Improving the Energy Efficiency of Existing Residential Buildings by Applying Passive and Cost-Effective Solutions in the Hot and Humid Region of Iran

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Abstract

This paper aims to investigate the improvement of the energy efficiency of typical apartment buildings in the hot and humid region of Iran by applying passive and cost-effective solutions. For this purpose, a residential building, that reflects the current typology, is selected in Bushehr, Iran, and its annual energy consumption is explored using electric and gas bills. Then, a primary and calibrated model of the building is made using a real occupancy schedule and hourly weather data of Bushehr in Design Builder Software to simulate its energy performance. Considering the architectural design of the baseline model and using passive solutions (including low-E glazing, thermal insulation of external walls, roof and ceilings, and pre-heating of domestic hot water), a developed model is made. The simulation results indicate that the annual carbon dioxide emission and energy consumption of the developed model is reduced by 18.7% and 20%, respectively. These passive solutions can be used to improve the energy efficiency of existing buildings to achieve low Carbon buildings and neighborhoods in this part of Iran. This study also proposed a new reference for the annual energy consumption of low-energy houses in the hot and humid area of Iran and the Persian Gulf region (75-76 kWh/m^2/Year). Moreover, the economic analysis in this study demonstrates that the above-mentioned passive solutions will be cost-effective if the government subsidies for the residential buildings' energy use are eliminated in this region.

Keywords**:** Energy Efficiency; passive Solutions; Hot and humid Climate; Energy Simulation; Cost-effectiveness

1. Introduction

Today, energy crisis and global warming-induced problems call for research into energy efficiency (Wu, Rangan, & Zhang, 2012). Energy used in the buildings includes commercial and residential end-users accounts for 20.1% of the overall delivered energy consumed worldwide (EIA, 2016). The building sector is in charge of high energy use, and it is expected that its universal demand will increase in the next few decades. Among developing countries, Iran has 41 % of building energy demand (IDA, 2019). Besides, 61 % of the total energy is consumed for cooling and heating in the building sector as the greatest source of energy consumption in this country (Brebbia, 2011). Nestled in the hot and humid part of Iran (Fig. 1a), Bushehr city has harsh weather conditions, and the energy efficiency of the building is challenging (Mohammadi, Saghafi, Tahbaz, & Nasrollahi, 2017). In 2012, there was the highest domestic electricity demand for this small city (10000 kWh per capita) in Iran (Brahmand Zadeh, 2014). Thus, at present, it is of great importance to conduct applied research on the energy efficiency improvement in the building sector in this city to reduce GHG emissions. One of the most effective measures to reduce CO_2 emission and energy consumption in buildings is to enhance the energy efficiency of existing buildings (Yudelson, 2010). Optimizing energy consumption in existing buildings can be effective in achieving the social and environmental goals of sustainable development (Wu, Guo, Huang, Liu, & Xiang, 2018). Typically, retrofitting strategies for energy efficiency in buildings can be grouped into active and passive solutions. Active solutions include improving building services applications like HVAC systems and lighting; however, the objective of passive solutions is to provide further energy-efficient architectural elements to break the reliance on active solutions (Sadineni, Madala, & Boehm, 2011). While these strategies can improve the energy efficiency of existing buildings, they can be slightly expensive. The main objective of this study was to investigate the improvement of the energy efficiency of existing residential buildings by applying passive and cost-effective solutions in the hot and humid region of

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Iran. The results of this research can be used directly in the energy retrofitting of existing residential buildings.

In countries such as Saudi Arabia, Kuwait, United States, Malaysia, United Arab Emirates, Turkey, Paraguay, Singapore, and Hong Kong, there has been much research conducted on retrofitting solutions in hot and humid climates; in which the role of active and passive solutions in improving the energy efficiency of residential buildings have been particularly referred (Aldossary, Rezgui, & Kwan, 2017; Ameer & Krarti, 2016; Burgett, Chini, & Oppenheim, 2013; Chuan-Rui, Han-Sen, Qian-Cheng, & Rui-Dong, 2020; Haase & Amato, 2009; Kwame, Troy, & Hamidreza, 2020; Rehman, 2015; Sağlam, Yılmaz, Becchio, & Corgnati, 2017; Silvero, Montelpare, Rodrigues, Spacone, & Varum, 2018; Silvero, Rodrigues, & Montelpare, 2019; X. Sun, Z. Gou, & S.-Y. Lau, 2018; Tan, Liu, Zhang, Shuai, & Shen, 2018). Other studies were also conducted in different climates of Iran. The optimum retrofitting strategies (renewable, constructional, and architectural) for rural buildings in the four represented climates of Iran (Tabriz, Shiraz, Mashhad, Sari) were defined based on their comfort benefits, environmental impact, and economic viability for retrofitting projects in the form of the multi-criteria decision support tool, which is the main result of this study for prioritizing retrofitting strategies for rural houses (Tahsildoost & Zomorodian, 2020). To apply passive energy-reducing measures in existing and historical buildings of Shiraz for reducing energy consumption, they were prioritized and identified. According to the nature of the passive measures, they were categorized into three groups including thermal, acoustic, and lighting. Literature review, Questionnaire, and interview with experts were used for data collection. The results showed that durability, compatibility, and reduction of energy consumption were the most important criteria for the passive measure selection and improving the building airtightness, using sunspaces, and increasing the thermal mass of the building were the most suitable passive measures in acoustic, lighting, and thermal groups (Balali, Hakimelahi, & Valipour, 2020). The impact of different solutions such as thermal insulation of envelopes, shading system, window types, and renewable energy source on energy efficiency enhancement and global cost for a multi-family building in Shiraz city with a cold semi-arid climate were studied and it was revealed that acquiring cost-optimal levels in a high-performance building can be fulfilled just by governmental financial support and subsidies (Alvand, Gholami, Ferrara, & Fabrizio, 2017). An airflow window with integrated shading in a residential building placed in Yazd has been simulated. The findings attained with the Energy Plus software indicated that compared to the usual and double-glazed windows, airflow windows outperform in terms of energy efficiency (Abazari & Mahdavinejad, 2017). Two building types such as apartment and single-family as the current house typology in Yazd city were undergone a parametric analysis of retrofitting actions. Two approaches to balance the energy demand and supply of the models were proposed: minimization of the annual energy demand and provision of electricity by PV panels. Balance analysis and evaluation of energy demand and supply revealed that up to 36 % decrease in energy can be obtained and electricity generation was incremented up to 9.25 % using the proposed retrofitting actions (Aghamolaei, 2019). Physical indicators, local climate, and characteristics have been investigated in a research work regarding two neighborhoods in Tehran city. The research aimed to analyze and define the relationships between various parameters in the neighborhoods and their effects on urban energy demand. The results showed that physical, socio-economic, and local climate features are of great importance in urban energy use (Khodabakhsh, Fathi, & Mashayekhi, 2015). The effectiveness of some cooling strategies including appropriate orientation, solar shading, and thermal mass with night-time ventilation was evaluated using the dynamic thermal modeling and simulation of a residential apartment building in Tehran city. The results showed that these effective solutions can disperse excess heat and control heat gain during the summer (Nooraei, Littlewood, & Evans, 2013).

However, the potential of passive and cost-effective solutions for energy efficiency improvement in existing residential dwellings in the hot and humid parts of Iran has not been investigated. This paper goes further to investigate the improvement of energy efficiency by applying passive and cost-effective solutions in mid-rise apartment buildings in southern Iran. This study can fill the research gap in this region.

The key concepts of ‘energy efficiency improvement in existing buildings’ and ‘passive and cost-effective solutions’ are clearly central to this study. In this article, the relationship between these two key concepts has been investigated through the study of the appropriate passive and cost-effective solutions and their effects on the energy efficiency improvement of an existing residential building in Bushehr city. Meanwhile, these solutions have been proposed for the improvement of energy efficiency in this building with respect to the climatic conditions of Bushehr and the energy performance of the building.

2. Methodology

Figure 1 shows the research process diagram. The following methodologies were employed in this study:

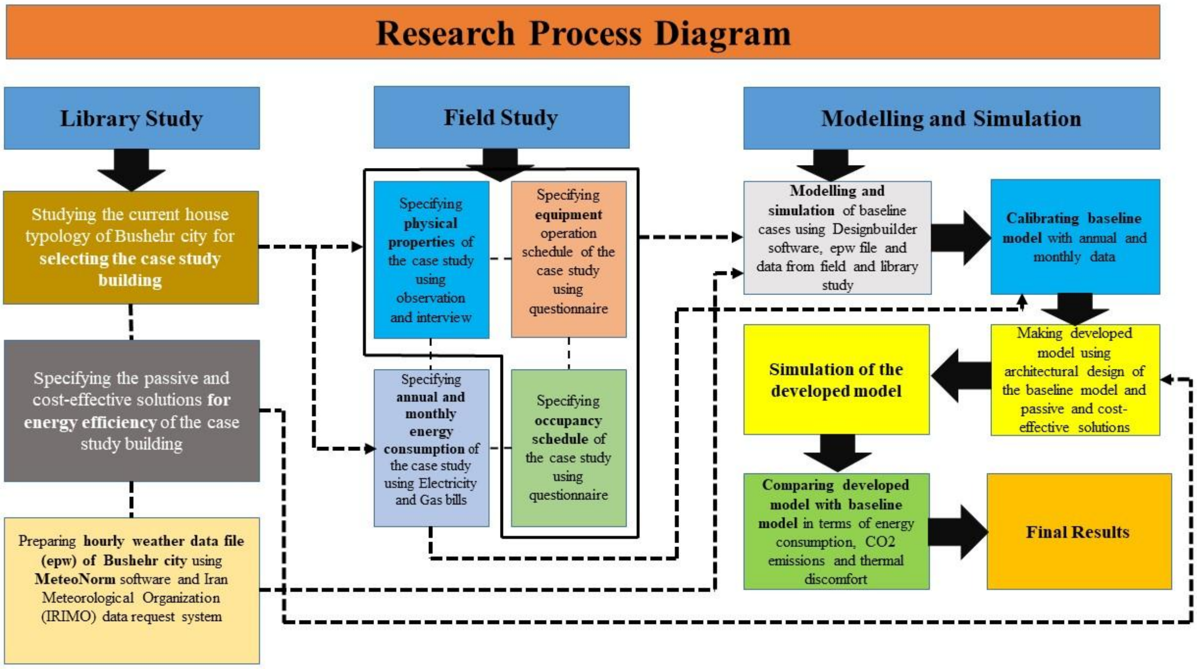
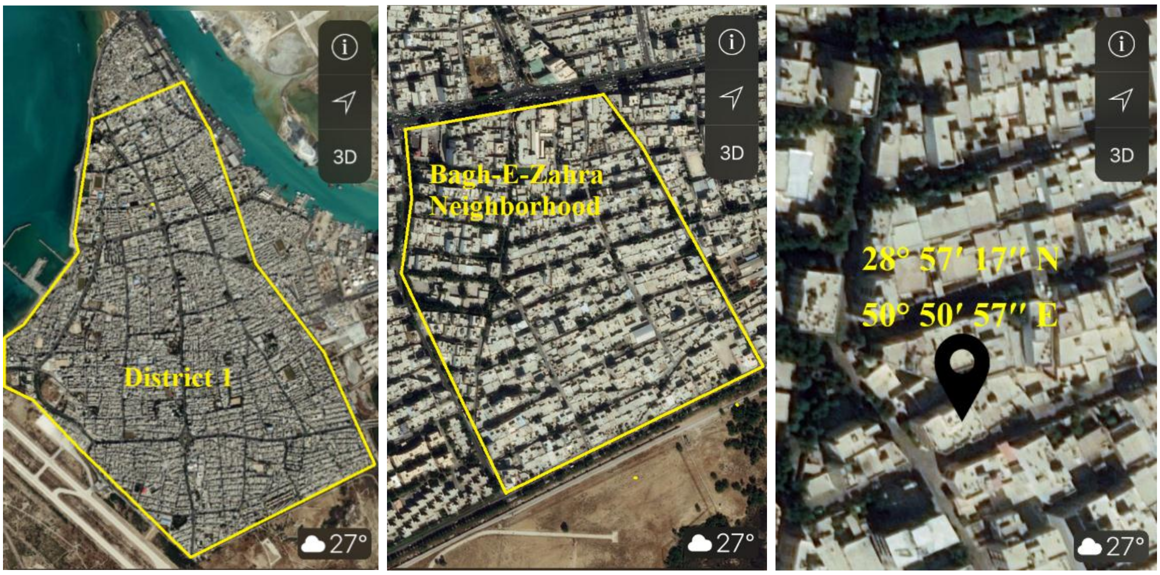


Fig. 1. The research process diagram

2.1. Library study

Considering previous research, the current house typology in Bushehr was investigated to find a suitable and accessible case study among the existing buildings and to study its location and architectural drawings. According to the statistics provided by Bushehr Municipality, the four-story mid-rise apartment buildings were the current house typology in Bushehr. Therefore, given the study by Mohammadi et al. (2018), an apartment building located at 50° 50′ 57″ E and 28° 57′ 17″ N in Bagh-e Zahra Neighborhood, District 1, Bushehr City was chosen as the case study and baseline case of this research. Fig. 2 shows the locations of Bushehr City (a), district1 (b), Bagh-e Zahra Neighborhood (c), and the selected building (d), respectively.

(a)



(b) (c) (d)

Fig. 2. a) The locations of Bushehr city in Iran, b) District 1 in Bushehr, c) Bagh-e Zahra Neighborhood, and d) the selected building (Source: Google Image)

According to our observations and the interview with the building owner, the construction process was completed in 2014, but the owner changed the building layout according to his requirements in 2017. The changes included adding a basement as parking (its structure and space were considered in the previous design), changing the ground floor plan into a residential unit and an independent work office, and adding a floor to the building. Furthermore, several shadings were added to the south, north, and west facades of the building. The building had no windows on the eastern side, while large windows along with terraces were added to the west facade. Thus, the renovated building consisted of seven residential units each with three bedrooms, an independent work office, and a parking space. The parking, stores, and facility rooms were located in the basement. The ground floor involved a separate work office and a residential unit while the upper floors, each being accessed via stairs and the elevator, had two independent residential units. Fig. 3 shows the different floors of the building studied.

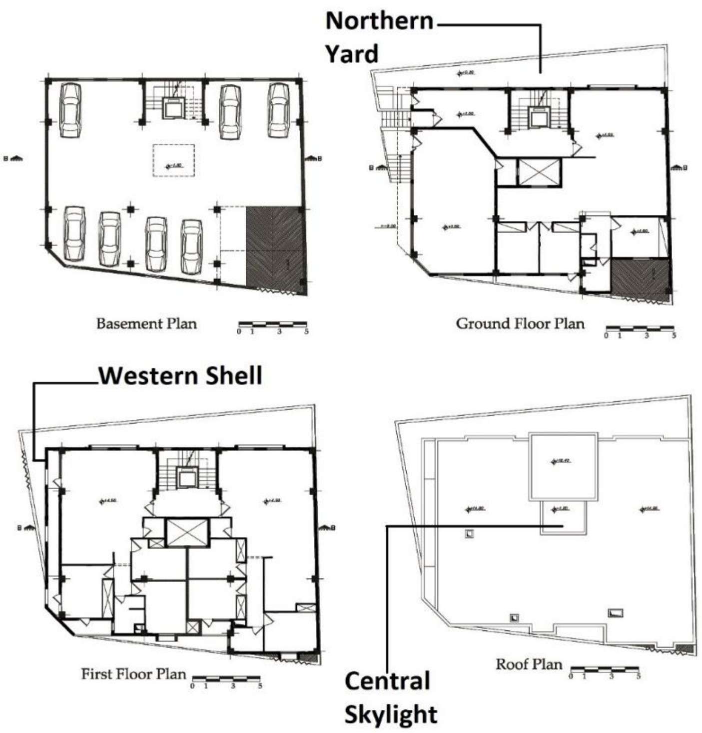
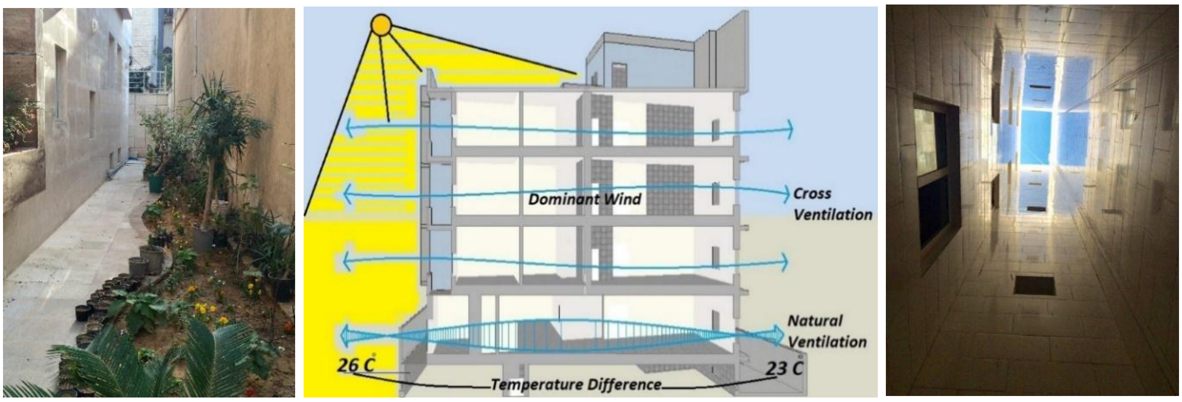


Fig. 3. Different floors of the case study building

2.2. Field studies

Bushehr City has very hot and humid summers and temperate winters. The weather is sultry in over six months of the year, rainfalls are scarce but torrential and the solar radiation intensity is excessive. Iran's meteorological calendar shows that July and August have the highest temperatures, and the average maximum temperature of the hottest month was 38.1°C, while January and February have the lowest temperatures, and the average minimum temperature of the coldest month was 10.1°C (Mohammadi, Saghafi, Tahbaz, & Nasrollahi, 2018). In the layout of the new building completed in 2017, three passive and climate-responsive solutions (Mohammadi et al., 2018) including thermal insulation of building envelopes and roof, shading, and natural ventilation were used.

To improve the natural ventilation, the northern yard of the building (Fig. 4a), which was always shaded during mild and warm seasons, was employed. The difference between the outdoor temperature in the northern yard and the Southern part of the building, which is always exposed to the sunlight, made a pressure difference between the two sides. As a result, natural ventilation was provided by simply opening the northern and southern windows on the ground floor (Fig. 4b). Also, cross ventilation was provided on the upper floors due to their heights, the building orientation toward the southeast, and the dominant winds from the northwest (Fig. 4b). The central skylight (Fig. 4c) could also help to enhance the natural ventilation when the wind speed was low on the upper floors. Natural ventilation is used in the building only in the temperate months (i.e., March and April), meaning that the windows of the building are controlled and opened at this time of year taking into account the natural ventilation set-point. However, through most of the hot and cold days of the year, the windows of the building are closed, natural ventilation is minimized, and only cooling/heating systems and mechanical fans are used.



(a) (b) (c)

Fig. 4. a) The Northern Yard; b) a schematic of the natural ventilation in building and c) the central skylight

For external walls, Clay blocks with 3-cm polystyrene foam (Fig. 5b) were used to provide thermal insulation. The UPVC frames, composed of a double-glazed glass and a 1-cm air layer, were utilized for the external doors and windows (Fig. 5a); while for the thermal insulation of the roof, a 20-cm air layer was used.

(a) (b)

Fig. 5. a) UPVC door and window, and b) clay block with a 3-cm polystyrene foam

The external shadings, with 40 cm and 60 cm depth on the north and south facades, respectively (Figs. 6d and 6c), can prevent direct solar radiation inside the building in hot seasons. Besides, the western shell with an 80-cm depth

(Fig. 6b) protects the west facade in the hot summer evenings. The void behind the shell helps the warm air to exit (Fig. 6a).

(a) (b) (c) (d)

Fig. 6. a) The void behind the western shell, b) western shell, c) south facade, and d) north façade

Table 1 shows the physical properties and the lighting, heating, cooling, and domestic hot water equipment of the building.

Table 1
Physical properties and equipment of the building

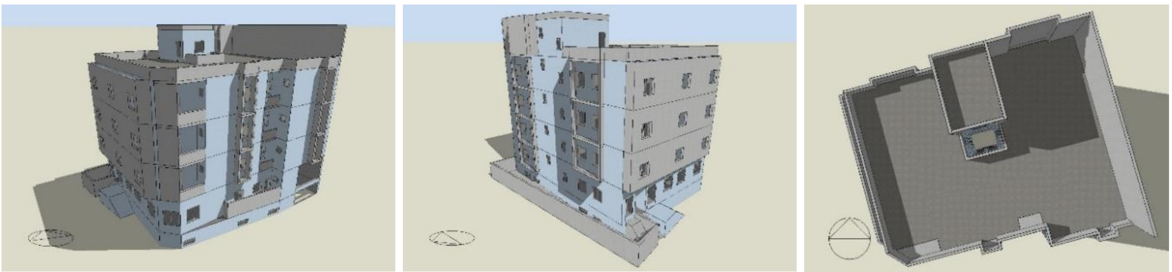
Physical properties and equipment	Study Building
Total area	1187 m^2
Northern shading device	40 cm depth – overhangs and side fins
Southern shading device	60 cm depth - overhangs and side fins
Western shading device	80 cm depth - shell
Eastern shading device	---
Natural ventilation schedule	March and April
Natural Ventilation Set-point	24°C
Infiltration Rate (ac/h)	1 (1/h)
Cooling system, CoP, and schedule	The split unit, 1.8, May to December
Heating system, CoP, and schedule	Radiator and gas heater, 0.85, January and February
General lighting	LED with energy label of A^{++} and a power density of 1 W/m^2
Domestic hot water (DHW), CoP	The gas-fired hot water system, 0.85
Window frame material and thickness	UPVC – 4 cm
Number of panes and type of glass	Double pane with 1-cm air- Ordinary
Heat transfer coefficient of glazing	2.66 W/m^2K
Solar heat gain coefficient (SHGC) and direct solar transmittance (DST) of glazing	0.70 and 0.60
The external wall thickness	25 cm
The materials of external walls	Inside, gypsum plastering, clay block, cement mortar, marble, outside
Heat transfer coefficient of external walls	2.01 W/m^2K
Material and thickness of the thermal insulation of external walls	Polystyrene foam, 3 cm
Material and thickness of the thermal insulation of roof	Air layer, 20 cm

The electricity and gas bills of the building demonstrated that the total energy consumption was 112,687 kWh/year in 2018. Moreover, 600,000 liters of water were consumed this year. While the total gas consumption was 36,626 kWh, the total electricity consumption of the building was 76,061 kWh, which is more than twice that of gas. The annual water consumption of the building (505 lit/m^2/year) was very high due to the harsh weather condition in Bushehr, but the annual energy consumption of the building was 95 kWh/m^2/year. Given the reference of the low-energy houses in the Middle East Region (Aldossary et al., 2017), this residential building was a low-energy house. It seems that the aforementioned passive solutions have been effective in reducing energy consumption.

2.3. Simulation

2.3.1. Modeling and simulation of the building

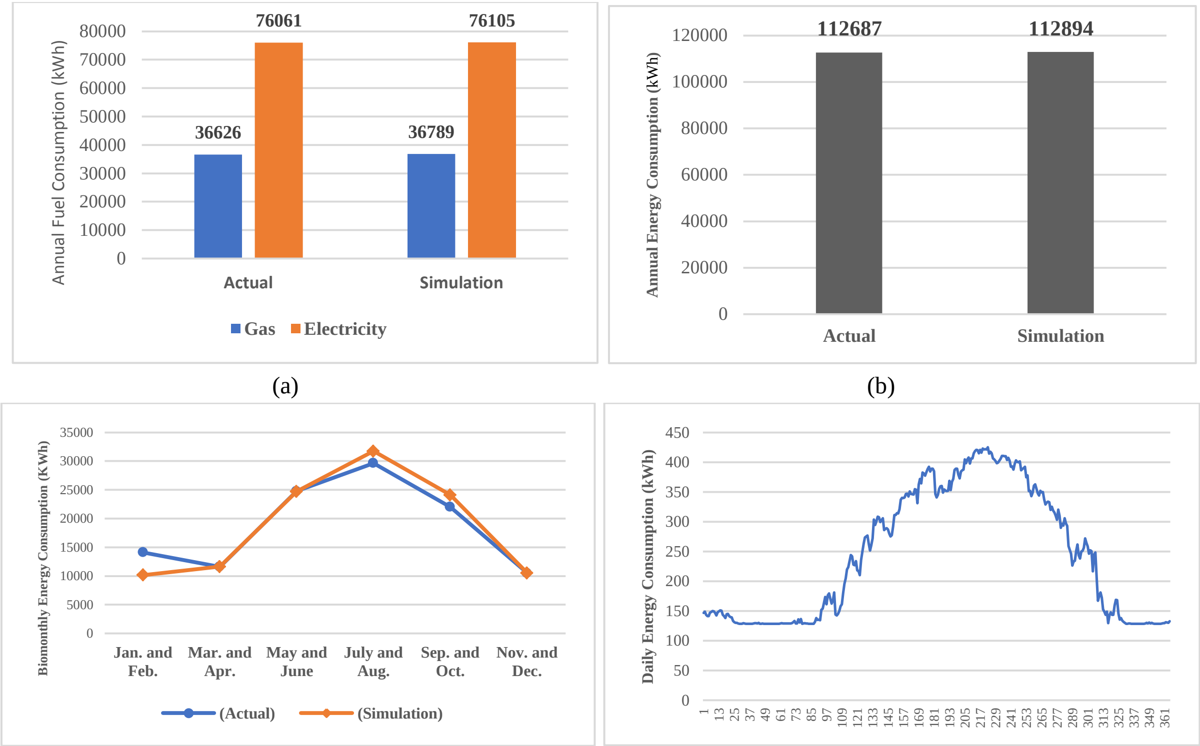
The Design-Builder Software (V.6) was employed for modeling and simulation of the structure based on its ability compared to similar energy simulation software. Since it uses EnergyPlus as its simulation engine, it is not only very powerful and accurate but also has a very easy-to-use interface (DesignBuilderLtd, 2019). Since the weather data and occupancy considerably affect simulation results (Rotimi, Bahadori-Jahromi, Mylona, Godfrey, & Cook, 2017), an updated hourly weather data file of Bushehr, which was made using MeteoNorm software (V.7), and Iran Meteorological Organization (IRIMO) data request system ("Hourly Weather Data of Bushehr," 2018), and the occupancy schedule of the building (Fig. 16, Appendix B), which was provided using a questionnaire, were used. The heating set-point in cold seasons (i.e., January and February) is assumed to be 20℃. So, the heating system of the building will be switched on when the indoor air temperature drops below 20℃ in cold seasons. The cooling set-point in hot seasons (i.e., May to December) is considered to be 25℃, meaning the cooling system is switched on whenever the indoor air temperature exceeds 25℃ in hot seasons. The natural ventilation set-point in temperate seasons (i.e., March and April) is considered to be 24℃, meaning the windows of the building are opened to allow for natural ventilation whenever the indoor air temperature is between 20 and 24℃ in temperate seasons. The internal heat sources included direct solar radiation, people, lighting, cooking, computers, and home appliances. The building simulation was based on the assumption that thermal comfort was completely provided by the air-conditioning systems during the hot seasons. However, thermal comfort may not be entirely provided by natural ventilation, which is preferred when temperatures are moderate, and discomfort hours may increase. Therefore, given the physical properties and equipment of the building in Table 1 and the equipment operation schedule in Fig. 17 (Appendix B), the whole building was simulated considering other features, such as the number of inhabitants and their clothing and activities. Figs. 7a, 7b, and 7c illustrate the modeling of the structure in the software.



(a) (b) (c)

Fig. 7. a) Southwest view, b) top view, and c) Northwest view of the building in Design Builder

In Fig. 8a, the actual and simulated energy consumptions of the building have been compared. According to this figure, the real and simulated energy consumptions of the building were 112,687 kWh and 112,894 kWh, respectively, and the difference between them is very slight. Moreover, Fig. 8b shows that there is a little difference between the actual and simulated electricity and gas consumptions of the building, but Fig. 8c (bimonthly energy consumption of the building) makes the model performance more clear, suggesting the building was modeled accurately, and the simulation results are reliable. Therefore, the model is considered "calibrated". Fig. 8d shows the simulation results of the daily energy consumption of the building. In this study, the actual results of the daily energy consumption of the building were not available; however, given the accuracy of modeling, it could be expected that the actual results of the daily energy consumption of the building will be similar to the simulation results in Figure 8d. Moreover, the results of the daily consumption can be monitored and compared with the simulated form in the future using a building energy management system (BEMS). Using this calibrated model, the energy consumption of the building can be investigated in different sectors, and various energy efficiency solutions could be evaluated.



(C) (d)

Fig. 8. Actual and simulated energy consumption of the building: a and b) Annual c) Bimonthly; (d) Daily simulation results

According to Figure 9, the building annual energy consumption associated with cooling, heating, DHW, lighting, appliances, and cooking are 54915, 1072, 18759, 3054, 17684, and 16958 kWh, respectively. Most of the energy consumption is related to building cooling and DHW; therefore, the building energy consumption should be optimized in these areas by adopting appropriate and cost-effective solutions. There has been a significant reduction in building energy consumption in the lighting section due to using extremely energy-efficient LEDs labeled A^{++} with extremely low lighting power density (LPD) (i.e., 1 W/m^2), and the smart system in public spaces, which accounts for 3% of the total energy consumption of the building.

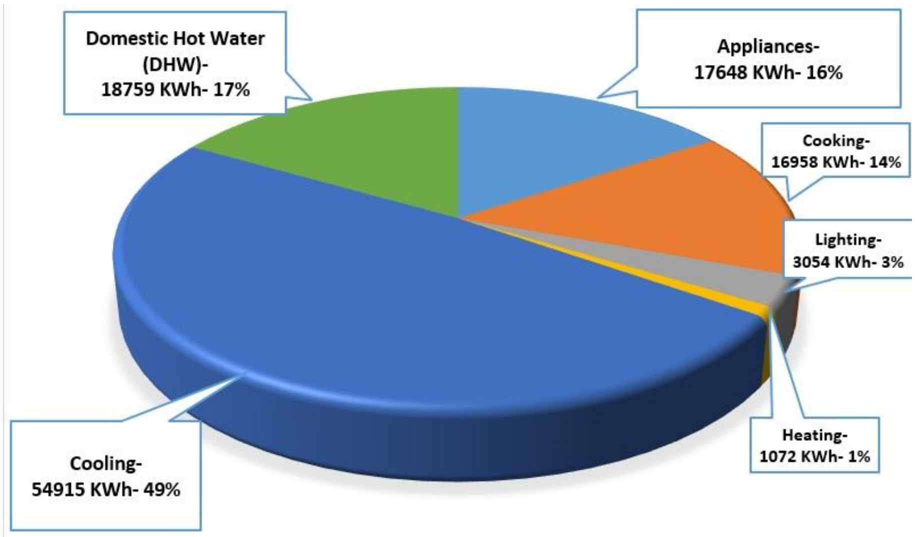


Fig. 9. Annual energy consumption of the building in different sectors

Equations (1), (2), and (3) were used in the simulation to calculate the daily building energy consumption in different sections. The equation (1) is applied for obtaining the daily energy amount $Q_{H,nd,day}$, (Wh), which is needed for heating space to adjust its temperature to the heating design internal air temperature $\theta_{i,H,ds}$, (℃), (Monstvilas, Stankevičius, Karbauskaitė, Burlingis, & Banionis, 2012):

$$Q_{H,nd,day} = \sum(Q_{H,t} \,.\, \Delta t),\ t=1,\ldots,24 \quad \textbf{(1)}$$

Where $Q_{H,t}$, (W) is the required thermal energy flow at every time step *t* (See appendix C for more details).

Equation (2) is employed for obtaining the total daily cooling energy $Q_{C,nd,day}$, (Wh), that is needed for cooling the space down to adjust its temperature to the cooling design internal air temperature $\theta_{i,C,ds}$,(℃), (Monstvilas et al., 2012):

$$Q_{C,nd,day} = \sum(Q_{C,t} \,.\, \Delta t),\ t=1,\ldots,24 \quad \textbf{(2)}$$

Where $Q_{C,t}$, (W) is the required cool flow at every time step *t* (See appendix C for more details).

The energy content of the domestic hot water (DHW) delivered to the user Q_w, (MJ/day), depends on the volume delivered and the water temperature. Equation (3) is employed for calculating the energy content (reference, 2007):

$$Q_w = 4.182 * V_w * (\theta_{w,t} - \theta_{w,o}) \quad \textbf{(3)}$$

Where V_w , (m^3/day) is the volume of domestic hot water delivered at a specified temperature, $\theta_{w,t}$ (℃) is the specified temperature of domestic hot water at tapping point, $\theta_{w,o}$ (℃) is the temperature of the inlet water.

The amount of energy consumed for lighting, home appliances, and cooking in residential buildings is determined by the power consumption of the equipment, operation schedule, and the number of them.

2.3.2. Developed Case

This study used a developed model to optimize the energy consumption of the actual building (baseline case). The developed model was made according to the architectural design of the baseline model. Table 2 shows the Passive and cost-effective solutions used in this model.

Table 2
Passive solutions used in the developed model compared to the baseline case

Solution	Baseline Case	Developed Model
Number of panes and type of glass, heat transfer coefficient, SHGC*, and DST**	Double pane with a 10-mm air layer-Ordinary, 2.66 W/m^2K, 0.7, and 0.6	Low-E double pane with a 13-mm air layer, 1.62 W/m^2K, 0.29, and 0.20
Type and thickness of roof insulation	Air, 20 cm	Rolled glass wool, 20 cm
Type and thickness of ceiling insulation	No thermal insulation	Rolled glass wool, 14 cm
The material and thickness of the thermal insulation of external walls	Polystyrene foam, 3 cm (Fig. 4b)	5-cm rolled polystyrene with a wooden frame
Pre-heating of domestic hot water	---	Water reservoirs with dark color

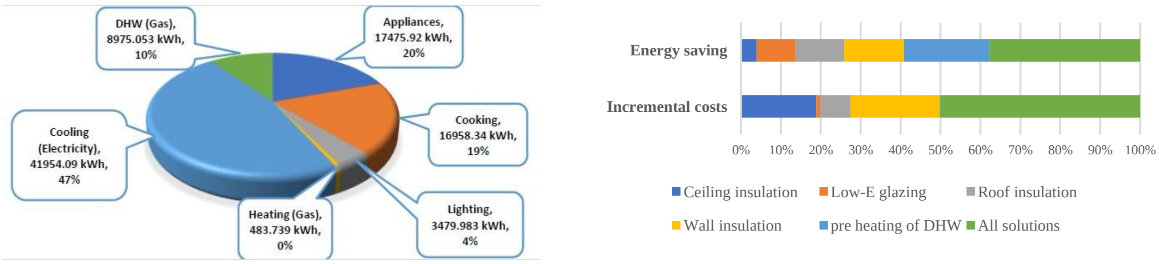
** Solar Heat Gain Coefficient ** Direct Solar Transmittance*

To optimize the cooling energy consumption in the developed model, the following solutions were used: replacing the ordinary glass with low-emission glass, and the thermal insulation of the roof, ceilings, and external walls. Furthermore, it is required to apply a dark color to the water reservoirs on the roof to preheat the domestic hot water. The temperature of the supply water in the gas-fired hot water system can be significantly increased by connecting these reservoirs to the network. Hence, it is required to apply a dark color to the external surface of the water reservoirs on the roof (Fig. 10) so that they could absorb more solar radiation. In the developed model, the hot water supply system temperature was considered to be 40℃. However, during a typical summer day in Bushehr, considering the solar radiation intensity, the temperature of water in reservoirs even exceeds 40℃.

Fig. 10. Dark and white water tanks on the roof

Other physical properties and equipment of the developed model were similar to the baseline case (Table 1). Also, it was simulated in the Design-Builder Software.

This study aimed to optimize energy consumption in the cooling and DHW sectors of the actual building by applying passive and cost-effective solutions. According to Table 2, thermal insulation was used in external walls, roof, and windows of the actual building to reduce cooling loads. However, this amount of thermal insulation appears to be inadequate for a low-energy building given the National Building Codes of Iran (Table 5). To enhance thermal insulation in the developed model, the same solutions used in the actual building (including thermal insulation of exterior walls, roofs, and windows) have been reinforced and a layer of thermal insulation has been added to the ceilings. Moreover, energy consumption in the domestic hot water sector was optimized by preheating. In this study, the thermal insulation of roof and external walls reduces the heat exchange between indoor and outdoor spaces and can save 7550 and 9384 kWh energy per year, respectively. The thermal insulation of ceilings prevents heat exchange between interior spaces and can save energy consumption up to 2467 kWh per year. The low-E glass absorbs less heat due to the lower solar heat gain coefficient (SHGC), and in the case of this study, using these glasses can save 6086 kWh energy per year. Preheating domestic hot water (DHW) requires less energy for these purposes and can save 13348 kWh energy per year, speaking of this study. It should be noted that employing all of the above solutions in the developed model has the greatest impact on optimizing energy consumption and can save energy consumption up to 23568 kWh per year. Figure 11a shows the annual energy consumption of the developed model in different sections, and figure 11b presents the energy saving and incremental costs of each of the solutions in the developed model. According to this Figure, solutions such as preheating of DHW, roof insulation, and the use of low-E glazing have less incremental costs than combined solutions (i.e., using all solutions). Nevertheless, since combined solutions are more energy-saving, a combination of all solutions has been selected and used in the developed model.



(a) (b)

Fig. 11. Developed model: a) Annual energy consumption in different sections and b) Energy Saving and incremental costs

It is noteworthy that the energy consumption of buildings should be optimized concerning thermal comfort. This study has used PMV and PPD indices to evaluate internal thermal comfort conditions. The PMV index examines the indoor thermal comfort conditions using a set of parameters including clothing level, activity, air temperature, mean radiant temperature, relative humidity, and airspeed. A set of values of these parameters are referred to as design conditions. It is known that the predicted mean vote (PMV) model is the most commonly applied thermal comfort index so far. This model is just applied to human beings who are exposed to steady-state conditions for a long time in terms of activity and microclimate. The following equations (4 to 8) were used in the simulation to calculate the PMV model (Albatayneh, Alterman, Page, & Moghtaderi, 2018):

$$PMV = [0.303\ e^{-0.036M} + 0.028]\ \{(M\text{-}W) - 3.96\ E^{-8} f_{cl}\ [(t_{cl} + 273)^4 - (t_r + 273)^4] - f_{cl} h_c\ (t_{cl} - t_a) - 3.05\ [5.73 - 0.007\ (M\text{-}W) - p_a] - 0.42\ [(M\text{-}W) - 58.15] - 0.173M\ (5.87 - p_a) - 0.0014M\ (34\text{-}t_a)\}; \quad (4)$$

$$F_{cl} = 1{+}0.2\ I_{cl}; \quad (5)$$

$$T_{cl} = 35.7 - 0.0275\ (M\text{-}W) - R_{cl}\ \{(M\text{-}W) - 3.05\ [5.73 - 0.007\ (M\text{-}W) - P_a] - 0.42\ [(M\text{-}W) - 58.15] - 0.0173M\ (5.87 - p_a) - 0.0014M\ (34 - T_a)\}; \quad (6)$$

$$R_{cl} = 0.155\ I_{cl}; \quad (7)$$

$$H_c = 12.1\ (V)^{1/2}; \quad (8)$$

Where,
M (Met): metabolic index;
W (W/m^2): external work (assumed = 0 W/m^2);
f_{cl}: clothing factor;
t_c (℃):the surface temperature of clothing;
t_r (℃): mean radiant temperature;
h_c(W/m^2): convective heat transfer coefficient;
t_a (℃): air temperature;
p_a (KPa): the partial pressure of water;
I_c (clo): clothing insulation factor;
R_{cl} (m^2k/W): clothing thermal insulation; and
V (m/s): relative air velocity inside the room.

PPD can be defined as the proportion of occupants that are uncomfortable in their thermal environments. The proposed appropriate PPD thermal comfort zone is below 10 % of occupants, who are not satisfied with their conditions (ASHRAE, 2009). PPD is a PMV function (the average comfort response of a large population). The experimental relation between thermal environment and PPD is a PMV function (Jorissen, 2018) as shown below (Chartered Institution of Building Services, 2006):

$$PPD = 100 - 95e^{(-0.03353 * PMV \wedge 4 - 0.2179 * PMV \wedge 2)} \quad (9)$$

The average design conditions (average values for all zones), as well as PMV and PPD, were extracted for each of the models from the Design Builder software and presented in Table 3 for an overall estimation of the indoor thermal comfort conditions of the models and their comparison. According to the design conditions of the models in this table and the thermal comfort graph in Fig. 12, the PMV index declined from 0.50 in the baseline model to 0.39 in the developed model, and the PPD index decreased from 10.17% in the baseline model to 8.24% in the developed model, indicating the improved internal thermal comfort conditions.

Table 3
Design conditions of the models

Design Conditions (Average)*	Baseline Model	Developed Model
Clothing (Clo)	0.77	0.77
Activity (MET)	1	1
Air Temperature (°C)	25.64	25.41
Mean Radiant Temperature (MRT) (°C)	26.15	25.65
Relative Humidity (%)	57.58	58.76
Air Speed (m/s)	0.10	0.10
Operative Temperature (°C)	25.90	25.53
Comfort indices (Average)*	Baseline Model	Developed Model
Predicted Mean Vote (PMV)	0.5	0.39
Predicted percentage of Dissatisfied (PPD) (%)	10.17	8.24

** Source: Design Builder software*

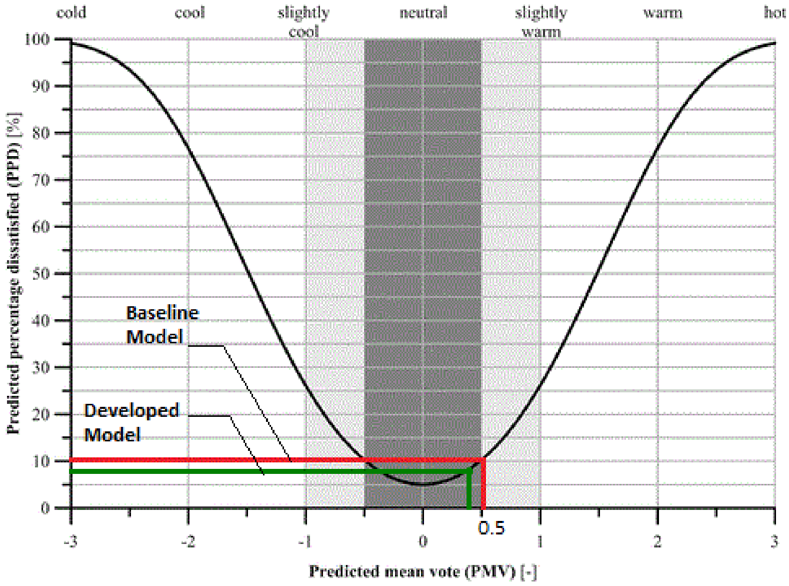


Fig. 12. Thermal Comfort Graph and design conditions of the models *(Source: Design Builder software)*

3. Results and discussion

3.1. Energy consumption analysis

Fig. 13 compares the energy consumption in different sections of the developed and baseline models. According to this figure, the cooling and domestic hot water energy consumptions decreased from 54,915 kWh and 18,759 kWh in the baseline model to 41,954 kWh and 8,975 kWh in the developed model, respectively, suggesting that the cooling and domestic hot water energy consumptions were reduced by 23.6% and 52% in the developed model, respectively.

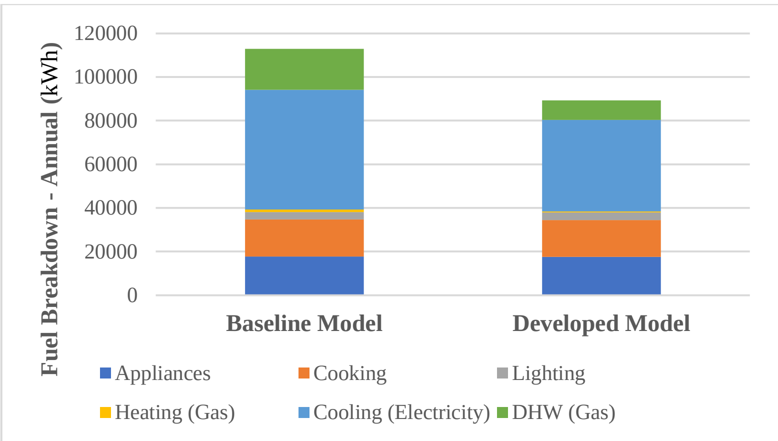
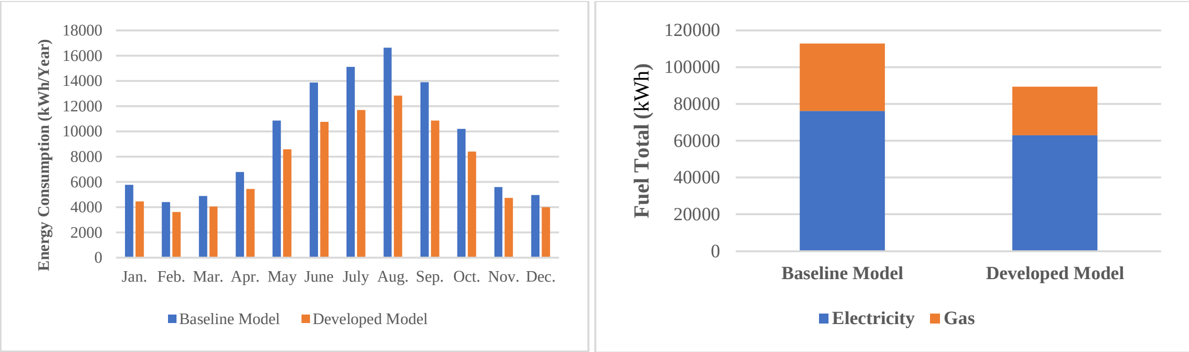


Fig. 13. Comparison of the baseline and developed models in energy consumed in different sections

The monthly energy consumption of the baseline and developed models have been compared in Fig. 14a. According to Fig. 14b, the annual energy consumption declined from 112,894 kWh in the baseline model to 89,327 kWh in the developed model, meaning the annual energy consumption of the developed model declined by 20% using the proposed passive solutions. As a result, the annual carbon dioxide emission decreased from 53.02 tons in the baseline model to 43.07 tons in the developed model, suggesting an 18.7% reduction in annual carbon dioxide emission.



(a) (b)

Fig. 14. a) Comparison of the monthly energy consumption and b) comparison of the annual energy consumption of the models

In this study, the annual energy consumption of the baseline and developed models have been compared with the low-energy building references in the hot and humid regions of the Middle East and Saudi Arabia in Fig. 15. These references were made taking into account environmental factors and socio-cultural context. These references were mainly provided for three common home typologies in Saudi Arabia, however, they can also be used for other countries in the region. According to figure 15, the annual energy consumption of a low-energy building in the hot and humid regions of the Middle East must be 77 kWh/m^2 to 98 kWh/m^2 per year (Aldossary et al., 2017). While, the annual energy consumption of the developed model in this study was 75.93 kWh/m^2/year, suggesting better results than the low-energy building references of the Middle East region.

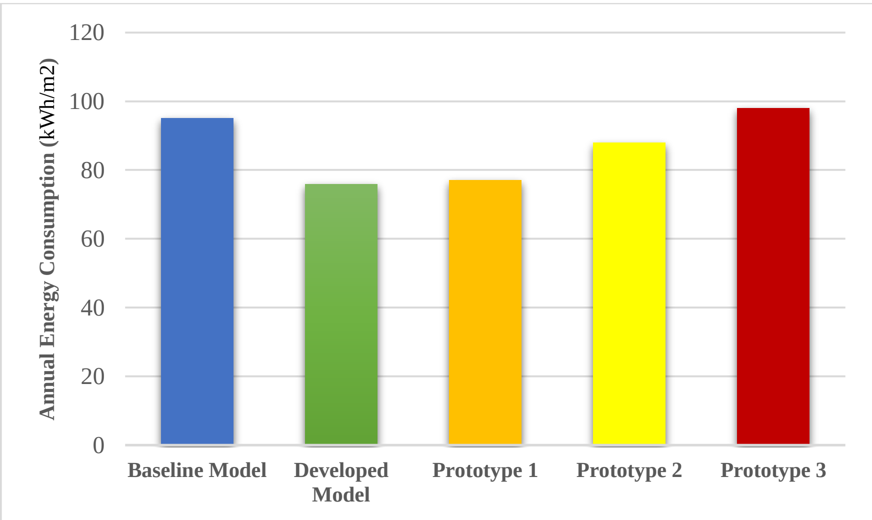


Fig. 15. Benchmarking energy consumption with the Middle East region references

As previously mentioned, the annual energy consumption of the baseline model is in the range of the Middle East region references. Given the geographical location of Bushehr and the National Energy Codes of Iran, the baseline model must be designed under group 1; i.e., very low-energy buildings with a volume heat transfer coefficient of 0.10 w/m^{3}k to 0.75 w/m^{3}k (Table 4). However, according to Table 5, the heat transfer coefficient of the external walls and roof, and the volume heat transfer coefficient of this model (Red cells) do not match the national energy codes of Iran (yellow cells)(National Building Regulatory Office, 2011). But, the developed model complies with the very low-energy building references in Iran. Although the heat transfer coefficient of the roof in this model is not compliant with the National Energy codes, the heat transfer coefficient of the external walls and glazing, and the volume heat transfer coefficient of this model (Green cells) are fully compliant with the National Energy codes of Iran for very low energy buildings. Thus, the developed model of this study complies with the national references of Iran and the references of the Middle East region for low-energy buildings, and its annual energy consumption (i.e., 75-76 kWh/m^2/year) can be considered as a new reference for low-energy residential buildings in the hot and humid parts of Iran and the Persian Gulf region.

Table 4
Buildings classification under National Building Regulations of Iran

Group	**Description**	**Volume Heat Transfer Coefficient of the building or F_v (w/m^3k)**
1	Buildings obliged to save a lot of energy	0.10-0.75
2	Buildings obliged to moderate saving	0.75-1.10
3	Buildings obliged to low saving	1.10-1.40
4	Buildings not obliged to save energy	1.40-2.00

(Source: National building regulations-Issue 19: Energy Saving in Buildings)

Table 5
Compliance of the models with the National Energy codes of Iran

Building Specifications	**Baseline Model**	**Developed Model**	**National energy codes of Iran**
Net Conditioned Building Area (m^2)	843.09	843.09	---
Net Conditioned Building Volume (m^3)	2529.27	2529.27	---
Gross Wall Area (m^2)	1070.37	1070.37	---
Window Opening Area (m^2)	92.56	92.56	---
Gross Roof Area (m^2)	294.71	294.71	---
U-Value of External Walls (W/m^2K)	**2.01**	**0.51**	**≤ 0.8**□
U-Value of Glazing (W/m^2K)	2.66	**1.62**	**≤ 2.7**□
U-Value of Roof (W/m^2K)	**1.85**	1.18	**≤ 0.5**□
$H_c = \sum U.A$ (w/k)	2942.85	1043.57	---
$H_{ac} = 0.34 .n .V_T$ (w/k)	808.35	808.35	---
$H = H_c + H_{ac}$ (w/k)	3751.2	1851.92	---
$F_v = H/V_T$ (w/m^3k)	**1.4**	**0.73**	**(0.10 - 0.75)**□

n: Air change per hour (ac/h); V_T: Conditioned building volume; Hc: specific heat transfer coefficient through building fabric; H_{ac}: specific heat transfer coefficient through ventilation; H: Specific heat transfer coefficient of the building; F_v: Volume heat transfer coefficient of the building; □: Mandatory codes for very low energy buildings in Iran

3.2. Economic analysis

To evaluate the cost-effectiveness of the passive solutions, this study employed an economic analysis involving a price list for buildings obtained from the Planning and Budget Organization of Iran (Expert Working Group and Editor, 2019). Table 6 provides a summary of the economic analysis. According to this table, the combined solutions will save 23,568 kWh energy per year, and the incremental costs will be 3,328,815,000 IRR (for more details, see Appendix A-Table 7). Considering the end-use energy price on the domestic scale without subsidies (i.e., 18,000 IRR per kWh) (MOP, 2018; NGC, 2018), 424,224,000 IRR will be saved per year, and the incremental costs will be returned in 7 years. While, considering the end-use energy price on the domestic scale with subsidies in the hot and humid region of Iran (i.e., 2,268 IRR per kWh) (MOP, 2018; NGC, 2018), 53,452,224 IRR will be saved, and the incremental costs will be returned in 62 years. The results of this analysis clearly show that the end-use energy price on the domestic scale with subsidies in the hot and humid region of Iran is meager. As a result, improving energy efficiency by applying passive solutions in this region of Iran would be cost-effective only without subsidies. It should be noted that the existing references for low-energy buildings of the Middle East region were established by using passive solutions along with renewable energy resources (photovoltaic panels) which can be very expensive. Meanwhile, the reduced energy consumption of the developed model in this study only relied on passive and cost-effective solutions.

Table 6
Economic analysis of the developed model

Passive strategies	Energy-saving (KWh/year)	Incremental cost (IRR)	Annual energy cost saving with subsidies (IRR) - (1 KWh = 2,268 IRR)	Annual energy cost-saving without subsidies (IRR) - (1 KWh = 18,000 IRR)	Cost-effectiveness* with subsidies	Cost-effectiveness* without subsidies	Payback ** period with subsidies (Years)	Payback ** period without subsidies (Years)
Ceilings insulation	2,467	1,252,580,625	5,595,156	44,406,000	0.004	0.035	>100	28
Low-E glazing	6,086	71,850,000	13,803,048	109,548,000	0.192	1.52	5	1>
Roof insulation	7,550	501,246,875	17,123,400	135,900,000	0.034	0.271	29	3
External walls insulation	9,384	1,492,712,500	21,282,912	168,912,000	0.014	0.113	70	8
Pre heating of DHW	13,348	10,425,000	30,273,264	240,264,000	2.90	23.04	1>	1>
combined solutions	23,568	3,328,815,000	53,452,224	424,224,000	0.016	0.127	62	7

** Cost-effectiveness = Annual energy cost-saving / Incremental cost (X. Sun, Z. Gou, & S. S.-Y. Lau, 2018)*
*** Payback period = Incremental cost / Annual energy cost saving*

4. Conclusion

In this study, the annual energy consumption of a common residential building of the dominant typology in the hot and humid region of Iran was re-examined under the condition of improving its passive solutions and applying new effective solutions, and the cost-effectiveness of these solutions was also assessed. Implementing these strategies, including improvement of the thermal insulation of external walls and roof, thermal insulation of ceilings, using low-E glass, and preheating of domestic hot water, can reduce annual energy consumption and carbon dioxide emissions in addition to improving indoor thermal comfort. The economic analysis in this study showed that the proposed passive solutions might not be cost-effective due to the low price of energy in this region. In other words, subsidized energy prices are very cheap in this part of Iran. As a result, the energy efficiency solutions will not be accepted by owners as long as this issue continues. Undoubtedly, eliminating energy subsidies and allocating them to the energy efficiency solutions in this region can enhance the importance of energy efficiency for residential buildings so that the owners choose energy retrofitting solutions rather than the excessive consumption of cheap energy. In this study, in addition to passive and cost-effective solutions for improving the energy efficiency of existing mid-rise residential buildings in the hot and humid region of Iran, a new reference was proposed for the annual energy consumption of low-energy buildings in the hot and humid area of Iran and the Persian Gulf region, which is upgraded compared to the previous low-energy house references of this region. While the previous references for low-energy buildings in this region relied on passive and renewable energy resources which could be very expensive, the new reference was established by using passive and cost-effective solutions. The passive and cost-effective solutions of this study could be employed in energy retrofitting of existing buildings and designing new low-energy houses to achieve low-Carbon buildings and neighborhoods and to tackle the increasing trend of climate change. Future research can be concentrated on the feasibility study of Net-zero energy buildings and their cost-effectiveness in the hot and humid parts of Iran.

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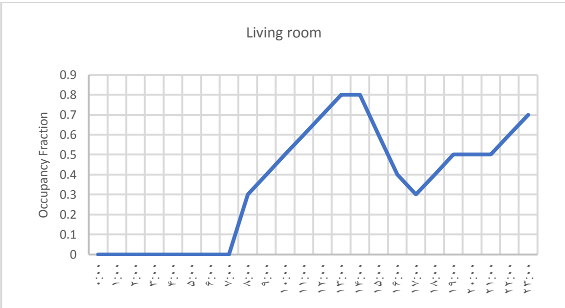
Conflicts of Interest
None.

Table 7
Details of the building renovation costs

Group Element/ Element	Area (m^2)	Cost per area (IRR/m^2)□	The total cost of the element (IRR)
Demolition works	260	181,500	47,190,000
Thermal insulation of roof	260	1,288,000	334,880,000
Thermal insulation of ceilings	780	966,000	753,480,000
Thermal insulation of external walls	1070	640,000	684,800,000
Roof finishes	260	454,000	118,040,000
Ceiling finishes	780	454,000	354,120,000
Wall finishes	1070	618,500	661,795,000
Painting of building components	2110	138,500	292,235,000
Replacement of glazing	93	450,000	71,850,000
Painting of water reservoirs	50	208,500	10,425,000
Total renovation cost (IRR)			
3,328,815,000			

□ Based on the price list for buildings obtained from the Planning and Budget Organization of Iran



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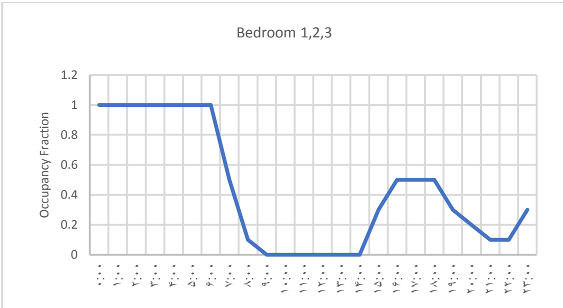

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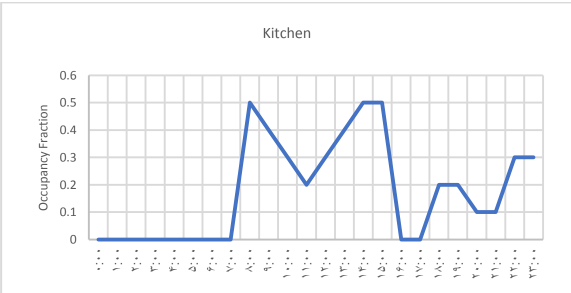

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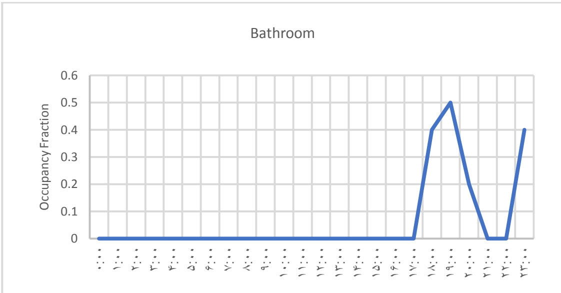
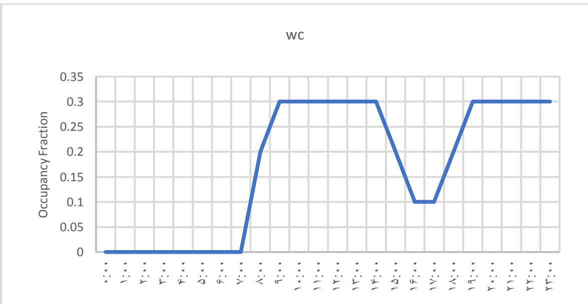
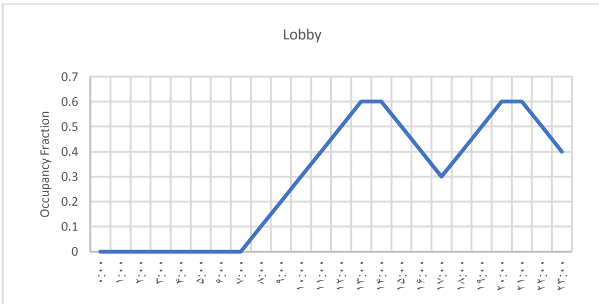


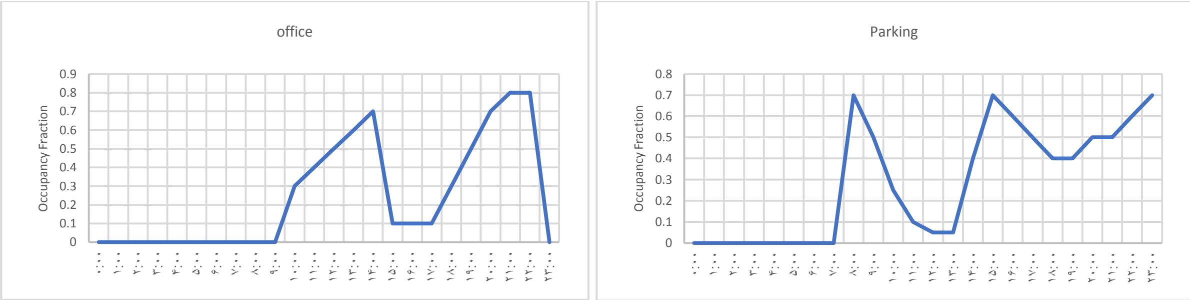
(d)



(e)

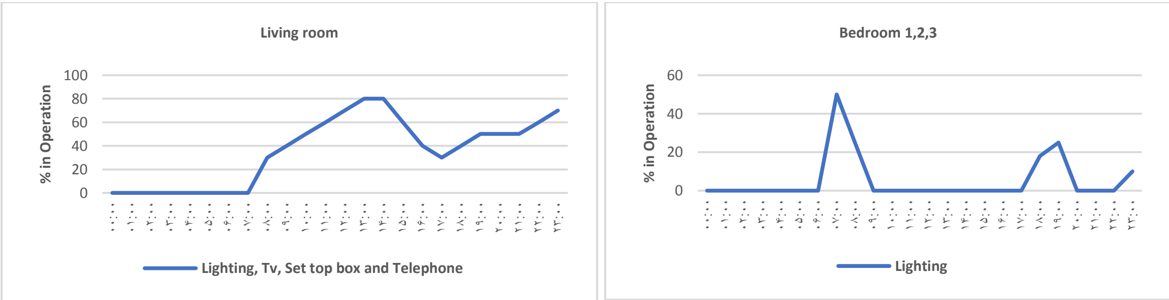


(f)

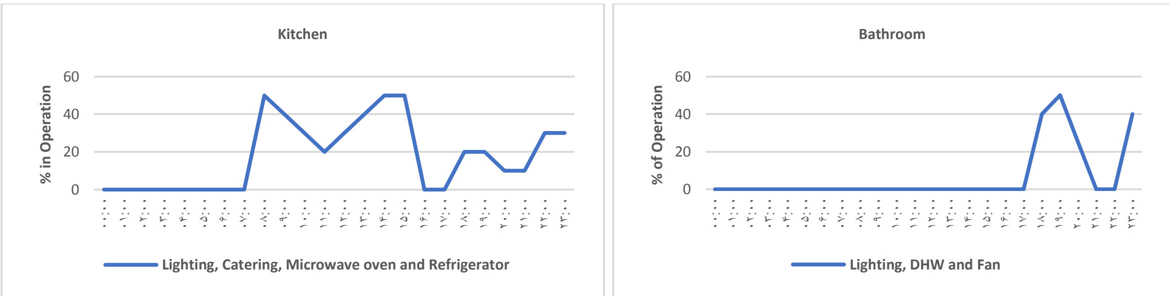


(g) (h)

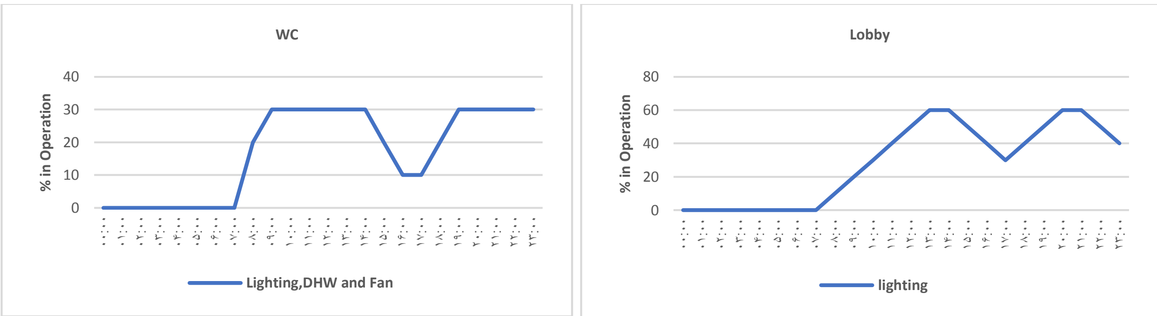
Fig. 16. A sample of occupancy profiles for different spaces in the models: a. Living room, b. Bedroom 1,2,3, c. Kitchen, d. Bathroom, e. WC, f. Lobby, g. Office, h. Parking



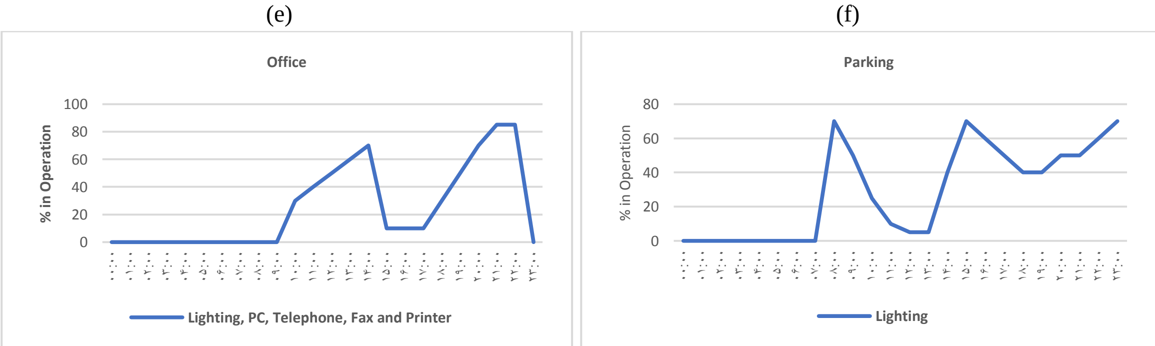
(a) (b)



(c) (d)



(e) (f)



(g) (h)

Fig. 17. A sample of lighting and equipment operation schedules for different spaces in the models

Table 8
Details of the equations (10) to (17) (Monstvilas et al., 2012)

Parameters	Units	Descriptions
$\theta_{i,t}$	℃	Indoor air temperature
$\theta_{e,t}$	℃	Outdoor air temperature
H_{tot}	W/K	Total heat transfer coefficient of the building
H_{tr}	W/K	Transmission heat transfer coefficient of the building
H_{ve}	W/K	Ventilation heat transfer coefficient of the building
n	h^{-1}	Air change rate for ventilation
V	m^3	Inside volume of the building
b_{ve}	---	Temperature adjustment factor
$\rho_a . c_a$	Wh/m^3K	Heat capacity of air per volume = 0.34
$Q_{in,t}$	W	Decrease of thermal energy flow for heating
$q_{int,t}$	W/m^2	Internal heat gains for floor area unit of the heated spaces
A_f	m^2	The floor area of the heated spaces
K	---	Number of appropriate opaque and transparent building elements
$F_{r,k}$	---	Form factor between the external surface of the building element and the sky; for unshaded vertical elements $F_{r,k} = 0.5$; for unshaded horizontal elements $F_{r,k} = 1$
$h_{se,r}$	W/m^2k	External surface radiative heat transfer coefficient could be taken as equal to 5 ε_{lw} (the value of long-wave hemispherical emissivity); it corresponds to the average temperature of 10 ℃
$\Delta\theta_{er}$	℃	The average difference between the external air temperature and apparent sky temperature; in the sub-polar areas $\Delta\theta_{er}$ =9k; in the tropics $\Delta\theta_{er}$ =13k; in the intermediate zones $\Delta\theta_{er}$ =11k
$\varepsilon_{lw,se,k}$	---	the hemispherical emissivity of the external surface of the element k
U_k	W/m^2k	thermal transmittance of the element k
A_k	m^2	the overall projected area of the element k with the given orientation and tilt angle
$I_{sol,k,t}$	W/m^2	the mean global solar radiation over the time step of the calculation onto appropriate element k of a given orientation and tilt angle
$\alpha_{sw,se,k}$	---	the solar radiation absorption coefficient of the element k of external surfaces of the building
$F_{sh,k}$	---	shading factor by external obstacles for the surface A_k

Since the hourly calculation method of building energy demand for space heating and cooling based on THE steady-state heat balance equations is used in the Energy Plus, the followings are the equations for calculating the energy demand for the heating (1) and cooling (8) of buildings. It is assumed that in the calculation, the time step is equal to one hour, i.e. Δt = 1h. Heat transfer is assumed to settle into a steady-state mode during this time step (Monstvilas et al., 2012):

$$\mathbf{Q_{H,t}} = H_{tot} . (\theta_{i,t} - \theta_{e,t}) - Q_{in,t} + Q_{r,t} - Q_{sol,ab,t} ; \tag{10}$$

$$H_{tot} = H_{tr} + H_{ve} ; \tag{11}$$

$$H_{tr} = \sum (U_k . A_k) ; \tag{12}$$

$$H_{ve} = \rho_a . c_a . \sum (n.V.b_{ve}) \tag{13}$$

$$Q_{in,t} = q_{int,t} . A_f \tag{14}$$

$$Q_{r,t} = (h_{se,r} . \Delta\theta_{er} / h_{se,c} + h_{se,r}) . \sum [\varepsilon_{lw,se,k} . F_{r,k} . U_k . A_k], k=1,\dots,n \tag{15}$$

$$Q_{sol,ab,t} = (I_{sol,k,t} / h_{se,c} + h_{se,r}) . \sum [\alpha_{sw,se,k} . F_{sh,k} . U_k . A_k], k=1,\dots,n \tag{16}$$

$$\mathbf{Q_{C,t}} = H_{tot} . (\theta_{i,t} - \theta_{i,C,ds}) \tag{17}$$

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