IOP Conference Series: Materials Science and Engineering

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To cite this article: Kawar Salih *et al* 2021 *IOP Conf. Ser.: Mater. Sci. Eng.* **1090** 012018

Simulation of Energy Efficiency Measures for the Residential Building Stock: A Case Study in the Semi-Arid Region

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Abstract. Global energy use has risen due to increased demands and inefficient grids in developing countries. Energy saving is detrimental in countries in which their energy supply capacity is lower than their demand. Energy Efficiency Measures (EEMs) can easily be incorporated in new buildings; however, existing buildings have limitations in geometry, orientation, and materiality which restrict their applicability. This research analyses the efficiency of applying several EEMs in the residential stock in hot semi-arid regions to reduce their energy demand. A typical residential house in Duhok, Iraq was selected as a case study. The EMMs efficiency was analysed using building energy simulation. As heating and cooling loads have similar contributions to the house thermal demand -with 56% and 44% respectively, the potential energy reduction considered both loads simultaneously. The optimal combination of EEMs can reduce the thermal load by 48.7%, while individual passive measures can only reduce the thermal load up to 16%. In urban scale, the energy reduction potential presented in this paper would represent a shift from a heating-dominated scenario to a cooling-dominated one. This in turn would aid in decreasing the energy demand during winter months in which the largest energy shortages in the city are registered.

1. Introduction

The rapid increase in energy demand and the limited supply is still a significant challenge worldwide, particularly in the middle-east [1]. In 2018, the global energy demand increased twice its average growth rate since 2010, mainly due to an increment in thermal conditioning loads in developing countries [2]. The existing building stock is responsible for one-third of the total energy use worldwide [3], of which, a considerable amount is destined for the conditioning of indoor spaces. For energy reduction, new buildings offer the best deployment opportunities as energy efficiency measures (EEMs) are incorporated from the design stage. On this note, most developed countries –and some developing- have mandated energy efficiency compliance codes for all new construction projects.

On the other hand, existing buildings have limitations on geometry, orientation, materiality, and design, which restrict the applicability of passive strategies. Considering that around 75 to 90% of the building stock worldwide is already built [4], deep energy retrofits are needed to reduce their energy use intensity. However, only seldom countries have implemented mandatory energy codes for building retrofits. Though various EEMs are feasible for both newly built and refurbished buildings; most strategies are overlooked in retrofitting projects due to lack of awareness and cost-effectiveness.

Several studies have aimed at providing a roadmap for energy retrofitting strategies. However, few studies deal with the energy refurbishment of the residential stock in the semi-arid regions. A theoretical approach was used in [5] for comparing the energy efficiency of different residential units in a developing country suffering from severe electricity shortages. That study suggested some EEMs for reducing the energy demand in semi-arid climates –mainly insulating the building envelope, solar shading, and modified microclimates- but failed to provide quantifiable data. A study on improving thermal comfort in reinforced concrete frame houses using passive and active EEMs in Quetta, Pakistan suggested that passive solar heating, shading, high thermal mass, natural ventilation, and humidification are the best-suited strategies [6]. The same authors went on to conduct a sensitivity analysis on the effect of 21 EEMs on indoor thermal comfort [7]. Only 13 of the 21 strategies increased the hours in the thermal comfort range, showing that the selection of EEMs needs careful consideration. However, the previous researches did not quantify the energy expenditure of the house nor the potential energy saving. A study in Phoenix, USA evaluated the performance of several standard energy-saving options for two-single family dwellings. A maximum energy reduction of 6.1% from the baseline was achieved by combining daylight control, SIP insulation panels, efficient windows, internal blinds, and high window-to-wall ratios [8]. That study also suggested that pre-construction energy-saving strategies are four times more efficient than post-construction techniques. Another study tested six configurations for thermal insulation of the building envelope on a semi-detached house in Morocco [9]. Insulating the roof has the most significant energy savings -26 and 40% in heating and cooling respectively. However, insulating the external walls is more efficient in reducing the heating load.

This research aims at analysing the energy efficiency of retrofitting the residential stock in the hot semi-arid region of Duhok, Iraq. In contrast to available studies dealing with cooling-dominated climates, the geographical context studied here is heating dominated, and only seldom studies have been found in these conditions [10,11]. Additionally, the objective functions used throughout this study are the thermal load and final energy demand as thermal comfort metrics in free-running mode did not seem adequate in the referred climatic conditions. Previous studies in semi-arid regions have shown that the percentage of hours in thermal comfort could not be improved beyond 58% in free-running operation [6]. Despite the resemblance in building materials with some of the studies in the Gulf regions, the specific configuration for the typical residential unit in Duhok (row houses) has not been previously studied. Duhok suffers from severe electricity shortages and has on average 18 hours a day of electricity [12]. Hence, the importance of applying passive conditioning techniques aimed at reducing the final energy demand of the residential sector.

The objectives of this study are first to analyse the actual energy demand in full-conditioning mode for a typical residential unit, and then to assess the energy savings achieved by several passive techniques. For fulfilling these objectives, energy dynamic simulation models were created for the base case and the proposed retrofit scenarios. The following sections refer to the characterization of the study context, the methodology used, the description of the retrofit scenarios tested and their effect on energy reduction, and concludes with recommendations and suggestions for the efficient retrofit of the built park.

2. Study Context

The city of Duhok is located in the Kurdistan region of Iraq (north-west of Iraq). Its coordinates are 36.52°N and 42.94°E. Its altitude is 565 m above sea level. The climate is semi-arid (BSh) according to a recent study [13]. It has semi-desert conditions during the summer months (May to September) with peak day temperatures of 45°C and minimum night temperatures of 26°C. In winter months (December to February), the average temperature ranges from 3 to 13°C and can drop below zero during the nights. The heating degree-day method was used to determine the required heating and cooling based on actual comfort temperatures for the city (see table 1). Both heating and cooling loads are significant in the city; however, heating is required on average 12% more than cooling. The base temperatures reflect the high thermal transmittance values for the building components in the city –uninsulated buildings with high air leakage.

Table 1. Heating and cooling degree days for Duhok, Iraq

Base temperature	HDD	CDD
*18 °C	1250	2140
19 °C	1424	-
24 °C	-	1107
Heating degree days (HDD) = sum (baseline temp- average daily temp.) Cooling degree days (CDD) = sum (average daily temp. - baseline temp.)		
*18°C is used in ASHRAE standards		

2.1. Energy demand and supply

The Kurdistan region of Iraq suffers from energy shortage as many other cities in the middle-east. Studies have reported that the imbalance between energy demand and supply in the region is due to problems in the energy transformation and high losses in the distribution system [6]. The energy supply capacity is always below the required energy demand of the city (see Figure 1) [12]. Therefore, the continuous supply of electricity is not guaranteed. This situation is especially relevant during winter and summer months as the high conditioning loads can double the city energy suply. On average, the number of hours with supplied electricity to the residential sector varies from 22 hours-a-day in spring and fall, to 18 hours in summer, and 12 hours in winter. The residential sector is the primary electricity consumer with a share of 79% of the total energy demand. This value is one of the highest reported in the region, where the residential sector accounts for an average of 50% of the demand [7,14,15].

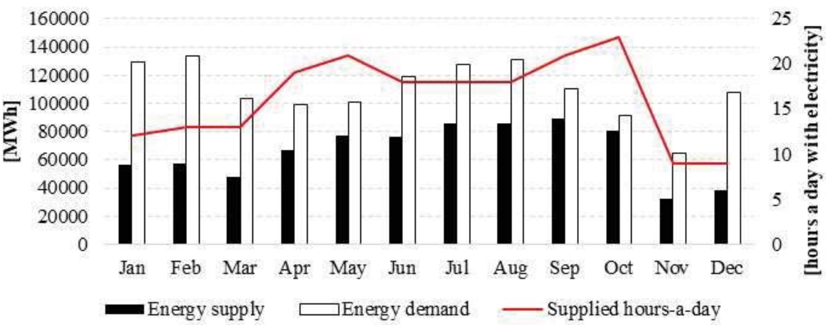


Figure 1. Electricity supply and demand for Duhok city in 2016 based on the data from [12]

2.2. Residential building stock

Duhok has experienced an exponential growth in the last decades. The urban expansion of the city has been in controlled phases attributed to the political and socio-economic conditions of the region [16]. The largest growth was during the last two decades of the 20th century; situating the average age of the building park between 30 and 40 years old. Most of these buildings have reached their lifespan and require refurbishment. According to [17], the residential building park is comprised of 92.6% single-family dwellings and 1.1% apartment buildings. The remaining stock corresponds to illegal constructions and occupations. A study on urban plots of the city defined the typical residential unit to be a 2-storey row house in 200 m^2 urban plots (10m width x 20m depth) [18]. The typical urban plot and residential unit are shown in Figure 2. Official statistics of the city mention this residential unit as a representative of 80% of the residential stock. The front facades have natural stone coverings while the remaining facades have only cement/sand renderings. The construction system is a concrete frame with dense masonry and unfinished concrete slabs as roofs [19]. There are not any energy efficiency standards nor legislations in the region [5,18]. These characteristics make the existent residential park to have high energy consumption when compared to international energy use intensity standards [18].

Figure 2. Standard models for a) urban plots of 200m^2, and b) 2-storey row house

3. Methodology

As stated previously, the objective of this paper was to investigate the effect of several Energy Efficiency Measures (EEMs) on the heating and cooling loads for a typical single-family house and then to up-scale these results to the city level. The thermal conditioning loads were selected as objective functions due to their high contribution to the final energy demand for the residential sector -from 49 to 71% in arid and semi-arid regions [14]. The EEMs considered include the enhancement of the building's envelope to reduce the thermal exchange between indoor and outdoor environments, and two passive heating and cooling strategies based on their feasibility for implementation in existing buildings. The impact of each EEM on the reduction of thermal loads was analysed systematically, along with two strategies considering the combination of various EEMs.

The sequential framework used in this research is presented in Figure 3, it includes the identification of the typical housing unit, the creation and validation of a dynamic energy simulation model, and the identification of the best-fit retrofit strategies. The method is based on an inductive approach, starting from the observation of the problem, the detailed analysis of its causes, and finally, the identification of solutions. In this paper, the validity of each EEM for the case study is cross-checked with available literature and local construction practices. Then, the impact of each EEM in the thermal loads is compared between all tested EEMs, and only the most influential are incorporated into the combined strategies. These strategies provided clear guidelines for the energy retrofit of the residential stock in Duhok.

3.1. Characterization of the typical housing unit

The first step was the selection of a typical housing unit that accurately represents the majority of the residential stock in the city. As stated in section 2.2, single-family houses account for 92.6% of the residential stock, and 80% of these correspond to urban plots of 200 m^2. Additionally, the highest building growth in Duhok was produced between the years 1984 and 2000. A random sample of 80 houses -corresponding to that construction period and urban plot- was selected for surveying the building layout, the number of floors, gross-floor area, setbacks, open areas (courtyards, gardens, light-wells), and floor-area ratio. A stratified sampling technique was used for minimizing the alignment risks and permitting the abstraction of a typical model [20]. Moreover, 15 houses were further examined to obtain the window-to-wall ratio, specifications of the shading devices (type and depth), and the envelope's materiality. The common characteristics of the sample were obtained, and the house that resembled more closely to the statistical typology was selected as the typical housing unit.

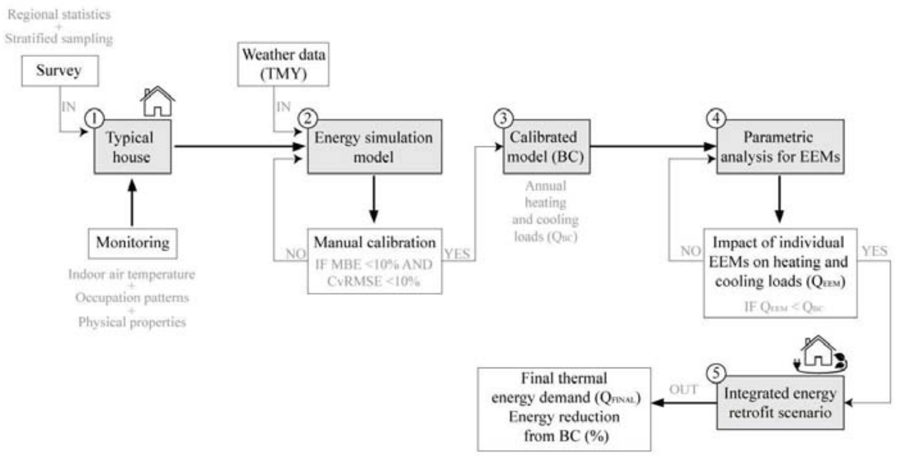


Figure 3. Framework for the calculation of potential energy savings in a typical house by using energy-efficiency measures

The typical unit is a 270 m^2 two-storey row house (adjacent to other housing units from three sides) built in 1998. The construction system is a load-bearing concrete block wall and reinforced concrete slabs. The house has not been refurbished. The distribution layouts and 3D model of the house are presented in Figure 4. The external walls are made of 200 mm high-density solid-concrete blocks with gypsum-plaster interior rendering. The front façade has a limestone covering –as per common use in the city- while the other exposed facades are rendered with cement-plaster resulting in conductivities of 2.45 and 2.65 W/m^{2}K, respectively. The roof is an unfinished 200 mm RC solid slab with an exposed area of 110 m^2 and a thermal conductivity of 2.33 W/m^{2}K. Granite tiles over a cement-sand mortar bedding and serve as ground floor, dry areas have carpet covering (1.97 W/m^{2}K) and wet areas have ceramic tiles (2.1 W/m^{2}K). The window-to-wall ratio is 0.24 and 0.31 for the front façade and light-well, respectively, representing a total of 26 m^2 of translucent façade. The windows are 3 mm clear single-glazing with cast iron frames and no thermal sealing with an overall U-value of 5.87 W/m^{2}K. Deep overhangs protect the windows from direct solar radiation. The thermal transmittance of the building components was calculated according to ISO 6946 and ISO 13370 [21,22]. Due to the lack of local data, a constant value of 0.7 ACH was assumed for air leakage [15]. This value is adequate for poorly insulated buildings without a thermal break in the fenestration. The thermal conditioning system includes individual local electric air heaters, air coolers, and single-zone split units located throughout the house but not in the wet and storage areas (see Table 2). The heating and cooling systems are operated manually considering the climatic conditions and occupational patterns of the house.

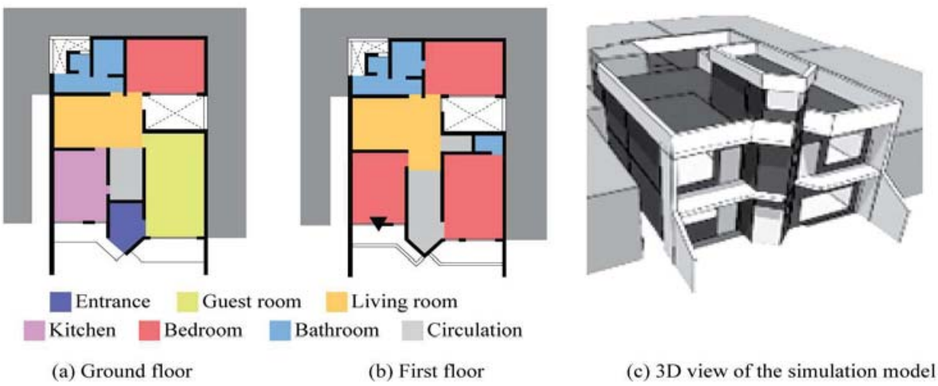


Figure 4. The layout of the residential unit in a) ground floor, b) the first floor, and c) 3D model

The house is currently occupied by five people -which corresponds to the average family size in the city. The house was monitored for ten days in March 2020. The monitoring included the collection of indoor environmental data using an Elitech GSP-6 datalogger with an accuracy of 0.5 °C for temperature and 5% for relative humidity; and the collection of behavioural patterns employing interviews and questionnaires to the household members. The questionnaires included aspects related to the occupancy of the spaces, operation of windows, setpoints and schedules for the conditioning systems, level of activity, and clothing. The data was later used for the creation of occupation profiles for the dynamic simulation model.

Table 2. Types of active systems, coefficient of performance, and setpoints

System	Type	Function	Service zone	Specifications	Setpoint
Thermal conditioning	Single-zone split	Main	All dry zones	COP 2.2	19-24
Heating (additional)	Electric air heaters	Complement	All dry zones	Nominal power	500-1500 W
Cooling (additional)	Air coolers	Complement	All dry zones	Nominal power	500 W
DHW	Electric heater	Main		COP 0.8	
Lighting	LED			Nominal power	15-25 W

3.2. Dynamic Building Model

The typical house was modelled in IESve 2019 software based on field measurements, schedules, and as-built specifications. This dynamic simulation engine is a reliable tool for energy and thermal simulation [23].

The model for the typical house includes 13 single thermal zones (see figure 5). Adjacent building blocks were included and the boundaries were set to adiabatic conditions. The construction profiles correspond to those detailed in section 3.1. Occupancy, lighting, natural ventilation, and heating and cooling schedules were determined based on the interviews and questionnaires. For the natural ventilation, windows were set to open when the indoor air temperature exceeded 24°C and the external temperature was lower than this. The setpoints for thermal conditioning and the coefficients of the performance of the HVAC systems were set according to standard local practices (see Table 2). The weather file for a Test Meteorological Year (TMY) for the city of Duhok was retrieved from Meteonorm.

3.3. Model Validation

The simulation model was validated to measured data using hourly indoor air temperatures in a controlled space. A data-logger was hanged at the centre of an unoccupied room at a height of 1.5 m. The air temperature was recorded at 15-minute intervals from March 11 to March 19. The temperature was free-floating during this period (no conditioning systems were on) as to eliminate the level of uncertainty during the validation. The free-running temperature was used as a control variable in the validation due to the impracticality of measuring energy consumption when electricity power-offs are common, and electricity is provided exclusively for an average of 18-hours a day in the city.

For validation purposes, the external weather conditions were retrieved from the nearest city's monitoring weather station. These data were taken for 20 days including the 10-days monitoring and the prior 10-days. A new weather file was then created based on this data, and the simulation was run. Specific profiles were included in the simulation to better reflect the as-is operation of the house during the validation period. These include a heating setpoint of 22°C for the four heated thermal zones in the houses (heating was ON only in 4 of the 13 thermal zones) and the exclusion of natural ventilation as windows remained closed. The Mean Bias Error (MBE) and the Coefficient of Variance of the Root Mean Square Error (CvRMSE) as described in ASHRAE 14 [24] were used for accounting for the variability between the measured and simulated data. Many authors have used a threshold of +-5% for the MBE and 10% for the CvRMSE for calibration against air temperature [25,26]. A total of 15 iterations were performed until calibration. The model is capable of predicting the indoor air temperature with an error of 1.19°C. The calibration indexes for the model are in Table 3.

Table 3. Calibration indexes for the validation of the simulation model

Index	Threshold ASHRAE 14	Validated model
Mean Bias Error (MBE)	0-10%	5.69
Root Mean Square Error (RMSE)	0-30%	6.46
Coefficient of the variance of the RMSE	-	1.19

3.4. Energy Efficiency Measures

This study evaluated the individual and combined contributions of several energy efficiency measures on the reduction of the heating and cooling load for a typical house. Improving the building envelop can significantly reduce the energy demand of a building if correctly designed according to the climate conditions. Three strategies were tested for improving the thermal transmittance of the envelope, one specified to each major system: roof, external walls, and windows. The improvement of the ground floor was not considered due to technical feasibility.

Previous studies have shown that both heating and cooling loads are significant in the semi-arid regions [10], and have suggested that the use of passive conditioning techniques could reduce their demand. In hot and arid climates, the use of overhangs in windows is an effective cooling technique [27]. However, there is a disseminated use of balconies and deep overhangs in the city; and hence, the typical building already includes effective shading devices. Another possible passive cooling strategy that could be applied to the building is the shading of the roof to diminish the absorption of direct solar radiation [28]. For passive heating, solariums are one of the most effective methods to increase heat gains during winter months [23]. Solar energy is trapped inside the solarium contributing to a reduction in heating demand. Both the shading of the roof and a solarium were considered for simulation. The scenarios tested in this research are described below.

Scenario 1 - Energy efficient fenestration: external windows and doors were replaced with lower U-value units with thermal breaks. The new windows are PVC frames double glazing with argon filling in a configuration 4-8-4, with a thermal transmittance of 1.6 W/m^{2}K and SHGC of 0.39. The steel doors are replaced with PVC units with a U-value of 3.6 W/m^{2}K. The inclusion of thermal brake frames would result in a diminishing of the infiltration rate [29]. Hence, the air leakage was reduced from 0.7 to 0.25 ach.

Scenario 2 – Insulating external walls: 5cm XPS insulation was added to the inner side of all the walls exposed to outdoor environmental conditions. A previous study on hot semi-arid climates showed that the increment in energy savings is insignificant after the first 5cm of insulation [15]. The improved thermal transmittance of the walls is 0.6 W/m^{2}K. 5 cm XPS sheets were used considering the local availability of the insulation sheets.

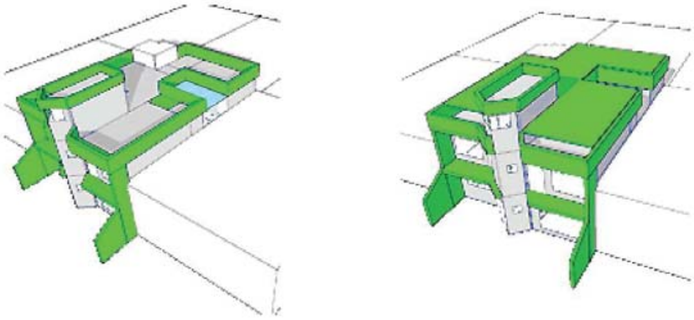
Scenario 3 – Insulating the roof: an inverted roof system with 5cm XPS insulation was considered to both decrease the U-value to 0.5 W/m^{2}K, and to provide protection and waterproofing to the unfinished slab.

Scenario 4 – Shading the roof: a lightweight steel structure covered with a high-reflective surface material (steel corrugated sheets) was included (see Figure 5). The use of reflective materials in roofs is commended in the literature to diminish the cooling loads [1].

Scenario 5 – Solarium: The existent light-well (10 m^2) was enclosed with double-glazing of thermal transmittance 2.3 W/m^2K and SHGC of 0.55 (see Figure 5). For avoiding overheating, an openable skylight of 50% of the area was set to operate when the temperature inside the courtyard exceeds 24°C, and the outside temperature is lower than that.

Scenario 6 – Combined strategy: includes the combination of all the effective individual EEMs described previously. This scenario renders a deep understanding of the behaviour of the house after an integral energy retrofit.

Scenario 7 – Combined +10 cm insulation: the insulation was doubled in thickness for both roof and walls (U-values of 0.3 W/m^2K). All other EEMs are the same as those in scenario 6. This scenario was included to test the effectiveness of increasing the insulation.



(a) Inclusion of glass skylight in lightwell (b) Inclusion of roof shading

Figure 5. Passive heating and cooling scenarios including a) the inclusion of a solarium in the existent light well and b) Shading of the roof

4. Results and discussion

The annual thermal conditioning loads were calculated for the as-is state for the typical housing building –named hereafter as Base Case scenario- and for the seven energy-efficient retrofit scenarios detailed in the previous section. For the sake of comparison, all scenarios were simulated under full-conditioning mode (heating and cooling on 24/7). A multi-zone split system was set to provide heating and cooling within setpoints of 19°C and 24°C respectively. These setpoints are within the acceptable comfort ranges provided in both European and American Standards.

The base case scenario is used as a benchmark for comparing the efficiency of the EEMs. However, it also provides valuable insights into the real final-energy demand for the residential sector in Duhok. Due to the electricity shortage in the region, energy is limited throughout the year; and hence, estimating the primary energy needs for the residential stock is not possible by relying exclusively on measured power data. The validated simulation shared light on the real thermal behaviour and expected conditioning loads for a typical housing unit in the city. The annual loads for the base case are 34.73 MWh and 26.8 MWh for heating and cooling respectively. Considering a usable area of 190 m^2, the house has a thermal demand of 323 $kWh/m^2/year$. Concerning international standards, this demand is 2 times the average demand for the residential sector in Europe. A previous study had shown that heating loads are more significant than cooling for the semi-arid regions –heating and cooling represent 60 and 40% respectively of the total conditioning load [10]. However, that study disregarded the effect of internal loads on the final energy demand of the house. By incorporating into the dynamic simulation the heat gains and losses due to occupancy, lighting, equipment, and natural ventilation –considering the post-occupancy state of the building park- cooling accounts for 44% of the final thermal load. Similar percentages for cooling demand were reported in other semi-arid geographic contexts [11]. A clear distinction needs to be made between semi-arid regions, as the residential thermal demand varies considerably depending on the heating and cooling degree days. For example, a study on the energy performance of housing units in the USA concluded that heating loads are smaller than cooling loads for semi-arid climates [8]. Those results were case-specific as the research was conducted in a context with extreme hot summer and relatively mild winters.

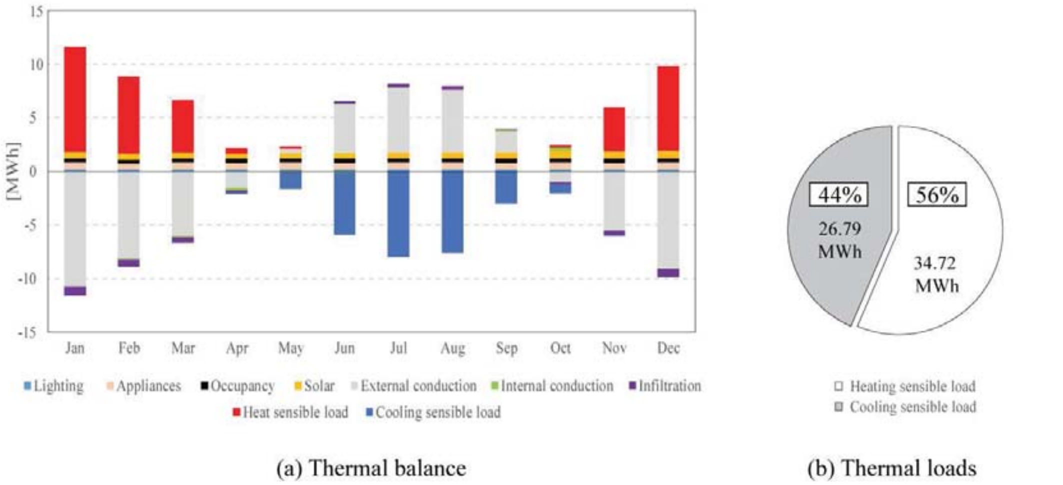


Figure 6. Annual simulation of the base-case scenario showing a) the heat gain and losses and b) the heating and cooling plant sensible loads.

As shown in the thermal balance in Figure 7, only in April and October, the house thermal losses and gains compensate without the need for active equipment. The most influential heat exchange occurs through the building envelope and accounts for the majority of the total conditioning demand. Though infiltration is responsible for 13% of the energy losses in hot climates [30], only an average 5% heat exchange is due to air leakage in the typical housing. During winter the envelope heat loss is 41.8 MWh, while in summer it is responsible for 18.6 MWh of heat gains. This major heat flow occurring during winter is due to the large thermal amplitude of 14°C between indoor and outdoor environmental conditions; in contrast to the thermal amplitude in summer of 7°C. Hence, the importance of insulating the building envelope to prevent heat from escaping in winter; however, insulating the envelope is not expected to have a significant reduction for the cooling load as the heat exchange is much lower during summer months.

4.1. *Effect of single energy efficiency measures*

The annual thermal loads for the seven retrofit scenarios are shown in Table 4. The impacts of the single energy retrofit measures and combined scenarios are explained below. The percentages of reduction for heating and cooling loads for each of the scenarios are shown in Figure 8. It is worth noting that the simulation results are site-specific considering climate conditions and standard cultural behavioural patterns, and do not take into account the uncertainty due to occupant’s behaviour and subjective preferences. The total energy savings have been reported to vary from 14.4 to 47.6% due to operation conditions related to occupants’ preferences [1].

Concerning the single energy efficiency measures (S1 to S5), the most significant improvement is insulating the roof with a total energy saving of 15.74% from the baseline -9.7 MWh annual reduction.

Table 4. Annual total sensible, heating and cooling loads for each of the energy retrofit scenarios

Scenario	Description	Total sensible load [MWh]	Heating load [MWh]	Cooling load [MWh]
BC	Baseline	61.60	34.75	26.80
S1	Efficient fenestration	57.29	31.89	25.40
S2	Insulating the walls (5cm XPS)	55.00	30.15	24.90
S3	Insulating the roof (5cm XPS)	51.90	28.80	23.10
S4	Roof shading	60.20	35.30	24.90
S5	Solarium	57.80	31.50	26.30
S6	S1+S2+S3+S5	31.60	14.00	17.60
S7	S1+S5+(S2-10cm XPS)+(S3-10cmXPS)	28.00	11.70	16.30

A study in the cold semi-arid of Pakistan also found that the best energy efficient measure is roof insulation [7]. However, it did not provide the percentage of energy savings. A study in Oman established that insulating the external walls is more efficient than insulating the roof for energy savings [15]. However, Scenario 2 (insulating the wall) achieved lower energy savings than for insulating the roof. The heating and cooling loads were reduced by 13 and 7% respectively, and resulted in a total energy saving of 6.6 MWh annually (see Figure 8). Replacing the existing fenestration with energy-efficient units is the strategy that provides a better balance between heating and cooling savings; however, the annual saving with this strategy is less than half that of insulating the roof. The high cost associated with replacing the windows with double glazing argon filling units is not compensated by the electricity savings. Other low investment options could be considered for the fenestration including coating films to reduce the SHGC and sealing the frames with insulating barriers to reduce air leakage. Such low-cost strategies were adequate for increasing the energy efficiency of houses in the UAE arid climate [1]. However, the cost-efficiency of the selected strategies is not part of the scope of this study, but it is considered as part of future research works.

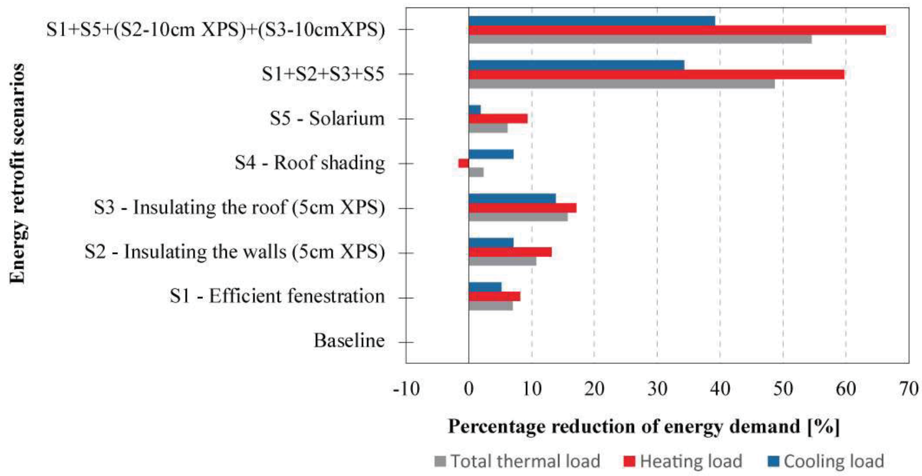


Figure 7. Energy savings for each of the retrofit scenarios

Both passive conditioning strategies (S4 and S5) have significant savings either in the heating or cooling loads. By shading the roof with a lightweight structure, the cooling demand reduces by 7% but increases the heating by 2%. This result contrasts with previous findings in the literature, where roof shading for residential buildings in Oman reach energy savings comparable to those of 15cm roof insulation [15]. This passive cooling strategy may prove more useful in climates with severe summers and where cooling loads are dominant. By enclosing the existent light-well with high-performance glazing, the energy saved is three times more than the savings obtained by shading the roof. The inclusion of openable skylights in the solarium permitted heat to be expelled from inside the house during the summer months. Hence, resulting in significant savings for both heating and cooling -9 and 2% respectively.

4.2. Effect of combined energy retrofit scenarios

The simulation of the integrated effect of various EEMs is commended in literature as their combined energy efficiency is not equal to the sum of the individual effects for each EEMs [31]. In a climatic context like the one used in this study – where both heating and cooling loads share similar importance- the passive retrofit techniques must be carefully selected as not to nullify their combined effect. Two scenarios were tested for understanding this energy behaviour. For scenario 6, all single EEMs were combined but excluding scenario 4 (shading the roof) as no significant savings were achieved (see section 4.1). Scenario 7 is a variation of Scenario 6 in which additional 5cm XPS insulation is added to both external walls and roof.

Both scenarios show significant reductions in the total and disaggregated thermal loads. The energy savings are 30 and 33.6 MWh for Scenario 6 and Scenario 7, respectively. By increasing the thickness of the insulation, the energy efficiency increase only slightly when compared to Scenario 6 -6% total load, 6% heating, and 5% cooling. This result is in line with previous findings stating that after the first 5cm insulation, the incremental energy savings are insignificant [15]. In terms of cost efficiency, the monetary expenditure of installing 10 cm XPS insulation is not compensated by the mere 6% additional energy savings. Hence, 5cm insulation provides a better compromise between energy efficiency and investment costs. It is also noteworthy that as the insulation must be installed in the inner side of walls, 10 cm XPS sheets would result in considerable reductions of the internal usable area.

The combined strategies are particularly effective in reducing heat loss during winter, achieving savings of over 60% in the heating loads. Though the cooling load is also reduced (average 37%); the final energy demand is higher for cooling than for heating. This indicates the need to include additional cooling techniques like cross-ventilation, night ventilation, and high thermal inertia. A study in Morocco showed that thermal inertia responds better than insulation in severe summer conditions [6]. The thermal improvement of the building envelope caused a shift in the conditioning pattern, from a heating dominant base case (56 heating - 44 cooling) to a dominant cooling scenario (44 heating - 56 cooling).

Similar final energy saving as those obtained in this study were reported for residential units in Saudi Arabia (50% energy saving) [14], UAE (25.1%) [1], Qatar (50%) [32], and Oman (37.6%) [15]. There is a high energy-saving potential for countries in the GCC region despite the climatic intra-variability. Though the energy-saving results obtained in this study are case-specific, the energy efficiency measures can be applied to any semi-arid region. However, their effect on the final energy demand will require recalculation. To the best of the authors' knowledge, this is one of the first studies on residential energy efficiency in Iraq. Based on the favourable results, further research is commended to both confirm their experimental validity, and to test additional energy passive measures. Replacing active systems for energy-efficient HVAC units can downsize the energy demand by 36% [14], future work will consider the stand-alone efficiency for active retrofit measures and the integration of passive and active techniques.

5. Conclusions and future work

This research aimed to examine the impact on energy savings for several passive retrofitting strategies for single-family houses in semi-arid climates. Thermal conditioning loads account on average for 55 to 65% of the final energy demand for the residential sector. Retrofitting the built park based exclusively on passive strategies –non-dependant on mechanical systems- provided a significant reduction in the thermal demand without compromising the indoor environmental quality. Using a calibrated dynamic simulation model, the annual thermal demand for a typical housing unit in Duhok, Iraq was calculated to be 61.6 MWh under full-conditioning mode (56% for heating and 44% for cooling). Seven energy-efficient scenarios were modelled and compared to the baseline to analyse the percentage of reduction in energy demand.

The most significant energy-saving measure is insulating the roof with 5cm XPS; this reduces the thermal load by 16%. Lower savings were achieved by insulating the walls (11%) and replacing the fenestration for energy-efficient units (7%). As residential units are mostly row houses, the major heat flux is produced through the roof. However, increasing the thickness of the envelope insulation over 5cm is not recommended as the energy savings do not compensate for the additional economic expenditure. The replacement of the windows for double-glazing argon filling PVC thermal break frames underperformed. Hence, low-cost strategies like sealing gaps and coating films could be more appropriate for the refurbishment of the residential stock. The use of passive heating conditioning systems showed significant savings in the heating loads but requires combination with natural and force ventilation techniques as not to overheat the house during summer months. The feasibility of turning the existent light-wells in the houses to solariums, paired with their estimated annual energy savings of 6%, makes them a viable option for retrofitting the residential sector. On the other hand, cooling passive techniques underperformed and revision of other more suited strategies are commended for future studies. The combined energy saving with passive measures reached a high value of 49%. By retrofitting the entire residential stock with the energy-efficient measures considered in this paper, the energy demand of the city could be shifted from heating to cooling dominated. This would aid in reducing the energy demand during the winter months -in which the higher electricity consumption of the city is registered.

The results and recommendations presented in this paper could aid in the creation of feasible guidelines for the energy retrofit for the residential stock of the city; and, could be extrapolated to an energy efficiency building code. Additional research is required concerning the energy performance of the remaining built park of the city, including multi-family housing, apartment blocks, commercial and industrial buildings. The assessment of the energy demand of the building stock would serve as a solid background for the generation of energy policies and renewable generation grids. Future works will also consider the applicability of active energy efficiency measures like the replacement of lighting fixtures, high-performance HVAC systems, evaporative cooling, floor heating, and cool ceilings.

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