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Impact of building characteristics and occupants' behaviour on the electricity consumption of households in Abu Dhabi (UAE)

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ABSTRACT

The per capita consumption of electricity in Abu Dhabi is one of the highest in the world. Air cooling (AC) in the residential sector is responsible for much of this consumption. A preliminary energy survey of 36 residential units (18 villas and 18 flats) was carried out in Abu Dhabi, followed by a more detailed energy audit of 15 villas owned and occupied by Emirati citizens. The mean per capita use of electricity in villas was 16,874 ± 4421 kWh/ca/yr and the mean energy intensity was 349.1 ± 102.6 kWh/m^2. AC and domestic water heating (DWH) systems operate 24 h/day in most rooms of 12 villas, including times of no occupancy, and at least 9–14 h/day in most rooms of the other three dwellings. Building characteristics of the villas audited do not meet minimum Estidama Pearl 1 requirements, and their orientation often maximizes exposure to solar radiation. Model simulations provided estimates of the large energy savings achievable by increasing the AC thermostat temperature to 24 °C, by switching off AC and DWH when these are not needed and by retrofitting villas with roof insulation. These results highlight the importance of occupants' behaviour for energy conservation in the residential sector of Abu Dhabi.

1. Introduction

The Paris Agreement of the 2015 United Nations Climate Change Conference (UNCCC) committed 195 countries (including the United Arab Emirates) to reduce atmospheric emissions with the aim of holding this century's global temperature rise below 2 °C. In 2012, the UAE energy sector was responsible for 74.1% of the 115 million tons CO_2 equivalent direct GHG emissions, and the Abu Dhabi Emirate accounted for 48.8% of these [1]. Abu Dhabi is the largest of the seven UAE emirates, making up 87% of the country with an estimated mid-2015 population of 2.78 million (2.25 million expatriates on working visa and 0.53 million citizens), of which about 1.72 million in the Abu Dhabi Region, 0.74 million in the Al Ayn Region and 0.32 million in the Al Gharbia Region [2].

In 2014, the UAE per capita consumption of electric power was 11,245 kWh, lower than other Gulf countries with similar hot semi-tropical climate such as Qatar (16,736 kWh) and Kuwait (15,333 kWh), but significantly higher than most European countries (in the range of 4000–8000 kWh), and comparable to the per capita consumption in the USA (12,962 kWh) and Australia (10,002 kWh) [3].

The 2015 per capita electric power consumption in the Abu Dhabi Emirate was 22,620 kWh, one of the highest in the world [2]. The domestic sector accounted for 26.9% of the total electric power consumption, and 63% of this electricity was used in the Abu Dhabi Region of this emirate, the remaining 37% shared between the Al Ain Region and the Al Gharbia Region [2].

The UAE climate is hot and arid, due to very high level of sunlight input and long daylight hours. Summer lasts from April to September, with temperatures rising to about 50 °C in coastal cities and humidity levels often reaching 90%. In Abu Dhabi, the mean summer temperatures range 28–36 °C and the mean winter temperatures range 17°–27 °C [4]. During June to September, temperatures are usually above the comfort zone. They can occasionally be below the comfort zone in the winter period (December to February). Relative humidity is high (about 70–80%) during the night hours of most of the year, decreasing to minimum values of about 30–50% during the day. In the UAE, the main contribution (about 40% on average) to the electrical load is air cooling, reaching 60% during the summer months [5]. In Abu Dhabi, up to 80% of the electricity is used to meet the air cooling demand [6].

AlNaqbi et al. [7] estimated the large number of residential units built in the UAE in the period 1974–2012. As stringent energy saving requirements in Abu Dhabi were introduced in 2011 [8], most

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of the emirate's building stock was constructed without having to follow energy efficiency measures. The Estidama (Arabic for "sustainability") framework includes a green building code based on the "pearl" rating system. All government buildings, schools and mosques must have a minimum pearl rating of 2. All other buildings are required to have a minimum pearl rating of 1. The maximum rating is 5 [8].

Previous studies (e.g. [9,6,4,10–12] used simulation models to estimate the potential energy savings achievable in the UAE and in other countries of the Gulf region via retrofitting of buildings and assuming the implementation of the Estidama pearl regulations. AlAjmi and Hanby [13] used the Transient Systems Simulation program (TRNSYS) to simulate the effect of changing several parameters and materials of a domestic building in Kuwait, namely: building envelope, size and direction, window type, infiltration and ventilation. The best reduction in energy consumption was found to occur when orienting windows in a North-South direction, reducing the infiltration rate, and using the classic insulated cement-wall construction. AlNaqbi et al. [7] carried out simulations (using the IES-VE program) based on an existing villa constructed in the UAE in 1991 to calculate potential savings that could be achieved by upgrading the original design to the Estidama 1 pearl requirements (minimum requirements). The result was a 37.2% reduction in the total yearly cooling load of the studied villa. Taleb's [4] study of a residential building in Dubai concluded that a 23.6% reduction of the total annual energy consumption could be achieved using passive cooling strategies. Tabet Aoul et al. [10] simulated energy saving options (using eQuest software) to optimize the envelope of a 1986 hospital in Dubai. Significant energy savings were shown to be possible by applying relatively low cost retrofitting solutions (lighter envelope colour, optimized window-to-wall ratio, a more efficient cooling system, thermostat temperatures set at different values depending on the use of the areas to be cooled, integration of hot water heating by installing solar thermal collectors on the roof). Based on eQuest simulations, Assaf and Nour [11] estimated the potential reduction (31–38%) in electricity consumption obtainable by complying with the minimum Estidama pearl 1 requirements for three types of buildings in Abu Dhabi, i.e. a medium-size two-storey villa, a 16-storey residential building, and a 10-storey office building). Afshari et al. [12] evaluated the cost-effectiveness of various retrofit options for a 15-floor mixed-use office building in Abu Dhabi. This building had an insulated roof and a window-to-wall ratio of 70%. The cooling load accounted for 61% of the annual electricity use. Improving the performance of the cooling equipment would have been top priority among the measures involving capital investment, given the electricity cost considered in the modelling. However, the most cost-effective (zero cost) solution was found to be a change of cooling temperature set-point. Increasing the set-point from 22 °C to 24 °C would result in a 16% reduction of cooling load, increasing to 23% at 25 °C and 29% at 26° Friess and Rakhshan [14] provided a comprehensive review of the work carried out in the UAE to estimate energy savings achievable by passive envelope measures (building layout, wall and roof insulation, reflective coating, green walls, fenestration levels and glazing, natural ventilation systems). However, the electricity consumption of residential buildings depends on three main factors: climate, building design/materials, and occupants' behaviour. Less research has been published on the importance of occupants' behaviour in the Gulf region and more specifically in the UAE. Occupants' behaviour can lead to excessive and un-necessary energy consumption in buildings. Existing literature on this subject (e.g. [15–18] has shown that this is a very important factor affecting domestic energy use. A passive building design that minimizes energy consumption for cooling during the warm months is of paramount importance in a hot and humid climate, but an efficient use of energy by the building occupants is also needed. Al-Mumin et al. [19] conducted a study to determine the reasons of high electricity usage by Kuwaiti citizens living in 30 surveyed houses. The results showed that lights were left switched on regardless of whether the rooms were vacant or occupied. Also, occupants preferred a relatively cool temperature of 22 °C. Data analysis revealed that by setting the air conditioning thermostat to 24 °C, the yearly electricity usage would decrease by 39%. The energy simulations of Aldossary et al. [20] focussed on three typical houses and three typical flats in Riyadh (Saudi Arabia) and identified energy consumption reductions of 15–34% potentially achievable with shading devices, on-site photovoltaic systems, and more efficient glazing. Other, more expensive retrofitting solutions to improve the envelope characteristics were not considered as they are unlikely to be adopted when energy costs are quite low and further reduced by a 50% government subsidy. These authors mentioned that "wasteful" occupant behaviour was incorporated in their model based on user profiles, though limited details were provided. AlFaris et al. [21] monitored 10 villas in Abu Dhabi for 12 months after the installation of relatively low-cost energy conservation measures (i.e. improved glazing by installing a window film that reduces the shading coefficient, a roof white coating to increase the solar reflection factor, improved air tightness around doors and windows, use of programmable thermostats for AC systems, improvement of the AC operating conditions, and use of efficient LED lights). The results were compared to the energy bills of the previous year. On average, the energy savings were 25.1% (range: 14.4%–47.6%). The mean energy use index decreased from 471 kWh/m^2/year to 353 kWh/m^2/year. The lower than expected effectiveness of the energy conservation measures in some of the villas surveyed was attributed to the level of education and awareness of the occupants.

Most studies that investigated the introduction of energy conservation measures in the residential sector in countries that have a hot climate confirmed that large energy savings can be achieved by retrofitting solutions of existing buildings. However, besides the costs associated with these measures, another important factor that can hamper or compromise their implementation and effectiveness is the environmental awareness and behaviour of the building occupants. Therefore, in addition to providing a description of building characteristics and energy use in typical villas and flats in the city of Abu Dhabi, this study also focusses more specifically on occupants' behaviour and their energy conservation awareness.

2. Aims

The aims of this study were (i) to carry out a preliminary survey of the energy consumption in residential dwellings (villas and flats) of Abu Dhabi and gather information on the energy conservation awareness of randomly selected Emirati citizens and expatriates (foreign nationals), (ii) to audit a number of villas and understand the factors (building characteristics, cultural factors, occupancy profiles, management of cooling and domestic water heating systems, illumination) that have an impact on residential energy load, and (iii) to estimate potential energy savings achievable in this type of residential units by means of retrofitting measures (double glazing, roof insulation), and a different management of the air cooling (AC) and domestic water heating (DWH) systems.

3. Methodology

3.1. Questionnaire

A preliminary energy survey was carried out by means of a questionnaire (Appendix A). Most questions were about building characteristics (e.g. age, size, construction, glazing), management of AC and DWH systems (e.g. thermostat setting, hours of use per