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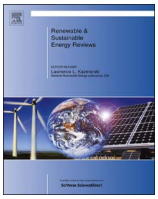

Energy saving evaluation of passive systems for residential buildings in hot and dry regions

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ABSTRACT

Over the recent decades, the excessive consumption of fossil fuels and its ensuing problems has become a major issue of concern in many countries. This paper assesses the effect of four passive systems, including green roof, roof pond, wind catcher and underground house, for energy saving of a sample house built in Iran's hot and dry region. The objective is pursued by evaluating the impact of each system on a residential house with the dimensions of 13.16 m×11.11 m×2.8 m, located in Kerman city, Iran. This study is conducted for a period of 138 days from May to October, during which the use of cooling energy is considered to be required. The life cycle cost (LCC) including initial, operation and maintenance and the potential of cooling energy saving of each system over a period of 20-year is evaluated. Results show that wind catcher is the most efficient system for saving the cooling energy, and roof garden, roof pond, and underground house hold the next ranks in this respect. In addition, wind catcher is able to reduce cooling energy demand from May to October; while, using other passive techniques decrease total annual energy loss through building envelope. Economic analysis shows that wind catcher and roof pond are the most economical approaches.

1. Introduction

Building sector accounts for about 30–40% of the total energy consumption in the word and this share is expected to increase by 2050 to 50% [1,2]. Buildings are also responsible for more than 30% of the GHG emission, which contributes to global warming, climate change and also irresponsible depletion of natural resources [3]. Residential buildings account for about 1/3 of the world's total energy use in building sector and the purpose of about 33% of all energy consumed in buildings is for heating, cooling and air conditioning [4,5]. In the developed countries, HVAC systems are responsible for about 10–20% of total energy consumption in buildings, and in the developing countries this figure reaches to 50% [6].

Passive system can also combat climate change renewable energies in order to reduce carbon emission. Iran (known as Persia) was the first country which used renewable energy sources in the past [7]. The global demand for energy has forced many countries to implement different sources of renewable energy [8]. Renewable sources have been recognized as the main key solution for negative impacts of fossil fuels [9]. Solar energy is a kind of renewable which is available in most parts of Iran which has many applications such as solar air heaters, solar water heaters, solar driers, furnaces, and so on [10]. Mostafaeipour and Abesi [11] investigated the use of renewable energy such as wind in Iran, but it was found that wind energy was not available in many parts of Iran such as Kerman Province. Global reserves of fossil fuel are limited, also high demand for fossil fuels caused negative environmental impacts such as greenhouse gas emissions, global warming and air pollution. Therefore, there should be an attempt to solve this problem [12,13]. Unlike fossil fuels, renewable energies do not have negative impacts on environment [14]. There have been numerous research works related to renewable and sustainable energy issues in Iran recently such as cities and provinces of Zahedan [15], Zarrineh [16], Aligoodarz [17], Tabbas [18], North and south Khorasan [19], Jarandagh [20], three free economic zones of Salafchegan, Kish, and Chabahar [21], and Sistan Baluchestan [22].

One of the effective approaches for reducing the cooling and heating energy consumption in the residential buildings is the use of passive techniques. These techniques can reduce the energy use, peak loads, and indoor air temperature fluctuations, increase the thermal comfort of building and also reduce the fossil fuel consumption and GHG emission [23,24]. Some examples of these passive techniques developed for buildings include green roof [25], roof pond [26], phase change materials (PCM) [27], thermal energy storage (TES) [28], wind catcher [29], underground building [30], earth to air heat exchanger

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(EAHE) [31], green wall [32] and trombe wall [33].

Different passive techniques have different cost and efficiency levels, so the passive techniques best suited to a particular building must be chosen based on building function, thermal comfort expectations, energy loss and gain of the building, cost and energy saving potential of the passive technique, location and environment, consumer affordability and weather data [34,35]. As a result, comparing the construction costs and long term efficiency and maintenance costs of different passive techniques is of particular importance, because a poor choice of a passive technique not only fails to reduce energy consumption but also imposes new costs on the occupants.

Performance and efficiency of different passive techniques have been compared in many studies. Sadineni et al. [36] has studied the efficiency and energy saving performance of several building components that can be used in the building envelope. Santamouris and Kolokotsa [37] have examined three passive dissipation techniques including ground cooling, evaporative cooling and night ventilation. Campaniço et al. [38] have studied and compared the cooling potential of four passive ventilation-based methods, including direct ventilation, EAHE, controlled thermal phase-shifting and evaporative cooling, and have reported that the use of above systems can provide up to 38% cooling demand saving. Augugliaro et al. [39] have review the potential of vernacular passive strategies to provide thermal comfort in residential buildings. The passive techniques investigated in this study include solar heating, humidification, evaporative cooling and natural ventilation. Toe and Kubota [40] have performed a comparative analysis on the vernacular passive techniques in Malaysia. In this study, the efficiency of elements such as day and night ventilation, terraces, courtyard, roof and ceiling insulation in the hot and humid climates have been investigated. Saljoughinejad and Sharifabad [41] have reviewed the passive techniques such as wind catcher, water and vegetation, semi open space, closed courtyard and underground buildings in the Iranian vernacular architecture. Most of these methods have been historically used in hot and dry climates.

Samani et al. [42] have compared the performance of four passive cooling techniques, including shading, natural ventilation, cool painting and increasing the thickness of interior gypsum plaster for reduction of cooling load. This study has reported that although all four techniques can reduce the indoor temperature, their efficiency ranking depends heavily on weather conditions, and that the best performance can be achieved by combining all four techniques. Zinzi and Agnoli [43] has compared the effect of two passive techniques, cool material roof and green roof, on the energy performance of residential buildings. This study has reported that the use of green roof leads to 2.8–13.9% cooling energy saving while for the cool roof, this figure is in the range of −13.7% to 30.1%.

Cost-effectiveness and life cycle cost (LCC) of different passive techniques have also been the subjects of many studies. Esen et al. [44] have investigated the efficiency and cost-effectiveness of a ground source heat pump (GSHP) in Turkey. Peri et al. [45] have assessed the cost-effectiveness of green roof through a life-cycle cost analysis, and have reported that the maintenance cost, initial cost and disposal cost are, in that order, the greatest costs of this system. Chel and Tiwari [46] have studied the efficiency and cost-effectiveness of the EAHE system in an adobe building, and have reported that this system can induce a 16 t annual decrease in carbon emissions, which is equivalent to € 340. The LCC analysis has also shown that payback period of the EAHE system is less than 2 years.

Badea et al. [47] used CYCO-pH software to develop a model to calculate the life cycle cost (LCC) of passive buildings. According to this study, the use of passive techniques, including PV cells, solar collectors and heat pumps increases the investment costs of passive buildings as compared to conventional buildings. Esen et al. [48] have compared the efficiency and cost-effectiveness of two systems of Ground-Coupled heat pump (GCHP) and Air-coupled heat pump (ACHP). Results have shown that GCHP provides a more cost-effective cooling than ACHP. Mostafaeipour et al. [49] have studied the use of wind catcher and ground cooling for reducing the cooling energy consumption of a warehouse located in the city of Yazd. They have also used the equivalent uniform annual cost (EUAC) method to compare the cost-effectiveness of these two passive techniques with absorption chillers. According to their results, the use of wind catcher or ground cooling is more economical than the use of chiller. They have also reported that the wind catcher has a better energy saving efficiency than the ground cooling.

Given that efficiency and cost of passive techniques vary with country and climate, this study investigates, for the first time, the potential of energy saving and life cycle cost (LCC) of four passive techniques, green roof, roof pond, wind catcher and underground building, for the hot and dry climate of Iran. To achieve this objective, we first evaluate the mean daily efficiency of each technique in reduction energy loss, and then estimate the cost-effectiveness of each system for the purpose of cooling energy saving.

The rest of this paper is organized as follows: Section 2 provides an introduction to the four passive techniques studied in this paper. Climate characteristics of Kerman describes in Section 3. In Section 4 the calculation methods of energy loss and energy saving through conduction, convection and air penetration for the model and each techniques is presented. In Section 5, the specifications of studied model are described and the daily weather data of Kerman's synoptic stations is used to calculate the impact of each passive system on daily energy consumption of that building. Section 6 compares the mean daily performance of the four studied passive techniques. Section 7 investigates the short-term and long-term cooling energy saving and cost saving of the four techniques for the city of Kerman. This is achieved by calculation of cooling energy saving of each passive technique for the period of May 15th to October 1st, during which indoors need to be cooled by air conditioning. This section also analyzes the initial, maintenance and operation costs of the studied passive techniques. Conclusions are presented in Section 8.

2. Passive techniques

2.1. Green roof

About 20–25% of the total energy loss of building is through its roof, and green roof can reduce this portion of energy loss in buildings [50]. This technique increases the thermal resistance and reduces the solar gain of the roof. Green roof also absorbs the heat during the day and release it into the house at night [51,52]. Energy saving performance of the green roof can be enhanced by improving the thermal insulation, shading and thermal mass used in the design [53]. According to a research by Ekateriniand and Dimitris [54], plants reflect 27% and absorb 60% of the solar radiation, so only about 13% of solar energy can pass the green roof. The study of Jaffal et al. [55] on the impact of insulation has shown that good insulation of the green roof can reduce the heating energy demand by 48%. It has also been reported that the use of a green roof instead of uninsulated roof can reduce building energy consumption by 22–45% [56]. Another study on the roof of a school in Greece has reported 6–49% cooling energy saving due to the use of green roof [57]. Ascione et al. [58] have studied the impact of green roof on heating and cooling energy saving, and have reported that the energy savings to be expected in Italy and Spain is about 8–11%.

Kumar and Kaushik [59] have developed a mathematical model for analyzing the efficiency of green roofs. According to the results, the use of green roof can cause 4 W/m^2 reductions in heat flux, 5.1 °C reduction in daytime indoor air temperature, and 3.02 kW/h reduction in daytime cooling energy. According to the study of Bevilacqua et al. [60], the use of green roof in the Mediterranean climate reduces the indoor air temperature by 2.3 °C. Another factor that can affect the efficiency of a green roof is the moisture content of its soil. The study of