Energy Consumption Patterns for Domestic Buildings in Hot Climates Using Saudi Arabia as Case Study Field: Multiple case study analysis

Naief A. Aldossary[1]; Yacine Rezgui[2] and Alan Kwan[3]

[1]Ph.D Candidate at Cardiff School of Engineering, Cardiff- UK, Lecturer at School of engineering – Al-Baha University- KSA; Email address: dr_naief@hotmail.com
[2]Professor of Engineering Informatics, Director BRE Institute in Sustainable Engineering School of Engineering, Cardiff University, Cardiff – UK; Email address: RezguiY@cardiff.ac.uk
[3]Head of the Discipline of Architectural, Civil and Civil & Environmental Engineering, Cardiff University, Cardiff- UK; Email Address: kwan@cardiff.ac.uk

ABSTRACT

The paper presents the evaluations and debates surrounding residential energy consumption in Saudi Arabia, a country distinguished by its fiercely hot weather and geographical position in a global area prominent for heightened energy consumption and carbon emissions. The cases chosen for the research comprise several residences situated in various climatic situations across Saudi Arabia. Specifically, the case study concerns multiple domestic buildings in the scorching, arid climate of Riyadh, multiple domestic buildings in the hot but humid weather of Jeddah City, and multiple domestic buildings in the hot, dry mountainous area of Al Baha City. The main objective of the evaluation is to identify the average energy consumption in the residential sector in Saudi Arabia, based on (a) monthly electricity bills for each residence, (b) occupant behaviour as determined by interviews for every chosen residence, and (c) analysis and discussion of energy consumption through modelling and simulation for every selected dwelling, using the IES-VE software tool. Energy consumption for the residential division is thus explored and debated, with an emphasis on architectural design, building materials used and occupants' conduct. Subject to established failures, several solutions were proposed with the objective of reducing energy consumption; they encompass shading techniques, renewable energy techniques, and efficient glazing. The proposed solutions were assessed by remodelling every residence using IES-VE and the outcome was a decrease in energy utilisation, varying but reaching 37%, subject to local weather circumstances. The regional, financial and environmental benefits of the energy saving that would result from these measures being implemented for existing dwellings across Saudi Arabia were then presented.

INTRODUCTION

Interest in energy-oriented research has increased. However, this growth has resulted from recent concern over energy saving as well as economy (Alzoubi and Alshboul 2010). Over the previous two decades, the performance of buildings has become known as a key contributor to adverse environmental impacts. Buildings are responsible for 50% of the CO2 emissions released to the environment and about 70% of the sulfur oxides (C. Ghiaus 2004). As for the intensive pressure on the environment, the building sector consumed 40% of the world's energy, 16% of its fresh water, and 25% of its forest timber (C. Ghiaus 2004).

Thus, there has recently been considerable interest in the developed world in the concept of sustainable architectural buildings that promote environmental protection. Currently, architects are focussing on the design stage of buildings with the aim of making them more economical in terms of energy consumption for cooling, heating, lighting, and the supply of hot water (Woolf 2003). It is well known that architectural practice is increasingly focussing on aspects related to environmental protection through better energy performance; but this can sometimes be at the cost of other architectural factors such as aesthetic or functional qualities (Schlueter and Thesseling 2009).

To indicate the scale of the problem more specifically, over 50% of the electricity in the Kingdom of Saudi Arabia is consumed in the operation of residential dwellings, according to the Ministry of Electricity and Water. As Saudi Arabia has a hot climate, large amounts of energy are needed to run the air conditioning in dwellings. The unreliable energy resources and the rising price of crude oil worldwide necessitate the use of available renewable energy such as wind and solar energy (Alzoubi and Alshboul 2010). In this regard, Saudi Arabia has a high amount of natural resources such as solar radiation, but this is not used because the Ministry of Electricity generates energy by burning fossil fuel, resulting in CO2 emissions. Despite Saudi Arabia's abundance of solar radiation, there is no use of energy generation techniques such as photovoltaics (PV) (Al-Saleh 2009; Taleb and Pitts 2009). Many developed countries have dealt with this problem with an eye to energy saving and established sustainable energy consumption codes, depending on the local climate. Saudi Arabia still needs to establish a compulsory energy consumption code (covering form, fabric, and on-site energy generation) to reduce energy consumption and CO2 emissions.

To this end, this paper presents the problems related to the absence of sustainable architectural design (form and fabric) and shows the high level of energy consumption based on the evidence of multiple case study simulation and analysis. An in-depth account of how to investigate and deal with these problems in particular places in Saudi Arabia will be presented, using an analytical methodology based on selection of different houses and flats, to be examined and simulated using IES-VE simulation software tools. The analysed weaknesses of these selected houses will be discussed separately to present the problems that result in high energy consumption and CO2 emission. Later, many solutions will be recommended for these houses, as well as for similar cases, supported by new IES-VE simulation of these solutions and examination of the selected houses after retrofitting. The simulated results following retrofitting were compared with the previous results to validate the impact of these solutions.

METHODOLOGY

The methodology used in this paper consisted of selecting nine houses including three different houses, in three different climatic locations across Saudi Arabia. These houses were subjected to deep analysis and simulation in order to achieve the study's goals by identifying: (a) design weaknesses related to the architectural form and building fabric; (b) the behaviour of occupants within each dwelling; and (c) the current average annual energy consumption for each dwelling in kWh/m² in this region. It was taken into account when selecting the dwellings that the number of occupants in each property and the building sizes should follow the common style known to the Ministry of Municipality in Saudi Arabia.

For each house in this study, the actual architectural layout plans, structural and construction plans were provided. In addition, to support the study, the annual electricity bills from the Ministry of Electricity in Saudi Arabia for each house were provided, to be compared with the final simulation results for each dwelling. These annual electricity bills give the energy consumption of each property for every quarter of the year.

IES-VE software tools were employed in this study to simulate the buildings individually. As the official electricity bills provided by the ministry present the energy consumption registered by the meter of each property, the annual energy consumption according to the IES-VE simulation results was similar to that shown on the official bills, but was also accompanied by details of what the energy was consumed for. This information identified the purpose of most of the energy consumption.

The IES-VE model needs to input data related to a user profile for each occupant; thus an interview was conducted with each occupant of each dwelling, in order to create detailed user profiles and record how the users operate their dwellings. The interview examined how the occupants operate each room individually, which equipment was included, the period of operation of the room, occupants' life style and activities, and the internal temperature.

A three-dimensional IES-VE model for each house was established, each model encompassing the details of the actual house envelope used; the architectural design (areas of each room and design style); and the way the occupants operate their properties (occupant behaviour). The locations of these dwellings were recognised through the established data base of the IES-VE software tools, including features of the local environment (temperature, solar radiation, humidity level, wind speed). The final simulation result of each model for these dwellings reflected the energy consumption based on the input data for behaviour, building envelope, architectural design and local environment.

The huge amount of energy consumed as well as the CO_2 emissions for each property were presented. Based on this information, the weaknesses of each simulated dwelling could be identified and some helpful solutions for retrofitting these selected dwellings and similar ones could be offered.

After identifying the causes of high energy consumption for each dwelling, an IES-VE model of each dwelling was retrofitted in accordance with the suggested solutions, to predict the potential reduction of energy consumption. The new IES-VE model of each dwelling was simulated again, then compared with the previous annual energy consumption as revealed by IES-VE (before retrofitting), to demonstrate the degree of success of the suggested solutions.

Some recommendations for future dwellings will thus be outlined to help prevent high energy consumption and achieve sustainability in this region.

ANALYSIS AND DISCUSSION

The annual energy consumption kWh/m² and Co2 emission rates in these simulated dwellings seems to be high (fig 3.1- fig 3.2) compared with the energy consumption in domestic buildings in other developed countries and/or some established energy consumption codes. These high energy consumption levels result from poor design of the buildings, including architectural design (form) and house envelope (fabric); occupant behaviours; and non-use of on-site renewable energy. These weaknesses suggest great potential for improving existing dwellings as well as for providing more sustainable future dwellings.

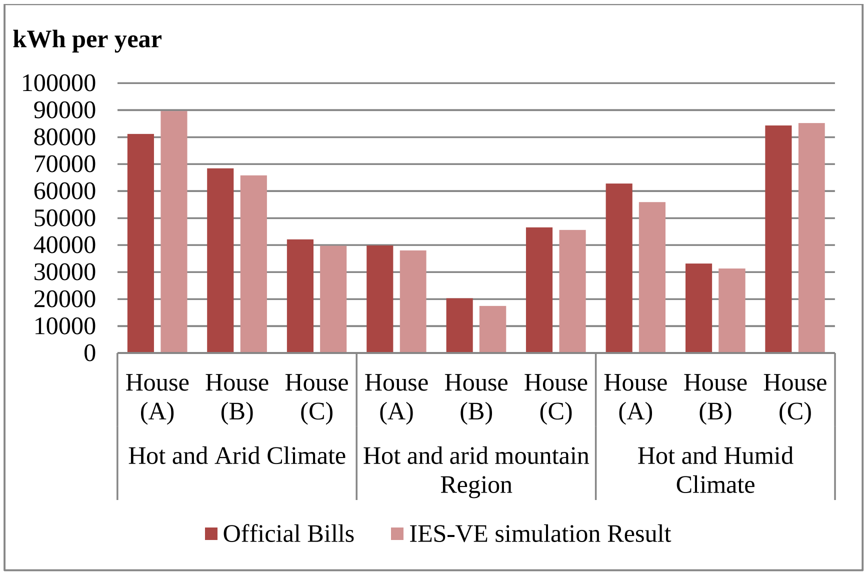

Figure 1. Annual Energy consumption for each house according to official bills and IES-VE simulation results

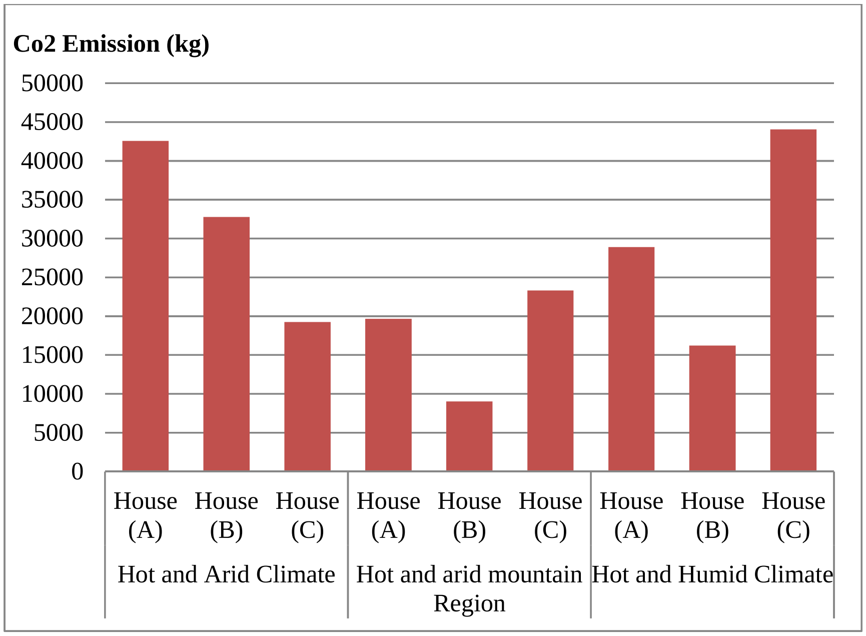

Figure 2. Annual Co2 emission rates (kg)

Those reasons underlying high energy consumption which include weaknesses of the building design and envelope (form and fabric) will be discussed separately. They will be based on the findings for the six analysed properties, the building designs provided for each dwelling, and the behaviour of the occupants of each property. Potential solutions will be suggested for these selected dwellings and any similar cases. In order to determine the success of these suggested solutions, the dwellings were remodelled in keeping with the solutions and simulated again to predict the potential energy savings. The simulation results for the new model of each dwelling (after retrofitting) were compared with the previous simulation result (before retrofitting) to find out how successful the potential solutions adopted for each dwelling were.

To present these findings clearly, the discussion will be divided into two main sections: weaknesses of the analysed dwellings; and suggested solutions that can be adapted to fit these or similar cases.

Weaknesses of the analysed dwellings

The weaknesses of each dwelling can be related to building design (form), building envelope (fabric), on-site renewable energy and/or occupant behaviour. The discussion of weaknesses will be presented as follows:

- ✓ Architectural design (form)
- ✓ Building envelope (fabric)
- ✓ On-site renewable energy and behaviour.

Architectural Design (Form). Many architects currently focus at the design stage on planning buildings that will be more economical in their consumption of energy for cooling, heating, lighting, ventilation, and hot water supply (Woolf 2003)

Many weaknesses were found in the category of architectural design that can result in high energy consumption. First of all, the building sizes and areas are too spacious for the number of occupants. This extra area must be served with electricity for cooling and lighting, resulting in high energy consumption and high CO2 emission rates. Rooms in all the simulated dwellings consist of large spaces accommodating few occupants. For example, the areas of the bedrooms in house (A) in (Al-baha) vary from (25) to (30) m², while the number of occupants in each bedroom is no more than two. The extra space requires extra energy to cool it by air-conditioning, as well as extra heating and lighting.

Secondly, the building shape used in the building design can lead to high energy consumption. As we know, Saudi Arabia has an aggressively hot climate, receiving huge amounts of solar heat. A flat, box-like building shape, the design style found in the majority of Saudi dwellings, is used for all the investigated cases. Because of this flat shape, the building will face a huge amount of solar heat, increasing the load on the cooling system needed to provide thermal comfort inside the building. The result is high energy consumption. Socially, the rooms on the top floor of the houses, such as bedrooms and seating areas, are used the most, requiring extra energy to cool them for longer periods. For future buildings, many possible solutions can be applied within the design process, through techniques related to the slope of the roof, which can be adjusted to fit on-site renewable energy technology such as PV. Shading techniques provide a well-known solution, especially for hot climates, according to many previous studies (Farrar 2000; Baldinelli 2009). This opportunity was not taken up in the cases examined in this study, which demonstrates an additional weakness of architectural design in Saudi dwellings.

House envelope. The building envelope is recognised as playing a significant role in energy saving. It was found, in all cases involved in this study, that there was a lack of efficient design of the building envelope. One of the weaknesses in the house envelope was that the efficiency of external walls was too low (e.g U-Value= 2.3 w/m2.K). In Saudi Arabia, where the temperature can reach 50 degrees, this lack of strong external walls can transfer the heat from outside to inside, requiring an extra energy load to operate the air conditioning if a satisfactory level of human comfort is to be achieved. Many previous studies have agreed that an efficiently insulated building fabric plays a significant role in energy saving. For example, energy consumption can be reduced by at least 33%, rising to 60%, through using an efficient building fabric (external walls) (Balaras, Gaglia et al. 2007), yet inadequate building fabric has been observed in the construction of the houses and flats in the study.

On-site renewable energy. On-site renewable energy plays a major role in reducing energy consumption as well as CO2 emissions through the use of natural energy sources such as solar radiation, replacing the burning of fossil fuels to generate electricity. Saudi Arabia is rich in solar radiation that can be used instead. According to Shafiqur Rehman et al., (Rehman, Bader et al. 2007) Saudi Arabia has up to 1980 kWh/m² solar radiation every year. However, up to 15% of this solar radiation can be generated as electricity, so up to 297 kWh/m²/year can be produced in Saudi Arabia from solar radiation by using PV techniques for each property.

Unfortunately, on-site energy generation techniques were absent in all the analysed dwellings. Yet all these dwellings and similar ones have a great opportunity to install PV techniques and use natural energy instead of the energy provided by the original company. This solution will protect the environment by minimising the CO2 emission rate.

Wasteful behaviour. The behaviour of occupants within the dwelling plays a major part in energy consumption. However, in interviews with the occupants of these dwellings, they disclosed some behaviour that results in high energy consumption. For example, the annual energy consumption of house (B) is quite different from that of house (C), although the areas and numbers of household members are not very different. Another example can be found in the varied annual energy consumption, according to official bills, in flat (A), compared to that in flats (B) and (C); all these flats are similar in size (less than 100 m^2 for each), with different numbers of occupants. In general, it can be stated that the behaviour of occupants leads to different energy consumption patterns, according to both the official electricity bills and the final simulated results. Since the behaviour of occupants has a considerable influence on energy consumption in the homes, public awareness of the need to improve energy conservation behaviour should be promoted.

Potential energy retrofitting solutions. On the basis of the weaknesses discussed, the occupants still have some opportunities to retrofit their dwellings to save energy. However, some solutions unfortunately cannot be adopted for existing buildings because they need to be taken into account at the design stage. For instance, it is not possible to destroy the existing house envelope in order to build a more efficient one.

Some possible ways of retrofitting these analysed houses and flats were suggested, then simulated again using IES-VE. The new simulation result was based on three recommended solutions: replacing windows with new, efficient triple glaze; installing shading devices; and installing on-site PV for energy generation. As mentioned, the new simulation result (after retrofitting) was then compared with the previous simulation result (before retrofitting) and the comparison made clear how successful these solutions would be in reality in these and/or any similar cases. It was found that an energy reduction of up to 37% compared with the original consumption could be achieved by using the above-mentioned limited solutions to retrofit the dwellings.

CONCLUSION

This paper evaluated and examined the energy consumption patterns in hot climates, using Saudi Arabia as a case study field. It investigated the energy consumption patterns and CO2 emission rates, based on simulations of multiple case study analyses, augmented by actual utility electricity bills. The method used was to employ IES-VE software tools to simulate three typical houses in three different climatic locations. The simulation results were supported by official utility bills, actual layout plans, and interviews with each occupant of each dwelling. The findings of the paper were that (a) the average energy consumption for a typical house. (b) Many identified weaknesses, related to form, fabric, on-site energy generation and occupant behaviour of these simulated dwellings, were discussed. And (c) providing some limited solutions were suggested and applied in these houses and flats with the goal of reducing the annual energy consumption for each property. These solutions were retrofitted in each house and flat model separately and simulated again by IES-VE software. The new result shows that a reduction of energy consumption based on the suggested solutions can reach 37%. Therefore we can conclude this research with general recommendations for existing and new dwellings.

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