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Sustainable Retrofit Solutions for Decreasing Energy Consumption and CO2 emission of a Residential Building in Tabriz, Iran

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Abstract

The rapid growth of Iran's population in the last four decades has caused many residential buildings. Since Iran subsidizes energy costs as well as water and electricity tariffs, energy is cheap in Iran, and most buildings are not occupied with energy efficiency measures. Therefore, the number of conventional residential buildings is increasing. This study aims to retrofit a residential building in Tabriz, Iran, to show the importance of sustainable retrofits for decreasing building energy consumption. For this purpose, a case study building (i.e., reference building) was modeled using Design Builder and PVSOL®. Four scenarios addressing sustainable retrofits were applied to decrease the energy consumption and co_2 emission of this residential building. The results demonstrate that all four scenarios successfully reduced the building's total energy usage to 65%. Accordingly, this study contributes to the architecture, engineering, and construction (AEC) literature and industry by demonstrating the significance of sustainable retrofits to reduce building energy consumption and carbon emissions.

Key Innovations

- Determine the most effective scenario for decreasing energy consumption to achieve the best results in residential buildings with cold and dry climates
- Help reduce CO_2

Practical Implications

The AEC industry practitioners will benefit from the results of this study. The sustainable retrofit solutions presented in this paper help residential buildings save energy, increase their value, reduce CO2, and increase the durability of the building. Further, these strategies can be implemented in the AEC industry to achieve the government's ambitious target of reducing carbon emissions by 2050.

Introduction

One of the most challenging global problems is the vast amount of energy consumption and carbon release in the buildings and construction industry. Energy consumption is a critical problem affecting the natural environment in a negative manner and causing the release of pollutants, including carbon emissions (Li et al. 2021). Controlling and lowering CO2 emissions is one of the most important strategies to address such issues, which are the fundamental reasons for climate change (Hu et al. 2022). Due to global warming and the limitation of non-renewable energy sources, global energy demand has been increasing over the past few decades (Rakhshan and Friess 2017). Therefore, all nations have concentrated on increasing energy efficiency to address this critical issue. The U.S. Energy Information Administration (EIA) announced that global energy consumption would increase by about 50% between 2018 and 2050. The majority of this increase is attributed to the nations outside the Organization for Economic Cooperation and Development (OECD), including Iran (International Energy Outlook - U.S. Energy Information Administration (EIA) 2022). According to studies, Iran's overall energy consumption will increase by 2.8% yearly, and it will double by 2030 (Moshiri et al. 2012). Iran's high energy intensity index is mainly caused by the conduct of its citizens, poor infrastructure, and, most importantly, excessive energy subsidies from the government. Iran was ranked the first country globally in terms of energy subsidies in 2020. Oil is still the most subsidized fuel; however, gas and electricity are getting up. Cost change is challenging politically, but it is economically and environmentally essential. (Figure 1). Although these subsidies are meant to lower energy costs for consumers, they boost energy usage across various industries, including the building industry (Mirzaei et al. 2020).

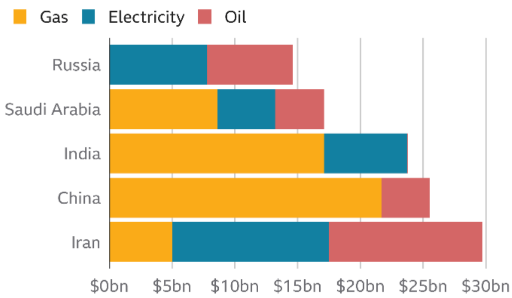

Figure 1: Subsidy amounts for fossil fuels by fuel, 2020 (IEA 2022)

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Since the residential sector has taken a large share of Iran's growing global energy demand, improving building energy efficiency in Iran is an essential strategy. Additionally, finding the best retrofit strategy in the residential sector is challenging because more than 30% of energy waste in the country is related to the residential buildings and construction industry (Rahmani et al. 2020). Retrofitting projects in Iran face more challenges due to the specific characteristics of this country, such as subsidised energy costs as well as water and electricity tariffs (Tavakolan et al. 2022). Moreover, due to the cheapness of energy, basic measures for energy consumption in residential buildings have not been considered, and the factors affecting energy consumption have not been identified. (Keshavarz Moraveji et al. 2022). Therefore, there is an urgent need for more studies on increasing building energy efficiency since many existing buildings in Iran do not comply with energy efficiency rules (Tahsildoost and Zomorodian 2015). In addition, it is emphasised that most of the studies in this research field have been conducted on case studies in regions with high energy costs, such as East Asia, America, and Europe. However, their findings do not apply to the nations like Iran (Balali et al. 2020). Even though Iran is rich in sustainable energy resources, this country faces energy poverty due to a lack of proper energy usage and savings policies, specifically in residential areas. Between 2001 and 2011, Iran's final energy consumption and carbon intensity increased by 67% and 81%, respectively. In other words, Iranian CO2 emissions grew from 302 MT in 2001 to 547 MT in 2011, representing an 81 percent rise. Iran's total energy consumption increased from 637.8 million barrels of crude oil in 2001 to 1068.4 in 2011. The household sector is the primary factor affecting the total energy use in Iran. Iran's total energy consumption can be reduced by concentrating on the residential sector, attempting to transition to renewable energy sources, and advancing production technology (Ahmadi et al. 2020). Tavakolan et al. (2021) developed a simulation-based multi-objective optimisation framework to increase building energy efficiency and optimise the economic advantages of retrofitting. Javid et al. (2019) provided a multi-objective optimisation framework to reduce the financial expenses and global warming potential (GWP) effects of two educational buildings in Iran. Mirzaei et al. (2020) calculated the life cycle cost and thermal discomfort of a residential structure in Iran using a multi-objective optimisation framework by using Energy Plus, NSGA-II, and the jEPlus to decrease energy consumption. Tahsildoost et al. (2015) performed experimental research that prioritised scenarios based on energy modelling and retrofitted two typical school buildings in Iran. Balali et al. (2020) conducted expert interviews to identify and prioritise energy-saving strategies in Iranian extant and historic structures. However, none of these studies examines reliable retrofit strategies for residential buildings considering the Tabriz climate. Each city has different climate conditions, so each of them should be considered carefully to find the best appropriate sustainable retrofit solution(s) to improve the energy performance of existing buildings in that location. Hence, this study aims to retrofit a residential building in Tabriz, Iran to show the importance of sustainable retrofits for decreasing building energy consumption. For this purpose, a case study building (i.e., reference building) was modelled using Design Builder and PVSOL®, and the annual energy usage of this building was calculated. Four scenarios were applied to decrease the energy consumption of this residential building.

Methods

This study conducts a case study to fulfil the research objective. The steps of the research methodology are provided below:

Step 1: Determine the case study building referred to as the reference building (RB) and specify RB characteristics and climate conditions.

Step 2: Calculate the energy performance of the RBs.

Step 3: Determine and describe the single and combined scenarios for retrofit measures that apply to this case study based on climate. And the definition of energy efficiency strategies.

Step 4: Analyse building energy retrofitting scenarios.
Step 5: Perform assessment analyses of the result of single and combined scenarios for achieving the best retrofit option.

Determining the characteristics and climatic conditions of Reference Building

The analysis has been performed for a case study building in Tabriz, Iran. Tabriz is a town in north-western Iran. Tabriz's climate is cold and arid, and the winter season is freezing, wintry, snowy, and partly overcast. Throughout the year, temperatures typically vary from -5°C to 33°C, with temperatures seldom dropping below -11°C or going over 37°C (Table 1 and 3). The case study has 4 floors; on each floor, there is 1 unit with a 3.10 m height and 3 bedrooms. The orientation of the building is north-south Figure 2. Also, the RBs energy consumption in 1 year is shown in Table 2. The total energy consumption for this building is equal to 235.22 kWh/m^2.

Table 1: Climate Characteristics

Latitude	38.07° N
Longitude	46.23° E
AVG daily temperature in summer	27 °C
AVG daily temperature in winter	8°C
Climate zone	Cold and dry area
Elevation above sea level	1351m

Table 2: Primary energy consumption of RB

Parameter	Value	kWh/m^2
Total Energy	235.22	**kWh/m^2**
Lighting	9.66	**kWh/m^2**
Electricity	12.71	**kWh/m^2**
Natural gas	222.50	**kWh/m^2**

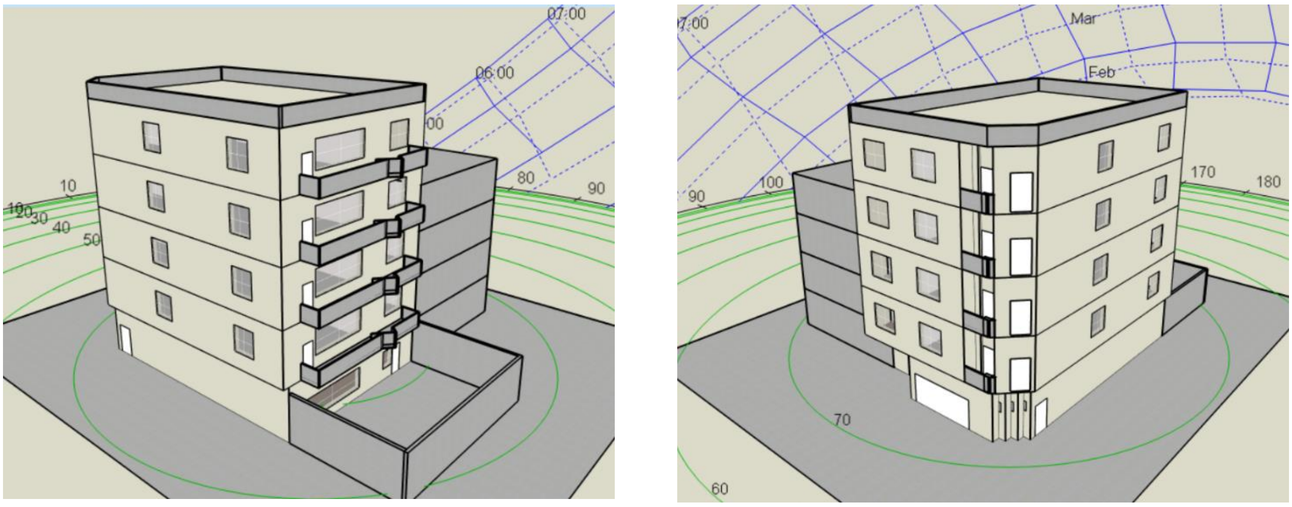

Figure 2: (Left) South view of RB, (Right) North view of RB

Table 3: Geometrical data for RB

Parameter	Unit	Value
Total building area	m^2	843
Net conditioned area	m^2	651
Story	-	4
Each floor area	m^2	183
Total building volume	m^3	2819
Roof area	m^2	183
Windows glass area	m^2	88
Gross wall area	m^2	806
Floor height	m	3.2

Performing single and combined scenarios for the Reference Buildings

Single and combined building scenarios were applied in the simulation software on RB to simulate the retrofitted building and compare it with the reference building. The energy performance of RBs is deficient because there are no shading elements above the windows to keep direct sunlight out, the windows are single-pane glass, and the lighting fixtures are incandescent lamp, which increases heat and energy consumption. Moreover, the lack of proper wall insulation led to increased heat escaping in winter and reduced the amount of heat entering in summer. As a result, the annual end uses energy is very high. To improve RB's building energy performance, windows are replaced with double-glazed argon gas, photo voltaic panels are applied, lighting fixtures are replaced with LED, and the external insulating layer is used on the building's exterior wall.

Also, shading elements are considered on the windows as retrofit measures. DesignBuilder uses Energy Plus to simulate energy consumption, environmental lighting, comfort, and CO_2 emissions. The next step is to apply scenarios to the case study after designing the building with the DesignBuilder program. The following scenarios have been simulated for the case of a home renovation using the DesignBuilder. To increase energy productivity, four scenarios were simulated:

Scenario 1: Replace single windows with double-glazed windows, adding shading elements in the south and west façades (Table 4 and Figure 10).

Scenario 2: Apply external wall insulation and replace lighting fixtures with LED (Table 4 and Figure 10).

Scenario 3: Considering photovoltaic panels on the rooftop and external wall insulation (Table 4 and Figure 10).

Scenario 4: Combined Sc1, Sc2, and Sc3 scenarios to earn the best result (Table 4 and Figure 10).

Results and discussion

Sustainable retrofitting solutions applied within the scope of the case study are using shading elements, replacing single-glazed windows with double-glazed ones, implementing external insulation for walls, replacing LED and installing photovoltaic panels. All the outputs of the scenario analyses are shown in Table 4.

The carbon dioxide generation for the RBs and scenarios is shown in Figure 3. This figure shows that the amount of CO2 in sc3 and the combined scenario is negative from May to October. Given that it is impossible to emit a negative amount of carbon, carbon negative represents the building's net emissions. Hence, the exterior insulation and combination scenarios have the lowest carbon emissions, which helps to lower CO_2 levels. By lowering heat loss from the building, insulation reduces the demand for gas or central electric heating. Thus, in any country, a good government policy strategy may dramatically reduce carbon emissions at the building and urban scale.

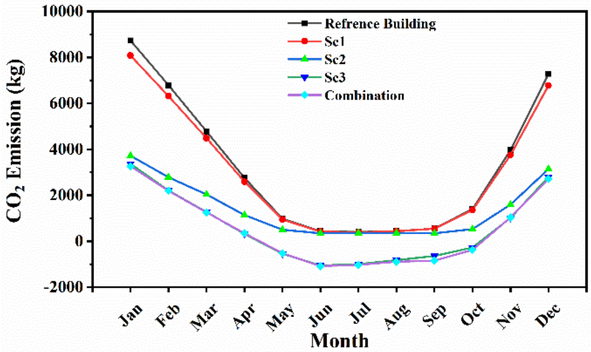

Figure 3: CO2 emission in RB and scenarios

Table 4: Summary of the result for total energy consumption before and after applying scenarios

	RB's	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total Energy [MWh]	153.131	142.236	60.432	61.025	63.484
Normalised Total Energy [kWh/m²]	235.22	218.48	92.82	93.74	97.51
Interior lighting [kWh/m²]	9.66	9.55	5.87	9.26	5.87
Natural gas [kWh/m²]	222.50	205.89	84.04	81.56	88.72
Photovoltaic power [kWh/m²]	0	0	0	24.97	24.97
Net Electricity from Utility [kWh/m²]	12.71	12.59	8.78	-11.55	-14.93
Total electricity end uses [kWh/m²]	12.71	12.59	8.78	12.17	8.79

Shading elements

One of the most important and basic measures is to place shading elements under sunlight at the right angle and direction to achieve the best and highest efficiency. Since Iran is located in the northern hemisphere, to receive the lightest from the sun, shading elements should be placed in a southerly direction with an angle of 30 to 35 degrees to the earth's surface so they can receive the best sunlight throughout the day. Considering that the first, second, third, and fourth floors have balconies on their southern sides and those balconies have a shading effect, the considered shading elements are only applied to the southern facade of the fifth floor. In addition, in order to achieve the best results, a specific schedule has been considered for the shading elements. In this schedule, the shading elements work only in the summer period (May 1st to September 30th) from 9:00 AM to 5:00 PM.

Replacing single-glazed windows with double glazed

The usage of double-glazed windows decreases energy consumption and increases insulation by up to 40%. Moreover, double-glazed windows in the building are a suitable low-cost strategy to control energy consumption. Thus, standard single-glazed windows are replaced with double-pane windows with low E glass with high solar gain and 13mm argon gas filling.

Additionally, these windows are designed to reduce heat loss but accept solar gain. Moreover, the double-glazed retrofit option decreases annual energy from 153.131 MWh to 142.23 MWh in Sc1.

External insulation for wall

Another method for reducing energy usage is applying a layer of polystyrene to the outside of the building. And this feature saves a lot of energy annually by placing a small layer of this insulation. Therefore, compressed EPS expanded polystyrene (Heavyweight) thermal insulation boards with 0.0350 W/m-k thermal conductivity are applied to increase insulation levels and achieve thermal comfort inside the building. The thermal conductivity of polystyrene is relatively low, and this low thermal conductivity leads to the material conducting less heat energy. The simulation findings, as shown in Table.4, imply an annual energy savings of 18% in the overall heating load of the understudied building (Figures 4 and 5).

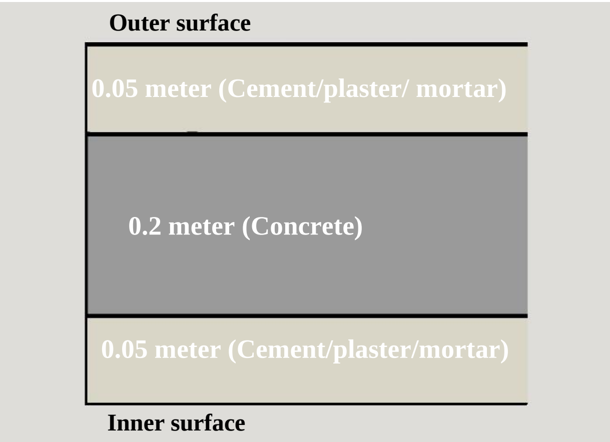

Figure 4: Exterior wall arrangement before applying insulation

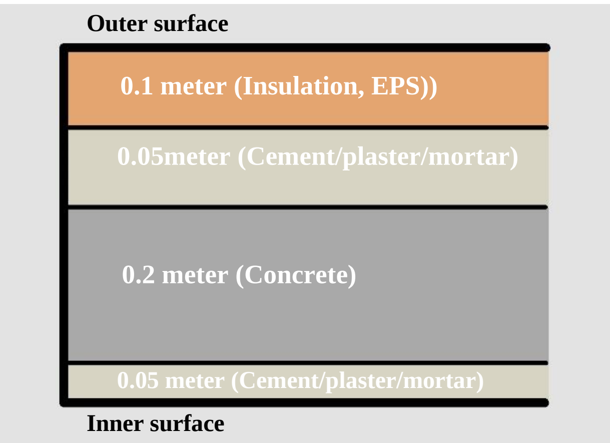

Figure 5: Exterior wall arrangement after applying insulation

Replacing LED

In this option for decreasing energy consumption, LED lighting fixtures have been applied with incandescent lamps. Also, LED lighting saves energy from 30% to 90%, and LED lighting is mercury free and generates less heat which helps sustainability. As shown in Table 4, results show a significant reduction in energy consumption in the end-use lighting energy consumption from 9.66 kWh/m^2 to 5.87 kWh/m^2 in Sc2, which is approximately 40%.

Photovoltaic panels

PV panels, i.e., renewable energy sources, can reduce buildings' dependence on electricity and carbon emissions. Figure 6 shows Iran's high potential for using photovoltaic electricity (Solargis Prospect 2022). Thus, the photovoltaic system design and simulation exercise was carried out using PVSOL® premium 2021 software on RB. The PVSOL® program allows users to work on 2D or 3D models. For this case study, the 2D option is selected. This program asks the user for array and inverter data, such as the number of modules, installation conditions, slope, and direction of elements. On the other hand, the 3D design option allows the creation of a 3D model of building geometry, including roof elements, and the production of PV modules.

Fifty-four panels with 1.001 m x 1.675 m module dimensions have been calculated for the south orientation of RB, and the inclination was studied at an ideal tilt angle of 30 degrees. Figure 7 and Table 5 give a complete overview of essential parameters relating to PV array size. The inter-row spacing (d1), which is the distance between the front edge of a module in one row and the front edge of a module in the next row, was optimised to be 0.922 m. The mount height (h) and row spacing (d) values were 0.50 m and 1.789 m, respectively. Figures 8 and 9 show the power conversion of sunlight into electrical energy in these panels, equal to -11.55 kWh/m^2. Also, net electricity from the utility is minus. Therefore, in this retrofit option, generated electricity is more than the building's demand, which helps to save a large amount of energy (Table 4 and Figure 10).

Table 5: PV panels characteristics

Required number of panels	54
Inclination	30°
Model	260 Wp - Si polycrystalline

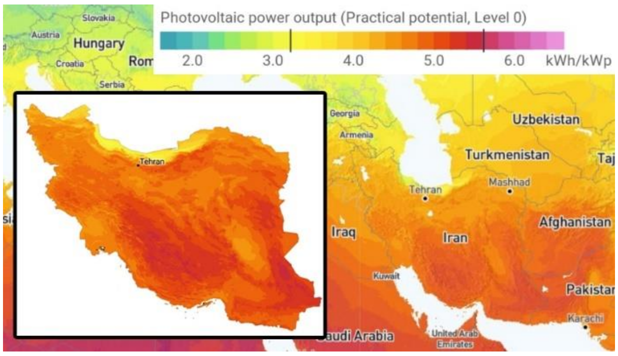

Figure 6: Potential of photovoltaic power in Iran (Solargis Prospect 2022)

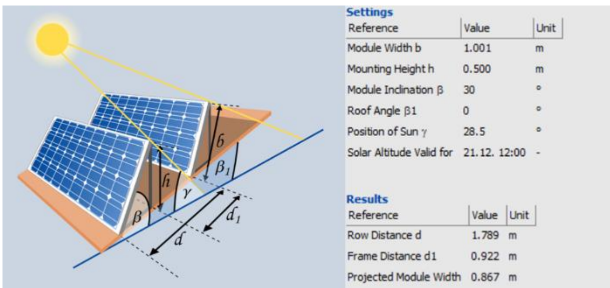

Figure 7: Photovoltaic panels parameters

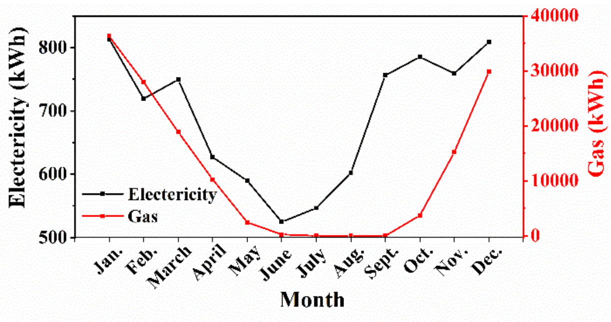

Figure 8: Fuel usage breakdown of RB; Electricity (black cure) and gas (red curve)

results. They reported the annual normalised energy consumption, 245.75 kWh/m^2 and the RB's annual normalised energy consumption, 235.22 kWh/m^2, which is in consistence with calculated results. Also, they calculated the heating load of residential building and RB 240.8 kWh/m^2 and is 222.5 kWh/m^2, respectively. Furthermore, they obtained cooling load 4.31 kWh/m^2, while that value of RB is 1.25 kWh/m^2. Therefore, the result of previous studies shows a good overlap with the outputs of the study. Furthermore, the outputs were calibrated using different heating, cooling and lighting schedules in the winter and summer to make the energy consumption close to the actual consumtion.

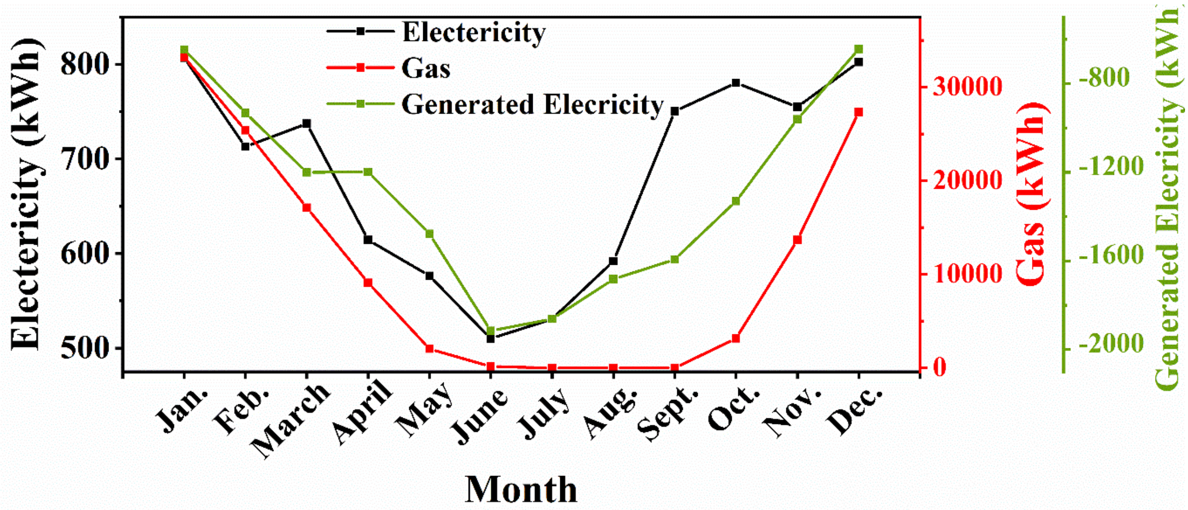

Figure 9: Fuel usage breakdown of retrofitted RB by PV panel; Electricity (black cure), gas (red curve), and generated power (green curve)

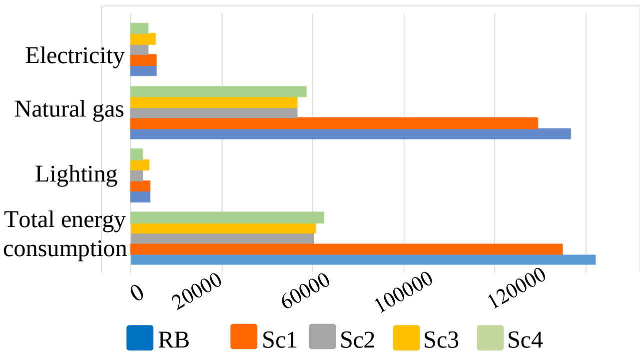

Figure 10: End-use energy consumption of RB and scenarios

Figure 10 and Table 4 show that the use of retrofit solutions to reduce building energy consumption and CO_2 has a positive impact. Considering that Tabriz is located in a cold climate and winter is freezing in Tabriz, scenario 2, 3, and 4, which includes external insulation, has the best energy consumption to reduce heat loss. Therefore, this research confirms that applying an external insulation layer can be helpful in the climate of Tabriz.

(Ebadati and Ehyaei 2020) conducted energy consumption analysis for residential building in Tabriz. The results of Ebadati et al. used to calibrate the RB's

Conclusion

This study presents the importance of sustainable retrofitting for decreasing building energy consumption and co2 emission by applying several sustainable retrofitting solutions to a residential building in Tabriz, Iran. In this study, a case study building (i.e., reference building) was modelled using DesignBuilder and PVSOL® software.

Four different scenarios were applied in the study to decrease the energy consumption in the existing building. These scenarios include replacing single-glazed windows with double-glazed windows with clear glass and high solar gain with 13mm argon gas filling. Also, putting two horizontal shading elements on the 4th-floor southern side windows with an angle of 30 to 35 degrees allows us to earn the best result. Therefore, the analysis of 1st scenario shows 142.23 MWh annual energy consumption. In the second scenario, the thermal insulating layer on the building's outer wall with 10cm thickness and compressed EPS expanded polystyrene material. In addition, LED lamps are replaced with incandescent lamps. RB's total annual energy consumption is 153.131 MWh, but after applying the 2nd scenario, it is reduced to 60.431 MWh.

This result implies more than 65% energy saving which is the best result among all four scenarios. The third scenario is combined with applying PV panels and replacing LED lamps. The analysis result of integrating the two highest effective measures is calculated as 61.025 MWh energy consumption in one year, which is a good achievement for the RB. And the last scenario, which is a combination of all three scenarios and applies all of them simultaneously to RB, the analysis result of this scenario is 63.483 MWh, which is almost 60% less energy consumption than the annual energy consumption of RB. Results show that each technique has different effects on reducing energy consumption and co_2 emission in the existing buildings. The result of this research proves that integrating several retrofit options has a significant impact in saving energy up to 65% in residential buildings in the Tabriz climate. In addition, the annual CO_2 emission in RB's is 38,503.42 kg, which is reduced to 6,068.35 kg in the combined scenario and 6,632.24 kg in Sc3. It represents an 84% reduction in CO_2 emissions in the combined scenario and 82% in Sc3. Therefore, the results show that the external insulation of residential buildings in Tabriz can play an essential role in reducing CO2 emissions.

Accordingly, this study contributes to the architecture, engineering and construction (AEC) literature and industry by demonstrating the significance of sustainable retrofits to reduce building energy consumption and carbon emissions. Industry and academic professionals can benefit from the results of this study. However, the limitation of this study is the lack of specifications for the materials implemented in the reference building, as there are no specifications available for the local material producers in Iran. In addition, one of the future research directions of this study could be using cost analysis for each scenario. Another future research could be considering solar collectors for reducing hot water consumption in residential buildings.

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