Received: 14 November 2022 | Revised: 4 March 2023 | Accepted: 6 March 2023 | Published online: 13 March 2023

RESEARCH ARTICLE

Green and Low-Carbon Economy
2023, Vol. 1(1) 28–40
DOI: 10.47852/bonviewGLCE3202545

BON VIEW PUBLISHING

An Assessment of Building Energy Consumption Characteristics Using Analytical Energy and Carbon Footprint Assessment Model

Abdullahi Mohammed Usman[1,*] and **Mohammad Kamil Abdullah**[2]

[1]*Department of Mechanical Engineering, Modibbo Adama University, Nigeria*

[2]*Center for Energy and Industrial Environment Studies, Universiti Tun Hussein Onn Malaysia, Malaysia*

Abstract: This study aims at developing an analytical assessment model for use in assessing building energy consumption and associated greenhouse gas (GHG) emission characteristics. The methodology includes selecting appropriate indicators, tool development and description, indicators description, energy and carbon characteristics assessment, and performance evaluation. The characteristics measured are renewable energy adoption, overall and roof thermal transfer values (OTTV), (RTTV), and (U-value), natural ventilation and daylighting access, thermal comfort index, and daylighting access factor. Operational characteristics indexes are building energy and carbon indexes (BEI_x) and ($BECI_x$), energy and carbon reduction indexes (BERI) and (BECRI), energy and carbon intensities (BEI_y) and ($BECI_y$), and billing cost reduction (BCR). Four faculty buildings and a library building were assessed and tagged as case studies A, B, C, D, and E. The case studies assessed have BEI of 79.85, 131.37, 60.21, 161.47, and 63.86 kWh/m^2/year and BECI of 55, 91, 42, 112, and 44 kg.CO_2e/m^2/year, respectively. These values lead to BERI and BECRI of 22, 16, 27, 16, and 36%, respectively. From these results, it can be seen that case studies A, C, and E have the lowest BEI of 80, 60, and 64 kWh/m^2/year and the highest BERI and BECRI of 22, 27, and 36%, respectively. These give them a higher BCR of 36%, greater than 80 points, and indicate a performance level above the recommended threshold. The tool provides all the project-level design and operational considerations, emission reduction strategy, and estimation. The ability of the tool to assess the case study buildings makes it suitable for adoption by organizations and governments for accounting and monitoring energy usage and GHG emission associated with building life cycle activities. This study shows that utilizing appropriate strategies and practices on building design and operation, respectively, improves building energy usage.

Keywords: assessment model, building, carbon footprint, energy usage, greenhouse gas

1. Introduction

Carbon footprint (CFP) is an indicator of climate performance and a major identifier of greenhouse gas (GHG) emission sources and quantification measured in kg.CO_2e. Energy, transportation, and industrial processes were the major sources of GHG emissions. Buildings (i.e., industrial, residential or non-residential, etc.) are the major energy and industrial product consumers. Therefore, building construction, operation, and maintenance have long been acknowledged as the most significant artificial structures. This is because, building's activities imposed reasonable impacts on the global environment (Joseph & Mustaffa, 2021). Nduka & Ogunsanmi (2015), Allard et al. (2018), and Yue et al. (2022) reported that buildings and their associated activities have been accounted for being responsible for about 25–40% of world energy usage and 30–40% of GHGs released into the atmosphere globally.

*Corresponding author: Abdullahi Mohammed Usman, Department of Mechanical Engineering, Modibbo Adama University, Nigeria. Email: amugfuty@gmail.com

Excessive resources and energy use and growing demand for raw materials are largely responsible for the depletion of natural resources worldwide and hence the acceleration of global warming. About 40% of the world's resources and energy used are linked to the construction, operation, and maintenance of buildings. This contributes to one-tenth of the global economy (Allard et al., 2018; Hussin et al., 2013; International Energy Agency, 2020). Hussin et al. (2013), Balaras (2021), and Jain et al. (2021) reported that more than half of all resources consumed globally are used in construction industry. Also, about 45% of the energy generated across the world is used to heat, light, ventilate, and power our buildings and industries. Several international reports and researches like Hoornweg et al. (2011), Leggett & Carter (2012), Construction Industries Development Board Malaysia (2018), International Energy Agency (2020), and Jain et al. (2021) highly emphasize on the implementation of sustainable building and construction concepts. This will serve as a means of conserving energy and other resources which consequently mitigate global warming and hence climate change.

According to several international reports from Intergovernmental Panel for Climate Change (IPCC) and United

Nation Framework Convention on Climate Change (UNFCCC), etc., previous studies of Usman (2019) and Usman & Abdullah (2022) discussed about greenhouse (GH) effect. GH effect is a natural phenomenon that is induced when atmospheric gases trap the ultraviolet rays from the sun within the earth's atmosphere. The effect is also essential in maintaining the earth's temperature and climatic conditions. GHGs are measured qualitatively through global warming potentials (GWPs). GWP is a measure of the amount of radioactive force absorbed by the one-unit mass of a GHG to that of the one-unit mass of reference gas for a specified time. GWPs are used to convert individual GHGs to carbon dioxide equivalents (CO_2e), a standard format for reporting emissions. The combination of these individual converted gases for a certain process or product is measured as the CFP of that material, process, or product (Usman & Abdullah, 2022; Yue et al., 2022).

Assessment and accounting of GHG emissions from various human activities have become the daily sentences of speeches at various sustainable development summits and conferences. These lead to the establishment of several organizations and standards for accounting and reporting GHG emissions. The famous among the documents and standards is the united nation GHG emission inventories guides (Eggleston et al., 2006; IPCC, 2014). Others include GHG protocol guide standards for accounting and reporting various activities. These activities include product value chain (GHG Protocol, 2011) and policies-related issues in GHG emission reduction (GHG Protocol, 2014). GHG protocol developed another called GHG emission standard for international scale accounting and reporting from which various products GHG emission assessment models were developed (GHG Protocol, 2016). In line with this achievement, several researches were conducted on different assessment models for GHG emissions from various activities. CFP estimation tool for transportation in construction projects is one of the reported models by Melanta et al. (2013). Master's thesis titled CFP, a Case Study on the Municipality of Haninge by Wu (2011), is one such models. Others models include GHG emission calculation tools and guides for various types of buildings developed by Green Star (2022a). These include a tool for multi-residential buildings (Green Star, 2020), healthcare buildings (Green Star, 2021), industrial buildings (Green Star, 2019b), office buildings (Green Star, 2022b), and building performance (Green Star, 2022c). MyCrest was developed for the assessment of energy, water, material, and waste for an existing building developed by Construction Industry Development Board (CIDB) as reported in Construction Industries Development Board Malaysia (2017, 2018). Among the available rating standards for assessing building sustainability, little consideration is given to direct accounting and reporting of GHG emissions from building activities as proposed by UNFCCC, IPCC, and GHG protocol.

The energy considered in these rating systems developed by Green Star, CIDB, and several researchers covers only electricity sources. These among others lead to the concept of the idea of developing a CFP assessment model for energy consumption in buildings from design through to construction and operational phase. Even though, energy consumption in the form of electricity, burning fuel for cooking, heating, and production of secondary material, etc. is not the only source of GHG emission in the building lifecycle but it forms the major component (Balaras, 2021; Clausen et al., 2021; Jain et al., 2021; Pereira et al., 2021).

CFP as an indicator of industrial performance helps identify major GHG emission sources and potential areas of improvement (Clausen et al., 2021). In the context of greatly expanding sub-national climate efforts, research on CFP accounting at intermediate and consumption levels is timely and necessary. This is to facilitate the establishment of local, state, and national climate change and mitigation strategies. This study aims at exploring the methodologies for GH emission assessment in the form of CFP at a consumer level based on the case study of Malaysian standards and conditions. Specifically, the aim is to develop a building lifecycle energy and associated CFP assessment model (BECAM) and use it to determine the fundamental energy usage and CFP characteristics.

2. Methodology

This section describes the processes involved in the development of the model, description of indicators, and the procedure for energy characteristics assessment. In addition, the compliance with international tool development standards (socio-economic and quality assurance guides), applicability, and measurability of the indicators was also considered as reported in the previous studies of Usman (2019) and Usman & Abdullah (2022), and building sustainability tools such as Green Star SA (2014) and Marchi (2016).

2.1. Model development framework

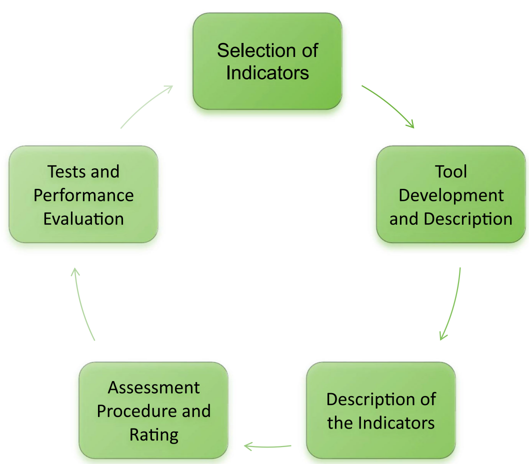
The five-step framework adopted describing the steps involved in the model development is shown in Figure 1.

2.2. Data collection

The data for the performance evaluation of the model were obtained from the Centre for Energy and Industrial Environment Studies, Universiti Tun Hussein Onn Malaysia (UTHM). The data collected contain monthly electricity consumption for the period of 2015–2019 and 2022. These data were collected using an energy monitoring (recording and fault detection) system installed in all the buildings. The installation is followed by proper building management (corrections of faults, installation of new appliances) and observing the effect over a specified period. Non-electricity sources were collected directly from the buildings.

The non-electricity source includes fuel burned in café inside the buildings, welding gas, and fuel consumed in laboratories. Data for design assessment were collected using apparatus such as a lux meter, combined thermo and speed meter, and humidity.

Figure 1
Five-step framework model for BECAM development



Five case study buildings were selected for evaluating the performance of the developed model. These buildings were the Tunku Tun Aminah Library (*PTTA*), the faculty of computer science and information technology (*FSKTM*), and the faculty of management technology (*FPTP*). The remaining buildings assessed are the faculty of vocational and technology education (*FPTV*) and the faculty of civil engineering and built environment (*FKAAB*) all at the UTHM. These selected buildings were tagged as case studies A, B, C, D, and E.

2.3. Scope and limitation of the model

The developed model and the assessment of the characteristics are limited to Malaysian commitment to the United Nation vision 2050 that there will be a reduction of GHG emissions by 40%. The study and the model are limited to some specific conditions: electricity and fuel consumed for cooking, heating rooms, and fuelling generator. The energy source must be for building lighting, cooling, ventilation, conditioning, vertical transportation, heating, cooking, laboratories, and powering faculty machinery. The study will not consider fuel consumed for vehicle and truck transportation and water generation. The models parameters and their descriptions were derived from IPCC reports (Eggleston et al., 2006), GHG protocols reports (2014, 2016), Environmental Protection Agency reports (2014), Malaysian and Singapore standards for energy efficiency MS 1525 (2014) and Building and Construction Authority (2004) as reported in previous studies of Usman (2019) and Usman & Abdullah (2022). The development of the model, assessment of energy consumption and GHG emission characteristics, and the variation of monthly energy characteristics for the selected academic buildings were only considered under Malaysian conditions.

2.4. Acronyms and abbreviations

The abbreviations used in the current study are shown in Table 1.

3. Model Development Process

3.1. Selection of indicators

The indicators selected for developing the model were adopted from previous studies of Usman (2019) and Usman & Abdullah (2022). These indicators were selected because they have measurable physical quantities called energy and carbon emission and reduction characteristics. The schematic flow diagram of the developed building energy and associated carbon assessment model (BECAM) for the design and operational phases is shown in Figures 2 and 3, respectively.

3.2. Model development and description

The building life cycle in this study was viewed in four different phases which are building design, building construction, building operation, and refurbishing and demolition. These selected indicators were described analytically to qualitatively and quantitatively account for direct and/or indirect GHG emissions associated with the building's life cycle in the form of CFP. The analytical description of these indicators as well as their corresponding sub-indicators forms the assessment model. The study covers the design, construction, and operational phase, while the performance evaluation and the data available at the time of the research support design and construction strategies and operational phase activities assessment and analyses. The model may be used for any other country by simply changing the specified data, carbon reduction target, and other conditions and constants.

The model was developed from several indicators and sub-indicators which together form the major components of building design, construction, and operation. The building design and construction phase comprise activities from the design stage of building construction that supports GHG emission reduction. These activities include providing the building with features and fittings that will monitor, control, and help in reducing unnecessary energy consumption. Providing the building with natural lighting and ventilation design will reduce the use of artificial lighting ventilators in the building, thereby reducing their associated energy consumption. Providing the building with natural ventilation will reduce the number of building components requiring an air conditioning system which consequently reduces the operational GHG emission. Also, providing the building with renewable energy readiness and adoption will reduce the use of un-renewable energy usage. The other component is designing the building facades with sustainable materials to reduce the heat conduction into the building, thereby reducing the cooling load of the building.

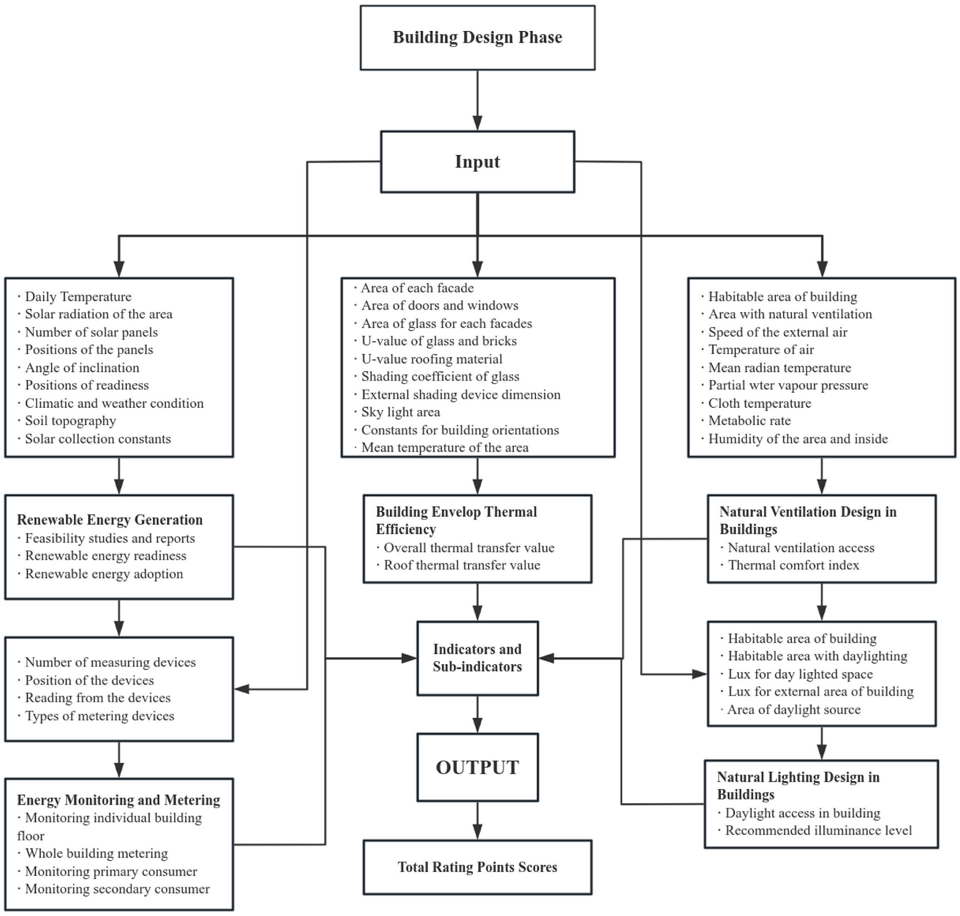
The construction phase comprises four major components regardless of the building type. These are site preparation, construction project, landscaping, road construction, and secondary material production. All these components involve the use of energy either from national grid and/or generator set for powering static and mobile construction machineries, and lighting. There are also other energy sources from burning fuel for heating and secondary material production process during construction operations. The operation phase regardless of the building type can be used mainly for heating, air conditioning systems, lift, sensors, sockets, and lighting. Also, these energies can be sourced either from the national grid, use of generator set, or by direct burning of fuel for either cooking, heating, or any other process that requires burning fuel (Usman, 2019; Usman et al., 2021; Usman & Abdullah, 2022).

The model also involve inputs that are used in the indicators and sub-indicators to describe and compute the qualitative and quantitative

Table 1
Acronyms and abbreviations

CO_2e: Carbon dioxide equivalent	BEI_Y: Building energy intensity	EF: Emission factor
CFP: Carbon footprint	BERI: Building energy reduction index	kg: kilogram
BEP: Building energy performance	$BECI_X$: Building energy carbon index	KWh: kilo Watt hour
RTTV: Roof thermal transfer value	$BECI_Y$: Building energy carbon intensity	%: Percentage
OTTV: Overall thermal transfer value	BECRI: Building carbon reduction index	J: Joules
GHG: Greenhouse gas	EC: Energy consumed	GWP: Global warming potential
BEI_X: Building energy index	FC: Fuel consumed	GFA: Gross floor area
REA: Renewable energy adoption	NDA: Natural daylighting access	DAF: Daylighting access factor
NVA: Natural ventilation access	TCI: Thermal comfort index	

Figure 2
Schematic flow diagram of the BECAM for design strategies indicators



nature of the building. The indicators for the design and construction phase are the integration of GHG reduction design specifications and policies in the building design and adopted during construction. Their integration will impact the operational energy consumption and hence reduce the CFP of the building. The input to direct construction and operation phase GHG emission include the source and type of energy used and the types of machinery used for the energy source. Others are the types of fuel used for generating the energy and the nature and type of equipment, fuel, and energy consumption during the period of assessment. To determine the energy and carbon densities, the values of the total energy usage and that of the CFP computed (either during construction or operation) were divided by gross floor area (GFA) and the average yearly occupant or organization's employees. These define the energy and carbon densities for the building or organization under assessment.

3.3. Model indicators for design strategies

Parts of the descriptions of indicators used in this study were reported in the previous studies of Usman (2019), Usman & Abdullah (2022), and Usman et al. (2021). Some indicators require physical assessment, data collection, analyses, and verification, while others require model equations for computation.

3.3.1. Renewable energy generation (REG)

Renewable energy feasibility and readiness involve designing the building to have provisions from roofing design, building environment, to the electrical components, and wiring ready to accommodate renewable energy sources, installation, and application. Renewable energy adoption (REA) includes onsite generation of renewable energy which can reduce the building operational power consumption, consequently the carbon emissions. It will be assessed by comparing the percentage quantity of non-renewable energy replaced during the operation of the building and can be calculated using equation (1) (Usman, 2019; Usman & Abdullah, 2022).

$$REA = \frac{Renewable\ Energy\ Generated}{Total\ Energy\ Requirement\ of\ the\ Building} \times 100\% \quad (1)$$

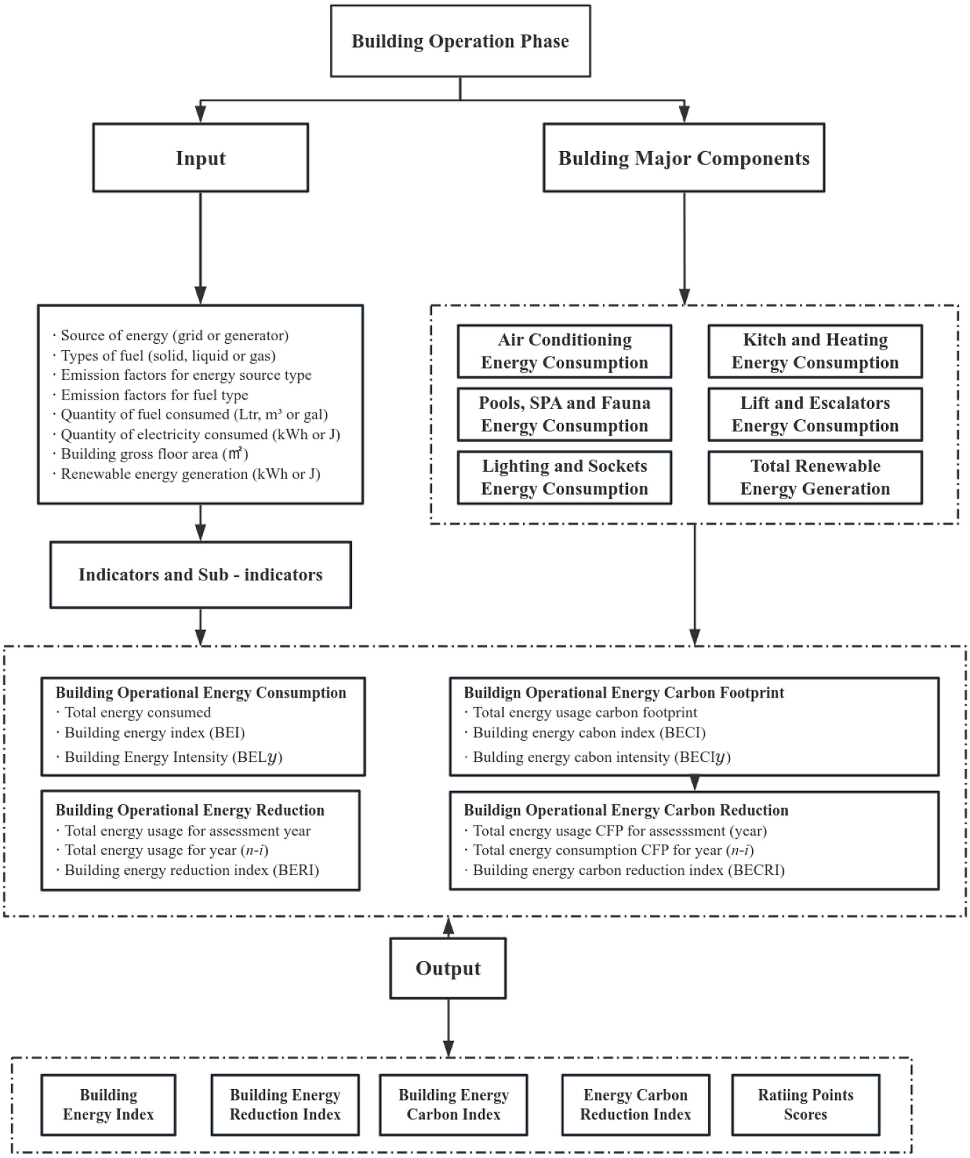
3.3.2. Energy monitoring and metering (EMM)

This indicator encourages the design of a system that monitors and manages electricity consumption. The points here can be achieved by providing metering and sub-metering in all the applicable areas. The major sub-indicators are monitoring systems capable of providing energy-loading profiles of the whole building, individual floors, and primary and secondary consumer units.

3.3.3. Envelops thermal efficiency (BETE)

This describes the solar heat gain through the building envelope. Heat gain constitutes a substantial share of the cooling load in an air-conditioned building which leads to high energy consumption. In non-air-conditioned buildings, the solar heat

Figure 3
Schematic flow diagram of BECAM for operational indicators



gains through the envelope causing thermal discomfort. This indicator encourages minimizing solar heat gain and the cooling load of the building. Fundamentally, the building envelope has to block out heat gain into buildings via conduction and solar radiation as described in MS 1525 (2014), Usman (2019), and Usman & Abdullah (2022). The indicator can be measured using the overall thermal transfer value (OTTV). This is a design sub-indicator that indicates the solar thermal load transmitted through the building envelope excluding the roof. OTTV of the building envelope for Malaysia should not exceed 50W/m^2. For all the facades, the OTTV can be computed using equation (2), while the individual facades and orientation can be computed using equation (3) (MS 1525, 2014).

$$OTTV = \frac{(A_1 \times OTTV_1) + (A_2 \times OTTV_2) + \ldots + (A_n \times OTTV_n)}{A_1 + A_2 + A_2 + \ldots + A_n} \quad (2)$$

$$OTTV_i = 15\alpha_A(1 - WWR)U_w + 6(WWR)U_f + (194 \times OF \times WWR \times SC) \quad (3)$$

where: A_i= gross exterior wall (Façade) area for orientation ($i = 1\text{-}n$); $OTTV_i = OTTV$ for different orientation ($i = 1 - n$); α_A = solar absorptivity of the opaque wall ($Ws^{1/2}m^{-1}K^{-1}$); WWR = window-to-gross exterior wall area ratio for the given orientation; U_w = thermal transmittance of an opaque wall ($Wm^{-2}K^{-1}$); U_f = transmittance of fenestration system; OF = solar orientation factor; SC = shading coefficient of the fenestration system.

These variables and constants are dependent on the region around the world for a given country. Therefore, the computation is dependent on the various countries' standards. The U-value can be computed if not supplied for the material of bricks, glazing, etc. using equations (4)–(6). For this study, the values used are reported in Usman (2019; MS 1525, 2014).

If

$$R = \frac{b}{\alpha_c}; KW^{-1} \quad (4)$$

Then

$$R_T = R_o + \frac{b_1}{\alpha_1} + \frac{b_2}{\alpha_2} + \ldots + \frac{b_n}{\alpha_n} + R_i \quad (5)$$

Therefore,

$$U = \frac{1}{R_T} \quad (6)$$

where R is the thermal resistance (K/W), b is the thickness of the components (m), and α_c is the thermal conductivity of the material ($Wm^{-1}K^{-1}$).

For the shading coefficient (SC), equations (7) and (8) are used. SC_1 usually comes with the material. If P is the extended length of the shading device from the wall and A is the height of the fenestration system, then SC_2 values for a range of R_1 for Malaysian conditions are tabulated as reported in Usman (2019) and MS 1525 (2014).

$$SC = SC_1 \times SC_2 \quad (7)$$

$$R_1 = \frac{P}{A} \quad (8)$$

Another sub-indicator under this category is the roof thermal transfer values (RTTVs) which consider whether the roof of the building has a skylight or not. The concept of RTTV is applied for roof provided with or without skylight, and the entire enclosure below is fully air-conditioned. For a roof with a skylight, the RTTV should not exceed 25 W/m^2 while for a roof without a skylight, the U-value of the roof is used and should range between 0.4 and 1.2 W/m^2 as reported in Building and Construction Authority (2004), MS 1525 (2014), Usman (2019), and Usman & Abdullah (2022). The equation for calculating RTTV for various roof types is shown in equation (9), while for the overall RTTV equation (10) (Usman, 2019; MS 1525, 2014; Building and Construction Authority, 2004).

$$RTTV_i = \frac{(A_r \text{x} U_r \text{x} T_{Deq}) + (A_s \text{x} U_s \text{x} \Delta T) + (A_s \text{x} SC \text{x} SF)}{A_0} \quad (9)$$

$$RTTV = \frac{(A_{01} \text{x} RTTV_1) + (A_{02} \text{x} RTTV_2) + \ldots + (A_{0n} \text{x} RTTV_n)}{A_{01} + A_{02} + \ldots + A_{0n}} \quad (10)$$

where $RTTV$ = roof thermal transfer value (W/m^2); A_r = opaque roof area (m^2); U_r = thermal transmittance of opaque roof area ($Wm^{-2}K^{-1}$); T_{Deq} = equivalent temperature difference (K); A_s = skylight area (m^2); U_s= thermal transmittance of skylight area ($Wm^{-2}K^{-1}$); ΔT = temperature difference between exterior and interior design condition (5K); SC = shading coefficient of the skylight; SF = solar factor (W/m^2); A_0 = gross roof area (m^2); and $A_0 = A_r + A_s$.

The U-value for the roof is a constant for any given material, but for a combination of different materials equation (11) was used (Usman, 2019; MS 1525, 2014; Building and Construction Authority, 2004).

$$U_r = \frac{(A_{r1} x U_{r1}) + (A_{r2} x U_{r2}) + \ldots + (A_{rn} x U_{rn})}{A_{r1} + A_{r2} + \ldots + A_{rn}} \quad (11)$$

where U_r = average thermal transmittance of the FA ($Wm^{-2}K^{-1}$); U_{r1} = respective thermal transmittance of different roof sections ($Wm^{-2}K^{-1}$); and A_{r1} = respective area of different roof sections (m^2).

The average weight of the roof is calculated using equation (12) (Building and Construction Authority, 2004; MS 1525, 2014; Usman, 2019).

$$W_r = \frac{(A_{r1} x W_{r1}) + (A_{r2} x W_{r2}) + \ldots + (A_{rn} x E_{rn})}{A_{r1} + A_{r2} + \ldots + A_{rn}} \quad (12)$$

where W_r = average weight of roof (kg/m^2); $A_{r1\text{-}n}$ = respective area of different roof sections (m^2); and $W_{r1\text{-}n}$ = respective weight of different roof sections (kg/m^2). Thermal transmittance U_s and $SC1$ of the skylight area can be obtained with the material, while the solar factor is tabulated as standard for every country.

3.3.4. Natural ventilation design

This encourages and recognizes the provision of increased outside air rates. This promotes a healthy indoor environment and also encourages building that facilitates good natural ventilation for a non-air conditioning space. This indicator will be accessed using two sub-indicators (Usman, 2019; Usman & Abdullah, 2022). Natural ventilation access (NVA) measures the percentage of habitable space with NV in the building. It is a design indicator that encourages reserving of appreciable areas for NV for healthy indoor air quality and the reduction of spaces requiring an air conditioning system. It is calculated using equation (13) for a single-floor building, while equation (14) was used for each floor and the average value gives the space for the entire building (Usman, 2019; Usman & Abdullah, 2022).

$$NVA = \frac{\textit{Floor Area with Natural Ventilation}}{\textit{Building Gross Floor Area}} \times 100\% \quad (13)$$

$$NVA = \frac{\textit{Floor Area with Natural Ventilation}}{\textit{Individual Floor Gross Area}} \times 100\% \quad (14)$$

The other sub-indicator is the thermal comfort index (TCI) which measures the percentage of people in the building satisfied with the NV in the habitable space provided. TCI can be calculated by summarized Finger's predicted mean vote (PMV) model and the percentage of people dissatisfied (PPD) (equations (15) and (16)). These models give the optimal thermal comfort for human activity level and clothing insulation (Beizaee et al., 2012; Usman, 2019). It is obtained for all combinations of environmental variables like air temperature (T_a), air pressure (P_a), mean radiant temperature (T_{mrt}), and relative air velocity (V_{air}) (Almeida, 2010; Parsons, 2017; Xu et al., 2017; Usman, 2019; Usman & Abdullah, 2022).

$$PMV = 0.039 * \{49.001 + 4.376 * 10^{-8} * [(T_{mrt} + 273)^4 - (T_{cl} + 273)^4] + 13.371 * \sqrt{V_{air}} * (T_a - T_{cl}) + 4.659 P_a + 0.130 T_a\} \quad (15)$$

$$PPD = TCI = 100 - 95e^{[-(0.3353PMV^4 + 0.2179PMV^2)]} \quad (16)$$

3.3.5. Natural lighting design (NLD)

This is an indicator that encourages the use of a design that optimizes the use of effective daylighting to reduce energy use from artificial lighting. This indicator can be assessed using two different sub-indicators. Natural daylighting access (NDA) in buildings assesses the percentage of habitable areas with access to daylight. This area must have a minimum illuminance for the respective application of the space at an average depth of at least 30%. This sub-indicator can be calculated using equation (17) (Usman, 2019; Usman & Abdullah, 2022).

$$NDA = \frac{Area\ Exposed\ to\ Daylighting\ in\ each\ Level}{Total\ Floor\ Area\ of\ the\ Level} \times 100\% \quad (17)$$

Recommended illuminance level (*RIL*) is a sub-indicator under this category that uses the daylighting access factor (*DAF*) of the habitable spaces. It measures the quality of the daylighting in the area considered. The DAF is the ratio of the internal illuminance ($E_{internal}$) at a point in a room to the instantaneous external illuminance ($E_{external}$). Alternatively, the ratio of E_{int} to standard illuminance level (*SIL*) for the space activity (equations (18) or (19)) was used (MS 1525, 2014; Usman, 2019; Usman & Abdullah, 2022).

$$DAF = RIL = \frac{E_{Internal}}{E_{External}} \times 100\%; \quad (18)$$

$$DAF = RIL = \frac{E_{Internal}}{SIL} \times 100\%. \quad (19)$$

3.4. Operational assessment model

3.4.1. Operational energy usage (BOEU)

This indicator recognizes improvements in the energy performance of the building above national building regulations regarding heating, cooling, and other major and primary energy consumption component. The energy usage characteristics cover all energy consumption either from the use of stationary sources, national grids, or burning of fuels for cooking, house heating, and any other energy need. This indicator was measured using two characteristics called building energy index (BEI_X) and building energy intensity (BEI_Y). BEI is the measure of the total yearly energy usage density over the building's GFA and average yearly building occupant, respectively (MS 1525, 2014; Jamaludin et al., 2017; Usman, 2019; Green Star, 2019a; Usman & Abdullah, 2022) as in equations (20) and (21).

$$BEI_X = \frac{Building\ Yearly\ Energy\ Consumption}{Total\ Building\ Floor\ Area} \quad (20)$$

$$BEI_Y = \frac{Building\ Yearly\ Energy\ Consumption}{Average\ Yearly\ Building\ Occupant} \quad (21)$$

3.4.2. Operational energy reduction (BOER)

This parameter recognizes the total energy consumption reduction of a building or industry. It can be measured using the relationship between some consecutive yearly energy consumptions and calculated using the building energy usage reduction index (BERI). If E is the total energy usage in *kWh* or *kJ*, n is the current assessment year, and i is any considered year before the assessment year which depends on the need and agreement of stakeholders, then BERI can be calculated using equation (22) (Hassana et al., 2014; Usman, 2019; Usman & Abdullah, 2022).

$$BERI = \frac{E_n - E_{n-i}}{E_{n-i}} \quad (22)$$

3.4.3. Operational energy CFP (BOEC)

This parameter covers building energy usage associated with GHG emissions for the assessment operational period of the building. The emission computation may involve the use of tier 1, 2, or 3 emission factors and scope one emission depending on the availability of data or the country's stakeholder's need. The total CFP can be calculated by multiplying the quantities of fuel energy consumed in appropriate units with appropriate emission factors (either $kgCO_2e$ per kWh or kJ). The assessment of the sub-parameters was through building energy carbon index ($BECI_X$) and building energy carbon intensity ($BECI_Y$) considering three (Environmental Protection Agency, 2014; Eggleston et al., 2006; ISO 14067: 2018, 2018; Eggleston et al., 2006; Usman, 2019; Usman & Abdullah, 2022). In the first scenarios through the National grid, the CFP contribution of the energy consumption will be through tier 1 and/or 2 using equation (23).

$$GHG\ Emission_N = \sum (EC_N * EF_N) \quad (23)$$

where N = define the source of the national grid, EC_N = quantity of energy consumed from the national grid (kJ or kWh), and EF_N = emission factor of the national grid in (kg/kJ or kg/kWh).

The second is through the use of a generator unit in the site, and the CFP associated with this category will be calculated using equation (24).

$$GHG\ Emission_F = \sum_{F=1}^{n} (FC_F * EF_F) \quad (24)$$

where F = type of fuel, FC_F = quantity of fuel consumed measured in kg, ltr. Gal, m^3, and EF_F = emission factor of the fuel used in kg/ltr., kg/Gal, kg/kg, $kg.m^3$.

The third is through the use of burning fuels for any other purpose in the building. The CFP from this phase of emission can also be obtained by multiplying the quantity of fuel used with the emissions factor of that fuel using equation (23). The total energy usage CFP can be obtained by adding all the GHG emitted for energy usage purposes. The energy-associated GHG emission characteristics BECI can be obtained by dividing total GHG emission from all the energy sources with the building GFA over the assessment year as shown in equations 25 and 26. It is measured in $kgCO_2e/m^2$/year (Eggleston et al., 2006; ISO 14067:2018, 2018; Usman, 2019; Usman & Abdullah, 2022).

$$BECI_X = \frac{Total\ GHG\ emission\ (kgCO_2e)}{Gross\ Floor\ Area/Year} \quad (25)$$

$$BECI_Y = \frac{Total\ GHG\ emission\ (kgCO_2e)}{Average\ Yearly\ Occupant} \quad (26)$$

3.4.4. Operational carbon reduction (BECR)

This parameter encourages the overall energy usage associated with GHG emission reduction over the operational period. The assessment of this parameter utilizes the building energy carbon reduction index (BECRI). The assessment of this parameter considers determining the percentage reduction in the entire energy-associated CFP over the years of assessment. The boundary of the point's distributions depends on the national emission inventories for the energy and its associated CFP. The index in comparison with the country's GHG emission inventories and standards determines the point's distribution. The index subsequently assessed the performance of the building regarding standard building energy-associated CFP reductions. If *CFP* is the emission released, n is the assessment year, and i is any other year before the assessment year as approved by the country's standard and guide, then BECRI can be calculated using equation (27)

(Environmental Protection Agency, 2014; Eggleston et al., 2006; Usman, 2019; Usman & Abdullah, 2022).

$$BECRI = \frac{CFP_n - CFP_{n-i}}{CFP_{n-i}} x100\% \tag{27}$$

3.5. Building energy assessment model

3.5.1. Points scoring model

The buildings were assessed using points scoring in all the proposed parameters. Total points scored (TPS) for GHG emission reduction strategies (s) were calculated using equations (28) and (29) (Usman & Abdullah, 2022). For assessing GHG emission quantification (q) and the average points score, equations (30) to (32) were used.

$$TPS_S = \sum_{P1}^{Pn} \Pr_s \tag{28}$$

$$\sum_{Pi=1}^{Pn} Pr_S = REG_{P1} + EMM_{P2} + TEBE_{P3} + NVD_{P4} + NLD_{P5} \tag{29}$$

$$TPS_q = \sum_{P1}^{Pn} \Pr_q \tag{30}$$

$$\sum_{Pi=1}^{Pn} Pr_q = BOEU_{P1} + BOER_{P2} + BOEC_{P3} + BOCR_{P4} \tag{31}$$

$$OPS = \frac{TPS_s + TPS_q}{2} \tag{32}$$

where P is the points scored in parameters *1* to n and Pr_s is the parameter under consideration in the emission reduction strategies. Pr_q is the parameter under consideration in emission quantification. The value from equation (32) gives the overall points scored for building performance (Usman & Abdullah, 2022).

3.5.2. Energy and CFP accounting model

The total building energy consume (BEC) in *Kj, kW*, or *kWh* and GHG emissions in the form of CFP measured in carbon dioxide equivalent (CO_2e) for available GHGs emissions. The total energy consumption and CFP can be obtained by adding energy consumed from electricity (*e*), generator (*g*), welding gas (*wg*) and cooking gas (*cg*), firewood (*cf*), and charcoal (*cc*) and subtracting renewable energy consume. For specific building operations, the total energy and CFP can be obtained using equations (33) and (34), respectively.

$$\sum BEC = BEC_e + BEC_g + BEC_{wg} + BEC_{cg} + BEC_{cf} + BEC_{cc} - REG \tag{33}$$

$$\sum CFP = CFP_e + CFP_g + CFP_{wg} + CFP_{cg} + CFP_{cf} + CFP_{cc} - CFP_{REG} \tag{34}$$

3.5.3. Energy and emission indexes models

Energy and emission characteristics are REA, OTTV, RTTV, NVA, TCI, NDA, and DAF measured in their appropriate units using equations (1)–(18). The characteristics for the quantification section include BEI_X, BEI_Y, BERI, $BECI_X$, $BECI_Y$, and BECRI in their respective units using equations (19)–(26), respectively (Usman, 2019; Usman & Abdullah, 2022).

3.5.4. Characteristics and indicators boundaries

According to previous studies by Usman (2019) and Malaysian energy standard MS 1525 (2014) and report by Evans et al. (2009) and Lim (2018), the BEI for the average Malaysian building is between 100 and 200 kWh/m^2/year, while the BECI is between 60 and 110 $kgCO_2e/m^2$/year. Also maximum thermal envelop efficiency is $50W/m^2$, $25W/m^2$, and $1.2W/m^2$ for OTTV, RTTV, and U-value, respectively (MS 1525, 2014), and 70% satisfaction is required for habitable space subjected to natural ventilation. According to the previous studies of MS 1525 (2014), Usman (2019), Usman et al. (2021), and Usman & Abdullah (2022), the average allowable value for the remaining parameters was up to 40%. These parameters include REG, daylighting provision, energy motoring, and all the operational emission quantification parameters. These are recommended by the Malaysian emission reduction target (Ministry of Natural Resources and Environment, 2015). Two points are scored for any improvement (decrease or increase as the case may be) in the characteristics indexes values. All the indicators and the characteristics indexes are assumed to have equal weight. For buildings reaching or even exceeding the recommended level, they will have a significant level of performance. As shown by Usman & Abdullah, (2022), the different energy sources were converted to kWh or MWh for easier computation of CFP. The comprehensive assessments of the case study buildings were described in the previous studies by Usman (2019) and Usman & Abdullah (2022). According to the available data obtained, the dimensions of the building facades and roofs are not the same. The material used for the buildings was approximately the same; hence, the values of OTTV, RTTV, and U-value of the buildings and roofs were the same, and all the buildings have no skylights.

4. Performance Evaluation Results

4.1. Design strategies assessment

This section described the assessment of GHG emission characteristics of one of the case study building.

Renewable energy adoption: The REA is calculated using equation (1) with solar energy generation of 764,714.4 kWh out of 5,098,096.0 kWh for the ministry of public works (JKR) Malaysia. Hence:

$$REA = \frac{764,714.40}{5,098,096.00} * 100\% = 15\%$$

Overall thermal transfer values: The remaining design and construction characteristics components were tested using data from case study A. The OTTV of the building is calculated using equations (2)–(10) as was seen from Tables 2, 3, 4, and 5 and the gross façade area of 17,511.13 m^2.

Total heat conduction through the wall facades is calculated from Table 3 and equation (3) to be:

$$\sum 15 * \alpha * (1 - WWR) * U_w = \sum (A * OTTV_{hcw}) = 45,964.97W$$

Total heat conduction through glazing material is calculated from Table 4 and equation (3) to be:

$$6 * (WWR) * U_f = \sum (A * OTTV_{hcg}) = 107,244.12\ W$$

Total solar heat radiation through glazing material is calculated from Table 5 and equation (3) to be:

Table 2
Building facades area dimensions

Facades	Gross area	Gross wall area		Gross window area
		Wall 1	Wall 2	
East Facade	3630.66	1060.29	397.80	2172.57
West Facade	5161.83	2395.26	–	2765.80
North Facade	3630.66	1060.29	397.80	2172.57
South Facade	5088.75	662.49	795.60	3630.66

$$= 194 * OF * (WWR) * SC = \sum (A * OTTV_{hrg})$$

$$= 561,612.89\ W$$

The OTTV was calculated using a total area of 714,821.98 W, and a total façade area of 17,511.13 m^2 in equation (2).

$$OTTV = \frac{\sum (A * OTTV)}{Total\ Fe\ Area} = \frac{714,821.98}{17,511.13} = 40.82Wm^{-2}$$

Roof thermal transfer value: The RTTV in the form of a U-value for a roof without a skylight is calculated using data in Table 6 and equation (6). Therefore,

$$U - Value = \frac{1}{\sum R_i} = \frac{1}{2.059} = 0.486Wm^{-2}$$

Natural ventilation access: This is calculated using equations (13) or (14) with 1093.64 m^2 naturally ventilated area out of 56,189.45 m^2 total area.

$$NVA = \frac{1,093.64}{56,189.45} * 100\% = 2\%$$

Thermal comfort index: The TCI of the naturally ventilated area is calculated using equations (15) and (16) with data in Table 6 at five various locations in the study area exposed to natural ventilation.

Using data from Table 7, T_{cl} as 35ºC, and equations (15) and (16), the *PMV* is 2.56 while the *PPD* = *TCI* = 100%.

Natural daylighting access: The NDA of the building is calculated using equation (17) with 42,142.088 m^2 daylighted area out of 56,189.45 m^2 total building floor area.

$$NDA = \frac{42,142.088}{56,189.45} * 100\% = 75\%$$

Daylighting access factor: The DAF of the daylighted area is calculated using equation (19) with data in Table 8 (at seven various locations in the study area exposed to natural lighting) and minimum recommended internal illuminance level of 500 lux for reading, library, group discussion, and teaching (MS 1525, 2014). From the data in Table 8, the DAF was

$$DAF = \frac{693.036}{500} * 100\% = 139\%$$

Case study A was used for testing the performance of the indicators in the design and construction strategies. Also, the case study has excellent REA of 15%, and OTTV and U-value of 40.82 W/m^2

Table 3
Thermal conduction through building walls (A * OTTV$_{hcw}$)

Facades	AREA	Constant	Solar absorption	WWR	(1-WWR)	U-Value	OTTV	A * OTTV$_{hcw}$
East Wall 1	1060.29	15	0.40	0.520	0.480	2.870	8.26	8758.09
East Wall 2	397.80	15	0.25	0.520	0.480	2.230	4.01	1595.71
West Wall	2395.26	15	0.40	0.520	0.480	2.870	8.26	19,785.14
North Wall 1	1060.29	15	0.40	0.520	0.480	2.870	8.26	8758.09
North Wall 2	397.80	15	0.25	0.520	0.480	2.230	4.01	1595.71
South Wall 1	662.49	15	0.40	0.520	0.480	2.870	8.26	5472.22
South Wall 2	795.60	15	0.25	0.520	0.480	2.230	4.01	3191.42

Table 4
Solar heat conduction through glazing materials (A * OTTV$_{hcg}$)

Facades	AREA	Constant	WWR	U-Value	OTTV	A * OTTV$_{hcg}$
East Glass	2172.57	6	0.52	3.20	9.98	21,690.94
West Glass	2765.80	6	0.52	3.20	9.98	27,613.77
North Glass	2172.57	6	0.52	3.20	9.98	21,690.94
South Glass	3630.66	6	0.52	3.20	9.98	36,248.49

Table 5
Solar heat radiation through glazing materials (A * OTTV$_{hrg}$)

Facades	AREA	Constant	WWR	OF	SC1	SC2	SC	OTTV	A * OTTV$_{hrg}$
East Glass	2172.57	194	0.52	1.23	0.75	0.68	0.51	63.28	137,484.61
West Glass	2765.80	194	0.52	0.94	0.75	0.71	0.53	50.50	139,660.49
North Glass	2172.57	194	0.52	0.90	0.75	0.71	0.53	48.35	105,036.66
South Glass	3630.66	194	0.52	0.92	0.75	0.71	0.53	49.42	179,431.14

Table 6
U-value computation for roofing material

S/No	Material	Thickness (b) (m)	Thermal Conductivity (α)	Thermal Resistance (R = b/α)
1	External surface	–	–	0.044
2	Steel structure	0.0040	50	0.000080
3	Internal air cavity	–	–	0.090
4	Cement screed (60 mm)	0.06	0.51	0.118
5	Water proof membrane	0.00092	0.23	0.004
6	Expanded polystyrene (60 mm)	0.060	0.04	1.500
7	RC slap (250 mm thick)	0.25	2.3	0.109
8	Internal air cavity	–	–	0.090
9	Plasterboard liner (15 mm thick)	0.015	0.25	0.060
10	Internal surface	–	–	0.044
	Total (R)			2.059

Table 7
Average TCI parameters at various points

Parameters	Point 1	Point 2	Point 3	Point 4	Point 5	Average
T_{mrt}	37.5	39.0	38	37	38.5	38°C
P_a	5.96	6.63	6.63	6.85	7.10	6.63 kPa
T_a	33	32	30	30	30	31°C
V_{air}	0.45	0.55	0.50	0.45	0.55	0.5 m/s

Table 8
Average inside illuminance for each floor of the library

Floor	N1	N2	N3	N4	N5	N6	N7	Average
1st floor	700	650	720	500	690	450	750	637.143
2nd floor	750	450	650	630	750	620	710	651.429
3rd floor	740	730	750	740	750	700	750	737.143
4th floor	750	740	750	740	750	745	750	746.429
Average	735	642.5	717.5	652.5	735	628.75	740	693.036

and 0.486 W/m^2, respectively, which show low heat conduction into the building. It can also be seen that the building has less space subjected to natural ventilation with poor thermal comfort of 100% of dissatisfaction except with electric ventilation systems especially, standing, and wall or ceiling fans. Up to 75% of the building's total floor area was exposed to natural daylighting with an excellent illuminance level of an average of 693 lux. In comparison, the building has about 40% above the minimum allowable illuminance in the floor area. These results show that the components of the model were assessed using simple data obtained from the daily running of the organization. A similar procedure was used to assess the remaining case study buildings, and the results of the assessment, rating, and points score are shown in Table A1.

4.2. Operational characteristics assessment

The summary of the computation of the operational energy usage characteristics is shown in Table A1. The summary of the variation of energy and carbon indexes and intensities is shown in Figures 4 and 5. Additionally, the yearly billing cost analysis is also examined and presented in Table A2. The percentage reductions in energy usage, carbon emission, and billing costs are shown in Figure 6.

These results in Figures 4, 5, and 6 show that the buildings with the highest energy consumption were the library, FKAAB, and FPTV with 3767.97 MWh and 3581.76 MWh in 2022, respectively. Due to the highest GFA of the library building utilising air conditioning (as the major energy-consuming device) make it's BEI to be 67.06 kWh/m^2/year. This value is reasonably low even below the recommended level. This gives the library building more advantage over the other buildings. FPTP and FKAAB have the lowest BEI_x of 58.48 kWh/m^2/year and 55.09 kWh/m^2/year, respectively, making them the most energy-efficient buildings followed by the Library building. FPTV building with a BEI_x of 135.54 kWh/m^2/year becomes the building with poor rating due to its heavy machinery as compared to GFA. Even though, energy consumed by the FSKTM building is smaller than Library, FPTV, and FKAAB and

Figure 4
Variation of energy and carbon indexes for the case study buildings

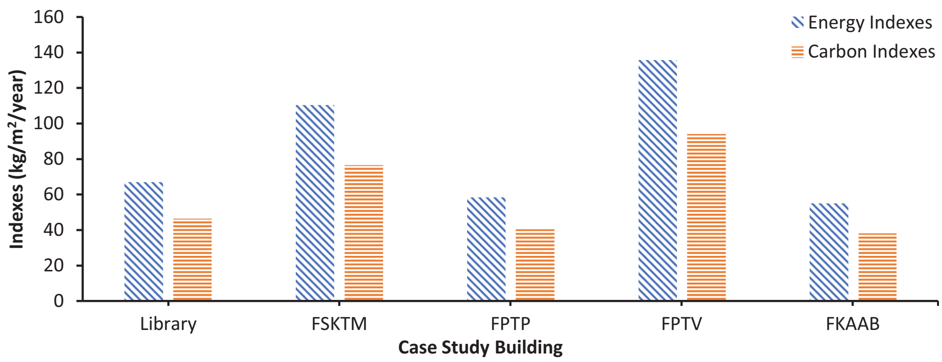


Figure 5
Variation of energy and carbon intensities for the case study buildings

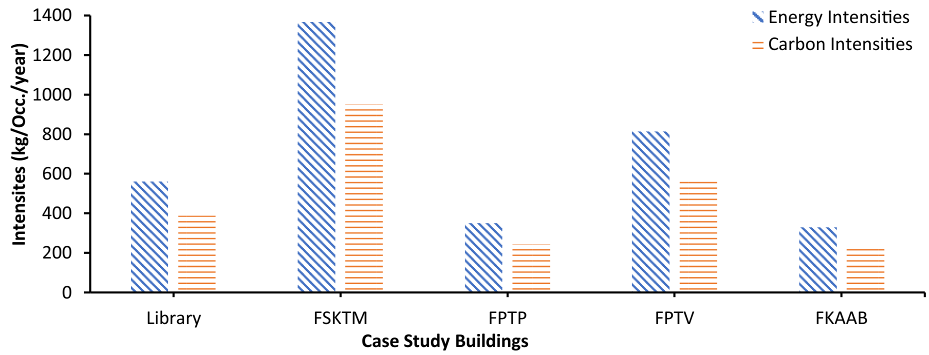
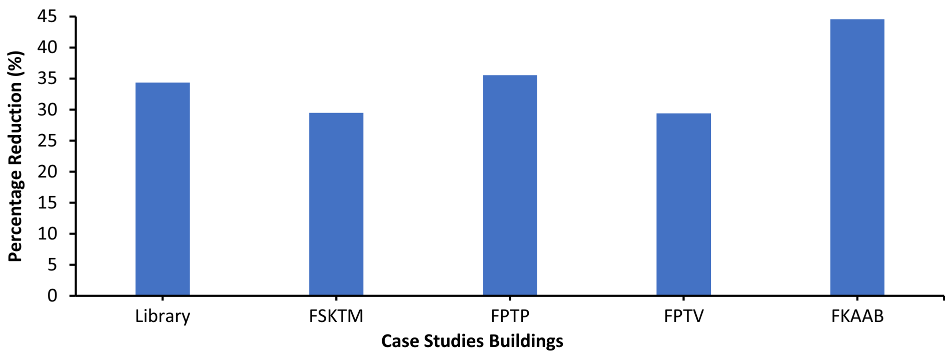


Figure 6
Percentage reduction in energy consumption, carbon footprint, and energy billing cost



also has the smallest GFA as compared to all the case study buildings. But still its BEI_x of 110.28 kWh/m^2/year is second to the highest which makes it together with FPTV (having the highest BEI_x) less energy-efficient building. This can also be seen from their percentage energy and carbon reduction of 30–36%, respectively.

Therefore, these two buildings need proper energy monitoring systems to critically monitor their unusual energy consumption. The buildings with better energy and CFP reduction were FKAAB and FPTP with 45% and 36%, respectively, making buildings with better reduction performance. Considering the quantity of GHG emitted as a result of energy consumption, the best building is FPTP followed by FKAAB and Library with $BECI_x$ of 38.23, 40.59, and 46.54 kgCO_2e/m^2/year, respectively, which also defines their energy-efficient practices, while the remaining two buildings having 76.53 and 94.06 kgCO_2e/m^2/year carbon densities were buildings with low energy-efficient practices. The values of energy and carbon characteristics measured were within the range reported in Building and Construction Authority (2004), MS 1525 (2014), and GBI (2017) and research by Evans et al. (2009) and Lim (2018). The values of the energy and carbon intensities BEI_Y and $BECI_Y$ are directly proportional to that of BEI_X and $BECI_x$; hence, their impact on the indicators and other rating characteristics were the same as was presented in Table A1. The poor points score for the buildings in the design assessment other than the library was a result of the lack of provision of natural lighting and sources of ventilation and renewable energy design readiness in all the buildings. This makes the buildings score less than 35 to 39 points in the design assessment while the highest score was seen in the Library building with 58 points due to the provision of NLD and proper EMM. FPTP and FKAAB followed by Library building have five-star rating, while FSKTM and FPTV have two stars and one star, respectively.

From the results in Table A2, it can be seen that case study E has the highest percentage reduction in billing cost of 45% after 3 years of proper energy management. This building is followed by case study A and C with 34% and 36% reduction from the other buildings and the remaining building reported a 29% reduction each. In terms of percentage billing cost reduction (BCR), case study E is the best performed building followed by case studies A and then C. Considering individual case studies in Table A2, case study A shows the highest BCR of RM 719,249.79 even though with average BCR of 34%. This is followed by case study E and D with about RM 679,385.34 BCR but with highest percentage reduction of 45% and RM 544,472.01 and 30% BCR, respectively. All the case studies provide a total of RM 2,265,067.28 reduction in the billing cost from 2015 to 2022. This amount of money is more than the amount spend on the purchase and installation of energy monitoring systems in the buildings. In terms of amount of BCR, it can be seen from the result that case studies A, E, and D are the most energy-efficient buildings. Therefore, proper design and monitoring of energy consumption not only reduce the CFP of the building but also recover a large amount of money that might be spent on purchasing energy from the utility.

Green technology provides the ability for buildings to use energy resources effectively, create a favorable environment, and reduce their environmental impact and operating costs (Wilson, 2022; Zhigulina & Ponomarenko, 2018). These results and analyses show that the energy management systems installation and proper management of these buildings reduce the energy consumption of the buildings. The reduction of 6,205,648.42 kWh of total energy consumption from the buildings shows a reduction of about 4,306,720.0 kgCO_2e of GHG per year. These reductions in energy usage associated with GHG emissions in turn reduce the impact of the buildings on local and universal climate change. The reduction in energy consumption means reducing the energy purchase cost of up to RM 2,265,067.28 ($503,328.28) in the assessment period which is a surplus of the yearly budget. These amount reductions in the maintenance cost increase the economic sustainability of the assessed buildings.

5. Conclusions

The building design phase considers factors that when considered and complied with during the construction will lead to a reduction of direct operational GHG emission and hence reduce the CFP of the building. The operational phase considers the monthly and yearly energy consumption from various sources and its associated GHG emission in the form of CFP. It was concluded that BECAM covers the entire energy consumption associated with building design and operation. It helps to fully identify the major energy consumption components and the variation of monthly energy consumption as well as CFP. The BECAM was successfully developed analytically using state-of-practice methodologies comprising available global as well as national regulations and standards. The energy and CFP characteristics assessed define the energy usage efficiency and management of the building life cycle assessment and will provide insight into unnecessary energy usage in the building. The indexes used for analyzing the behavior of the model on the case study buildings were the basic building performance assessment parameters. These include building energy and carbon indexes BEI and BECI, as building energy, and carbon intensities which define the behavior of the consumption against the GFA and occupant. The model also describes the behavior of the building energy consumption reduction over successive periods by assessing the building energy and carbon reduction indexes BERI and BECRI.

The model was specifically developed for either new or old building structures to aid in the quantification of emissions from all major building life cycle stages and components. To assess a new building, the design phase and construction phase assessment will be considered as they provide a CFP reduction strategy and the CFP for the entire new construction process. To assess the building in its second year and above, the design phase and the operational phase footprint should be used. This is because, the operational phase assessment provides the CFP for the yearly operational periods and their corresponding yearly CFP reduction. Malaysian standard and IPCC national GHG emission inventories guides were the major basis for this study. From this standard, the basic conceptual formulations were selected for emission reduction strategies and emission estimation from the assessment.

The design assessment indicators considered cover the design aspect of reducing the building CFP. The analytical procedure followed to describe the categories and parameters fully coverage of the building life cycle CFP assessment. The construction and operational GHG emission assessment indicators as well as sub-indicators define the major and minor energy consumption components and sources from the building activities. The assessment reveals that case studies A, C, and E with BEI of 67, 58, and 55 kWh/m^2/year, respectively, were the building with better performance and five-star ratings. This can be seen from their BERI and BECI in Table A1 and Figure 4. Utilizing appropriate strategies and practice from building design and operation, respectively, improves the building energy usage, CFP, and billing cost by up to a maximum of 45%. These also reduce the billing cost to a total of RM 2,265,067.28 for all the case study buildings which are highly significant.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

References

Allard, I., Olofsson, T., & Nair, G. (2018). Energy evaluation of residential buildings: Performance gap analysis incorporating uncertainties in the evaluation methods. *Building Simulation*, *11*, 725–737. https://doi.org/10.1007/s12273-018-0439-7

Almeida, H. S. (2010). *Thermal comfort analysis of building using theoretical and adaptive models*. Spain, Instituto Superior Tecnico.

Balaras, C. A. (2021). Energy efficiency and building performance. In *Educational Webinar on Managing Energy Markets in a Complex World, 2021*, 1–26. http://doi.org/10.13140/RG.2.2.11495.78245

Building and Construction Authority Singapore. (2004). *Guidelines on envelope thermal transfer value for building*. Building and Construction Authority.

Beizaee, A., Firth, S. K., Vadodaria, K., & Loveday, D. (2012). Assessing the ability of PMV model in predicting thermal sensation in naturally ventilated buildings in UK. In *Proceedings of 7th Windsor Conference: The changing context of comfort in an unpredictable world*. 2012, 1–17.

Construction Industries Development Board Malaysia. (2017). *Malaysian carbon reduction and environmental sustainability tool (MyCREST)*. Construction Industries Development Board. Retrieved from: https://www.scribd.com/document/270240656/myCrest-pdf

Construction Industries Development Board Malaysia. (2018). *Construction industries development board*. Retrieved from: http://www.cidb.gov.my/

Clausen, A., Arendt, K., Johansen, A., Sangogboye, F. C., Kjærgaard, M. B., Veje, C. T., & Jørgensen, B. N. (2021). A digital twin framework for improving energy efficiency and occupant comfort in public and commercial buildings. *Energy Informatics*, *40*, 1–19. https://doi.org/10.1186/s42162-021-00153-9

Environmental Protection Agency. (2014). *Emission factors for greenhouse gas inventories*. USA Goverment. Retrieved from: https://www.epa.gov/climateleadership/ghg-emission-factors-hub

Evans, M., Shui, B., & Takagi, T. (2009). *Country report on building energy codes in Japan*. United States. https://doi.org/10.2172/978545

Green Star. (2019a). *Energy consumption and greenhouse gas emissions calculation Guide*. Green Building Council of Australia.

GBI. (2017). *Green building index rating systems*. Green Building Index Bhd, Sdn. Retrieved from: www.greenbuildingindex.org

GHG Protocol. (2011). *GHG protocol: product life cycle accounting and reporting standard*. Retrieved from: https://ghgprotocol.org/sites/default/files/standards/Product-Life-Cycle-Accounting-Reporting-Standard_041613.pdf

GHG Protocol. (2014). *Policy and action standard: An accounting and reporting standard for estimating the greenhouse gas effects of policies and actions*. Retrieved from: https://ghgprotocol.org/sites/default/files/standards/Policy%20and%20Action%20Standard.pdf

GHG Protocol. (2016). *Emission calculation tools*. Retrieved from: http://www.ghgprotocol.org/calculation-tools

Green Star. (2019b). *Green star industrial building: Greenhouse gas emission calculator guide*. Green Building Council Australia.

Green Star. (2020). *Green star multi-residential buildings: Greenhouse gas emission calculation guide*. Green Building Council Australia.

Green Star. (2021). *Green star health care building: Greenhouse gas emission calculator guide*. Green Building Council Australia.

Green Star. (2022a). *Green star greenhouse gas emission calculator guide*. Green Building Council Australia.

Green Star. (2022b). *Green star office: Greenhouse gas emissions calculator guide*. Green Building Council Australia.

Green Star. (2022c). *Green star building performance: Greenhouse gas emissions calculator guide*. Green Building Council Australia.

Green Star SA. (2014). *Green star SA – Socio-economic category: Fact sheet*. Green Building Council South Africa.

Hassana, J. S., Zin, R. M., Abd Majidc, M. Z., Balubaid, S., & Hainina, M. R. (2014). Building energy consumption in Malaysia: An overview. *Jurnal Teknologi*, *70*(7), 33–38.

Hoornweg, D., Sugar, L., & Trejos Gomez, C. L. (2011). Cities and greenhouse gas emissions: moving forward. *Environment & Urbanization*, *23*(1), 207–227. http://10.1177/0956247810392270

Hussin, J. M., Rahman, I. A., & Memon, A. H. (2013). The way forward in sustainable construction: issues and challenges. *International Journal of Advances in Applied Sciences*, *2*(1), 15–24. http://iaesjournal.com/online/index.php/IJAAS

International Energy Agency. (2020). *Energy efficiency 2020.* Energy Efficiency Division of International Energy Agency.

Eggleston, H. S., Buendia, L., Miwa, K., Ngara, T., & Tanabe, K. (2006). *2006 IPCC guidelines for national greenhouse gas inventories*. Japan: PCC National Greenhouse Gas Inventories Programme.

Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M., & Troxler, T. G. (2014). 2013 supplement to the 2006 IPCC guidelines for national greenhouse gas inventories: Wetlands.Switzerland. International Panel for Climate Change.

International Organization for Standardization. (2018). *Greenhouse gases: Carbon footprint of product: Requirements and guidelines for quantification.* International Organization for Standardization.

Jain, N., Burman, E., Mumovic, D., & Davies, M. (2021). Managing energy performance in buildings from design to operation using modeling and calibration. *Building Services Engineering Research and Technology*, *42*(5), 517–531. http://10.1177/01436244211008317

Jamaludin, A. A., Mahmood, N. Z., & Ilham, Z. (2017). Performance of electricity usage at residential college buildings in the University of Malaya campus. *Energy for Sustainable Development*, *40*, 85–102. https://doi.org/10.1016/j.esd.2017.07.005

Joseph, V. R., & Mustaffa, N. K. (2021). Carbon emissions management in construction operations: a systematic review. *Engineering, Construction and Architectural Management*, *30*(3), 1271–1299. https://doi.org/10.1108/ECAM-04-2021-0318

Leggett, J. A., & Carter, N. T. (2012). *Rio+20: The United Nations Conference on Sustainable Development, June 2012.* Congressional Research Service.

Lim, J. (2018). *Building energy index and green building index Malaysia*. Green Building Index. Retrieved from www.blog.japhethlim.com

Marchi, L., Antonini, E., & Politi, S. (2021). Green Building Rating Systems (GBRSs). *Encyclopedia, 1*(4), 998–1009. https://doi.org/10.3390/encyclopedia1040076

Melanta, S., Miller-Hooks, E., & Avetisyan, H. G. (2013). Carbon footprint estimation tool for transportation construction projects. *Journal of Construction and Management*, *139*(5), 547–555. http://doi.org/10.1061/(ASCE)CO.1943-7862.0000598

Ministry of Natural Resources and Environment. (2015). *First biennial update report submitted to the United Nations framework convention on climate change in December 2015*. Ministry of Natural Resources and Environment, Malaysia.

Malaysia Standards. (2014). *MS 1525-2014, Malaysian standard: Energy efficiency and use of renewable energy for non-residential buildings – Code of practice*. Department of Standard Malaysia.

Nduka, D. O., & Ogunsanmi, O. E. (2015). Construction professionals' perception on green building awareness and accruable benefits in construction projects in Nigeria. *Covenant Journal of Research in the Built Environment*, *3*, 30–52.

Parsons, K. (2017). *Overview of design regulations for thermal comfort – Reviews and highlights of latest thermal comfort standards*. Loughborough University.

Pereira, V., Santos, J., Leite, F., & Escorsio, P. (2021). Using BIM to improve building energy efficiency – A scientometric and systematic review. *Energy and Buildings*, *250*, 111292. https://doi.org/10.1016/j.enbuild.2021.111292

Usman, A. M. (2019). *Development of carbon footprint quantification and reduction (cafquar) assessment tool for selected non-residential building*. Doctoral dissertation, Universiti Tun Hussein Onn Malaysia.

Usman, A. M., & Abdullah K. (2022). Development of comprehensive energy usage impact and carbon footprint parameters for green building life cycle assessment. *Journal of Engineering, Design and Technology, ahead-of-print*, 1–25. https://doi.org/10.1108/JEDT-11-2021-0655

Usman, A. M., Mohammed, A. N., Mohideen, M. F., Ali, M. F. M., Abdullah, K., & Taweekun, J. (2021). Energy profiling for residential college buildings. *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences, 81*(2), 139–145. https://doi.org/10.37934/arfmts.81.2.139145

Wilson, A. (2022). *Revision of the energy performance of buildings directive: Fit for 55 package.* Belgium. European Parliamentary Research Service.

Wu, W. (2011). *Carbon footprint – A case study on the municipality of Haninge*. Masters Thesis, KTH Royal Institute of Technology.

Xu, Z., Hu, G., Spanos, C., & Schiavon, S. (2017). PMV-based event-triggered mechanism for building energy management under uncertainties. Building and Energy, *152*, 73–85. https://doi.org/10.1016/j.enbuild.2017.07.008

Yue, J., Li, W., Cheng, J., Xiong, H., Xue, Y., Deng, X., & Zheng, T. (2022). A dynamic calculation model of the carbon footprint in the life cycle of hospital building: a case study in China. *Engineering, Construction and Architectural Management, 30*(10), 4735–4761. https://doi.org/10.1108/ECAM-05-2022-0395

Zhigulina, A. Y., & Ponomarenko, A. M. (2018). Energy efficiency of high-rise buildings. In *E3S Web of Conferences, 33*(02003), 1–6. https://doi.org/10.1051/e3sconf/20183302003

How to Cite: Usman, A. M. & Abdullah, M. K. (2023). An Assessment of Building Energy Consumption Characteristics Using Analytical Energy and Carbon Footprint Assessment Model. *Green and Low-Carbon Economy* 1(1), 28–40, https://doi.org/10.47852/bonviewGLCE3202545

Appendix

Table A1
Operational energy usage and GHG emission characteristics assessment

Description	Library case study (A)	FSKTM case study (B)	FPTP case study (C)	FPTV case study (D)	FKAAS case study (E)
Building operational energy consumption					
a. 2022 Total energy usage (kWh/year)	3,767,968.4	1,261,074.2	847,358.35	3,581,760.9	2,317,070.3
b. Building gross floor area (m^2)	56,189.45	11,435.68	14,489.04	26,426.00	42,057.50
c. **Building Energy Index (kWh/m^2/year)**	**67.06**	**110.28**	**58.48**	**135.54**	**55.09**
d. Building allowable design occupant (Occ.)	6723	923	2415	4404	7010
e. **Building Energy Intensity (kWh/occ./year)**	**560.46**	**1366.28**	**350.87**	**813.30**	**330.54**
Building operational energy consumption reduction					
a. 2022 Total energy usage (MWh)	3,767.97	1,261.07	847.36	3,581.76	2,317.07
b. 2015 Total energy usage (MWh)	5,738.52	1,787.95	1,202.56	5,073.47	4178.40
c. Difference (MWh)	-1,970.55	-526.88	-355.20	-1,491.71	-1,861.33
d. **Building energy reduction index (%)**	**(-) 34%**	**(-) 29%**	**(-) 36%**	**(-) 29%**	**(-) 45%**
Building energy consumption CFP					
a. 2022 Total energy consumption (MWh)	3,767.97	1,261.07	847.36	3,581.76	2,317.07
b. Energy emission factor (kg/MWh)	694	694	694	694	694
c. Operational CFP (kgCO_2e)	2,614,970.1	875,185.48	588,066.7	2,485,742.1	1,608,046.8
d. Building gross floor area (m^2)	56,189.45	11,435.68	14,489.04	26,426.00	42,057.50
e. Energy carbon index (kgCO_2e/m^2/year)	**46.54**	**76.53**	**40.59**	**94.06**	**38.23**
f. Building allowable design occupant (Occ.)	6723	923	2415	4404	7010
g. **Energy carbon intensity (kgCO_2e/occ./year)**	**388.96**	**948.20**	**243.51**	**564.43**	**229.39**
Building energy consumption carbon reduction					
a. 2022 Total CFP (TCO_2e)	2,614.97	875.19	588.07	2,485.74	1,608.05
b. 2015 Total CFP (TCO_2e)	3,982.53	1,240.84	834.58	3,520.98	2,899.81
c. Difference (TCO_2e)	-1,367.56	-365.65	-246.51	-1,035.24	-1291.76
d. **Energy carbon reduction index (%)**	**(-) 34%**	**(-) 29%**	**(-) 36%**	**(-) 29%**	**(-) 45%**
Points scoring and rating					
a. Average Points Score (Points)	89	43	80	37	80
b. Star Rating	✰✰✰✰✰	✰✰	✰✰✰✰✰	✰	✰✰✰✰✰
Remarks	Excellent Practice	Satisfactory	Excellent Practice	Fair	Excellent Practice

Table A2
Summary of cost analysis for the case study buildings

Case Studies	Yearly Energy Usage Cost (RM) (0.365RM/KWh)						Total Reduction	Percentage
	2015	2016	2017	2018	2019	2022		
A	2,094,558.27	1,747,382.75	1,637,566.66	1,535,772.05	1,467,216.24	1,375,308.48	719,249.79	34
B	652,601.95	584,727.82	548,345.31	513,996.47	491,052.02	460,292.07	192,309.88	29
C	438,936.06	393,074.28	318,416.35	345,371.60	329,954.44	309,285.80	129,650.26	36
D	1,851,814.75	1,657,183.98	1,557,435.61	1,459,876.44	1,394,708.55	1,307,342.74	544,472.01	29
E	1,525,116.00	1,074,847.17	980,395.65	944,405.95	902,248.31	845,730.66	679,385.34	45
Total	6,419,300.23	5,457,216.00	5,042,159.59	4,799,422.49	4,585,179.56	4,297,959.75	2,265,067.28	