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Effects of Building Density on Energy Demand for Indoor Cooling Under Extreme Hot Weather

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Abstract. This paper studies the impact of building density on energy consumption for indoor cooling in regions with very hot climate. While high building density increases shading on buildings and in turn decreases energy consumption for cooling, the internal heat gain resulting from a larger population has an adverse effect on cooling load. We use Abu Dhabi's weather data to analyze the cooling load required to sustain thermal comfort for optimal health and productivity in 2 urban design schemes. The objective is to explore the impacts of urban development options such as population density, indoor temperature set point, the number of working hours, thermal insulation level of the envelope and lighting power intensity on energy consumption per capita and per square meter. While the analysis results are sensitive to weather conditions, it shows that the optimal building density in terms of minimizing energy consumption for indoor cooling can be identified by balancing shading and internal heat gains.

Keywords: Energy consumption, cooling load, shading effect, passive cooling design.

1. Introduction

The reduction of the cooling load is one of the main levers enabling the attenuation of buildings' eco footprint in urban areas especially in regions where the climatic conditions are extreme and cooling is almost mandatory in order to maintain a thermally comfortable, healthy and productive working environment [1]. In numerous countries in the world, the largest share of energy consumption in buildings goes to indoor space conditioning [2]. The adoption of passive energy design for buildings which improves indoor thermal conditions is recommended to reduce the cooling energy demand [3]. Strategies to lower energy consumption through passive design include shading devices to limit solar gains and natural ventilation system. Existing buildings in countries like the UAE consume a large amount of energy because of the hot and humid climate. Energy consumption in buildings represents, in average, more than 80% of the total energy budget in Abu Dhabi. A large share of this energy (close to 70%) is imputable to building indoor space conditioning [4]. Energy consumption in insulated buildings may be 5–30% less than in non-insulated buildings [5]. The appropriate design of thermal insulation can have significantly lower the amount of energy used to cool buildings by reducing the gains from the outdoor environment and prolonging the period of comfortable climate with the same amount of cooling energy consumption. The extent of cooling energy saved when using insulation in buildings depends on several factors such as the size of the building, the usage of the building and occupant density. External shading reduces solar gains and therefore reduces the cooling load required to offset those gains. Proper shading strategy may lower the cooling load by up to 30% [5]. The building orientation is also an important factor in the improvement of natural ventilation and lowering of sun exposure [6].

In a study of the effect of thermal insulation on energy consumption of buildings in Dubai an hourly model was simulated by DesignBuilder/EnergyPlus. The study concluded that by using proper thermal insulation for external walls and windows savings of 30% can be achieved [7]. In a case study in summer in

Palermo and Milan (Italy), researchers found that cooling energy savings due to shading can reach 20% [8]. The study showed that the efficiency of shading is higher in hotter places. The building in Palermo decreased its cooling consumption by 20% with only 8% reduction in Milan's building which indicate even higher potential for a more extreme climate like that of Abu Dhabi. The aim of this research is to study the impact of building density on energy consumption for indoor cooling in regions with very hot climate. By analyzing whether and how passive design may help to reduce energy consumption while sustaining quality of life, this study will provide useful insights on the development of energy efficient infrastructure.

2. The Model

We analyze an arbitrarily defined urban system which comprises nine office buildings that are separated by streets (see Fig. 1). Our analysis focuses on calculating the year-round cooling load of the central building given the shading effect from the neighbouring eight buildings, the heat gain from the occupants and energy demand for lighting and equipment. For Simplicity, the effect of shading on energy demand for lighting is not included in the analysis and we are not accounting for ventilation/infiltration gains.

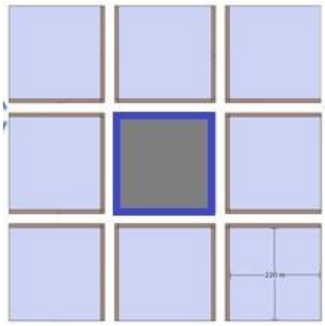

Fig. 1: Urban System Layout

Let s be the percentage of the central building's façade under shading (the shading ratio). We calculate s with Google Sketchup by defining the arbitrary urban system on the program with the coordinate of Abu Dhabi city (24.4667 °N, 54.3667 °E) and a northeast/southwest orientation (34 °from North). Let Q generally denote the energy demand for cooling. Neglecting the sensible and latent load due to ventilation/infiltration, the total energy demand for cooling Q_c is determined by:

$$Q_c = Q_s + Q_I \tag{1}$$

where Q_S is the cooling energy demand required to offset external gains and Q_I is the cooling energy demand required to offset internal heat gains. Q_S is determined by the difference between the dry bulb temperature and the desired indoor temperature if the façade is shaded, and is determined by the difference between the sol-air temperature and the indoor temperature if the façade is not shaded according to ASHRAE Fundamentals Handbook, 2013. Incorporating the shading ratio s, Qs can be expressed as:

$$Q_S = u \cdot a\{\max([T_{sol}(1-s) + T_0 s] - T_i, 0)\} \tag{2}$$

where u is the thermal insulation U-value, a is the total surface of the façade, T_{sol} is the sol-air temperature, T_o is the dry bulb temperature of ambient air, and T_i is the desired indoor temperature to sustain optimal level of health and productivity. The maximization function ensures that no energy is consumed for air-conditioning if the external temperature is lower than T_i (i.e., no heating). The sol-air temperature T_{sol} measures the air temperature under the effect of solar irradiation and is determined by:

$$T_{sol} = T_0 + \frac{(\alpha \cdot I - \Delta Q_{ir})}{h_0} \tag{3}$$

where α is the solar radiation absorptivity, I is the global solar irradiance, h_0 is the convective heat transfer heat coefficient, and ΔQir is the extra infrared radiative exchange caused by the difference between the apparent sky temperature and external air temperature. In our analysis, Q_I is determined by energy demand to offset heat gains from occupants and office appliances as well as energy used for lighting. Let E_M be the standard metabolic gain from each occupant, E_A the standard heat gain for appliance per occupant, P the total number of occupants, L the heat gain from lighting per floor area, U the utilization rate of lighting, and h the working hours. Then Q_I can be formulated as:

$$Q_I = (E_M + E_A)P + L \cdot F \cdot U \cdot h \quad (4)$$

3. Data and Assumptions

We derive hourly dry bulb temperature and global solar irradiance data for Abu Dhabi in 2010 from the National Centre of Meteorology & Seismology of the United Arab Emirates. Fig. 2 shows the dry bulb temperature as a function of time. The mean temperature in summer is substantially higher than the mean temperature in winter. Fig. 3 shows that global solar irradiance in Abu Dhabi exhibits less seasonality than the dry bulb temperature. Table 1 summarizes the statistics of the weather data.

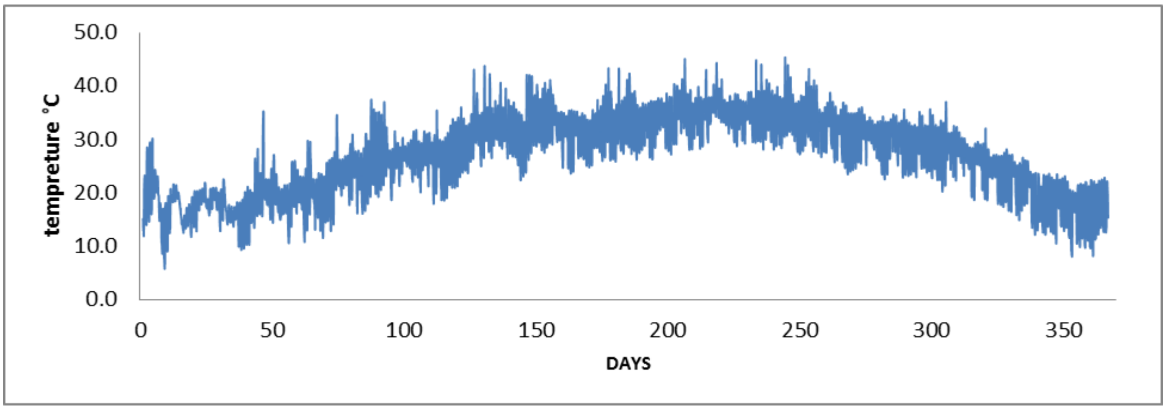

Fig. 2: Dry Bulb Temperature Profile for Abu Dhabi in 2010

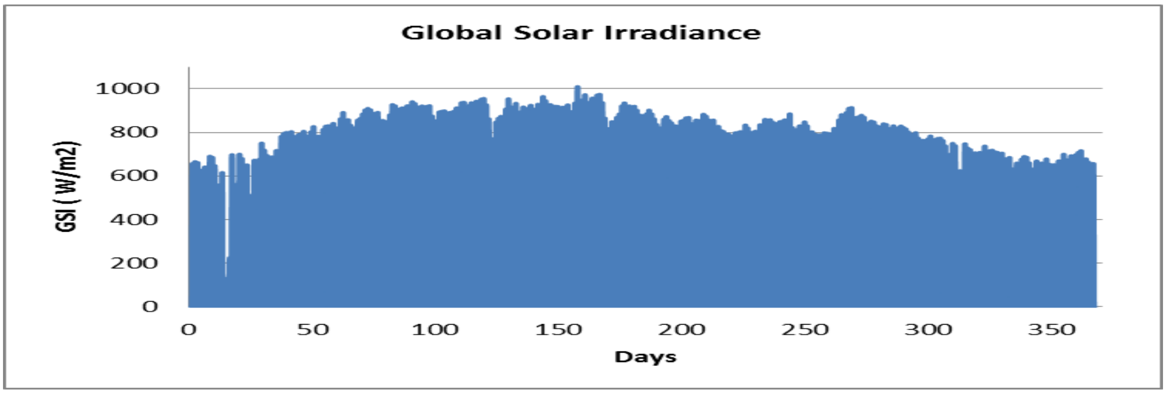

Fig. 3: Global Solar Irradiance Profile for Abu Dhabi in 2010

Table 1: Summary Statistics of the Weather Data

Data	Average	Min	Max	Median	Variance
Dry Bulb Temperature	27	5.7	45.3	28	53
Global Solar Irradiance	234.6	0	1009.9	14.52	93622.35

Table 2: Parameters of the Three Urban Design Schemes

Parameter	Unit	Scheme 1	Scheme 2	Scheme 3
Height	m	17	57.8	17
Number of floor		G+4	G+17	G+4
Distance between buildings	m	10	30	10
Gross floor area	m2	50000	170000	50000
Population density	m2/people	15	15	4.4

We calculate indoor cooling load under three urban design schemes. As shown in Table 2, Scheme 1 represents an urban design principle with high building density and low rise buildings. Scheme 2 has low building density and high rise buildings. Scheme 3 is a mixture of Scheme 1 and 2. More specifically, Scheme 3 has high building density and low rise buildings as Scheme 1, but it accommodates the same amount of population as Scheme 2. Scheme 1 and 3 thus share the same building size but differ in population density. Scheme 3 shows the impact of population density on energy consumption for cooling.

The assumptions used in the analysis are summarized as follows: The occupancy period is 9 hours per day (from 8 am to 5 pm). There are 5 working days per week so a total of 2340 working hours per year. The consumption of lighting energy is 10 W/m^2, with 50% of lighting utilization. Occupancy-dependent internal heat gain includes 120 W/person for metabolic gains and 135 W/person for equipment gains following the ASHRAE standard. The desired indoor temperature T_I is set at 23 ^oC to sustain thermal comfort and maximize productivity and health [9]. The thermal insulation U-value is 0.5 W/m^{2}K for the building. Solar radiation absorptivity is assumed to be 0.48. The heat coefficient of convection, h_0, is 25 W/m2K with a wall thickness of 35 cm [10]. The extra infrared radiation, ΔQir, is determined by the difference between the apparent sky temperature and the external air temperature and is assumed to be zero.

4. Results

Fig. 4 and Fig. 5 show daily energy consumption for space cooling electricity (exclusive of the fresh air conditioning load) for Scheme 1 and 2 in January, the coldest month, and July, the hottest month. Scheme 1 consistently consumes less energy for space cooling than scheme 2. Given that Scheme 1 produces less shading for buildings than scheme 2, it is found that shading, in general, has greater (negative) impacts on cooling load in hot days than in cold days.

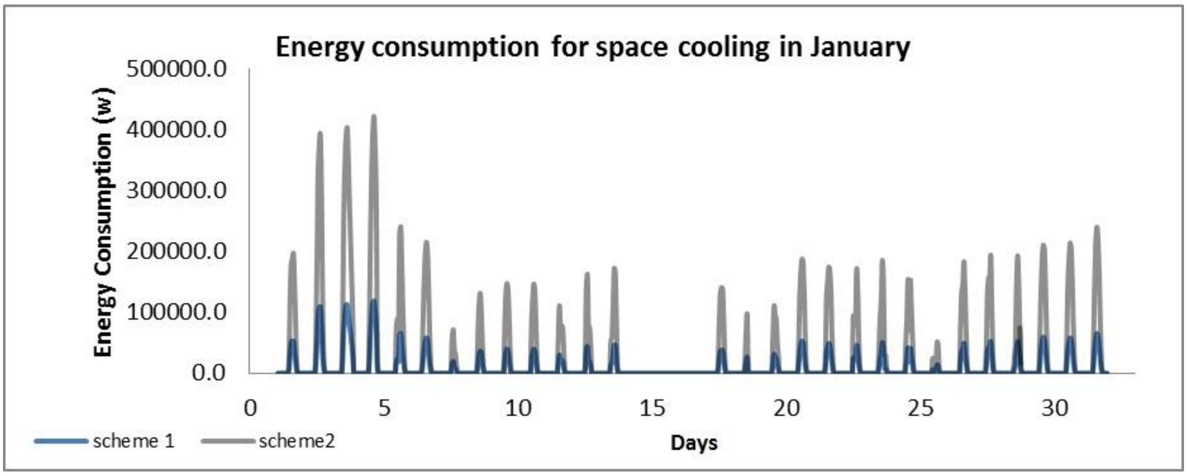

Fig. 4: Energy Consumption by Urban Design Scheme in January

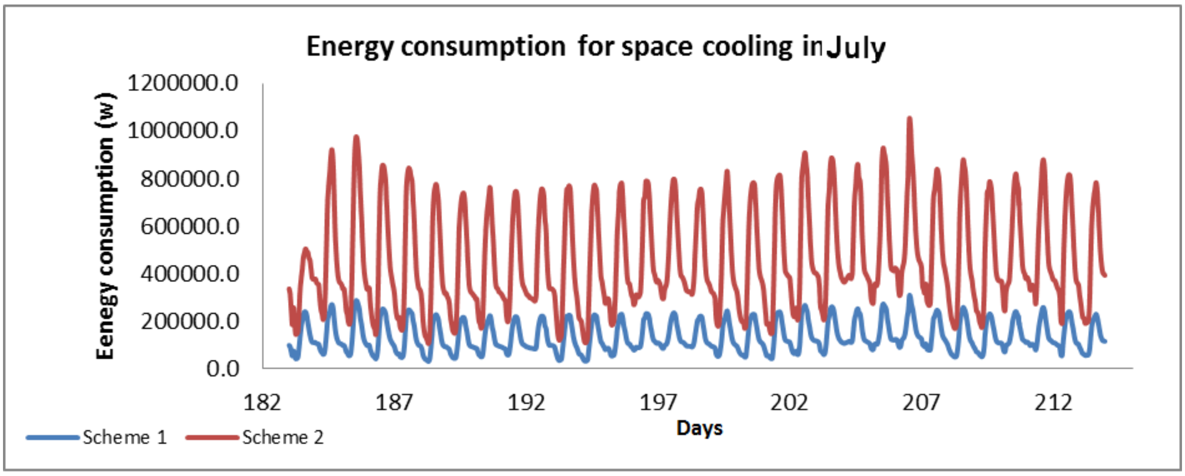

Fig. 5: Energy Consumption by Urban Design Scheme in July

Table 3 shows Scheme 1 is the most efficient design in terms of energy consumption in comparison to scheme 3 which represents a highly populated office and scheme 2 which is a high rise office building. Scheme 3 shares the same energy demand for spacing cooling and lighting with Scheme 1 and consumes same amount of energy to offset heat gain from occupant and appliances as Scheme 2. In terms of energy efficiency, Scheme 1 has optimal performance by space, whereas Scheme 3 has best performance by person. Due to high population density, Scheme 3 consumes less than half of energy for cooling by person than the other two schemes.

Table 3: Energy Consumption by Urban Design Scheme

Urban System	Cooling Energy to Offset External Gains (MWh)	Occupants & Equipment (MWh)	Lighting (MWh)	Total Cooling Energy (MWh)
Scheme 1	1616	1989	585	4190
Scheme 2	5514	6763	1989	14266
Scheme 3	1616	6763	585	8964

Table 4: Energy Efficiency by Urban Design Scheme

Urban System	Efficiency per area (kWh/m2)	Efficiency per Occupants (kWh/ occupant)
Scheme 1	83.8	1257
Scheme 2	84	1258
Scheme 3	180	790

5. Conclusion and Discussions

We use Abu Dhabi weather data to analyze the cooling load required to sustain thermal comfort for optimal health and productivity in 3 urban development schemes. The result shows the trade-off effect between shading and population on indoor cooling load. While the results are sensitive to weather conditions, the optimal building density in terms of minimizing energy consumption for indoor cooling can be identified by balancing shading and internal heat gains. Further study on the effect of ventilation on energy demand for cooling will further validate the effect of population density on cooling load. Sensitivity study on the major parameters and coefficients used in the model will help to validate the robustness of the results.

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