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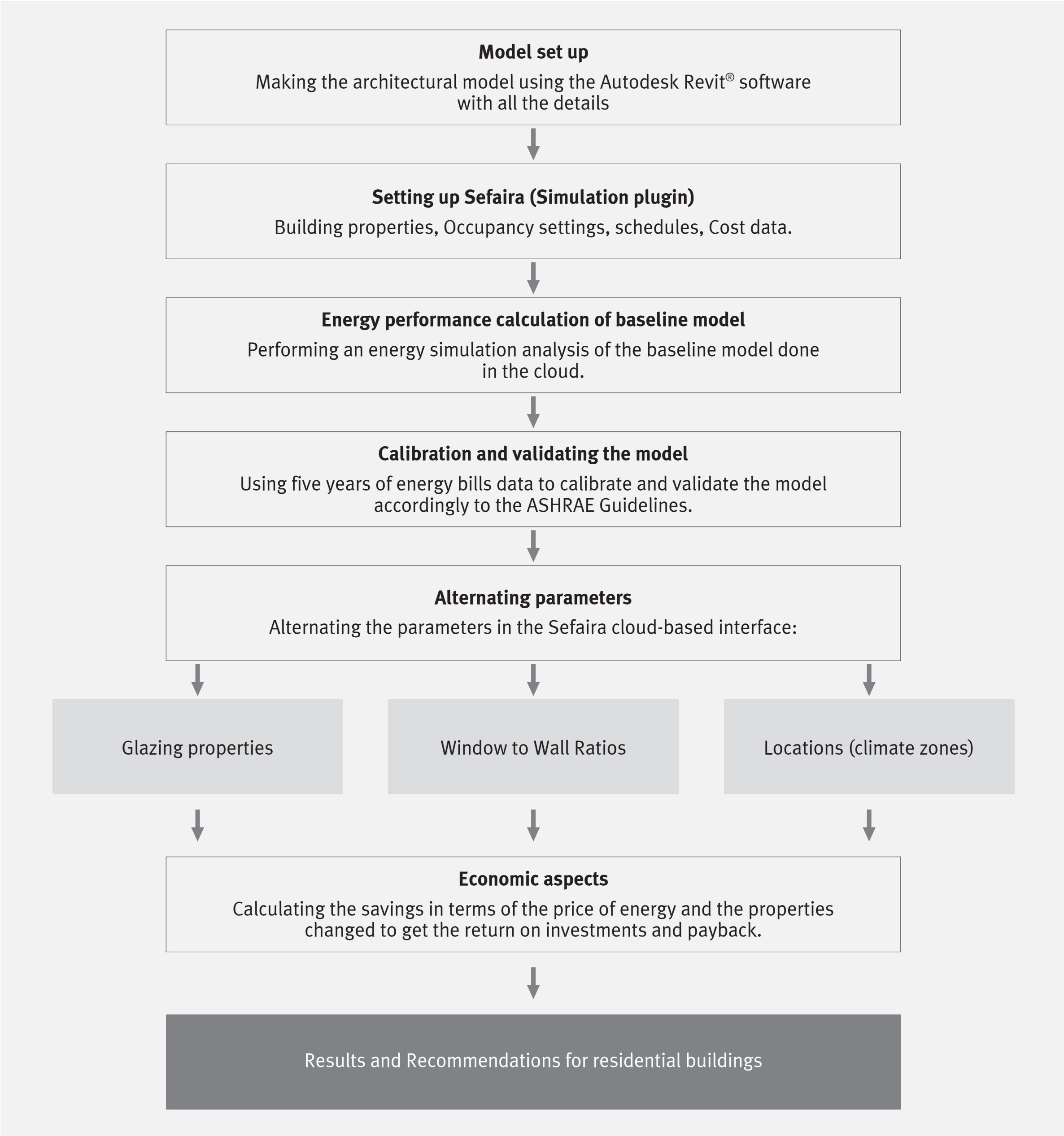

Fig. 1 Summary of the methodology used

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The Impact of Glazing Types and Window-to-Wall Ratios on Energy Consumption in Semi-arid, Mediterranean and Arid Climates

Glazing types
Net zero energy
Payback period
Residential buildings
Window-to-wall ratios

A reduction in energy consumption and energy efficiency improvement in buildings have become one of the main objectives in national and international energy policies. In an optimization process, and in order to find the most influential parameters to achieve net zero energy, several ameliorations need to be made to residential buildings. In this paper, two measures are discussed; the effects of locally available glazing types and window-to-wall ratios, tested under three different Algerian climates; semi-arid, Mediterranean and arid-climate. For the purpose of calculating energy use intensity savings, optimal values and payback periods for each of the mentioned measures the building information modelling software Autodesk Revit® and the energy simulation plugin Sefaira have been used. According to the findings, double glazing with Argon has the greatest potential for lowering the energy use intensity, whereas the window-to-wall ratios has a significant effect on the energy consumption of buildings in the studied climates, and the optimal ratio for a given orientation varies according to the type of glazing used. Moreover, very high payback periods were found compared to other countries, and only a few studied variables could be achieved with profitability. This paper is helpful for professionals who are responsible for decision-making during the design process of energy-efficient residential buildings.

Introduction

Global warming, resulting from increasing carbon emissions, has become the most pressing issue for the planet. The onset of the COVID-19 pandemic and its measures made people spend most of their daily lives indoors and use active comfort tools, pushing the building industry as one of the largest energy consumers in the world even further. Today this industry accounts for almost one third of the total energy consumption and CO_2 emissions (IEA, 2021). According to the International Energy Outlook (IEO), this consumption will increase by 42% by 2040 (EIA, 2016).

Mainly due to economic and population growth, energy demand is expected to be higher than ever in developing countries in Africa and Asia. In the meantime, energy efficiency technologies are not receiving sufficient attention. In Algeria, due to the shortage and lack of housing, typical and standard building production prevails in most regions and climate zones of the country (Ministère de l'Habitat, 1997). Either in relation to the type of architecture and design or the building materials, studies focus more on quantity rather than quality. Resulting in buildings far from those that would meet required criteria in terms of environmental issues or user needs. Consequently, the residential building sector is responsible for more than 30% of CO_2 emissions and 36.6% of the national final energy consumption, which reached 17.6 million TOE in 2020, with an increase of 17% compared to 2017 (Ministère de l'énergie, 2020).

Nowadays, the reduction of energy consumption and the improvement of energy efficiency in buildings are mandatory objectives in energy policies at regional, national and international levels. The process of energy reduction went through several paradigms during the last century, such as bioclimatic, environmental, green, and sustainable architecture (Attia, 2016). It kept evolving in an attempt to lower energy consumption, with examples such as low energy buildings (BBC), high energy performance (HPE), passive house, up to neutral or positive energy buildings (BEPOS). The final objective of these concepts is buildings that can be self-sufficient in energy without relying on external sources.

Within this framework, the topic of the Net Zero Energy concept is receiving increasing attention in the building sector. Torcellini et al. define the Net Zero Energy Building as *"a building that has reduced energy consumptions in order to be balanced between the energy demand and the energy supply from renewable energy technologies"* (Torcellini *et al.*, 2006). Albadry et al. also define it as a building with zero energy consumption over a year, with lowered electrical heating demands, and renewable energy supplies, and sum up the characteristics of NZEB stated by the EPBD, which are: a high energy efficient building with a demand for energy reduced to nearly zero or with very low energy demand, fulfilling the rest of it with renewable energy resources (Albadry, Tarabieh and Sewilam, 2017).

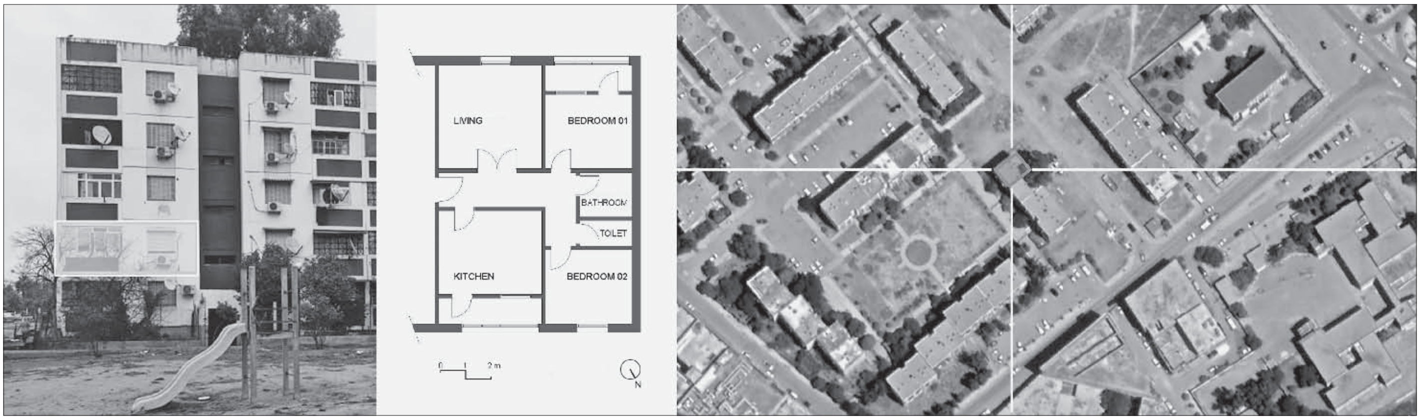
Nonetheless, it's not simple to tackle the building as a whole because it is composed of multiple components and layers. Treating each component individually is crucial to achieve high energy performance, and starting with the building envelope is the way to go. The envelope affects the energy flows in and out of the building, thus it should have a well-balanced ratio between its opaque and transparent elements (Marino, Nucara and Pietrafesa, 2017). Openings and windows, are used to afford views and daylight, as well as to provide good thermal enclosure for buildings, whereby they are regarded as one of the most important parts of the building envelope (Troup *et al.*, 2019). Regardless of the regulatory frameworks that exist in Algeria (DTR C3.2/4), most building envelops are not designed to fit the local climates nor the energy efficiency measures (Ministère de l'Habitat, 1997).

However, several studies investigating the glazing types have been carried out on an international stage. Lee et al. identified a number of window properties that should be studied, such as thermal transmittance (U-value), visible transmittance (Tvis), and solar heat gain coefficient (SHGC), and evaluated these properties with different WWR in five typical Asian climates (Shanghai, Seoul, Manila, Taipei, and Sapporo), resulting in a design guideline for selecting windows that are energy efficient and optimised for each climate (Lee *et al.*, 2013). Westphal's and Andreis's results have confirmed that energy consumption and performance are highly affected by the glazing properties and configuration. In MENA countries (Dubai UAE, Cairo Egypt and Algiers Algeria) Tarabieh et al. investigated three types of glazing that are supposed to be available on the market in order to seek out their performance and return in an office building. The results demonstrated that the SHGC was the most effective factor in saving energy compared to the U-value and pointed out that any study of energy efficiency should include the payback and return on investment to investigate the economical effectiveness of these energy efficiency measures (Tarabieh, Mashaly and Rashed, 2017). Hassouneh et al. pushed the research even further and analysed a variation of eight types of glazing to find the most appropriate type for an apartment building in Amman, Jordan and noted that the usage of different glazing types combination in each orientation can be more energy efficient (Hassouneh, Alshboul and Al-Salaymeh, 2010). In a similar way, Alhagla performed a series of simulations in the Egyptian climate and ascertained that different glazing types with higher U value and transmission tend to be more beneficial in terms of energy savings (Alhagla, Mansour and Elbassuoni, 2019). In a case study of a patient room located in Bologna Italy, Cesari et al. demonstrated that with the appropriate glazing properties such U-value and SHGC (around 1 to 2 $W{\cdot}m^{-2}{\cdot}K^{-1}$ and 0.55 respectively), the adoption of wider window glazing can be done, enabling a reduction and optimization of overall energy consumption and needs for both winter and summer (Cesari *et al.*, 2018).

Furthermore, previous simulation-based research and investigations tried to determine if window-to-wall ratios (WWR) have an impact on the energy efficiency of buildings, and if there is an optimal WWR for each climate, type, and function of the building. Troup et al. carried out a statistical investigation on the CBECS dataset in the USA and found that, on average, the EUI of buildings will increase accordingly to the increase of the WWR (Troup *et al.*, 2019). Cesari et al. confirmed that a higher percentage of WWR increases energy loads, but it can be significantly reduced when used with the appropriate shading system and glazing types (Cesari *et al.*, 2018). In this matter, Alsehail & Almhafdy pointed out that WWR is an essential factor in the energy and thermal performance of buildings, yet the study implies that it can be influenced by other factors such as climate, type of window, degree of insulation, shading devices and many more. In other words, modern glazing technologies can help to increase the value of WWR without increasing the energy consumption of a building to a certain state (Alsehail and Almhafdy, 2020). Westphal and Andreis also studied the influence of WWR and façade configuration in the energy consumption of air conditioning in five Brazilian locations and found that the WWR can be significantly increased when using a better glazing system in terms of U-value and SHGC, with a low impact on energy the consumption of buildings (Westphal and Andreis, 2016).

Several results about the effects of WWR in their respective climates can be found in the literature. Marino et al. investigated the existence of an optimal WWR for office buildings in twelve different cities in Italy and the differential impact of insulation features, luminaires, and switchable shading devices on this parameter. The results of various simulations showed that there is an optimal WWR between 23.5% and 25.9% but that there are no significant changes to the optimal WWR when the individual factors mentioned previously are used separately (Marino, Nucara and Pietrafesa, 2017). Harmaati and Magyar demonstrated that in the Serbian climate, an office building's energy consumption can be reduced by 83% when appropriate WWR and glazing types are used (Harmati and Magyar, 2015). Chiesa et al. performed a similar series of simulations in office buildings with a constant rate of occupation for two different European climates (temperate and Mediterranean), and suggested that the optimal WWR can be found for both locations at around 30% (Chiesa *et al.*, 2019). Mahdavi et al. investigated the differential impact of WWR using parametric studies in the hot climate of Zahedan, Iran, and concluded that an optimal WWR of 40% with good orientation can reduce the energy consumption significantly and also has a potential of decreasing the carbon dioxide production to half (Mahdavi Adeli, Sarhaddi and Farahat, 2019). Chi et al. conducted a series of parametric changes in terms of orientations (18 intervals) and WWR (8 intervals) in China, to find their optimal values and their effects on indoor temperatures, daylight factors, and mean indoor air velocities and found that the optimal WWR for north and south walls is 40% and 35% respectively (Chi *et al.*, 2020).

More recent pieces of research have focused on the economic aspect of achieving the NZE



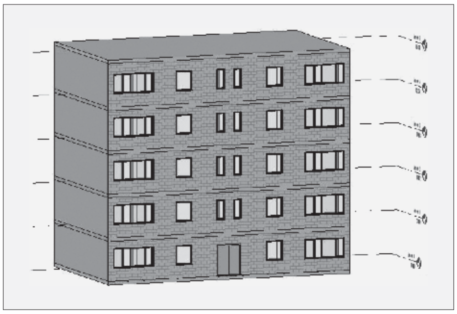


Fig. 2 Case study building: (a) case study building façade real picture, (b) plan of the case study apartment, (c) site plan with case study building located

Fig. 3 Simulated building model developed using Revit

concept, as well as its strategies. Several researchers found that the cost issue is one of the biggest problems in achieving NZE buildings. There are only a few studies that investigated these cost barriers (Hu, 2019; Taherahmadi, Noorollahi and Panahi, 2021). Albadry et al. mentioned that saving money on projects is one of the motivators for investors to pursue advanced energy methods (Albadry, Tarabieh and Sewilam, 2017).

This paper aims to fill gaps in the knowledge about windows and fenestration elements such as the glazing type, window-to-wall ratios (WWR), and payback periods (PBP). The research was conducted in a residential building whose characteristics, configuration, and structure represent a typical and standard reference case of the Algerian building stock, in three different cities; Constantine, Algiers, Ghardaïa, and different climate zones; semi-arid, Mediterranean, and arid. The first part of this research uses a simulation software, Sefaira plugin integrated to Autodesk Revit®, to gather information about the effects of locally available glazing types in different WWRs on energy consumption and energy use intensity and to seek out their optimal values. The second part aims to determine the financial return and the feasibility of such measures and find their optimal values accordingly to the economic aspect.

Methods

• **General description** – In an optimization process, and in order to find the most influential parameters on energy consumption with the aim of achieving NZE residential buildings; several ameliorations need to be made. In this study, two measures were chosen. The usage of three different types of glazing, which are simple clear glazing, double clear glazing with no fill, and double clear glazing filled with Argon. The WWR varies from 10% to 90%. The study was conducted in three types of climates: semi-arid climate which hosts the case study building in the city of Constantine, Mediterranean climate in the city of Algiers and arid climate in the city of Ghardaïa. All with the purpose of calculating their EUI and return on investment using Sefaira and Autodesk Revit®. Performing such a comparative analysis required the following work phases, as resumed in Fig. 1.

• **Description of the building case study** – A reference building was selected to conduct different building simulations, the case study is a simple rectangular multi-family residential building containing five levels and two apartments in each, as shown in Fig. 2 (a). Located in EL Khroub, Constantine, Algeria (coordinates: 36°15'20.7"N, 6°41'39.7"E, altitude: 603 m). The building is oriented 30° from the North/South axis. This building was chosen because it is one of the most common types of residential buildings in the Algerian territory. Each floor contains two apartments. The first one is a 75 m^2 apartment with two bedrooms, a kitchen, a living room, a bathroom and a toilet. The second one is an 85 m^2 apartment with three bedrooms, a kitchen, a living room, a bathroom and a toilet. The case study apartment illustrated in Fig. 2 (b) is a 75 m^2 apartment located on the second floor, containing a bedroom and a living oriented South/East, and another bedroom and a kitchen oriented North/East, with simple glazing aluminium windows and a WWR of 22%.

• **Simulation software** – The criteria for selecting the simulation tool and the modelling software were based upon the fact that glazing types and WWR are the main elements of this study. Because of its BIM benefits in automatically calculating areas and costs, as well as its widespread use and adoption among architecture firms, students, and professionals, Autodesk Revit® was chosen as the modelling software. It was used in combination with the simulation tool Sefaira, which is based on EnergyPlus, and offers a simple workflow, the ability to change parameters,

Table I The main simulation building's characteristics

		Thickness in m	λ Thermal Conductivity in W m⁻¹ K⁻¹	R Thermal Resistance in m² K W⁻¹	U-Value in W m⁻² K⁻¹
External wall	Plaster	0.02	0.35	0.06	0.95
	Hollow Brick	0.1	0.48	0.21	
	Air gap	0.05	0.11	0.45	
	Hollow Brick	0.15	0.48	0.31	
	Cement	0.02	1.15	0.02	
Internal wall	Plaster	0.02	0.35	0.06	3.10
	Hollow Brick	0.1	0.48	0.21	
	Plaster	0.02	0.35	0.06	
Floor	Floor tile	0.01	2.1	0.00	5.63
	Mortar	0.02	1.15	0.02	
	Slab	0.2	1.45	0.14	
	Mortar	0.02	1.15	0.02	
Roof	bitumen	0.02	0.23	0.09	4.13
	Slab	0.2	1.45	0.14	
	Mortar	0.02	1.15	0.02	
Windows	Aluminium	0.10	/	/	5.68

Table II Occupancy and operation schedules

Issue	Sefaira settings
Occupant density	15.0 m²/person
Equipment power density	15.0 W/m²
Light power density	8.6 W/m²
Heating setpoint temperatures	20 C°
Cooling setpoint temperatures	28 C°
Outside air rate/person	8.1 L/s.person
Infiltration	1.45 L/s-m
Operating hours	24h/24h
Days Schedules	7 days per week

and the ability to simulate on a cloud-based platform.

• **Simulation model characteristics** – The main simulation building's characteristics cited in Table I are the most commonly ones used in the Algerian territory according to the (DTR C3.2/4) and to the case study (Ministère de l'Habitat, 1997). They will remain unchanged in different simulation variations only to seek out the effect of the location, glazing types, and WWR on the energy behaviour of the building, which is the main focus of the study.

• **Occupancy and operation schedules** – The occupancy and operations schedules used are resumed in Table II.

• **Simulation variables: Glazing types, WWR** – The aim of this research is to seek out the differences between using various types of windows both in terms of energy and economic savings, as well as to verify the existence of an optimal value of the ratio of the glazed surface (S_w) to the wall surface (S_f) defined in Eq. (1) with an equal interval of 10% from 0.1 (10%) to 0.9 (90%).

$$WWR = \frac{S_w}{S_f} \quad (1)$$

After conducting several interviews with window manufacturers in local markets, we concluded that the three most common types of windows and glazing used in Algerian residential buildings and easily available on the local market are: simple clear glazing, double clear glazing without gas fill, and double clear glazing with Argon fill. Both windows with krypton gas and triple glazing windows are neither used nor found on the market. We conducted our research to alternate between

Table III Type of windows used in the simulations

	Single Glazing Window (Simple)	Double Clear Glazing Window with No Fill (Double)	Double Clear Glazing Window with Argon (Double Ar)
Section			
Specification	6 mm Clear	4 mm Clear / 16 mm Air / 4 mm Clear	4 mm Clear / 16 mm Argon / 4 mm Clear
U-Value in W m⁻² K⁻¹	5.68	2.83	1.40
SHGC	0.90	0.74	0.61
Tvis	0.86	0.80	0.60

FIG. 4 LOCATION OF THE STUDIES CITIES

TABLE IV CLIMATIC CONDITIONS IN STUDIED CITIES

	Altitude (m)	Gh (kWh/m²)	Dh (kWh/m²)	Bn (kWh/m²)	Ta (C°)	Td (C°)	FF (m/s)	RR (mm)	RD (days)
Constantine	650	1724	673	1791	15.9	8.4	2.6	485	94
Alger	25	1659	740	1538	18	12.7	2.8	600	92
Ghardaïa	468	1983	722	2055	22.7	5.1	3.6	145	23

the different types that are commonly found on the market, illustrated in Table III.

Furthermore, the purpose of the proposed energy analysis is to calculate the changes and variations that these values of WWR and glazing types might undergo under different weather and climate conditions.

- **The weather conditions** – Taking into consideration its vast territory and altitude disparity, as well as different climate zones in Algeria, three cities were chosen for this study as illustrated in Fig. 4. Constantine, Algiers and Ghardaïa which represents semi-arid, Mediterranean and arid climates respectively. The climate data and elevations were imported from the climatological software Metronome 8 as shown in Table IV.

The first climate zone is the location of the case study building, which is in the city of Constantine, specifically in El khroub 36° 16' 00" N, 6° 41' 00" E, 650m altitude, with a semi-arid climate. This climate is characterised by large temperature oscillations; hot and humid in summer and cold and wet in winter, where the average temperature and precipitations are 15.6 C° and 469 mm. The second climate zone is a Mediterranean climate represented by the city of Algiers 36° 46' 34" N, 3° 03' 36" E, which is characterized by a warm and dry summer with high humidity, and a mild winter with 18.2 °C as a yearly average temperature, alongside with high precipitations with a mean of 615 mm per year. For the third city of Ghardaïa the climate is arid, characterised by a hot and dry summer with high temperature differences between day and night, as well as between summer and winter. The average temperature is 21.1 °C and the precipitation is rare, with an average of 66 mm per year.

- **Model calibration and validation** – In order to produce correct results and validate the energy simulation, the outputs of the simulation tool, including energy consumption and demand, were compared with the values obtained from five years of utility bills from the case study building. The validation was done according to the recommendations of the ASHRAE Guideline 1 4-201 4 (ASHRAE, 2014), using both Mean Bias Error (MBE) and Coefficient of Variation of the root mean squared error value to calculate the level of potential error between the measured and predicted data. The methodology of calibration and validation was developed using Eq (2) and Eq (4).

$$MBE = \frac{\sum_{i=1}^{n}(Q_{pred\ i} - Q_{data\ i})}{nQ_{data}} \quad (2)$$

$$RMSE = \frac{\sqrt{\sum(Q_{pred\ i} - Q_{data\ i})}}{n} \quad (3)$$

$$CV(RMSE) = \frac{RMSE}{Q_{data}} = \frac{\frac{\sqrt{\sum(Q_{pred\ i} - Q_{data\ i})}}{n}}{Q_{data}} \quad (4)$$

Where:

MBE: Mean Bias Error

RMSE: Root Mean Squared Error

CV(RMSE): Coefficient of Variation of the root mean squared error

$Q_{pred\ i}$: predicted value during period i

$Q_{data\ i}$: measured value during period i

Q_{data}: measured avg during the period

In our case, the measurements of the MBE and CV(RMSE) were conducted and we achieved the results resumed in Table V.

- **Payback period (PBP)** – As stated by previous studies, the cost and the economic aspect are one of the greatest obstacles to the achievement of NZE buildings, making money savings the investors' motivator to pursue advanced energy methods, with only a few papers studying these aspects compared to environmental and comfort criteria (Hu, 2019) (Taherahmadi, Noorollahi and Panahi, 2021). (Albadry, Tarabieh and Sewilam, 2017). The payback period (PBP) study was chosen to establish whether or not different alternatives are profitable. The PBP can be calculated with the Eq (5), using the costs of the initial investment (USD and DZD), divided by annual savings or benefits (USD/year or DZD/year), which can be resumed through the following formula:

$$PBP = \frac{\text{Initial investment}}{\text{Annual savings}}(\text{years}) \quad (5)$$

In our case the initial investment is the window type prices and the annual savings or benefits in terms of energy from changing dif-

Table V Model Calibration According to ASHRAE Guideline 14-2014

	MBE	(CV)RMSE
ASHRAE Guidelines 14-2002	≤5%	≤15%
Error value of the model	-0.16%	6%

Table VI Algerian Energy Prices in DZD and USD

Type / Price	DZD	USD
Electricity	4.179	0.0297
Gas	0.324	0.0023

Table VII Type of windows prices

(a) Prices in DZD

Type /Price	Price 01	Price 02	Price 03	Price 04	Price 05	Average
Single Clear	16000	15000	15000	14000	19000	15800
Double Clear	20000	19000	22000	16500	22000	19900
Double Clear with Argon	22000	20500	22500	17500	23000	21100

(b) Prices in USD

Type /Price	Price 01	Price 02	Price 03	Price 04	Price 05	Average
Single Clear	113.6	106.5	106.5	99.4	134.9	112.18
Double Clear	142	134.9	156.2	117.15	156.2	141.29
Double Clear with Argon	156.2	145.55	159.75	124.25	163.3	149.81

ferent types of windows are calculated with the help of energy simulation and then multiplied by the price of energy. This can be summarised with Eq (6).

$$\text{Annual Savings} = \\ = \text{Energy savings} \times \text{Cost of energy} \quad (6)$$

For the calculation of energy prices Algerian government rates were used as demonstrated in Table VI.

To get an accurate and average price for the three types of windows, different local window manufacturers were asked for their prices for the square meter, and the results are illustrated in Table VII.

- **Profitability (P)** – To find out if the changes made are worth it economically, profitability (P) should be calculated, considering the building's life cycle and windows life span (BL), in our case, 30 years were considered together with its PBP. P is determined by Eq (7).

$$P = \frac{BL - PBP}{BL} (\text{years}) \quad (7)$$

With:
BL: Building life (years);
PBP: Payback period (years).

Results and discussion

Glazing type

The energy analysis simulation showed that in the semi-arid climate of Constantine, replacing a single clear glazing window with a double clear glazing window with an air gap ensures a saving of 20.81 kWh/m²/y and using double clear glazing filled with Argon gas, increases the savings to 30.77 kWh/m²/y, which means that the savings in total will be 1560.75 and 2307.5 kWh per year respectively, scoring the highest benefits in comparison with other climates.

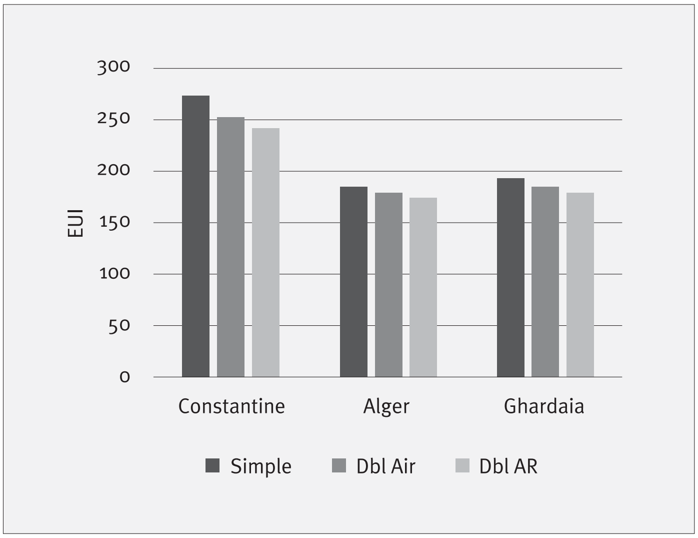
However, changing the locations to the Mediterranean climate, Algiers in this case, using the same two design variables made a saving of 5.8 kWh/m²/y and 9.85 kWh/m²/y which means 435 and 738.75 kWh yearly savings, respectively.

In the last case scenario, using the arid climate of Ghardaïa, the previous variables change, resulting in a saving of 7.63 kWh/m²/y made for the double clear glazing windows, which equals 572.25 kWh yearly and 13.52 kWh/m²/y for the double clear glazing windows filled with Argon gas, which equals 1014 kWh yearly.

These findings in the three different climates confirm that in terms of energy savings double clear glazing windows with Argon gas are the optimal option, followed by the double clear glazing windows with no fill, and in the last place come the simple glazing windows. Thus, there isn't a big difference between the double clear glazing windows with no fill and the double clear glazing windows with Argon gas. Its maximum is reached in the semi-arid climate of Constantine with a value of 9.96 kWh/m²/y and its minimum in the Mediterranean climate of Algiers with a value of 4.05 kWh/m²/y, which means respectively 747 and 303.75 kWh yearly, confirming the findings in other studies like (Tarabieh, Mashaly and Rashed, 2017) and (Alhagla, Mansour and Elbassuoni, 2019).

Window-to-wall ratio

Multiple energy simulations were carried out to find the most suitable WWR Eq. (1) with



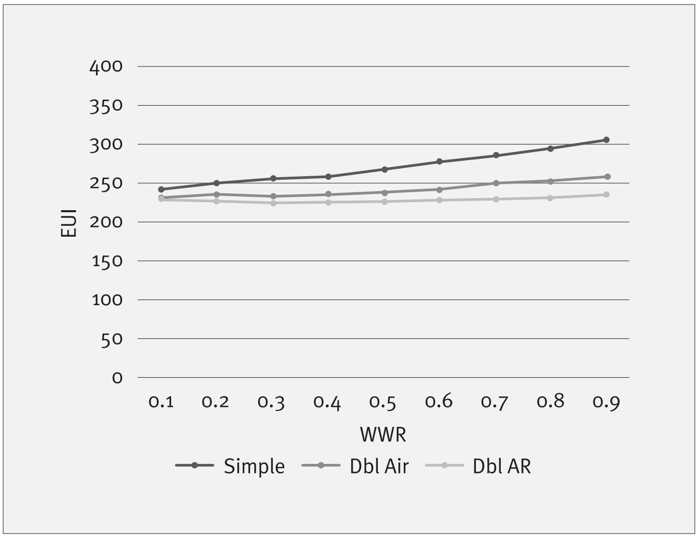


FIG. 5 EUI FOR TYPES OF GLAZING IN THE STUDIED CLIMATES

FIG. 6 EUI OF DIFFERENT WWRS IN THE SEMI-ARID CLIMATE

equal intervals from 0.1 (10%) to 0.9 (90%) for the three types of window glazing.

For the semi-arid climate simple glazing windows show that minimum energy consumption can be reached with 10% WWR and a linear relationship with the EUI. A large difference in consumption can be seen between greater and smaller WWR percentages (10% and 90%), reaching a maximum of 63 kWh/m^2/y (4725 kWh yearly). Using the double clear glazing windows with no fill as an alternative can decrease the overall EUI for different values, and reduce the difference between the minimum and maximum WWR to approximately half in comparison with simple glazing windows at 29 kWh/m^2/y (2175 kWh yearly).

The second alternative, which is double clear glazing windows filled with Argon gas, has the optimum energy consumption decrease potential. It decreases the overall energy consumption and the difference between the smallest and biggest WWR percentages (10% and 90%), to only 6 kWh/m^2/y, which is 450 kWh yearly.

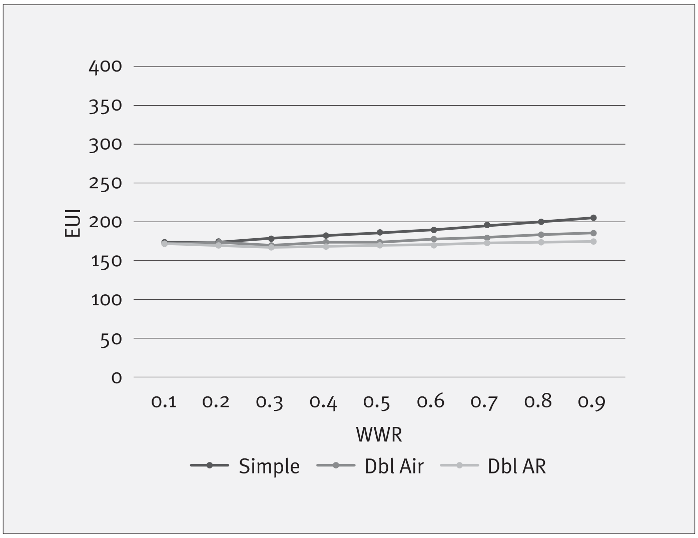
The results obtained from the Mediterranean climate show that there are no significant differences between different types of glazing windows in the lowest WWR values, with a 1.96 kWh/m^2/y difference between simple glazing and double clear glazing (147 kWh yearly), and 2.32 kWh/m^2/y difference between simple glazing and double clear glazing with Argon (174 kWh yearly).

Interestingly, the EUI of the double clear glazing windows with no fill and the double clear glazing windows with Argon gas were observed to be decreasing from 10% until reaching their peak at 30% and 40%, with a saving of 0.62 kWh/m^2/y (46.5 kWh yearly) and 4.13 kWh/m^2/y (309.75 kWh yearly) respectively.

In the same way, the results from the arid climate show similarities with the previous climates as it has almost the same EUI in smaller WWR with a small difference of 2.74 kWh/m^2/y (205.5 kWh yearly) for the double clear glazing windows with no fill and 3.79 kWh/m^2/y (284.25 kWh yearly) for the double glazing windows with Argon gas. Only for this climate did the double glazing windows with Argon gas reduce the EUI until reaching a WWR of 30%, making a saving of 0.62 kWh/m^2/y (46.5 kWh yearly).

These results suggest that in the three different climates the simple clear glazing window is the one achieving the least energy consumption reduction, and that the two others types are close in their energy efficiency, which further supports the idea that there are differences between the energy consumption comportment in the three climates when used with different types of glazing and WWRs as found in several other studies such as: Tarabieh, Mashaly and Rashed, 2017; Alhagla, Mansour and Elbassuoni, 2019; Troup *et al.*, 2019; Marino, Nucara and Pietrafesa, 2017.

As in the semi-arid climate with the smallest WWR of 10% in this case, there is a slight difference between single glazing and the two other double types of glazing. In other words, it's clear that for single glazing the optimal WWR is the lowest one as energy consumption keeps rising when we increase the WWR. Thus, there is a part between 30% and 40% where it stabilizes. It seems that there is only a slight difference for the double glazing types with 10%. This gap will increase when the WWR increases. We can notice that the optimal WWR for the double clear glazing window with no fill is 30% while it's 40% for the double clear glazing window with Argon gas. It is somewhat surprising that energy



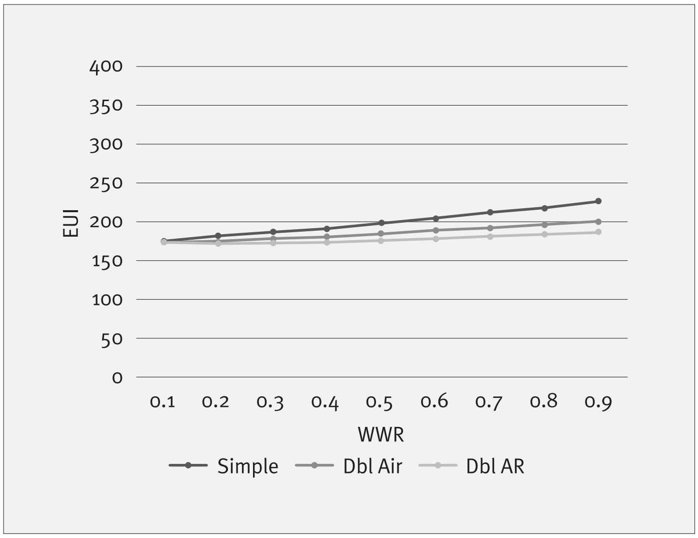


FIG. 7 EUI OF DIFFERENT WWRS IN THE MEDITERRANEAN CLIMATE

FIG. 8 EUI OF DIFFERENT WWRS IN THE ARID CLIMATE

consumption with different WWRs doesn't increase a lot when the double clear glazing window with Argon gas is used. These findings can suggest that this type is most suitable when high WWRs are needed.

For the Mediterranean climate it seems that the results are much closer for all three types of glazing. The single glazing optimum WWR can be increased with 10% to reach 20% in comparison with the semi-arid climate, but the optimal WWR for the double glazing remains the same at 30% and 40% for the double clear glazing windows with no fill and the double clear glazing windows with Argon gas respectively. This finding confirms that double clear glazing windows with argon gas keep energy consumption stable with different WWRs and have the smallest gap between the greatest and smallest WWR compared to the other two climates.

For the arid climate, the results show some similarities in the pattern of energy consumption but have some differences in terms of optimal WWR. As we can see, the optimal WWR for both single and double clear glazing windows is 10%, while we can reach a 30% value for the double clear glazing windows with Argon gas. We can also notice that the double clear glazing windows with Argon gas has the biggest gap in energy consumption between 10% and 90% WWR, which is double in comparison to what we found in the semi-arid climate and almost four times the results of the Mediterranean climate.

PAYBACK PERIOD

- Payback period for Constantine – When analysing the PBP data for the city of Constantine, which has a semi-arid climate, we can notice that the PBP is smallest when energy is set to the electricity price (in the case of using an electricity-powered HVAC system), with a peak reaching 7.31 years, and the highest payback time is when it is set to the gas price (in the case of using a gas-powered HVAC system) with a peak reaching 95.33 years. When the energy price is set to accommodate the energy mixture in the Algerian HVAC systems, as a combination of gas and electricity, the PBP is between the two previous results, reaching 28.99 years at its maximum. Interestingly, as far as the glazing types go, it seems that the double clear glazing windows filled with Argon gas have the shortest payback time when compared to the double simple glazing windows with no fill. This is with the three types of energy prices (Table VIII).

- Payback period for Algiers – For the city of Algiers and the Mediterranean climate, it is apparent from these tables that the payback time is really high, reaching astronomic results for the gas price table (342.04 years at its peak) and 19.96 years at its lowest point when calculated with electricity. For the type of glazing, it seems that the double clear glazing windows filled with Argon gas show the best results in terms of payback for the three types of energy usage methods (Table IX).

- Payback period for Ghardaïa – The results for the city of Ghardaïa and its arid climate indicate similar results, with electrical energy showing the best payback time with a peak of 19.93 years compared to the two other types of energy, reaching 79.07 and 260.01 years for gas and the mixed energy type. Turning now to the glazing type, the double glazing windows filled with Argon gas have the best payback time for the three types of energy reaching 14.54 years at its best for electricity and 189.70 years at its maximum for gas (Table X).

Table VIII Payback period calculations for the semi-arid climate of Constantine

	EUI kWh/m²/y	Saving per m²	Yearly Savings in kWh	Price per m²	Glazing Area m²	Window Prices In $	Price Difference In $	Price Electricity In $	Payback for new in years	Payback In years
Simple	274.12	/	/	112.18	11.76	1,319.24	/	/	/	/
Double	253.31	20.8	1560.8	141.28	11.76	1,661.45	342.22	46.82	35.48	7.31
Double Ar	243.35	30.8	2307.8	149.80	11.76	1,761.65	442.41	69.23	25.45	6.39
	EUI kWh/m²/y	**Saving per m²**	**Yearly Savings in kWh**	**Price per m²**	**Glazing Area m²**	**Window Prices In $**	**Price Difference In $**	**Price Electricity In $**	**Payback for new in years**	**Payback In years**
Simple	274.12	/	/	112.18	11.76	1,319.24	/	/	/	/
Double	253.31	20.8	1560.8	141.28	11.76	1,661.45	342.22	3.59	462.84	95.33
Double Ar	243.35	30.8	2307.8	149.80	11.76	1,761.65	442.41	5.31	331.90	83.35
	EUI kWh/m²/y	**Saving per m²**	**Yearly Savings in kWh**	**Price per m²**	**Glazing Area m²**	**Window Prices In $**	**Price Difference In $**	**Price Electricity In $**	**Payback for new in years**	**Payback In years**
Simple	274.12	/	/	112.18	11.76	1,319.24	/	/	/	/
Double	253.31	20.8	1560.8	141.28	11.76	1,661.45	342.22	11.80	140.75	28.99
Double Ar	243.35	30.8	2307.8	149.80	11.76	1,761.65	442.41	17.45	100.93	25.35

Table IX Payback period calculations for the Mediterranean climate of Algiers

	EUI kWh/m²/y	Saving per m²	Yearly Savings in kWh	Price per m²	Glazing Area m²	Window Prices In $	Price Difference In $	Price Electricity In $	Payback for new in years	Payback In years
Simple	185.42	/	/	112.18	11.76	1,319.24	/	/	/	/
Double	179.62	5.8	435	141.28	11.76	1,661.45	342.22	13.05	127.31	26.22
Double Ar	175.57	9.85	738.75	149.80	11.76	1,761.65	442.41	22.16	79.49	19.96
	EUI kWh/m²/y	**Saving per m²**	**Yearly Savings in kWh**	**Price per m²**	**Glazing Area m²**	**Window Prices In $**	**Price Difference In $**	**Price Electricity In $**	**Payback for new in years**	**Payback In years**
Simple	185.42	/	/	112.18	11.76	1,319.24	/	/	/	/
Double	179.62	5.8	435	141.28	11.76	1,661.45	342.22	1.00	1660.62	342.04
Double Ar	175.57	9.85	738.75	149.80	11.76	1,761.65	442.41	1.70	1036.80	260.38
	EUI kWh/m²/y	**Saving per m²**	**Yearly Savings in kWh**	**Price per m²**	**Glazing Area m²**	**Window Prices In $**	**Price Difference In $**	**Price Electricity In $**	**Payback for new in years**	**Payback In years**
Simple	185.42	/	/	112.18	11.76	1,319.24	/	/	/	/
Double	179.62	5.8	435	141.28	11.76	1,661.45	342.22	3.29	505.02	104.02
Double Ar	175.57	9.85	738.75	149.80	11.76	1,761.65	442.41	5.59	315.30	79.18

Table X Payback period Calculations for the arid climate of Ghardaïa

	EUI kWh/m²/y	Saving per m²	Yearly Savings in kWh	Price per m²	Glazing Area m²	Window Prices In $	Price Difference In $	Price Electricity In $	Payback for new in years	Payback In years
Simple	193.34	/	/	112.18	11.76	1,319.24	/	/	/	/
Double	185.71	7.63	572.25	141.28	11.76	1,661.45	342.22	17.17	96.78	19.93
Double Ar	179.82	13.52	1014	149.80	11.76	1,761.65	442.41	30.42	57.91	14.54
	EUI kWh/m²/y	**Saving per m²**	**Yearly Savings in kWh**	**Price per m²**	**Glazing Area m²**	**Window Prices In $**	**Price Difference In $**	**Price Electricity In $**	**Payback for new in years**	**Payback In years**
Simple	193.34	/	/	112.18	11.76	1,319.24	/	/	/	/
Double	185.71	7.63	572.25	141.28	11.76	1,661.45	342.22	1.32	1262.33	260.01
Double Ar	179.82	13.52	1014	149.80	11.76	1,761.65	442.41	2.33	755.36	189.70
	EUI kWh/m²/y	**Saving per m²**	**Yearly Savings in kWh**	**Price per m²**	**Glazing Area m²**	**Window Prices In $**	**Price Difference In $**	**Price Electricity In $**	**Payback for new in years**	**Payback In years**
Simple	193.34	/	/	112.18	11.76	1,319.24	/	/	/	/
Double	185.71	7.63	572.25	141.28	11.76	1,661.45	342.22	4.33	383.89	79.07
Double Ar	179.82	13.52	1014	149.80	11.76	1,761.65	442.41	7.67	229.71	57.69

Table XI Profitability in the studied climates

		Electricity Energy			Gas Energy			Mixture (81% Gas; 19% Electricity)		
		BL in years	PBP in years	P	BL in years	PBP in years	P	BL in years	PBP in years	P
Constantine	Double	30	7.31	76%	30	95.33	-218%	30	28.99	3%
	Double Ar	30	6.39	79%	30	83.35	-178%	30	25.35	16%
Algiers	Double	30	26.22	13%	30	342.04	-1040%	30	104.02	-247%
	Double Ar	30	19.96	33%	30	260.38	-768%	30	79.18	-164%
Ghardaïa	Double	30	19.93	34%	30	260.01	-767%	30	79.07	-164%
	Double Ar	30	14.54	52%	30	189.70	-532%	30	57.69	-92%

Table XII Payback Period of Algeria compared to France and USA in USD

	EUI kWh/m²/y	Total Saving kWh yearly	Price kWh of energy FR in $	Price kWh of energy US in $	Price kWh of energy DZ in $	Price Window per m² (FR) in $	Price Window per m² (USA) in $	Price Window per m² (DZ) in $	Payback FR in years	Payback US in years	Payback DZ in years
Simple	274.12	/				79.45	100	115.53	/	/	/
Double	253.31	1560.75	0.200	0.109	0.008	130.53	150	145.64	1.92	3.46	28.99
Double Ar	243.35	2307.75				227.01	255.06	158.54	3.76	7.25	25.35

It is worth noting that in all of the climates studied, there is a significant difference in the payback periods depending on the type of energy: electricity, gas, and a combination of both, which can be explained by the difference in prices, as electricity costs thirteen times more than gas. Surprisingly, when compared to each other, the results indicate that the semi-arid climate of Constantine is the one with the shortest payback period, followed by Ghardaïa and then last comes the Algiers climate. For all these climates and with the three types of energy the double clear glazing windows with Argon gas seem to be the most suitable option with the shortest payback period overall.

Profitability

Interestingly, with electrical energy, the results obtained showed really good profitability possibility with the different climates and glazing types, with the best results for the city of Constantine, reaching a 79% P for the double clear glazing windows with Argon gas, and the worst for the city of Algiers, amounting to a 13% P for the double clear glazing windows with no fill. However, for gas all these results were negative. None of the cities nor the glazing types could achieve profitability, reaching a peak of -1040% for the double clear glazing windows with no fill in the city of Algiers and a minimum of -178% for the double clear glazing windows with Argon gas in the city of Constantine. For the last type of energy combination, it is apparent from the table that only a few of the results can be profitable for the city of Constantine with barley minimum results. Further results are summarised in Table XI.

Comparison to other countries

As seen on the field and in the literature review, developing countries are far behind in terms of the usage of energy saving technologies (passive or active). An investigation was made to seek out the different prices for energy and windows in different parts of the world, more specifically in France as a representative country of Europe and the United States of America as a representative of America, as summarised in Table XII. This comparison was made to point out the difference in payback times between developed and developing countries and to see if it is one of the points that is keeping these countries from using more energy savings strategies when comparing them to our previous research results. One unanticipated finding was that Algerian energy prices are really low compared to other countries, approximately 14 times lower than in the USA and they are 31 times lower than French rates. In terms of the price per square metre of windows, Algerian prices appear to be the highest for simple glazing windows and double clear glazing with no fills, and the lowest for double clear glazing windows filled with Argon gas. When comparing the Algerian payback time results with the USA and France results, it can be seen that the Algerian payback time is longer than in the two other countries, with respectively 8 and 15 times more for the double clear glazing windows with no fill and 4 and 7 for the double clear glazing windows with Argon gas.

Overall, a profit can be made for all cities if energy usage is set to electricity, and no profit can be made if energy usage is switched to gas. Only Constantine can make a profit out of the combination of the two types of energy with the two types of glazing. This study is in accordance with (Missoum *et al.*, 2016) who studied PV system application in bioclimatic houses, and confirms that the payback periods of different strategies used to achieve NZE proves them to be hardly economically profitable.

Conclusion

The current study's main goal was to determine the effects of glazing types and window-to-wall ratios on energy consumption in three Algerian climates: semi-arid, arid, and Mediterranean, using energy simulation tools Autodesk Revit® software and Sefaira plugin, Three types of glazing with different U-value, SHGC and visual transmittance, with a series of WWR from 10% to 90% were tested. According to the simulation, the results can be summarised as follows:

– First, after conducting several investigations with local windows manufacturers, single glazing, double clear glazing with no fill, double clear glazing filled with Argon gas windows were identified as the ones that are widely available and can be found locally for a reasonable price.

– Second, according to the comparison of the three types of glazing, double glazing windows with Argon gas have the greatest potential for energy savings and are the most stable in terms of energy efficiency when increasing the WWR in all the studied climates.

– Third, the WWR has a significant effect on the energy consumption of residential buildings in the studied climates. The optimal WWR for a given orientation can't be selected without considering other elements of intervention, like in our case, the type of glazing.

– Fourth, the payback periods of the different types of glazing are really long when compared to other countries, and that is due to low energy prices in Algeria. Only a few studied cases could be implemented with profitability depending on the life time of these elements and their warrantee.

– Fifth, shorter payback periods could be achieved if the price of the building elements is lowered or the energy price subvention is removed.

– Sixth, because of the nature of economic strategies that are heavily dependent on fossil fuel exports, the amount of energy that is saved from energy efficiency measures and renewable energies could be calculated at the government level as an equivalent of exported energy to other countries.

[Written in English by the authors]

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Authors' biographies and contributions

Abdelhakim Walid Makhloufi, Ph.D., with several years of experience in the field joined and tutored by Dr **Samira Louafi** both working in the speciality of Architecture and environment in the laboratory Laboratory of Bioclimatic Architecture and Environment, having previous many publications and conferences as cited in the google scholar profile.

Conceptualization AWM and SL; methodology AWM and SL; software AWM; validation AWM and SL; writing – original draft preparation AWM; review and editing SL; visualization AWM; supervision SL; project administration AWM.

Both authors have read and agreed to the published version of the manuscript.

Abbreviations

ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
BIM	Building Information Modelling
BL	Building Life (years)
CV (RMSE)	Coefficient of Variation (Root-Mean-Square Error)
EUI	Energy Use Intensity
HVAC	Heating, Ventilation, and Air Conditioning
MBE	Mean Bias Error
PBP	Payback Period (years)
P	Profitability
TOE	Tonne Oil Equivalent
WWR	Window to Wall Ratio
NZEB	Net Zero Energy Buildings
NZE	Net Zero Energy
EPBD	Energy Performance of Buildings Directive
DTR	Regulatory Thermic Document
U-value	Thermal transmittance ($W\ m^{-2}\ K^{-1}$)
Tvis	Visible Transmittance
SHGC	Solar Heat Gain Coefficient
MENA	Middle East and North Africa
CBECS	Commercial Buildings Energy Consumption Survey