Exploring The Potential of Energy Savings Through Retrofitting Traditional Heritage Buildings

A Case Study of Abu Jaber House in Al Salt, Jordan

KAMAL HADDAD[*,1] SIMON LANNON[,1] ESHRAR LATIF[,1]

[1]Welsh School of Architecture, Bute Building, Cardiff University, King Edward VII Ave, Cardiff CF10 3NB

ABSTRACT: Reducing energy demands in buildings has become a key interest to achieve net-zero goals. Jordan, as a country, imports over 95% of its energy from neighbouring countries, initiating the need to find strategies to reduce energy consumption. This research investigates the feasibility of achieving energy savings by retrofitting heritage buildings with preservation conditions. Specifically, the study assesses the effects of building's fabric interventions and systems interventions on heating, cooling, and lighting loads using Ladybug tools in Grasshopper3D as a modelling method. Retrofit measures encompass changes in glazing type, incorporation of shading devices for existing windows, reduction in infiltration rates, addition of thermal insulation, enhancement of sensible heat recovery efficiency, and interventions in the lighting system by lowering lighting power density and introducing a daylight control system. Additionally, the study explores the potential of integrating renewable energy sources, such as photovoltaic panels for sustainable energy production. Results indicate that fabric interventions, like adding a 30 mm aerogel layer for thermal insulation, yield over 10% energy savings. Similarly, introducing a daylight control system can reduce the demands by 11%. The study establishes a systematic framework for energy modelling applicable to buildings with similar conditions, providing valuable insights for sustainable retrofitting strategies.
KEYWORDS: Energy consumption, heritage buildings, retrofit, daylight control, renewable energy.

1. INTRODUCTION

Significant efforts are being made globally to mitigate the environmental impacts resulted from the climate change crisis [1]. Various strategies are proposed to address this issue, including the debate between promoting energy efficiency in new builds or retrofitting existing buildings [2]. Energy retrofit is an effective method for reducing energy consumption [2], but it requires assessing the compatibility of the building fabric with the retrofit plan.

In Jordan, to reach net zero targets, governmental and non-governmental initiatives have made great strides in decarbonising the built environment and lowering operational energy [3]. Such policies are being implemented since Jordan is a country that imports over 95% of its energy from neighbouring countries [3]. Therefore, conducting energy simulations to evaluate a building's energy performance is a critical factor in resolving the energy crisis in the country.

This research works on presenting an overview of the energy performance in one of the most significant buildings in the heart of the UNESCO protected city of Al-Salt, Jordan. The research is carried out a thorough simulation-based analysis of the original function of the building, in addition to its newly adopted function, which was changed recently, to compare the energy performance and the impact of the transformation. Additionally, several retrofit solutions that range from fabric adjustments to systems interventions are studied to understand the anticipated performance.

2. RESEARCH BACKGROUND

Jordan's population has increased drastically in the past few decades, resulting in a huge impact on the residential sector, and increasing demand for energy [3, 4].

This section presents the current energy circumstances in Jordan, shedding light on the importance of undertaking such research in the country. Additionally, the climatic conditions of Al-Salt city are discussed to highlight the energy demands required for operating the building's services. Furthermore, the selected building for the study is introduced with an emphasis on its heritage significance in the city as well as its current fabric conditions which will be used as a base to model and simulate the overall loads.

2.1 Energy in Jordan

The residential sector in Jordan is thought to account for 43% of the country's overall power usage [3]. The heating and cooling of residential structures in Jordan account for almost 38% of total energy consumption, according to a 2016 assessment of rising zero-emission building sector objectives in the Middle East and North Africa (MENA) region [3].

Jordan faces two primary issues in its energy landscape: a rising demand for energy and a severe shortage of domestic resources to meet this demand [5]. In 2019, the peak load of Jordan's electrical system peaked at 3,380 MW in January, surpassing the January 2018 figure of 3,205 MW by approximately 5.5% [6]. The average annual growth rate from 2010 to 2019 stood at around 2.7%, but the load has consistently grown at a rate of approximately 3 to 5% each year. This steady increase poses an additional challenge for the adaptation of the systems in Jordan [4]. However, the Renewable Energy Law of 2012 set a goal for 10% of the nation's energy composition to be sourced from renewables by 2020, equivalent to a capacity of 1,800 MW, primarily derived from wind (1,200 MW) and solar (600 MW). Jordan has since increased its target for the proportion of renewables in the power mix, which has increased from an initial 31 to 50% by 2030 [6].

2.2 The climate in Al Salt City

Al Salt experiences long, warm, and dry summers, as well as cold and generally clear winters. The temperature typically ranges from 4°C to 31°C throughout the year, with rare occurrences of it falling below 0°C or rising above 34°C. The hot season typically lasts for 4.4 months, from May to October, with the daily high temperature averaging above 27°C. July is the hottest month in Al Salt, with an average high of 30°C and low of 19°C. On the other hand, the cool season spans 3.2 months, starting from December to March, and has an average daily high temperature below 15°C. January is the coldest month, with an average low of 4°C and high of 11°C [7].

In Jordan's mid-region, there are approximately 3290 annual sunlight hours on average. This abundant sunlight creates an efficient opportunity for using photovoltaic systems to generate electricity, offering a potential to reduce energy costs through renewable resources. Additionally, the solar radiation in Jordan is high where it varies between 4 and 8 kWh/m^2, which implies a potential of 1400-2300 GWh per year annually [8].

Throughout the year, Al Salt experiences varying amounts of rain days. From November to March, which is the start of the wetter season, there is a larger than 13% probability that any given day will be rainy. With an average of 7.2 days with at least 1 mm of precipitation, January has As Salt's wettest days. From March to November, there are 8.0 months during which it is drier. With an average of 0.1 days with at least 1 mm of precipitation, July has the fewest rain days in As Salt [7].

2.3 Abu Jaber house

One of the unique heritage buildings and currently most visited attraction in the city centre of Al Salt City is Abu Jaber House. The building was built in multiple phases between 1896 and 1905, which can be noticed from the colour of the stone which differs between floors and sections. The ground floor level has stone walls 60 – 100 cm thick and is currently used as shops in addition to including the entrance to the upper levels. The first floor, however, is arranged around a vaulted courtyard that is used to distribute the different zones and rooms. The second floor also consists of three courtyards that are connected to the different rooms and spaces [9].

Figure 1*: A street view of Abu Jaber house.*

3. RESEARCH METHODS

Due to its cultural and architectural significance, Abu Jaber house was selected as a case study aiming to communicate to the industry, the benefits of energy modelling and retrofitting similar buildings. The study works on building an energy model that is a simplified representation of the building's geometry, considering the materials used and the adopted construction systems.

The research uses Grasshopper3D [10] as a computational environment for modelling along with Ladybug tools [11] to simulate the energy performance with special focus on the building's thermal loads and lighting loads as they have the largest contribution to overall demands. Initially, the energy model will be studied to understand the original state of the building as a residential building. However, currently the buildings functionality has been transformed into a museum and show case of the city and its culture. Hence, a simulation of the building with its new adopted program is required to understand the impact on the change of energy consumption and to build a baseline model to assess potential energy retrofit interventions.

Nonetheless, this research explores different retrofit measures that can be adopted to mitigate the energy crises in the country. Even though some of the proposed measures can be difficult to implement due to its listing and UNESCO protection status, the study of such scenarios can be potentially reflected on other similar buildings in the city or beyond that may not share the same listing status.

In this study, the modelled floor area of the building is 632 m2. It is also critical to mention that the ground floor of the building was not considered in the energy model as its functionality remained the same as shops.

The study works on simulating different shallow and deep retrofit solution to understand the impact of each case on the overall energy performance as follows; (i) examining the impact of the glazing system by testing various types of glazing; (ii) adding a horizontal shading device with different depths to the existing windows,

(iii) improving the airtightness of the building by exploring reductions of the infiltration intensity rates by 5%, 10%, 25%, 40%, and 60%; (iv) enhancing the fabric's insulation by adding an internal layer of aerogel (u value = 2.1 W/m2 k) with thicknesses of 10mm, 20mm, 30mm, 40mm, 50mm ; (v) enhancing the sensible heat efficiency factor of the used HVAC system (Ideal air) by testing a factor of 0.6, 0.7, 0.8, 0.9, and 1; (vi) Optimising the used lighting systems by exploring lighting power densities between 9 and 5.

Additionally, this paper investigates the implications of introducing a daylight control sensor system that works on dimming the lights when natural daylighting is satisfied. For exploring the impact of applying such system, the sensors were defined at the centre of each room's floor area. The illuminance setpoint was set to 300 lux while the lowest power and lowest lighting output the lighting system can dim to, are set to 0.3 and 0.2 respectively.

Besides, this research works on performing a multi variant optimisation using Galapagos solver in Grasshopper3D, to find the most optimised values for the investigated parameters to reach the lowest EUI.

Furthermore, a comparative analysis of the potential savings when installing photovoltaic (PV) panels using PVGIS-SARAH2 dataset within PVGIS tool [12] to estimate the electricity production of the PV panels, where the azimuth and slope of the panels was optimised to 16° and 27°.

Table 1 below demonstrates the setup of the activity program for the residential case (intended use), and the museum case (current use). The used values for the used parameters were retrieved from archival documents [9] or from Ladybug Tool's dataset [11] when not available.

Table 1: The activity and HVAC programs for the residential and the museum cases [9.11]

Parameter	Residential	Museum
Heating setpoint (°C)	21.7	21
Cooling setpoint (°C)	24.4	24
Occupancy density (people/m^2)	0.0196	0.1497
Equipment power density (W/m2)	0	3.5
Lighting power density (W/m2)	6.4	10.7
Air Changes per Hour (ach per hour)	2.88	5.76
HVAC sensible heat recovery factor	0.6	0.5

Currently, the fabric's exact construction details are not fully documented, however, the researchers have worked on approximating the tectonics of the different fabric elements using available archives and site visits. As discussed, the external walls are primarily made of an average of 600 mm hard limestone, while the internal walls were made of soft limestone with an averaged thickness of 400mm. The floor of the first level is 650 mm of dense concrete, while the second level and the external floors are 300 mm and 400 mm respectively made of concrete.

For examining the impact of glazing type on the building's performance, the specifications of the tested glazing types which includes the u value, SHGC factor, and the visible transmittance factor were retrieved from the standard assessment procedure (SAP 10.2) [13] as listed in table 2 below.

Table 2: The activity and HVAC programs for the residential and the museum cases

Scenario	U-value (W/m^2 K)	SHGC	Transmittance factor
Single glazing (Original)	4.80	0.70	0.85
Double glazing (Air filled)	2.20	0.77	0.76
Double glazing (Low emissivity)	0.90	0.77	0.76
Double glazing (Argon filled)	2.60	0.54	0.76
Triple glazing	1.60	0.35	0.64

4. RESULTS

4.1 Exploring the impact of changing the building's activity on the energy performances

As discussed, the original building design was residential, necessitating a simulation under those conditions. Results showed normalized annual heating and cooling loads of 103 kWh/m2 and 58.3 kWh/m2, respectively, with an annual lighting load of 3.4 kWh. Simulations of the current conditions, serving as a benchmark for retrofit measures, revealed changes due to the building's transformation into a gallery and showcase. New parameters, such as equipment loads, people's density, and lighting power density (see Table 1), were considered. The simulation indicated a 6.7% increase in Energy Use Intensity (EUI) post-activity change. Internal heat gains led to reduced annual heating loads (78 kWh/m2) but increased cooling demand (80 kWh/m2), with lighting demands rising to 36 kWh/m2.

Based on the simulation of the current conditions, it was demonstrated that the loads from, cooling, heating, infiltration, lighting, window conduction, and fabric conduction, have fluctuated throughout the year, therefore, the measures discussed in the upcoming sections were proposed in attempt to reduce the demands.

4.2 Exploring the impact of glazing type

The glazing percentage for Abu Jaber house is approximately 15%, therefore, studying the performance of different glazing types is crucial. Hence, five distinct types of glazing were explored; (a) the existing original single layered glazing as a benchmark (BM), (b) air filled double glazing, (c) low-e air-filled double glazing, (d) argon-filled double glazing, and (e) air filled triple glazing. The results of the investigation are demonstrated in table 3 below.

Table 3: The thermal loads and overall saving in implementing different glazing types.

Scenario	Heating (kWh/m^2)	Cooling Deman(kWh/m^2)	Potential savings
a (BM)	78.45	79.53	-
b	71.74	81.27	2.40%
c	67.72	82.71	3.80%
d	79.66	72.72	2.90%
e	83.11	66.71	4.30%

Based on the previous simulations, it is noticed that the change of glazing type helps in reducing the overall EUI of the building and therefore reducing the energy costs.

4.3 Exploring the impact of using shading devices on the widows

In this exploration, different depths of horizontal shading devices were tested that varied between 10 cm and 50 cm. Adding a shading device contributed with an increase in the annual heating and lighting demands and a similar decrease in the cooling loads. Overall, this behaviour has maintained the building’s EUI at around 208 kWh/m^2. Therefore, adding shading devices is proven to be an insufficient solution for this building which is contributed to having the largest area of glazing on the northern façade, therefore, the heating and lighting demands would increase.

4.4 Exploring the impact of reducing infiltration rates

According to the simulations of Abu Jaber house, it was noticed that airtightness of a building and the increase in infiltration heat losses through the building's age can greatly increase the annual energy demands. Therefore, controlling the air tightness of the building can reduce both heating and cooling loads of the building as presented in figure 2.

The infiltration intensity rates of the building relate to the fabric's efficiency. Therefore, increasing the air tightness of the building can be performed by reducing the cracks and gaps in the fabric and any potential thermal bridging zones. In addition, replacing the old windows frames with newer ones would contribute to reducing the infiltration rates.

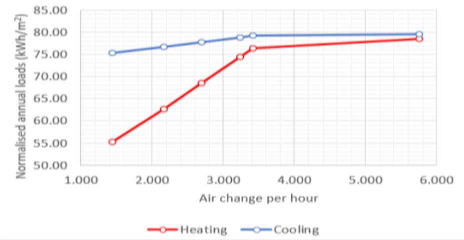

Figure 2: Explored thermal demands at different air changes per hour.

4.5 Exploring the impact of thermal insulation

As no records imply the presence of any type of thermal insulation layers, it is critical to understand the impact of adding a single layer of thermal insulation to the internal faces of the walls. Due to the impracticality of adding the insulation within the fabric, the simulation was based on experimenting adding an insulation layer with different thicknesses that varied between 10 mm and 50 mm. Figure 3 demonstrates that adding a 30 mm layer of aerogel had the largest difference in minimising the heating loads. However, adding thicker layers had smaller impact. The impact of adding insulation had insignificant impact on the cooling loads.

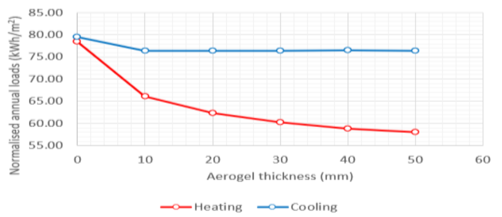

Figure 3: The impact of adding aerogel insulation on thermal demands.

4.6 Exploring the impact of enhancing HVAC system efficiency

Currently, the building's heating is primarily dependant on portable heating units. Therefore, an ideal air HVAC system (non-mechanical) was used in the energy modelling of the building. To test the impact of improving the efficiency of the heat recovery and heat preservation within the building, the sensible heat recovery factor was changed between 0.6 and 1, where 1 represents a 100% heat recovery efficiency.

Figure 4 illustrates that the increase of the heat recovery efficiency would have significant positive implications on reducing the heating and cooling loads. Such improvements can be assured by performing other measures like adjusting the glazing type as well as reducing the infiltration intensity rates.

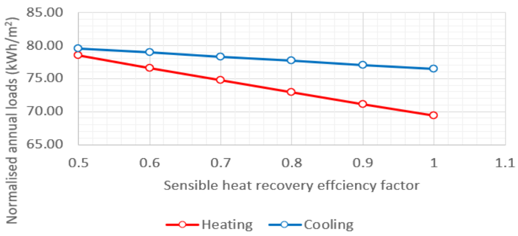

Figure 4: The normalised annual thermal demands with different HVAC system efficiency factors

4.7 Exploring the impact of optimising installed lighting systems

Based on initial comparative simulations between the building's lighting loads, it is noticed that a massive increase in the lighting loads have occurred. Hence, studying the impact of optimising the lighting system is needed. The lighting power density (LPD) which is controlled by the lighting type and illuminance was used to test the implications on the thermal loads as well as the lighting loads. The graph in figure 5, presents the impact of the reduction of lighting power densities on the thermal loads. It is observed that lower LPD increases the heating demands since the lighting system emits less heat, which consecutively reduces the cooling loads.

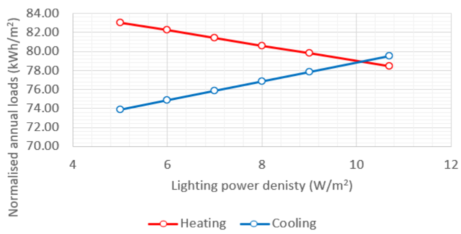

Figure 5: The impact of adjust lighting power densities on heating and cooling demands.

Nonetheless, the simulation highlights the significant role of optimising the lighting system in reducing the lighting loads of the building which can be reduced up to 53% if LPD is reduced to 5 W/m^2. This solution can be one of the most effective, where reducing LPD to 6 W/m^2 can reduce the overall energy consumption by 9%.

4.8 Exploring the impact of introducing a daylight control sensor system

This measure introduces coupling the building with a daylight control system that involves dimming the lights and turning it off if the senor reading reaches the illuminance set point of 300 lux. Such measure was performed on all the individual measures discussed in this paper. All results have presented a significant reduction on the EUI in total and its breakdown of thermal loads and lighting loads. The EUI of the baseline model was reduced by 10.58%. The highest reduction was noticed when changing the glazing type to low emissivity double glazing with total reduction of 11%.

4.9 Performing Multi Variant optimisation to reduce EUI

After running the optimisation using Galapagos solver in Grasshopper 3D, it was demonstrated that applying the suitable measures results in a drastic reduction of the energy use intensity and its breakdowns. EUI was reduced by 50.5% when compared to its current situation with a reduction in heating, colling and lighting demands of 48%, 16% and 69% respectively. The simulation was run for around 112 hours after it has been terminated due to reaching 50 stagnant without improving the optimisation objective as defined in the optimisation setup. Table 4 presents the measures and their associated values in addition to the reduction percentage in energy consumption compared to the current conditions.

Table 4: The measures and values that were concluded based on the multi variant optimisation.

Measure	Value	Reduction (%)
Glazing type	Low e	14.4
Air changes per hour	2.7 ach	16.4
Insulation thickness	3 cm	21.6
Sensible heat efficiency	0.8	14.4
Lighting power density	7 W/m^2	13.5
Shading Device	0.0 m	-

The simulation has demonstrated that applying the different measures results in a drastic reduction of the energy use intensity and its breakdowns. EUI was reduced by 50.5% when compared to its current situation with a reduction in heating, colling and lighting demands of 48%, 16% and 69% respectively.

4.10 Exploring the impact of installing PVs

Considering the total floor area of the building and its current EUI of 208 kWh/m^2 and using Crystalline silicon PV panels with 19% efficiency, the PV peak capacity was approximated to 46 kWp. According to the simulation, the normalised annual production of energy is estimated to reach 121 kWh/m^2. Furthermore, the calculations have taken into consideration that the total loss of production is around 23.16% considering 14% system loss, 2.28% losses caused by the angle of incidence, 0.6% loss due to spectral effects, and 8.02% of losses that may be caused by the temperature and low irradiance.

Figure 6 illustrates the energy balance, comparing estimated PV production to the heating, cooling, and lighting loads of the most effective measures discussed in section 4.9 throughout the year. PV panel production peaks in July, with the lowest output occurring in January. Simultaneously, the highest energy demand coincides with hot months, causing a shortfall in PV energy to meet demands. However, considering the cumulative net production over the year, the system generates an export of 1.8 kWh/m^2 after satisfying heating, cooling, and lighting needs. These findings underscore the necessity of implementing an energy storage system to supply the building with renewable energy during periods of lower electricity production.

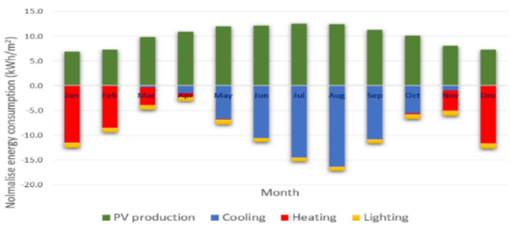

Figure 6: Energy balance of fix-angle PV production compared to the thermal and lighting demands.

It is critical to mention that this study was considering the thermal and lighting loads due to clear consequence on the energy consumption of the building. However, other loads in the building contribute to the overall energy consumption such as the infiltration loads, hot water supply and the electric equipment used in the building urging the need to apply such measures.

5. CONCLUSION

The study systematically analyses a UNESCO-protected heritage building, assessing thermal and lighting loads, energy demands, and potential retrofit solutions. Accordingly, the developed system is encouraged to be used for buildings with similar conditions. This energy modelling approach is advised before any intervention to anticipate potential consequences, understand implications of changes on the building's heritage value, and suggest precautions and measures to minimise negative results.

The study demonstrated that interventions on the fabric had the highest impact on reducing the annual energy consumption. For instance, independent interventions such as adding 30 mm layer of aerogel as a thermal insulation can result in over 10% of energy savings, in parallel, reducing the infiltration intensity rates by 40 % can result in over 13.5% of energy savings. Additionally, interventions on the used lighting system have promising impact when reducing the lighting power density from 10.7 W/m^2 to 7 W/m^2 can contribute to over 8% of savings. In parallel, implementing effective measures coupled with a daylight control sensor system can further reduce energy consumption by 50.5%. Based on the discussed results, the following points can be highlighted:

- Changing a building's program and functionality without proper consideration can greatly increase energy demands.
- Introducing daylight control sensors to high-lighting-demand buildings like museums significantly reduces overall energy use and its breakdowns.
- Integrating PV panels have proven to be sufficient in satisfying the building's major demands after applying retrofit measures with a production of 121 kWh/m^2 making an electricity export of 1.8 kWh/m^2.
- While implementing different can significantly reduce energy consumption, the heritage value of the building must be taken into consideration.

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