Energy and Buildings 91 (2015) 131–138

Contents lists available at ScienceDirect

Energy and Buildings

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

Effect of housing density on energy efficiency of buildings located in hot climates

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ARTICLE INFO

Article history:
Received 1 April 2014
Received in revised form
20 November 2014
Accepted 20 January 2015
Available online 28 January 2015

Keywords:
Housing
Density
Energy
Hot climate
Thermal modelling

ABSTRACT

Residential buildings are considered among the most important elements in the city, as they form most of our built environment. Among the factors that affect urban planning and energy consumption of residential neighbourhoods, the role of housing density is essential. Thus, this study aims to examine the effect of housing density on energy efficiency of buildings considering the hot climatic conditions. To achieve this aim, a numerical analysis based on computerized simulation has been carried out to compare different configurations of housing densities in terms of their energy consumption. The study concluded that energy efficiency in residential buildings is highly dependent on their density. This is true when housing type is changed, or even within the same housing category. In addition, the study found that compact horizontal housing configurations can perform better in terms of energy efficiency when compared to the vertical ones. In this context, the examined row houses configuration offers a reduction in average energy consumption that reaches 28% compared to the rest of examined residential buildings types located in urban situation.

1. Introduction

Energy is one of the most fundamental needs in our life. As population of the world increases, reliance on energy produced from non-renewable resources should be gradually reduced and replaced by renewable energies. This is in addition to the environmental benefits of renewable energy sources in facing the problems of pollution, global warming, and climate change. The role of architects and engineers is essential here. They have large share of responsibility for designing buildings in a green way that ensures healthy and environmental friendly built environment. In this regard, the role of housing is essential as it represents most of our built environment. Housing is the largest or at least one of the largest sectors in energy demand [1]. Thus, every little helps when it comes to energy savings in this sector. In this context, housing modernization and utilization of technology can lead to a significant reduction in energy consumption and CO_2 emissions [2]. There are many sustainability design guidelines related to the design of individual residential buildings and the planning process of green neighbourhoods. This includes housing density, which can, if planned properly, help reducing construction and energy costs of housing [3].

Housing density is usually measured in dwelling unit per land area unit. This could be acre (du/acre), or hectare (du/ha). Housing density is an essential planning indicator as it helps estimating how many land for housing is needed, and this would affect other land uses. If the prescribed limit of density is exceeded, then housing units are considered overcrowded. In general, increasing density properly has the advantage of reducing housing cost. This is because higher density means [4]: less land to be developed, shorter roads and infrastructure lines, and smaller housing units which are more affordable for low-income people. On the other hand, high density may reduce solar potential of building as a result of increasing shading of neighbouring buildings [5]. Thus, it is required to achieve a balance between advantages and disadvantages of compact housing environment. Increasing housing density can be achieved through implementing several housing patterns. This includes walk-up and mid-rise apartments, courtyard and row houses, single family homes on small plots, and high-rise apartments.

There are different methods to measure housing density in residential neighbourhoods. These methods are as follows [6]:

- *Gross housing density:* This refers to number of housing units (or inhabitants) in a given area including all land uses in the

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http://dx.doi.org/10.1016/j.enbuild.2015.01.030
0378-7788/

neighbourhood. This includes roads and parking, commercial services, schools, and public open spaces. This method is useful for planning new neighbourhoods.
- *Net housing density:* As above, but land considered here is the one used for residential purposes only. This method is useful for planning housing clusters within existing residential sites, where services and roads already exist.
- *Site coverage ratio:* This is simply the percentage of the built area to the site area. Although this method does not consider building height, it is a useful indicator in the case of housing projects of uniform building height.
- *Plot ratio or floor area ratio (FAR):* This density is the most accurate method when it comes to design issues like natural ventilation and lighting as it takes building height into account. It simply means the ratio of building floor area to the total site area multiplied by number of floors.

The interacting connection between climate, urban form, and energy consumption of buildings is a demanding subject of research that has been discussed in several studies [7–9]. More specifically, several studies have tackled the effect of housing density on energy consumption. For example, Hui [10] investigated how urban density affects building energy design strategies in highly populated cities, considering Hong Kong as a case study. The paper evaluated the major factors that affect low energy building design in this context. The study concluded that "densification" of cities could have both positive and negative effects on total energy consumption related to transport, infrastructure, thermal performance, and natural lighting and ventilation. However, with conscious urban and building design, the overall environmental quality can be improved. Heinonen and Junnila [1] carried out a holistic analysis of energy consumption patterns in housing urban and rural environment in Finland. This has been done based on a field survey and data collection for selected cases. These cases included apartment buildings, row houses, and detached houses. The study found that the different cases appear to be less energy-consuming in rural areas. For example, the overall average energy use per housing unit increases from 12,600 kW h/a in apartment buildings located in rural areas to 15,500 kW h/a in apartment buildings located in urban ones. Hachem et al. [11] investigated the influence of geometry, density and site layouts on solar energy utilization potential of two-story housing unit. This has been done using numerical analysis implemented by EhergyPlus simulation package. Several configurations of attached and detached houses have been investigated, where spacing between housing rows and the resulting shading was a key determinant of solar potential of the examined housing unit. The study found that at higher densities achieved by configurations such as row houses, shading effect is fundamental on irradiation. This effect is strongly dependent on the distance between the rows of units, and can offer a reduction in insolation that reaches 55% in some configurations.

Strømann-Andersen and Sattrup [12] investigated the effect of urban density on daylight and passive solar gains in office and domestic buildings. Density is examined by changing the aspect ratio of urban canyon in several orientations. The study found that there is in general an increase in energy consumption as density increases. With reference to the cold climatic conditions, the observed increase in energy loads is mainly related to heating loads increase due to the reduction in solar gains. On the contrary, cooling demand decreases with density due to overshadowing. These studies show that the use of parametric numerical analysis to investigate the relationship between urban density and energy consumption is a practical approach. This is facilitated by the use of computer simulation using a variety of tools. However, most studies focus on the cold climatic conditions. Thus, this study offers further investigation of additional housing configurations with reference to the hot climatic conditions.

2. Methodology

This research is carried out using parametric numerical analysis. This has been implemented using Ecotect program as a main tool to estimate energy consumption in several hypothetical cases. Ecotect is a widely used program in environmental performance simulation studies, where its three-dimensional CAD interface makes it more practical in building simulation. Ecotect is known to give a reasonable estimate of energy loads in buildings [13], and has been solely used in several recent energy modelling studies [14–18]. In addition, its thermal modelling of buildings has been compared to other tools [19] and field measurements [20] where good agreement has been observed. Ecotect is based on the Chartered Institute of Building Services Engineers (CIBSE) admittance method. This method uses a flexible algorithm which has no restrictions on building geometry or number of analysed thermal zones. Several outputs can be produced by the software including external and internal temperature profiles, thermal comfort, heating and cooling loads, and heat gain and losses profiles.

Design Builder program has been used as a secondary tool. This has been done at the beginning of the study to ensure proper use of Ecotect modelling code. Design Builder is a powerful software tool for assessing thermal performance of buildings. It can be used for several applications including energy consumption, shading design, and lighting control systems. It uses Energy Plus simulation engine to simulate thermal performance of buildings, but with a more user-friendly interface. Several graphical or tabulated outputs can be obtained including energy consumption, mean radiant and operative temperatures and humidity, heat transmission through building fabric, and CO_2 generation.

As mentioned above, results of Ecotect and Design Builder are compared to ensure proper use of Ecotect modelling code. Table 1 shows the implemented modelling settings in both programs. Several residential blocks with different types and urban configurations have been simulated. In all simulation cases, energy consumption was the dependent variable, presented as heating, cooling, and total loads as an indicator of energy consumption. If these loads are counted by a factor 1 to 1, then refrigeration kW h equals electricity kW h. Thus, it was possible to observe the effect of

Table 1
The implemented settings in the comparison of Ecotect and Design Builder.

	Ecotect	Design Builder
Location and site		
Location		
Weather data	Al-Arish city	Al-Arish city
Terrain types	Urban	Urban
Site orientation	NS	NS
Thermal condition		
HVAC system	Full air conditioning	Full air conditioning
Thermostat range (°C)	18.0–26.0	18.0–26.0
Heating set point	18.0	18.0
Cooling set point	26.0	26.0
Design condition		
Occupancy (occupants/unit)	6	6
Occupancy pattern	Continuous	Continuous
Internal sensible gain (W/m^2)	15	15
Internal latent gain (W/m^2)	–	–
Infiltration rate (air change/hr.)	1	1
U-value (W/m^2 K)		
Exterior walls	2.30	2.55
Roof	2.60	2.51
Floor	2.56	2.24
Window	5.50	6.12