Evaluation of various passive cooling solutions in decarbonizing the Indonesian residential building sector in tropical climates

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Abstract. The buildings sector in Indonesia is dominated by homes—the number of which has been growing rapidly to meet population-driven demand. However, most buildings built over the past four to five decades lack adequate natural ventilation and other passive cooling measures suited to tropical climates and rely at least partly on air-conditioning. This study focuses on a parametric analysis of passive and low-energy "whole-building" cooling solutions for the tropical climate of Indonesia, evaluating the benefits of 12 passive or low-energy cooling solutions: solar-reflective "cool" roofs, cool walls, insulated roofs, insulated walls, low thermal-emissivity ("low-E") windows, solar-control window films, ceiling fans with temperature setback, ceiling fans without temperature setback, exterior window shades, interior window shades, natural ventilation based on schedule and outside air temperature, and natural ventilation based only on outside air temperature. Results indicate that a ceiling fan with thermostat setback (raising the cooling setpoint to 28.1 °C from 25 °C while maintaining constant thermal sensation) provided both the highest nationwide electricity savings and the highest net present value for households, followed by insulated walls, insulated roofs, and cool walls.

Keywords: tropical climates; passive cooling; low energy; cool roofs and walls; decarbonization

1. Introduction

Indonesia stands as the largest energy producer and consumer in Southeast Asia, representing more than 36% of the region's energy demand. In 2021, the energy consumption of buildings in Indonesia accounted for 4.9% of direct CO_2 emissions, with residential buildings contributing to over 90% of the direct CO_2 emissions within the building sector [1]. The residential and commercial sectors accounted for 41% and 21.9% of the electricity consumption, respectively. Given the potential for electricity demand to double by 2040, coupled with rapid urban expansion, the role of energy efficiency and urban house planning in cities is increasingly critical. To address this challenge, Indonesia has been implementing building energy efficiency codes and standards, focusing mainly on commercial buildings since 2010. In late 2018, Indonesia introduced new minimum energy performance standards (MEPS) and energy efficiency labels for residential air conditioning, with a progressive increase to an energy efficiency ratio (EER) of 2.92 W/W after July 2020. Nevertheless, the rising adoption of residential air conditioning is expected to significantly increase electricity demand for cooling in the coming decades. On the other hand, most buildings built over the past four to five decades lack adequate natural ventilation (NV) and other passive cooling measures suited to tropical climates and rely at least partly on air-conditioning. Considering the growing urban space of Indonesia, extending low-energy and passive cooling solutions for residential buildings will be an important intervention in reducing emissions from the building sector.

This study focuses on a parametric analysis of passive and low-energy "whole-building" cooling solutions for low-to-moderate income (LMI) households in the tropical climate of Indonesia, evaluating the benefits of 12 passive or low-energy cooling solutions [2]: solar-reflective “cool” roofs [3], cool walls [4], insulated roofs, insulated walls, low thermal-emissivity (“low-E”) windows, solar-control window films, ceiling fans with temperature setback, ceiling fans without temperature setback, exterior window shades, interior window shades, natural ventilation based on schedule and outside air temperature, and natural ventilation based only on outside air temperature. The main objectives of this parametric simulation study are to

- Develop a prototype model for LMI homes in Indonesia and other Southeast Asia countries
- Evaluate and compare the performance of individual and packaged passive cooling solutions using energy and thermal comfort metrics
- Quantify the absolute and relative electricity consumption savings for cost-benefit analysis of each cooling solution

The remainder of this paper is structured as follows. Section 2 describes the prototype residential building model, passive and low-energy “whole-building” cooling solutions, as well as the design of the parametric simulation framework. Section 3 presents a summary of the parametric simulation results. Section 4 concludes the performance of passive cooling solutions for low-income homes and outlines the next step of work toward their market adoption in both new construction and retrofits of existing households.

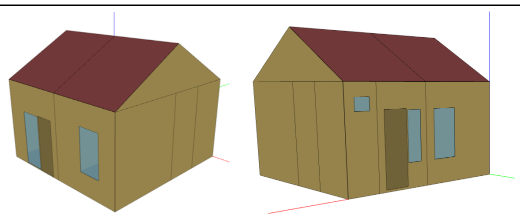
2. Methodology

In this study, we used the building simulation software platform EnergyPlus® to model the annual hourly energy use and internal temperatures of a 36 m² floor area, single-story LMI household (living room, kitchen, bathroom, two bedrooms, attic) in four locations: Balikpapan (East Kalimantan), Jakarta, Padang (West Sumatra), and Waingapu (North Maluku). A total of 12 passive or low-energy cooling solutions have been chosen for energy-savings evaluation through parametric simulation runs. These solutions are categorized into building envelopes, glazing systems, ceiling fans with smart thermostats, and natural ventilation.

2.1. Building prototype characteristics

Table 1 presents a summary of the model descriptions for LMI homes. A typical LMI residential house has a floor area of 30-40 m^2, featuring a compact layout that includes a living room, kitchen, bathroom, and bedrooms. Each house has its own front and back yards and shares adjacent walls with neighbors (these are not included in the model). Windows are located on both the front and back facades, accounting for approximately 20% of the window-to-wall ratio. The baseline model has no awnings or shading devices.

Table 1. Low-middle income home description.

Building parameters	Descriptions
Total floor area	36 m^2
Building shape	
Number of floors	1
Window-to-wall ratio	North: 18%, South: 23%
Window locations	Front and back
Shading geometry	None
Orientation	Front of the house faces south, west, north, or east

Thermal zoning	The house is divided into seven thermal zones
Floor-to-ceiling height	3.4 meters

Table 2 outlines the specific model parameter inputs, which include the layer-by-layer construction of the building envelope, infiltration rates, internal loads, and HVAC systems (the air conditioner [AC] type, cooling coefficient of performance [COP], and thermostat cooling setpoint). To the best of our knowledge, these input values accurately reflect the current state of building structures and cooling features found in LMI homes in Indonesia.

Table 2. LMI residential prototype model inputs.

Category	Component	Description	Value
Envelope	Exterior Wall	100 mm brick/plaster board	U-Factor: 3.57 W/m²K
	Roof	Clay tile/metal decking	U-Factor: 3.48 W/m²K
	Ceiling	19 mm gypsum board	U-Factor: 2.59 W/m²K
	Partition Wall	Plasterboard	U-Factor: 2.58 W/m²K
	Ground Floor	100 mm concrete	U-Factor: 4.67 W/m²K
	Window	Single pane clear glass	U-Factor: 4.98 W/m²K SHGC: 0.70 Visible transmittance: 0.70
Infiltration	Air Changes per Hour (ACH)	Bedroom #1	4.8
		Bedroom #2	6.9
		Living room	3.0
		Kitchen/dining room	3.0
Internal Loads	People (Number)	Bedroom #1	2
		Bedroom #2	1
		Living room	3
		Kitchen/dining room	3
	Lighting Power Density	Bedroom #1 (W/m²)	3
		Bedroom #2 (W/m²)	3
		Living room (W/m²)	5
		Kitchen/dining (W/m²)	5
	Equipment Power Density	Bedroom #1 (W/m²)	10
		Bedroom #2 (W/m²)	5
		Living room (W/m²)	15
		Kitchen/dining room (W)	90
	Gas Range	Kitchen/dining room (W)	540
HVAC	Cooling System	Mini-split air conditioners	Single speed
	Capacity	Cooling sizing factor	1.15
	Efficiency	Coefficient of performance (COP)	2.5
	Thermostat	Cooling setpoint (ºC)	25
Domestic Hot Water	Water Heater	N/A	N/A

2.2. *Passive cooling solutions*

International Energy Agency Energy in Buildings and Communities (IEA EBC) Annex 80 provides comprehensive guidelines for resilient low-energy and low-carbon cooling systems in buildings [5]. We have selected the following cooling solutions as suitable for LMI homes in tropical climates.

- Cool roof and cool wall

    - Baseline: Existing roofs and walls with a medium-brightness color (long-term solar reflectance 0.25).
    - Cooling solution: Apply white coatings with higher long-term solar reflectance (0.40 or 0.60) to roofs and walls.
- Insulated roof and insulated wall
    - Baseline: No insulation layer in existing building envelope.
    - Cooling solutions: Install radiant barriers (e.g., aluminum foil or insulated radiant panels) in attics to reduce ceiling radiant heat gains, and add insulation layers in roofs and exterior walls.
- Window glazing
    - Baseline: Single-pane clear glass (U-value: 4.98 $W/m^2{\cdot}K$; solar heat gain coefficient [SHGC]: 0.70) in existing windows.
    - Cooling solutions: Replace with double low-emissivity (low-E) windows to lower both U-value and SHGC, or apply solar-control window films to existing windows to reduce SHGC while potentially affecting visual comfort due to decreased visible transmittance.
- Exterior and interior shades
    - Baseline: No exterior or interior shading devices.
    - Cooling solutions: Install awning or a high-performance exterior screen (e.g., white screen with 1% openness factor) to reduce solar heat gain, and add interior shades (e.g., a slat-type shading device).
- Low-energy air circulation or passive ventilation
    - Baseline: Use of air conditioning for thermal comfort.
    - Cooling solutions: Use ceiling fans, with or without integrated thermostat control, to achieve equivalent thermal comfort levels through increased air movement and reduce air conditioning use by adjusting cooling setpoints. Encourage opening windows to enable single-sided, cross-, and stack-ventilation effects during cooler nights or any time of the day.

Table 3 presents detailed parameters for baseline and proposed cooling solutions. We categorize passive cooling solution level #1 as standard and level #2 as a deep retrofit.

Table 3. Model inputs of baseline and proposed cooling solutions.

Cooling Solutions	Model Parameters	Baseline	Level #1	Level #2
Cool Roof	Solar Reflectance (-)	0.25	0.40	0.60
Cool Wall	Solar Reflectance (-)	0.25	0.40	0.60
Insulated Roof[a]	Additional Layer Thermal Resistance ($m^2{\cdot}K/W$)	N/A	0.176 (R-1)	2.55 (R-12.3)
	Bottom-of-Insulation Thermal Emittance (-)	N/A	0.04	0.04
Insulated Wall	Insulation Layer Thickness (m)	N/A	0.025 (R-5)	0.075 (R-13)
Low-E Window	U-value ($W/m^2{\cdot}K$)	4.98	3.41	2.27
	SHGC	0.70	0.30	0.20
	Visible Transmittance	0.70	0.48	0.40
Solar-control Window Film	U-value ($W/m^2{\cdot}K$)	4.98	4.98	4.98
	SHGC	0.70	0.49	0.30
	Visible Transmittance	0.70	0.52	0.31
Ceiling Fan	Cooling Thermostat Setpoint (°C)	25.0	26.9	28.0
	Air Speed (m/s)	0.1	0.4	0.8
Awning	Awning Depth (m)	N/A	0.5	0.5
	SHGC	0.70	0.70	0.10
	Visible Transmittance	0.70	0.70	0.09
Exterior Shade	U-value ($W/m^2{\cdot}K$)	4.98	2.64	N/A
	SHGC	0.70	0.13	N/A

	Visible Transmittance	0.70	0.09	N/A
Interior Shade	Slat Solar Reflectance (-)	N/A	0.1	0.8
NV Day and Night	Window Open Area Fraction	0.0	0.5	1.0
NV Night Only	Window Open Area Fraction	0.0	0.5	1.0

[a] The Insulated Roof measure affixes insulation to the underside of the roof deck.

2.3. *Parametric simulation framework and scenarios*

In the parametric simulation, the EP-Macro tool within EnergyPlus is utilized to define model parameters and assign their values during the pre-processing of energy models. Following the completion of batch runs for all EnergyPlus models, a series of Python scripts is deployed to process the outputs from EnergyPlus, producing summaries and graphical representations of the results. Table 4 outlines the scenarios examined in this study, considering factors such as location, orientation, air conditioning usage, and cooling solutions.

Table 4. Parametric simulation scenarios.

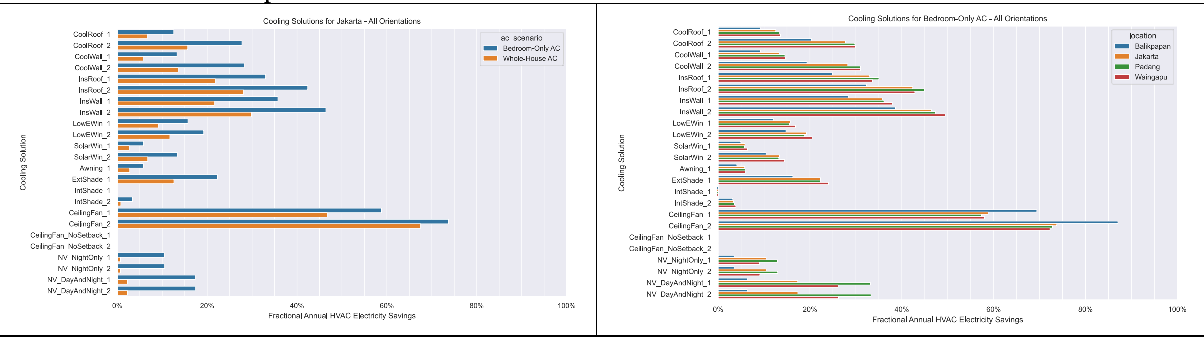
Category	Scenario	Description
Location	Balikpapan, Jakarta, Padang, Waingapu	Selected representative cities
Orientation	South, West, East, North	Front house facing direction
Air conditioning	Bedroom-Only AC	Two bedrooms, 9 pm-5:30 am, cooling setpoint 25 °C
	No AC	No AC installed
	Whole-House AC	Whole house except bathroom, 24/7, cooling setpoint 25 °C
	Whole-House AC 12h	Whole house except bathroom, 6pm-6am, cooling setpoint 25 °C
Cooling solutions	Building envelope	Cool wall, cool roof, insulated wall, insulated roof
	Glazing	Low-e window, solar-control window film, exterior shade, interior shade, awning over the window
	Air circulation or ventilation	Ceiling fan, natural ventilation

3. Results

In this section, we evaluate the effectiveness of the suggested passive cooling strategies through the key performance indicators (KPIs) related to energy usage and thermal comfort. Energy-related KPIs include both the absolute savings in annual electricity consumption, measured in kilowatt-hours (kWh), and the percentage reduction in annual electricity use compared to the baseline. The absolute savings KPI is calculated as the average HVAC electricity savings across models with south, west, east, and north orientations. The fractional saving KPI is calculated by dividing the absolute savings by the average baseline HVAC electricity consumption. For thermal comfort, KPIs focus on the occupancy- and thermal sensation scale unit (TSSU)-weighted discomfort exceedance hours, as outlined in ASHRAE Standard 55-2020. Discomfort-weighted exceedance hours is the sum of the positive values of (Predicted Mean Vote [PMV] - threshold) during occupied hours, where PMV is capped at +4. This study uses discomfort-weighted warm exceedance hours, using a threshold of +0.7, as the primary metric for assessing impacts on thermal comfort, expressed in TSSU・h.

3.1. *Building envelope*

Figure 1 displays fractional annual HVAC electricity savings for bedroom-only and whole-house AC scenarios in Jakarta (Figure 1a), and bedroom-only AC in selected locations. Within the building envelope category, insulated roof/walls, cool roof/walls, exterior shades, and low-E windows are the top cooling solutions, capable of yielding annual HVAC electricity savings of 15-45%. Between the cool roof and cool walls, cool walls are more effective for west-facing houses due to the cooling load through exterior walls on the east and west sides. Low-E windows and solar-control window films yield annual HVAC electricity savings of 15-20%, which is about the benefit attainable from opaque-surface (wall and roof) cooling solutions. Although insulated roof level #1 affixes aluminum foil wrap with minimal insulation to the bottom of the roof deck, its low thermal emittance significantly reduces radiant heat gains, achieving annual HVAC electricity savings of 10-35%. These savings are about 80% of those achieved with more expensive foil-faced foam-board insulation.

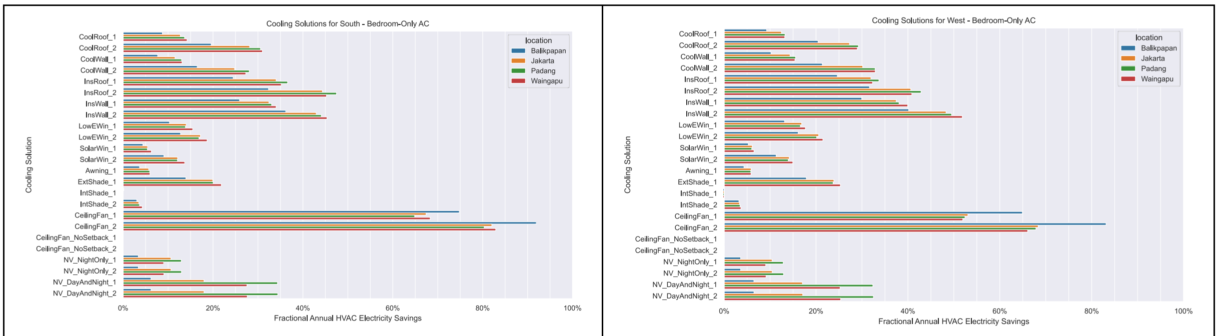


(a) AC scenarios | (b) Locations

Figure 1. Fractional annual HVAC electricity savings by different scenarios.

We propose two AC scenarios in LMI houses: the first installs ACs in bedrooms only, and the second equips the entire house except for the bathroom with ACs. Results indicate that passive cooling solutions implemented in a portion of the house result in higher fractional HVAC electricity savings in the context of bedroom-only AC, when compared to running the full house AC 24 hours. Natural ventilation can potentially save up to 20% of bedrooms' HVAC electricity consumption (9 pm - 5:30 am) due to high indoor and adjacent space temperatures when the AC unit starts.

Figure 2 depicts fractional annual HVAC electricity savings of exterior and interior shading devices for south-facing (Figure 2a) and west-facing (Figure 2b) houses respectively for the bedroom-only AC scenario. High performance exterior shade yields annual HVAC electricity savings of 16-24%. Compared with Interior Shade #1 (interior shade with low solar reflectance), Interior Shade #2 (interior shade with high solar reflectance) is preferred for both south- and west-facing houses, yielding annual HVAC electricity savings of 5%. Interior Shade #1 (interior shade with low solar reflectance) performs poorly in reducing HVAC electricity consumption due to the increased radiation heat gains. Interior shades with low solar reflectance can absorb more solar energy, increasing their surface temperature and radiating heat into the occupied space. Compared to interior shade #2, "Awning on windows" yields similar HVAC electricity savings (5-8%) for both south- and west-facing houses across all locations.



(a) South facing | (b) West facing

Figure 2. Fractional annual HVAC electricity savings for bedroom-only AC scenario in Jakarta.

3.2. *Low-energy air circulation (ceiling fans) and passive ventilation*

Air movement save energy in an air-conditioned space by maintaining occupant comfort at higher indoor air temperatures. Increasing indoor temperature can reduce a building's overall HVAC energy consumption by approximately 5-10% per degree Celsius, with variations depending on climate [6]. As depicted in Figure 1b, the use of ceiling fans equipped with integrated thermostat control can decrease annual HVAC electricity consumption by 56-87%. The use of ceiling fans has been a common cooling practice in LMI homes in Indonesia, and the results confirm their deployment as the most effective low-energy cooling strategy, with air conditioners serving as a secondary cooling option. Additionally, under conditions of cool outdoor air temperatures and suitable wind conditions, natural ventilation through operable windows can effectively create air movement and flush out warm air from the house. Regarding operation, natural ventilation can be twice as effective when windows are opened based on outside air temperature rather than according to a schedule. As described above, the effectiveness of natural ventilation is highly dependent on the local climatic conditions. Natural ventilation can yield annual HVAC electricity savings of 26-33% in the Padang and Waingapu areas.

3.3. *Thermal comfort impact*

Figure 3 compares occupancy- and TSSU-weighted warm discomfort exceedance hours in different AC scenarios. A whole-house AC system yields the fewest baseline occupancy- and TSSU-weighted warm discomfort exceedance hours when compared to other AC scenarios, and a south-facing orientation is preferred in the four locations.

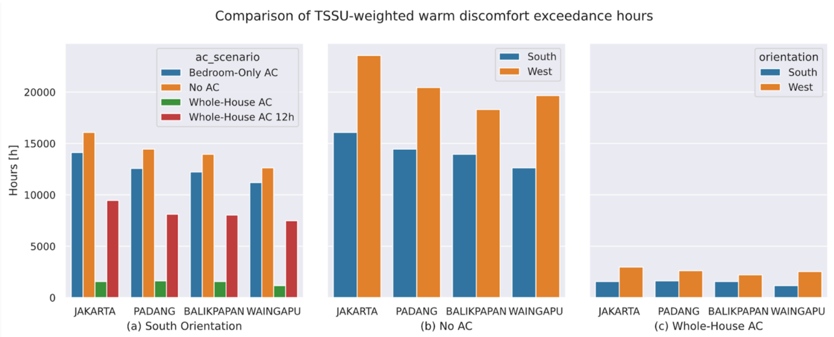


Figure 3. Comparison of occupancy- and TSSU-weighted warm discomfort exceedance hours by different scenarios.

Most passive cooling solutions can reduce the occupancy- and TSSU-weighted discomfort exceedance hours while saving HVAC electricity consumption to varying degrees, except for "Natural Ventilation by opening windows". For the bedroom-only AC scenario, as depicted in Figure 4, the performance leaders in the fractional reduction of occupancy- and TSSU-weighted discomfort exceedance hours are ceiling fan, insulated roof, insulated wall, cool roof, cool wall, and low-e window, with reductions ranging between 20% and 60%.

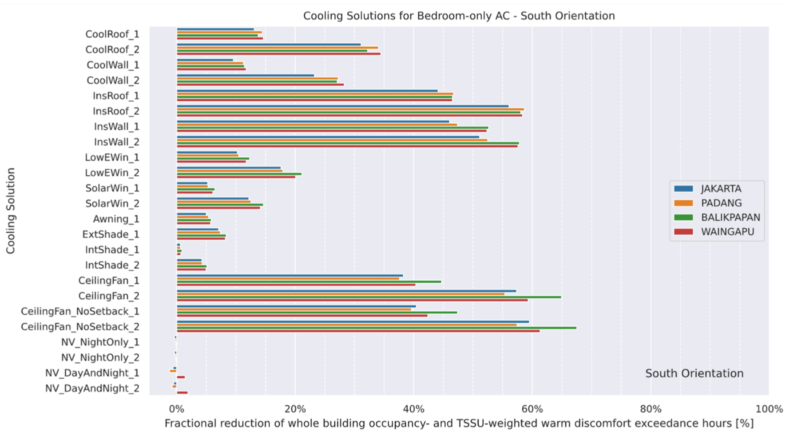


Figure 4. Fractional reduction of whole building occupancy- and TSSU-weighted warm discomfort exceedance hours.

4. Conclusion and Next Steps

In this study, we developed a prototype model tailored for LMI homes in Indonesia. The parametric simulation framework introduced here enables the evaluation of individual or combined passive cooling solutions, offering a valuable tool for others conducting similar research. Our findings show that insulated and cool roof/walls yield annual HVAC electricity savings of 15-45% for the bedroom-only AC scenario. High performance exterior solar screen shade yields annual HVAC electricity savings of 16-24%. Low-E window and solar-control window film can be very effective in homes with large window-to-wall ratios. In the context of low-energy air circulation and passive ventilation, ceiling fan is the most effective low-energy cooling strategy, with air conditioners serving as a secondary cooling option. Natural ventilation can yield annual HVAC electricity savings of 26-33% in the Padang and Waingapu areas. Results indicate that passive cooling solutions implemented in a portion of the house result in higher fractional HVAC electricity savings in the context of bedroom-only AC, when compared to running the full house AC 24 hours. Regarding the thermal comfort impact from passive cooling solutions in the bedroom-only AC scenario, ceiling fans, insulated roofs, insulated walls, cool roofs, cool walls, and low-E windows are performance leaders in the fractional reduction of occupancy- and TSSU-weighted discomfort exceedance hours.

As the next step of work, the presented model is applicable to similar residences across Southeast Asia and can be extended to urban households with adjusted characteristics of building envelope, end-uses, and resident behaviors. The outcome of this study can help develop net-zero affordable housing pilot projects that incorporate passive design, low-cost cooling, and resilient strategies for LMI homes in Indonesia.

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