Energy and Buildings 86 (2015) 104–117

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Optimal design of residential building envelope systems in the Kingdom of Saudi Arabia

Alaa Alaidroos, Moncef Krarti *

Civil, Environmental, and Architectural Engineering Department, University of Colorado at Boulder, Boulder, CO 80309, United States

A R T I C L E I N F O

Article history:
Received 7 April 2014
Received in revised form 31 August 2014
Accepted 7 September 2014
Available online 16 October 2014

Keywords:
Net-zero energy
Optimization
Residential buildings
KSA

A B S T R A C T

In this paper, a comprehensive analysis study is presented in order to improve the energy performance of residential buildings in the Kingdom of Saudi Arabia (KSA) through optimizing the building envelope elements. The building envelope energy conservation measures included in the study are wall insulation, roof insulation, window area, window glazing, window shading, and thermal mass. The optimization process was based on life cycle cost and energy savings. Optimum packages of energy efficiency measures for a residential building located in five climate zones in KSA have been determined for subsidized and non-subsidized energy costs. The results showed optimal energy savings of 39.5%, 33.7%, 35%, 32.7% and 22.7% for Riyadh, Jeddah, Dhahran, Tabuk and Abha, respectively, can be obtained for the subsidized energy cost case. For the non-subsidized energy cost case, the optimal energy savings were 47.3%, 41.5%, 43.19%, 41.1% and 26% for Riyadh, Jeddah, Dhahran, Tabuk and Abha, respectively. Moreover, a sensitivity cost analysis indicated that the cost of energy has more influence on optimal energy savings and life cycle costs than the initial costs of the energy efficiency measures. Finally, this study concluded that substantial savings in annual energy costs subsidies can be achieved by the KSA government if it aggressively promotes, through investments and incentives, energy efficiency programs for both existing and new buildings.

1. Introduction

Buildings are increasingly requiring high energy demands in the Kingdom of Saudi Arabia (KSA), especially during summer season, due to high air conditioning demands associated to very high outdoor temperatures during the summer even at night throughout most of the Kingdom. In 2010, buildings in KSA consumed about 65% of the total electricity, 47% higher than the world average during 2010 [1]. The annual rate of growth of energy consumption continues to increase mainly due to the increase in population with an annual growth rate of 1.54% [2]. Fig. 1 illustrates the electricity consumption distribution by sector in 2010. As noted in Fig. 1, 52% of the total KSA electricity consumption is attributed to the residential buildings. Moreover, it has been estimated that 2.32 million new residential buildings will be built by 2020, indicating an even more significant increase in electricity demand associated to residential buildings for KSA in the coming years [3]. In addition, more than a quarter of the produced oil is consumed locally in KSA, and large portion of this oil consumption is needed for the electricity production [4]. It is well known that Saudi Arabia's economy depends solely on oil export revenues. Therefore, this continuous growth of local energy consumption would jeopardize the ability of KSA to maintain its reliance on oil export revenues [5]. Some studies have indicated that if energy efficiency measures are considered for new buildings, KSA annual electricity demand from residential buildings can be reduced by 10%, while reducing air conditioning requirements alone can have an equivalent return in investments up to the cost of building 500 M_W power plant [6].

Building envelope components such as walls, roof, floor and windows have other functions than just structural or architectural elements. Indeed, building envelope components can be designed to maintain safe and comfortable indoor environment. In particular, building envelope components affect the energy required for thermal comfort within buildings. For instance, heat storage capability of some building envelope components, such as walls, can help in controlling the indoor temperatures without the need of mechanical systems. So there are sustainable approaches to achieve thermal comfort in buildings without utilizing significant amounts of energy especially for cooling or heating.

In addition, the efficiency of cooling systems has a significant impact on the total energy consumption of any building as well. The less is the efficiency of the cooling system, the more energy it will

* Corresponding author. Tel.: +1 303 492 3389; fax: +1 303 492731.
E-mail address: krarti@colorado.edu (M. Krarti).

http://dx.doi.org/10.1016/j.enbuild.2014.09.083
0378-7788/

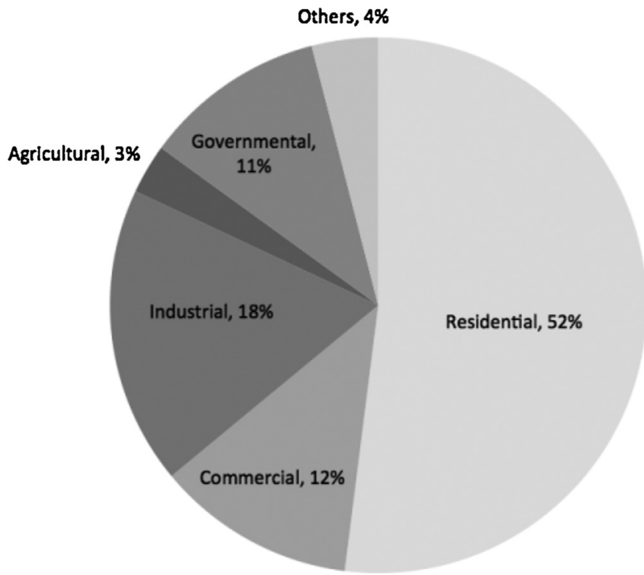

Fig. 1. Total energy consumption per sector in Saudi Arabia in 2010 [3].

use, thus, resulting in a large contribution of environmental pollution. Al Anzi and Al-Shammeri discussed the potential of energy consumption reduction of Mosques in Kuwait due to increasing the efficiency of the air-conditioning system [7]. The results indicated that energy savings of 17% can be achieved when increasing the energy efficiency ratio (EER) from 8 to 12.

Commonly, heat avoidance is the first approach to design buildings that can minimize heat gains especially those associated with direct solar radiation and high outdoor temperatures. The impact of building envelope energy efficiency measures that are investigated in the analysis described in this paper include exterior wall and roof insulation, window shading, window size, glazing type, and thermal mass. Detailed energy analysis is carried to define an optimal design for high performance thermal residential building envelope system in Riyadh and some other locations representatives of different KSA climate zones.

First, the existing literature is reviewed to assess previous studies and their findings related to improving energy performance of residential building envelope systems in KSA. Then, the analysis method used in the study presented in this paper is outlined. Finally, selected results are presented and discussed.

2. Literature review

A large number of research studies have been reported to assess the benefits of energy conservation measures for residential buildings in Saudi Arabia. In this paper, the review covers in particular the research efforts in investigating optimum insulation, thermal mass, window glazing and window shading for Saudi Arabia's hot climates.

Several studies have specifically investigated the appropriate thickness and location of thermal insulation for KSA buildings. Saleh [8] studied the impact of three different thickness of wall and roof insulation (5, 7.5 and 10 cm) in Riyadh's climate based on cooling and heating loads. The National Bureau of Standards Load Determination (NBSLD) was used to conduct the energy simulation. This study concluded that thermal insulations with thickness of 5–10 cm located within the outside layer of the exterior wall gave the best energy performance in reducing cooling loads. However, for an air-conditioned space, insulation located in the inside layer of the wall performed better than the one located in the outside layer. Abdelrahman and Ahmad [9] developed a design procedure to select the type and thickness of the insulation material. The study involved the investigation of optimum position of polyurethane board and expanded polystyrene board for either clay bricks wall or hollow concrete block wall. The assessment also included a life cycle cost analysis to find the optimum insulation thickness. The findings of this study indicate that walls with clay bricks require less insulation thickness. For example, in Dhahran's hot and humid climate a wall with hollow concrete block needs an insulation thickness of 5.5 cm, while a wall built with clay bricks requires 5.0 cm of insulation thickness. Moreover, it was recommended that the insulation layer placed on the outside of the exterior wall for locations with high diurnal range of wall surface temperature to prevent the development of thermal stresses. Al-Sanea and Zedan [10] performed a study to optimize the thickness and location of wall insulation under steady periodic conditions in Riyadh. Three wall configurations were examined: walls with one, two and three layers of insulation. The optimization is based on energy consumption and the present worth method. The results showed that the optimum thickness of the insulation depends on its location within the wall. The wall with three layers of insulation achieved the best energy performance; each had a thickness of 2.6 cm placed at the inside, outside and at the middle of the wall. The wall with two insulation layers came next, where each insulation layer had a thickness of 3.9 cm placed at the middle and outside of the wall. The performance of the wall with the three insulation layers was compared to the wall that consists of just one insulation layer with thickness of 7.8 cm placed on the inside. The comparison showed an increase in time lag from 6 to 12 h and a reduction of 20% in peak cooling load.

Thermal performance of building roof elements was investigated by Al-Sanea [11]. The study compared the thermal characteristics of six typical roof structures used in building constructions in Saudi Arabia. Energy simulations performed using a validated numerical model based on an implicit finite-volume method. It was found that the contribution of solar radiation is more than twice than that of heat convection and conduction through the building envelope components. The simulation results were compared with an un-insulated roof that consists of heavy weight concrete foam as a leveling layer. The comparison showed a 32% reduction of the daily average heat transfer load when using a 5.0 cm of molded polystyrene insulation, and a 27% reduction for extruded polystyrene. Polyurethane insulation with a thickness of 5.0 cm gave a 22% reduction in the daily average heat transfer load.

In addition, the impact of thermal mass on the energy performance of buildings in Saudi Arabia's hot climate has been investigated extensively as well. Abdelrahman et al. [12] have examined the cost effectiveness and energy consumption of four masonry materials used in building construction in Saudi Arabia. The energy simulation carried out using DOE-2 software. The masonry materials that were investigated in the study include clay bricks, concrete blocks, sandlime bricks, and prefabricated walls. The clay bricks provided the best energy performance in terms of capital investments and running cost of a typical residential building in KSA. Furthermore, it is found that the clay brick consumed less energy by 16% compared to the concrete block, 23% compared to the sandlime bricks, and 25% compared to the prefabricated walls. Al-Sanea et al. [13] have investigated different types of masonry materials and its effect on optimal thermal mass thickness in insulated buildings for a fixed wall nominal thermal resistance. A validated computer model has been used to calculate the transmission loads assuming steady periodic conditions for Riyadh's climate. The location of the thermal mass was tested (inside and outside relative to the insulation layer), and the thickness of the thermal mass was varied between 0 and 50 cm while fixing the value of the wall resistance. The results of this study showed that walls with solid concrete blocks achieved higher energy savings, and the walls with