ANALYSING AND OPTIMIZING THE PERFORMANCE OF HYBRID HOUSING DESIGN IN THE MIDDLE EAST

Traditional and Technological Solutions to Make the Most of Solar Radiation

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ABSTRACT

Countries in the Middle East are increasingly developing eco-friendly residential architecture. This is in response to high housing demand and to high energy demand. This study combines passive and active elements to develop a hybrid eco design strategy. The key aims of this study were (i) to evaluate the impact of a hybrid design on the energy performance of a typical contemporary house for areas in the Middle East that experience very cold winters and extremely hot dry summers; (ii) to construct an analytical framework for examining the feasibility of hybrid designs in the region.

INTRODUCTION

Residential buildings in the Middle East accounted for about 6.4% of total world residential energy consumption in 2010, with a projection of an annual average growth rate of 1.2%t over the next three decades until 2040. Further, the residential energy use per capita is expected to remain higher than the world average (EIA 2013, 118) due to the climate change, population growth (as the population of the region is expected to grow by about 50 million people over the next decade) and insufficient performance of the residential buildings (The World Bank 2012, 42-46). In recent years, there has been an increasing interest in sustainable architecture in the region. Nevertheless, the practical examples of hybrid solar design in the housing sector are still limited. So far, there has been little discussion about the integration of modern technological solutions and traditional architectural approaches, particularly in areas of the Middle East, for example, where there is a wide diversity in temperatures between summer and winter. The gap in knowledge is well described by Kwok and Grondzik (2007, 10): *'Solar buildings are often characterized by an "either/or" of passive or active techniques. Passive systems strategically use walls, window placement, and overhangs to capture and control solar gain, whereas active systems deploy pumps, piping, and manufactured devices to collect, store, and redistribute the sun's energy. The choices are often complex and may result in adopting a hybrid of the two approaches.'*

This study attempts to answer three questions:

(i) What are the possibilities of creating a comfortable environment inside Middle East dwellings by relying on either passive or active strategies?

(ii) What are the abilities of each system in providing thermal and visual comfort?

(iii) How might a hybrid solar design reduce the energy consumption and CO^2 emissions for dwellings in areas of the Middle East that experience very cold winters and extremely hot dry summers?

METHODOLOGY

Investigations were undertaken using the DesignBuilder software, which was chosen because of its flexibility of use in a design context and its proven track record from previous research studies of Middle East housing. Lund University in 2005 invited, in collaboration with the Centre for the Study of the Built Environment (CSBE), three architectural firms to create a green building in Jordan. They used DesignBuilder in the process of analysing the AREE house (Rosenlund, Emtairah and Visser, 2010). Further, many academics relied on the software in their studies take an example, a study titled 'Modelling an existing building in designbuilder/e+: custom versus default inputs'. This paper published in the conference proceedings of building simulation 2009 in Glasgow in July 2009, which showed the accuracy of the software and won the ARUP prize for the best paper on the application of building performance simulation in the design process in 2009. Tehran, the capital of Iran, was chosen as the site for the study due to its challenging climatic range between summer and winter.

Initially, a computer model of a conventional house was developed (using a typical specification in terms of structure, materials, thermal mass, window opening ratio etc.) in order to obtain realistic data for the conventional dwelling's CO^2 emissions and energy requirements to provide indoor thermal comfort. The next step was to add, parametrically, specific passive and active strategies to the conventional house model. Finally, the effectiveness of each strategy was evaluated individually and then collectively for all the strategies.

The base prototype house was a two-storey building with a total floor area of 142.9 m^2. It consisted of a living room, a kitchen, a dining area, a sanitary zone, a store room and a guest bedroom on the ground floor, and the main two family bedrooms on the first floor. Further, the house was orientated in a virtually southerly direction (175° from north) in line with an orientation optimisation analysis done by the Ecotect software for the weather data of Tehran.

All the spaces had single glazed windows with PVC frames, linking the outdoor and indoor environments visually and encouraging natural lighting and solar heat gain. The window area to external wall area ratio was 30% and there was no shading. Installed was a typical mechanical system, with a split unit air conditioning unit and an electric hot water boiler with a consumption rate of 0.530 l/m^2 per day, along with the use of suspended 8 W/m^2 per 100 lux florescent lamps for lighting the house. Figures 1 to 5 show the form of the house and Table 1 the constructional materials used in the house.

Table 1
The constructional materials used in the house

ELEMENTS	MATERIAL LAYERS (OUTER TO INNER)	U-VALUE
Roof	1.Concrete Tiles 40mm 2.Roof Screed 70mm 3.Reinforced Concrete (Dense) 200mm 4.Gypsum Plastering 20mm	1.991 W/m^{2}K
External Walls	1.Cement Plaster 30mm 2.Hollow Concrete Block (Medium weight) 200mm 3.Gypsum Plastering 30mm	1.641 W/m^{2}K
Ground Floor	1.Concrete (Medium Density) 100mm 2.Floor Screed 70mm 3.Timber Flooring 30mm	1.495 W/m^{2}K
Internal Partitions	1.Gypsum Plastering 25mm 2.Hollow Concrete Block (Medium weight) 150mm 3.Gypsum Plastering 25mm	1.862 W/m^{2}K
Internal Slabs	1.Timber Flooring 30mm 2.Roof Screed 70mm 3.Reinforced Concrete (Dense) 200mm 4.Gypsum Plastering 20mm	1.470 W/m^{2}K
Doors	Painted wood (Oak) 35mm	2.251 W/m^{2}K
Windows	Single Glazing 6mm	6.121 W/m^{2}K
Window Frames	PVC 40mm	2.467 W/m^{2}K

ANALYSIS

The research method consisted of analysing the designed conventional house before applying passive and active solutions and finally assessing their effectiveness. Since energy efficiency is the main concern behind the environmental dwellings the quantitative effects of the strategies on the thermal and visual performance of the house were evaluated by examining energy consumption rates and CO^2 emissions of the house. The evaluation indicators in this study area were thermal comfort measured by the annual percentage of comfort hours, annual total energy requirements, annual heating and cooling requirements, visual comfort, natural day lighting, annual artificial lighting requirements and annual CO^2 emissions. The architectural and mechanical parameters to be altered were constructional elements (structural materials and insulation), windows (glazing type, opening ratio to the external walls and the possibility of having east and west facing windows), shading devices (fixed elements and movable slats), natural ventilation, HVAC system, lighting system efficiency with lighting controls and building orientation.

RESULTS

Firstly, the conventional house was assessed to give a preliminary idea about the performance of the typical house design. The outcomes showed negative aspects and gave an idea about the weak thermal and energy performance of the building. Without activating the HVAC system, the average monthly temperatures were not stable; overheating occurred in summer and a high amount of heating was required in winter due to the weak resistance to heat loss. The first floor rooms were the most affected by this as they were more exposed to the outdoor environment than the ground floor level. The electricity energy needed for operating the artificial lighting, domestic hot water (DHW), and appliances was about 31 kWh/m^2.year. Later, when the typical mechanical system was integrated to provide better thermal performance the energy demand rose dramatically by 730%. Consequently, CO^2 emissions increased by a similar percentage, from 3066 kg CO^2/year to 25465 kg CO^2/year. Additionally, for this conventional dwelling, an annual cooling load of around 243 kWh/m^2 of floor area was required to keep the house comfortable in summer. This was almost twice as much as the annual heating load, due to the high solar heat gain from the external windows (mostly in summer) that equated to 29 kWh/m^2 of floor area per year. Further, the sun supplied the rooms with a typical illuminance of more than 600 lux, which is far above the standard requirements for lighting and could create glare.

Improving the performance

The poor energy use performance of the conventional dwelling required improving by making modifications and improvements to the building, and these consisted of a set of passive and active strategies. Before applying any active strategies, the building envelope's thermal quality was upgraded with treatment of thermal bridges to reduce negative heat transfer in winter and summer. Higher quality building materials were selected to improve the performance, such as replacing the typical 200mm hollow concrete blocks with 200mm autoclaved aerated concrete (AAC) blocks, using aerated lime based concrete with recycled reinforcement steel to construct the roof and floors, and adding stone wool insulation material with better finishing materials gave higher thermal performance. Table 2 shows the U-values of the improved envelope components.

Table 2
The U-values of the improved envelope components

ELEMENTS	MATERIAL LAYERS (OUTER TO INNER)	U-VALUE
Roof	1.Sand Stone 40mm 2.Roof Screed 70mm 3.Stone Wool Insulation 200mm 4.Reinforced Concrete (Dense) 200mm 5.Hard Wood 20mm	0.144 W/m^2K
External Walls	1.Cement Plaster 30mm 2. Stone Wool Insulation 200mm 3.AAC Block 200mm 4.Hard Wood 30mm	0.127 W/m^2K
Ground Floor	1.Stone Wool Insulation 200mm 2.Concrete 100mm 3.Floor Screed 70mm 4.Hard Wood Timber Flooring 30mm	0.149 W/m^2K
Internal Partitions	1.Gypsum Plastering 25mm 2.Stone Wool Insulation 150mm 3.Gypsum Plastering 25mm	0.175 W/m^2K
Internal Slabs	1.Hard Wood Timber Flooring 30mm 2.Roof Screed 70mm 3.Reinforced Concrete (Dense) 200mm 4. Stone Wool Insulation 200mm 4.Hardwood 20mm	0.137 W/m^2K

Then, the typical single glazed windows were replaced by argon filled triple glazing with a high quality timber frame that has an excellent U-value 0.786 W/m^2K. The potential impact of controlling direct solar gain was assessed by installing fixed and movable shading devices. This shading also helped in achieving satisfactory natural lighting in the dwelling, with illuminance levels of around 100-150 lux for the rooms. Natural ventilation was integrated in the cooling season to compliment the role of thermal mass. The openings were designed to allow natural ventilation during summer time between May and October according to a schedule of opening and closing actions.

The conventional house could only achieve satisfactory thermal comfort levels for approximately 20% of the year, whilst in the passively upgraded design that percentage rose to around 45% of annual hours without operating any mechanical systems. When the mechanical system was operating then, in both the conventional and passively upgraded house, at least 90-95% annual comfort hours could be achieved. However, the passive strategies had positive effects on reducing the energy demand needed for operating the typical mechanical equipment to achieve this high percentage of comfort hours. Firstly, the passive solutions cut the heating and cooling loads by 94% and 79% respectively. The annual heating load reached a low of 12 kWh while the cooling load settled at 52 kWh. Secondly, as a result, the annual electricity demand dipped from 260 kWh/m^2 to 68 kWh/m^2 of floor area per year. Subsequently, annual carbon dioxide emissions per year dropped by 74%, changing from 25.464 tonnes/year to 6.637 tonnes/year.

Activating the split unit HVAC system provided high comfort levels. However, in the summer as the natural ventilation had run all day long, it conflicted with the mechanical system. Thus, it had taken cooled air away from the building and put an extra load on the HVAC system. Therefore, the natural ventilation was scheduled by using sensitive sensors so that whenever the outside air temperature dropped below 20°C, the natural ventilation was activated and the mechanical system deactivated, which was usually between the hours of 23:00 to 6:00 during the summer. This simple step reduced the annual cooling load of the passively improved house by an extra 18% to about 43 kWh/m^2 of floor area. Additionally, by replacing the split unit system with a variable air-conditioning volume (VAV) with heat recovery (HR) system, the annual cooling load descended sharply to 27 kWh/m^2, with a slight change in the heating load to 12 kWh/m^2, see Figure 6. The newly installed heating system ran on hot water supplied by a gas fired condensing boiler, which also provided the house with DHW. For cooling the chiller required electricity in order to operate. Consequently, the upgraded house with VAV and HR system required 50 kWh/m^2 and 17 kWh/m^2 of electricity and gas respectively. That meant an extra 12% saving on the annual energy bills because, according to DesignBuilder, the site to source energy conversion factor for electricity is 3.167 and for gas is 1.084.

In terms of lighting, the conventional house's lighting system was suspended fluorescent lamps with a rating of 8 W/m^2 per 100 lux and using 2810 kWh of electricity per year. However, upgrading the system by installing glare control sensors to control the strength of the light, and upgrading the artificial lighting bulbs to higher efficiency bulbs that required 3 W/m^2 per 100 lux, saved more than 2000 kWh of electricity each year.

The efficiency of the hybrid design is appealing. Compared to the conventional house design (with an annual energy demand of 986 kWh/m^2) , the hybrid house had an annual energy demand of 120 kWh/m^2, equating to an 88% reduction in the net source annual energy demand, see Figure 7.

The final stage of the study investigated any impact different orientations for the hybrid house might have on energy use. Along with south facing, the hybrid house was orientated to face east, south-east, south-west and west. The results confirmed the Ecotect suggestion that south facing provided the best energy efficiency and comfort. However, as far as the building rotated away from the South towards East/West, the heating/cooling load increased. Generally, after South orientation, the dwellings with a main facade towards the east have advantages over the western orientated ones.

DISCUSSION

The present study was designed to determine the effect of passive design and active systems on a dwelling's thermal performance and energy demand. The modelling indicated the feasibility and desirability of a hybrid design in reducing the energy consumption and CO^2 emissions significantly in a Middle East dwelling as shown in Figure 8. The results indicate that the building responded well to the passive solar strategies - shading elements reduced the indoor temperatures by at least 10^{o}C in summer and natural ventilation decreased it by an extra 5^{o}C. The highly insulated envelope kept the indoor temperatures stable all year round which, with an upgrading the mechanical system, led to a reduction of around 90% in heating and cooling loads. Further, more than 70% of lighting energy was saved by replacing the regular bulbs with energy efficient ones. Additionally, it is important to note that the hybrid design was not that sensitive to the change of orientation as well as windows ratio or windows facing direction if the shading devices are well designed. On the other hand, surprisingly, one unexpected finding was that if only some of the selected passive strategies were used individually then it could have had a negative impact on the design. For example, when only the building's envelope thermal resistance was improved, it boosted the indoor temperatures to nearly 50^{o}C in summer.

However, the feasibility of the hybrid solar design is encouraging; the appropriate passive solar design of the house with the upgraded active systems reduced by almost 90% the demand for electricity and fossil fuels to heat, light, and cool the dwelling compared to the conventional dwelling. In fact, the hybrid solar design created a high quality indoor environment. Figure 9 shows the impact of the hybrid design on keeping the temperatures levels consistent all year round by providing more than 95% comfort hours. Generally, passive solutions do not necessarily add significant extra cost to a building (as the roof and wall's mass, insulation layers, windows, and shading elements are part of the house's structure). The cost feasibility of the hybrid approach, although not analysed in this paper, might be attractive, given the scale of the energy savings over the conventional house.

CONCLUSIONS

The results from this study indicate that the passive improvements helped in achieving stable indoor temperatures in the range 17°C and 32°C all year round and minimized the reliance on the active system to reach optimum indoor comfort. The findings suggested that the hybrid house required only 12% of the energy used by the conventional house to provide the same levels of thermal comfort throughout the year.

The passive solar design was able to provide nearly 45% of comfort hours but, alone, could not meet year-round optimum indoor comfort requirements. In contrast, the active system, acting alone and without the passive features, provided more than 90% annual comfort hours but greatly increased energy demand by more than 700%.

The results from this study indicate the feasibility of adopting a hybrid design in the housing sector for the Middle East in order to achieve low energy eco dwellings. The findings support the idea that if a house is passively improved before applying active strategies it can easily save energy and reduce CO^2 emission rates. However, although the current study was based on one type of housing, which was a detached house, the findings are possibly applicable for other house types. This is because the detached house is the most exposed to the external surroundings and so the most affected by environmental factors. A number of limitations need to be noted regarding the study. It is acknowledged that only some passive and active elements have been tested and assessed. Other parameters that could be considered in future studies include the impact of different building shape and form; a range of potential renewable energy systems, changes in the prices of energy and carbon and a life cycle analysis of the various types of building materials that might be used. Future climate changes in the Middle East may also effect the future energy needs and performance of dwellings.

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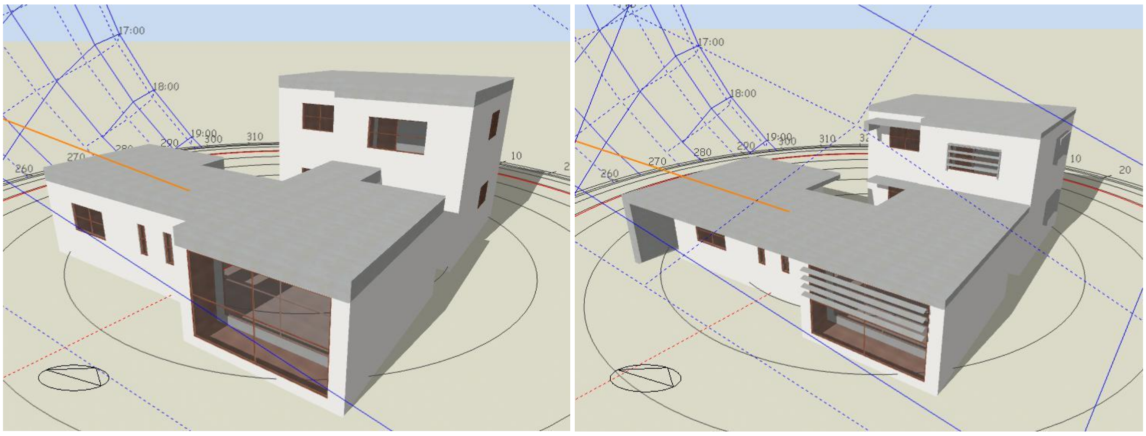

Figure 1: The conventional house (Left) and the hybrid House's (Right) DesignBuilder models.

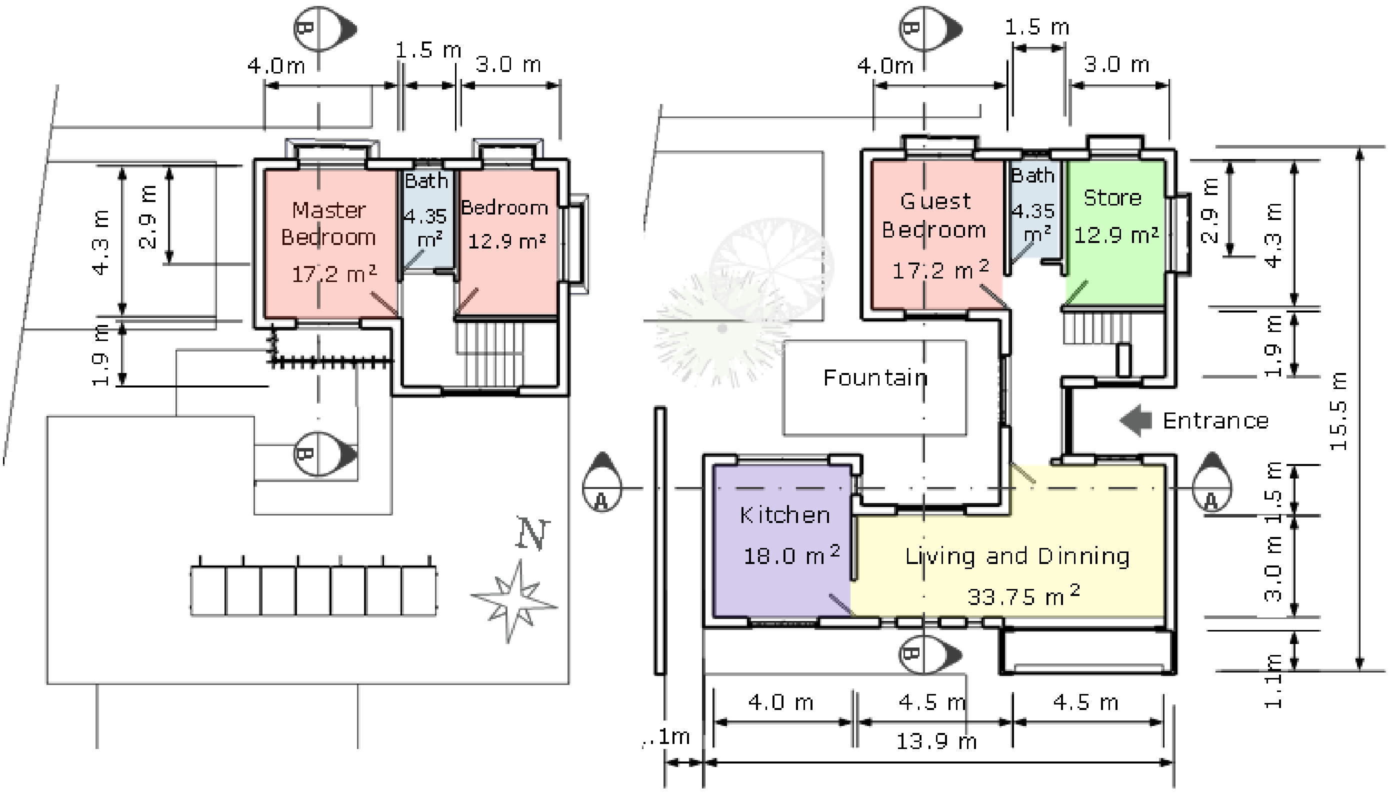

Figure 2: The house's ground floor (Left) and first floor (Right) plans.

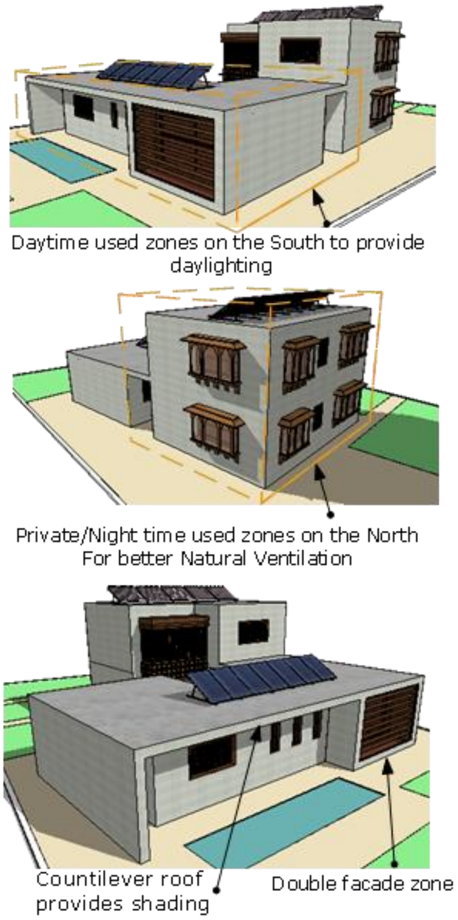

Figure 3: Hybrid design's perspective views

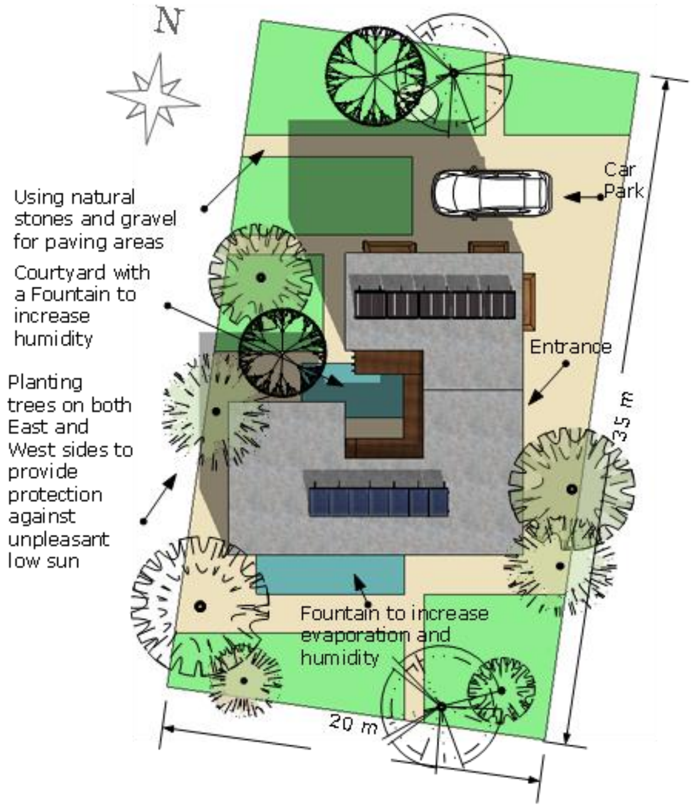

Figure 4: Hybrid design's site plan

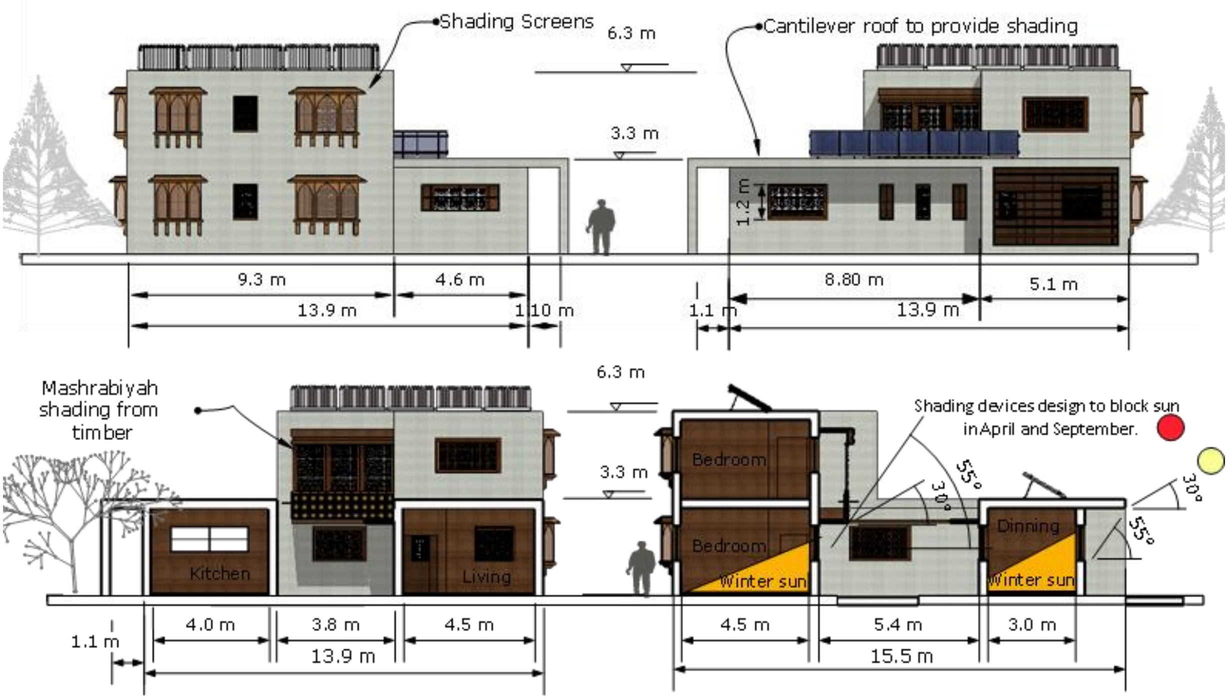

Figure 5: Hybrid design's elevations (Top) and sections (Below).

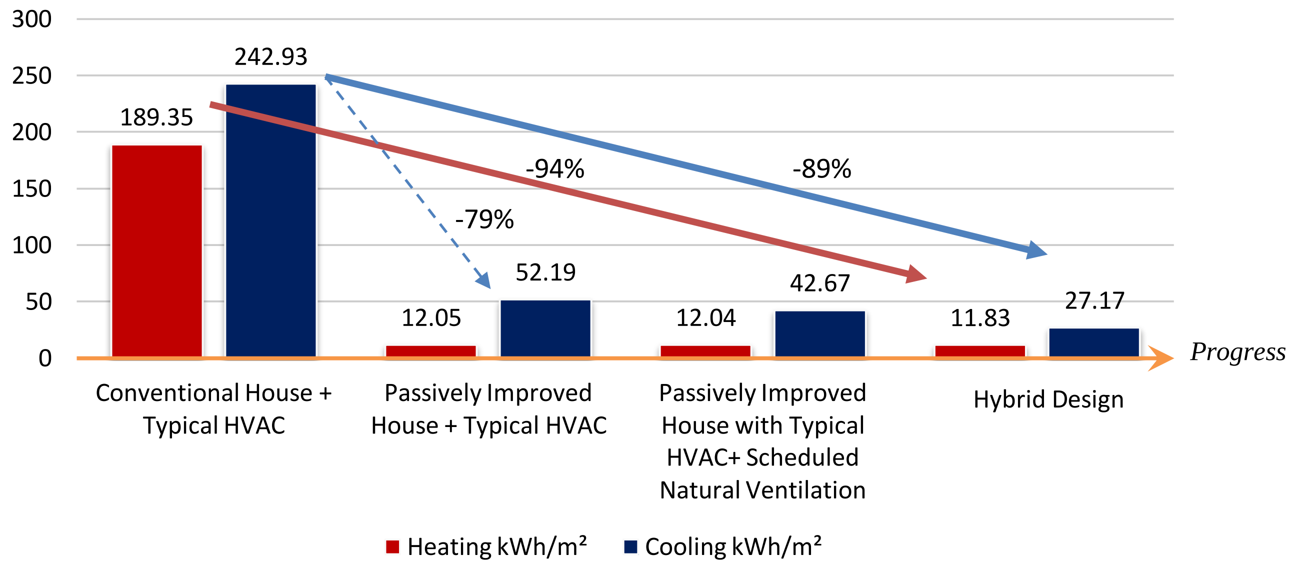

Figure 6: The impact of the building improvement on reducing the amount of heating and cooling loads.

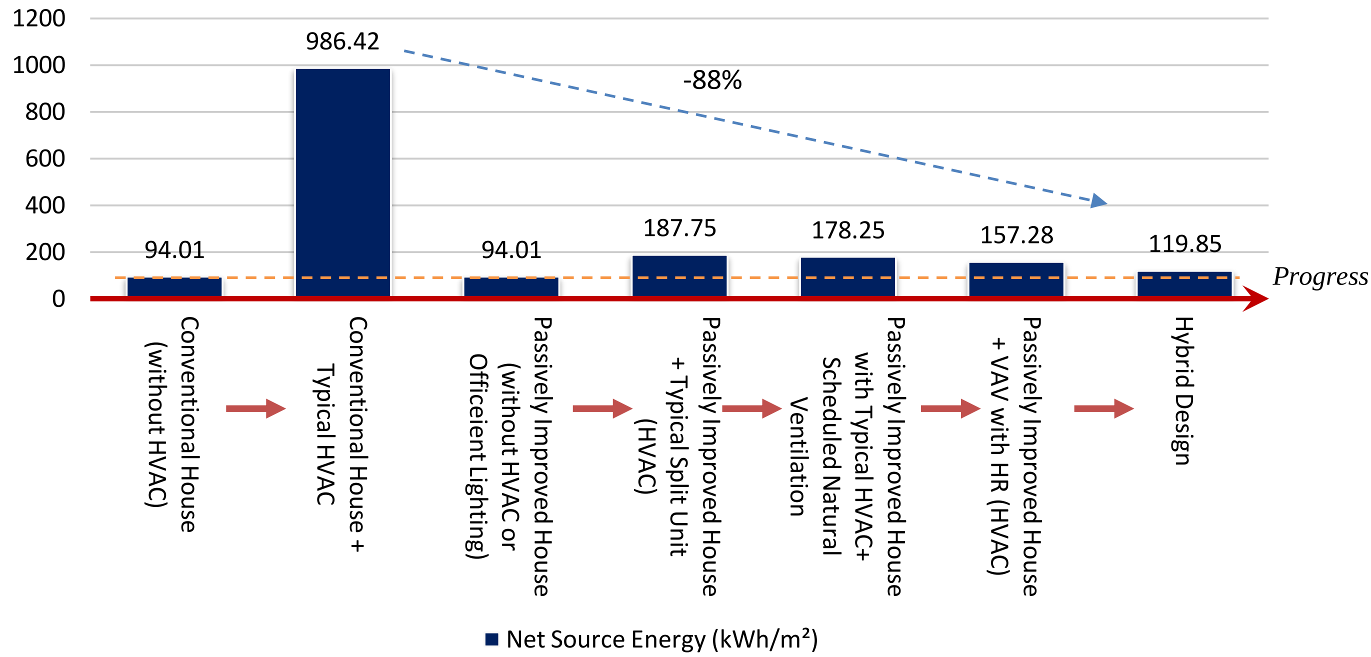

Figure 7: Steps that improved the building's performance and the improvement's reflection on the annual energy demand.

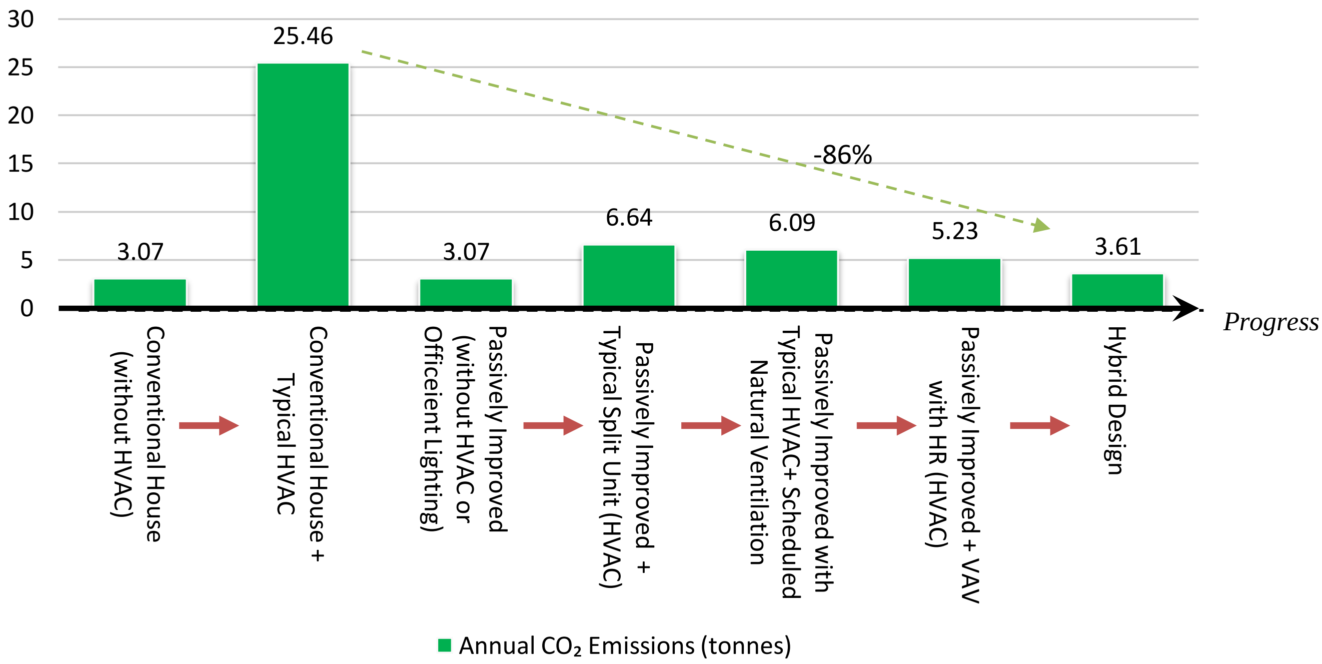

Figure 8: Steps that improved the building's performance and the improvement's reflection on the CO2 emissions from the building.

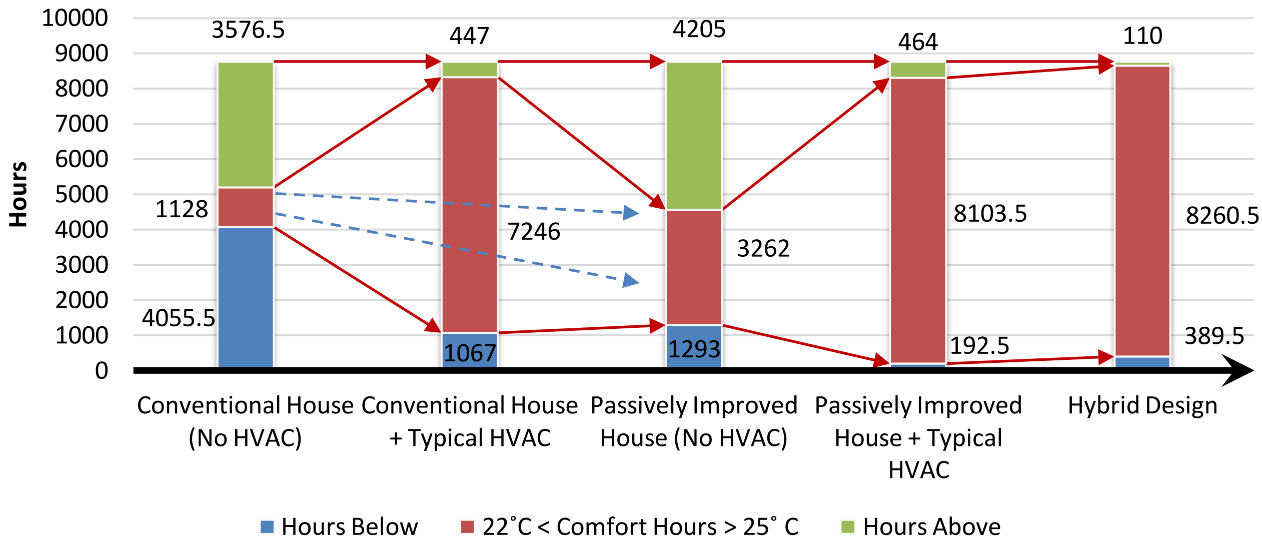

Figure 9: The effect of the improvements on providing better comfort hours.