Thermal Performance of Contemporary Residential Buildings in Hot-Arid Climates

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Keywords

Sustainability; Housing; Thermal performance; Hot weather.

Abstract

Due to increasing envoronmental awareness in the era of global warming, thermal performance and architectural sustainable design standards have become targets for many architects. The need for such standards is even more pronounced when designing for hot and harsh desert countries. This study explores the impacts of different design factors on the sustainability performance of housing units in arid climates and analyzes the thermal performance of five semi-attached housing units located on the campus of Umm Al-Qura University in Makkah, Saudi Arabia. To achieve the study objectives, 3-dimensional models of these five housing units were constructed to be used as simulations. Appropriate construction materials, mechanical and electrical systems were included. The orintations were unified for all the selected units. A simulation run to predict the thermal performance of each unit was conducted and results were analyzed. The impacts of different design factors on the environmental performance of these residentail units was tested. These factors include: outer shell area to volume ratio, percentage of windows to wall areas, window shading percentage, window orintations, presence of courtyards, wall thicknesses, materials and insulation types used, and mechanical and electric systems. The impact of each of these factors on the thermal performance of the housing units was tested separately. General guidelines to achieve sustainable architectural designs in terms of reduced energy consumption and better thermal performance in arid climates were formulated and introduced and modifications to improve the performances of existing buildings were mentioned.

1. Introduction:

This is why reducing energy consumption has become a focus of all global organizations and local geovenments in both developed and developing countries.(Kairamo, 2015) Increasing levels of energy consumption coupled with rapidly diminishing energy resources have negative impacts on the environment. For this reason, designing and building energy efficient buildings that mitigate strains on local environments has become a prime objective of both architects and urban planners. The environmental performance of a building is measured by its electrical and mechanical systems' thermal performance and energy consumption rates. In extreme climates, passive architectural techniques alone cannot faclilitate thermal comfort or create the optimum energy consumption conditions for a building. Studying different design factors and their impacts on the thermal performance of buildings is essential for creating optimum energy consumption structures. (Rubio 2015) Residential and commercial global energy consumption rates have increased to around 40% of total consumed energy with further increases anticipated. In the last three decades, HVAC systems have become widely used to control air temperature and humidity in hot and humid climates for occupant comfort, accounting for approximately 50% of climate-control systems (Luis 2008). Incorporating passive strategies can reduce the amount of electricity consumed by air conditioning in buildings. (Mohammad, 2017) This study investigates the impacts of various design parameters on the environmental performance and energy consumption levels of residential units and the possibile modifications of such builidngs to improve performance.

Hegger, (2008) argues that energy conservation efforts should focus on efficiency rather than effectiveness. Efficiency means achieving goals with minimum efforts and resources while effectivness means achieving results without regard for conservation. Ling examined the impact of shape geometrics on the environmental performance of high-rise buildings. He concluded that a square shape with a W/L ratio of 1:1 in a north-south orientation receives the lowest annual total solar heat insulation compared to other square shapes. (Ling 2007).

Although Saudi municipal construction regulations mention conditions related to building heights and setbacks, they do not contain guidelines or standards related to energy conservation or environmental preservation. Although energy has been subsidized by the geovernment for decades, sustainable development and an end to energy subsidies are intergral to Vision 2030 for the Kingdom of Saudi Arabia. The objective of this study is to explore the impact of passive design approaches on reducing energy consumption. This research is related to other studies that have successfully utilized simulation tools to ascertain the energy profiles of housing units (Al-Tamimi, 2011). Aldossary cited earlier studies focused on design factors such as building mass, function, spatial relationships, envelopes including construction materials for external shells, the presence of external windows, thermal insulation and shaded surfaces' areas (Aldossary 2014). The main outputs from the energy simulation of this study are estimates of annual energy consumption in kWh and in kWh/m2, CO2 emission rates as well as calculated energy consumption patterns throughout the year. Moreover, different energy uses like air conditioning, lighting and domestic hot water (DHW) were taken in to consideration during these studies. According to the Saudi Arabian Central Department of Statistics and Information, Saudi Arabian families have an average 6.2 individuals. The usage of each room was individually established according to the duration and conditions of use (e.g. lighting,air-conditioning, equipment, and DHW). (Aldossaryet, 2014)

2. Methodology and scope:

This study evaluates of the impacts of different architectural design parameters and elements and details of residential housing units related to passive design on their energy consumption profiles and thermal performances in arid climates. To achieve the research objectives, 3-dimensional models of five different types of residential dwellings were constructed. Their construction materials, thermal data, locations, size, design and orientations were taken in to consideration. The impact of each of these design parameters on energy consumption was investigated and analyzed by REVIT and ENERGY PLUS. These simulation tools have weather profiles of major cities, with the configuration of the most important climatic condition. The five housing structures investigated in this study have been simulated using climatic data configurations for the city of Makkah, Saudi Arabia, one of the hottest and most extreme arid climates in the world. A comparison was made between the results of design variations in the five case studies and the impacts of each design parameter variation were concluded. The simulation predicted the energy consumption patterns of each one of the case studies, in terms of their annual energy consumption, monthly energy consumption, energy profiling (i.e. consumption applications), and annual CO2 emissions rates. The results were then compared to each other.

3. Case study climatic context:

The city of Makkah has an arid climte. Its elevation ranges from 330 to 1100 meters above see level. Many of its urban and suburban areas have mountainous topography. Figur one shows that the wind direction is primarily southwest and northwest with a frequency rate of 120/220 day from the direction of north-west and with a speed of between 20 and 60 km/h. The temperature is above 30 degrees celsius for approximately 4000 hours per year. Figure 2 (a) shows the annual temperature in centigrade distributed per time extension. Humidity is very low most of the year as shown in figure 2 (b). It ranges from between 15% and 49%.

A

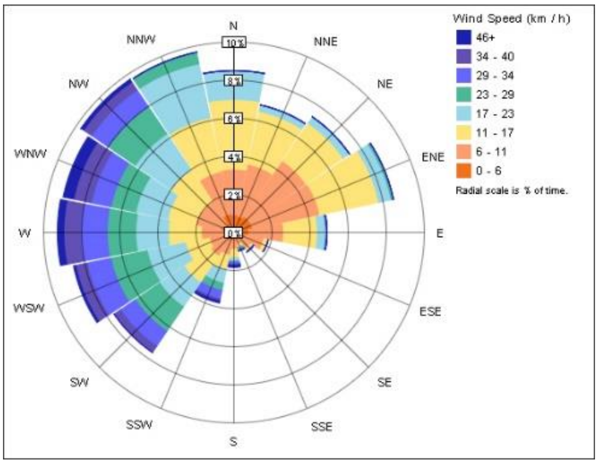


Figure 1 (a) Annual wind-speed in Makkah City.

B

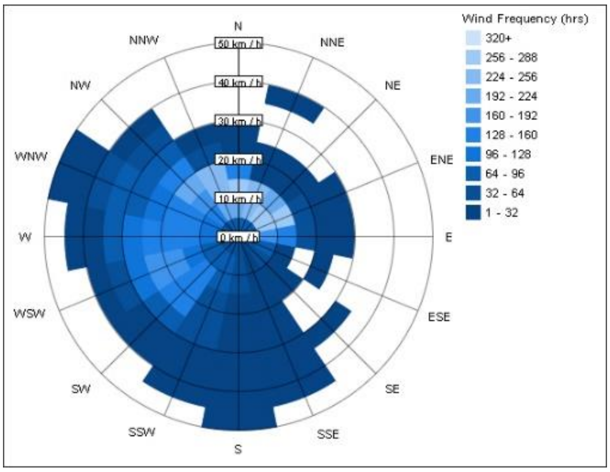
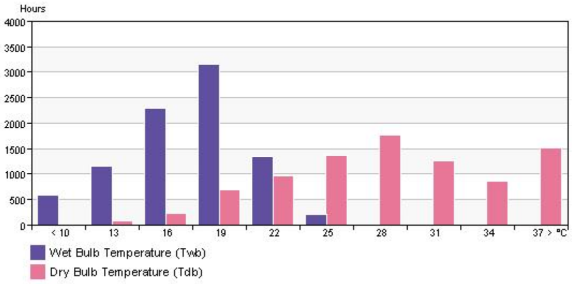


Figure 1 (b) Annual wind-rose frequency in Makkah City.



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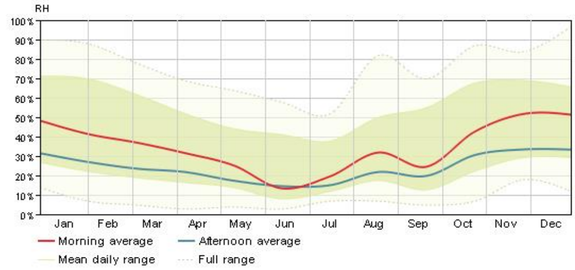
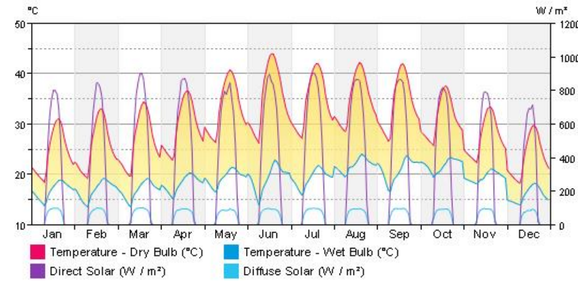


b

Figure 2 (a) Annual temperature for Makkah City.

Figure 2 (b) Humidity Percentage in Makkah City

Overall weather conditions in Makkah are illustrated in Figures 3 (a) and (b). At least six months of the year are characterized by very hot and sunny weather.



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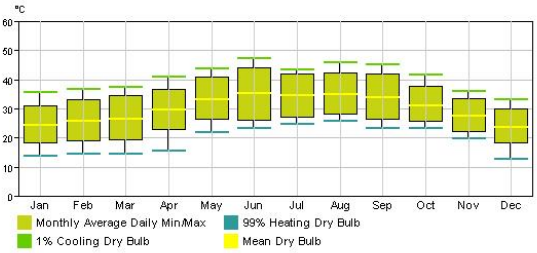

Figure 3 (a) Diurnal weather averages for Makkah City.

Figure 3 (b) Monthly design data for Makkah City.

4. Case study overview:

Staff and faculty housing at Umm Al-Qura university is comprised of five different types of residential units. They have different forms, compositions and sizes. Five of these units were selected for investigation. The criteria for the selected units was that they are all semi-attached dwellings and have the same orientations, spatial relationships and components. They all consists of two floors in addition to a partial service floor.

5. Architectural details:

The selected five types share the same orientation with entrances set south. Their windows are double glass with shading devices. They have 250cm-thick double-wall structures with 50mm polyethylene insulation and 210mm floor slabs with 70mm polyethylene insulation. After noting common data for the five housing types, thermal performance and energy consumption were calculated. The housing types vary in their areas but are all similar in their masses and covered openings. Unit type-A contains two bedrooms, a livingroom, diningroom and service areas (open garage, kitchen, maid's room, toilets and bathrooms). All unit componantes are distributed over two floors with a total area of 103 m^2. Figures 4a and 4b illustrate the ground and first-floor plans of this unit. This dwelling type (B) contains three bedrooms, a reception area, living area, dining area and service areas (open garage, kitchen, maid's room, and bathrooms) distributed over two floors with total area of 124 m^2. It should be noted that this unit-type has a courtyard and about 40% of the second floor area is comprised of open terraces. Figures 4c and d show the ground and first floor plans for this unit-type .

a b c d

Figures 4a and 4b: Ground and first floor plans for type-A housing units
Figures 4c and 4d: Ground and first floor plans for type-B housing units

Type-C housing units contain three bedrooms, a reception area, livingroom, diningroom and service areas (open garage, kitchen, maid’s room, and bathrooms) distributed over two floors. Figures 5a and 5b show the ground and first floor plans for this unit. This unit has total area of 136 m^2. It should be noted that 15% of this unit is comprised of a courtyard. There is a setback on the first floor as an open terrace comprising 35% of the floor area. Type-D housing units have three bedrooms, a reception area, living room, dining room and service areas (covered garage, kitchen, maid’s room, and bathrooms) distributed over two floors. Figures 5c and 5d show the ground and first floor plans of this unit. This unit has total area of 168 m^2. Type-D housing units also have a courtyard comprising 12% of its area and an open terrace comprising 45% of the first floor area.

a b c d

Figures 5a and 5b: Ground and first floor plans for type-C units.
Figures 5c and 5d: Ground and first floor plans for type-D units.

Building type-E is the largest type with an area of 329m^2. Each unit contains four bedrooms, an office, reception area, livingroom, diningroom and service areas (open garage, kitchen, maid's room, driver's room, toilets and bathrooms) distributed over three floors. Figures 6a, 6b and 6c show ground, first and second floor plans for this housing type. This unit has a service area on the second floor.

a b c

Figure 5: Ground, first and second floor plans for unit type-E

6. Modeling and simulation:

Three dimensional Revit models were built for each of the five housing units using their actual construction materials with their specified thicknesses as mentioned on their construction documents. The exact coordinates of each building were defined. Energy settings in terms of location, insulation, windows and shading devices etc. were defined and modeled. Energy models were built and analyses run. Ratios of outer shell areas to footprints were calculated. Total energy consumption data was analysed in terms of monthly and yearly consumption. Energy consumption per square meter was predicted. Monthly energy consumption loads for each of the five types of housing units were calculated for comparison. Detailed simulations were conducted for the building types with the highest and lowest energy consumption rates to investigate the impacts of different design aspects on efficiency and energy consumption. The efficiency of utilizing PV systems on the energy preservation and reduction of CO2 emissions for these buildings, based on the solar characteristics and the consumed fuel for domestic use was also considered.

7. Energy consumption patterns:

Figures 7 illustrates the total outer shell area for each housing type. It should be noted that the internal courtyard of building types B, C and D increased their outer shell areas. It should also be noted that building type-E has almost double the floor and outer shell areas of building type A. Despite the large floor and outer shell areas of building type-E, it has the least percentage ratio of outer shell to footprint. The ratios outer shell to footprint of building types B, C and D shown in chart 8 were increased by the presence of courtyards and recesses. The compact design of building type-E reduced The ratio of its outer shell to its foot print area. Figure 9 shows that building type-D, with its large outer shell and floor area, has the lowest rate of energy consumption. It can be concluded that building type-E has the greatest consumption rate, which is 14% greater than that of building type-D. Building types B, C and D are not considered to be efficient due to their large outer shell to footprint area ratios. In general, as the floor area of a building increases, energy consumption per-square meter decreases (figure 10). Thus, it can be concluded that large buildings with compacted designs are more efficient in arid climates. It can also be concluded that building type-A has the smallest outer shell area and the second largest outer shell to footprint ratio as well as the greatest energy consumption rate per square meter. Building type E has the largest area, the smallest outer shell to footprint ratio and the least energy consumption rate per square meter.

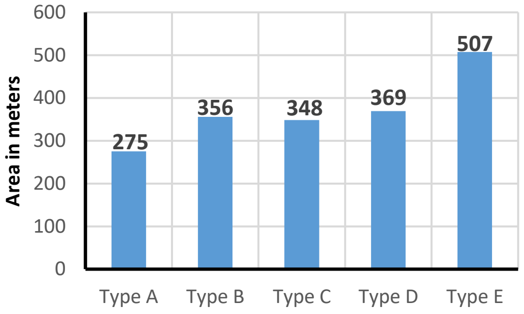

Figure 6: Outer shell area for each type

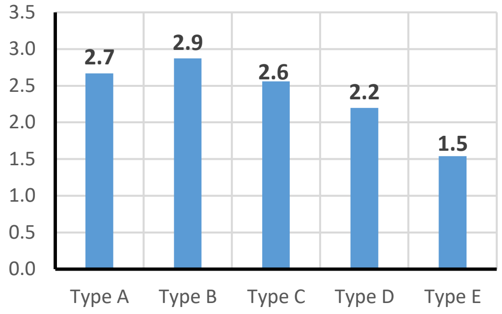

Figure 7: Ratio of outside shell area to foot print area

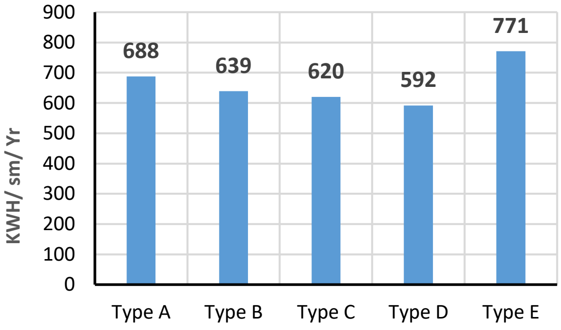

Figure 8: Annual energy consumption for each type

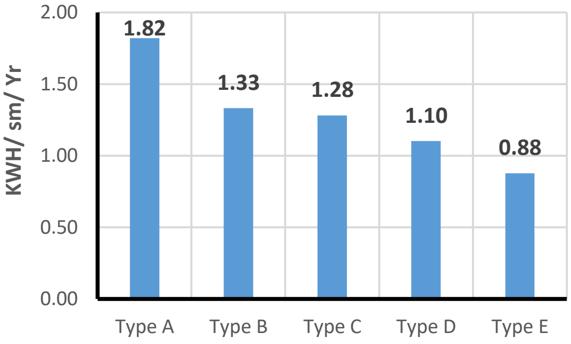

Figure 9: Energy consumption per square meter

8. Energy consumption of different usage profiles:

Figure 11 represents the monthly energy consumption usage profile and the distribution of total energy consumption for the different usages and systems for each of the five building types. From the charts, it can be noted that building type E has more than double the consumption rate of buildings types B, C and D despite that there is no significant difference between their footprint areas. HVAC Consumes more than 50% of the total energy consmption of all the investigated units.

Figure 12 illustrates the monthly cooling loads for each building type. It should be noted that the peaks and cooling loads for building types B, C, and D are identical. Simulated monthly electricity consumption rates are presented in figure 13. Building type-E has the greatest consumption rate. Figure 14 represents the annual energy cost per square meter, in dollars, for each building type. The total average for all types is 9 US$/ m^2.

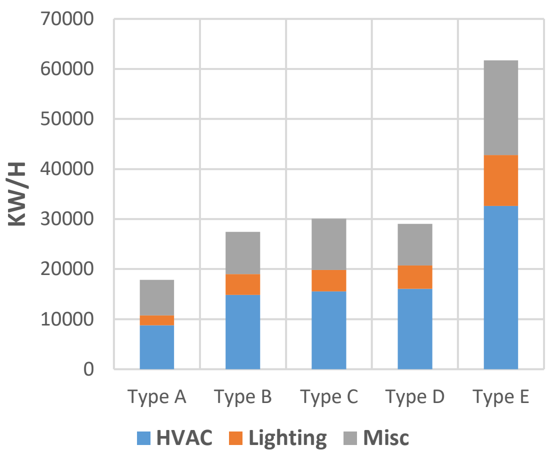

Figure 10: Monthly energy consumption use profile

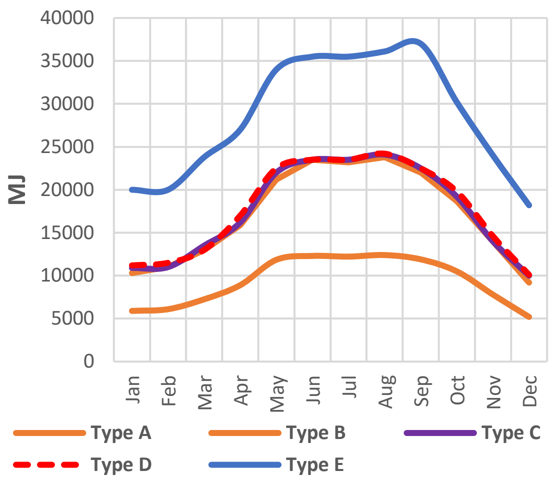

Figure 11: Monthly cooling loads

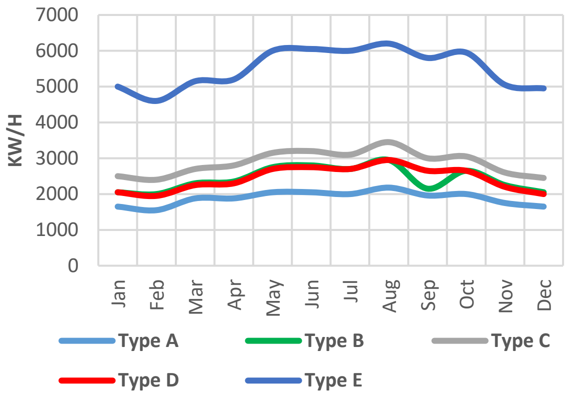

Figure 12: Simulated monthly electric consumption

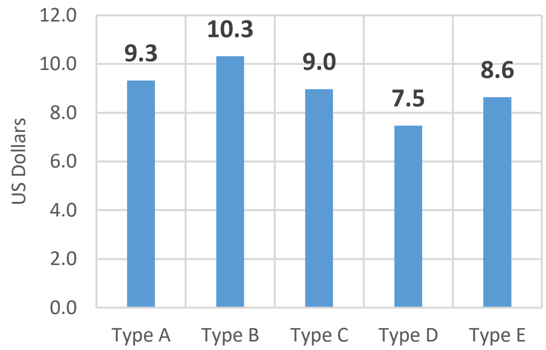

Figure 13: Annual energy cost per meter in dollars

9. Design parameters:

Daoud argued that significant improvements in thermal performance can be achieved by varying parameters such as volume, geometry and proportions of the building (Daoud, 2009). AlAnzi suggested that building shapes and aspect ratios, window-to-wall ratios, and glazing types have impacts on design performance and energy consumption. (AlAnzi, 2008). Hachem studied the effects of roof configuration, in terms of its layers and inclination angle, window size and location, and and façade specification on thermal performance. Results indicated that shading facades in-self-shading geometries and their relative dimensions are the major parameters affecting solar incidence and transmitted radiation. He concluded that manipulating building shapes and window locations can lead to the optimization of solar radiation and its utilization for electricity generation and passive solar gain. (Hachem 2011). Zerrin proved that changing the main material of the envelope does not significantly affect inside air and inner surface temperatures. He also concluded that changing the wall material and the inter-space distance does not significantly affect overall envlope system performance. (Zerrin, 2008) This study considered the effects of several design parameters, including orientation, window design, in terms of glass type, window area and shading, HVAC system alternatives, construction materials, thicknesses of walls and roofs, and the presence of PV solar systems on the rooftops, on thermal performance and energy consumption.

10. Design parameters impact on energy consumption:

The presence of courtyards has a negative impact on energy consumption rates due to the consideration of increased outer shell area. Insulating roofs and walls allow designers to easily orient their buildings in any direction with almost no effect on their energy consumption. Installing glass type “Trp LoE” reduces thermal loads by 80%, while increasing the shadows on windows by two thirds at the southern elevations reduces the thermal loads by 6.32 US dollars per square meter per year. Using the right HVAC system can improve electricity consumption rates dramatically for all five building types investigated. Using high-efficiency VAV air-cooling systems instead of split systems can reduce energy consumption rates by 4.76 US dollars per square meter per year. Increasing thermal insulation increases overall building thermal performance. It is worth metioning that investigations proved that installing wall insulation has a greater impact on the overall thermal performance of buildings than the roof insulation. In arid climates, having an angled (between 16 and 20%) solar panel system that covers between 60 and

90% of the roof area will reduce electricity consumption by approximately 2.96 US dollars per square meter per year. Figure 15 illustrates the total percentage of annual energy consumption reduction that can be achieved through the implementatoin of design factor mainapulation for the five building types. As shown in the figure, modifications have a lesser impact on compact buildings with smaller outer shell to footprint ratios. Consumption can be improved by 13% to 15% in buildings with courtyards

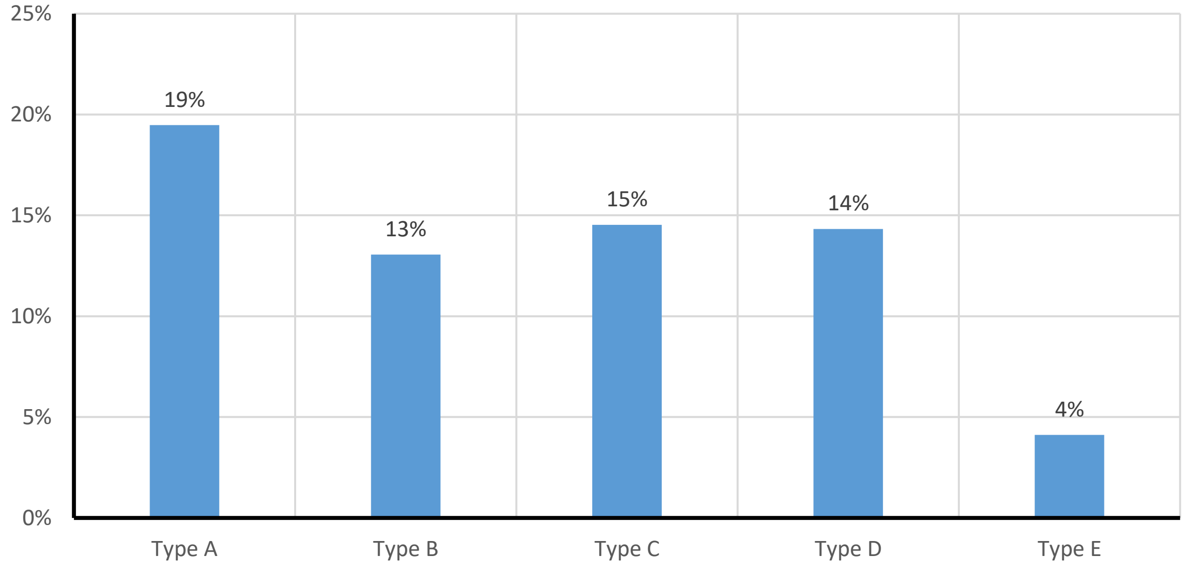

Figure 14: Percentage of achieved total reduction in annual energy consumption.

11. Conclusion:

Investigated building types have lower consumption rates than the average energy consumption rate for a typical house in SaudiArabia, which can be up to 60.000 kWh per year, depending on climatic conditions. (Aldossary, 2014) The results of this study prove that reducing energy consumption can be achieved with passive design solutions such as increasing shading, using the right HVAC systems and insulating external walls and roofs. These results are similar to the work of Hong in Taiwan (Radhi, 2010) and the results of Taleb in Dubai city. (Taleb, 2014). HVAC systems consume 50% of the overall energy consumption of housing units in arid climates. Insulation of external walls and roofs in residential buildings in the arid climate of Makkah can considerably improve energy consumption and reduce CO_2 emissions in these buildings. Moreover, lower annual energy consumption can be achieved by using compact buildings with smaller outer shell to footprint ratios. This study is limited in its investigations to improve energy efficiency in low-rise housing buildings. Further studies should be done on different building heights and types to explore other types of solutions such as sustainable urban strategies. The energy performance of the investigated buildings has been validated using thermal simulation tools to establish the extent of energy reduction that can be achieved through mainapulating the design parameters. Previous discussions on architectural modifications concluded that buildings rotation angles have minor impacts on their thermal performances. It can be also concluded that insulating walls has a greater impact on building performnce than insulating roofs. Having a windows to wall ratio of 10% is recommended while shading windows at southern elevations to improve building performance. As for building systems, results showed that increasing the usage of daylight and lighting efficiency and providing automatic lighting control systems improves performance. Using VAV systems has the greatest impact on reducing the overall power consumption of a building. Utilizing effective solar panel systems on roofs with money-back periods of 20 to 30 years is beneficial to the sustainabilty of buildings. Installing roof and wall insulation and adapting more efficient mechanical and electrical systems can effectively reduce energy consumption and increase the thermal performance of buildings in arid climates.

12. Acknowledgement:

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