to the reduction in energy consumption, culminating in the lowest emission value of 6821.12 kg at the lowest U-value. This reduction emphasizes the environmental advantage of improved insulation, resulting in reduced CO_2 emissions, further reinforcing the argument for prioritizing energy efficiency in construction to reduce greenhouse gas emissions.

3.2.2 Shading device and glazing

Fig. 8, and illustrates the impact of the selected shading devices—overhang projectors and fin projectors with different lengths on the annual energy consumption and CO_2 emissions for a specific structure. The projection ranges from 0 to 1.5 meters and shows a direct correlation between the extent of the overhang projection (Fig. 8a), energy consumption, and CO_2 emissions. Starting from a baseline simulation model for a building with no overhang projection (0 m), the building's total energy consumption is measured at 12,938.97 kWh, with CO2 emissions totaling 7,841.007 kg. As the projection increases to 0.5 m, there is a slight decrease in CO_2 emissions (to 7839.291 kg) and a negligible reduction in energy consumption of 0.02%. However, increasing the projection to 1 m results in a marginal increase in energy consumption by 0.3% and CO2 emissions (to 7865.877 kg) and further increasing the projection to 1.5 m leads to a 0.6% increase in energy consumption and CO2 emissions of 7885.143 kg.

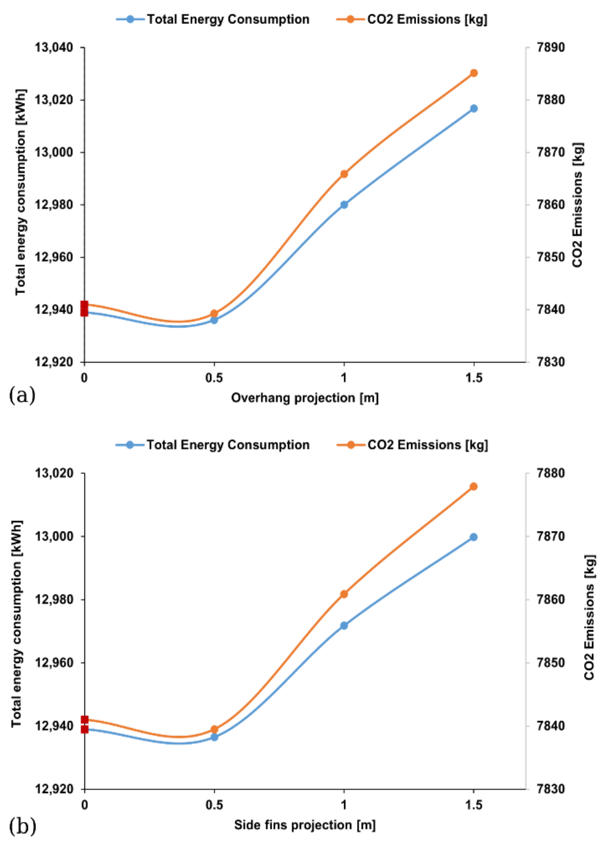


Fig. 8 The impact of shading device (a) overhangs projectors and (b) side fins projection on energy consumption and CO2 emission.

According to Fig. 8b, the baseline model for side fin projection is 0m. Increasing the projection to 0.5m results in a minor 0.01% decrease in energy consumption and CO2 emissions of 7839.496 kg, demonstrating a slight improvement in energy efficiency. However, extending the projection to 1m leads to a slight increase in energy consumption (0.25%) and CO_2 emissions (7860.902 kg). Furthermore, a 1.5-meter projection results in a total energy consumption of 0.47% and CO_2 emissions of 7877.909 kg, suggesting a proportional relationship between the side fin projection and the energy and emissions footprint.

Additionally, according to Figure 9a, the windows with the highest U-value of 5.894 W/m^2K are linked to the maximum recorded total energy consumption, the baseline model. Additionally, there is a low reduction in energy consumption, ranging between 0.02% and 1.5%, when using previous shading devices.

The simulation indicates that although features such as overhangs, side fins, and windows with low U-values can have advantages, such as decreasing solar heat gain, they may also lead to unintended consequences, such as increased energy

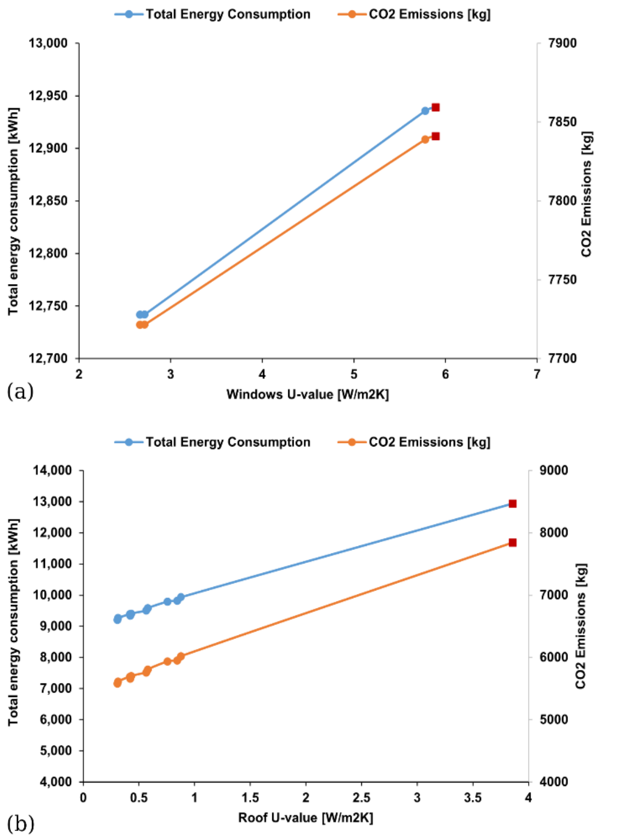


Fig. 9 The impact of (a) windows U-values and (b) roof U-values on baseline model energy consumption and CO2 emission.

consumption and CO_2 emissions. This may be due to factors such as altered natural lighting, which can affect indoor lighting requirements, or reduced absorption of solar radiation during the winter, which can impact the building's heating load. Additionally, the small ratio of windows to walls in the typical house limits the effectiveness of these features. Therefore, it is essential to consider the implications of structural elements in the context of overall building performance and sustainability.

3.2.3 Roof insulation

To examine the effect of improved roofing on energy consumption, ten different insulation materials with varying U-values were simulated. The provided dataset in Fig. 9b systematically correlates the thermal transmittance values of these roofing materials, indicated as the roof U-value in W/m²K, with the resulting total energy consumption and CO_2 emissions of a building. The roof U-value is a critical indicator of the material's insulation capacity, with lower figures representing enhanced insulation effectiveness and a lower heat transfer rate.

At the beginning of the dataset, a roof U-value of 3.858 W/m²K is associated with the highest total energy consumption of 12938.97 kWh and CO2 emissions amounting to 7841 kg, which serves as the baseline model. However, subsequent reductions in the U-value to 0.876 W/m²K result in a significant decrease in energy consumption by 23.25% and a reduction in CO2 emissions to 6017.82 kg. This pattern of diminishing energy consumption and CO2 emissions continues as the U-value decreases, with the lowest recorded U-value of 0.308 W/m²K corresponding to the minimum energy consumption of 9203.5 kWh (28.8%) and the most minor CO_2 emissions of 5577.32 kg within the dataset.

Table 6
Electrical specifications of the selected PV solar panel model.

Electrical data	Value
Cell type	Poly-crystalline
Cell dimensions	156.75 mm x 156.75 mm
Maximum power (Pmax)	320 W
Maximum power voltage (Vmpp)	36.8 V
Maximum power current (Impp)	8.69 A
Open circuit voltage (Voc)	45.3 V
Short circuit current (Isc)	9.26 A
Temperature coefficient (Voc)	-0.15402
Temperature coefficient (Isc)	0.006019
Dimensions (mm)	1954 × 982 × 40

The results clearly demonstrate an inverse relationship between the insulation quality of the roof (lower U-value) and both energy consumption and carbon emissions. This trend highlights the significant impact of roofing insulation quality on buildings' energy efficiency and environmental footprint. Therefore, it is crucial to carefully select roofing materials with lower U-values in order to optimize energy consumption and minimize CO_2 emissions, ultimately enhancing the overall sustainability of the building.

3.3 Solar PV panels

In order to address the electricity shortage in Erbil City and reduce reliance on local generators, this study explores the feasibility of installing an on-grid solar PV system. According to the availability in Erbil City markets, the proposed model will use the MAX POWER CS6X-320P module, a 6-inch, 72-cell poly-crystalline solar panel type, for EnergyPlus simulation. Table 6 shows the technical specifications of the solar panel chosen for simulation.

After analyzing the roof area, it has been determined that installing 12 solar panels for the chosen photovoltaic (PV) system can produce an annual output of 6936 kWh. This will result in a notable decrease in the building's annual electricity demand from 12938.97 to 6002.97 kWh, equivalent to a 53.6% reduction in the electrical load, reducing Co2 emissions from 7841 kg to 3638.2 kg from this redaction of operating electricity.

3.4 The most effective building envelope element and redaction energy demand

The base model was simulated by using 12 different insulation materials with varying U-values for the exterior walls. The roof was also analyzed using ten types of insulation materials, along with three different window U-values and two types of shading devices with three lengths. The results indicated that the roof has the highest impact on energy consumption, with savings ranging from 23.25% to 28.8% when U-values were reduced. The exterior wall was the second most significant factor affecting energy consumption, and improvements in this aspect can lead to energy savings ranging from 4.9% to 13.01%. On the other hand, lower window U-values or shading devices such as overhangs and side fins had a negligible effect on energy savings by 0.01% to 1.5% and can be neglected.

Using low U-values for the exterior walls and roof combined, energy savings can be increased significantly, up from 28.15% to 41.81%, resulting in a corresponding reduction in operational CO2 emissions. During power outages, using alternative clean energy sources such as photovoltaic panels with an improved building envelope may help reduce reliance on the neighborhood generator or eliminate the need for it. This would further decrease operational CO2 emissions from electricity usage and the neighborhood generator.

The study also found that installing 12 solar panels for the chosen photovoltaic (PV) system can produce an annual output of 6936 kWh, which is equivalent to a 53.6% reduction in electrical energy demand and reduces the dependence on neighborhood generators. As a result, by enhancing the building envelope's insulation and integrating photovoltaic (PV) panels, the building's energy demand can be significantly reduced, achieving savings between 81.75% and 95.41% compared to the baseline model.

4. Discussion

This study observed and assessed various U-values for the building envelope in a hot-dry climate for a single-family house as a typical residential building in Erbil City to reduce energy consumption, minimize CO2 emissions, and reduce reliance on neighborhood generators. Our result indicates that changing wall material or using insulation on external walls could reduce energy consumption by 4.9% to 13.01%. In comparison, using the clay hollow brick in Erbil City by Mustafa *et al.* (2020) decreased the energy consumption for cooling by 11.3%. Additionally, a study conducted by Al-Tamimi (2022) achieved energy savings of 14.7% using 25mm of XPS insulation for walls and roofs. This difference in results can be attributed to variations in the case study, the study area's climate, and the building's orientation. Therefore, improving thermal insulation is crucial for reducing energy consumption and improving thermal comfort in hot regions (Alwetaishi 2022).

The impact of building envelope variables on energy consumption varies. Our study found that shading devices (overhangs and fins) and windows U-values have low savings from 0.01% to 1.5% energy savings, with an increase in heating energy. This result was also found by (Mustafa *et al.* 2020) in Erbil City. The low window-to-wall ratio in our case study explains the result of energy saving. In contrast, other studies found that low window U-values and shading effectively improve the energy performance of residential buildings in KSA (Cho *et al.*2014; Alaidroos & Krarti 2015; Alhuwayil *et al.* 2019). However, more studies on suitable shading devices and glazing types are necessary to optimize the energy consumption of other types of buildings.

Additionally, our study concluded that various U-values for roofs can effectively reduce energy consumption by 23.25% to 28.8% compared to previous studies. For example, Goussous *et al.* (2015) demonstrate that green roof technology can significantly improve the thermal performance of buildings by minimizing heat transfer, controlling indoor temperature, and decreasing the energy consumption of HVAC systems. Further, in Saudi Arabia's hot climate, a study by Khan and Asif (2017) resulted in a reduction of up to 50% in peak cooling load and up to 31% in annual energy consumption. However, further research is required to explore various methods for reducing energy consumption through the impact of roofs, including the study of shading, the angles of obstacles, and the effects of other building features on shadow creation.

Furthermore, it was investigated whether installing an on-grid solar PV system in Erbil City could mitigate the electricity shortage and reduce reliance on local generators. Our simulation results indicate that the selected PV system can generate 6,936 kWh per year, leading to a significant reduction of 53.6% in required electricity for the baseline model. Moreover, after using the improved building envelope with PV panels, the results showed that the total energy demand was reduced by 81.75% to 95.41%, and that will reduce the Co2 emissions of operation by the same ratio while reducing the impact of local generators on the environment. Similarly, Alkhalidi and Aljolani (2020) studied the use of PV solar panels as a clean energy source and found that it led to a 57.7% reduction in the building's total electrical load.

5. Limitation and contribution

It is important to note that the present study has a few limitations. While investigating various strategies' energy and environmental benefits, it is crucial to consider the economic feasibility and cost-effectiveness of implementing building envelope variables. Additionally, our study focused on typical houses attached from one side and did not compare them to other types that are attached from two or three sides, which is also common in Erbil. The orientation of the case study during the simulation was fixed, and this study did not compare it with other cases with different orientations. Although our study examined energy usage and Co2 emission patterns, it should be noted that variability in occupant behavior can significantly affect energy consumption. This paper presented several building envelope variables suitable for a typical house in Erbil City in a hot and dry climate, such as wall material, insulation for exterior walls and roofs, different window materials, clean energy resources, and how they impact energy consumption. Therefore, further empirical studies on green strategies are recommended to reduce environmental impact and improve energy efficiency.

Despite these limitations, our study provides a practical reference point for designers, construction engineers, and decision-makers in hot and dry regions to implement strategies that can effectively reduce energy consumption and CO2 emissions while reducing reliance on local generators. Designers should select insulation types and wall materials with low u-values for external walls to minimize heat gain and loss, reducing cooling and heating energy consumption. Engineers can also employ roof insulation to reduce heat transfer from the roof and use it as a natural barrier for direct and diffuse radiation. Decision-makers should consider investing in solar panels as a clean energy source to reduce the total energy load of residential projects. Additionally, shading devices and double glazing for facades with high windows-to-wall ratios or faces that gain high solar radiation can efficiently reduce cooling loads and total energy consumption.

6. Conclusion

This paper investigated the impacts of applying various building envelope variables to determine the most effective element for reducing energy consumption and operating CO2 emissions. Also, the effectiveness of photovoltaic panels as an alternative energy source for neighbourhood generators during electricity cuts in a typical residential building in a hot and dry climate was examined. The simulation results indicated that the baseline model consumed 12938.97 kWh of electricity annually, with heating being the biggest contributor at 39.6%. Implementing building envelope variables resulted in energy savings of 28.15% to 41.81% overall. Additionally, using photovoltaic panels led to a 53.6% reduction in electrical energy demand and CO2 emissions, which can serve as a secondary resource for electricity during the cut periods instead of the neighborhood generators. For future studies, investigating the effectiveness of building design parameters for future climate conditions is crucial to mitigating the impact of climate change on energy consumption and CO2 emissions, especially with different prototypes of residential buildings. It is highly recommended that designers, engineers, and decision-makers consider investing in clean energy sources such as solar panels to reduce the overall energy consumption of residential projects and to decrease reliance on local generators. Also, choosing the proper insulation for walls and roofs is crucial to improving energy efficiency.

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