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The overlooked criteria in green building certification system: Embodied energy and thermal insulation on non-residential building with a case study in Malaysia

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ABSTRACT

A green building certification system (GBCS) is essential for sustainable city development. However, the building's embodied energy (EE) and thermal insulation have often been overlooked in GBCSs. The correlation of thermal insulation envelopes to EE and operational energy (OE) has also yet to be extensively investigated. This study adopts life cycle energy assessment methodology to evaluate the EE and OE of non-green and green-rated non-residential buildings with hotspot analysis and analyse the trade-offs between EE production and OE saving for five types of insulation envelopes. Taking Malaysia as a reference, results show EE holds 16–19% of total energy in non-green and green-rated non-residential buildings; hence EE should not be neglected in GBCS. The material consumption phase incurs half a quarter of the total EE, indicating that major recycled and low-embodied building materials (e.g., recycled steel and green cement) should be rewarded with higher points in GBCS. Insulated building envelopes save 84–87% of cooling demand than non-insulated walls, with cellulose fibre insulators consuming the least EE. It is hoped that this study can provide evidence-based outcomes to policymakers when formulating the proportion of EE and OE, and integrating insulation envelopes in GBCS to enhance energy savings further.

1. Introduction

Building construction is booming with urban growth and has induced significant energy and natural resources consumption [89] in every stage of a building life cycle, from pre-use to demolition phase [2]. Buildings are responsible for over 36% of global energy demands and nearly 37% of energy-related CO_2 emissions in 2020 [3]. Energy-related greenhouse gas (GHG) emissions from buildings are projected to grow faster over the next 25 years due to the continued use of fossil resources such as coal, oil, and natural gas for electricity, heating, and cooling [4]. To achieve the global climate ambitions set in Paris Agreement, the International Energy Agency estimated that the energy intensity per square meter of building sector should be reduced by 30% in 2030 compared to 2015 [5]. Rapid deployment of energy-efficient buildings, low carbon fuels, and embodied energy (EE) reduction in buildings assists the world on a sustainable trajectory [6]. Thus, sustainable buildings practices are being established to cope with the rising demand for energy services.

Green Building Certification System (GBCS) is a market-driven approach to transforming conventional construction into sustainable construction [7]. It is a rating model used to verify and assess the sustainability and environmental impact of a building or construction project [8]. According to the World Green Building Council, GBCS is a tool to ensure the development of green buildings by reducing or eliminating negative impacts on the environment during the whole building life cycle, consisting of the embodied, operation, and demolition phases [9]. More than 100 GBCS were developed in different countries or regions for comprehensive building assessment, such as Building Research Establishment's Environmental Assessment (BREEAM), Leadership in Energy and Environmental Design (LEED), and German Sustainable Building [10]. The assessment is based on the requirement of energy efficiency, site planning and management, water efficiency, materials and resources, waste, indoor environmental quality, transportation, and innovation [11] in evaluating green buildings. These criteria could be categorized into the life cycle energy of a building, where EE refers to the materials and resources criteria, operational energy (OE) falls under the energy efficiency criteria, and demolition energy (DE) is categorized as part of the waste management criteria where only demolition waste is considered.

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Abbreviation

BEI	Building energy index
BREEAM	Building Research Establishment's Environmental Assessment
CDD	Cooling degree day
CLT	Cross-laminated timber
DE	Demolition energy
EE	Embodied energy
EPS	Expanded polystyrene
GBCS	Green building certification system
GGBS	Ground granulated blast furnace slag
GHG	Greenhouse gas
LCEA	Life cycle energy assessment
LEED	Leadership in Energy and Environmental Design
NRB	Non-residential building
OE	Operational energy
OPC	Ordinary Portland cement
SDG	Sustainable development goal
XPS	Extruded polystyrene

Significant efforts have been put into improving OE efficiency whereby most regulations and strategic plans have focused on the operational stage of the buildings [12] due to the long period of performance (e.g., 30–50 y), resulting in the overlooking of EE in the GBCS [13]. As summarized in Table 1, energy efficiency criteria have the highest scoring in all different GBCSs, ranging from 19 to 61%, while EE only accounts for 9–12.5%. Amiri et al. [14] pointed out that fewer points and attention were allocated to EE in both LEED and BREEAM rating tools; Crawford and Stephan [15] demonstrated that GBCS neglected the evaluation from EE of envelope materials, namely the insulation and triple-glazed windows that were used to achieve greater OE saving in certified green building (i.e., passive house). However, EE should merit practitioners' attention [16]. In particular, a building's EE could contribute up to 60% of life cycle energy for an energy-efficient building, and 40% for a net-zero energy building [17]; the manufacturing phases of low-energy industrial buildings could yield 71% in primary energy consumption [18]; installing an insulation material envelope has been proven effective in reducing OE by saving 23.5% in air conditioning energy consumption [19] but also affects the EE of buildings significantly [20]; over 50% of life cycle EE comes from polymers in the form of insulating materials [21]. Thus, neglecting EE could knock off an opportunity in environmental and energy conservation and undermine the short-term CO_2 reduction targets of the Intergovernmental Panel on Climate Change [14].

The fundamental influence of the total life cycle energy for a building should be identified as it is challenged to provide relevant support to design energy-saving buildings when different criteria must be considered in GBCS [28]. Wang et al. [29] reported that energy consumption in manufacturing and transportation stages should be prioritised in reducing 11–22% of EE for building in Hong Kong; Chang et al. [30] reported that countries depend heavily on importing building materials affect the university's EE; Chen et al. [31] revealed that cement, steel, and brick accounted for over 70% of the total EE of a building; Llantoy et al. [32] found that insulated building incurred higher environmental impact during the material manufacturing phase, but the lower environmental impact in building's operational phase during winter compared to an uninsulated building; Moradibistouni et al. [20] found that the selection of optimal insulation materials is affected by the type, EE coefficient, and climate characteristics. Several studies analysed the life cycle energy of buildings and the impact of insulation material on building. Still, the analysis has yet to deal with the GBCS perspective as shown in Table 2. The life cycle energy consumption incurred in different green-rated buildings was not clearly defined. Two studies involved the assessment GBCS: Amiri et al. [14] analysed the embodied emissions of a different combination of building materials following LEED rating tool, focused on the concrete and wooden materials in the main building structure. The changes in insulation materials were not considered in the study; Bisegna et al. [33] evaluated the effect of insulation materials on energy efficiency and resource criteria in GBCS. The scope did not include the quantification of building's life cycle energy and energy saving after installing insulation materials; Geng et al. [34] compared the energy consumption of a green-rated building designed under GBCS with the energy used index and concluded an unclear relationship between actual energy used and GBCS.

The highlighted research gap is that the life cycle energy (i.e., EE and OE) of green-rated buildings is not thoroughly examined from the GBCS perspective. This study aims to provide quantitative insights into the life cycle energy of a non-green building and GBCS-certified green buildings by evaluating their EE and OE via life cycle energy assessment (LCEA). This is crucial as deciding on an individual life cycle stage without considering the EE in analysis leads to the underestimation of the environmental impacts of the buildings [45]. Hotspot analysis is conducted in the life cycle energy of non-green and green buildings to investigate the culprits behind the energy impact. To provide

Table 1
Point allocation of the criteria from various GBCS.

Major Criteria	Green Building Certification System[a]									Average Percentage (%)
	BEAM	BREEAM	CASBEE[b]	GBI	Green Mark	GreenRE	Green Ship	Green Star	LEED	
Energy Efficiency	✓ (30)	✓ (19)	✓	✓ (35)	✓ (61)	✓ (58)	✓ (31)	✓ (22)	✓ (25)	35
Indoor Environmental Quality	✓ (25)	✓ (15)	✓	✓ (21)	✓ (4)	✓ (4)	✓ (17)	✓ (16)	✓ (22)	16
Water Efficiency	✓ (15)	✓ (6)	–	✓ (10)	✓ (9)	✓ (8)	✓ (17)	✓ (11)	✓ (7)	10
Innovation	–	–	–	✓ (7)	✓ (4)	✓ (4)	–	✓ (9)	✓ (7)	4
Sustainable Site Planning	✓ (18)	✓ (12)	✓	✓ (16)	–	–	✓ (14)	✓ (15)	✓ (10)	11
Materials and Resources	✓ (12)	✓ (12.5)	✓	✓ (11)	–	–	✓ (10)	✓ (9)	✓ (19)	9
Environmental Protection	–	–	–	–	✓ (22)	✓ (24)	✓ (11)	–	–	7
Transport	–	✓ (8)	–	–	–	–	–	✓ (6)	✓ (10)	3
Land use and Ecology	–	✓ (10)	–	–	–	–	–	✓ (6)	–	2
Carbon Emission of Development	–	–	–	–	–	✓ (2)	–	✓ (6)	–	1
Waste	–	✓ (7.5)	–	–	–	–	–	–	–	1
Ecology and Pollution	–	✓ (10)	–	–	–	–	–	–	–	1
Total Percentage (%)	100	100	–	100	100	100	100	100	100	100
Reference	[22]	[23]	[24]	[25]	[23]	[26]	[27]	[7]	[27]	

Note.
[a] "✓" indicates the available category in GBCS, while "-" indicates information is not applicable. The number in the bracket indicates the percentage for each major category.
[b] CASBEE is not a score-based rating tool. The assessment is based on the built environment efficiency factor. Hence, no marks are allocated for each category.

Table 2
Past studies on building life cycle energy assessment and insulation materials life cycle assessment.

Reference	Country	Building Type	Methodology	Life Cycle Stage	GBCS Analysis	Insulation material analysis	Findings
[35]	Thailand	Office	LCEA	E_M, E_T, E_C, E_O, E_R, E_D	×	×	• E_O and E_M have the most significant contribution, 81% and 17%, respectively. • In EE, steel reinforcement and concrete account for 42.2% and 35%, respectively.
[36]	Indonesia	High-rise residential	LCEA	E_M, E_T, E_C	×	×	• Double-wall has higher EE than single-wall but performs lower total life cycle energy.
[90]	Malaysia	NA	LCEA	E_M, E_T, E_C	×	×	• A LCEA framework was developed to quantify the EE during the construction phase.
[38]	Australia	Residential	LCEA	E_M, E_C, E_O, E_R, E_D	×	×	• Eo accounts for 40%, EE 37%, and E_R 22% of total LCE.
[39]	European	Educational	LCEA	E_M, E_T, E_C, E_O, E_R, E_D	×	×	• Eo is the most significant contributor during the building life cycle (56.6%), followed by E_M (37.1%), E_R (4.7%), E_D (1.2%), and lastly E_C (0.5%).
[40]	Malaysia	Office & Residential	LCEA	E_M, E_T, E_C	×	×	• The allocation of low EE and EC building materials, products, and components reduced the total EE and EC intensities of building to 43% and 41%, respectively.
[29]	Hong Kong	High-rise office	LCEA	E_M, E_T, E_C, E_O, E_R	×	×	• The E_O contributes around 78–89%, and EE takes 11–22%. • Focus on material manufacturing and transportation phases to reduce EE.
[30]	Singapore	University	LCEA	E_M, E_T, E_C, E_O, E_R, E_D	×	×	• E_O constitutes 90% of total life cycle energy, while the remaining 10% is from EE. • E_M accounts for the highest percentage (51–71%), followed by E_R (24%).
[41]	Nigeria	Existing residential apartment	LCEA	E_M, E_T, E_C, E_O, E_R	×	×	• Eo shared 85% of total life cycle energy while EE accounted for 15%. • Substitute alternative materials to replace cement as it contributed 67.6% of EE.
[42]	China	NA	LCA	E_M, E_T	×	✓	• Density and energy production efficiency parameters affect the life cycle energy of conventional insulation materials.
[43]	Romania	NA	LCA	E_M, E_T, E_C, E_O, E_R, E_D	×	✓	• Conventional insulation materials save 55% energy in the use stage after refurbishment.
[44]	Moscow	Apartment	LCA	E_M, E_T, E_C, E_O	×	✓	• Mineral wool insulation saves 67.87 times more energy than the amount used in embodied phase.
[20]	Australia and New Zealand	Residential	LCEA	E_M, E_R, E_O	×	✓	• The energy efficiency of the building is affected by the type, volume, EE coefficient, R-value, and location of insulation materials.
[32]	NA	NA	LCA	E_M, E_T, E_C, E_O, E_R, E_D	×	✓	• Conventional insulation materials save 23–27% energy saving in a Mediterranean climate.
[14]	Europe	University	LCA	E_M, E_T, E_O	✓	×	• Wooden and hybrid concrete-wood buildings have the lowest environmental impact which can be categorized as green buildings.

Note: E_M – Embodied Energy of Material; E_T – Embodied Energy of Transportation; E_C – Construction Site Energy; E_O – Operational Energy; E_R – Recurring Energy; E_D – Demolition Energy; EE – Overall Embodied Energy in the Building; LCEA – Life Cycle Energy Assessment; LCA – Life Cycle Assessment; NA – information not available.

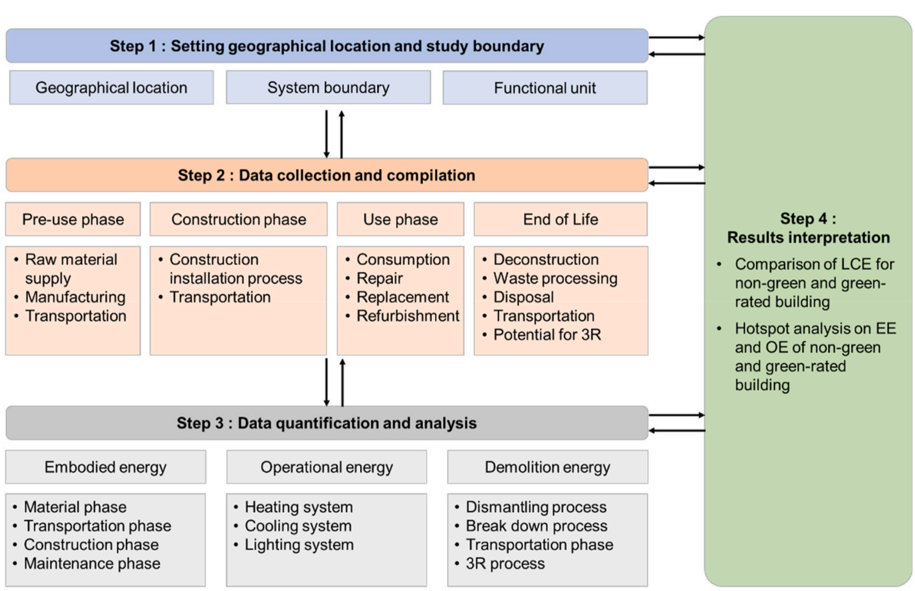

Fig. 1. The overall framework for LCEA in building.

recommendations from the energy efficiency aspect for environmental improvement, and integrate the key aspect of EE and OE into GBCS. Insulation materials significantly impact green building management since they can improve energy efficiency in the overall life cycle of a building [33]. This study also analyses the trade-offs between the insulation materials' EE and building's OE; benchmarks with the base case scenario to determine the net life cycle energy consumption after introducing the insulation materials. In accord with SDG 11 (sustainable cities and communities) and SDG 12 (responsible consumption and production), this study provides data-driven insights to the decision-makers, focusing on the proportion of EE and improving GBCS guidelines to form a sustainable built environment.

2. Life cycle energy assessment

This study employed LCEA methodology to assess the energy input for different building phases, which can be sub-divided into EE, OE, and DE. The overall framework for LCEA is illustrated in Fig. 1. EE is the energy used to extract raw materials, manufacture materials, install and assemble building components, on-site construction, and renovation [46]. OE is the energy consumed by heating and cooling, domestic hot water, electrical appliances and equipment, ventilation system, and lighting to maintain indoor comfort conditions [47]. DE is the energy utilized in the demolition process and consumed in waste transportation [48]. The assessment method for LCEA is as follows: 1) setting geographical location and study boundary; 2) LCEA data collection and compilation; 3) LCEA data quantification and analysis; 4) LCEA results interpretation. The detailed assessment method for this study is presented in the following (Sections 2.1-2.4).

2.1. Setting geographical location and study boundary

This study takes a non-residential building (NRB) located in Malaysia. The selected building is one of the typical NRBs found in tropical metropolitan cities (i.e., mixed-use buildings with commercial areas and offices). The selected NRB comprises two 14-storey office towers and a 9-storey common podium, complying with Malaysia Multimedia Super Corridor status. This reference building consists of reinforced concrete with a total gross floor area of 107,017 m^2, including the car park, as shown in Table 3.

The building components and system boundary involved in this study are as shown in Fig. 2. The overall system boundary consists of the material, construction, transportation, and use phases. The DE is beyond the scope because it has an insignificant impact on buildings' total life cycle energy [48]. The functional unit is defined per square meter (m^2) based on building gross floor area. The life span of the building is assumed to be 50 y, following the standard set by Construction Industry Development Board Malaysia [49]. The operating hours of the NRB are 12 h/d, while the common podium operates 24 h/d. The electricity consumed is solely based on Malaysia's electricity generation mix profile (42.8% coal, 40.2% oil and gas, 14.8% hydro, 0.5% diesel, and 1.7% others) [50].

2.2. Data collection and compilation

This study evaluates two types of NRBs: non-green and green-rated buildings. The baseline data adopted for the examination is the on-site survey of the selected uninsulated non-green building that follows the Malaysian Standard 1525:2014 guideline specifies. According to the GreenRE rating tool, the green-rated buildings are determined based on the baseline building. GreenRE is a certified GBCS that was established in 2013 by the Malaysian Real Estate and Housing Development Association [26], with over 70 million square feet of structures certified under GreenRE as of December 2020 [51]. GreenRE is chosen as the reference GBCS as it is developed based on Singapore's Building and Construction Authority Green Mark, which is the first GBCS designed explicitly for tropical climate, and in line with other established GBCSs. The specifications for both non-green and green-rated NRBs are presented in Table 4.

GreenRE has four levels of certified green building: bronze, silver, gold, and platinum, with a maximum score of 193 points based on six criteria (i.e., energy efficiency, water efficiency, environmental protection, indoor environmental quality, green features, and development carbon emissions). Only the energy efficiency and environmental protection criteria are employed to evaluate the green-rated building in this study because they are related to OE and EE. The credit scores in OE, such as the electricity consumption of the air-conditioning system and artificial lighting of green-rated buildings, are calculated based on the percentage improvement over the baseline (non-green NRB). For instance, 0.35 credit can be scored for every percentage improvement in chiller plant efficiency and lighting provision.

In terms of EE evaluation, two quantifiable criteria are selected to access green-rated buildings: sustainable construction and sustainable products. For example, 50% substitution of OPC with green concrete earns a maximum of 5 credits; more than 50% replacement of essential construction parts with environmentally-friendly or recycled products earns 2 credits. Fewer points could be obtained due to reduced replacement percentage with environmentally friendly building materials. The exact criteria and credit score for studied cases are tabulated in Table S1 in Supplementary Material. The detailed inventory data, such as the quantity of material, energy demand for cooling and lighting systems, and the number of fittings collected from the on-site survey and calculated according to the specifications, are tabulated in Tables S2–S7 in Supplementary Material.

For the thermal insulation investigation, five types of insulation materials: expanded polystyrene (EPS), extruded polystyrene (XPS), cellulose fibre, rock wool, and fibreglass, are selected for assessment as these are common and commercialized insulation materials in tropical countries [52]. The inner layer position of insulation material is investigated in this study since Nematchoua et al. [53] revealed that internal insulation is more favourable for tropical climates. Fig. 3 shows the building's energy demand circumstances after installing insulation materials.

Table 3
Selected NRB information.

Level	Gross Floor Area (m^2)
Ground Floor and Level 1 (Commercial area)	10,083
Level 2–8 (Car park)	36,940
Level 9–22 (Office tower)	56,005
Level 23 (Lift motor room)	3,989
Total Gross Floor Area	107,017

2.3. Data quantification and analysis

This section presents the analysis of EE (Section 2.4.1) and OE (Section 2.4.2) involved in buildings. The calculation methods for EE and OE are applicable for non-green and green-rated buildings in determining the life cycle energy consumption. The analysed data are elucidated in Tables S8–S14 in Supplementary Material.

2.3.1. Embodied energy

The total EE is calculated based on Eq (1). It is the summation of the EE in the material, transportation, construction, and maintenance phases. The value on MJ is converted to kWh using the equation of 1 kWh = 3.6 MJ.

$$EE = E_M + E_T + E_C + E_R \tag{1}$$

where EE represents the embodied energy of the buildings (MJ); E_M represents the material EE (MJ); E_T represents the transportation EE

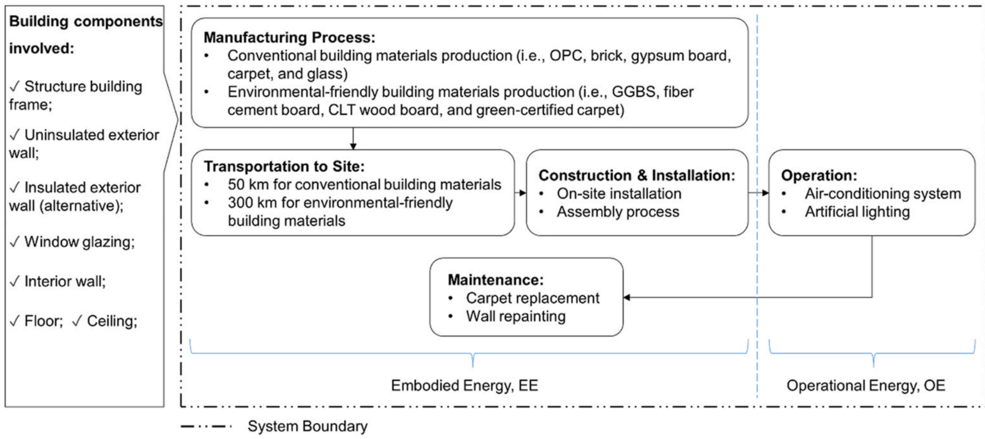

Fig. 2. System boundary for the study.

Table 4
Specification for non-green and green-rated buildings.

Parameter	MS 1525:2014	GreenRE Building Rating Level			
	Non-green	Bronze	Silver	Gold	Platinum
Embodied phase					
OPC	100%	80%	70%	60%	50%
GGBS	0%	20%	30%	40%	50%
Glass	flat glass (6 mm)	flat glass (6 mm)	flat glass (10 mm)	laminated glass (10.38 mm)	laminated glass (12.38 mm)
Green-certified carpet	0%	0%	30%	50%	100%
CLT wood board	0%	0%	0%	40%	80%
Fibre cement board	0%	0%	10%	40%	70%
Operation phase					
Chiller efficiency (kW/RT)	0.75	0.75	0.7	0.678	0.65
Lighting power consumption (reduced %)	0%	10%	20%	30%	86.44%

Note: OPC: Ordinary Portland Cement; GGBS: Ground Granulated Blast Furnace Slag; CLT wood board: Cross-laminated timber wood board.

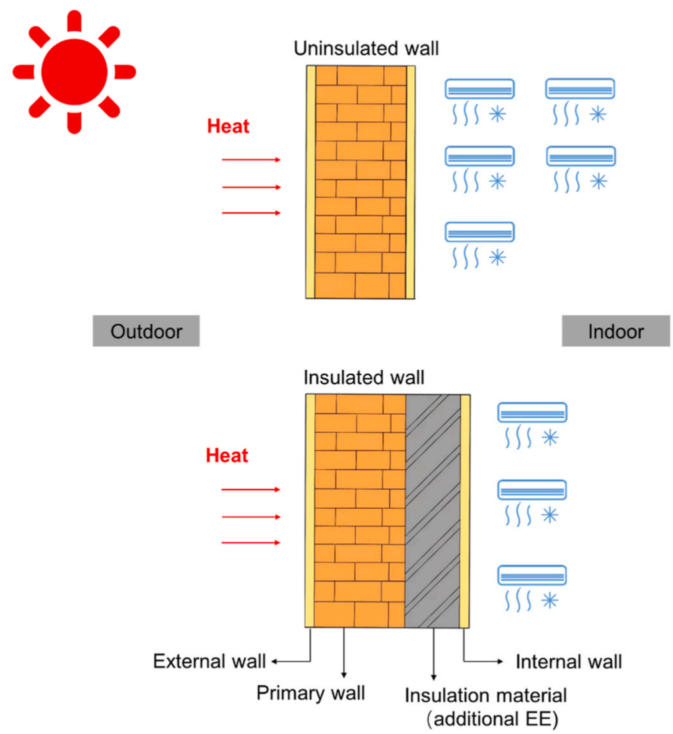

Fig. 3. Building wall structure and the relationship between the cooling demand and EE before and after implementing insulation material.

(MJ); E_C represents the construction EE (MJ); E_R represents the recurring EE (MJ).

Material phase: Main building materials include concrete, steel, glass, brick, carpet, paint, and ceiling board, while insulation material is an alternative material to reduce the building's internal temperature. Concrete mixed design and quantities of building materials are shown in Tables S2–S3. The steel information is calculated based on 100–130 kg of reinforcement steel in 1 m^3 of concrete [30], where 110 kg of reinforcement steel is used in this study, based on the previous studies in tropical countries [30]. Except for the insulation materials, which their EE is sourced from the Environmental Performance in Construction database, the other materials are obtained from the on-site survey report. The EE during the material phase can be expressed in MJ, as shown in Eq (2).

$$E_M = V_m \times \rho \times EEF \quad (2)$$

where E_M represents the EE of the material phase (MJ); V_m represents the volume of materials (m^3); ρ represents the density of materials (kg/m^3); *EEF* represents the EE factor (MJ/kg).

Transportation phase: The energy incurred in the transportation stage relies on the mass of building materials, the distance between the manufacturing site and construction site, and the transportation energy for different transportation modes. Conventional building materials (i.e., OPC, brick, and gypsum board) are obtained from a local state within a 50 km transportation distance. Environmental-friendly products (i.e., GGBS, green-certified carpet, CLT wood board, and fibre cement board) acquire a longer transportation distance (i.e., 300 km) as fewer manufacturing plants for environmental-friendly products in Malaysia. According to Ishak et al. [91], less than 20 green manufacturers are certified by the Standard and Industrial Research Institute of Malaysia (SIRIM) eco-label documentation. The transportation energy, E_T, can be expressed as Eq (3).

$$E_T = M_i \times D_i \times EEC \quad (3)$$

where E_T refers to the EE of transportation (MJ); M_i refers to the mass of transported materials (t); D_i refers to the distance between manufacturer site and construction site (km); *EEC* refers to the fossil fuel energy required for transportation (MJ/tkm).

Construction phase: The construction energy refers to the energy required for the on-site installation and assembly process is estimated as 120 MJ/m^2 [30]. The construction energy can be expressed as Eq (4).

$$E_C = 120\ (\mathrm{MJ}/\mathrm{m}^2) \times GFA \tag{4}$$

where E_c refers to the construction energy (MJ); *GFA* refers to the gross floor area of the NRB (m^2).

Maintenance phase: The energy consumption in the maintenance phase is also known as recurring energy. In this study, only carpet and painting are replaced as they have the highest average annual replacement rate over the studied period [55]. It is examined based on the estimated life span of the building materials and calculation followed with the same procedure in determining the E_M. The recurring embodied energy, E_R, can be expressed as Eq (5).

$$E_R = \left(\frac{L_b}{L_m} - 1\right) \times V_m \times \rho \times EEF \tag{5}$$

where E_R represents the recurring EE (MJ); L_b represents the life span of the building (y); L_m represents the life span of building materials (y); V_m represents the volume of materials (m^3); ρ represents the density of materials (kg/m^3); *EEF* represents the EE factor (MJ/kg).

2.3.2. Operational energy

In the operation phase, the energy consumptions of cooling and lighting are involved, while the heating system is excluded as it is not necessary for tropical countries like Malaysia. The total OE is determined by the annual electricity consumption in buildings.

$$OE = E_{AC} + E_L \tag{6}$$

where *OE* represents the operational energy of the building (MJ); E_{AC} represents the energy consumed by the air-conditioning system (MJ); E_L represents the energy consumed for the artificial lighting (MJ).

Air-conditioning system: The building cooling load is retrieved directly from the on-site survey report of the selected NRB. The chiller plant system efficiencies for non-green and green-rated buildings are set according to the specification, and their daily electricity consumption is shown in Table 5.

Besides, the annual cooling demand for an insulated non-green building can be expressed as Eq (7). The thermal properties of the studied insulation materials are collected as shown in Table 6. The CDD is assumed to be 1900 $^\circ$C/y, based on the average CDD from 2016 to 2020 with a based temperature of 23 °C in Malaysia's weather station [56]. The COP value (i.e., 0.21) used in this study is based on the non-green non-residential cooling system efficiency (0.75 kW/RT) set in MS 1525 guideline. The insulation materials' EE and net energy saving are present in Table S16 in Supplementary Material.

Table 5
Chiller plant system efficiency and the daily electricity consumption of air-conditioning system in each non-green and green-rated building.

Types of NRBs	GreenRE Rating	Efficiency of Chiller Plant System (kW/RT)	Daily Electricity Consumption of Air-Conditioning System (kWh)	
			Weekdays	Weekends
Non-green building	–	0.75	29,686	12,685
Green-rated building	Bronze	0.75	29,686	12,685
	Silver	0.7	26,908.9	11,496.1
	Gold	0.678	25,687	10,973
	Platinum	0.65	24,131.8	10,307.3

Table 6
Thermal properties for each building wall component.

Type of wall component		Thermal conductivity (W/m.K)	Thickness (m)	Thermal resistance (m^2.K/W)	Reference
External surface	–	–	–	0.04	On-site survey
External wall	Cement plaster	0.530	0.02	0.04	On-site survey
Primary wall	Brick wall	0.770	0.10	0.13	On-site survey
Internal wall	Cement plaster	0.530	0.02	0.04	On-site survey
Internal surface	–	–	–	0.13	On-site survey
Insulation material	Rock wool	0.040	0.08	2.00	[57]
	Fibreglass	0.035	0.08	2.29	[58]
	EPS	0.039	0.08	2.05	[59]
	Cellulose fibre	0.040	0.08	2.03	[57]
	XPS	0.031	0.08	2.58	[59]

Note: "-" indicates the information was not applicable.

$$E_{C,\ year} = \frac{86400 \times CDD}{(R_{w,t} + R_{ins}) \times COP} \tag{7}$$

where $E_{C,year}$ - Annual energy need for cooling (J/m^2/y); *CDD* - Cooling degree day ($^\circ$C/y); *COP* - Coefficient of performance for the cooling system; $R_{w,t}$ - Thermal resistance of wall layers without insulation (m^2. K/W); R_{ins} - Thermal resistance for insulation material (m^2. K/W).

Artificial lighting: The lighting energy consumption is quantified as shown in Eq (8).

$$E_L = N_b \times (E_b + B_L) \times t \tag{8}$$

where E_L represents the energy of artificial lighting (kWh); N_b represents the number of fittings; E_b represents the energy consumption of fitting (kW); B_L represents the ballast loss (W); *t* represents the operating time of light bulb (h).

2.4. Results interpretation

The obtained results are structured and interpreted to help determine the significant issues in the building following the goal of this study. The proportion of OE and EE of non-green and green-rated buildings are analysed, and the hotspot of the buildings is investigated by quantifying the highest energy consumption of building phases. The total life cycle energy is calculated as follows.

$$LCE = EE + OE \tag{9}$$

where *LCE* represents the total life cycle energy of the building (MJ); *EE* represents the total embodied energy of the building calculated from Eq (1); *OE* represents the total operational energy of the building calculated from Eq (6).

The life cycle energy and trade-off analysis of building insulation is further investigated to discover the changes in the building's life cycle energy after installing the building insulation materials and how it can be entailed in GBCS. The net energy saving after insulating is determined from Eq (10).

$$ES_{Net} = E_{C,ng} - (EE_{ins} + E_{C,ins}) \tag{10}$$

where ES_{Net} represents the net energy saving (MJ); $E_{C,ng}$ represents the cooling demand for non-green building (MJ); EE_{ins} represents the EE of insulation material (MJ); $E_{C,ins}$ represents the cooling demand for insulated buildings.

3. Results and discussion

3.1. Life cycle energy of non-green and green-rated buildings

Fig. 4 demonstrates the total energy consumption and proportion of OE and EE for non-green and four types of green-rated (i.e., bronze, silver, gold, and platinum) NRBs. The green-rated buildings favourably lower the total energy consumption. Compared to non-green buildings, the bronze, silver, and gold green-rated buildings saved 4%, 13%, and 19% of energy, respectively. Platinum-rated buildings produced substantially more significant energy savings, with 41%. It has the lowest energy consumption of the green-rated buildings, with a consumption of 15,000 MJ/m^2. The use of low-embodied construction materials and energy-efficient electric appliances, as shown in Table 3, accounts for the significant reduction in energy usage in platinum constructions. For instance, 50% of OPC replacement with GGBS, 100% green-certified carpet used, and around 86% reduction in artificial lighting power use. This shows that green-certified buildings can conserve energy and reduce negative environmental impacts.

The Building Energy Index (BEI) is a Malaysian benchmark for assessing a building's energy efficiency. BEI is the ratio of a building's total annual electricity consumption (kWh/y) to its gross floor area (m^2). To be classified as a Zero Energy Building in Malaysia, a low carbon building should achieve a BEI value of at least 51 kWh/m^2/y [60]. Although the green-rated buildings in this study have yet to achieve Zero Energy Building status, there is a significant success for the platinum building, which can cut energy intensity per square metre by 41%. This also indicates that platinum buildings are ready to achieve the global climate ambitions established in the Paris Agreement, as more than 30% of energy intensity per square metre has been improved [5].

Throughout the 50 y of operation, OE accounts for a high portion of buildings' total life cycle energy, ranging from 81 to 84%. The remaining portion, 16–19%, is accounted for EE. A direct comparison between OE and EE is inappropriate since EE is one-time energy use in the early stages of construction that cannot be modified. This high initial EE consumption is primarily due to the building elements, including the upper floor, façade, and roof components, where the materials used in construction are energy-consuming [40]. It is projected that the manufacturing of cement, iron, steel, and ceramics will become the biggest energy consumer in the future [61]. It is evident that incorporating low EE and embodied carbon emission materials into these building elements could minimize 42.56% of the total EE [40] and approximately 265 kg CO_2-eq/m^2. The effects of EE on climate change can be reduced by paying closer attention to the importance of the embodied phase in building and incorporating EE into GBCS to gain access to green-rated buildings. Neglecting EE in building assessment would make the Intergovernmental Panel on Climate Change's short-term CO_2 reduction targets unattainable [14].

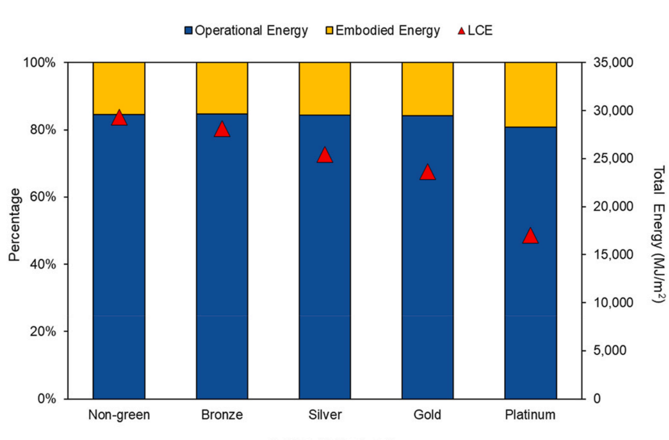

Fig. 4. The LCE for non-green and green-rated NRBs.

3.2. Hotspot analysis of building

3.2.1. Embodied energy

Fig. 5 displays the detailed breakdown of EE for different NRBs and the energy consumption for material types. The results show that material EE accounts for the most significant proportion of total EE, ranging from 68 to 74%. This is attributed to the three main building materials: concrete, steel, and carpet. Due to the building's colossal quantity requirement, concrete consumes the most significant energy. Substituting OPC with GGBS in green-rated buildings can reduce EE consumption. The energy consumed in the cement industry depends on the high temperature at which sand, clay, and limestone are heated to form clinker [62]. GGBS, as a by-product of the steel industry, moves away from this energy-intensive calcination process (i.e., clinker formation) to reduce the overall EE [63]. Around 7.9 MJ of energy can be eliminated from the total life cycle energy when 1 kg of OPC is replaced with 1 kg of GGBS [64]. GGBS also incurs a small CO_2 emission, with only 143 kg CO_2-eq/tonne emitted compared to OPC, which produces approximately 820 kg CO_2-eq/tonne [65]. This proves that GGBS provides resource efficiency and CO_2 emission reductions in line with the objective of green building construction.

The use of virgin steel in buildings leads to the second highest energy consumption in material EE and the total EE, where steel becomes the most significant impact in the platinum building. This is because GBCS does not allocate any point for the implementation of recycled steel in reinforcement concrete buildings. Exploring recycled steel to reduce building EE and GHG emissions further is critical. Recycling steel scrap can avoid virgin steel production, where 13.4 MJ primary energy and 1.5 kg CO_2-eq emissions can be saved using 1 kg of recycling steel scrap [66]. The use of recycling building materials eliminates more than 5% of the EE in a building [67] and does not affect the structural strength of the building. American Iron and Steel Institute [68] reported that structural steel does not lose any of its metallurgical properties during the recycling process (i.e., basic oxygen furnace technology or electric arc furnace technology), making the performance characteristics of recycled steel equivalent to virgin steel.

Another hotspot observed is recurring energy, accounting for 22–30% of total EE. Carpet replacement is the main contributor to recurring energy in 50 y building life span [30]. The result shows a decrease in recurring energy from bronze to the platinum green-rated building. Utilising environmentally friendly materials rather than conventional materials can minimize energy consumption in buildings and reduce CO_2 emissions [69]. Recurring energy is also correlated to the building's service life, which impacts the LCE. This indicates that the recurring energy proportion is expected to increase when the life span of the building is greater than 50 y. A study of secondary schools in Australia by Ding [70] found that the recurring energy, over the 60-year service life, was 72% of the calculated life cycle EE; Cellura et al. [71] computed the recurring energy of a multi-family residential building equivalent to 45% of the total EE over a 70-year service life. This could be optimized by implementing low EE building materials with long service life and requiring less maintenance [72]. For instance, carpets can be replaced with ceramic tiles due to their long service life [73].

Although transportation energy contributes less than 1% of the total EE, an increment of transportation energy is reflected from bronze to platinum buildings, as a farther place is needed to source the environmentally friendly building materials. This could be similar to those countries or regions that rely heavily on imported building materials [14]. The transportation phase would remain the issue in total EE. To conclude, the use of low EE or recycling materials would be the most effective way to eliminate EE and embodied emissions in a short time. This is only applicable when building materials are sourced locally, or a reverse effect could be obtained.

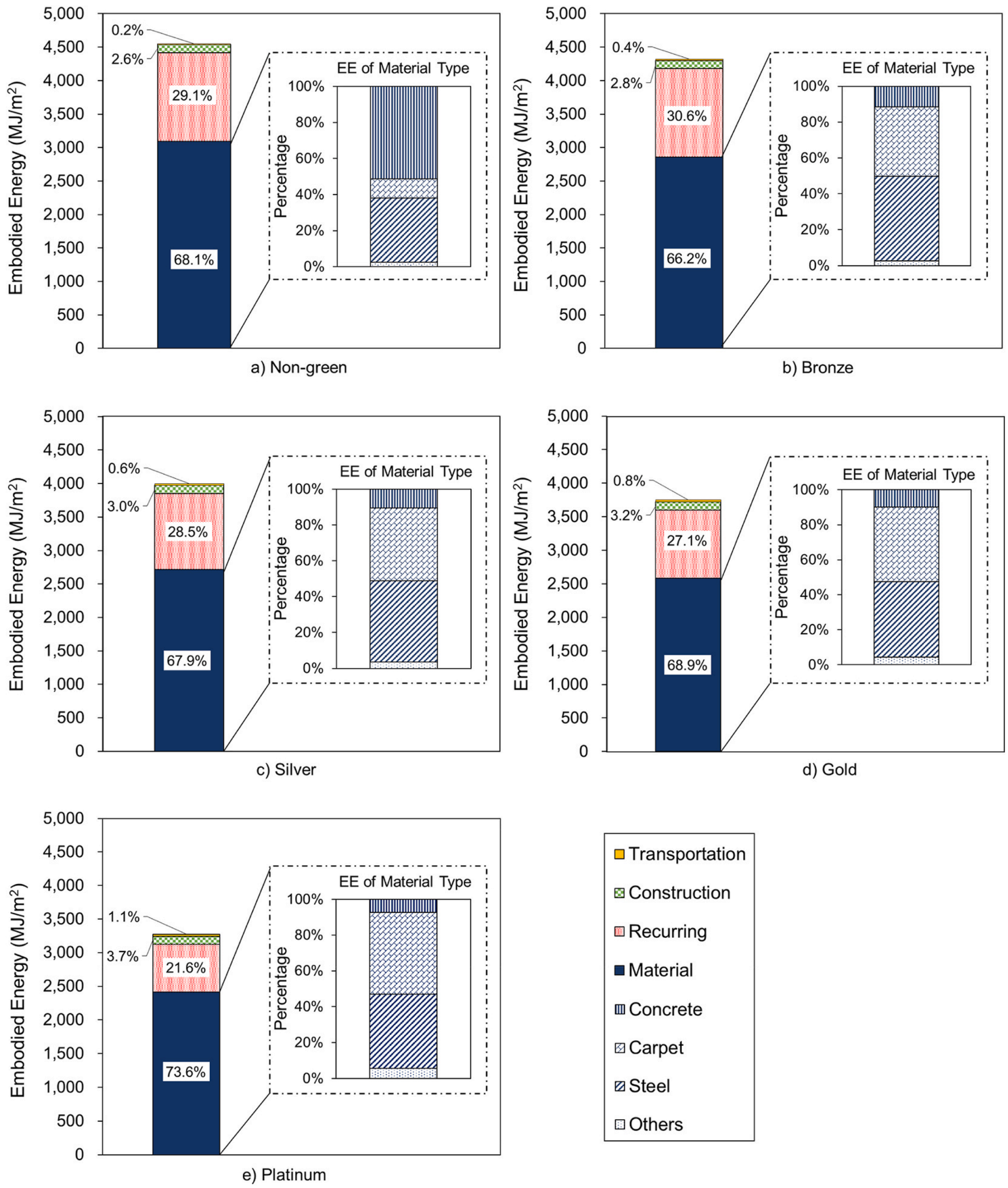

Fig. 5. The breakdown of material EE for non-green and green-rated NRBs.

3.2.2. Operational energy

As shown in Fig. 6, the OE of the non-green building is effectively eliminated after the implementation of GBCS. More than 900–11,000 MJ/m^2 is reduced in the green-rated buildings. It is mainly contributed by the energy reduction of artificial lighting. The replacement of fluorescent lamps with LED lamps is the most energy-efficient way of saving energy for artificial lighting [74]. Although the cost of a LED is 4–6 times greater than a fluorescent, it saves 48.6–55.9% of electricity cost. A LED is 60% energy efficient and has a longer lifespan than a fluorescent [75]. It can be concluded that replacing lighting systems with LED lamp is a more sustainable solution.

Air-conditioning energy consumption shares the greatest portion for all the buildings, ranging from 62 to 90% in total OE. The air-conditioning system is often used in hot and humid climates to maintain thermal comfort [76] – higher energy consumption for space cooling, especially during hot days when the air-conditioner is used at full capacity. Highly efficient air-conditioner units are encouraging to improve energy performance. For instance, appliances that are certified under Minimum Energy Performance Standards to ensure energy-efficient air-conditioning system [77]; A higher annual performance factor corresponds to better performance in Japan [78]; Air-conditioner rated under seasonal energy efficiency ratio in the U.S [79]. Implementing domestic regulations would help reduce cooling demand and be on track with the Net Zero Emissions by 2050 [80].

3.3. Life cycle energy efficiency of the insulated building wall

3.3.1. The embodied energy of insulation materials

As shown in Fig. 7, the EE for each insulation material varies and does not have a parallel relationship with the cooling energy demand. Cellulose fibre has the lowest EE (i.e., 230 MJ/m^2) among the insulation materials because it is a natural biobased material made from recycled paper fibres. Unlike rock wool insulator, it requires more energy in the production stage of 1,500 °C to melt rock in the wheel [81]. Petrochemical insulation material (i.e., EPS) requires 70 MJ/kg of energy in the production stage and is responsible for over 6 kg CO_2-eq/kg

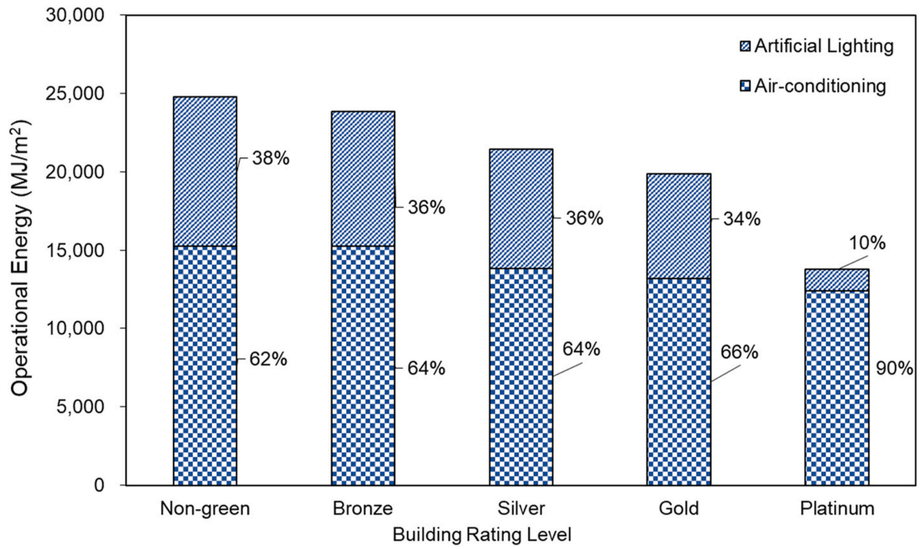

Fig. 6. The breakdown of OE for non-green and green-rated buildings.

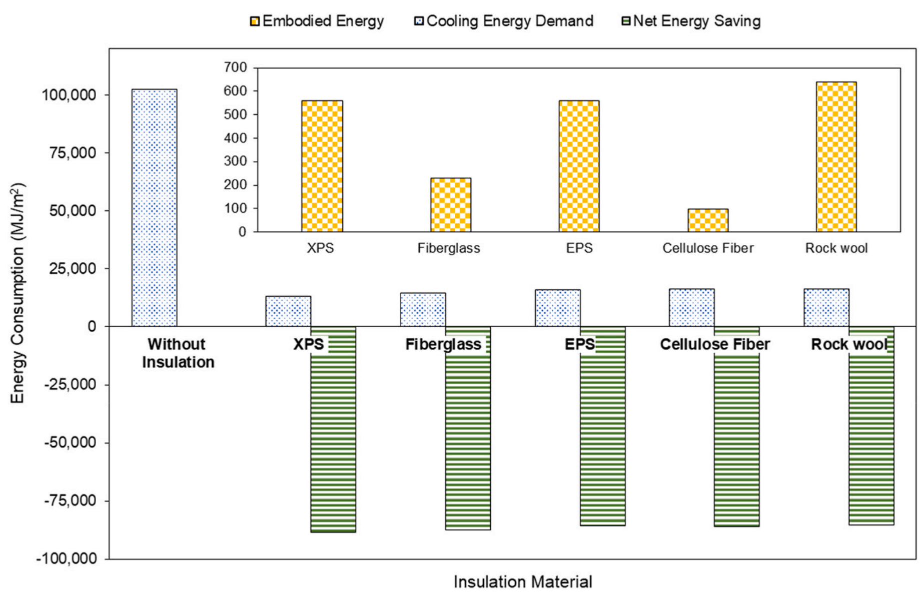

Fig. 7. The EE, cooling energy demand, and net energy saving in different insulation materials.

emissions to the environment [81]. However, the EE could vary as the insulation material's thickness changes [58]. From the view of EE, cellulose fibre would be the most suitable material as it has the lowest EE and least impact on the environment.

3.3.2. Trade-offs between EE and cooling energy demand of insulation materials

The net energy saving for each insulated building is presented in Fig. 7. The total energy in insulation (i.e., EE and cooling energy demand of insulation materials) is subtracted from the cooling energy demand of the base case (i.e., without insulation) to obtain the net energy saving after installing insulation materials. The results show that XPS is the most energy-efficient insulation. However, XPS has considerably higher EE than other materials and is highly combustible. It could catch fire easily if exposed to a fire condition. Due to the lower water vapour diffusion resistance factors, fibreglass and rock wool insulators induce greater cooling energy demand with increased thermal conductivity of insulation materials [82]. For long-term usage, both insulation materials might have a risk of warming up the building rather than improving the indoor comfort.

To strive for both energy saving and environmental aspects, cellulose fibre would be the recommended insulation material for buildings. It is renewable and recyclable material as it can be produced from recycled paper or even biomass waste [83]. Cellulose can be extracted from agricultural waste to produce high tensile strength, high thermal stability, and low water sorption green building materials [84]. It also has similar thermal properties among the insulation materials. Therefore, using cellulose as insulation in buildings can improve OE, at the same time, incur the smallest EE.

3.3.3. The cooling energy demand of building with the implementation insulation materials

The cooling energy demand for the non-insulated wall is 1.02×10^5 MJ/m^2. An average of 85% energy consumption is eliminated with the inclusion of insulation materials. XPS is the most energy-efficient as it only consumes 1.32×10^4 MJ/m^2 energy, followed by fibreglass, EPS, cellulose fibre, and rock wool. Further energy reduction could be achieved by improving the thermal resistance of insulation as more heat can be resisted from the environment.

3.4. Implications of EE and thermal insulation in GreenRE and other GBCS guidelines

In the total of 193 GreenRE points, 18 points (9%) are directly related to the embodied phase of building. The percentage of embodied phase is pretty similar to other GBCSs, such as BREEAM and LEED. In BREEAM, only 12 points (8%) are related to material selection: in LEED, 14 points (13%) are tied to the material phase [14]. However, the results in this study show that EE exists in green-rated buildings and accounts for up to 19% of total life cycle energy. The small proportion of EE in existing GBCSs leads to the ineffectiveness of energy elimination in the early stage of building.

Efforts to enhance EE proportion in GBCSs should be made. This can be done by encouraging recycled reinforcement steel in green buildings. The current GBCS shows recycled materials only applicable to non-structural building elements rather than structural ones. Another sub-category could be added to assist stakeholders in utilising recycled steel. More points should be provided to stimulate low-embodied and green-certified building materials in GBCS, while simultaneously raising the minimum attainable scores in environmental protection criteria to assure user focus in material selection. A few factors could be addressed to minimize the recurring energy consumption. For instance, apply a long service life span, high durability, low maintenance and maintainability, recyclable and reusable, and low EE building materials [85]. It is also recommended to allocate points if building materials are sourced locally. Using locally available building materials and products can save a significant amount of recurring energy through reduced transportation distance [86].

As for the high energy consumption of the air-conditioning system, insulating materials in GBCS should be encouraged because it considerably reduces cooling demand. The insulation material is practical in managing sustainable buildings from the EE perspective. For example, using kenaf and wood fibre as insulators can result in a gold LEED green-rated structure, whereas EPS insulators can achieve a silver grade due to their higher EE [33]. Changing the insulation material may impact both energy efficiency and material selection criteria and the final score in GBCS. To emphasise the environmental benefits of sustainable insulating materials, the EE of the material, which affects the entire material life cycle, should be taken into account.

4. Conclusion

The life cycle of green-rated NRBs (bronze-, silver-, gold-, and platinum-rated buildings) is evaluated through LCEA methodology by benchmarking to a non-green NRB. The trade-offs between EE and cooling energy saving after implementing insulation materials to building envelopes are investigated. The key findings are:

1) EE accounts for up to 19% of the total life cycle energy of green-rated buildings in the building phase. As EE has a relatively short time frame compared to OE, EE is significant to be considered in building development. The low emphasis of EE assessment in the existing GBCSs resulted in the ineffectiveness to minimize the overall energy use for green-rated buildings.
2) To effectively reduce the EE from the building life cycle, efforts could be focused on the construction materials as it shares 68–74% of the total EE. Low-embodied and recycled building materials can reduce the EE. Recycled steel should be included in GBCS as one of the assessing criteria to eliminate the EE effectively.
3) Implementing insulation materials in building walls saves up to 85% of cooling energy demand. Cellulose fibre would be a suitable insulation material in achieving energy savings.

In line with the Paris agreements aimed to achieve a 30% energy intensity reduction by 2030, EE should be included along with the GBCS assessment to reduce the short-term energy consumption. This study analyses only the energy efficiency criterion of NRB. Other criteria, such as water efficiency and indoor environmental quality, are suggested to be evaluated to enhance the overall environmental performance of the building. The building's life cycle carbon analysis is strongly encouraged to be conducted and benchmarked with the global carbon emission target. This analysis could discern the need for carbon criterion in GBCS to achieve zero carbon building. Expanding the research focus from NRB to urban industrial symbiosis is recommended. The EE performance obtained would be more justified in weighting EE in GBCS as it involves green city development. Economic analysis for the embodied material is suggested to be incorporated to verify the involvement of embodied criteria in GBCS more comprehensively. This study facilitates the stakeholders and policymakers to increase concern on EE and ensure the comprehensiveness of GBCS development towards sustainable cities and communities by putting more emphasis on the embodied energy criteria.

Credit authorship contribution statement

Wai Lam NG: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Visualization. **Min Yee CHIN**: Validation, Formal analysis, Writing – original draft: **Jinqin ZHOU**: Validation, Formal analysis, Visualization, Writing – review & editing. **Kok Sin WOON**: Supervision, Resources, Conceptualization, Validation, Project administration, Writing – review & editing, Funding acquisition. **Ann Ying CHING**: Investigation

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

I have attached the research data in the Supplementary Material at Attach File step

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Appendix A. Supplementary data

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