JOURNAL OF ASIAN ARCHITECTURE AND BUILDING ENGINEERING
https://doi.org/10.1080/13467581.2023.2287221

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BUILDING STRUCTURES AND MATERIALS

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Effects of utilizing various types of facade material on the Embodied and operational energy; a case study of apartment building in Indonesia

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ABSTRACT

This study investigates the impact of using prefabricated facade materials on the embodied energy (EE) and operational energy (OE) consumption of apartment buildings. To analyze the total EE, a life cycle assessment (LCA) was conducted, which calculated the EE from cradle-to-use each of the products employed. In addition, a building energy simulation was performed for the case study building using various prefabricated facade materials to assess its OE. The findings reveal that the selection of facade wall materials with low energy intensity must be favored to optimize building energy and that layered materials, such as insulated panels, can reduce the cooling energy load due to their higher thermal resistance (*r*- values). Furthermore, the LCA results showed that solid precast concrete materials with thicknesses of 120 and 150 mm have EE and greenhouse gas emissions that are more than twice the average of all materials tested. In contrast, uninsulated Glass-Fiber Reinforced Concrete (GRC) removable walls (disassembly panels) exhibited the lowest EE, corresponding to 50% of the average. Finally, the results of the OE simulations using EnergyPlus software indicate that insulated GRC removable walls with a thickness of 120 mm can reduce the cooling energy load by 29.5% compared to precast concrete facades.

ARTICLE HISTORY
Received 28 April 2023
Accepted 20 November 2023

KEYWORDS
Apartment; embodied energy; facade; prefabricated; operational energy

1. Introduction

All buildings undergo various phases throughout their life cycle, with each phase requiring energy for both the production and installation of materials and the operation of the building. The energy associated with both types of activities is known as Embodied Energy (EE) and Operational Energy (OE), respectively. According to the UN's Global Alliance for Buildings and Construction (Global ABC 2019) report, in 2018 the building and construction sector contributed 36% of final energy use and 39% of energy and process-related carbon dioxide (CO2) emissions. Additionally, the report shows that 11% of energy and process-related CO2 emissions were generated during the manufacture of building materials.

Furthermore, the report identified that building-related CO2 emissions had increased for two consecutive years, with the demand for housing and other building facilities being a significant contributor to this growth. In 2017, the International Energy Agency (IEA) established (Global ABC 2020) a mandatory policy on building and equipment performance that aimed for a reduction of 40% of the energy use and half of the CO2 emissions from buildings. However, this reduction target has not been met in countries without energy-related building regulations. As a result, there is a pressing need for extraordinary efforts to adopt energy-efficient practices and incorporate environmentally friendly measures in construction.

Inefficient in construction sector could harm environmental energy conservation. Extensive methods used in the sector lead to environmental losses that contradicting with sustainability goals (Kou 2022). Conventional construction practices tend to waste resources, which can lead to energy inefficiencies (Qi et al. 2019). This impact spans from the construction period to the entire occupancy period, which increases energy consumption (Llamosas, Abdolmaleki, and Bugallo 2022). These impacts span construction and occupancy, elevating energy consumption (Llamosas, Abdolmaleki, and Bugallo 2022). Beyond energy inefficiency, conventional construction methods generate emissions and pollution (Cao, Fujii, and Managi 2015).

EE is crucial in determining the potential release of CO2 emissions and in the subsequent measurement of their potential environmental impact. The use of cement-based materials, ceramics, and prefabricated materials is consistently one of the top contributors

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of CO2 emissions, regardless of the building design configuration (Hanifah et al. 2019; Sadeghifam et al., 2016; Saleem et al. 2018). Therefore, during the design phase, designers need to focus on selecting building materials that can help reduce energy consumption and CO2 emissions (Reztrie and Larasati 2019).

The design of the building envelope significantly affects the energy consumption of buildings (Aksamija 2013). The primary function of the building envelope is to regulate the thermal characteristics inside the building and reduce energy consumption for cooling loads, particularly in the tropics, by reducing heat transfer between the interior and exterior of the building (Azari 2014; Yang et al. 2020). The facade, as a component of the building envelope, plays a key role in energy consumption; by controlling the thermal resistance, admittance, and thickness of the facade materials, the building energy consumption can reduce by up to 8% (Sadeghifam et al., 2016). Additionally, the porosity of the facade materials can impact the energy efficiency of buildings by enhancing their ability to absorb moisture (Saleem et al. 2018). For instance, by changing the outer wall material of a library building in Malaysia, the building cooling load decreased by up to 8% (Sadeghifam et al. 2016).

Several previous studies have discussed the passive design strategy of adding insulation to the facade walls and roof of a building, in addition to changing the primary materials (Tokbolat et al. 2020) and (Alvarado and Martinez 2008) found that adding insulation to the external walls on the east and west facades can prevent a larger increase in solar heat gain (Farhanieh and Sattari 2006) found that adding insulation to building facade walls can reduce energy consumption by up to 35.2% per square meter, while (Kolaitis et al. 2013) indicated that using insulation on the outer walls of buildings is 8% more efficient than using thermal insulation on the internal walls.

Facades can also be significant contributors to the EE of buildings due to their energy consumption, particularly in multi-story buildings with a large building envelope area. Wasteful material use and inefficient construction methods for the facade of multi-story buildings can significantly increase the EE of buildings. Since a building's performance is determined by its EE and OE (Azari 2019; Hong, Arehart, and Srubar 2020; Saleem et al., 2018), to reduce this EE, the facades of multi-story buildings have been constructed using prefabricated components. Many countries worldwide have promoted precast construction methods through existing development policies and implementation roadmaps (Bari et al. 2012; Blismas, Wakefield, and Hauser 2010; Gao and Tian 2020; Jaillon and Poon 2009; Jiang et al. 2018; Kamar, Hamid, and Alshawi 2010; Luo et al. 2020; Majid et al. 2010; Murray 2003; Park et al. 2011; Wong, Ng, and Chan 2010). The successful implementation of precast construction methods in developed countries, such as the UK, Australia, and the United States, shows that the method is effective in promoting sustainable development (Li, Shen, and Xue 2014).

Similarly, with the increasing demand for high-rise residential and apartment buildings, the Indonesian government has mandated the use of prefabricated facades in construction (Kementerian Pekerjaan Umum 2007). Compared to in-situ alternatives, prefabricated facades are more efficient in many aspects, and their quality can be better controlled (Bari et al. 2012; Jaillon and Poon 2009; Wu, Ann, and Shen 2017). This construction method also results in a cleaner construction site and is considered more sustainable than the conventional in-situ method (Gan et al. 2018; Jaillon and Poon 2008; Ji et al. 2017). According to (Okodi-Iyah 2012), the use of precast concrete can lead to a 44% reduction in EE and a 7% increase in building performance during the occupancy process over 50 years. Additionally, a study by (Hay and Ostertag 2018) demonstrated that precast walls with composite materials can reduce annual OE and CO2 emissions by 9.2%, despite having a higher EE than conventional in-situ facades.

Most previous studies have only compared the performance of precast walls with that of in-situ walls (Bari et al. 2012; Jaillon and Poon 2009; Wu, Ann, and Shen 2017). Given the multiple advantages of using precast walls in building facades, it is necessary to identify the performance of different types of precast wall materials in more detail, especially those that enhance the energy performance of buildings. The objective is to determine the potential of each type of precast wall in reducing both the EE and OE of buildings by comparing the effect of using various prefabricated materials on building performance, particularly in the context of a tropical climate.

To achieve this objective, the study investigates the energy performance of buildings using 10 types of facade materials with varying thicknesses. The materials are incorporated into the simulation of a case study building in Indonesia. Specifically, the study aims to identify the effect of using various precast facade materials on both the EE and OE in the context of a tropical climate. It is expected that the findings of this study will be useful in recommending facade materials that can enhance building energy performance.

2. Material and methods

The study was conducted in several stages, beginning with the identification of facade materials commonly used in apartment construction in the West Java area of Indonesia. The province was chosen due to its successful completion of the public housing construction (Central Bureau Statistic 2016, 2017,

2018, 2019). Next, the EE value of the identified facade materials was measured using a case study building model, with the EE value calculated using the input-output (IO) table method. The subsequent stage involved measuring the effect of the façade materials on OE using the simulation method with the same case study model. Figure 1 illustrates the methodology of this study.

2.1. Apartment facade wall types

This study aimed to identify the types of facade materials used in apartments in West Java Province. Out of the 217 low-cost apartments surveyed, 101 apartments were identified based on the type of facade materials used. Of these, 74 apartments used the precast construction method as facade walls (73%), while only 27 apartments used cast in situ materials (27%). Among the precast walls used, 66% were reinforced concrete precast. Moreover, precast components were primarily used in high-rise apartments as opposed to mid- and low-rise apartments (Figure 2).

Table 1 lists the types of walls used in the construction of apartment buildings according to the results of the study.

The EE and OE values of the various facade materials in Table 1 will be evaluated based on their individual characteristics. Detailed specifications for each material are shown in Table 2.

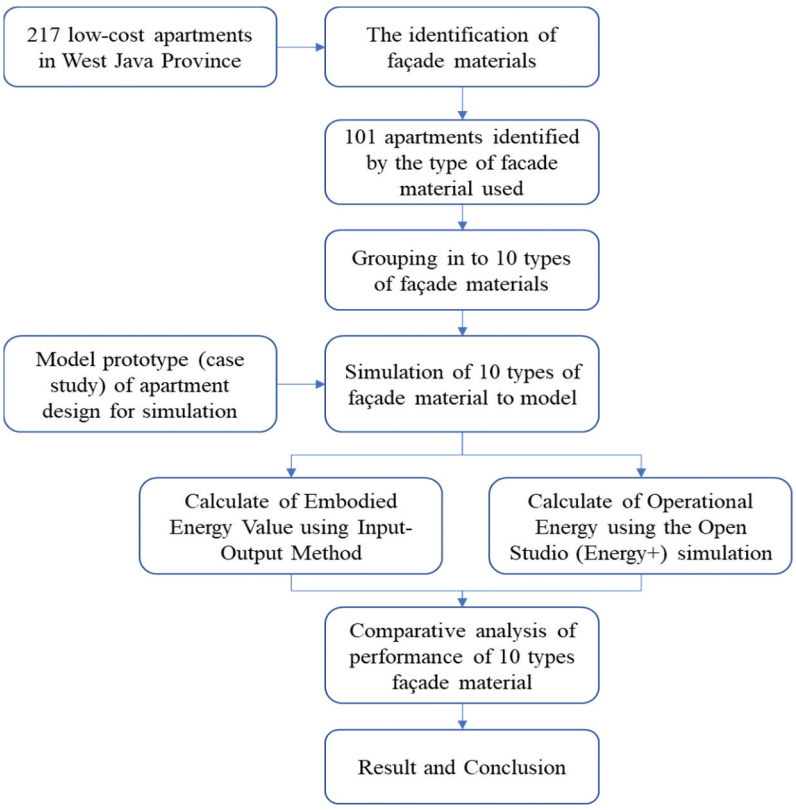


Figure 1. Flowchart of the research methodology.

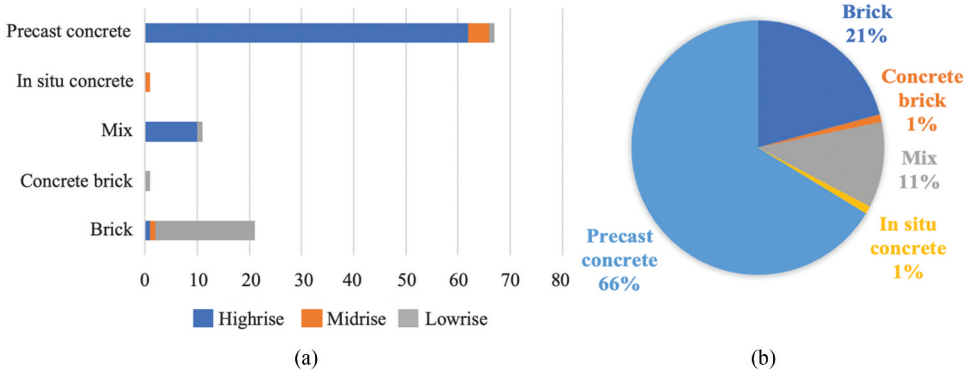
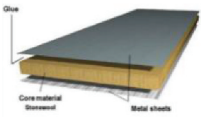
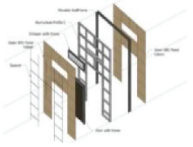
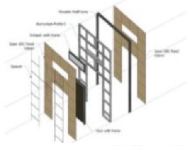
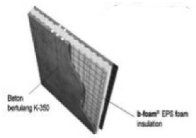
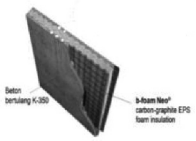


Figure 2. (a) comparison of various types of facade walls in high-, medium-, and low-rise apartment buildings. (b) percentage of each type of facade materials in apartment buildings.

Table 1. Type of facade of low-cost apartments in West Java.

No	Types of Facades	Material Specification	Insulation Types	Construction Method	Image of Material
1	Eco-lite concrete panel, thickness: • 60 mm • 75 mm • 100 mm	Prefabricated cement fiber board hollow wall panel	Expanded polystyrene (EPS) and cement	Precast	
2	Solid precast concrete, thickness: • 100 mm • 120 mm • 150 mm	Prefabricated reinforced concrete with concrete strength of fc 31.2 MPa	Non-insulated	Precast	
3	EPS Sandwich panel, thickness: • EPS 50 mm • EPS 75 mm • EPS 100 mm	Galvalume sheet and Expanded polystyrene (EPS)	Expanded polystyrene (EPS)	Precast	
4	Rockwool sandwich panel, thickness: • 50 mm • 75 mm • 100 mm	Galvalume sheet and synthetic material	Rockwool	Precast	
5	Insulated removable wall, thickness: • 95 mm • 120 mm • 145 mm	Glass-fiber-reinforced concrete sheet with hollow frame	Rockwool	Precast	
6	Uninsulated removable wall, thickness: • 95 mm • 120 mm • 145 mm	Glass- fiber-reinforced concrete sheet with hollow frame	Non-insulated	Precast	
7	Standard concrete panel, thickness: • 100 mm • 120 mm • 150 mm	Prefabricated reinforced concrete + Styrofoam	Expanded polystyrene (EPS)	Precast	
8	Neo concrete panel, thickness: • 100 mm • 120 mm • 150 mm	Prefabricated reinforced concrete + Styrofoam	Expanded polystyrene (EPS) with carbon graphite mixture	Precast	
9	Lightweight brick, thickness: • 100 mm • 120 mm	Lightweight brick	Non-insulated	Cast in place	
10	Red brick 75 mm	Red brick	Non-insulated	Cast in place	

2.2. Life Cycle Assessment (LCA) and Input-Output (IO) table method for building energy analysis

Life Cycle Assessment (LCA) is a method that simplifies the calculation of the environmental impact of buildings by dividing a building's life cycle into several phases (Rasmussen and Birgisdottir 2016). In this study, the life cycle of a building's facade was calculated from the material extraction process to its utilization, specifically the cradle-to-use phase. This phase was further divided into the cradle-to-handover phase and the operational phase. In the cradle-to-handover phase, the LCA of the building's facade

Table 2. Wall variant product specifications.

No	Type of Facades	Facade Wall Variant	Specification
1	Panel eco-lite	Panel eco-lite 60 mm	A mixture of concrete and EPS (*expanded polystyrene*) 40% coated with 10 mm GRC boards on both sides. Total thickness: 60 mm.
		Panel eco-lite 75 mm	A mixture of concrete and EPS (*expanded polystyrene*) 40% coated with 10 mm GRC boards on both sides. Total thickness: 75 mm.
		Panel eco-lite 100 mm	A mixture of concrete and EPS (*expanded polystyrene*) 40% coated with 10 mm GRC boards on both sides. Total thickness: 100 mm.
2	Solid Precast concrete	Precast concrete panel 100 mm	A fc 31.2 MPa concrete wall panel. Total thickness: 100 mm.
		Precast Concrete Panel 120 mm	A fc 31.2 MPa concrete wall panel. Total thickness: 120 mm.
		Precast Concrete Panel 150 mm	A fc 31.2 MPa concrete wall panel. Total thickness: 150 mm.
3	EPS Sandwich Panel	EPS Sandwich Panel 50 mm	EPS (*expanded polystyrene*) insulation with a density of 12 kg/m^3 (49.4 mm) sandwiched between galvanized steel sheets 0.3 mm thick on both sides. Total thickness: 50 mm.
		EPS Sandwich Panel 75 mm	EPS (*expanded polystyrene*) insulation with a density of 12 kg/m^3 (74.4 mm) sandwiched between galvanized steel sheets 0.3 mm thick on both sides. Total thickness: 75 mm.
		EPS Sandwich Panel 100 mm	EPS (*expanded polystyrene*) insulation with a density of 12 kg/m^3 (99.4 mm) sandwiched between galvanized steel sheets 0.3 mm thick on both sides. Total thickness: 100 mm.
4	Rockwool Sandwich Panel	Sandwich Panel 50 mm	Rockwool insulation with a density of 12 kg/m^3 (49.4 mm) sandwiched between galvanized steel sheets 0.3mm thick on both sides. Total thickness: 50 mm.
		Sandwich Panel 75 mm	Rockwool insulation with a density of 12 kg/m^3 (74.4 mm) sandwiched between galvanized steel sheets 0.3mm thick on both sides. Total thickness: 75 mm.
		Sandwich Panel 100 mm	Rockwool insulation with a density of 12 kg/m^3 (99.4 mm) sandwiched between galvanized steel sheets 0.3mm thick on both sides. Total thickness: 100 mm.
5	Insulated Removable Wall	Insulated Removable Wall 95 mm	GRC panel 10 mm on both sides with hollow frame and Rockwool insulation 50 mm and 25 mm. Total thickness: 95 mm.
		Insulated Removable Wall 120 mm	GRC panel 10 mm on both sides with hollow frame and two layers of Rockwool insulation 50 mm. Total thickness: 120mm.
		Insulated Removable Wall 145 mm	GRC panel 10 mm on both sides with hollow frame and two layers of Rockwool insulation 50 mm and one layer of Rockwool insulation 25mm. Total thickness: 145 mm.
6	Uninsulated Removable Wall	Uninsulated Removable Wall 95 mm	GRC panel 10 mm on both sides with hollow frame 75 mm- air gap in between. Total thickness: 95 mm.
		Uninsulated Removable Wall 120 mm	GRC panel 10 mm on both sides with hollow frame 100 mm- air gap in between. Total thickness: 120 mm.
		Uninsulated Removable Wall 145 mm	GRC panel 10 mm on both sides with hollow frame 125 mm air gap in between. Total thickness: 120 mm.
7	Standard concrete panel	Standard concrete panel 100mm	EPS (expanded polystyrene) insulation with a density of 15 kg/m3 (40mm) coated with plaster (30 mm) and given additional plastering finishing (10 mm) on both sides. Total thickness: 100 mm.
		Standard concrete panel 120mm	EPS (expanded polystyrene) insulation with a density of 15 kg/m3 (60 mm) coated with plaster (30 mm) and given additional plaster finishing (10mm) on both sides. Total thickness: 120 mm.
		Standard concrete panel 150mm	EPS (expanded polystyrene) insulation with a density of 15 kg/m3 (90 mm) coated with plaster (30mm) and given additional plaster finishing (10mm) on both sides. Total thickness: 150 mm.
8	Neo concrete panel	Neo concrete panel 100 mm	A mixture of EPS (*expanded polystyrene*) and carbon-graphite insulation with a density of 15 kg/m^3 (40 mm) coated with plaster (30 mm) and given additional plaster finishing (10 mm) on both sides. Total thickness: 100 mm.
		Neo concrete panel 120 mm	EPS (*expanded polystyrene*) carbon-graphite insulation with a density of 15 kg/m^3 (60 mm) coated with plaster (30 mm) and given additional plaster finishing (10 mm) on both sides. Total thickness: 120 mm.
		Neo concrete panel 150 mm	EPS (*expanded polystyrene*) carbon-graphite insulation with a density of 15 kg/m^3 (90 mm) coated with plaster (30 mm) and given additional plaster finishing (10 mm) on both sides. Total thickness: 150 mm.
9	Lightweight Brick	Lightweight Brick 100 mm	Hebel brick with a thickness of 100 mm and a plaster finish on both sides. Total thickness: 120 mm.
		Lightweight Brick 120 mm	Hebel brick with a thickness of 120 mm and a plaster finish on one side. Total thickness: 150 mm.
10	Red Brick	Red Brick 75 mm	Red brick with a thickness of 75mm and a plaster finishing on both sides. Total thickness: 120 mm.

focused on the EE used in the material extraction and construction, including the energy used for transporting the material. On the other hand, the operational phase focused on the building's energy consumption. Figure 3 illustrates the LCA method used in the cradle-to-handover and operational phases.

The life cycle of a building's embodied energy (EE) measurements involves four stages as defined by standards 14,000 and 14,040: defining research objectives and scope, inventory analysis, measuring the impact on the studied life cycle, and interpretation (Dixit et al. 2010). The initial embodied energy and environmental impact analysis can be conducted through three main methods: process-based analysis methods, economic input-output (IOA)-based analysis, and hybrid analysis methods (Dixit 2017).

The IOA is an economic analysis of the relationship between the industrial sector and households in terms of the national economy (Crawford 2004; Nansai 2002). This relationship is expressed through the supply and consumption of goods and services, capital formation, and exchange of income and labor. Input-Output

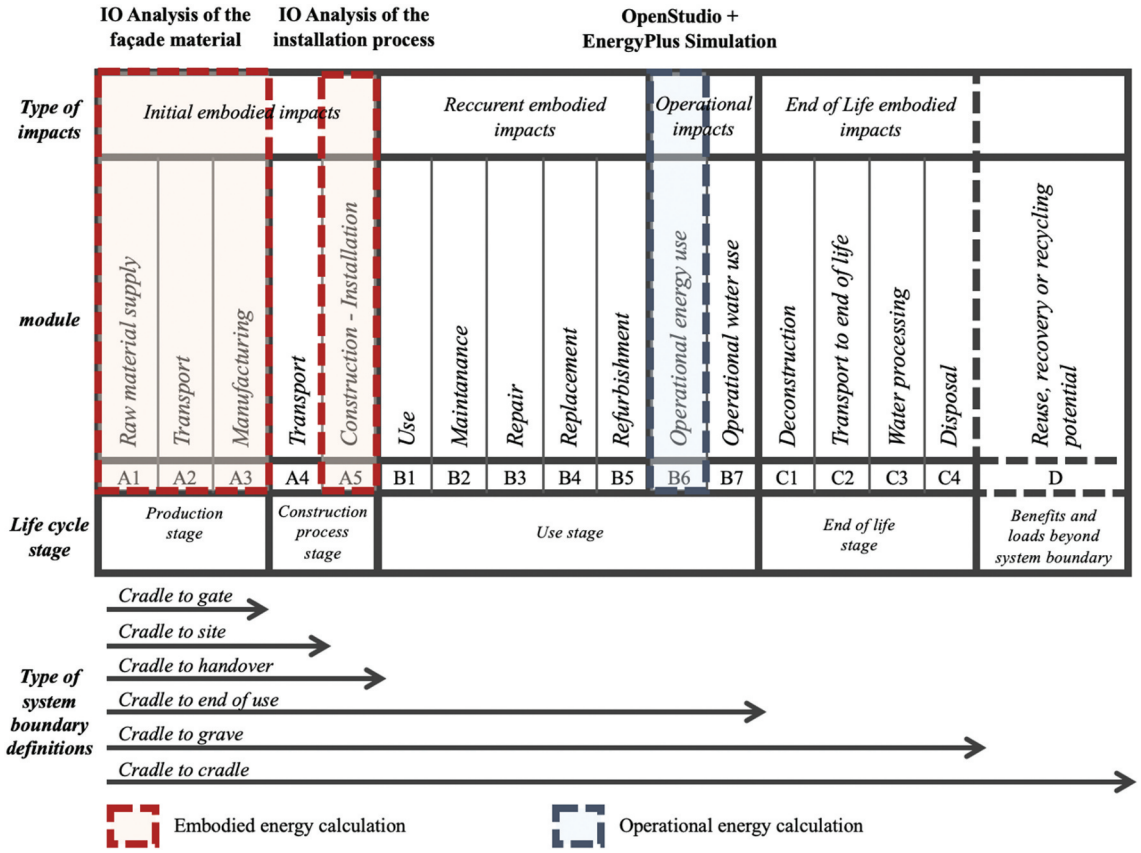


Figure 3. Scope of LCA (adapted from (Rasmussen and Birgisdottir 2016)).

Tables (IOT) contain the average monetary terms of all economic sectors, the amount each sector buys from other sectors, and the number of units produced in that sector (Finnveden et al. 2009) The IOA calculation is based on data for the industrial sector, and the results are obtained for the average product of the industrial sector. These data can be used as an estimate for a particular product or product group from the sector. However, the accuracy of the results depends on how a product or product group is studied in relation to other products in the sector (Khasreen, Banfill, and Menzies 2009).

This study used the Input-Output Analysis (IOA) method to calculate the embodied energy (EE) of building materials. This method is considered more thorough as it has a wider system boundary and can calculate both the EE value and greenhouse gas (GHG) emissions value (Wu, Ann, and Shen 2017). To obtain the EE calculation results, national sectoral economic data and environmental accounting data must be used (Crawford 2004; Nansai 2002). The calculating method created by Nansai, Moriguchi, and Tohno (Nansai 2002), later modified by Surahman and Kubota (Surahman, Kubota, and Higashi 2014, 2015), was used in this study. The IO table method consists of six steps: determining the import and domestic inverse matrix (A), estimating fuel consumption (B), determining the net contribution rate (C), determining the net calorific value (D), determining the calorific value, and estimating the intensity of embodied GHG emissions (D) (Nansai 2002; Surahman, Kubota, and Higashi 2014, 2015). The calculation procedure of the IO method can be grouped into four stages and later compiled in a data inventory. These stages are:

(1) calculation of material quantity,
(2) calculation of material price intensity,
(3) calculation of energy intensity and carbon emissions, and
(4) calculation of EE values on buildings.

The following stages were conducted to identify the EE value of apartments based on the various types of facade materials used in the case studies (see Figure 4).

In this study, the quantification phase was based on the facade component elements. The IO value was primarily determined by the work value, and thus, embodied GHG emissions were calculated based on the use of construction materials, equipment, and labor wages through the Work Unit Price Analysis (WUPA) calculation (Hanifah et al. 2019; ZR et al. 2017). The WUPA calculation data provided information on material price intensity, which was determined by material quantity data, its price, and its work coefficient. So those calculations can be arranged into formulas, which are equation 1–3.

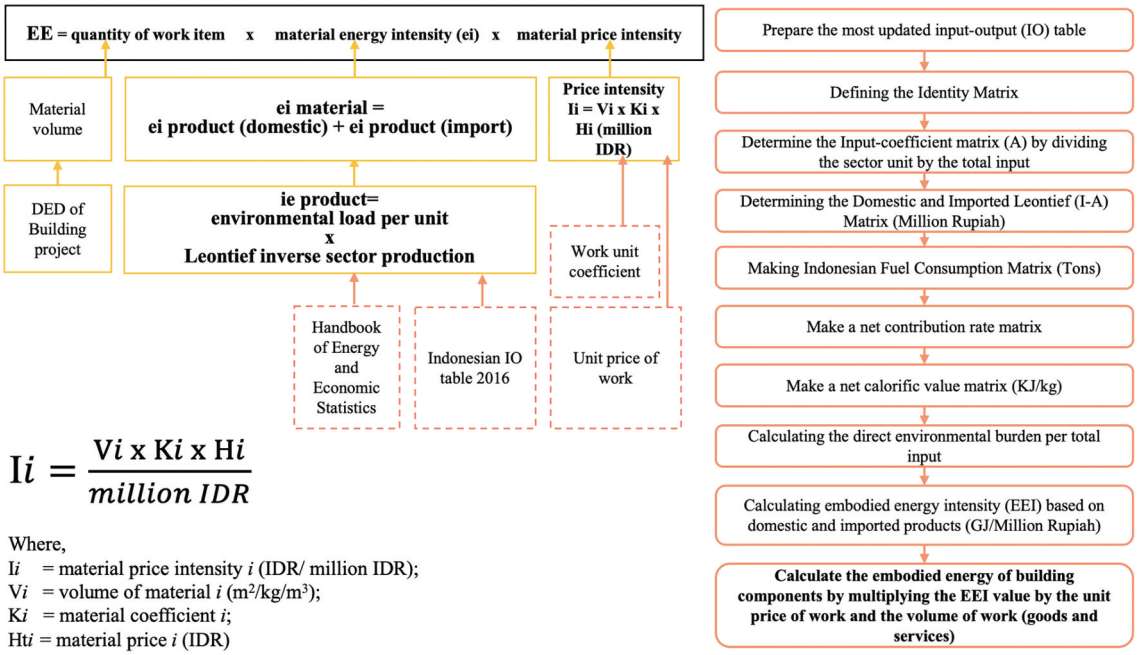


Figure 4. Phase 2 research method, adapted from Larasati et al., (2020), Nansai (2002), and Surahman et al. (2014).

$$\sum_{i=1}^{n} \text{EE construction works} = EE_m + EE_w \quad (1)$$

while:

$$EE_m = Qty_m . \propto_m . Y_m . EEI_m \quad (2)$$

$$EE_w = Qty_w . \propto_w . Y_w . EEI_w \quad (3)$$

EE : Embodied Energy (GJ)

EE_m : EE material

EE_w : EE workers

EEI : Embodied Energy Intensity (GJ/Million Rupiah)

Q_{ty} : Quantity (unit: m/m2/m3)

$\propto$: Coefficient

Y : Price/Quantity (Million Rupiah/unit)

Having obtained the material price intensity, the next step was to determine the EE value and carbon emissions by multiplying the material price intensity value by the energy intensity and carbon emissions of each material. The same process was applied to worker wages.

Subsequently, inventory data was prepared for the same functional unit, which was per square meter of wall, for the purpose of the next analysis step. This involved conducting a comparative analysis to determine the differences in the energy value of each prefabricated material used in the model building facade.

2.3. Simulation for the calculation of operational energy

The main component of operational energy is the energy used to operate equipment for cooling purposes, followed by lighting. Previous studies have identified that operational energy in residential areas is contributed by cooling loads, lighting loads, and equipment loads (Le and Pitts 2019; Rahmadyani 2020). Building operational energy is influenced by various factors such as the level of user comfort required, climatic conditions, and the duration of building operations (Ramesh, Prakash, and Shukla 2010). Optimizing the factors that affect the operational stage is crucial because operational energy is a significant contributor to the overall energy consumption of a building, accounting for up to 55% (Krishan 2001). Furthermore, the operational phase is the longest stage during the building life cycle; therefore, considering operational energy is important when designing energy-efficient buildings (Jabri 2018; Koezjakov et al. 2018).

This study uses case studies to calculate operational energy. The building in this study is a low-energy, low-carbon apartment building prototype designed by researchers from Institut Teknologi Bandung, Hiroshima University, and the Ministry of Public Works of Indonesia. The building is located in the city of Tegal and is illustrated in Figure 5 (Larasati et al. 2020).

Regarding thermal comfort, Tegal City has a hot climate throughout the day. The Potential Evapotranspiration (PET) in Tegal City is very high from 10 am to 4 pm, and only reaches warm conditions after 4 pm, with an average temperature of 42.65 degrees Celsius throughout the year (Figure 6a). This condition makes the thermal sensation very uncomfortable when compared to the ASHRAE standard (Figure 6b). Under such climatic conditions, achieving acceptable comfort without controlling the air conditions is difficult. As a result, high energy consumption

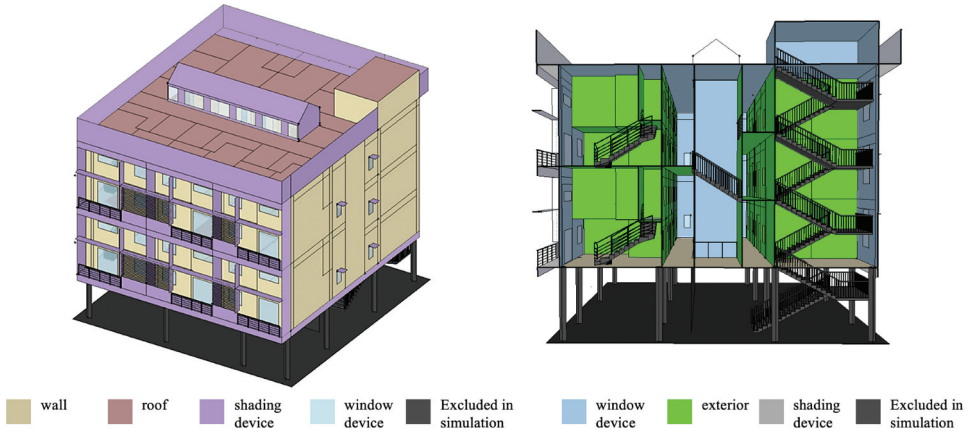
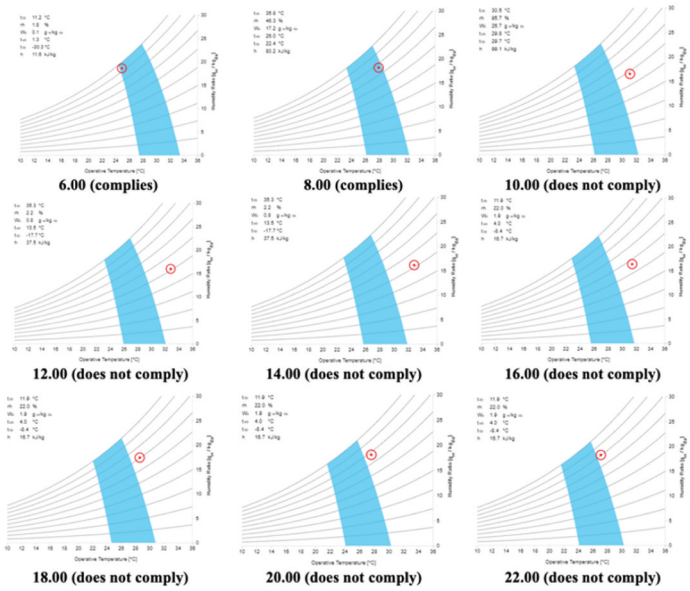


Figure 5. Prototype apartment building model.

Time	PET	Thermal sensation
h:mm	°C	
6.00	20.2	Cool
8.00	32.8	Slightly warm
10.00	42.1	Very hot
12.00	45.4	Very hot
14.00	45.2	Very hot
16.00	37.9	Warm
18.00	24.5	Slightly cool
20.00	23.5	Slightly cool
22.00	23	Slightly cool

(a)



(b)

Figure 6. Climate conditions of case study location in Tegal City based on (a) Rayman 1.2 and (b) on CBE simulation.

is required for cooling loads, and building design must consider various measures to reduce the cooling energy load.

To determine the average cooling load of a building in a year, an OpenStudio simulation was conducted. OpenStudio is a Graphical User Interface (GUI) application used for building energy simulations that rely on EnergyPlus and Radiance simulation engines (Al-Zubaydi 2013). This application enables users to create and edit models, run simulations, and set cooling loads or HVAC systems by setting the climate, dividing thermal zones, and entering weather data. OpenStudio is a plug-in that works with the SketchUp modeling application, simplifying the creation of building geometries that can be processed by the EnergyPlus simulation engine (Guglielmetti, Macumber, and Long 2011). Simulation results are shown in the form of a report using the "Result Viewer" feature in OpenStudio, which can browse, plan, and compare simulation output data, especially cooling loads.

The OE and cooling load in the case study building model were simulated, which was tested with the existing facade walls and precast facade wall variants that were previously identified. Other building components such as roofs, windows, and floors, and building structures were compared to the existing building conditions. This study only discussed the amount of life cycle assessment (LCA) up to OE, and the calculated OE was only the cooling load energy because it had the largest percentage of building OE consumption (Giordano et al. 2017; Sun, Gou, and Lau 2018). The OE and cooling load were determined through simulations using the OpenStudio + EnergyPlus application. The simulation process used a prototype apartment building model, as shown in Figure 7. The climate data used in

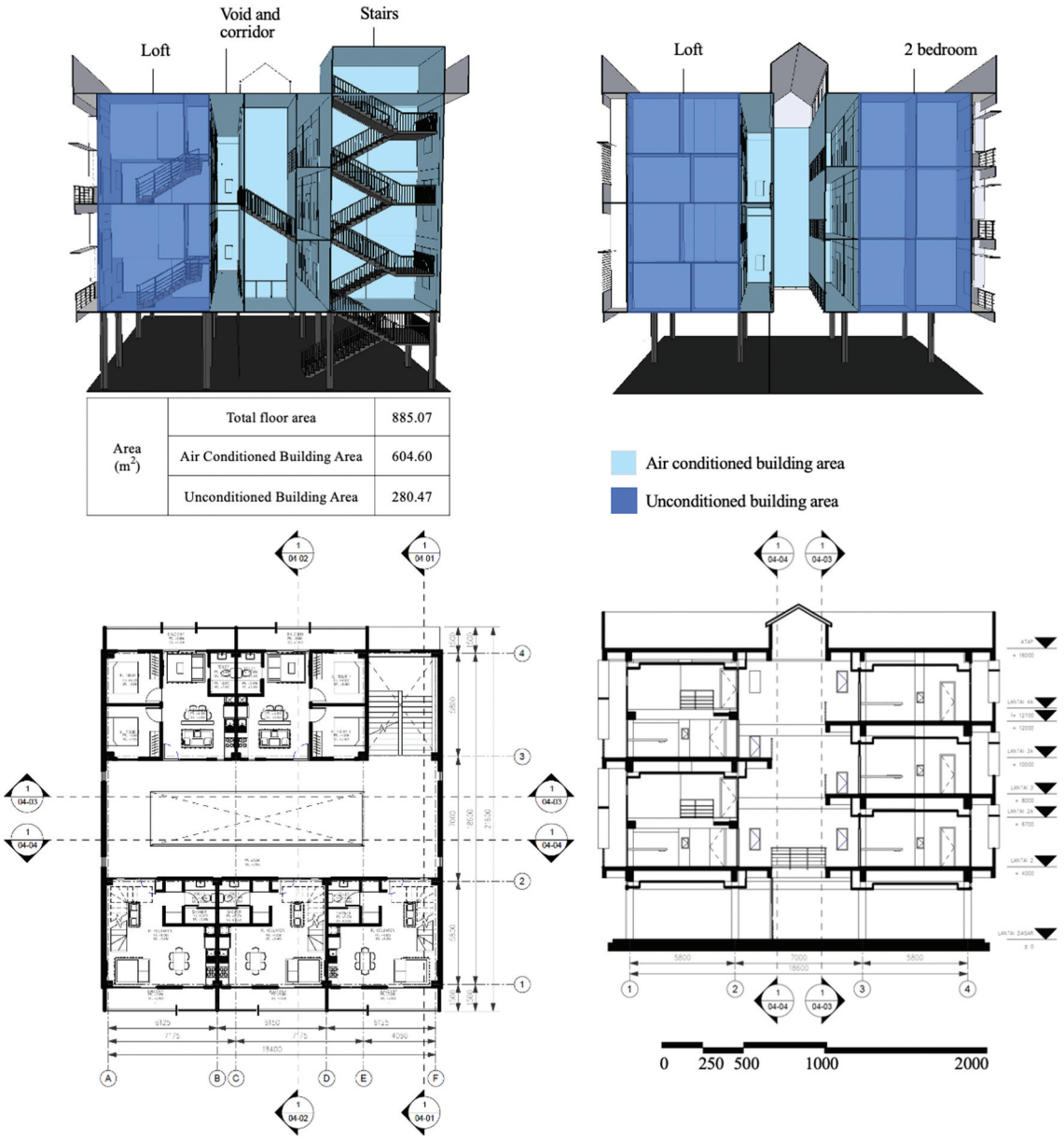


Figure 7. Conditioned-unconditioned rooms in the case study building simulation model and the building plan.

Table 3. Parameter of energy- plus simulation.

No	Parameter	Settings
1	**People definition**	
	People per space floor area	0.028309 people/m^2
2	**Light definition**	
	Energy per space floor area	10.656271 W/m^2
3	**Equipment**	
	Energy per space floor area	3.875008 W/m^2
4	**Infiltration rate**	
	Flow per exterior surface	0.00030226 m/s

calculating the cooling energy were the climate data for the location of the prototype apartment as the case study location (Tegal City).

Table 3 indicates the settings of HVAC and other major parameters that used for the Energy plus simulation.

3. Results and discussion

3.1. Embodied and operational energy of precast facade wall variants

The embodied energy (EE) value was calculated using the input-output (IO) method by determining the EE value of the material per square meter (m2) of the facade wall and calculating the material quantity based on the analysis of the construction work unit price. Table 4 shows the calculated EE value for the various types of predetermined facade materials.

Based on the data presented in Table 4, it can be observed that the total EE value tends to increase in direct proportion to the increase in wall thickness. This is because the amount of EE depends on the volume and type of material that forms the facade. This finding is consistent

Table 4. The EE value of affordable apartments facades.

No	Material	Thickness (mm)	EE of the Materials	EE of the Installation	Total EE	Total/Average EE
			(GJ/m^2)	(GJ/m^2)	(GJ/m^2)	(%)
0	Average Value	108.8	0.178	0.0693	0.248	100%
1	B-panel standard	110	0.183	0.047	0.229	92%
		130	0.188	0.047	0.234	94%
		160	0.196	0.047	0.242	98%
2	B-panel neo	110	0.186	0.047	0.233	94%
		130	0.193	0.047	0.24	97%
		160	0.203	0.047	0.25	101%
3	Eco-lite panel	60	0.080	0.087	0.167	67%
		75	0.093	0.087	0.18	73%
		100	0.113	0.087	0.2	81%
4	Solid precast concrete	100	0.357	0.057	0.414	167%
		120	0.504	0.057	0.561	226%
		150	0.567	0.057	0.624	252%
5	Red brick	105	0.129	0.051	0.179	72%
6	Lightweight brick	130	0.100	0.099	0.2	81%
		150	0.102	0.099	0.201	81%
7	Insulated GRC Removable Wall (disassembly)	95	0.108	0.077	0.185	75%
		120	0.120	0.077	0.197	79%
		145	0.157	0.077	0.234	94%
8	Uninsulated GRC Removable Wall (disassembly) 120mm	120	0.047	0.077	0.124	50%
9	Sandwich panel EPS	50	0.070	0.077	0.148	60%
		75	0.077	0.077	0.154	62%
		100	0.086	0.076	0.163	66%
10	Sandwich panel Rockwool	50	0.175	0.077	0.252	102%
		75	0.202	0.077	0.279	113%
		100	0.228	0.077	0.305	123%

The EE value is above 150% of the average.

The EE value is below 50% of the average.

with a study by (Venkatraj et al. 2020), which found that the type and quantity of material affect the energy of the embodied wall. The solid precast concrete facade with a thickness of 100 mm-150 mm has an embodied energy value far above the average, followed by the facade group with Rockwool-insulated Sandwich Panel material.

For instance, the EE value of a facade with solid precast material reaches 160–250% of the average EE value. In contrast, the Uninsulated GRC Removable Wall (disassembly) with a thickness of 120 mm can achieve an EE value of 50% of the average EE value. EPS sandwich panels also have a low EE value, with a thickness of 50 mm-100 mm, achieving an EE value between 62–66% of the average EE value. The linear relationship between the EE value and the wall thickness is depicted in Figure 8.

Precast concrete facades have a higher EE value compared to other types of facades due to their composition of cement, which has a high energy intensity value for the product sector (Lotteau, Loubet, and Sonnemann 2017) stated that the material energy intensity affects the EE value, as well as the material quantity or volume.

The total EE value of the facade wall, as shown in Table 2, comprises the EE value from the material production and the facade wall installation process. Figure 8 provides a comparison of the EE value of the material and installation as forming the total EE value (∑EE material + ∑EE installation = ∑EE total).

Figure 9 illustrates the proportion of the EE value of the materials and installation from the EE value of each facade material. The EE value of the light brick facade installation exceeds 50% of the total EE value because

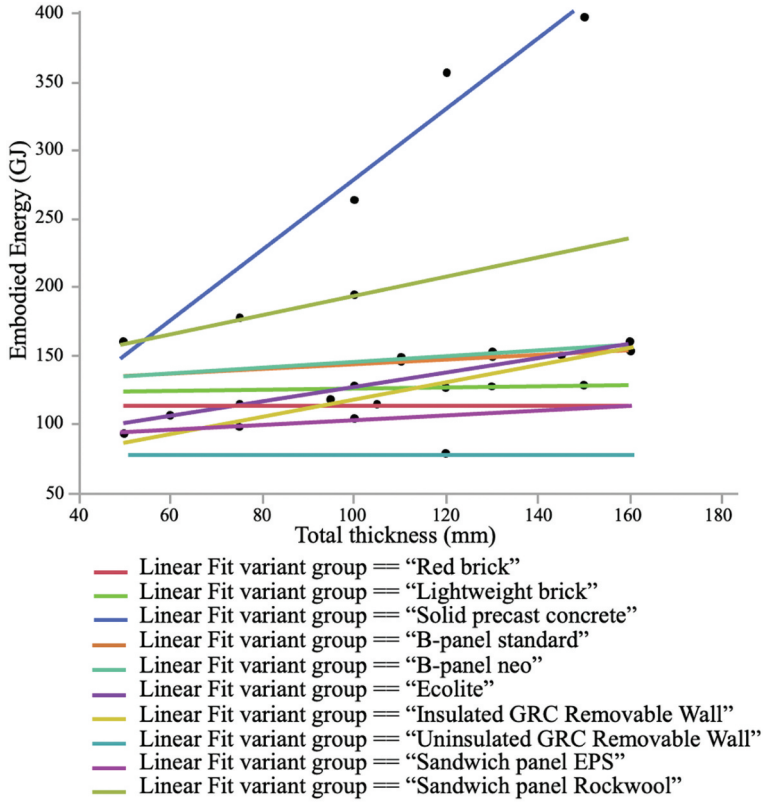


Figure 8. Linear relationship between facade wall thickness and EE.

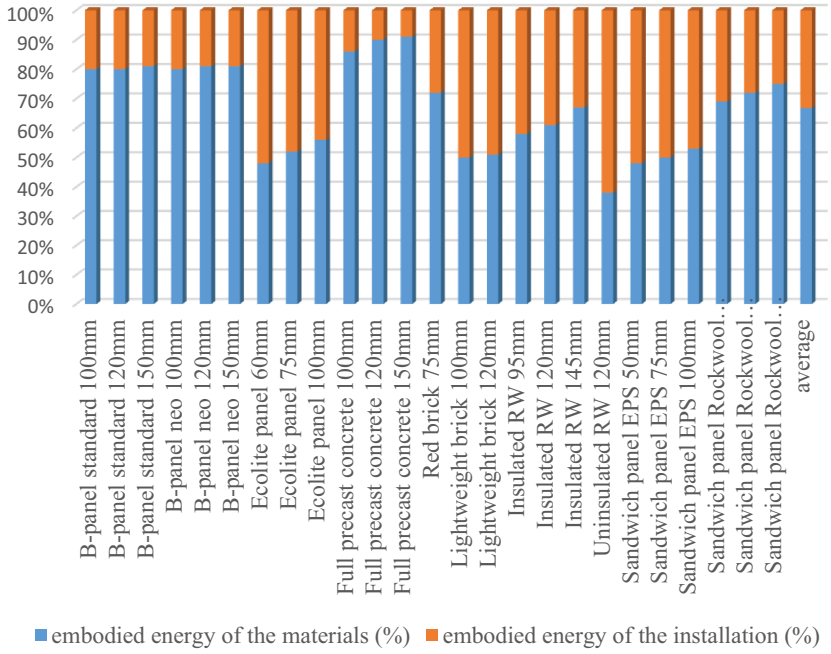


Figure 9. Comparison between total EE of materials and installation using calculations on the case study building model.

the construction work was carried out in situ. Similarly, eco-lite panels also have a high installation EE value, with the installation value exceeding 40% of the average value because the installation process of eco-lite materials requires special equipment and additional connection systems, such as anchor connections on precast prefabricated facade construction. High installation EE values may also be caused by connection requirements that demand materials with high EE intensity, such as skim-coat finishing for the installation of the Eco-lite Panel and light steel frames for Sandwich Panel and Removable Wall installations.

3.2. Operational energy simulation

An energy simulation was conducted using the OpenStudio + EnergyPlus application to evaluate the operational energy (OE) of buildings with different types of facades. To run a building energy simulation, a building simulation model was developed in Open-Studio Simulation Model (OSM) data format with plugin support in the SketchUp application.

The building energy simulation was performed 26 times by replacing the facade material in each simulation process. The facade materials were differentiated based on the following parameters:

(1) Physical characteristics such as thickness and density, which affect the external cooling load. In this study, the internal cooling load of the building was considered constant based on the typology and function of the building.
(2) Thermal characteristics, including the thermal conductivity value and heat capacity of each layer of material in the simulated facade wall material.

The simulation results generated by OpenStudio and EnergyPlus were in the form of the OE value of the case study building with various alternative facade materials over a year, as presented in Table 5.

Buildings using thicker materials tend to have lower OE values. Installing insulation on facade materials reduces the cooling energy load by increasing the r-value of the material. Thus, materials with insulation generate OE values below the average of all materials. The Insulated GRC Removable Wall material has the smallest OE value, which is 93–90% of the average OE value. Figure 10 illustrates the correlation between the thickness of the facade-wall variant and the operational energy of the building.

Cooling load energy accounts for a significant portion of the total OE value of buildings, with a total value for all variants above 70%, and an average of 77%. This is consistent with previous studies, which found that around 75% of the OE of buildings is affected by the building's thermal performance (Nugrahanti et al. 2020).

The cooling load of a building is closely related to the amount of heat transfer that enters the building. As such, the lower the heat transfer value, the lower the cooling load of the building. The facade, as a building envelope, plays a significant role in dispelling heat from outside the building. The ability of a building envelope to dissipate heat is indicated by the thermal resistance (r-value) of the material. The analysis results indicate that the higher the r-value, the lower the OE value of the building. Figure 11 shows that the decrease in the OE value of the building increases inversely with the increase in the r-value of each facade material. Although the relationship is sloping, the effect of the r-value on the OE value of the building can be described by an exponential equation. The characteristics of OE values in each group of facade types were identified, and the same pattern was found. However, the solid precast concrete material has a more curved graphic line, while the insulated Removable Wall has the most sloping graphic line. This suggests that the change in the r-value of the variant most significantly affects the OE value in variations in the thickness of the solid precast concrete material. In contrast, for the insulated Removable Wall type, the change in the r-value in material thickness does not significantly affect the OE value. Certain facade materials, such as Eco-lite, EPS sandwich panels, and Rockwool sandwich panels, have shown a decreasing trend of OE value up to 120 mm thick, and an increasing trend with thicknesses over 120 mm. This phenomenon may be caused a thicker air gap results in amplification of convection so that it can experience a degradation of the resulting thermal resistance (Ouédraogo et al. 2018). However, a more comprehensive investigation of this phenomenon is needed to better understand the underlying mechanisms.

Based on the aforementioned explanation, it can be concluded that the thickness and r-value of a material have a significant impact on the operational energy of a building. These variables show a linear relationship with the embodied energy value and an exponential relationship with the operational energy value, although both tend to slope. Table 6 presents the relationship between the thickness variable, thermal transmission value (r-value), embodied energy, and operational energy of building facades.

This finding is consistent with the results of previous research by (Venkatraj et al. 2020), which suggests that there is a trade-off between the embodied energy value of a building and efforts to save its operational energy. The findings of the calculations and simulations indicate that energy efficiency and conservation efforts can be achieved through the design of building facades by considering the material thickness, intensity value of the material product, use of insulation layers in the facade material, and thermal resistance value of the facade.

Further strategies for optimizing the selection of facade materials can be carried out using parametric methods that consider various variables that affect the amount of embodied energy and building operational energy. This can be done through a more comprehensive alternative design iteration process. Figure 12 and Table 7 provide a comparison of the total amount of energy for each alternative building facade material based on the prototype apartment case study.

Figure 12 illustrates the total energy consumption during both the building phase (cradle-to-

Table 5. OE of buildings per year based on simulation results with the OpenStudio + EnergyPlus application.

No	Material	Thickness (mm)	r-value total ($W/m^2.K$)	Total Operational Energy/Year	Total cooling Load	OE/average per year	Cooling load/ Total OE per year
				(GJ/Year)	(GJ/Year)	%	%
	Average	108.8	1.49	735.3	566.5	100.0%	77.0%
1	B-panel standard	110	1.16	708.2	539.4	96.3%	76.2%
		130	1.70	690.8	521.9	93.9%	75.6%
		160	2.50	676.8	508.0	92.0%	75.1%
2	B-panel neo	110	1.25	704.6	535.8	95.8%	76.0%
		130	1.82	688.1	519.3	93.6%	75.5%
		160	2.69	675.0	506.2	91.8%	75.0%
3	Eco-lite panel	60	1.07	713.3	544.5	97.0%	76.3%
		75	1.39	700.5	531.7	95.3%	75.9%
		100	1.91	687.3	5185	93.5%	75.4%
4	Solid precast concrete	100	0.07	901.7	732.9	122.6%	81.3%
		120	0.09	891.3	722.4	121.2%	81.1%
		150	0.11	877.2	708.4	119.3%	80.8%
5	Red brick	105	0.14	862.0	693.2	117.2%	80.4%
6	Lightweight brick	130	0.48	771.1	602.3	104.9%	78.1%
		150	0.57	756.9	5881	102.9%	77.7%
7	Insulated GRC removable Wall (disassembly)	95	2.11	683.2	514.4	92.9%	75.3%
		120	2.80	674.2	505.4	91.7%	75.0%
		145	3.49	668.5	499.7	90.9%	74.7%
8	Uninsulated GRC removable Wall (disassembly)	120	0.17	854.3	685.5	116.2%	80.2%
9	EPS Sandwich Panel	50	1.21	722.5	553.7	98.3%	76.6%
		75	1.82	699.6	530.8	95.1%	75.9%
		100	2.43	684.9	516.1	93.1%	75.4%
10	Rockwool Sandwich Panel	50	1.37	714.8	546.0	97.2%	76.4%
		75	2.07	693.8	525.0	94.4%	75.7%
		100	2.76	682.0	513.2	92.8%	75.2%

	The EE value is above 100% of the average OE value.
	The EE value is below 92% of the average OE value.

construction) and building operations (cradle-to-use), indicating that solid concrete material has the highest energy consumption. Meanwhile, Rockwool 145 mm is the facade material with the lowest operational energy value, as it can save up to 24% total energy (208.7 GJ per year) compared to solid concrete material with almost the same thickness (150 mm), as shown in the case study simulation. The OE value will have a significant effect on the building's energy consumption if it is estimated that the building will operate for 30 years following Indonesia's building lifetime regulated by Indonesia Government Regulation Number 18 the Year 2021 regarding the Management Rights, Land Rights, Vertical Housing Units, and Land Registration. Table 5 presents the total operational energy for 30 years plus the total embodied energy at the cradle-to-construction stage. Table 7 presents the total operational energy for 30 years plus the total embodied energy at the cradle-to-construction stage.

Table 7 also shows the influence of thickness and thermal resistance on EE and OE. Although insulated removable wall material does not have the lowest EE value of 75%–94% of the average value, depending on the thickness due to the use of insulation materials, it has the lowest OE value. Therefore, the total energy consumption value remains the lowest, as the OE value has a greater influence than the EE value throughout the building life cycle. Therefore, the consideration of the OE

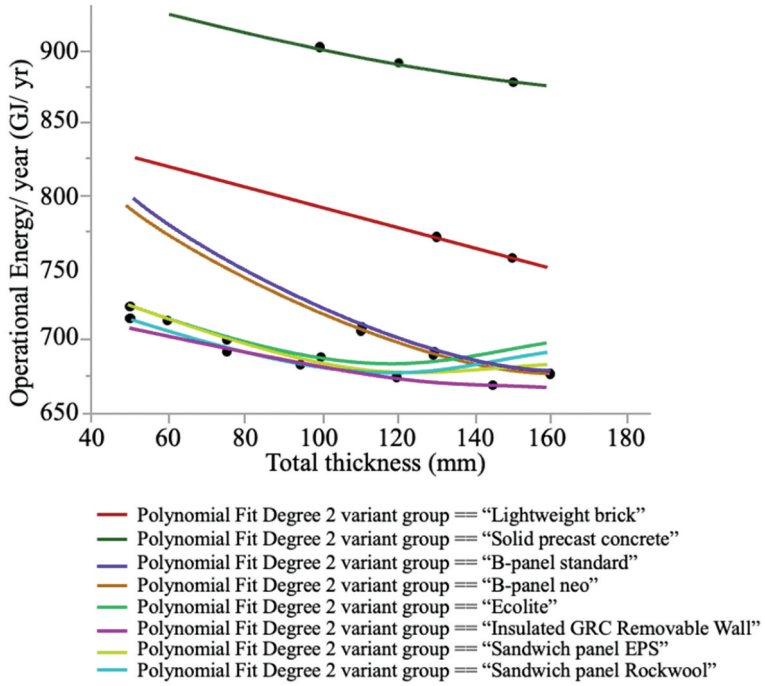


Figure 10. Relationship between material thickness and OE of the building.

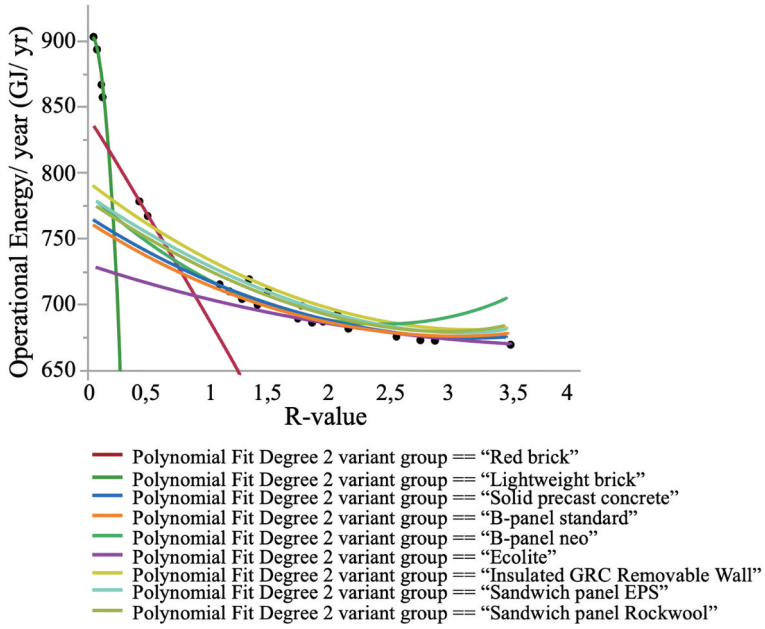


Figure 11. Relationship between thermal resistance of each facade material and OE of the building.

Table 6. Influence of thickness and thermal resistance value (*r*- value) of each type of facade material on the EE and building OE.

No	Material Variables	Relation between Embodied Energy and Material	Relation between Operational Energy and Material
1	Thickness*	Directly proportional/Linear	Inversely proportional (exponential)
2	Energy Intensity	Directly proportional (tends to be sloping, not significant)	-
3	Thermal resistance (r-value)	-	Inversely proportional (exponential but tends to be sloping)

Table 7. The influence of thickness and thermal resistance value (*r*- value) of each type of facade material on the EE and OE of the building.

No	Material	Thickness (mm)	Total Energy (OE of 30 year + EE building)	Total energy/Average
	Average Value	108.8	22,278.5	100.0%
1	B-panel standard	110.0	21,448.7	96.3%
		130.0	20,931.1	94.0%
		160.0	20,518.2	92.1%
2	B-panel neo	110.0	21,344.2	95.8%
		130.0	20,855.4	93.6%
		160.0	20,471.3	91.9%
3	Eco-lite panel	60.0	21,546.8	96.7%
		75.0	21,174.3	95.0%
		100.0	20,796.0	93.3%
4	Solid precast concrete	100.0	27,417.4	123.1%
		120.0	27,235.5	122.3%
		150.0	26,868.3	120.6%
5	Red brick	105.0	26,018.4	116.8%
6	Lightweight brick	130.0	23,310.0	104.6%
		150.0	22,884.9	102.7%
7	Insulated GRC Removable Wall (disassembly)	95.0	20,659.7	92.7%
		120.0	20,400.4	91.6%
		145.0	20,262.1	90.9%
8	Uninsulated GRC Removable Wall	120.0	25,738.7	115.5%
9	Sandwich panel EPS	50.0	21,806.0	97.9%
		75.0	21,124.3	94.8%
		100.0	20,691.3	92.9%
10	Sandwich panel Rockwool	50.0	21,667.0	97.3%
		75.0	21,060.9	94.5%
		100.0	20,729.9	93.0%

	Total Energy consumption is above 100% of average.
	Total Energy consumption is below 91% of average.

value is prioritized over the EE value, even though materials with an acceptable EE value (in this case, materials with an EE value below the average value) can still be used.

4. Conclusions

The choice of facade materials and their construction method has the potential to improve efficiency of building energy consumption and reduce contribution of building to CO2 emissions. The present study indicates that prefabricated facade materials are more advantageous than solid concrete facades, which have the highest EE. The use of the concrete facades in buildings results in 67–152% more EE and 20–22% higher OE than the average of the alternative materials considered in this study. This disparity is considerably higher when compared to materials with the best EE and OE performance. Solid concrete facade materials are also responsible for the building's highest cooling energy load when compared to other materials, accounting for 81% of the building's total OE. Moreover, the total energy consumed over a 30-year life cycle amounts to 123.1–120.6% of the average value. If the facade material is replaced with insulated GRC removable walls (disassembly), the energy consumption reduces approximately 30% compared to that using solid concrete.

In the context of Indonesia, the acceptance of these new prefabricated materials is limited due to several factors. These include restricted production, a scarcity of companies specializing in non-

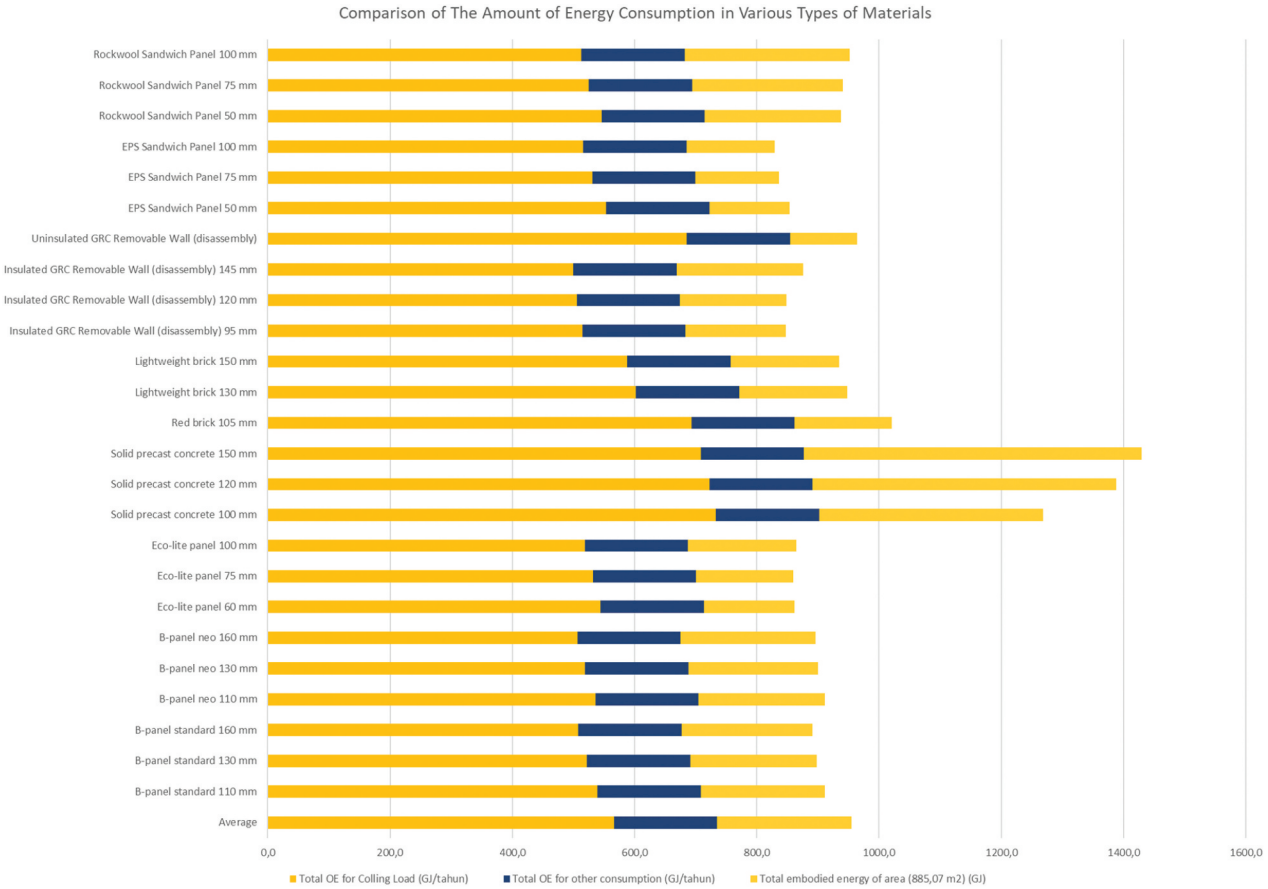


Figure 12. Total energy used by the building with different facade materials during the first year of construction.

concrete prefabricated facades, unclear pricing structures, and low public awareness of these materials. These challenges hinder the widespread use of these alternatives in the country's construction sector. Consequently, a more thorough investigation and deliberate consideration are necessary to effectively implement energy-efficient facade solutions.

In choosing an appropriate facade wall, a comprehensive assessment of both embodied energy (EE) and operational energy (OE) is imperative. This assessment considers various wall-related attributes, encompassing the material composition, thickness, associated costs, installation, and thermal resistance value. The cradle-to-construction EE of a material is greatly influenced by factors such as the intensity of production energy, installation work, and specific gravity of the material. On the other hand, the OE of the material is strongly influenced by its thermal transmission value, its thickness, and the addition of insulation as a material-forming element. Selecting materials with optimal OE and EE values can improve the facade's performance, allowing for the use of appropriate facade walls that can reduce the negative environmental impact of buildings, including CO2 emissions, and contribute to energy conservation efforts. By strategically selecting materials with optimized operational and embodied energy values, the performance of the facade can be enhanced, employing appropriate facade walls that mitigate the adverse environmental repercussions associated with buildings, including the emission of CO2. This endeavour aligns with energy conservation initiatives and contributes to broader sustainability objectives.

Currently, more than 60% of apartment buildings are constructed using solid precast concrete materials with low energy performance. There are alternative materials available that can be used to improve energy efficiency, such as insulated GRC removable walls (disassembly), Eco-lite panels, B-panels neo/standard, or sandwich panels EPS/insulated rockwool. However, considering the anticipated availability of more energy-efficient AC systems, a gradual decline in operational energy (OE) is widely acknowledged. This trend prompts the need for future applications of

diverse facade types in the region to be approached more comprehensively. In this context, it is advisable to undertake further studies employing a multi-objective parametric design approach that integrates intricate variables and considers multiple objectives.

The present study utilized an input-output (IO) analysis to compute the Embodied Energy (EE) value, while also considering the periodic release of government input-output data. It is advisable for future research efforts to incorporate the most up-to-date IO Table data, which are updated at five-year intervals. This practice ensures the continuous relevance and accuracy of EE calculations. Moreover, the utilization of IO analysis for EE calculation is encumbered by various limitations, notably its substantial reliance on market prices and the assumption of homogeneity in delineating material sectors. To attain more nuanced and dependable outcomes, it is advisable to pursue further research employing alternative EE analysis methods, such as hybrid-based input-output or process analyses. Furthermore, in the context of optimizing the selection of facade materials, additional research can be undertaken through the application of parametric and algorithmic approaches. Additionally, it is recommended to embark on a thorough investigation to delve into the causal factors contributing to the observed upward trends in specific facade materials. This proposed research trajectory is aligned with the objective of augmenting the depth and reliability of research findings.

Furthermore, a notable limitation in this paper is the omission of cost considerations, which could potentially serve as a factor undermining the application of prefabricated walls in Indonesia.In light of the prevailing tendency where users predominantly base their selection of facade materials on cost considerations, it is imperative that additional research is conducted to optimize energy performance, emission level, and the initial and operational costs throughout the entire lifecycle of the building. Subsequently, there arises a need for further research to offer a more holistic perspective regarding the implications of facade material choices, encompassing both environmental and economic considerations. In addition, it is imperative to conduct a more thorough investigation aimed at exploring the multifaceted aspects associated with facade performance. Subsequently, future research should endeavor to identify a more extensive range of detailed facade variables, encompassing considerations such as the thickness of gaps in sandwich facades, and explore the integration of alternative, environmentally sustainable, low-emission materials.

Glossry

Nomenclature		**Abbreviations**	
EE_m	EE material	ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
EE_w	EE workers	EE	Embodied Energy
EEI	Embodied Energy Intensity (GJ/Million Rupiah)	EPS	Expanded Polystyrene
E	Energy (GJ)	GRC	Glass-Fiber Reinforced Concrete
Q_{ty}	Quantity (unit: m/ m2/m3)	GUI	Graphical User Interface
Low-E	Low energy	GHG	Greenhouse Gas
r- value	Thermal resistance (m2·K/W)	Global ABC	UN's Global Alliance for Buildings and Construction
		HVAC	heating, ventilation, dan air-conditioning
Greek letters		IEA	International Energy Agency
$\propto$	Coefficient	IOA	Input-Output Analysis
Σ	Summation	IOT	Input-Output Table
		LCA	Life Cycle Assessment
		OSM	Open-Studio Simulation Model
		OE	Operational Energy
		PET	Potential Evapotranspiration
		WUPA	Work Unit Price Analysis

Acknowledgements

This paper is part of research on Implementation of Low Energy Affordable Apartment in The Hot-Humid Climate of Indonesia (Towards Nearly Zero Energy Building/NEZB), a collaboration between the Bandung Institute of Technology, the Tegal City Housing and Settlements Office, the Ministry of Public Works and Housing, and Hiroshima University, this part of the research was supported by the Ministry of Education Culture Research and Technology and the Education Fund Management Institute.

Disclosure statement

I hereby declare that the information contained in this paper is correct and that there are no actual, potential, or apparent conflict of interest situations known to me. I promise to notify you of any changes in these circumstances, including if any issues arises in the future.

The primary author holds the position of Associate Professor in Architecture at the Bandung Institute of Technology. The researcher's scholarly pursuits primarily

revolve around subjects pertaining to Sustainable Design and Construction. Research inquiries span a spectrum encompassing the implementation of the green building concept in Indonesia, both from technological and policy perspectives, exploration of themes surrounding energy efficiency and conservation (encompassing embodied and operational energy), Integrated Building Photovoltaic, optimization of green implementation utilizing a parametric approach, and studies related to green Building Information Modeling (BIM), smart building methodologies, among other relevant areas.

Funding

The work was supported by the Institut Teknologi Bandung [SAPPK.PN-6-09-2021].

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