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Vegetation and Cool Materials on Building Envelopes: Impacts on Indoor Temperature and Energy Use in Indonesian Tropical Residential Buildings

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Abstract: 'Green' and 'cool' building envelopes, which integrate vegetation and reflective materials on the roof and external walls, are recognised as effective solutions to mitigate overheating on the building and city scale. This study aims to assess the impact of these adaptations on residential buildings in the equatorial zone of East Kalimantan, Indonesia, which is characterised by high temperature and solar radiation year-round. Using DesignBuilder, this study compares green and cool strategies for roofs and walls across different building archetypes. Although the magnitude was low, results indicate that roof adaptations generally outperform wall adaptations in reducing indoor temperatures and cooling energy use. Among adaptations assessed, cool roofs exhibited the highest cooling potential. Differences in roofing systems influence the resulting daily cooling patterns. However, as the complexities increase, the cooling benefit of all adaptations becomes less pronounced. This research underscores the importance of sustainable building design in addressing climate change challenges in Indonesia.

Keywords: Overheating, Building Envelope, Tropical Climate, Indonesia

1. Introduction

The rise in global temperatures due to climate change significantly heightens the risk of overheating, particularly in urban areas where the Urban Heat Island effect is pronounced. Given that most time is spent indoors, prolonged exposure to elevated temperatures poses health risks and even mortality. Tropical countries like Indonesia are susceptible to overheating due to their continuous exposure to intense solar radiation and high temperatures year-round. This situation has led to a surge in demand for air conditioning (AC), which contributes to increased outdoor temperatures due to waste heat. As Indonesia develops its new capital in East Kalimantan, an equatorial region, it is imperative for buildings to implement strategies that mitigate overheating and minimise environmental impact.

Other than mitigating UHI, previous research has identified the use of "cool materials" and greenery elements in building envelopes as an effective solution for reducing internal heat loads. A green envelope is a building surface covered with vegetation, while a cool roof/wall is made from or coated with materials that have a solar reflectance (SR) value greater than 0.75. Studies in Southeast Asia indicate that green roofs can reduce energy consumption by up to 50% and lower indoor temperatures by 3-14°C (Pratama et al, 2023). However, other studies argue that cool roofs offer a more cost-effective solution to overheating (Sproul et al, 2014). Previous cool roofs in Indonesia and Singapore have been observed to reduce peak midday temperatures by up to 3°C (Zingre et al, 2015; Lapisa et al, 2019). In Indonesia, where lightweight materials such as metal roofing are prevalent, the structural demands of green roofs pose significant challenges. Therefore, assessing the cooling impact of cool roofs and green roofs is crucial to offer a different perspective.

With ongoing population growth and limited land availability, the demand for vertical housing is increasing. In single-story buildings, 70% of heat gain occurs through the roof

(Vijaykumar et al, 2007), whereas in multi-story buildings, external walls become the predominant source of heat transfer. This study compares the impact on indoor temperature and a cooling energy reduction of implementing cool materials and greenery elements on the roofs and walls of two residential building types: a single-detached house with a pitched roof and an eight-story vertical housing unit with a flat roof as illustrated in Figure 1.

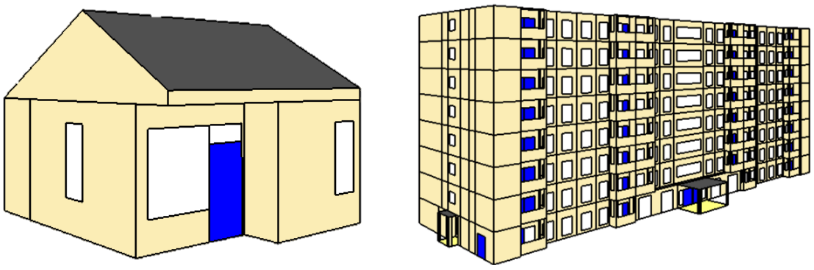

Figure 1 single-detached house (left) and eight-story vertical housing unit (right)

2. Methodology

Building case studies will be modelled under different adaptation scenarios, including green and cool roofs and green and cool facades, and simulated with current weather data relevant to the location using the DesignBuilder. The resulting indoor temperature reductions from the case-studies base-case and cooling energy use will be analysed to identify the most effective solutions. The best-performing adaptation is further simulated using future climate projections to assess its effectiveness under climate change conditions.

To obtain accurate weather data for the study of the planned new capital in North Penajam Paser, East Kalimantan, the weather file from the closest weather station, Balikpapan Sepinggan Airport, was utilised. Detailed information regarding the weather file is provided in the Table 1However, a Different weather file of Samarinda Termindung (Latitude: -0.485, Longitude: 117.157, WMO Station Identifier: 966070) was processed using CCWorldWeatherGen Version 1.9 for future climate projections for the years 2050 and 2080.

Table 1 Case study present-year weather file information

`	:	Balikpapan, Kalimantan Timur
Coordinates	:	Latitude -1.26 Longitude 116.89
Elevation	:	3 m
WMO Identifier	:	966330
Climate Classification	:	Tropical rainforest climate (Af)
Average outdoor dry-bulb temperature	:	27.52°C
Average relative humidity	:	85.54 %
Average monthly wind speed	:	2.18 m/s
Average Daily Direct Solar Radiation Rate	:	338.28 W/m^2

Case studies were selected from prototypes provided by the Indonesian Ministry of Public Works and Housing. Housing units typically feature two bedrooms, a combined living and kitchen area, a bathroom, and a terrace. For this research, the analysis was focused on bedrooms and the living-kitchen area. A detailed breakdown of the case study is presented in Table 2.

Table 2 Building case study information

	Single-Detached House	Vertical Housing
Gross internal area (m^2)	36	7242.81
Number of Units	1	92
Gross area per unit (m^2)	39	52

The base case (BC) building model employs construction materials as detailed in Table 3. Internal gains assumed in the model include occupancy, lighting, and equipment, following the guidelines outlined in CIBSE TM59:2017. A cooling setpoint of 25.8°C and a setback of 27.1°C were used, aligning with the Indonesian national standard SNI 03-6572-2001, which defines the optimal thermal comfort range as 22.8°C to 25.8°C, with 27.1°C as the maximum acceptable upper limit.

Table 3 Building case study construction material

Building Component	Single-Detached House		Vertical Housing	
	Build-up (Thickness (mm))	U-Value (W/m^2K)	Build-up (Thickness (mm))	U-Value (W/m^2K)
Roof	30°-Corrugated Zinc with steel structure (18.5)	3.448	Flat-Reinforced Concrete (194)	2.564
Building Component	Single-Detached House & Vertical Housing			
	Build-up (Thickness (mm))			U-Value
External Walls	Concrete block with plaster (150)			1.104
Partition	Double-sided gypsum plasterboard (124)			1.786
Ground Floor	Concrete slab with ceramic tiles (178)			3.010
Internal Ceiling	Gypsum Plasterboard (9)			3.065
Door	Painted Oak (35)			2.823
Window Glazing	Clear Glass Glazing (3)			5.778

This study assessed five building envelope strategies: base case (BC), green roof (GR), green wall (GW), cool roof (CR), and cool wall (CW), which incorporate changes in the roof and wall materials as shown in Table 4. For GR and GW, the eco-roof setting was adjusted as presented in Table 5 (Gagliano et al, 2016; Poddar et al, 2017)For CR and CW, the surface properties of the outermost material adjusted to a solar absorptance of 0.2 (SR =0.8).

Table 4 Simulation iteration scenario – changes in roof and wall materials

Iteration scenario	Single-Detached House		Vertical Housing	
	Build-up (Thickness (mm))	U-Value (W/m^2K)	Build-up (Thickness (mm))	U-Value (W/m^2K)
Green Roof (GR)	9.5°-Corrugated Zinc with extensive green roof (95.85)	1.421	Flat-reinforced concrete with extensive green roof (461.35)	0.951
Cool Roof (CR)	30°-Cool-coated Corrugated Zinc (18.5)	3.448	Flat-Cool-coated Reinforced Concrete (194)	2.564
Building Component	Single-Detached House & Vertical Housing			
	Build-up (Thickness (mm))			U-Value
Green Wall (GW)	Concrete block with plaster and indirect green facade (150)			0.836
Cool Wall (CW)	Cool-coated Concrete block with plaster			1.104

Table 5 Eco-roof setting for green wall and green roof in both case studies

Eco-roof setting	Green Roof (GR)	Green Wall (GW)
Height of Plants (m)	0.35	0.2
Leaf area index (LAI)	5	2.78
Leaf reflectivity	0.25	0.22
Lead emissivity	0.95	0.95
Minimum stomatal resistance (s/m)	180	180
Max Volumetric Moisture at saturation	0.5	0.5
Min residual volumetric moisture content	0.01	0.01
Initial volumetric moisture content	0.5	0.15

Indoor temperature analysis will focus on one housing unit with two bedrooms and one living-kitchen area during the summer design week of each weather file: October 8th-11th in

Balikpapan Sepinggan and November 5th-11th in Samarinda Termindung. Additionally, Annual cooling energy savings per square meter will be compared for the entire building.

3. Result and Discussion

3.2 Present-year

Simulation results indicate that single-detached and ground-floor vertical houses can generally maintain thermal comfort, although single-detached houses may cause discomfort during peak outdoor temperatures, as illustrated in Figure 2. Higher floors are more prone to overheating, as demonstrated in previous studies (Sharifi et al, 2019), due to hot air rising and accumulating under the roof.

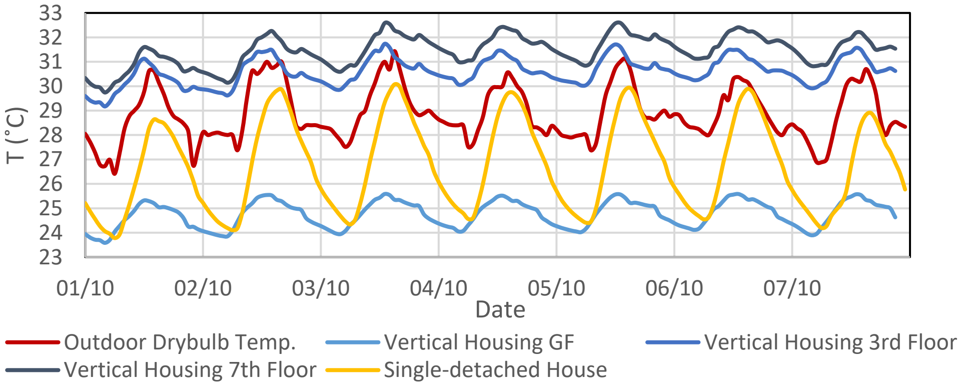

Figure 2 Average base case indoor temperature of two building case study

A comparison of average temperature reductions across different iteration scenarios revealed relatively modest decreases, ranging from 0.02°C to 1.33°C and, in one case, a modest increase of -0.03°C and -0.05°C as shown in Table 6. The results indicated that roof adaptations induced more substantial temperature reductions compared to wall adaptations despite the larger external wall area of vertical housing. This can be attributed to the sun's near-perpendicular position relative to the roof surface, resulting in minimal direct solar exposure on the walls. Despite the noticeable impact of wall adaptations on ground-floor vertical housing, roof adaptations provided a more substantial overall cooling effect, as presented in Table 6.

Table 6 Average temperature reduction due to adaptations relative to BC

Case studies		Average Temperature Reduction to BC (°C)			
		GR	GW	CR	CW
Single-detached House		0.62	0.14	0.70	0.48
Vertical Housing	Ground Floor	0.00	0.04	0.00	0.07
	Third Floor	0.02	-0.03	0.02	0.09
	Seventh Floor	1.09	-0.05	1.33	0.06

Overall, cooling benefits from cool adaptations outperformed green adaptations. Cool roofs exhibited the highest average temperature reduction, while green walls showed a potential for heating the space. The highest outdoor temperature occurred between 14:00-16:00. While both CR and GR effectively reduce peak temperatures, their performance varies by building type and time of day. Single houses with metal roofs benefit more from GR during midday, but CR maintains lower temperatures overall. This is due to GF's thermal properties, which reduce heat absorption, thermal inertia and thermal resistance (Sonne, 2006). Metal roofs caused significant temperature fluctuations, while concrete slab roofs in vertical housing remained relatively stable throughout the day, as shown in Figure 3.

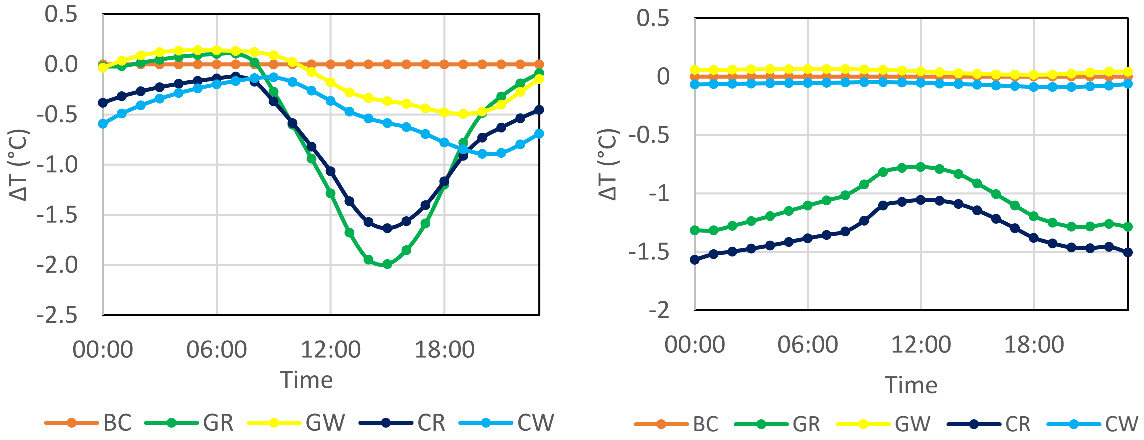

Figure 3 Average summer design week hourly temperature difference single-detached house (left) and Seventh-floor vertical housing (right)

As shown in Figure 4, temperature decreases affect the reductions in cooling demand. A slight difference is observed in cooling energy consumption for single-detached house, where GR exhibit the lowest consumption. This is likely due to reduced temperatures during peak cooling loads. However, limitations such as building model assumptions and simplifications, as well as the cooling load calculation, may not fully capture the actual building performance.

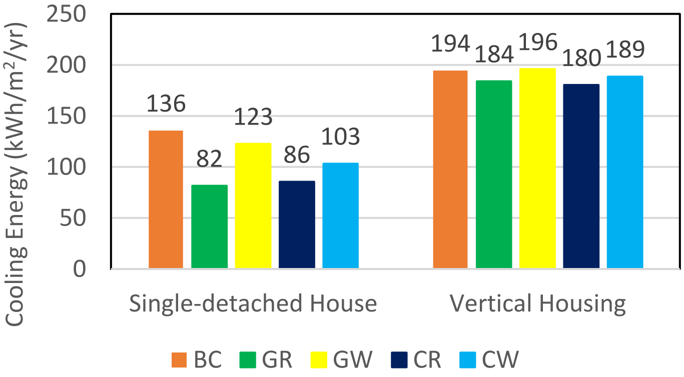

Figure 4 Cooling energy intensity reduction

3.2 Future Climate Projection

CR can effectively reduce indoor temperatures, lowering them by an average of 0.75°C in single houses and 0.26°C in vertical housing. However, their cooling benefits decrease with rising outdoor temperatures due to climate change. Compared to the base case without any envelope adaptations, cooling energy savings from CR are projected to reach 24% and 7% in 2050 and 20% and 6% in 2080 for single-detached and vertical housing, respectively, as shown in Figure 5. While the result shows that the direct effect of roof adaptation, particularly CR, on the indoor temperature in future climate projections is relatively low, previous studies demonstrated its advantage in modulating outdoor temperature. Elnabawi and Saber, (2023) demonstrated that CR slightly outperforms GR in regulating pedestrian-level microclimate in a hot climate, while Brousse et al, (2024) exhibits its potential to reduce city-scale outdoor temperature.

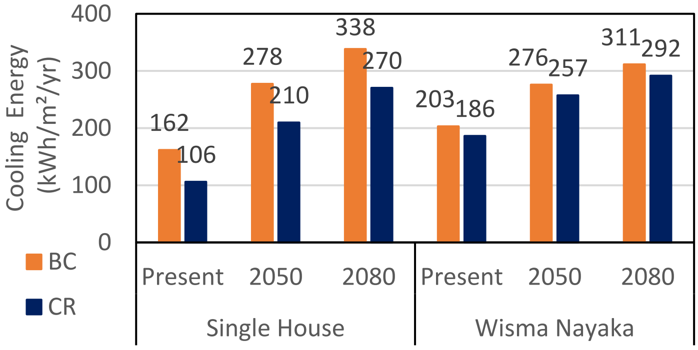

Figure 5 Cooling Energy Intensity Difference between BC and CR in Future Climate Change Projection

4. Conclusion

This study aimed to investigate the impact of adding vegetation and reflective materials on the roof and walls of a residential building in Indonesia using computer simulations. Although the magnitude was low, results indicate that roof adaptations generally outperform wall adaptations in reducing indoor temperatures and cooling energy use. Among adaptations assessed, cool roofs exhibited the highest cooling potential. Differences in roofing systems influence the resulting daily cooling patterns. However, as the complexities and climate change intensify, the cooling benefit of all adaptations becomes less pronounced. This study's limitation is that simulations may not reflect real-world performance. Future research should validate results with real buildings in the same climate conditions.

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