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An integrated life cycle assessment of different façade systems for a typical residential building in Ghana

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ABSTRACT

This study performs a comparative environmental and economic assessment of four different façade systems for low-cost residential buildings in Ghana. A framework is designed to incorporate BIM, Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) to perform a holistic comparison of a Shotcrete Insulated Composite Façade (Shotcrete ICF), Galvanised Steel Insulated Composite façade (G. Steel ICF) and Stabilised Earth Block Façade (SEBF) against the conventional Concrete Block and Mortar Façade (CBMF). BIM models are developed to compute the environmental and economic impacts of each façade. The results are then subjected to a comparative analysis for different life cycle stages. The SEBF is proved to be the most sustainable facade as it reduces cumulative energy demand (CED) by 39.13%, global warming potential (GWP) by 18.07% and LCC by 47.87% compared to CBMF. The Shotcrete IFC and G. Steel IFC are found to increase CED but decrease GWP. Other than the SEBF, the ranking of all façades under different indicators changes through the scenario analysis. The findings of this study provide useful guidelines for selecting facade systems and reducing the environmental and economic impacts of low-cost residential buildings in Ghana.

Keywords: Façade; Life Cycle Assessment; Life Cycle Cost; Cumulative Energy Demands; Global Warming Potential.

Nomenclature

AAC:	Autoclaved Aerated Concrete
BIM:	Building Information Modelling

BOQ:	Bill of Quantities
CBMF:	Concrete Block and Mortar Façade
CDD:	Cooling Degree Days
CED:	Cumulative Energy Demand
EE:	Embodied Energy
EE_c:	Construction Embodied Energy
EE_m:	Materials Embodied Energy
EE_t:	Transportation Embodied Energy
EPS:	Expanded Polystyrene
ETICS:	External Thermal Insulation Composite Systems
G. Steel ICF:	Galvanised Steel Insulated Composite Façade
GFA:	Gross Floor Area
GHG:	Greenhouse Gases
GWP:	Global Warming Potential
GWP_{EE}:	Embodied GWP
GWP_c:	Construction Embodied GWP
GWP_m:	Materials Embodied GWP
GWP_t:	Transportation Embodied GWP
GWP_{OE}:	Total Operational GWP
HDD:	Heating Degree Days
HVAC:	Heating Ventilation and Air Conditioning
ICE:	Inventory of Carbon and Energy
ICF:	Insulated Composite Façade
IES-VE:	Integrated Environmental Solutions Virtual Environment
ISO:	International Standardisation Organisation
LCA:	Life Cycle Assessment
LCC:	Life Cycle Cost
SEBF:	Stabilized Earth Block Façade
Shotcrete ICF:	Shotcrete Insulated Composite Façade

1. Introduction

Adequate housing remains a chronic challenge in Ghana as population growth continues to outstrip the development of housing projects. A report by the United Nations Human Rights Council (UNHRC) estimated Ghana's housing deficit at 2.4 million in 2018 and is expected to reach 3.8 million by 2020 [1]. The impacts of housing deficit has been profound on low-income groups in major cities as accommodation is usually expensive and beyond the average income of most residents [2]. To relieve this growing stress, the government and other estate agencies have expressed renewed interest in developing sustainable housing [3,4]. However, the increasing demand for buildings has caused major impacts on the environment as buildings consume about 40% of primary energy generated and 60% of raw materials extracted [5].

In particular, the impacts of building façades are profound given that it account for 60% to 70% of heat transfer between the indoor and outdoor environment[6]. Studies indicate that a judicious design of façades can reduce up to 50% electricity use [7,8]. Also, the average cost of a façade accounts for a quarter of the total construction cost, and its maintenance cost is argued to be significant [9]. Selecting a high-performance façade is therefore crucial to the sustainability of a building.

The use of concrete frames infilled with sandcrete blocks is very popular in Ghana. A survey indicated that about 64% and 35% of residential buildings are composed of sandcrete blocks and mud/burnt bricks respectively [10]. Other alternative materials have also been researched in the recent past [11]. According to Oppong & Badu (2013) interactions between concerns such as the construction duration, environmental and economic performance have motivated the use of alternative materials in Ghana. Some alternative materials include soil-based façades: Stabilized Earth Block Façade (SEBF) and two other composite façades: Galvanised Steel Insulated Composite Façade (G. Steel ICF) and Shotcrete Insulated Composite Façade (Shotcrete ICF). While these alternative façades are gaining attention in Ghana, their sustainability has not been studied. Mostly the operational performance of façades is prioritised by designers and researchers whereas their effectiveness on reducing life cycle impacts is debatable [13]. To fulfil a holistic sustainable design, Life Cycle Assessment (LCA) is universally accepted as a comprehensive measure of façade sustainability as briefly review in the following session.

Christoforou et al. (2016) evaluated different production scenarios of adobe bricks in Cyprus and found that using sawdust instead of wheat straw and the transport distances significantly vary the result. LCA was used to compare the environmental performance of naturally stabilized earth blocks and three conventional load-bearing walls in Spain [15]. The study suggests that stabilized earth blocks perform better in terms of the span, but the concrete block masonry has less wall mass. Joglekar et al. (2018) conducted a comparative LCA of five bricks incorporating different industrial and agro wastes in India and argued that these bricks outperform the conventional clay bricks. Guo et al. (2018) evaluated the mechanical and environmental impacts of recycled concrete aggregates in concrete building blocks. Their study shows that environmental impacts of normal concrete blocks are much higher due to longer transportation distances. Ben-Alon et al. (2019) evaluated the environmental impacts of cob wall materials used in USA and showed that the impacts of cob are highly dependent on the wall thickness and material source. An assessment of energy embodied in cement stabilized rammed earth wall construction suggests an optimization of the cement content and compaction due to clay content [19]. The embodied energy of a cement stabilised rammed earth building in India was found to be approximately 60% lower than a burnt clay brick alternative [20]. Sandanayake et al. (2018) compared the environmental impacts of a concrete and timber building in Australia which revealed that recycling and the use of regional materials make the most significant impacts. Autoclaved Aerated Concrete (AAC) and fired brick exterior walls were subject to environmental, economic and thermal assessment which indicates that the impact of the former wall system is less owing to the cement content [22]. Arrigoni et al. (2017) assessed the environmental impact of hempcrete blocks in Italy and identified the binder production as the most significant source of environmental impacts. Further investigation revealed that hempcrete blocks have a favourable environmental impact due to the uptake of CO_2 during hemp growth and carbonation. The environmental impact of an alkali-activated block and stabilized soil block were compared against a conventional concrete block and an architectural concrete block [24]. The results suggest both emergent masonry blocks reduce embodied carbons by over 40% when compared with conventional blocks. Environmental impacts of mud concrete block and other industrious walling materials in Sri Lanka were compared based on a fixed area of walls [25]. This study indicates the mud concrete block has the lowest environmental impact which can be further reduced using renewable energy.

On top of cement-based and soil-based façades, there are a few studies noteworthy on the environmental performances of insulated composite façades (ICF). To the best knowledge of the authors, only Yılmaz et al. (2019) conducted a comparative LCA on rockwool or polyurethane filled galvanised insulated composite façade panels in Turkey. The study concludes that for the same functional requirement, polyurethane filled panels are more environment friendly due to the less use of galvanised steel. Potrč et al. (2016) analysed the life cycle impact of External Thermal Insulation Composite Systems (ETICS) with expanded polystyrene (EPS), mineral wool and wood fibre board insulation filling. The study proves that insulation materials cause the major environmental impacts among which EPS contributes the least. Sierra-Pérez et al. (2016) evaluated the environmental performance of ETICS, ventilated façade and internal insulation façade for different climate zones of Spain and revealed that ETICS with glass wool filling has the least environmental impact. The study also focused on auxiliary materials used for each façade given their critical impacts. A multi-criteria decision-making process was developed to select the optimal façade system between the AAC panel, aluminium composite panel, ceramic cladding, concrete block and double brickwork in

Australia [29]. The study identified embodied energy/carbon of materials as the most critical factor and AAC panel is found to have the worst performance. Densley Tingley et al. (2015) evaluated the life cycle impact of EPS, phenolic foam and mineral wool insulation for UK homes and concluded that EPS had the least environmental impact in most categories. However, considering the embodied carbon alone, phenolic foam is the least impactful insulation material. Schmidt et al. (2004) evaluated the environmental performance of stone wool, paper wool and flax and concluded paper wool has the least environmental impacts whereas flax insulation has the largest impacts. Schiavoni et al. (2016) reviewed commercialized insulation materials and found that existing LCA studies lack a common boundary and calculation process which makes a direct comparison across studies very difficult. Hill et al. (2018) also presented an extensive review of insulation materials and emphasized the need for scenario specific LCA data when comparing insulation materials.

From the above literature review, it can be observed that the environmental impacts of ICFs strongly depend on their composition while the impact of G. Steel ICF has not been sufficiently evaluated. Also, no LCA study on Shotcrete ICF has been identified in existing literatures. Although LCA of similar soil-based façades has been conducted in regions such as India, Sri Lanka, Cyprus and Spain, their conclusions might not be applicable to Ghana due to variations in materials compositions, construction technology, energy/carbon database and other supporting structures of the façade. Thus, the environmental impacts of façade systems should be analysed within a context specific approach. Also, it is necessary to consider the impact of other facade supporting components as they may vary LCA results significantly. Given the steadily increasing demand for housing, more residential units are expected to be constructed with critical impacts on the environment. LCA is therefore required to select façades with the least environmental impacts while fulfilling economic targets. This study presents a framework to assess and compare the environmental and economic impacts of G.

Steel ICF, Shotcrete ICF and SEBF with the conventional Concrete Block and Mortar Façade (CBMF) used in Ghana. Major contributions of the work lie in the following aspects: (a) An informative LCA of four different façade systems (b) In-depth comparison of the impact of the four façades including supporting elements (c) A scenario analysis to further improve facade performances. This study contributes significantly to the Ghanaian housing sector as well as regions with similar realities by providing a comprehensive guidance to selecting a sustainable façade to cope with the growing housing demand.

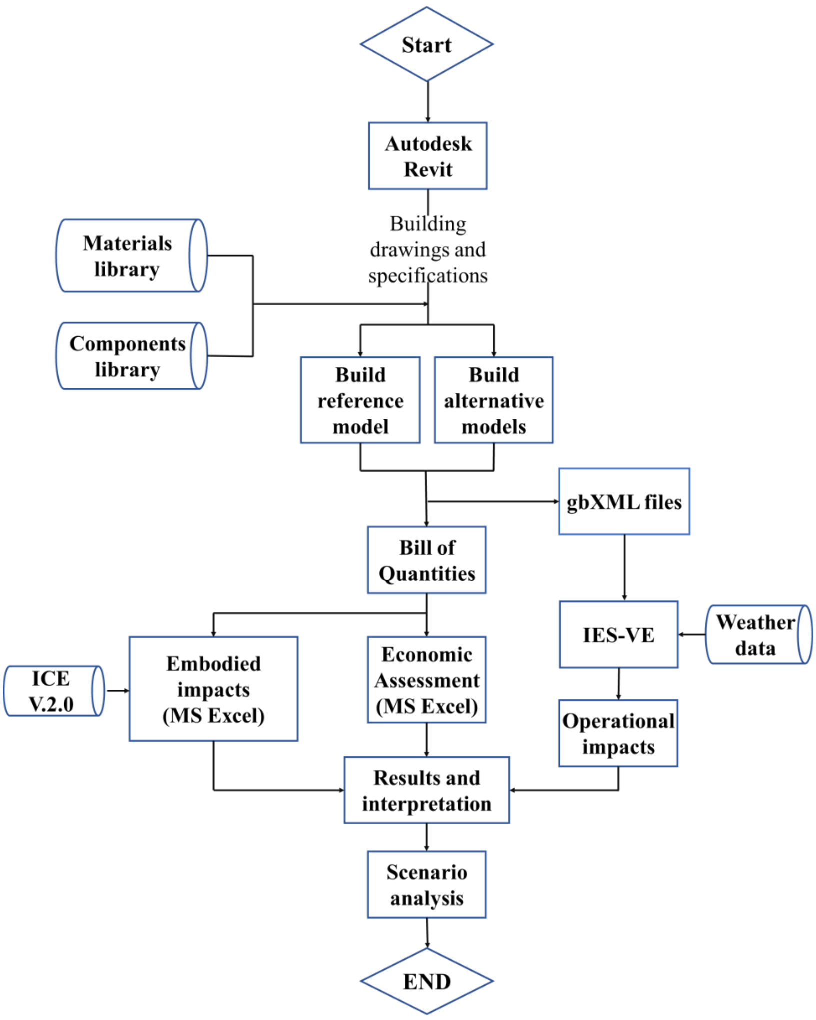


Fig. 1. Research framework

2. Research methodology

Fig. 1 summarises the entire research framework while details are specified in the following subsections. A BIM model is developed in Revit with reference to a selected case building which is constructed of CBMF. Separate BIM models are then developed for the three other façades as described in section 2.2. Each model is used to conduct a comprehensive LCA in accordance with the International Standardisation Organisation (ISO) 14000 series [34]. The embodied impacts and LCC are estimated in Microsoft Excel and Integrated Environmental Solutions Virtual Environment (IES-VE) is utilized to predict operational impacts. The results are then subject to an in-depth comparative analysis of different life cycle phases together with economic evaluations.

2.1. Goal and scope definition

The goal of this study is to compare the environmental and economic impacts of G. Steel ICF, Shotcrete ICF, SEBF with the conventional CBMF used in Ghana. The functional unit is set to 180.50 m^2 gross floor area (GFA) for a lifespan of 50 years. Therefore, all results presented are for 180.50 $m^2 \cdot 50$years. The impact of windows is included as it significantly affects the operational energy use.

LCA covers processes of the material extraction, product manufacturing, transportation, onsite construction and building operation but end-of-life phase due to the lack of reliable data for buildings in Ghana. Also only the impact of cooling is considered for the operational phase.

2.2. Case descriptions

Single storey buildings are common architypes in the Ghanaian residential sector. The case building, located in Amasaman, Accra is selected because the location is representative of the typical Ghanaian climate. The building is on a site with an altitude of 23m, longitude of 0.3019° W, latitude of 5.7062° N, a Tropical Savanna Climate (Aw) under the Koppen-Geiger climate classification, 761 heating degree days (HDD) and 3793.8 cooling degree days (CDD). The average annual temperature fluctuates between 23.0° and 30.0°, with a dominant cooling load. The building is compartmentalized into six zones: three bedrooms, a living room, a kitchen, two washrooms, a corridor and a porch. It has dimensions close to 12m (length) by 15m (width) and a height of 7m (from the apex of the roof to the ground plane). The floor plan and 3D model are shown in Fig. 2, while the main differences in the four façades are described below.

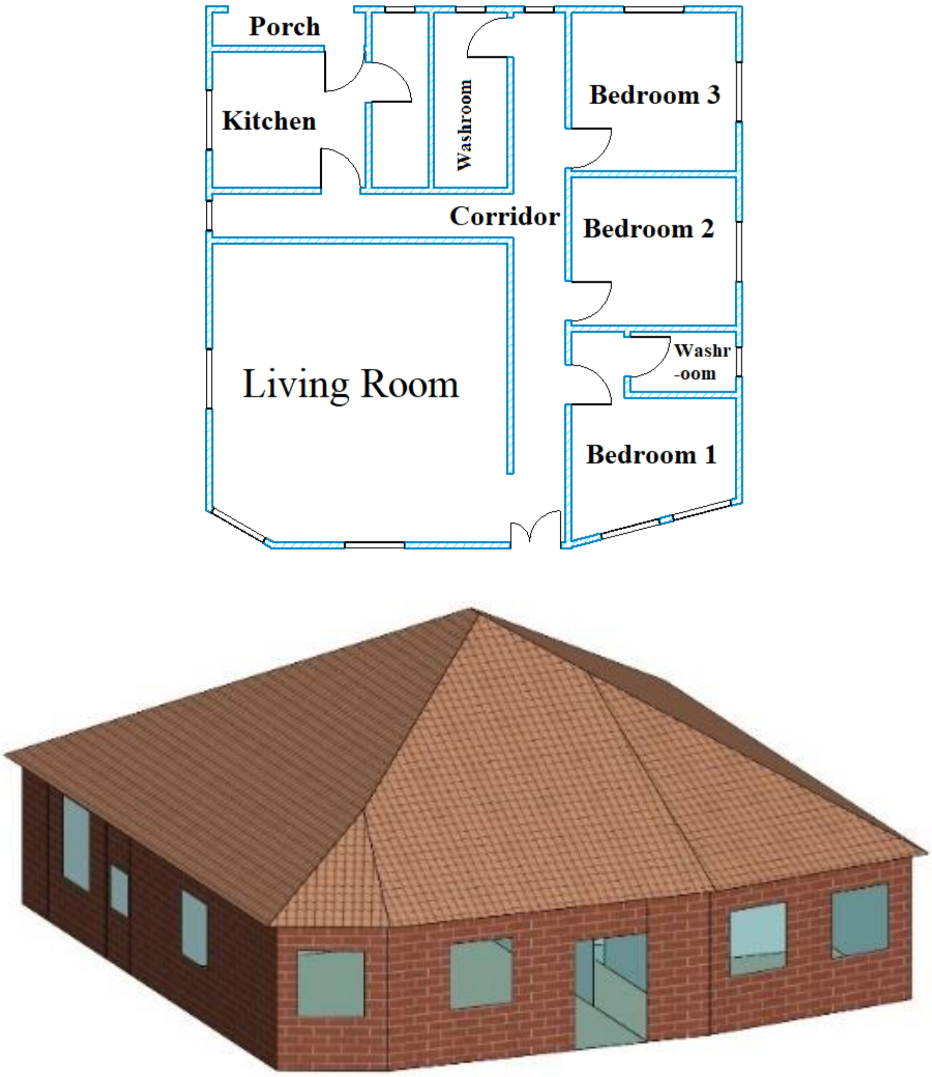


Fig. 2. Baseline model layout plan and developed simulation model

2.2.1. Concrete block and mortar façade

The case building's façade (CBMF) is composed of 150mm thick concrete blocks and 15mm thick mortar on both sides. Concrete blocks are manufactured from locally available cement, river sand and water in the ratio of 2:7:1. Cement and sand are manually mixed while adding water steadily until a homogenous mixture is reached. The mixture is then poured into moulds and compressed manually. They are subject to air-drying and curing before laid with mortar bonds. The structure is plastered with mortar after drying. The main supporting components are reinforced concrete beams and columns. Based on the information provided by the contractor it is assumed that a concrete mixer is used to prepare concrete. In the same regard, blocks are manufactured 200 metres from the site while aggregates and cement are manufactured 10.7 km and 43.1 km from the construction site respectively.

2.2.2. Stabilized earth block façade

The SEBF is made from locally sourced laterite and 8% cement as described in [35–37]. It is usually 180mm thick and requires no finishing as its natural surface is desirable. Laterite usually consisting of 10% to 20% clay, 10% to 20% silt and 50% to 70% coarser soil is first air-dried, grinded manually, sieved to attain uniform size particles after which the stabilizer (cement) is added. Water is added steadily while manually mixing until a homogenous mixture is attained. The mixture is poured in the mould and compressed manually to increase its density and strength. After demoulding, blocks are air-dried under shades pending use. The shape of blocks is altered using mould inserts so that corner sets and hollow cores for reinforcement can be manufactured. These blocks are interlocking and are therefore directly stacked on-top of each other except for a few portions where thin layers of cement-sand mortar are applied as jointing or for airtightness. These special portions include the first course of blocks, window levels and corners of wall. The same transportation distances used for the case building façade is assumed for this alternative design.

2.2.3. Galvanised steel insulated composite façade

G. Steel ICF is factory made in China and exported to Ghana. This façade consists of panels made up of a 50mm EPS core with 0.5mm galvanised steel sheets on both sides. The panels span a length of 3m and a width of 0.9m. In addition, cold-drawn light weight steel sections, and steel ties are used as the support frame for panels. It is assumed that small construction equipment for cutting, welding, riveting and finishing wall assemblies is powered by a diesel generator. Materials such as EPS, paints, steel bars and steel sections are all imported from China and both domestic and oversea transportations are considered. Distances are established from Google Map and Sea Distance respectively. Transoceanic vessels and trucks are used for oversea and domestic transport respectively. A direct transportation route from Tema harbour to the construction site is assumed as the material supplier is located on the same route.

2.2.4. Shotcrete insulated composite façade

Shotcrete ICF consists of a 70 mm thick expanded polystyrene core sandwiched between two 40mm thick reinforced shotcretes. The main reinforcement is a welded wire mesh, while vertical and diagonal steel bars at 8 mm diameters and at 100 mm intervals are provided for structural support. The EPS core is first placed and fixed by reinforcement bars extending from the concrete slab. The welded wire mesh, vertical steel and diagonal steel bars are then erected on the EPS core, after which the shotcrete is sprayed. Two diesel powered plants, a concrete mixer and a wet shotcrete spraying machine, are used for building this façade. EPS and the welded wire mesh for this façade are imported as individual units to be assembled on site. It is assumed EPS and steel reinforcement are imported from China whereas the raw materials for shotcrete are sourced locally.

All façades incorporate a double-slide single-pane window with aluminium frames. Windows are manufactured in a factory and transported to the site for assembly, so that it is possible to retrieve monthly electricity bills from the manufacturer. Energy demands for fabricating the windows are prorated over the number of windows used. Materials such as aluminium and glass are imported from China. The construction details of the analysed façade alternatives are illustrated in Fig. 3.

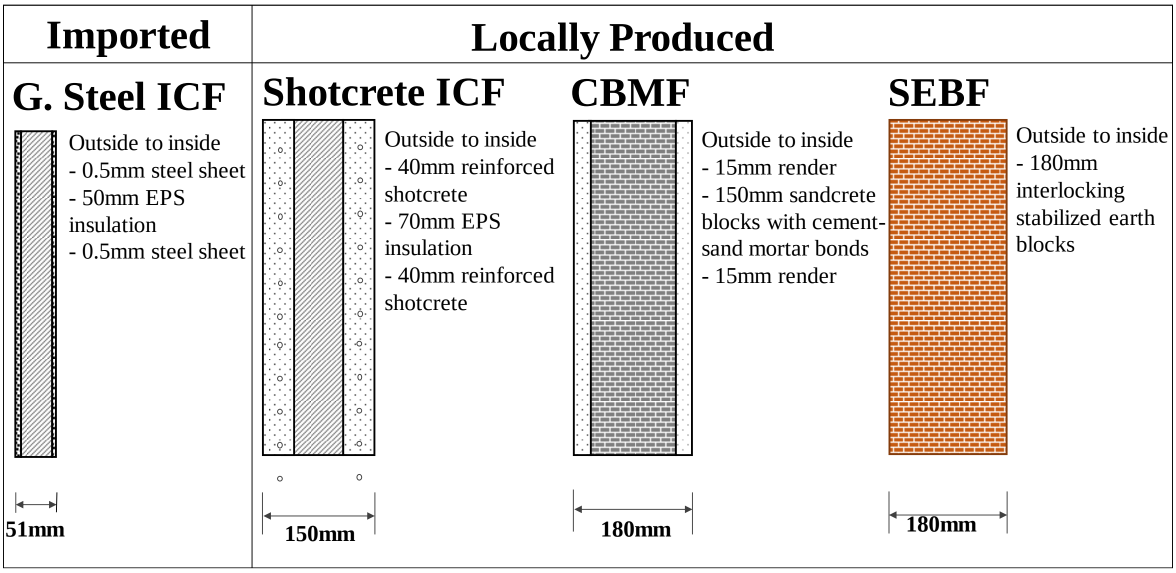
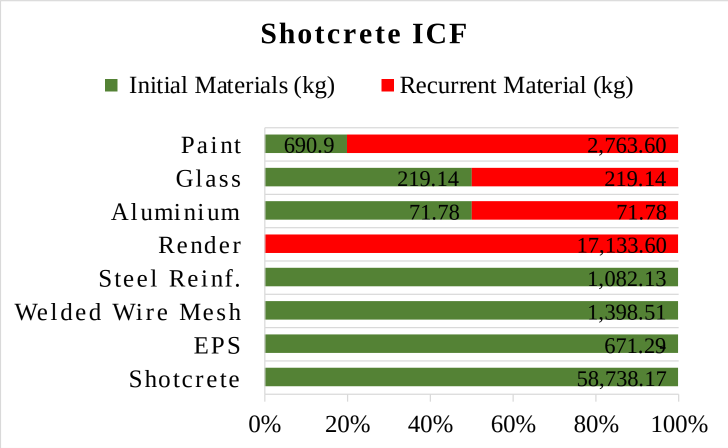


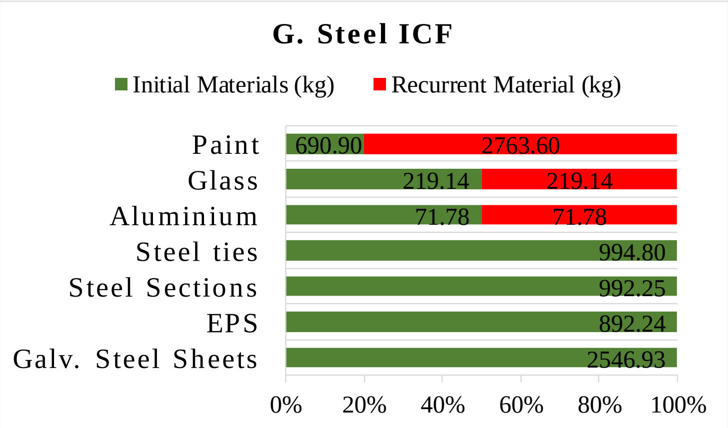
Fig. 3. Schematic diagrams of the four façades.

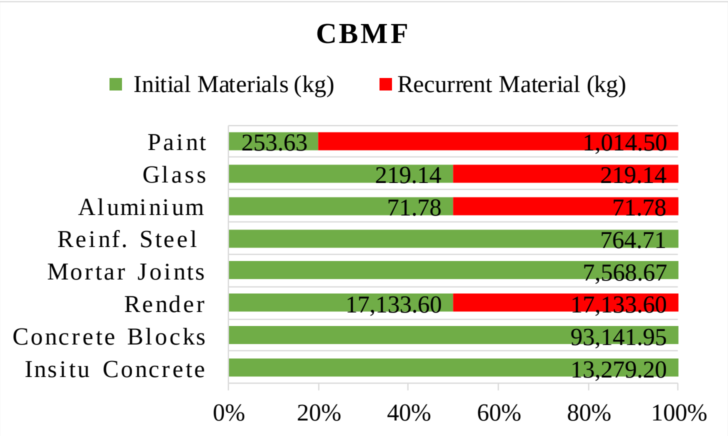
2.3.Life cycle inventory

A bottom-up approach is adopted to make a comprehensive inventory which involves collecting and quantifying input/output data for all materials and processes for the four façades. For the reference façades, primary data including building drawings, material specifications, sources of materials, transportation modes, method statements, electricity and fuel consumption for plants and equipment were retrieved from the owner and contractor. Drawings and materials specifications for alternative façades were sourced from multiple contractors to reach a convergence in designing the alternative models. Other data such as method statements and equipment use were retrieved through short interviews with the experts.

Material's inventory for all cases are generated using Revit's inbuilt scheduling function. Revit is a parametric modelling tool which enables building detailed 3D models and defining specific layers of construction materials. Its scheduling function enables the generation of Bill of Quantities (BOQ) which is particularly useful for the embodied energy assessment [38].


Shotcrete ICF
Initial Materials (kg)
Recurrent Material (kg)
Paint
Glass
Aluminium
Render
Steel Reinf.
Welded Wire Mesh
EPS
Shotcrete
690.9
2,763.60
219.14
219.14
71.78
71.78
17,133.60
1,082.13
1,398.51
671.29
58,738.17
0%
20%
40%
60%
80%
100%


G. Steel ICF
Initial Materials (kg)
Recurrent Material (kg)
Paint
Glass
Aluminium
Steel ties
Steel Sections
EPS
Galv. Steel Sheets
690.90
2763.60
219.14
219.14
71.78
71.78
994.80
992.25
892.24
2546.93
0%
20%
40%
60%
80%
100%


CBMF
Initial Materials (kg)
Recurrent Material (kg)
Paint
Glass
Aluminium
Reinf. Steel
Mortar Joints
Render
Concrete Blocks
Insitu Concrete
253.63
1,014.50
219.14
219.14
71.78
71.78
764.71
7,568.67
17,133.60
17,133.60
93,141.95
13,279.20
0%
20%
40%
60%
80%
100%

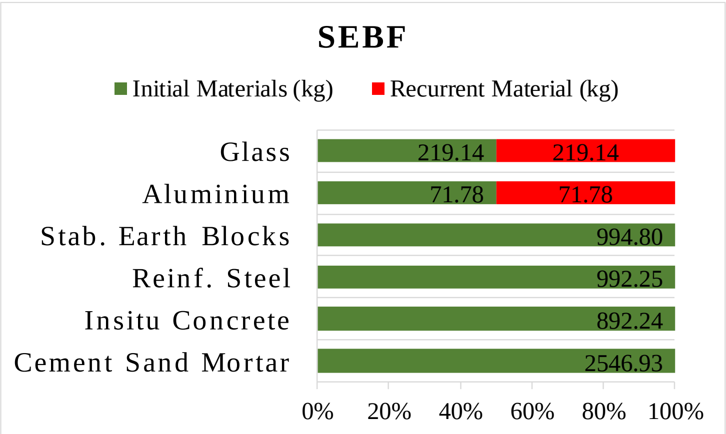

SEBF
Initial Materials (kg)
Recurrent Material (kg)
Glass
Aluminium
Stab. Earth Blocks
Reinf. Steel
Insitu Concrete
Cement Sand Mortar
219.14
219.14
71.78
71.78
994.80
992.25
892.24
2546.93
0%
20%
40%
60%
80%
100%

Fig. 4. Materials inventory of four façades

Fig. 4 illustrates the inventory of materials categorised into initial and recurrent for all cases presented. The initial materials represent materials used at the construction stage. It is assumed that maintenance activities including painting, rendering and window replacement are required as the building's lifespan exceeds the service life of some materials. In such scenarios, the differences are credited as recurrent materials per the replacement factors provided in Table 1. The net quantity of materials is adjusted to account for waste during the construction based on the recommendation of local contractors and existing literatures as summarised in Table 1.

Table 1 Material replacement and waste factors

Material	**Materials' Service Life (yrs.)**	**Material Durability (yrs.) (a)**	**Replacement Factors**	**Wastage (%)**
Aluminium	50	45	1.11	5
Cement Sand Mortar	50	50	1.00	5
Concrete Blocks	50	50	1.00	10
Expanded Polystyrene	50	50	1.00	10
Galvanised steel plates	50	50	1.00	5
Glass	50	36	1.39	5
Insitu Concrete	50	50	1.00	10
Paint	50	10	5.00	10
Render	50	20	2.50	10
Steel Reinforcement	50	50	1.00	10
Steel Sections	50	50	1.00	5

[a][39–41]

2.4. Life cycle impact assessment

Life cycle impact assessment translates the results of the inventory analysis to corresponding environmental impacts [42]. The Inventory of Carbon and Energy (ICE) database V2.0 developed by the University of Bath is selected for the impact assessment [43]. It is an excel document with energy and carbon coefficients of most commonly used building materials. The database is selected because its inventory data are based on a cradle-to-gate boundary and are estimated from many LCA studies with high credibility. For ICE V2.0, products are assessed by their energy use intensity (MJ/kg) and Global Warming Potential (GWP) (kg CO2eq/kg), which are the most commonly used LCA indicators for buildings [44]. Also, CO2eq/kg accounts for other greenhouse gases (GHG) as the carbon equivalent. Metered data in kWh of electricity or litres of fuel are retrieved from the contractor where possible to estimate the construction impact. Since no appropriate energy/carbon conversion factor was found for Ghana, their energy and carbon contents are estimated with reference to UK Greenhouse Gas Reporting: Conversion Factors 2018 [45]. The comparative analysis of façades remains valid as the same conversion factor is maintained for all façades. A similar approach is applied to local transportation. Also, the energy use and emission factors for cross continent transport are provided in Table 2 [46].

Table 2 The energy use, emission factor and transportation distance for the transport mode

Transport mode	**Energy use (MJ/ton.km)**	**Emission factor (g/ton.km)**	**Transportation distance (km)**
Cross continent transport	0.216	15.98	26211.36
Road Freight (local transport)	2.275	168.35	43.1

Furthermore, references are made to Nizam et al. (2018) as shown in Table 3 to complement equipment workload and rated power retrieved from the contractor. With these data, the direct and indirect energy consumption and environmental impacts are estimated.

Table 3 Equipment energy use and emission factors for the construction stage

Equipment	Workload per Machine per day (m^3)	Rated Power (kW)	kWh to MJ conversion factor	kWh to $kgCO^2eq$ conversion factor
Concrete mixer	50	4.4	3.6	0.26910
Shotcrete pump	24	3	3.6	0.26910

2.5. Estimating the energy use and emission of façades

A comprehensive assessment method which incorporates embodied and operational impacts is adopted to evaluate each façade system. Cumulative Energy Demand (CED) and Global Warming Potential (GWP) are adopted as the indicators for the environmental impact assessment.

2.5.1. Cumulative energy demand

The CED is computed as the total energy use associated with each façade expressed in $MJ/m^2/y$ as illustrated in Eq. (1):

$$\mathrm{CED} = \sum_{\mathrm{k}} \mathrm{EE}_{\mathrm{k}} + \sum_{\mathrm{c}} \mathrm{OE}_{\mathrm{c}} \quad (1)$$

where CED is the cumulative energy demand over the building life cycle; EE (MJ) is the sum of energy embodied in the materials manufacturing, transportation and construction of each material k used in the construction or maintenance; and OE (MJ) is the operational energy consumption.

Material embodied energy (EE_m) expressed in MJ is assessed through Eq. (2):

$$EE_m = \sum_{k=1}^{n} Q_k \, (1 + W) \times EI_k \quad (2)$$

where k is the type of material; n is the total number of material k; Q_k (kg) is the quantity of material k; W is the waste factor for each material; and EI_k (MJ/kg) is the energy coefficient of material k.

Transportation embodied energy (EE_t) expressed in MJ is estimated by Eq. (3):

$$EE_t = \sum_{k=1}^{n} Q_k \times D_k \times EI_t \quad (3)$$

where D_k (km) is the transportation distance of material k from its source to the construction site; and EI_t (MJ/tkm) is the energy coefficient of the mode of transportation.

The total construction energy (EE_c) expressed in MJ is given by Eq. (4):

$$EE_c = \sum_{w=1}^{n} (EI_w \times A_W) \quad (4)$$

where n is the total types of process w; EI_w (MJ/hr) is the energy coefficient of w; and A_w (hrs) is the duration of work to be performed.

The actual energy use during the operational phase of the case building is retrieved from monthly electricity bills for the year 2017. While the retrieved data cover energy demands for cooling, lighting and household appliances, the main interest lies in the cooling energy demand. Moreover, the energy use with alternative facade systems also needs to be predicted, so that IES-VE is used to predict operational energy uses. IES-VE is a platform for modelling the energy, daylight, renewable energy system, airflow performance related to buildings. The weather data used to assess the annual operational performance is generated from the ASHRAE database using IES-VE. For all models, U-values of walls are varied while all other assumptions (e.g. the floor properties, roof properties, occupancy and internal gains) are referenced to the case building. Table 4 shows main input settings for the building energy simulation.

Table 4 Input parameter for building energy simulations

Parameter	Value
Indoor cooling setpoint	23°C
Air change rate	1.2m/s
Equipment gain	10W/m^2
Illuminance setpoint	150 Lux
Lighting gains	15 W/m^2
Occupancy	4 persons
Occupancy gains	100 W/person

Operation schedule	Weekdays (18:30 - 07:30), Weekends (00:00 - 24:00)

2.5.2. Global Warming Potential

The GWP associated with each façade in $kgCO_2eq/m^2/y$ is estimated by Eq. (5):

$$\mathrm{GWP} = \sum_{\mathrm{k}} \mathrm{GWP}_{\mathrm{EEk}} + \sum_{\mathrm{c}} \mathrm{GWP}_{\mathrm{OEc}} \tag{5}$$

where GWP is the Global Warming Potential over the building life cycle; GWP_{EE} ($kgCO_2eq$) is the greenhouse gases embodied in the material manufacturing, transportation and construction for each material *k*; and GWP_{OE} ($kgCO_2eq$) is the greenhouse gases emitted during the operational stage.

Materials GWP (GWP_m) expressed in $kgCO_2eq$ is calculated through Eq. (6):

$$GWP_m = \sum_{k=1}^{n} Q_k \,(1 + W) \times CI_k \tag{6}$$

where CI_k ($kgCO_2eq/kg$) is the carbon coefficient of material k.

Transportation's GWP (GWP_t) expressed in $kgCO_2eq$ is determined by Eq. (7):

$$GWP_t = \sum_{k=1}^{n} Q_k \times CI_t \times D_k \tag{7}$$

where CI_t ($kgCO_2eq/tkm$) is the carbon coefficient of the transportation mode.

Construction GWP (GWP_c) expressed in $kgCO_2eq$ is given by Eq. (8):

$$GWP_c = \sum_{w=1}^{n} (CI_w \times A_W) \tag{8}$$

where CI_w ($kgCO_2eq/hr$) is the carbon coefficient.

Finally, operational GWP ($kgCO_2eq/kWh$) is estimated by applying a conversion factor retrieved from UK Greenhouse Gas Reporting: Conversion Factors 2018 to the energy use during this stage [48].

2.6. Life cycle cost (LCC)

The life cycle cost is calculated for both initial and recurrent investments, including the cost of all materials, plants and labours used for façade construction. The rates used are weighted averages from several contractors to avoid biases. Total amounts are calculated as a product of quantities and rates.

2.7. Scenario analysis for each façade

Scenario analyses have been increasingly applied in LCA studies [49–51]. To identify strategies for further improving the performance of each façade, scenario analyses are conducted to assess the variation induced in CED and GWP. At least two scenarios are defined stepwise for each façade combining design and material source variations. The ratio of the change in results to the variation of a parameter (i.e. Sensitivity Ratio) is expressed by Eq. (9).

$$\text{Sensitivity Ratio} = \frac{\text{Change in results}/\text{initial results}}{\text{change in parameter}/\text{initial paramter}} \tag{9}$$

The first two scenarios are defined for materials that are locally available although mainly imported. Scenario 1 considers modifying the sources of EPS and the paint, thus addressing the impact of transportation. It is assumed that importing EPS and paints increases the impact of transportation, as these materials are available in Ghana (i.e. a scenario is considered where they are locally supplied). Similarly, the energy embedded in transporting steel is also found to be significant. Besides importing steel from countries like China and Ukraine, Ghana produces some amount of steel from scrap sourced within the country and nearby regions like Kenya. Therefore, Scenario 2 is proposed to explore the impact of locally manufactured steel given that Ghana recycles some quantities of steel.

The third scenario is defined by varying the facade design. For SEBF, blocks account for a large portion of the material embodied energy considering its mass. Therefore, the impact induced by reducing the thickness of blocks and replacing reinforced concrete lintels with reinforced compressed-mud blocks are explored. Similarly, the mass of CBMF can be reduced using hollow blocks so that a scenario is set to explore its effect. Information retrieved from experts indicates the thickness of Shotcrete can be reduced from 40mm to 30mm so that its impact is also explored. All assumptions for the scenario analysis are summarized in Table 5.

Table 5 Main assumptions for scenario analysis

Scenario	**Shotcrete ICF**	**G. Steel ICF**	**CBMF**	**SEBF**
Paint and EPS Source	Accra, Ghana	Accra, Ghana	Accra, Ghana	Accra, Ghana
Steel Source	Accra, Ghana	Accra, Ghana	Accra, Ghana	Accra, Ghana
Wall design	With 30mm shotcrete thickness	-	With hollow concrete blocks	With reinforced mud block lintels, 300mm thick blocks

3. Results and discussion

This section expounds LCA results for four façades in various life cycle phases and scenario analysis. The simulation model is validated with the energy end-use data retrieved from the case building. Detailed environmental and economic impacts of the four façades are analysed and discussed in the following subsections.

3.1.Model validation

. For validation purpose, the simulated energy use for baseline model is compared with energy end-use data retrieved from the case building. Based on monthly electricity bills for the year 2017, the total energy use for HVAC, equipment and lighting is estimated as 25.60kWh/m^2/y. On the other hand, the baseline model is estimated to be 24.15 kWh/m^2/y. From Fig. 5, the simulated data is shown to be consistent with the end-use data with a minor difference of 5.65%. In this regard, the baseline model can sufficiently represent an average residential building in Ghana. . A breakdown of annual energy consumption for all four façade designs is presented in Table 6.

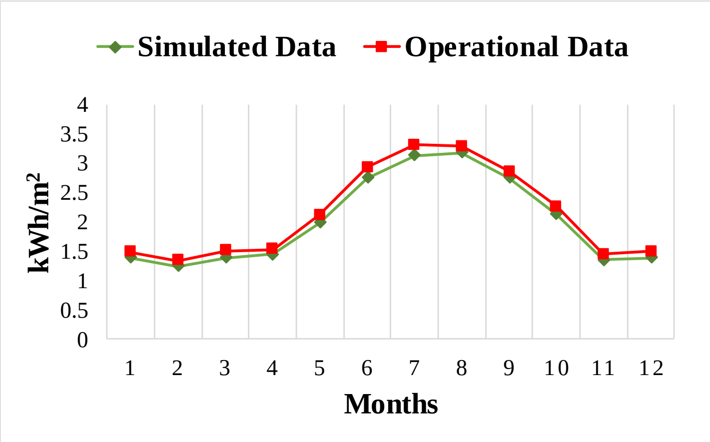


Fig. 5. Comparison of energy end-use data and simulation data of case building

Table 6 Breakdown of simulated annual energy demands during use phase of buildings

Energy use breakdown	**Shotcrete ICF (kWh)**	**G. Steel ICF (kWh)**	**CBMF (kWh)**	**SEBF (kWh)**
Chillers	14.88	14.96	16.33	14.87
Heat rejection fans	1.75	1.78	1.82	2.04
Total equipment	5.60	5.60	5.60	5.60
Total lights	1.85	1.85	1.85	1.85
Total electricity	24.07	24.18	25.60	24.36

3.2. Comparative LCA of façade types

3.2.1. Concrete Block and Mortar Façade

The baseline model (CBMF) is evaluated with a CED of 100.04 MJ/m^2/y. The contribution of various LCA phases is presented in Fig. 6 while a detailed breakdown is provided in Table 7. OE and EE contribute 65.10% and 34.90% of CED while GWP_{OE} and GWP_{EE} contributes 79.09% and 21.91% respectively. Material production contributes 93.60% of EE and 95.38% of GWP_{EE}. Most of these impacts are associated with the paint, sandcrete block, and cement plaster. The high impact of paints is explained by its high energy intensity and frequent replacement. Similarly, cement in concrete blocks and render is energy intensive in addition to the large quantities used [52]. This finding echoes with Evangelista et al. (2018) where coatings and masonry are found to make the large contribution to EE of single-family dwellings. Furthermore, EE_t is proved to be mainly associated with the importation of window, paint, and steel reinforcement materials, which is also indicated in an existing study that using local materials can significantly optimize the impact of transportation [54]. Like EE_t, majority of GWP_t originates from paint, steel reinforcement rods and sandcrete blocks. The contribution of the construction phase is however less important with close to zero EE and GWP [55]. The small amount of EE_c is mainly attributed to concrete and windows with 29.79% and 70.21% respectively.

Table 7 Embodied energy and global warming potential of Concrete block and mortar façade

Materials	**EE (MJ)**	**GWP (kg CO_2e)**
Materials Production Phase		
Concrete Blocks	69,856.46	12,036.22
Insitu Concrete	10,623.36	1,713.02
Mortar Joints	7,224.70	1,244.81
Paint	109,740.00	5,196.84
Reinforcement Steel	16,517.81	1,422.37
Render	49,064.81	8,453.83
Windows	30,115.53	1,759.81
Transportation Phase		
Concrete Blocks	2,411.71	179.36
Insitu Concrete	347.71	25.86
Mortar Joints	239.34	17.80
Paint	7,360.53	544.61
Reinforcement Steel	4,369.30	323.26
Render	1,625.42	120.88
Windows	3,335.10	284.50
Construction Phase		
Insitu Concrete	99.98	7.44

Materials	EE (MJ)	GWP (kg CO_2e)
Windows	235.58	12.04
Total	313,167.34	33,342.65

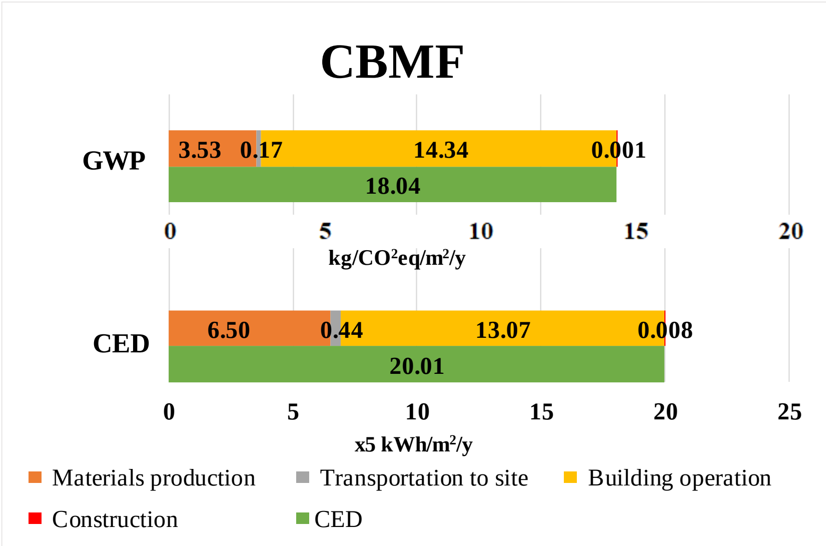


Fig. 6. CED and GWP for CBMF per unit GFA and across the building lifespan

3.2.2. Stabilized Earth Block Façade

SEBF is proved as the most sustainable façade. Its contributions to CED and GWP for different life cycle stages are shown in Fig. 7 while a detailed breakdown of EE and GWP_{EE} is summarized in Table 8. SEBF does not alter the ranking of lifecycle phases however, the difference in impacts of life cycle phases fluctuates within a range from 6.85% to 63.18% significantly influencing total CED. From Fig. 7, CED decreases from 100.4 MJm^2/y to 75 MJm^2/y which represents 39.13% CED saving. EE_c is increased by 25% but still approaching zero with a relatively less importance [56]. EE_t is increased by 14.68% which can be explained by the larger mass of soil materials for SEBF, which also leads to the decrease in EE_m. SEBF is characterised by higher soil contents with a low EE coefficient and lower cement contents with a high EE coefficient whereas this relationship between soil and cement is reverse for

CMBF. Furthermore, SEBF is constructed with interlocking joints which reduce the mortar joint extensively used in CBMF.

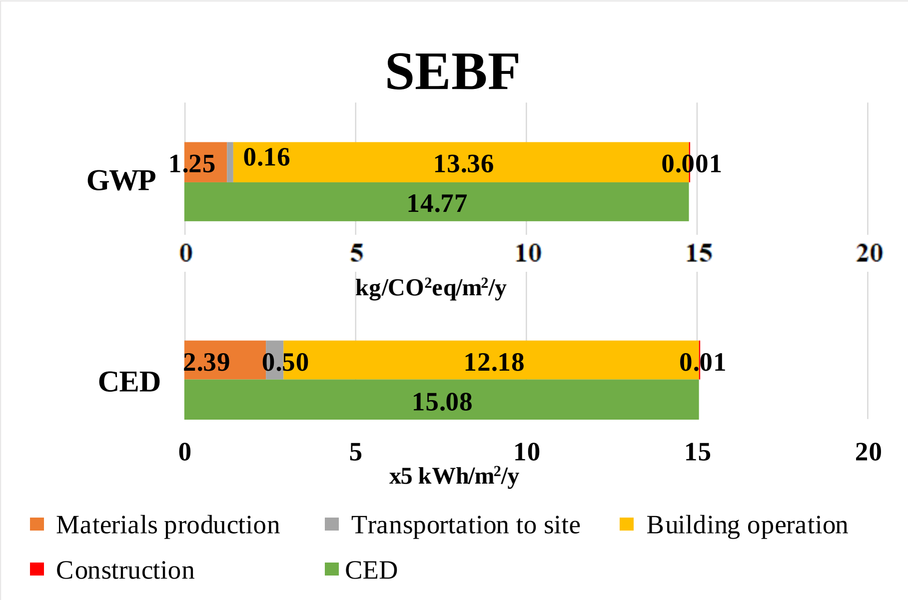


Fig. 7. CED and GWP for SEBF per unit GFA and across the building lifespan

Table 8 Embodied energy and global warming potential of Stabilised earth block façade.

Materials	**EE (MJ)**	**GWP (kg CO_2e)**
Material Production Phase		
Cement Sand Mortar	6849.81	1,123.02
Insitu Concrete	7,054.36	1,066.76
Stabilised Earth Blocks	5,3526.73	8,223.68
Steel Reinforcement	10,374.612	893.37
Windows	30,115.53	1,759.81
Transportation Phase		
Cement Sand Mortar	98.7173	7.34
Insitu Concrete	195.60	14.55
Stabilised Earth Blocks	16,185.34	1,225.825
Steel Reinforcement	2,755.46	203.87

Windows	3,335.10	284.50
Construction Phase		
Insitu Concrete	66.39	4.94
Windows	235.58	12.04
Total	130,793.23	14,819.71

SEBF is also characterised by a lower GWP of about 14.77 kgCO_2eq compared with 18.04 kgCO_2eq of CBMF, leading to a savings of approximately 18.07% in GWP. The main difference in GWP originates from the material manufacturing and operational phase. A change in façades from CBMF to SEBF decreases GWP_m by 64.59%. Given the same source of operational energy, GWP_{EO} covariates with EO in similar trends. The change in GWP_c and GWP_t is however relatively less significant especially as GWP_t approaches zero. Although not directly comparable, these findings are consistent with previous studies on small houses [57]. However, they contradict with one study which reported that concrete blocks performed better than stabilised earth blocks [58]. In summary, 39.13% and 18.07% savings in CED and GWP are achieved for adopting SEBF.

3.2.3. Galvanised Steel Insulted Composite Façade

As shown in Fig. 8, G. Steel ICF has no influence over the ranking of life cycle phases. However, an 8.32% increase is observed in total CED. The exact contribution of each life cycle phase also fluctuates but within a larger range of 7.81% to 100%. It is noteworthy that EE_m increases by 34.55% because of the extensive use of energy intensive materials in G. Steel ICF. This may be associated with the massive use of EPS, galvanised steel sheets, sections and ties which are energy intensive materials[59]. Due to the importation of these three materials, EE_t is also doubled from 2.18 MJ/m^2/y to 4.36 MJ/m^2/y. Although, the impact of EE_c on the total CED is not significant, a 50% increase is observed due to the use of welding and revetting equipment.

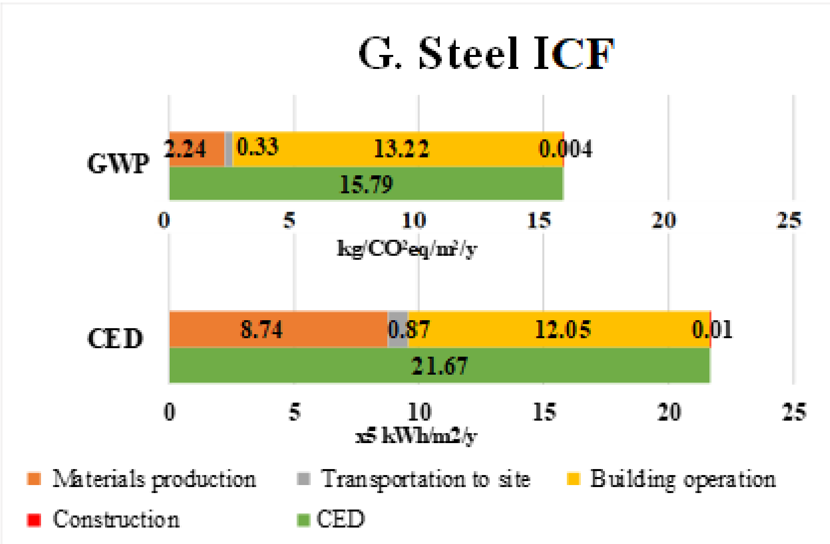


Fig. 8. CED and GWP for per unit GFA and across the building lifespan

Fig. 8 also illustrates the GWP. A decrease from 18.04 $kgCO_2eq$ to 15.79 $kgCO_2eq$ approximate to 12.47% is observed. The unique influence of each material explains the higher ratio of EE_m to GWP_m [60]. For CBMF, 32.48 $MJ/m^2/y$ of EE_m yields 3.53 $kgCO_2eq$ of GWP_{EEM} whereas 43.70 $MJ/m^2/y$ yields 2.24 $kgCO_2eq$. Like EE_t, GWP_t is significantly decreased by 234% although the absolute value is negligible. The results is not directly comparable with the existing studies as the impact of supporting frame is considered, nonetheless the main sources of CED and GWP are identified the same as [59]. A breakdown of EE and GWP_{EE} is provided in Table 9.

Table 9 Embodied energy and global warming potential of Galvanised Steel Insulated Composite Façade

Materials	**EE (MJ)**	**GWP (kg CO_2e)**
Materials Production Phase		
EPS	39,526.12	1,467.73
Galvanized Steel Sheet	81,501.84	5,628.72
Paint	189,441.00	7,343.28
Steel Sections	26,889.98	2,014.27
Steel ties	26,959.18	2,019.45

Window	30,115.53	1,759.81
Transportation Phase		
EPS	2,561.91	189.55
Paint	7,960.53	584.27
Steel Panel	15,173.31	1,122.56
Steel Section (Studs)	4,374.37	323.63
Steel ties	5,926.53	438.46
Window	3,335.10	284.5
Construction Phase		
Structure	534.87	39.78
Windows	235.58	12.04
Total	434,535.84	23,228.04

3.2.4. Shotcrete Insulated Composite Façade

Figs. 9 illustrates that Shotcrete ICF does not affect the lifecycle phase ranking. However, total CED and contributions of all life cycle phases are increased significantly. The contributions of each material to life cycle phases are presented in Table 10. The operational energy is predicted as 59.86 MJ/m^2/y corresponding to 8.39% decrease in EE_o. On the other hand, EE_m and EE_t are increased by 11.95% and 404.59% respectively. The cumulative impact of these increment significantly affects total CED. The total CED is increased by 7.32% (7.32 MJ/m^2/y) with the largest increase in EE_c for Shotcrete ICF. EE_c is increased by 250% although the absolute value remains comparatively less significant. In terms of GWP, Shotcrete ICF contributes the second highest impact. GWP is increased by 6.88%, equivalent to 1.24 kgCO_2eq/m^2/y. The contribution of construction and transportation phases to total GWP are increased while those of the material production and operational phases are decreased. It is observed that GWP_{EEc} is scaled up over 7 times while GWP_{EEt} is scaled up over 4 times of CBMF. On the contrary, GWP_{EEm} and GWP_{OE} are decreased by 22.38% and 8.37% respectively.

Table 10 Embodied energy and global warming potential of Shotcrete Insulated Composite Façade

Materials	EE (MJ)	GWP (kg CO2e)
Materials Production Phase		
EPS	59,476.59	2,208.56
Paint	109,740.00	5,196.84
Render	16,354.94	2,817.94
Shotcrete	58,150.79	9,104.42
Steel Reinforcement	23,373.92	2,012.75
Welded Mesh Fabric	30,907.12	1,636.26
Windows	30,115.53	1,759.81
Transportation Phase		
EPS	18,336.61	1,532.46
Paint	7,360.53	544.61
Render	541.81	40.29
Shotcrete	1,980.64	147.30
Steel Reinforcement	29,536.79	2,468.71
Welded Mesh Fabric	38,161.83	3,189.69
Windows	3,335.10	284.50
Construction Phase		
Shotcrete	1,061.40	78.94
Windows	235.58	12.04
Total	428,669.18	33,035.12

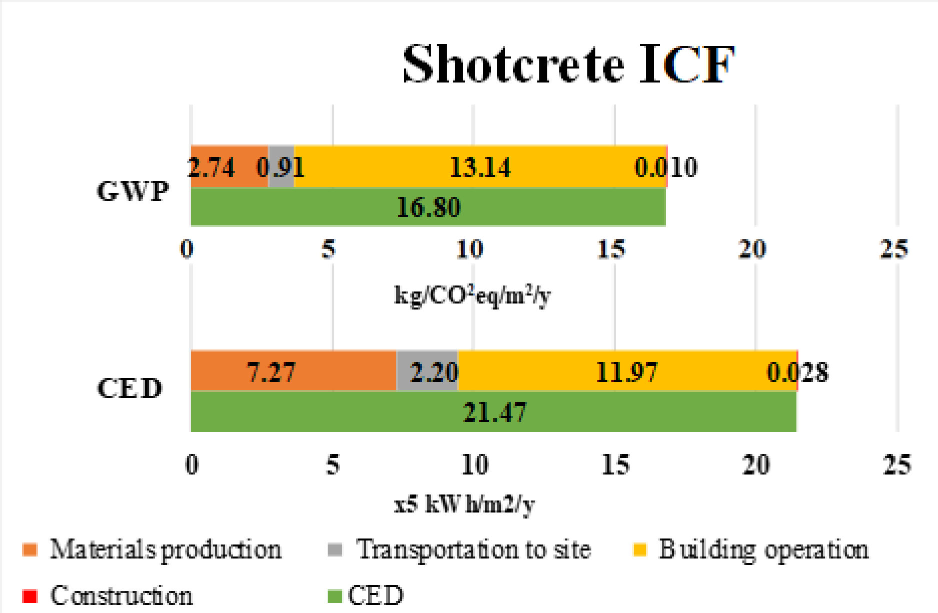


Fig. 9. CED and GWP per unit GFA and across the building lifespan

3.3. Life Cycle Cost

The life cycle cost for all façade systems are presented in Fig. 10. CBMF is proved as the most expensive among the assessed façades. Because of the higher replacement factor of materials used in Shotcrete ICF, G. Steel ICF and CBMF, their recurrent costs contribute up to 40% of the total cost. However, the recurrent cost of SEBF is much lower and constitutes to 21% of the total life cycle cost. The lower cost of SEBF can be associated with the lower cost of stabilised earth blocks as well as the relatively less amount of material used in this façade. The cost of Shotcrete ICF, G. Steel ICF and SEBF is 4.56%, 22.44% and 47.87% lower than that of CBMF.

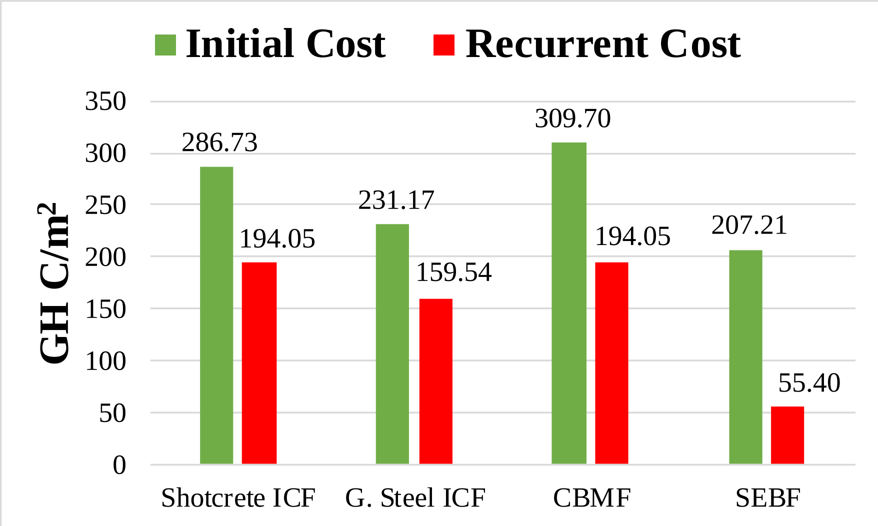


Fig. 10. Life Cycle Cost for all façades per floor area

3.4. Scenario analysis

The scenario analysis indicates that EE and GWP_{EE} of Shotcrete ICF are scaled down by 6.32% and 6.46% respectively when paints and EPS are sourced locally. By sourcing steel locally, EE and GWP_{EE} is reduced by 12.81% and 13.89% respectively. A reduction of the thickness of shotcretes by 10mm can lower EE and GWP_{EE} by 3.51% and 7.06%. Cumulatively, 22.64% and 27.41% reduction of EE and GWP_{EE} is attained. For G. Steel ICF, 2.36% of EE and 2.48% of GWP_{EE} is reduced by sourcing paints and EPS locally. Likewise, sourcing steel locally, reduces EE and GWP_{EE} by 4.80% and 6.32% respectively. Both scenarios reduce EE and GWP_{EE} by 7.16% and 8.80%. For CBMF, the hollow block scenario reduces EE and GWP_{EE} by 9.6% and 11.12%, while 2.29% of EE and 1.48% of GWP_{EE} reductions are attained by sourcing paints and EPS locally. Furthermore, the use of locally manufactured steel reduces EE and GWP_{EE} by 1.13% and 0.85% respectively. Thus, a total reduction of 13.02% of EE and 13.45% of GWP_{EE} are attained by applying all three scenarios. After replacing reinforced concrete lintels in SEBF with reinforced stabilized earth blocks, the total EE and GWP_{EE} is reduced by 11.68% and 15.58%. By sourcing steel locally, an additional 0.19% of EE and 0.29% of GWP_{EE} reduction are attained. Cumulatively the total EE and

GWP_{EE} is reduced by 11.87% and 15.87% respectively. Table 11 provides the percentage reduction in EE and GWP from the scenarios identified in Table 5. Also, ranking of the façades in accordance with CED, GWP and cost before and after the scenario analysis are provided in Table 12. It is observed that SEBF outperforms all alternatives except for GWP, in which CBMF ranks first after the scenario analysis.

Table 11 Percentage reductions after scenario analysis

Scenario	**Shotcrete ICF**		**G. Steel ICF**		**CBMF**		**SEBF**	
	CED	**GWP**	**CED**	**GWP**	**CED**	**GWP**	**CED**	**GWP**
Paint and EPS	6.32%	6.46%	2.36%	2.48%	2.29%	1.48%	-	-
Steel bars, plate, and ties	12.81%	13.89%	4.80%	6.32%	1.13%	0.85%	0.19%	0.29%
Wall design	3.51%	7.06%	-	-	9.60%	11.12%	11.68%	15.58%

Table 12 Ranking of four façade before and after scenario analysis

Rank		**Shotcrete ICF**	**G. Steel ICF**	**CBMF**	**SEBF**
By CED	Before scenario analysis	3	4	2	1
	After scenario analysis	3	4	2	1
By GWP	Before scenario analysis	3	2	4	1
	After scenario analysis	4	3	1	2
By cost		3	2	4	1

Overall, this study indicates that the operational phase makes the greatest environmental impact across all façade systems, followed by the material production phase, transportation phase and construction phase. In comparison with the reference façade (CBMF), total CED of SEBF is decreased by 39.13% while CED of Shotcrete ICF and G. Steel ICF is increased by 8.32% and 7.32% respectively. On the other hand, GWP is decreased by 18.07%, 12.47% and 6.88% for SEBF, G. Steel ICF and Shotcrete ICF respectively. The scenario analysis reduces

CED and GWP of all façades with a major impact on Shotcrete ICF. The economic assessment showed that the reference façade (CBMF) has the highest cost. In comparison, the cost of SEBF, G. Steel ICF and Shotcrete ICF is reduced by 47.87%, 22.44% and 4.59% respectively.

4. Conclusion

This paper presented a framework to evaluate the environmental and economic performances of building façade systems. A sustainable design process is modelled to guide stakeholders involved in the decision-making process to select façades with lower environmental impacts. In this approach, BIM, LCA and LCC are integrated to design building systems, generate Bill of Quantities, evaluate the energy use/carbon emission and lifecycle cost.

The framework is demonstrated by a comparative assessment of G. Steel ICF, Shotcrete ICF and SEBF with the conventional CBMF for a Ghanaian residential building. Given the expected increase in housing developments, findings of this study are useful for selecting sustainable façades to lower their environmental impacts. One important contribution of this study is the detailed life cycle assessment of Shotcrete IFC, G. Steel IFC in each stage and a deliberate consideration of the construction industry in Ghana. Also, the study serves as a pioneer research for more comprehensive life cycle assessments in future.

This study covers the entire life cycle of all four façade except the end-of-life stage where reliable data are not available for Ghana. The comparative assessment revealed that SEBF can save up to 39.13% of CED, 18.07% of GWP and 47.87% of the cost. Also, for all facades, the operational stage accounts for the largest life cycle impact whereas material production accounts for most of the embodied impact. Scenario analyses indicate that the impact of transportation is significant, as sourcing materials locally can reduce CED and GWP of Shotcrete IFC by over 18%.

The developed framework is also suitable for assessing buildings in similar regions with immature LCA applications given the adoption of the ICE database. The exact transportation, construction, operation and end-of-life situation can then be evaluated and combined with the material production stage to provide the total environmental impact of a building. The methodology can also be applied to different building elements/components as well as architypes.

Although the framework is applicable to the entire building, it is demonstrated for the façade system only. Future studies will consider the life cycle impact of the whole building as it is difficult to assess the operational impact of the façade alone. Furthermore, design optimizations and decision-making strategies should also be incorporated into the framework to investigate diverse building archetypes, multiple geographical regions and include the end-of-life stage.

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