Post Occupancy Energy Efficiency and Indoor Environment Performance in Selected Commercial Buildings in Nairobi, Kenya

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Abstract: The cost of electricity and health of occupants inside buildings has led to an increased need for sustainable green buildings. The construction industry has come up with designs, construction and occupancy guided on sustainable principles. In Kenya, a few buildings have been built with such guidelines. It is imperative to conduct post-occupancy studies to ascertain that the green buildings are sustainable. This study sought to evaluate energy efficiency and indoor environment performance in green buildings. A total of four buildings, two green and two non-green, were considered in this study. Energy efficiency were determined using electricity bills provided by Kenya Power while indoor and outdoor carbon dioxide (CO₂), relative humidity and temperature were measured using Carbon dioxide meters’ model HT-2000. The study found that energy consumption in green buildings was significantly different from that of non-green buildings (p<1.18E-12), but consumption for non-green buildings was not significantly different (p=0.7). Average mean CO₂ concentrations in green buildings were 534 ppm and 608 ppm and 689 ppm in non-green buildings. Mean temperature levels in green buildings were 21°C and 25°C and 23°C and 26°C in non-green buildings. Mean relative humidity in green buildings were 53% and 55% and 58% to 60% in non-green buildings. Mean airflow rates (ventilation rate) for green buildings were 0.06h⁻¹ and 0.03h⁻¹ while non-green buildings were 0.006h⁻¹ and 0.003h⁻¹.

Keywords: Green building, Carbon dioxide, Relative humidity, occupants, temperature, correlation.

1. INTRODUCTION

Energy efficiency in buildings has become a major consideration in the built-sector due to increasing consumptions, 60% of total energy consumed by buildings in USA and 40% in European Union, contributing to about 36% greenhouse gas emissions [1]. Green buildings quantify energy use during design through modeling and simulation, which may deviate during occupation by about 25% [2-6]. Globally 30-40% of energy is consumed in buildings (18,19). In Kenya, Benchmark and Baseline consumption were established in 2012, but no research has been undertaken to inform how efficient green buildings are during occupation.

Ventilation systems allow fresh air inside the buildings and removes humid and contaminated air out of the building while impacting energy losses in the building and comfort [7]. Air change rate in naturally ventilated buildings depend on geographical location, weather conditions, building characteristics and occupant behaviors [8]. Simulation and modelling are used to determine ventilation rates at design stage [910]. Natural air ventilation and indoor air quality in buildings is influenced by the tightness of the buildings [11]. Experimentally, adequacy of ventilation and air change (Mechanical, natural or infiltration) can be calculated using the tracer gas method and applying the mixed mass balance model. The method can either utilize metabolically generated CO₂ (as used in this study) or use CO₂ introduced mechanically and the evolution of the tracer gas concentration with time analyzed mathematically to determine the flow rates in the building envelop [7,8,12-14]. Although green buildings should have demand controlled ventilation, designing for natural ventilation require great considerations for the airflow in the buildings. Studying ventilation rates in the buildings is important to inform whether the buildings are performing optimally.

Classifying green buildings as green during occupation is equally important as classifying them as green at design and construction stages [17]. Relying on simulated and modelled energy consumption and airflow rates does not always give the actual performance of the buildings. Therefore, the study focuses on determining energy and indoor quality performance of green buildings in Nairobi Kenya.

2. FEATURES OF GREEN BUILDINGS

Several characteristics distinguish green buildings from conventional buildings; first, site selection should consider ecological sensitive areas such as public green areas, flood-prone areas and cultural areas. Secondly, green buildings should re-use, recycle and use locally available raw materials to reduce embodied energy and reduce greenhouse gas emission. Third,
green buildings should enhance indoor environment through enhanced daylighting, thermal comfort, acoustic and minimized use of volatile organic content paints. Fourth, green buildings should conserve energy used in its operations and use renewable energy sources to power the building and adopt energy management principles and systems to improve energy efficiency of the buildings. Lastly, green buildings should use water efficiently, harvest rainwater and treat gray water for reuse [20].

3. MATERIALS AND METHODS

3.1. Experimental Setup

The study was carried out in four buildings within two learning institutions in Nairobi County, Kenya. Selection of the buildings was purposeful due to scarcity of green buildings in Kenya. Buildings selected are coded as building A, B, C and D. Buildings A and B are the selected green buildings while C and D are normal buildings within the same institutions. The two green buildings are rated as green by Leadership in Energy and Environmental Design (LEED), Green Africa Foundation and Architectural Association of Kenya.

Energy efficiency is calculated using power bills provided by Kenya Power, for the year 2018. Buildings plans were used to determine occupied area. CO\(_2\) concentration, relative humidity and temperatures inside and outside the buildings were measured using a CO\(_2\) meter, model HT-2000 manufactured by Dongguan Xintai Instrument Co. Ltd shown in Figure 1. The sensor records CO\(_2\) concentration within a range of 0-9999 ppm.

![Figure 1: HT-2000 CO\(_2\) meter used in the measurement.](image)

3.2. Measurement Procedure

The study comprised of two sections namely;

1. Energy efficiency calculations,
2. Indoor environment determination

The year 2018 monthly electricity consumptions bills were used to calculate energy intensities and compared to Benchmark and Baseline set by the Energy and Petroleum Regulation Authority (EPRA) in 2012 to find energy efficiency of the buildings. Eq. 1 gives the building energy intensity

\[ \eta = \frac{E}{A} \]  Eq. 1

\(\eta\) = building Energy Intensity (BEI) (kWh/m\(^2\))

\(E\) = Total energy Consumption in kWh

\(A\) = is the total Area of the building m\(^2\)

Buildings at 1\(^{st}\) quartile are most energy efficient and 4\(^{th}\) quartile least energy efficient.

Indoor health environment performance was determined through calculation of ventilation rates and correlation of CO\(_2\) concentration with temperatures and humidity inside the buildings. Ventilation rates are measured through the tracer gas method using CO\(_2\) as the tracer gas. Outdoor CO\(_2\) concentrations were measured and mean values of 400 ppm and 408 ppm used. Indoor and outdoor measurements were done between 11:00 am and 4:00 pm at intervals of 10 minutes to allow for steady state equilibrium to be achieved in the buildings after occupation. Further, CO\(_2\), relative humidity and temperature measurements were taken in enclosed office blocks within the buildings which are experimentally manipulated to establish rate of air infiltration or airflow rate in the offices as per eq. 2.

\[ I = \frac{1}{t} \ln(c) \]  Eq. 2

\(I\) is the airflow rate (h\(^{-1}\))

\(c\) is the difference in indoor and outdoor CO\(_2\) concentration (ppm)

\(t\) is the time of the day (hours)

Air change rates are compared to the ASHRAE Standards 62.1 and BSI Standard which both require air change rate per hour per person to be between 18m\(^3\)/hr per person and 27m\(^3\)/hr per person. Eq.3 gives the ventilation rate of the building or room.

\[ v = I \times V \]  Eq. 3

\(I\) is the airflow rate (h\(^{-1}\))
ν is the ventilation rate (m$^3$/h)

V is the volume of the building (m$^3$)

4. RESULTS AND DISCUSSION

4.1. Energy Efficiency Calculation

Figure 2 presents monthly energy intensities for two buildings B, C and D. Monthly energy consumption for A are not factored as the buildings does not have independent metering system and relies entirely on solar power system for energy supply. Building A fits in category of Net Zero Energy Buildings (NZEBs) as it is powered by 600 kW solar PV. Building B has mean monthly energy intensity of 2.6 kWh/m$^2$ with a standard deviation of 0.3 kWh/m$^2$. Building C has a mean monthly energy intensity of 4.4 kWh/m$^2$ and a standard deviation of 0.2 kWh/m$^2$. Building D has mean monthly intensity of 4.4 kWh/m$^2$ and standard deviation of 0.1 kWh/m$^2$. Analysis variance indicate significant difference for consumptions of B, C and D (p=1.18E-12) while between C and D are not significantly different (p=0.7).

Table 1 presents annual energy intensities for buildings B, C and D compared to the benchmark and baseline values by the EPRA. At 1$^{st}$ quartile, a building is energy efficient than 75% of similar buildings while at 50% a building is efficient than 50% of similar buildings. Green building rating tools require buildings to use between 25-30% less than normal buildings and building A and B uses at least 40% less energy compared to buildings C and D.

4.2. Indoor Environment

Table 2 presents air change rate and airflow rates inside the buildings as per Eq 2.

Lower airflow rates indicate building envelop is air tighter [8], thus lower airflow at building A, C and D indicate that interior of the buildings are air tighter than building B. airtight building envelops increase the possibility of poor indoor air conditions, due to poor ventilation rates [11]. Higher airflow rates at B could be due to ventilation cowls and louvers absent in other buildings [22].

![Figure 2: Building Energy Index (BEI) for Buildings B, C and D.](image)

![Table 1: BIE for buildings B, C and D compared to Benchmark and Baseline values given by ERPA](table)
Air flow rates for occupied and scaled-down offices are presented in Table 3. Across all the buildings' offices selected, air change per person falls below the recommended 20 m³/hr per person set out by ASHRAE Standard [21]. Non-green buildings C and D have lowest airflow rates and B has better airflow rates, because they are designed to be airtight.

Table 3: Airflow Rate and Air Change Rate at Specific Offices in the Buildings

| Building (Office) | Gradient (Airflow rate h⁻¹) | Mean (Airflow rate) | Volume (m³) | Air Change (m³/h) | Occupants | Air change/person (m³/hr/person) |
|-------------------|------------------------------|---------------------|-------------|-------------------|-----------|---------------------------------|
| A office          |                              |                     |             |                   |           |                                 |
| CW                | 0.4172                       | 0.5507              | 0.48        | 242.7             | 116.5     | 10                              |
| OW                | 0.3788                       | 0.5723              | 0.48        | 242.7             | 116.5     | 10                              |
| CW                | 0.3722                       | 0.3179              | 0.35        | 242.7             | 85.0      | 4                               |
| OW                | 0.4577                       | 0.4127              | 0.44        | 242.7             | 106.8     | 10                              |
| NO                | 0.0079                       | 0.0051              | 0.013       | 242.7             | 3.2       | 10                              |

| B office          |                              |                     |             |                   |           |                                 |
| OW                | 0.0219                       | 0.031               | 0.027       | 107.2             | 2.9       | 4                               |
| OW                | 0.0198                       | 0.0185              | 0.019       | 107.2             | 2.0       | 4                               |
| CW                | 0.0832                       | 0.1035              | 0.093       | 107.2             | 10.0      | 4                               |
| CW                | 0.1525                       | 0.1249              | 0.139       | 107.2             | 14.9      | 4                               |
| CW                | 0.0135                       | 0.0084              | 0.011       | 107.2             | 1.2       | 4                               |
| OW                | 0.0178                       | 0.0355              | 0.027       | 107.2             | 2.9       | 4                               |
| CW                | 0.2015                       | 0.273               | 0.237       | 107.2             | 25.4      | 2                               |

| C office          |                              |                     |             |                   |           |                                 |
| CW                | 0.0052                       | 0.0106              | 0.056       | 32.3              | 1.8       | 2                               |
| OW                | 0.0088                       | 0.0061              | 0.0075      | 32.3              | 0.24      | 2                               |
| OW                | 0.0038                       | 0.0034              | 0.0036      | 32.3              | 0.12      | 2                               |
| CW                | 0.0114                       | 0.011               | 0.011       | 32.3              | 0.36      | 2                               |

CW-closed Window; OW- open window; NO- Normal Operation.
For comfort, temperatures in a building should range between 19°C and 27°C while relative humidity should be between 30% to 60%. Average CO₂ concentration of green building A varied between 507 ppm to 564 ppm with a mean of 534 ppm and standard deviation of 22.7. For green building B, average CO₂ concentration varied between 575 ppm and 645 ppm with mean of 608 ppm and standard deviation of 27. For non-green buildings the average concentration ranged between 689 ppm and 695 ppm with standard deviation of 43 and 50. Average temperature range for green buildings was between 23°C and 24°C whereas for non-green buildings the average range was 23°C and 26°C. Humidity levels for green buildings ranged between 52% to 55% while that of non-green buildings was between 58% and 60%. Low airflow rates.

Performing t-test for CO₂, temperature and relative humidity across the buildings indicate a significant variation between green buildings and non-green buildings. T-test CO₂ between green buildings was not significant, (t=3.1, df=3, t crit. 3.2), between non-green buildings was not significant (t=0.9, df=2 t crit. 4.3), however, t-test between green and non-green shows significant drift (t=4.2, df=3, t crit. 3.2). T-test for temperatures between green buildings was not significant (t=2.8, df=4, t crit=3.2), between non-green buildings was not significant (t=1.7, df=2, t crit=4.3), between green and non-green buildings significant levels were recorded (t=-7, df=3, t crit. =3.2). T-test for relative humidity however did not show any significant difference across the buildings. Between green buildings (t=0.95, df=6, t crit. 2.4), between non-green buildings (t=0.5, df=1, t crit=12.7), and between green and non-green buildings (t=-1.6, df=3, t crit. 3.2).

Figures 3-6 are graphical representation of CO₂ concentration against relative humidity and temperature in the 1st and 3rd floors of building A. the author performed Pearson correlation (r) to establish how the relative humidity and temperature varied with CO₂ concentrations. The first set of data (Figure 3), the r was 0.37, which suggests slight positive correlation between CO₂ concentration and relative humidity, an indication that relative humidity increased slightly with increase in CO₂ concentration. Pearson correlation for Figure 4 was -0.57, an indication of moderate reduction of temperature with increasing CO₂ concentration. Data set for Figure 5 resulted to r of -0.49, an indication that relative humidity decreased slightly with increasing CO₂ concentrations while that of Figure 6, r of 0.65 indicates increasing temperature with increasing CO₂ concentrations.

Figures 7-10 are graphical representation of CO₂ concentration and temperature levels against CO₂
concentration for building B, the researchers performed Pearson correlation, \( r \), to determine how variation in temperature and relative humidity varied with \( \text{CO}_2 \) concentrations. For data set in Figure 7, the \( r \) value was 0.19 indication of slight positive change in relative humidity with \( \text{CO}_2 \) concentration. For data set in Figure 8, the \( r \) value was 0.26, a slight possibility that temperature increased with \( \text{CO}_2 \) concentration. Similarly, Figure 9 data set \( r \) value was 0.32, indication of slight possibility that temperature increased with increasing \( \text{CO}_2 \) concentration. For Figure 10 data set, \( r \) value was 0.64, indication of moderate possibility that temperature increased with increasing \( \text{CO}_2 \) concentration.

![Figure 7](image1.png)

**Figure 7:** Measured \( \text{CO}_2 \) concentration and Relative Humidity at 1st floor of Building B.

![Figure 8](image2.png)

**Figure 8:** Measured \( \text{CO}_2 \) concentration and temperature in the 1st floor of building B.

![Figure 9](image3.png)

**Figure 9:** Measured \( \text{CO}_2 \) concentration and temperature in the 3rd floor of building B.

![Figure 10](image4.png)

**Figure 10:** Measured \( \text{CO}_2 \) concentration and Relative Humidity at 3rd floor of Building B.

Figures 11 and 12 are sample graphical presentation of \( \text{CO}_2 \), Temperature and humidity levels in building C. Pearson correlation, \( r \), between \( \text{CO}_2 \) and temperature and humidity indicate significant slight correlation \( r=0.18 \) for \( \text{CO}_2 \) and humidity (Figure 11), and no correlation with temperature (Figure 12).

![Figure 11](image5.png)

**Figure 11:** Measured \( \text{CO}_2 \) concentration and Relative Humidity at 1st floor of Building C.

![Figure 12](image6.png)

**Figure 12:** Measured \( \text{CO}_2 \) concentration and temperature in the 1st floor of building C.

Figures 13 and 14 is graphical presentation of \( \text{CO}_2 \), temperature and relative humidity for building D. Correlating the values give \( r \) value of 0.3 for \( \text{CO}_2 \) and relative humidity, an indication of slight positive correlation, and \( r \) value of 0.4 for \( \text{CO}_2 \) against, showing slight correlation.

5. CONCLUSION

The study key focus was on assessment of energy efficiency and indoor environment conditions of green
buildings under occupancy. The findings revealed potentials of green building technology adoption in Kenya. Energy efficiency for green building B is significantly different from buildings C and D (p=1.18E-12) whose consumption is not significant (p=0.7) from each other. Slight to moderate correlation between CO₂ concentrations, temperature and Relative humidity exists across all the buildings. T-tests performed indicate that significant correlation between green and non-green buildings for CO₂, temperature and relative humidity.

LIST OF ABBREVIATIONS

CO₂ = Carbon Dioxide
EPRA = Energy and Petroleum Regulation Authority
EU = European Union
HVAC = Heating, Ventilation and Air Conditioning
kWh/m² = kilo Watt-hour per square meter
LED = Light Emitting Diodes
LEED = Leadership in Energy and Environmental Design

PPM = parts per million
NZEBS = Net Zero Energy Buildings
PV = Photovoltaic

CONFLICT OF INTEREST

The authors have not declared any conflict of interest.

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