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Energy consumption and carbon emission of conventional and green buildings using building information modelling (BIM)

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Abstract

Purpose – Using building information modelling (BIM) technology, a conventional structure in this study was converted into a green building to measure its energy usage and CO2 emissions.
Design/methodology/approach – Digital images of the existing building conditions were captured using unmanned aerial vehicle (UAV), and were fed into Meshroom to generate the building's geometry for 3D parametric model development. The model for the existing conventional building was created and converted to an energy model and exported to gbXML in Autodesk Revit for a whole building analysis which was carried out in the Green Building Studio (GBS). In the GBS, the conventional building was retrofitted into a green building to explore their energy consumption and CO2 emission.
Findings – By comparing the green building model to the conventional building model, the research found that the green building model saved 25% more energy while emitting 46.8% less CO2.
Practical implications – The study concluded that green building reduces energy consumption, thereby reducing the emission of CO2 into the environment. It is recommended that buildings should be simulated at the design stage to know their energy consumption and carbon emission performance before construction.
Social implications – Occupant satisfaction, operation cost and environmental safety are essential for sustainable or green buildings. Green buildings increase the standard of living and enhance indoor air quality.
Originality/value – This investigation aided in a pool of information on how to use BIM methodology to retrofit existing conventional buildings into green buildings, showing how green buildings save the environment as compared to conventional buildings.

Keywords Carbon emission, Conventional building, Energy consumption, Green building

Paper type Research paper

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1. Introduction

Since the industrial revolution, human activities have contributed significantly to climate change by adding more carbon dioxide (CO_2) and other heat-trapping gases to the atmosphere and consequently disturbing the natural processes to reach equilibrium (EPA, 2022; IPPC, 2007). Approximately 80–90% of the energy in buildings is utilized during the operational phase of a building's life cycle, while the other 10–20% is used during the extraction and processing of raw materials, manufacturing of products and construction (Ecr, 2022; UNEP, 2009; UNFCC, 2019). The pressing need to meet carbon targets has spurred the growth of low-carbon buildings and technologies throughout the world. However, the growing performance gap between the designed and measured energy performance of buildings (and hence their CO_2 emissions) is a serious stumbling block to realizing these targets (ASHRAE, 2022; Gupta and Gregg, 2014). To comply with the 2050 EU carbon reduction agenda by reducing considerably, the CO2 emission caused by energy use in existing buildings requires retrofitting (EU, 2018).

According to Koranteng and Abaitey (2011), the increasing demand for energy in Ghana is among other factors, caused by the numerous newly constructed air-conditioned buildings, especially in the metropolitan areas of Accra and Kumasi (Koranteng *et al.*, 2021; Koranteng and Abaitey, 2011). There is a lack of energy simulation and analysis of a building before it is built (Abdullah and Alibaba, 2022; Michalak, 2022; Mohammed, 2022). Therefore, existing conventional buildings consume a lot of energy and emit CO_2. This leads to the conclusion that buildings must be simulated to be green and environmentally friendly (Koranteng *et al.*, 2021b).

According to Autodesk (2010), building information modelling (BIM) software can be used for the analysis of natural ventilation systems and optimization to reduce building energy use as well as to raise a building's thermal comfort level. Built on the key effects of building occupancy and equipment, BIM software can estimate the potential capacity for natural ventilation to handle the heating and cooling loads of buildings. Lu *et al.* (2017) observed that BIM software helps users evaluate the feasibility of using natural or mixed modes of ventilation strategies based on the predicted results. According to Kia (2013), several software applications that are available convert 2D design data into a 3D model. These models are capable of rotating the entire structure to view any side or zooming in on a particular design element. Agele (2012) listed several BIM software packages which include Autodesk Architectural Desktop, Autodesk Revit, Bently Systems, Graphisoft, ArchiCAD and Nemetschek. Gu and London (2010) acknowledge the practice of the current BIM technology. Green Building Studio (GBS) is a flexible cloud-based service that enables the running of building performance simulations to optimize energy efficiency and to work towards carbon neutrality in the early conceptual phase of the design process. This software is a whole model energy analysis tool. GBS will help extend your ability to design high-performance buildings at a fraction of the time and cost of conventional methods (Mousiadis and Mengana, 2016).

The world's energy consumption is divided into three major economic sectors, buildings transportation and the industrial sector. Among these sectors, buildings including residential, commercial, light commercial and institutional signify one-third of the total energy consumption compared to other energy-using sectors (Gul and Patidar, 2015; Mardiana and Riffat, 2013). Energy consumption has increased dramatically in buildings over the years due to population growth, more time spent indoors, increased demand for building functions, indoor environmental quality and global climate change (Cao *et al.*, 2016; Gamalath, 2017). According to Cao *et al.* (2016), proper design, construction and operation of a building can help save energy significantly. This can help achieve building energy efficiency and can provide key solutions to energy shortages, carbon emissions and their serious threat to our living environment. Building energy use currently accounts for over 40% of total primary energy consumption in the US and EU, and 27.3% in China. The building energy intensity in China is far lower than in the US and EU (Cao *et al.*, 2016). The primary fuel sources of building energy use in the US and EU are electricity and natural gas. Electricity is the largest energy source in the US building sector, with a 50.1% share of final energy use and over 70% of total energy consumption (Cao *et al.*, 2016). In the European residential sector, natural gas is the most commonly used fuel for heating purposes in all regions. The dominant energy for final building energy in China is the traditional biomass which accounts for 47.1% (Cao *et al.*, 2016). Architects and engineers are to use early energy simulation software coupled with BIM to create comparative energy analysis. It specified that the criteria of modelling should be based on information about the local climate and actual site conditions (Financing and Commission, 2013).

Previous studies on reviews of BIM literature have focused on specific research areas or themes such as facility management (Becerik-Gerber *et al.*, 2012; Edirisinghe *et al.*, 2017; Wetzel and Thabet, 2015) and environmental sustainability (Maltese *et al.*, 2017). Some studies have outlined the current practices and future directions via various research approaches such as surveys, critical literature reviews and interviews (Azhar, 2011; Gu and London, 2010; Kalibatas *et al.*, 2018; Utkucu and Sözer, 2020; Volk *et al.*, 2014). More so, researchers have carried out reviews and analyses on BIM which include contractors' blueprint to adopt BIM (Acquah *et al.*, 2018), the e-tendering process model (Aguiar Costa and Grilo, 2015), waste management (Akinade *et al.*, 2018) and education and knowledge (Abrishami, 2014; Ahn *et al.*, 2013; Danso, 2013; Rahadian and Sulistiawan, 2020). Others include social network simulation, cloud-BIM and technology adoptions (Al Hattab and Hamzeh, 2015; Alreshidi *et al.*, 2016; Eadie *et al.*, 2014). Extant studies also exist on BIM-GIS integration (Basir *et al.*, 2018; Borrmann *et al.*, 2018; Zhao *et al.*, 2019) and sustainability (Bynum *et al.*, 2013; João *et al.*, 2013). China has been the world's largest energy user country and the major carbon emitter in the sphere since 2011, according to calculations of the amount of energy consumed by structures in the country (Li *et al.*, 2014). A study by Jinkyun *et al.* (2014) used matrix analysis for subsystem combinations and found that it is difficult to include all the energy-depleting characteristics of HVAC&R systems because the energy savings offered by this plan depend on a variety of factors.

The reduction of embodied energy and GHG emissions from buildings "may have a tremendous effect on the reduction of global energy consumption and GHG emissions" (IEA, 2016; Zhou and Azar, 2018). There is a growing understanding that it is prudent to have a full life-cycle analysis of carbon emission reductions, thereby addressing embodied emissions as well as operating emissions (USAID, 2017). CO_2 analyses and evaluations are done by BIM software to help achieve carbon neutrality projects. Current BIM software has incorporated both building-system components and the external environment into carbon emissions analyses by using information such as local electricity emissions, hydrocarbon production on the construction site and other energy conversion approaches (Mousiadis and Mengana, 2016). To assess how such factors affect a building's carbon emissions throughout its life cycle, an external global database can be accessed by BIM software through the use of standard data. Besides carbon emissions analyses, current BIM software also provides alternative designs for carbon emission reduction, thereby helping designers and engineers optimize their original designs towards carbon neutrality (Lu *et al.*, 2017).

This study, therefore, sought to assess the energy consumption and carbon emission of a conventional and a green building through building retrofitting using BIM.

2. Why the existing conventional building?

The household and services sectors, both of which relate to buildings, contribute about 40% of the world's total final energy consumption (UN, 2020; Randolph and Masters, 2018; IEA, 2016). According to USAID (2017), the industrial sector consumes about 51.7% of the total world energy, followed by the transport sector consuming about 26.6%. In Ghana, however, the transport and industrial sectors alone consume 14 and 20% of the total primary energy, respectively. The rest of the 66% is consumed by other sectors including losses. A greater percentage of high electricity consumption in Ghana is attributed to residential customers, which resulted in unprecedented peak demand of 1423 MW (Dramani and Tewari, 2014). In 2008, about 78.5% of residential sector electricity consumption was attributed to the urban centres for lighting and cooling (GSS, 2017). Existing buildings represent the actual urban context; they participate with a significant share in the current energy problem but, at the same time, they symbolize the solution (Albadry, 2016). Existing buildings have clear evidence of all the parameters for analysis since they are in use. According to Miller and Buys (2008), "much less is known about how green building initiatives might be incorporated into existing buildings, which make up the bulk of the market. If the challenge of climate change is to be successfully addressed, therefore, this vast stock of older buildings (developed decades ago when sustainability was not a consideration) needs to be retrofitted."

Banfi (2017) observed that "The re-use of existing structures has been a common practice since the first buildings were constructed and yet very little theoretical analysis of the subject exists. At the start of this new century, in an attempt to preserve our cultural heritage, large numbers of existing buildings are remodeled in preference to demolition." This lent support to the essence of this study.

3. Literature

3.1 Energy retrofits in existing conventional buildings

Miller and Buys (2008) concluded that green buildings outperform conventional buildings concerning environmental, economic and social indicators. There is the need to incorporate green building initiatives into existing conventional buildings which form the greater part of the building stock (developed decades ago when sustainability was not a consideration) through retrofitting. Duah (2014) argues that retrofitting existing buildings to make them more energy efficient contributes immensely to energy savings and associated economic, environmental and health benefits to occupants. Although energy retrofitting has some benefits, its adoption comes with obstacles. Based on Crosbie and Baker's (2010) study, the improvement in technological issues and state-of-the-art approaches cannot be effective without the cooperation of building occupants. If occupants are not willing to engage with the installation and utilization of energy-efficient heating or lighting effectively, then the expected efficiencies cannot be achieved, regardless of how much these energy-efficient measures hypothetically could be energy-saving. Therefore, to boost the uptake of energy-efficient refurbishment, it is critical to understand why and how inhabitants react to these measures. Miller and Buys (2008) argue that designing or creating a new green building is simpler or easier as compared to retrofitting an existing building into a green building. Retrofitting or an upgrade of technology in an existing building into a green building needs the cooperation and participation of a wide range of stakeholders (i.e. owners, managers, occupants and contractors). Gholami *et al.* (2013) concluded that BIM has the potential to overcome retrofitting challenges. During retrofitting projects, energy simulation is not sometimes taken into account. BIM-based tools provide this benefit for retrofit projects in the early phases of retrofit projects (Utkucu and Sözer, 2020). Gathering information on the energy simulation performance of the existing stock can be easier in comparison with new buildings (Zhang *et al.*, 2022).

Duah *et al.* (2016) observed that the knowledge of construction professionals affects the success of the industry. The type of knowledge depends on specific attributes needed to succeed in the industry, some of which are of relative importance primarily due to their role in the industry. In a hierarchical order starting from the most important, the determinants of home energy retrofit expert knowledge, needed for success in this domain, are:

(1) Building science and construction knowledge

(2) Certification and continuing education

(3) Field experience and expert collaboration

(4) Computer and diagnostic equipment knowledge

3.2 Energy consumption of existing conventional buildings

The world's energy consumption is divided into three major economic sectors, buildings transportation and the industrial sector. Among these sectors, buildings including residential, commercial, light commercial and institutional signify one-third of the total energy consumption compared to other energy-using sectors (Gul and Patidar, 2015; Mardiana and Riffat, 2013). Energy consumption has increased dramatically in buildings over the years due to population growth, more time spent indoors, increased demand for building functions, indoor environmental quality and global climate change (Cao *et al.*, 2016; Gamalath, 2017). According to Cao *et al.* (2016), proper design, construction and operation of a building can help energy saving significantly. This can help achieve building energy efficiency and can provide key solutions to energy shortages, carbon emissions and their serious threat to our living environment. Building energy use currently accounts for over 40% of total primary energy consumption in the US and EU, and 27.3% in China. The building energy intensity in China is far lower than in the US and EU (Cao *et al.*, 2016). The primary fuel sources of building energy use in the US and EU are electricity and natural gas. Electricity is the largest energy source in the US building sector, with a 50.1% share of final energy use and over 70% of total energy consumption (Cao *et al.*, 2016). In the European residential sector, natural gas is the most commonly used fuel for heating purposes in all regions. The dominant energy for final building energy in China is traditional biomass, which accounts for 47.1% (Cao *et al.*, 2016). Architects and engineers are to use early energy simulation software coupled with BIM to create comparative energy analysis. It specified that the criteria of modelling should be based on information about the local climate and actual site conditions (Financing and Commission, 2013).

According to Gamalath (2017), global climate change is a major challenge in the world today. Global climate change has a significant impact on space heating and cooling demands. Globally, residential heating demand will decrease by 34% and cooling demand will increase by 72% in the next century. Total energy demand for heating and cooling will primarily increase in cooling-dominant and less-developed regions. According to Cao *et al.*, (2016), well-designed building envelopes can help reduce heating and cooling loads by 40%. Suitable energy-saving approaches can help solve global warming trends and reduce GHG emissions.

3.3 Computer simulation of building energy consumption

Simulation can be defined as "experimentation with a simplified imitation (on a computer) of an operations system as it progresses through time, for better understanding and or improving the system" (Eastman *et al.*, 2008). Krüger (1975) proposed one of the three simulation design process models, which is the documented definition of a simulation workflow model. Krüger (1975) presented that the simulation workflow begins with the problem definition and proceeds to the stages of data collection and model building, validation, data analysis, interpretation and documentation. Allen and Tildesley (2017) highlighted the importance of conducting experiments in the real world, and compared the results of the experiments with the simulation results using theoretical models.

Building energy simulation with a specific focus on sustainable building simulation was first initiated and started by the US Department of Energy (DOE) in consultation with experts in the construction industry (1973–1974) (Haves, 2011). According to Haves (2011), the simulation that was conducted was just to control room temperature. During the 1990s, computer-based simulation software applications were developed. Simulations with this application were faster than other methods. Lei (2012) stated that, in the field of energy efficiency, computer simulation of building energy consumption is one of the significant aided tools. The design process is done by architects; at any stage of the design, energy-saving evaluation by computer simulation or test can predict the future or existing building's energy consumption, and diagnostic analysis of building thermal process is done to optimize the building design and to minimize energy consumption to provide an accurate basis. Building energy simulation for energy efficiency is an important technology that plays a crucial role in energy conservation. With the strengthening of building energy management, local hourly weather database development and simulation software continuing to improve, building energy conservation, environmental protection and sustainable development will undoubtedly have far-reaching effects (Balbis-Morejón *et al.*, 2020; Lei, 2012).

3.4 Building contribution to carbon emissions

Traditional or conventional buildings have been in existence for years, without factoring their energy consumption or efficiency level and the negative impact concerning CO_2 emissions (Rodríguez-Vázquez *et al.*, 2020). Conventional buildings are among the highest energy consumers and also among the highest contributors to greenhouse gas emissions, accounting for approximately 40 and 33% of CO_2 emissions produced by developed countries and the rest of the world, respectively (Abokyi *et al.*, 2019; Gebreslassie, 2018; Rodríguez-Vázquez *et al.*, 2020). The annual greenhouse gas (GHG) emissions grew on average by 1.0 gigaton of carbon dioxide equivalent ($GtCO_2e$) per year from 2000 to 2010, compared to 0.4 $GtCO_2e$ from 1970 to 2000, and total anthropogenic GHG emissions were the highest in human history, reaching 49.0 $GtCO_2e$/y in 2010 (Ibn-Mohammed, 2017; Mehler, 2020). According to Cao *et al.* (2016), building energy consumption would only increase from 117 EJ to 130 EJ, and total CO_2 emissions would surprisingly decrease from 8.3 Gt to 2.7 Gt CO2 by 2050 when high energy-saving techniques are used in designing, construction and operation of buildings.

Ghana's total CO_2 emissions grew from 16.83 Mt in 1990 to 36.8 Mt in 2022 (Ecr, 2022; EPA, 2022; UNFCC, 2019). Riffat and Mardiana (2015) concluded that the building sector uses some amount of energy and emits an almost equal portion of carbon dioxide. This is based on several key factors which include urban density, spatial organization, economic growth, building size, building operation, building a life, occupant behaviour, geographic location, climatic conditions and service demands.

The GHG emission from final consumption is calculated as follows.

Equation (1). Greenhouse gas calculation as a result of energy consumption (Riffat and Mardiana, 2015):

$$GHG(MMtCO2e) = \sum_{t}^{n} \left(fi_g \,. P_t \right) \tag{1}$$

where fi_g is the CO_2 emission factor during generation, and P_t is the output power of technology.

4. Materials and methods (modelling and simulation)

4.1 The conventional building (library complex)

The library complex is a multi-story building located at the Akenten Appiah-Menka University of Skills Training and Entrepreneurial Development (AAMUSTED), Kumasi, Ghana. The building was constructed in 2009 with three (3) floors and a total floor area of 3,576 m^2. The structure houses computer laboratories, lecture halls, offices, storerooms and washrooms. Plate 1 shows the existing condition of the conventional building under discussion. The total gross floor area for heating/cooling analysis was 1,591.8 m^2. The exterior and interior walls of the structure are monolithic (sandcrete blocks), with a thickness of 150 mm. The floors are made of concrete with a tile finish. The ceilings are of wood, with tongue and groove plastic panels for the last floors. All floors below the last floor use concrete floors for their ceilings. The roofs are made of aluminium sheets with wooden frame trusses. Windows are of glass louvre blades, whereas the doors and frames are of timber and two

Plate 1.
Existing conditions of the conventional building under discussion (library complex)

Source(s): Figure by authors

glass doors. Table 1 shows the composition of the building element with its thickness (mm) and u-value (W/m^2 °C) for the conventional building.

4.2 Modelling and simulation process

A study that sought to assess the energy consumption and carbon emission of a conventional and a green building through building retrofitting using BIM technology takes into account Autodesk Revit Software for rapid energy modelling as its design. Rapid energy modelling is a streamlined, scalable approach for performing energy assessments of existing buildings. Figure 1 indicates a typical workflow that consists of three steps: capture, model and analyse (Autodesk, 2011).

Step 1: Capturing existing conditions

The first step in the rapid energy modelling process is to capture the existing conditions of the building(s). The format of the existing conditions (i.e. digital photographs, aerial or satellite images, or laser distance metre measurements) and the data collected on existing conditions

Table 1.
Composition of the conventional building elements

Building element	Thickness (mm)	U-value (W/m^2/°C)
Roof (aluminium sheet-primary purlin-secondary purlin)	220	7.999
Door frame (timber)	150	1.000
Door panel (timber)	30	8.000
External and internal walls (plaster-block-plaster)	200	11.633
Ground/Upper floors (tile, screed and concrete)	200	7.046
Windows (solar transmittance 0.820, light transmittance 0.890 and total transmittance 0.849	4	5.798
Window substitute element	204	2.700
Ceiling (purlin and plywood)	70	10.667

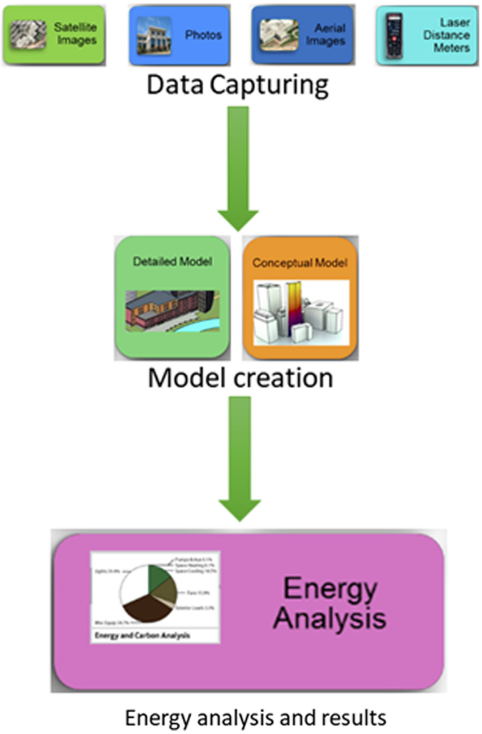
Source(s): Table by authors

such as design (geometry), utility history, materials, weather and operating schedules aided in the development of the 3D model.

An unmanned aerial vehicle (UAV) or drone was used to capture digital photographs of the existing condition of the building being studied. The drone was flown all around the building to capture digital images in series. The digital images were fed into a software called Meshroom to generate the building's geometry. Meshroom is a photogrammetry software that helped in generating the geometry of the building from digital photographs. The software converts pictures to 3D point clouds and meshes. This software application (Meshroom) is employed to convert digital photos taken from the study area (studied buildings) into a 3D point cloud. The 3D point cloud or the wireframe model is then exported as a DWG file and is used in the BIM solution (Autodesk Revit) to help create a full 3D model of the studied building. The traditional method of measuring was also employed as a check on the data obtained from the software. Figure 2 shows the process of generating building geometry for the existing conventional building from digital images using Meshroom.

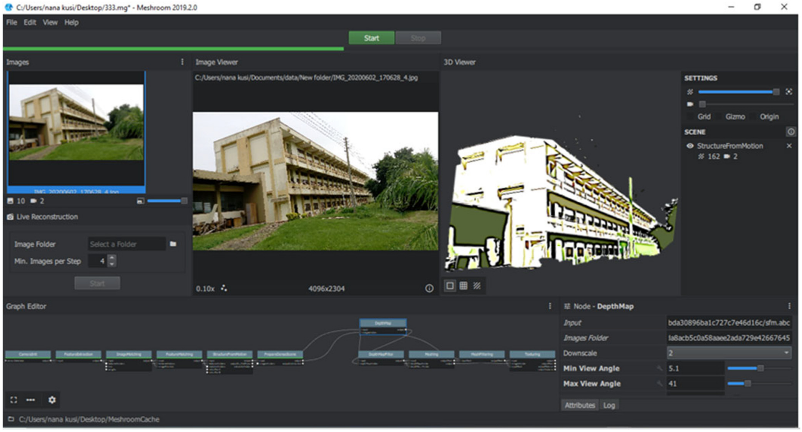
Step 2: Creating the existing building model (3D model)

The captured existing conventional building conditions and data from step 1 were used to develop a detailed 3D model for the existing conventional building using Autodesk Revit. Figures 3 and 4 show the plans and 3D model of the conventional building, respectively. Autodesk Revit is a parametric software; therefore, it incorporates building elements such as



Source(s): Figure courtesy of Autodesk (2011)

Figure 1.
Flow chart of the research design (rapid energy modelling)



C:/Users/nana kusi/Documents/data/New folder/IMG_20200602_170628_4.jpg

Image Folder: Select a Folder
Min. Images per Step: 4

Node - **DepthMap**
Input: bda30896ba1c727c7e46d16c/sfm.abc
Images Folder: 1a8acb5c0a58aaee2ada729e42667645
Downscale: 2
Min View Angle: 5.1
Max View Angle: 41

C:/Users/nana kusi/Desktop/MeshroomCache

Figure 2.
Generating building geometry for the existing conventional building from digital images using Meshroom

Source(s): Figure by authors

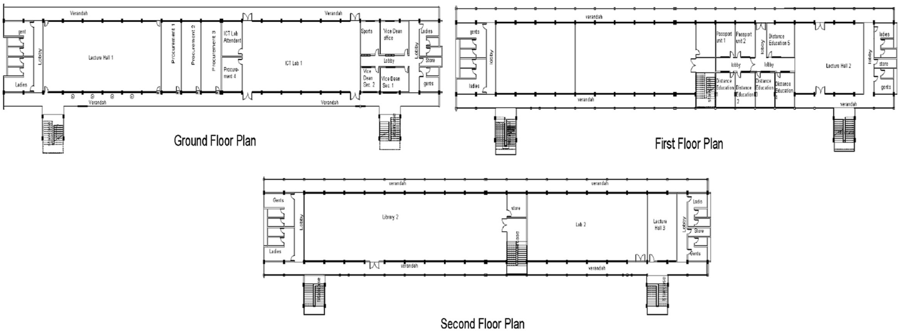


Figure 3.
Floor plans of the conventional building model (ground-, first- and second-floor plans)

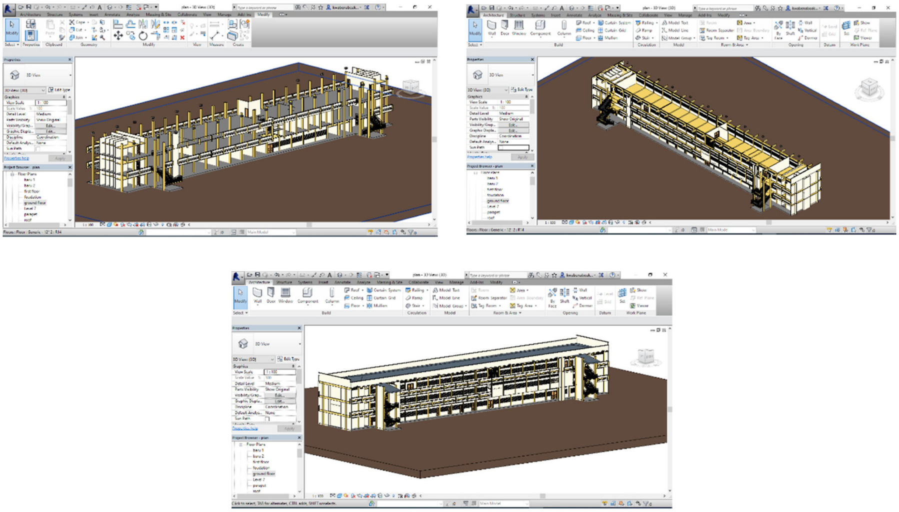
Source(s): Figure by authors

walls, floors, windows, roofs and rooms/spaces (parametric modelling). The parameters of the conventional building 3D model were calibrated or modified to ensure results match with utility (existing conditions).

After modelling in Autodesk Revit, the first phase of energy simulation was done using building space/room classification (Mep, 2011). The study used building space classification for pre-stimulation for heating/cooling calculations. Figures 5 and 6 indicate the U-value assigning interface (assigning U-values to building components) and the energy model generated in Autodesk Revit to be used in GBS.

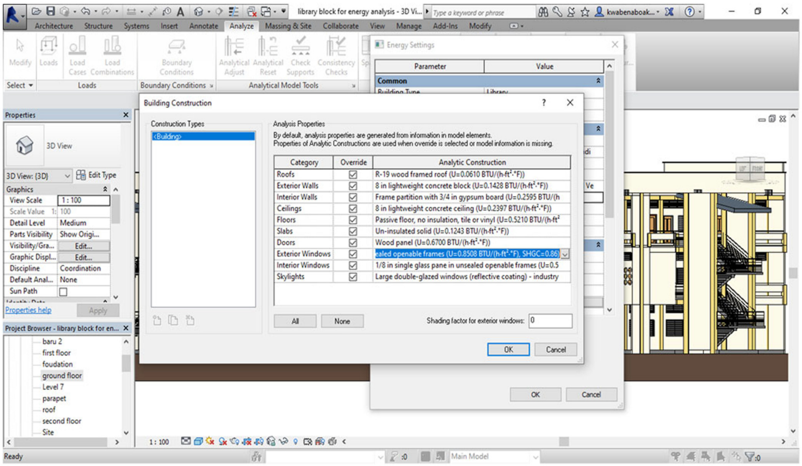
Step 3: Building performance analysis

Autodesk GBS, which is a web-based platform, was used to simulate the detailed conventional building model to assess and observe the performance of the building. The Autodesk GBS runs on DOE-2 for energy simulation. Several factors have an impact on the energy use of buildings: building components, such as floors, walls, ceilings, roof, windows and doors; air movement through the envelope of the building; heating, cooling and lighting systems; users and outside factors such as wind, solar radiation, temperature and humidity – all are considered in GBS. In GBS, project location, weather file, building type and weather



Source(s): Figure by authors

Figure 4. The conventional model at different stages in Autodesk Revit



Analysis Properties

By default, analysis properties are generated from information in model elements.
Properties of Analytic Constructions are used when override is selected or model information is missing.

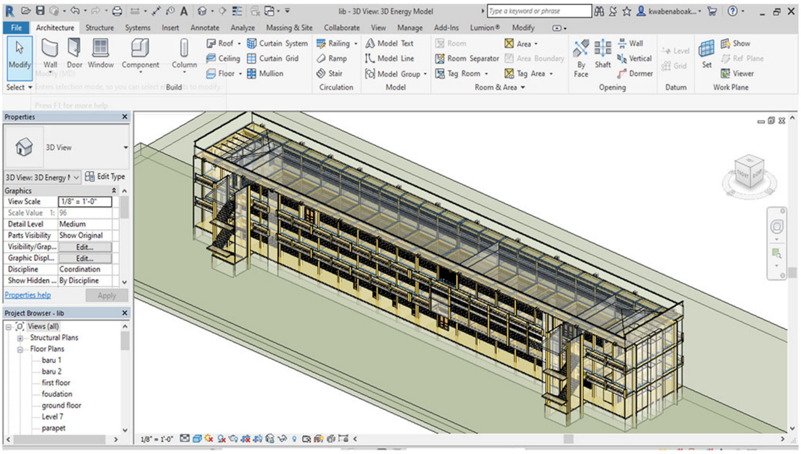
Category	Override	Analytic Construction
Roofs	☑	R-19 wood framed roof (U=0.0610 BTU/(h·ft²·°F))
Exterior Walls	☑	8 in lightweight concrete block (U=0.1428 BTU/(h·ft²·°F))
Interior Walls	☑	Frame partition with 3/4 in gypsum board (U=0.2595 BTU/(h
Ceilings	☑	8 in lightweight concrete ceiling (U=0.2397 BTU/(h·ft²·°F))
Floors	☑	Passive floor, no insulation, tile or vinyl (U=0.5210 BTU/(h·ft²
Slabs	☑	Un-insulated solid (U=0.1243 BTU/(h·ft²·°F))
Doors	☑	Wood panel (U=0.6700 BTU/(h·ft²·°F))
Exterior Windows	☑	ealed openable frames (U=0.8508 BTU/(h·ft²·°F), SHGC=0.86)
Interior Windows	☑	1/8 in single glass pane in unsealed openable frames (U=0.5
Skylights	☑	Large double-glazed windows (reflective coating) - industry

Shading factor for exterior windows: 0

Source(s): Figure by authors

Figure 5. U-value assigning interface (assigning U-values to building components)

station were set as was in the Autodesk Revit (see Table 2). The various parameters assessed for the performance of the conventional building model include energy use and annual carbon emissions, annual cooling loads, annual electricity and annual fuel consumption. The simulation was run, and results from the simulation were tabulated and illustrated. In the Autodesk GBS platform, the simulation is termed a Base Run. The existing conventional building model was then retrofitted into the green building model by introducing sustainable materials and green building technology (photo voltaic-powered evaporative cooling system, PV cell, rainwater harvesting wall, passive cooling). The retrofitting was done in the Autodesk GBS platform without necessarily going back to Autodesk Revit for a new model. The U-values were changed in the GBS. Table 3 shows the U-values for the green building. The retrofitted model (green building model) was also simulated to observe the outcome. The



View Scale	1/8" = 1'-0"
Scale Value 1:	96
Detail Level	Medium
Parts Visibility	Show Original
Visibility/Grap...	Edit...
Graphic Displ...	Edit...
Discipline	Coordination
Show Hidden ...	By Discipline

Figure 6.
Energy model generated in Autodesk Revit to be used in GBS

Source(s): Figure by authors

Table 2.
Project summary for both conventional and green building models runs

Location: Kumasi-Tanoso, Ghana	
Weather station	GBS_06M12_21_138040
Outdoor temperature	Max: 30 °C/Min: 23 °C
latitude	6.70°N
longitude	−1.63°N

Source(s): Table by authors

Table 3.
U-value for green building model components

Building element	U-value (W/m^2/°C)
Roof (PV cell)	0.8
External and internal walls (plaster-block-plaster)	12.633
Ground/Upper floors (tile, screed and concrete)	8.046
ASHIF5 8 in lightweight concrete	11.283
Interior 4 in slab	23.701
30 R2 door	13.543
121 R15 wood frame	1.965
Single glazing	5.8
Double glazing	3.7

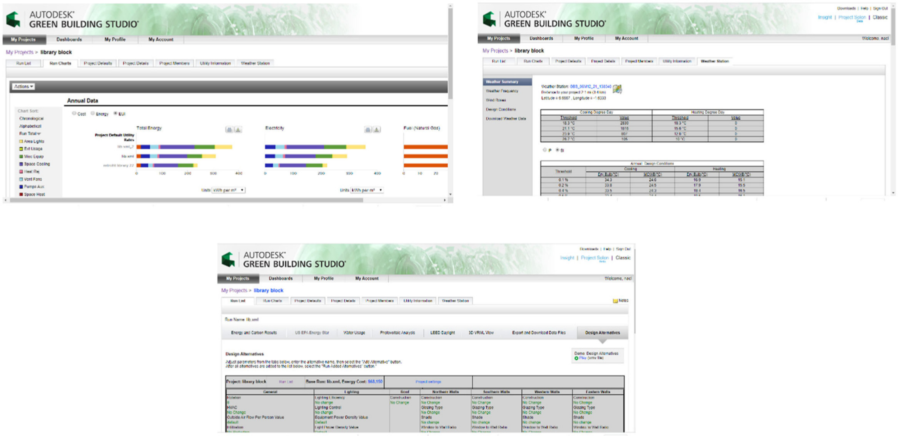
Source(s): Table by authors

parameters observed were the same as those of the conventional model (energy use and cost, annual carbon emissions, annual cooling loads, annual electricity, annual water consumption, annual fuel consumption and indoor environmental quality). Results from this simulation were also tabulated and illustrated. This simulation is also known as the Alternative Design Run. Figure 7 shows the interface of GBS indicating annual data (energy use/cost), weather files and design alternatives.

5. Results

5.1 Annual carbon emissions (operational CO_2 emission)

The annual carbon emissions as shown in Figures 8 and 9 consist of the annual energy use, energy generation potential and the net CO_2. The net CO_2 is the deduction of energy



Source(s): Figure by authors

Figure 7. Interface of GBS indicating annual data (energy use), weather files and design alternatives

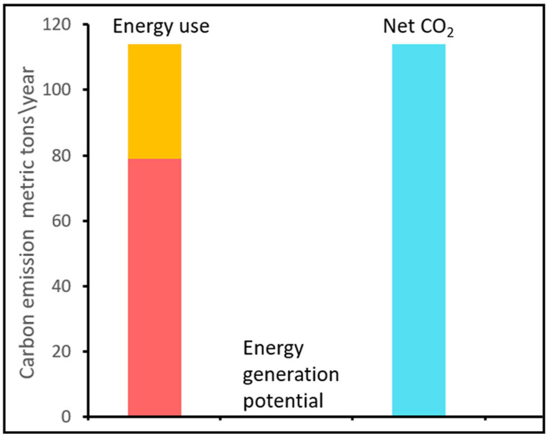


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Figure 8. Annual carbon emissions for the conventional building

generation potential from the energy consumption of the building (Gul and Patidar, 2015; Yim *et al.*, 2018). The net CO_2 emission for both the conventional and the green buildings was calculated as shown in Tables 4 and 5 respectively. The details of the calculation were obtained from the energy simulation results from the GBS platform. The net CO_2 was found to be equivalent to 114 and 61 metric tonnes per year for the conventional and the models of the green building, respectively. The green building model saw a reduction of 53 metric tonnes per year. This reduction was a result of the reduction in energy use by the green building model. For the green building to achieve carbon neutrality, there was a need for potential energy generation. The potential energy generation for the green building model was a renewable energy source from the PV cells installed on the roof. The PV cells were able to generate 128 kW and above, which made the green building model achieve carbon neutrality. This signifies that the green building obtained 67 metric tonnes as its carbon credit. This also

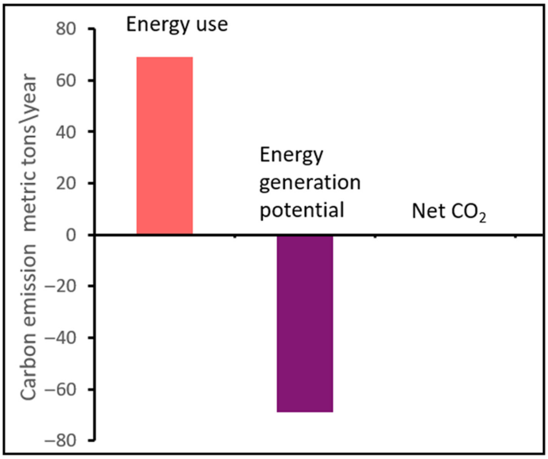


Figure 9. Annual carbon emissions for the green building

Source(s): Figure by authors

Table 4. Annual carbon emissions for the conventional and green building models

	Conventional building	Green building
Electric	79 Mg	43 Mg
Onsite fuel	35 Mg	18 Mg
Potential energy generation	0	0
Net CO_2	79 + 35 = 114	43 + 18 = 61

Source(s): Table by authors

Table 5. Annual carbon emissions for the conventional and the green building models about potential energy generation from PV cells installed on the roof of the green building

	Conventional building	Green building
Electric	79 Mg	43 Mg
Onsite fuel	35 Mg	18 Mg
Potential energy generation	0	128 kW
Net CO_2	79 + 35 − 0 = 114	43 + 18–128 = −67

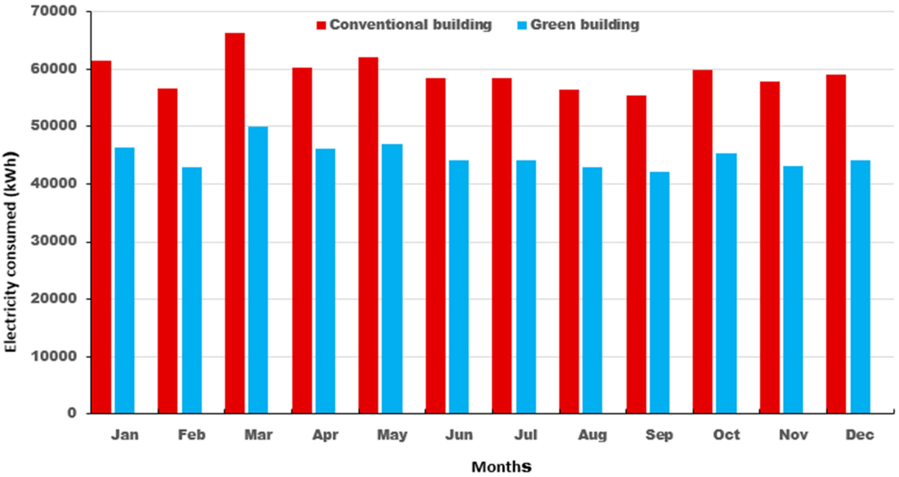
Source(s): Table by authors

denotes the amount of carbon in metric tonnes which was eradicated from the building with the use of renewable energy resources (PV cells).

The onsite renewable potential is a negative value because it represents the amount of carbon that can be removed from the building using renewable energy. There was a significant reduction in energy usage versus achieving carbon neutralities by the green building, which means that when energy consumption increases, especially that of fuel energy, the CO_2 emission also increases proportionally. The introduction of the PV cell was not only to yield high potential energy per kilowatt-hour but also to ensure the CO_2 negativity process.

5.2 Monthly electricity consumption for both conventional and green building models

From the Autodesk GBS platform, electricity consumption was higher during the hotter months of the year and lesser during the rainy months. Figure 10 shows that the electricity



Source(s): Figure by authors

Figure 10. Monthly electricity consumption for both conventional and green building models

consumed by the green building model is less than what was consumed by the conventional building model for each month. During January, March and May, the electrical supplied usage loads approach the maximum point, with March recording the highest energy consumption for both conventional and green building models, and September recording the lowest for both buildings.

5.3 Monthly fuel consumption

The monthly fuel energy consumption for the conventional and green building models is shown in Figure 11. The overall fuel consumption was reduced for the green building model due to the utilization of environment-friendly materials from 149,265 MJ to 138,658 MJ. It can

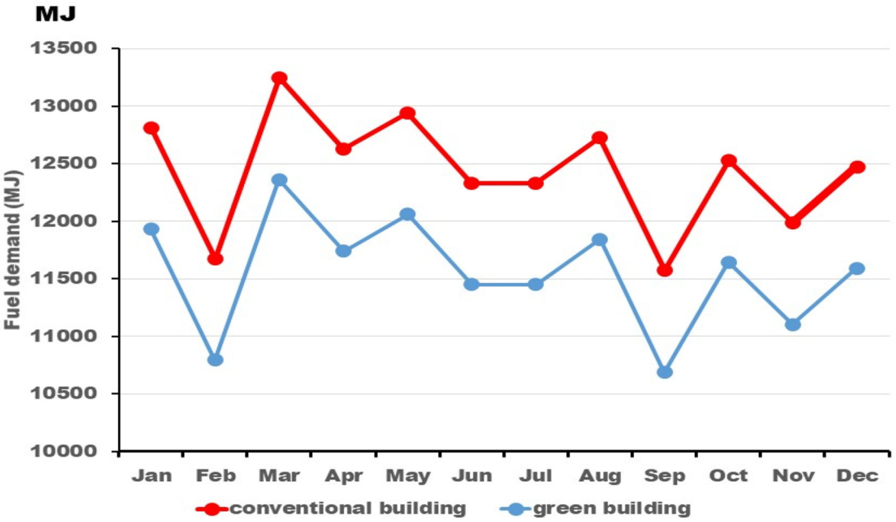


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Figure 11. Monthly fuel consumption for both conventional and green building models

also be observed from Figure 11, that March recorded the highest fuel consumption, with September being the lowest for both models. The month of March and September recorded 13246 and 11571 MJ, respectively, for the conventional building model. For the green building model, the months of March and September recorded 12362 and 10,686.8 MJ, respectively.

5.4 Annual and monthly peak load demand

Figure 12 shows the estimated annual peak electricity load demand in a monthly dispatch configuration for both conventional and green building models. The peak demand is the maximum instantaneous electrical load in a given limited period. The electricity peak demand for the conventional building model is higher than that of the green building models. The month of March recorded the highest peak demand of 154 kW for the conventional building model, and August recorded 131.7 kW as its lowest. The green building model recorded 116.5 and 99.4 kW as the highest for March and lowest for August, respectively. The annual average electricity demand for both conventional building and green building models was 141.33 and 106.13 kW, respectively. The conventional building model used a split cooling system as the main cooling supply, thereby increasing electricity usage during the hotter months of the year.

5.5 Testing of hypothesis

Testing of a hypothesis provides the formal framework to reject or not reject a hypothesis on parameters, depending on whether it is supported by given data (Hans-Michael, 2011). Table 6 indicates the various research hypotheses and their corresponding dependent and independent variables.

5.6 Statistical analysis

5.6.1 Descriptive statistics. Table 7 shows the descriptive statistics of the average annual energy consumption per square metre for the conventional building and the green building models and their corresponding values for carbon emission. The table shows that the mean,

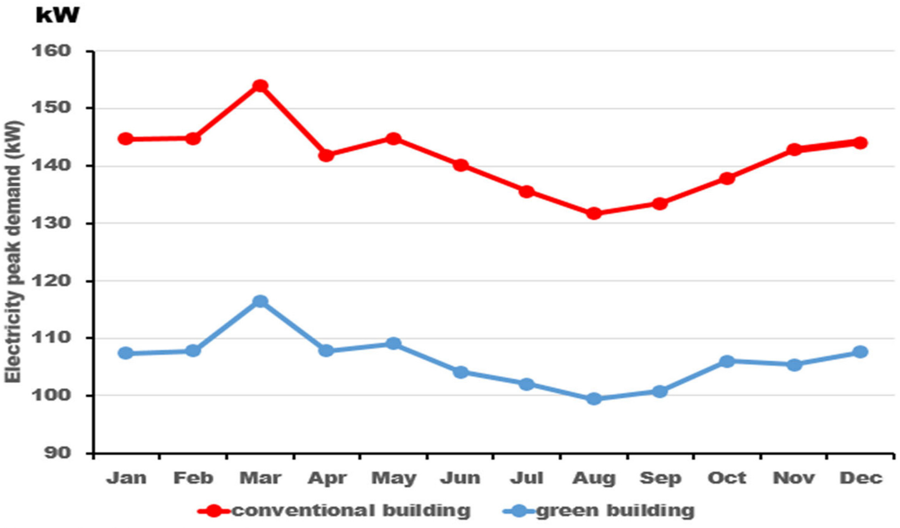

Figure 12. Monthly peak load demand for electricity for both conventional and green building models

Source(s): Figure by authors

median and standard deviation values of the conventional building models are higher than those of green buildings. The mean annual energy consumption per square metre of the conventional building and the green buildings ia16.60 kW/m^2 and 12.54 kW/m^2, respectively. The mean annual carbon emissions per metric tonne of the conventional building and the green building are 9.50 and 5.05, respectively.

> *H1.* The mean annual energy consumption of the green building model is not statistically different from that of the mean annual energy consumption of the conventional building model.

5.6.2 Analysis of variance by using single-factor ANOVA. Table 8 shows the results of the ANOVA test. The ANOVA test was performed to determine whether the energy consumption per square metre of the green building model was statistically different from that of the conventional building model. The ANOVA test results showed that the mean annual energy consumption per square metre of the green building model is significantly lower than that of the conventional building model. The *p*-value of 0.00 was found to be less than the alpha level of 0.05.

Table 6. Research hypotheses about the dependent and independent variables used in the data analysis

Hypothesis	Statement	*DI	*IV
H1	The mean annual energy consumption of the green building model is not statistically significantly different from that of the mean annual energy consumption of the conventional building model	Energy consumption	Building type
H2	Introducing a sustainable-inducing energy concept into a conventional building model does not result in significant differences in CO_2 emissions	Carbon emission	Building type

Note(s): *DV = dependable variable; *IV = independent variable
Source(s): Table by authors

Table 7. Descriptive statistics of annual energy consumption (kW/m^2) and carbon emission

		N	Mean	Median	Std. deviation
Carbon emission	Conventional building model	12	9.50	9.4	1.15
	Green building model	12	5.05	4.75	1.33
	Total	24	7.30		2.56
Energy consumption	Conventional building model	12	16.60	9.40	0.83
	Green building model	12	12.54	2.75	0.61
	Total	24	14.57		2.19

Source(s): Table by authors

Table 8. Single-factor ANOVA results of energy consumption (kW/m^2)

Building type	Mean	F-value	*P*-value	F-critical
Conventional building	16.60	8.31	0.00	4.26
Green building	12.54			

Source(s): Table by authors

The null hypothesis was rejected since the *p*-value of 0.00 is less than the alpha value of 0.05. The rejection of the hypotheses was also on the basis that the F-value (F-calculated), which was 8.31, is greater than the F-statistics (F-critical), which was 4.26.

> *H2.* Introducing a sustainable inducing energy concept into a conventional building model does not result in significant differences in CO_2 emission.

Table 9 shows the results of the ANOVA test. The ANOVA shows the annual mean of conventional and green buildings as 9.50 and 5.08 of carbon emissions, respectively. The ANOVA test results showed that the mean annual carbon emission of the green building model was significantly lower than that of the conventional building model. The *p*-value of 0.00 was found to be less than the alpha level of 0.05. In view of this, the null hypothesis is rejected as illustrated in Table 10.

5.6.3 Correlation analysis. For correlation, r-value between 0.10 and 0.29 is considered as not strong, between 0.30 and 0.49 is moderate and between 0.50 and 1.0 is regarded as strong (Greasley, 2008; Wong and Hiew, 2005).

A lesser *p*-value (≤0.05) shows a strong indication of contradiction to the null hypothesis. A large *p*-value (>0.05) indicates weaker evidence against the null hypothesis, and hence the null hypothesis is accepted (Greasley, 2008; Greenland *et al.*, 2016). The correlation coefficient (r-value) ranges from −1.0 to +1.0. How close an r-value is to +1 or −1 indicates how strong the relationship between the two variables is (Cohen, 1988; Greasley, 2008). An r-value closer to zero (0) shows a very weak or no correlation between the variables. A positive correlation coefficient means when one variable increases, the other variable also increases, and vice versa. A negative correlation coefficient also means when one variable increases, the other variable reduces, and vice versa (inverse correlation) (Cohen, 1988; Landau and Everitt, 2003). Table 11 indicates the correlation matrix (Pearson correlations). This table shows the correlation between the variables building type, energy consumption and CO_2 emission for the study.

5.6.4 Correlation between CO_2 emission and energy consumption. The correlation between CO_2 emission and energy consumption is shown in Table 11. The r-value (0.971) and *p*-value of 0.000 indicate a strong positive relationship between CO_2 emission and energy consumption. This is an indication that, when the energy consumption of the building model increases, CO_2 emission increases.

Table 9.
Single-factor ANOVA results of carbon emission metric tonnes per month from both conventional and green building models

Building type	Mean	F-value	*P*-value	F-critical
Conventional building	9.50	3.47	0.00	4.26
Green building	5.08			

Source(s): Table by authors

Table 10.
Summary of results from the Hypothesis

Hypotheses	Statement	Result
H1	The mean annual energy consumption of the green building model is not statistically different from that of the mean annual energy consumption of the conventional building model	Rejected
H2	Introducing a sustainable-inducing energy concept into a conventional building model does not result in significant differences in CO_2 emissions	Rejected

Source(s): Table by authors

		Energy consumption	CO_2 emission	Building type
Energy consumption	Pearson correlation	1		
	p-value			
	N	24		
CO_2 emission	Pearson correlation	0.971^{**}	1	
	p-value	0.000		
	N	24	24	
Building type	Pearson correlation	-0.945^{**}	-0.881^{**}	1
	p-value	0.000	0.000	
	N	24	24	24

Note(s): ** = Correlation is significant at the 0.01 level (2-tailed)
Source(s): Table by authors

Table 11.
Correlation matrix (Pearson correlations)

5.6.5 Correlation between building type and energy consumption. Table 11 shows the correlation between building type and energy consumption. The r-value (−0.945) and *p*-value of 0.000 show a strong negative relationship between building type and energy consumption. When the quality of the building type increases, the energy consumption of the building also decreases.

5.6.6 Correlation between building type and CO_2 emission. The correlation between building type and CO_2 emission is shown in Table 11. The r-value (−0.881) and *p*-value of 0.000 are an indication of a strong negative relationship between building type and CO_2 emission. When the quality of the building type increases, CO_2 emission also decreases.

5.6.7 Multiple regression analysis. According to Landau and Everitt (2003), multiple regression is computed using the following formula:

Equation (2). Multiple regression formula

$$y = \beta 0 + \beta 1\,x1 + \beta 2\,x2 \ldots\ldots\ldots + \beta k\,xk + \varepsilon \tag{2}$$

Where:

y is the value on the dependent variable.

β0 is the value of y if all Xs = 0, the y intercept.

X is the independent variables

β1 . . . k is the coefficient ascribed to the independent variables during the regression.

ε is the standard error.

5.6.8 Model summary^b of the regression analysis. Table 12 shows an adjusted R^2 value of 0.951, which indicates a 95.1% of the variance in the CO_2 emission by the building type was explained by the multiple regression model. A 95.1% of the observed variability in CO_2 emission by the building type was explained by building type and energy consumption as the independent variable ($R^2 = 0.955$, adjusted $R^2 = 0.951$). This indicates that CO_2 emission by the building type explains the variation in building type and energy consumption in a

Model	R	R square (R^2)	Adjusted R square	Std. error of the estimate	Durbin-Watson
1	0.977^a	0.955	0.951	0.56595	1.703226

Note(s): a. Predictors: (constant), building type, energy consumption b. dependent variable: CO_2 emission
Source(s): Table by authors

Table 12.
Model summary^b of the regression analysis

positive way. Durbin-Watson statistics was 1.703, which was between 1 and 3. The Durbin-Watson was used to check the independence of errors. Since the value (1.703) is greater than 1 and less than 3, the independence of observation was met.

5.6.9 Residuals statistics[a]. The residual statistics were used to check for outliers using the standardized residual. Table 13 shows the residual statistics[a]. The minimum and maximum values for standardized residual should be between −3.29 and + 3.29. In Table 13, the minimum and maximum standardized residual values were −1.924 and 2.243, respectively. This indicates that there are no outliers in the regression analysis since the standardized residual values obtained were within the range.

The regression analysis achieved normality. Figure 13 shows the P-P plot of the regression standardized residual. In the figure, the dots were generally lined up along the 45° line. This indicates the normality of residuals. The dependent variable CO_2 emission was also normally distributed as shown in Figure 14.

5.6.10 Summary of ANOVA[a]. Table 14 indicates the analysis of variance results. The result of the value of F (the ratio of the two mean squares) is 225.117 ($F = 225.117, p < 0.001$). The significance level observed was also less than 0.001. As a result, building type and energy consumption as independent variables influence the dependent variable which is CO_2 emission.

	Minimum	Maximum	Mean	Std. deviation	N
Predicted value	3.9414	12.4681	7.2917	2.50401	24
Residual	−1.08888	1.26952	0.00000	0.54079	24
Std. predicted value	−1.338	2.067	0.000	1.000	24
Std. residual	−1.924	2.243	0.000	0.956	24

Note(s): a. Dependent variable: carbon emission
Source(s): Table by authors

Table 13.
Residual statistics[a]

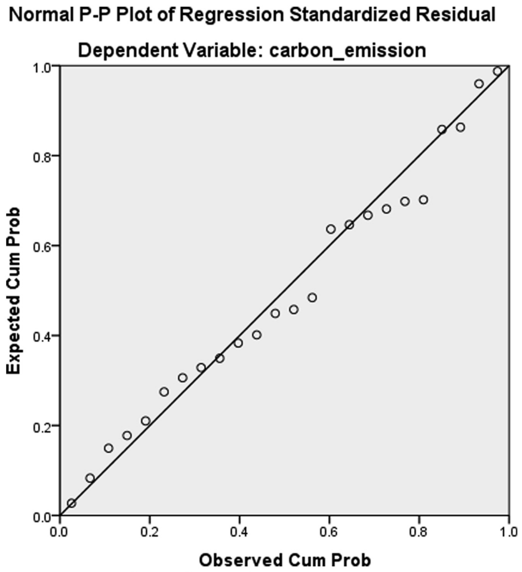

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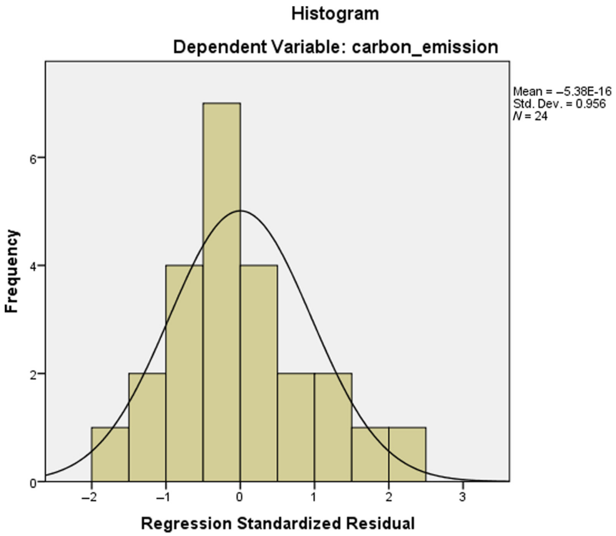
Figure 13.
P–P plot of regression standardized residual



Source(s): Figure by authors

Figure 14. Histogram of a dependent variable (CO_2 emission)

Model		Sum of squares	df	Mean square	F	Sig
1	Regression	144.212	2	72.106	225.117	0.000[b]
	Residual	6.726	21	0.320		
	Total	150.938	23			

Note(s): a. Dependent variable: carbon emission; b. predictors: (constant), building type, energy consumption
Source(s): Table by authors

Table 14. Summary of ANOVA[a]

5.6.11 Results for Regression Coefficients[a]. In summary, the influence of energy consumption ($\beta = 1.514$) and building type on CO_2 emission has a significant level of 0.00. R^2 is 0.955. These results indicated that 95.5% of the variance in CO_2 emission can be explained by building type and energy consumption. Table 15 shows results for regression coefficients[a].

Model	Unstandardized coefficients β	Unstandardized coefficients Std. Error	Standardized coefficients Beta	*t*-value	Sig	Collinearity statistics Tolerance	Collinearity statistics *VIF
(Constant)	−17.349	3.414		−5.081	0.000		
Energy consumption	1.514	0.164	1.295	9.210	0.000	0.107	9.310
Building type	1.718	0.705	0.342	2.437	0.024	0.107	9.310

Note(s): a. Dependent variable: CO_2 emission * variance inflation factor (VIF); b. predictors: (constant), building type, energy consumption
Source(s): Table by authors

Table 15. Results for regression coefficients[a]

6. Discussion of results

The study recorded a significant reduction of 35.3% in the cooling loads by the green building model. As concluded by Koranteng and Abaitey (2011), ensuring improvement measures (such as efficient windows and electrical lighting, natural ventilation and insulation) can reduce the buildings' cooling loads by 25–45% in the climatic context of Kumasi, Ghana. An earlier study by Petrullo *et al.* (2018) achieved a reduction of 42% in cooling load by a green building. Protection against direct sunlight and thermal insulation of the building shell has to be windproof and airtight (Lauber, 2005). However, thermal insulation of walls does not help in the reduction of cooling loads in the climatic context of Kumasi, Ghana (Koranteng and Abaitey, 2011; Lauber, 2005). The reduction of the cooling loads by the study was within the range of the findings by Koranteng and Mahdavi (2011) and Lauber (2005).

Heating loads were low, and heating was not an issue in the climatic context of Kumasi, Ghana. Therefore, heating loads were not discussed in this current study as was found in an earlier study conducted by Koranteng and Abaitey in Kumasi, Ghana (Koranteng *et al.*, 2021a; Koranteng and Abaitey, 2011).

Building performance analyses carried out for the green building model, and the conventional building model of the same area recorded a 22.5% savings in annual energy costs for the green building as compared to the conventional building. The annual energy consumption reduction was 25%. Reduction in energy consumption is observed as a significant benefit concerning green building, and an energy saving of 25–70% was empirically argued in literature (Ries *et al.*, 2006; Torcellini *et al.*, 2006). The decrease in energy usage by the green building model was made possible by the selection of appropriate sustainable construction material, the use of LED-approved lights and the use of a photovoltaic-powered evaporative cooling system for the green building. Reduction of cooling loads was through efficient windows, efficient electrical lighting and natural ventilation (Petrullo *et al.*, 2018). Typically, energy saving in green buildings ranges from 30% to 50% (Ijla and Broström, 2015; Khan *et al.*, 2019; Workbook, 2012; Yudelson, 2008). A study conducted by Jatav and Rastogi (2014) concluded that implementing energy-efficient construction practices in buildings can result in annual energy savings of between 25 and 30%. According to Kats *et al.* (2003), green buildings save energy on an average of 25–30% compared to conventional buildings. According to Jatav and Rastogi (2014), it is becoming more and more important to educate our surrounding society about adopting energy-saving practices and building due to the ageing of fossil fuel sources, their rapid depletion and the rising cost of electricity. A study by Shi *et al.* (2016) found that green buildings consume 26% less energy than orthodox constructions. Rough set theory was utilized to analyse the conflict between different plan goals from the perspective of investors. Chen and Luo (2020) found that green building reduces building energy consumption, reduces irrational building materials, increases the environmental protection value of buildings and better protects the ecological environment. Green building is helpful in lowering energy consumption; conserving water and land; lowering air, water and soil pollution from construction; meeting modern needs; and improving people's quality of life (Tong, 2017). Gamal *et al.* (2023) found that Hong Kong's climatic conditions is feasible to apply a double-skin green front to high-rise residential buildings to reduce the amount of energy used for refrigeration during the hot and muggy summer months. According to Khalid *et al.* (2016), the system's overall energy and energy efficiencies were 46.1 and 7.3%, respectively, in the research. Energy and energy analysis were used to design and evaluate a multigenerational greenhouse system that integrates renewable energy sources. A study on energy consumption patterns by Ramesh and Emran (2016) found that the construction industry may save 50% of its energy use. Maciej Serda *et al.* (2018) concluded that green buildings, also referred to as sustainable structures or zero-energy buildings, concentrate on using technology to enable climate adaptation. Green buildings are essential since they require 26% less energy. The findings of all these studies are in line with the findings of the current study.

The current study revealed a 46.8% decrease in CO_2 emission by the green building model as compared to the conventional building model. A study conducted by Cho and Chae (2016) recorded a 25% decrease in CO_2 emission by a green building. An earlier study conducted by Ijla and Broström (2015) concluded that green buildings recorded a 35% decrease in CO_2 emission. Khan *et al.* (2019) also recorded a decrease of 35% in CO_2 emission by a green building. The decrease in CO_2 emission by the current study was from the use of on-site energy. The green building was later sent to carbon neutrality due to the energy potential from the PV cell (green energy generation) and the natural ventilation potential. Buildings consume a significant portion of the energy produced and strain society as a whole due to energy scarcity and greenhouse gas emissions (Jatav and Rastogi, 2014). Maciej Serda *et al.* (2018) concluded that green buildings provide more occupant satisfaction and 33% less CO_2 emissions. Energy-efficient building design and construction techniques are gaining popularity as a low-cost way to lower CO_2 emissions related to the building's electrical generation (Jatav and Rastogi, 2014). According to a study conducted by Ahram and Zakaria (2023), conventional buildings have a detrimental impact on the environment. These effects can be summed up as massive CO_2 emissions, which cause catastrophic climate change and global warming. Conversely, the results showed that GBT contributes significantly to the reduction of CO_2 emissions by encouraging the use of clean energy and environmentally friendly building materials and techniques. The primary cause of the environment's ecological benefits being destroyed is CO_2 emissions. Improving the environmental and ecological advantages of green buildings as well as their overall life cycle control effect is even more crucial when considering CO_2 (Chen and Luo, 2020). A study by Liao and Li (2022) revealed that the efficiency of carbon reduction in the construction industry is positively impacted by the development of green buildings.

7. Implications of the study

According to the study, energy consumption is greatly reduced by green building features. This has consequences for occupant satisfaction, sustainability, environmental safety, financial savings and the prevention of climate change. Green buildings enhance the quality of indoor air, lessen the burden on nearby utility infrastructure, raise general standards of living and fortify ties within the community.

8. Conclusion

The study made it clear that green building is always beneficial to nature and the environment as compared to conventional building. Also, with the help of sustainable design applications, various aspects of sustainability were explored by the option of generating design alternatives. Passive cooling techniques introduced to the green building such as thermal mass, natural ventilation and external shading with a fan-induced air velocity optimized the green buildings' thermal comfort.

The study indicated that green building reduces energy consumption, thereby reducing the emission of $CO_{2.}$ Issues currently comforting the world as a whole are rising energy costs, shortage of sustainable supply, CO_2 emission, pollution produced by fossil oils and so forth. Increasing the generation of renewable energy with optimized usage pushes the building towards energy self-sustainability and carbon neutrality. The potential of the PV cell aided the green building to generate its electricity, thereby cutting off CO_2 emission.

From the simulation results, the introduction and improvement of efficient windows, electrical lighting and natural ventilation significantly reduced the buildings' cooling loads, which led to a reduction or decrease in overall energy use. The selection of a centralized air condition system that runs on PV cells for the green building saw a considerable reduction in energy consumption. Retrofitting the conventional building model to the green building model demonstrated the efficiency of BIM technology. BIM technology makes capturing existing conditions, modelling of existing buildings and simulation for performance easier, faster and more accurate, and all important decisions concerning the model can be made at the initial stages.

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