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(Re)thinking Resilience

An Analysis of Reflective Roof Insulations, Thermal Comfort and Carbon Emissions for an Elementary School Design in Indonesia

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ABSTRACT: Indonesia has pledged to achieve net-zero emissions by 2060, as announced at the UN Climate Change Conference in 2021 (COP 26). While the government has put frameworks and policies in place to reach this target, they have primarily focused on large-scale buildings, neglecting smaller ones such as schools. Ensuring that school buildings are optimised is of utmost importance in providing quality education for future generations. This research specifically focuses on the roof of a school, which is a crucial component of a building for reducing energy consumption and handling thermal loads. Additionally, the research investigates the use of reflective insulation in the elementary school building design prototype to enhance thermal comfort and improve the building's performance. The study's method involved computational modelling, building simulations, and life cycle assessments of the buildings. The findings show that reflective insulation improved thermal comfort more than uninsulated roofs. The white metal roof with glass wool insulation and aluminium foil demonstrated the best indoor operative temperatures of all the roof systems examined. However, this design generated significantly higher embodied carbon emissions due to the thermal insulation. These results highlight the need for a balanced strategy to enhance thermal comfort without producing significant carbon emissions.

KEYWORDS: Carbon Emissions, Indonesia, Operative Temperature, Reflective Insulation, Thermal Comfort.

1. INTRODUCTION

Indonesia has a hot and humid equatorial tropical environment, with little seasonal variations in the weather [1]. Indonesia's average land temperatures are approximately 28°C along the coast, 26°C inland, and about 23°C higher up in the mountains [2]. Indonesia also receives high levels of solar radiation, with an average Global Horizontal Irradiation (GHI) of 4.8 kWh/m^2 per day [3]. As a result, buildings acquire the most heat through radiation rather than conduction or convection, and the majority of heat transfers into buildings occur through the roof. As a result, the roof design must incorporate, ideally, a passive cooling approach, such as reflective thermal insulation. In Southeast Asia, reflective insulation is the most effective type of roof insulation and when comparing reflective insulation-covered roofs to uninsulated roof attics, a reduction in ceiling heat flux of 80% has been observed [4]. The use of reflective and radiative roofs, such as white-coloured roofs, is also recommended as a strategy to improve the thermal performance of buildings [5][6].

However, roof insulation has received inadequate attention from the Indonesian government in terms of building standards and regulations. For example, the roof of an Indonesian elementary school building prototype was designed with just clay tiles and no roof insulation, resulting in diminished thermal comfort inside the classroom throughout the day (Figure 1).

Figure 1: An elementary school building in Jakarta, Indonesia, with clay roof tiles with no insulation. Source: author

2. METHOD

This research evaluated the thermal performance of a prototype elementary school building design based on the Technical Guidelines in the Circular Letter published by the Indonesian Ministry of Public Works and Housing. A comparative analysis was undertaken, using DesignBuilder dynamic thermal simulation software [7], to evaluate the school's performance using different roof insulation configurations. EnergyPlus Weather (EPW) files were specifically generated for the designated location (Jakarta), using the climate software Meteonorm [8]. To assess future thermal performance Meteonorm also generated EPW files for 2050 and 2080 using a Representative Concentration Pathway RCP of 4.5 [9]. Additionally, the study used the life cycle assessment software One Click LCA [10] to evaluate the total (operational and embodied) carbon emissions for each roof option.

3. CASE STUDY – ELEMENTARY SCHOOL BUILDING PROTOTYPE DESIGN

The Indonesian standard school building design prototype employs conventional structural systems, such as on-site reinforced concrete constructions. The school building design standardisation using conventional structures varies based on the type of school. For elementary schools, the design standard for a one-storey classroom is measured at 7m x 8m in plan, with a capacity of 28 students, a total floor area of 56m², and a floor-to-ceiling height of 3.5m [11]. Typically, an elementary school building consists of one or three classrooms with pitched roofs, a connecting corridor in front of the classrooms, and separate building masses for toilets, a library, prayer rooms, and teacher rooms. For a long time, clay tiles with timber trusses have been commonly used as roof construction for school buildings; however, the use of metal roofs with steel trusses is increasing nowadays. The 3D visualisation of the elementary school building design prototype is illustrated in Figure 2. However, for the building simulation, the single classroom building with a clay roof tile is used as the base model.

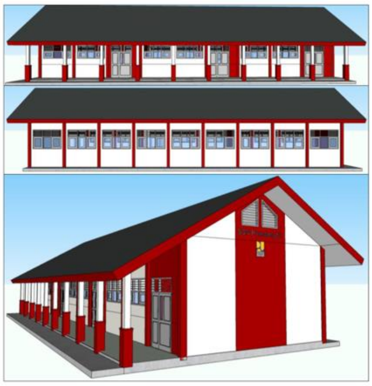

Figure 2: 3D Visualisation of Elementary School Building consists of 3 classrooms based on the prototype design. Source: Technical Guidelines in the Circular Letter published by the Indonesian Ministry of Public Works and Housing.

The roof combinations shown in Table 1 were selected for the school simulations in DesignBuilder after an examination of typical Indonesian school buildings. For each roof simulation, the school model's floor and walls remained unchanged.

3.1 Site Location

Jakarta, Indonesia was chosen as the site location for the building simulation. Jakarta is situated on the northwest coast of Java and has a latitude of -6.13 °N and a longitude of 106.75 °E. It is the largest city in Southeast Asia, one of the world's most populous islands, and serves as the diplomatic capital of the Association of Southeast Asian Nations (ASEAN).

Table 1. Constructional Layers for Building Simulation. Source: DesignBuilder

Case	Roof Constructional Layers	U-Value W/m²K	R-Value m²K/W
1	20mm Clay Tiles Roof	3.226	0.310
2	0.4mm Metal Roof	3.448	0.290
3	0.4mm White Metal Roof,0.8mm Bubble Foil	1.535	0.651
4	0.4mm White Metal Roof,8mm Aluminium Foil,25mm glass wool	0.889	1.125
5	0.4mm White Metal Roof,8mm Aluminium Foil,50 mm rock wool	0.571	1.750

Figure 3: Jakarta is located on Java's northwest coast.

The location was chosen because there is a nearby weather station that ensures accurate and reliable weather data collection. The temperature in Jakarta remains stable year-round, ranging from 27 to 29°C with minimal daily fluctuations. At 9.00 AM, the level of humidity spikes to a high of 88-94%, while at 3.00 PM, it remains uncomfortably high at around 67-77%. It is worth noting that the city's average dew point is approximately 24°C [12].

3.2 Climate Classification

The climate of the site location for the case study is justified using various climate classification sources, which include the ASHRAE and Köppen-Geiger climate maps. The weather files obtained from Meteonorm for use in DesignBuilder classify this case study as belonging to ASHRAE climatic zone 0A, which is classified as very hot and humid. According to the Köppen-Geiger climate classification, the climate of this location is considered a Tropical rainforest (Köppen climate classification: Af). This area has a tropical climate with consistent precipitation of at least 60mm throughout the year, low wind speeds, and an average temperature above 20°C, as per the Köppen-Geiger climate classification. The sun shines from the south for half the year and from the north for the other half [13].

4. SIMULATION RESULT AND FINDINGS

The impact of each roof configuration on the operative temperature was evaluated during the hottest and coldest months, in October, and February, respectively. The energy consumption of this building was simulated in DesignBuilder based on contemporary weather data for only interior lighting since the building is naturally ventilated. Furthermore, the operative temperature was chosen as it represents the average of the mean radiant temperature and ambient air temperatures.

4.1 Temperature Distribution and Comfort

Table 2 shows that, based on current and projected weather data, Case 2 had the highest operative temperatures and Case 4 had the lowest operative temperatures in both the coldest and hottest months.

Table 1. Mean Monthly Operative Temperature in the Hottest and Coldest Months, source: DesignBuilder

Case	Contemporary		2050		2080	
	Feb (ºC)	Oct (ºC)	Feb (ºC)	Oct (ºC)	Feb (ºC)	Oct (ºC)
1	27.5	28.7	28.3	29.9	28.8	30.3
2	27.6	28.8	28.4	29.9	28.8	30.4
3	27.0	28.1	27.8	29.2	28.2	29.7
4	26.8	27.9	27.6	29.0	28.0	29.5
5	26.8	28.0	27.6	29.0	28.1	29.5

Moreover, these different roof configurations' impacts on the operative temperature were compared during the hottest and coldest months in February and October, respectively. The results (Table 2, Figure 4, and Figure 5) show that all the insulated roofs (Cases 3, 4, and 5) performed better than the uninsulated roofs (Cases 1 and 2) in keeping a lower indoor temperature for both periods. Therefore, Case 2 had the highest operative temperature and Case 4 had the lowest operative temperature in both the coldest and hottest months based on contemporary and future weather data according to RCP 4.5. The data indicates that Case 5, which utilized 50mm rock wool insulation, exhibited a higher operative temperature than Case 4, which only had 25mm glass wool insulation.

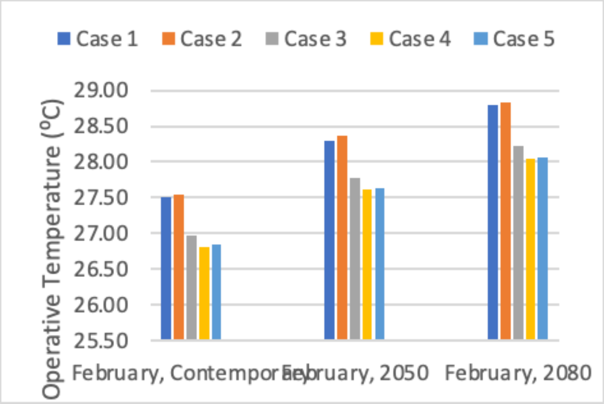

Figure 4: Comparison of the Mean Operative Temperature in February (the coldest month) based on the current and projected weather data. Source: DesignBuilder.

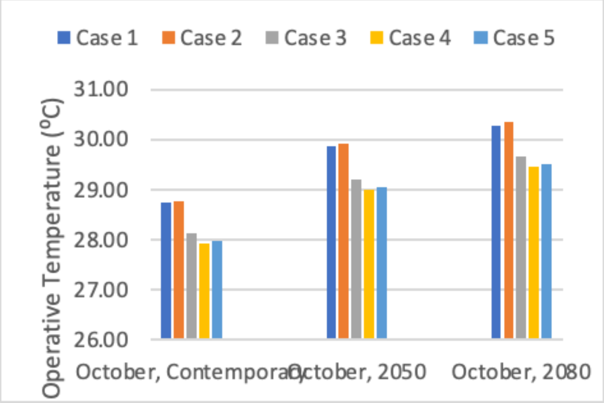

Figure 5: Comparison of The Mean Operative Temperature in October (the hottest month) based on the current and projected weather data. Source: DesignBuilder.

4.2 Overall Life Cycle Assessment

The carbon emissions of the buildings in this section were comprehensively analysed throughout their life stages using the life cycle assessment software in One Click LCA for the contemporary climate. It consists of embodied carbon energy from materials (A1-A3), transportation (A4), construction (A5), energy for maintenance and replacement (B1-B5), operational energy use (lighting only) (B6), and carbon emissions at the end of life (C1-C4). The carbon emissions levels of the building under study using One-Click Life Cycle Assessment software were based on Embodied Carbon Benchmark CH Q3 2021 Global - primary school since there is currently no specifically established benchmark for elementary school buildings in Indonesia. The embodied carbon benchmark results showed that Case 1 building, classed A had 245 $KgCO_2e/m^2$ of greenhouse gas emissions, and Case 2 in. class B, had 259 $KgCO_2e/m^2$ of emissions. On the other hand, Cases 3, 4, and 5 were in class C with 312 $KgCO_2e/m^2$, 316 $KgCO_2e/m^2$, and 320 $KgCO_2e/m^2$ of emissions, sequentially. A summary of the global warming emissions in the life cycle stages is presented in Table 3.

Table 3. Global Warming Life Cycle Stages. Source: One Click LCA

Case	**Global Warming Life Cycle Stages ($KgCO_2e$)**					
	A1-A3	A4	A5	B1-B5	B6	C1-C4
1	11,362	242	792	1,835	93,135	284
2	12,191	241	902	1,835	93,734	263
3	15,136	245	1,123	1,835	91,278	272
4	15,349	245	1,140	1,835	91,200	272
5	15,546	245	1,156	1,835	91,120	273

A building's life cycle evaluation examines every aspect of the building, including the materials, use, energy use, and end of life. Since this study was limited to the configurations of roof materials, Figure 6 examines the effects of these components on roof elements exclusively. Therefore, the Embodied Carbon of the buildings based on building elements is illustrated in Figure 7. Embodied carbon is the total impact of all greenhouse gas emissions related to a material's life cycle, from its extraction and manufacturing through its end-of-life phases. It is also known as Global Warming Potential (GWP) and is measured in kilogrammes of Carbon Dioxide Equivalent ($KgCO_2e$). The following are included in the calculation of embodied carbon: material extraction (module A1), transport to manufacturer (A2), manufacturing (A3), transport to site (A4), construction (A5), use phase (B1), maintenance (B2), repair (B3), replacement (B4), refurbishment (B5), deconstruction (C1), transport to end of life facilities (C2), processing (C3), and disposal (C4). Therefore, Case 1 had the lowest potential for global warming, while Case 5 had the highest potential for global warming, as shown by Figures 6 and 7.

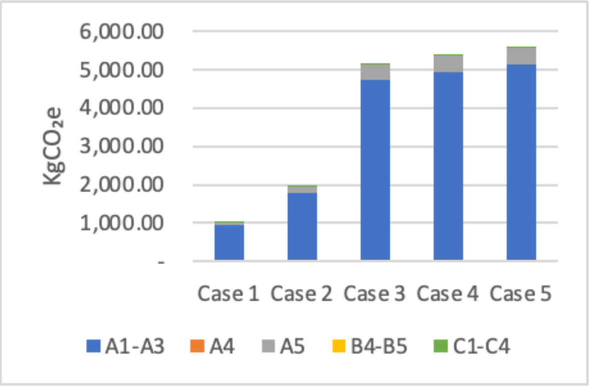

Figure 6: Life Cycle Assessment - Global Warming Potentials (Roofs Only). Source: One Click LCA

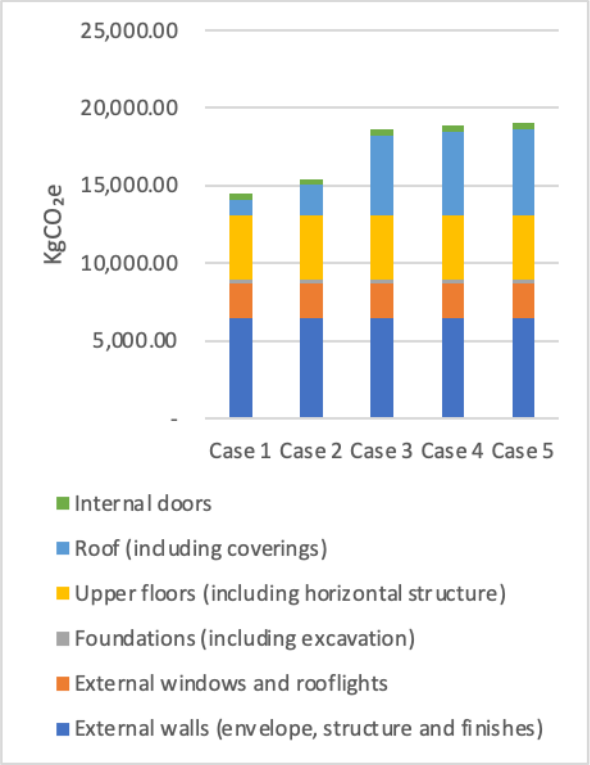

Figure 7: Embodied Carbon based on Building Elements. Source: One Click LCA

5. COMPARATIVE ANALYSIS AND DISCUSSION OF RESULTS

5.1 Indoor Thermal Comfort

The thermal comfort of school buildings is not explicitly regulated in Indonesia. However, earlier thermal comfort studies conducted in Indonesia, demonstrated that citizens of significant cities like Jakarta felt comfortable at air temperatures of 27.7 °C [14]. Therefore, the 27.7 °C temperature was chosen as the upper-end value of the comfort range for the thermal discomfort hours assessment.

Furthermore, as shown in Table 4, Case 2 had the largest percentage of discomfort hours for both current and future climates, while Case 4 had the lowest. Inserting thermal insulation, resulted in a considerable reduction in overall discomfort hours.

Table 4. Annual Discomfort Hours of the Case Study, source: DesignBuilder

	Contemporary		**2050**		**2080**	
	Hours at or above 27.7 °C					
Case	Hours	%	Hours	%	Hours	%
1	829.1	49.3	1009.3	60.1	1097.5	65.3
2	837.6	49.9	1018.3	60.6	1105.1	65.8
3	743.2	44.2	933.7	55.6	1031.3	61.4
4	712.4	42.4	905.2	53.9	1006.0	60.0
5	718.6	42.8	912.0	54.3	1012.9	60.3

5.2 Life Cycle Assessment

Following the overall life cycle assessment in section 4.2, it has been determined that Case 5 registered the highest total carbon emissions (operational and embodied) with 110,177 $KgCO_2e$, based on current weather data. It was followed by Case 4 with 110,042 $KgCO_2e$ and Case 3 with 109,890 $KgCO_2e$. Conversely, Case 1 marked the lowest total carbon emissions with 107,651 $KgCO_2e$, followed by Case 2 with 109,167 $KgCO_2e$. Notably, despite having lower total carbon emissions, Cases 1 and 2 consumed more energy (B6) when compared to Cases 3, 4, and 5.

Furthermore, based on Figure 8, it was observed that Case 1 emitted the least total carbon emissions in both current and projected years, while Case 5 had the highest total carbon emissions in current years, and Case 3 produced the most total carbon emissions in 2050 and 2080. However, it was found that Case 2 produced the highest B6 emissions for both current and projected years.

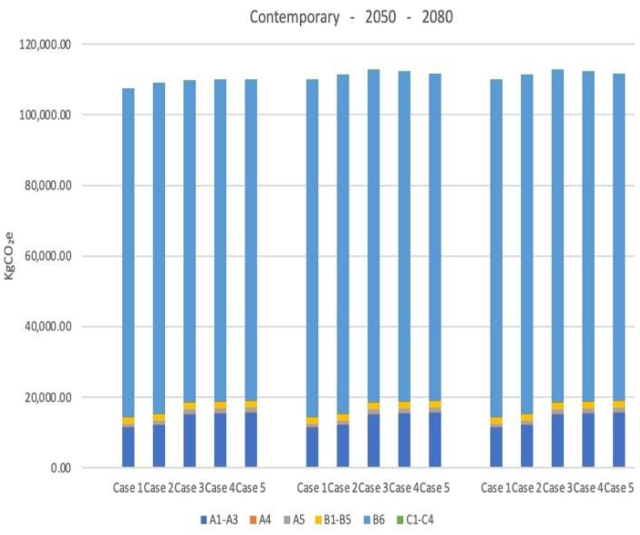

Figure 8: Total Carbon Emissions (embodied and energy) based on Current and Projected Weather Data. Source: DesignBuilder and One Click LCA.

Therefore, this study highlights that electricity generation poses the most significant potential for global warming, consuming no less than 83% of energy across all analysed roof configurations. Apart from electricity, external wall materials (envelope, structure, and finishes), foundations, and roof materials contribute significantly to global warming. Other materials, such as mortar and roof insulations, also have high emission levels. The material contributions to global warming rely on the building's roof system and the amount of material used in the building.

6. CONCLUSION

As analysed using a school case study with contemporary and future weather data, Case 4 provided better thermal comfort than uninsulated roofs. It was found that a building with white metal roofs and glass wool foil (Case 4) had an average of about 53.88% hours above the comfort temperature of 27.7^{o}C, while the base model with clay roof tiles without insulation (Case 1) had 60.08%. A building with the uninsulated metal roof (Case 2) had approximately 60.61% above the same temperature benchmark. In terms of carbon impact, Case 4 had 4,327 $KgCO_2e$ higher embodied carbon than Case 1 which had the least carbon impact on the environment. However, it is essential to note that if the building is designed to install mechanical cooling, Case 1 may not be the most energy-efficient option since it would have a higher energy consumption than Case 4. Case 4 can be a better choice in terms of reducing energy consumption and its impact on global warming. Overall, these findings highlight the importance of a balanced strategy to improve comfort without producing significant carbon emissions.

Moreover, according to the analysis performed using a case study, Case 4 had the roofing that is most suitable for buildings housing elementary schools in tropical regions. The roof configuration for Case 4 consists of a 0.4mm white metal roof, a 10mm higher air cavity, 4mm of aluminium foil, 25mm of glass wool, 4mm of aluminium foil, and 50mm of lower air cavity, which used reflective insulation and radiant barrier as thermal insulation technologies for energy efficiency. As per the findings in Section 4.1, it is observed that 25mm glass wool insulation performed better than 50mm rock wool insulation in building simulation. This suggests that thicker insulation may not be appropriate for this type of building. Consequently, radiant heat transmission was more effectively prevented by thermal insulation that uses reflecting technology, such as radiant barriers and reflective insulation, which employs a very thin coating of low-emittance aluminium foil [15] which is applied on the Case 4 roof configuration. Shrestha and Rijal also discovered that using Glass Wool insulation can reduce the operative temperature of a building by 2°C. [16]

Therefore, based on the overall building life cycle assessment using One Click LCA for the current climate, it is evident that Case 5 is the least sustainable building option. It had approximately 19,056 $KgCO_2e$ of embodied carbon. On the other hand, Case 1 (the base model) is the most environmentally friendly choice, with 14,515 $KgCO_2e$ of embodied carbon. As for the other cases, Case 2 had 15,433 $KgCO_2e$ of embodied carbon, Case 3 had

18,612 $KgCO_2e$ of embodied carbon, and Case 4 had 18,842 $KgCO_2e$ of embodied carbon.

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