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A Comparative Study of Cool Roof and Green Roof Performance in Tropical Area of Indonesia

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Abstract

This study examines the performance of cool roofs and green roofs in a tropical climate in Indonesia. It compares a modified pitched roof designed as a cool roof with a flat roof equipped with vegetation functioning as a green roof on single storey building. A simulation method using EnergyPlus is employed to model the building and evaluate roof performance. The evaluation focuses on their efficacy in mitigating heat flux, enhancing thermal comfort, and reducing energy consumption. The results indicate that green roofs can decrease heat flux by up to 91%, lower temperature by up to 13.14°C, and reduce energy consumption by approximately 60%. Meanwhile, cool roofs can achieve up to a 95% reduction in heat flux, a temperature decrease of up to 11.58°C, and an energy savings of up to 55%. Specifically, green roofs demonstrate superior performance in reducing heat gain within the room during daytime. Conversely, cool roofs are more effective in providing thermal comfort during nighttime. For buildings predominantly occupied during the day, the application of green roofs is likely to result in greater energy savings compared to cool roofs.

Keywords: *Cool Roof; Green Roof; Performance Comparison; Tropical Area*

Introduction

The tropical region of Southeast Asia, including Indonesia, is known for its high solar radiation levels, extended sunny periods, and elevated temperatures. These conditions contribute to several challenges, such as thermal discomfort, the urban heat island (UHI) effect, and increased energy consumption for cooling. In densely populated urban areas where over 60% of surfaces are covered by roofs and pavements, roofs play a crucial role in addressing these issues. Roofs help reduce the UHI effect, while also decreasing the amount of heat absorbed by buildings and lowering energy consumption. Roofs interact with solar radiation in various ways: some of it is released into the environment, some is stored in the roof materials, and some is transmitted into the building (Al-Obaidi et al., 2014; Zingre et al., 2015). To mitigate these problems, researchers suggest using cool roofs (CRs) and green roofs (GRs) as effective passive roofing technologies. In Indonesia, there is already a movement towards adopting these roofing systems as alternatives to traditional ones (Pratama et al., 2023; Sari, 2021; Wardhani et al., 2022).

CRs and GRs have different mechanisms to reduce the heat gain (Santamouris, 2014). A CR involves applying white paint or coating to roofing materials to reflect solar radiation, which helps to lower the roof temperature during the day. By reducing the surface

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temperature of the roof, cool roofs can decrease the surrounding air temperature and mitigate the UHI effect (Brito Filho & Santos, 2014). In tropical regions, the most effective CRs can reflect approximately 90% of solar radiation. However, their reflectivity can diminish over time due to dirt accumulation and weather conditions (Hes et al., 2016). Compared to GRs which require high initial and maintenance costs (Pratama et al., 2023), CRs offer the advantage of easier installation and maintenance, as the coating or paint can be applied to a variety of roofing types. GRs consist of a vegetated layer installed on top of a building’s roof, incorporating various components and depths. This added layer of thermal resistance helps to reduce a building's heating and cooling needs. The vegetation on GRs reflects solar radiation and performs evapotranspiration, which together provide a cooling effect and enhance air quality in their surroundings (Elzeyadi et al., 2009). GRs provide a range of benefits, such as helping reduce noise transmission into buildings and enhancing the thermal resistance of roofs. Additionally, GR mitigates stormwater runoff, the UHI effect, and pollution. By increasing biodiversity and sequestering carbon, GR contributes to a healthier and more sustainable environment (Ismail & Abdullah, 2016). However, not every rooftop is ideal for GR implementation, and factors like the tilt angle of pitched roofs need to be considered. Research has suggested that the angle should not surpass 35^{o} (Wang et al., 2022).

Research into the effectiveness of GR and CR in Indonesia's tropical climate has yielded promising results. Yuliani et al. (2021) found that concrete-based GR can reduce heat flow by up to 56% compared to conventional roofs. Mintorogo et al. (2017) reported that pakis-stem GR could lower surface temperatures by 16.4°C and ambient room temperatures by approximately 7°C at noon compared to traditional rooftops. Dewi & Paramitha (2021) discovered that intensive GR can cut cooling energy demands by up to 21%. Additionally, Lapisa et al. (2019) demonstrated that applying CR coatings, insulating ceilings, and enhancing attic ventilation could decrease temperature-related discomfort and overheating by 37.3%. Yin et al. (2023) indicated that insulated and CR systems could lead to a 45% reduction in electricity used for cooling.

Although CRs and GRs are seen as promising and environmentally friendly passive strategies, their full impact remains not entirely understood (Elnabawi et al., 2023). Previous studies have generally focused on analyzing the performance of CRs or GRs individually. Few studies have analyzed and compared the performance of both roofing systems simultaneously. For example, Yang et al. (2018) found that in Singapore's tropical climate, CRs reduced heat gain by 37%, while GRs achieved a reduction of 31%. However, those studies predominantly examined CR and GR applied on flat concrete roof, which is uncommon in Indonesia. Since the common roofs in Indonesia are pitched roofs with tile materials, this study will analyze the performance of CR applied on common pitched roofs compared to GR applied on flat concrete slab roofs, because GR is less suitable for pitched roofs, impacting both outdoor temperature regulation and indoor thermal comfort and cooling energy savings

Methodology

In this study, a simplified building model was created using Open Studio and EnergyPlus simulation software to assess roof performance. This software, frequently employed in previous research, evaluates potential energy savings and thermal conditions both indoors and outdoors. It features an EcoRoof model based on the FASST soil and vegetation models, which allows for the simulation of GRs by adjusting parameters related to vegetation and soil, and integrates the green roof's energy balance with the building's overall energy dynamics (Bevilacqua, 2021; Kolokotsa et al., 2013). Additionally, the software offers a range of parameters for modeling both CRs and GRs (Gargari et al., 2016).

A model of single-storey building with a 20x10 m2 floor area and 3.5 m height is used in this study. The U-value material of the wall, window, and floor is 1.039 W/m2-K, 5.894 W/m2-K and 4.178 W/m2-K, respectively and the window-to-wall ratio is around 30%. The U-value of the material is based on the U-value provided in EnergyPlus. Two different roofs are applied to the model: a pitched roof with concrete tile material (U-value= 6.622 W/m2-K) commonly found in Indonesia for conventional roofs, as the baseline, and for the CR model, and a 100 mm flat concrete roof with grass vegetation (U-value= 1.627 W/m2-K) for GR model (**Error! Not a valid bookmark self-reference.**). The characteristics of the roof material can be found in Table 1.

The model is assumed to be an office building that has operation hours from 8.00 AM to 18.00 PM with internal gains: people = 0.1 person/m^2 and lights = 8 W/m^2. The ideal HVAC system set with a 25^{o}C temperature is adopted in the simulation for simplifying the model, as it does not affect the building energy consumption general trend (Zhou et al., 2018). A one-year simulation is conducted using the weather file of Jakarta, Indonesia (Figure 2) to compare the heat flux, mean radiant temperature (MRT) and cooling energy consumption of the conventional, cool roof and green roof models.

Figure 1. Geometry of pitched roof building (up) and flat roof building (down)
Source: Author

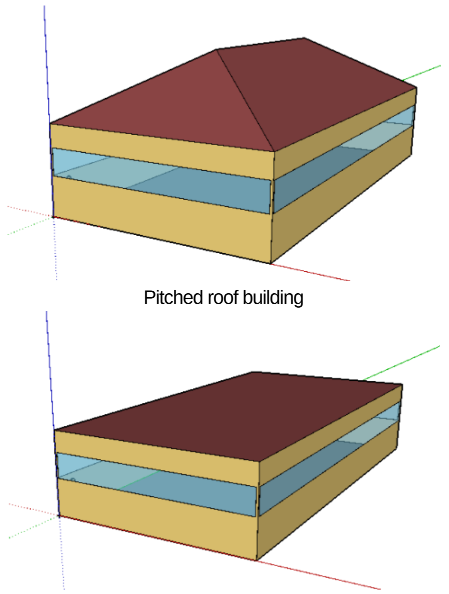


Table 1. Roof material characteristic

Baseline and CR	
Thickness	0.015 m
Conductivity	1.1 W/m-K
Density	837 kg/m^3
Specific heat	2100 J/kg-K
Solar reflectance	0.3 (for baseline) 0.7-0.9 (for CR)
GR	
Soil layer thickness	0.1 m
Conductivity of dry soil	0.35 W/m-K
Density of dry soil	1100 kg/m3
Specific heat of dry soil	1200 J/kg-K
Height of plants	0.2 m
Leaf area index	1-3
Leaf reflectivity	0.22
Leaf emissivity	0.95

Source: Author

Result and Discussion

1. Heat Flux Analysis

Since heat released from buildings to ambient air contributes to UHI, the heat fluxes of the CR and GR are analyzed to understand its effect on the surrounding environment. The sensible heat flux is calculated from roof surface's convective and radiative heat transfer to outdoor area (Hong et al., 2019). Figure 3 illustrates the sensible heat flux for a pitched roof model constructed with concrete tile material, simulated on October 12th. This date is chosen because it records the highest dry bulb temperature and global solar radiation for the given period. The baseline model, which features a roof solar reflectance (SR) of 0.3, is compared with several CR models that have increased SR values ranging from 0.7 to 0.9.

In the baseline scenario, the peak heat flux is observed at 13:00 PM, reaching approximately 217.99 W/m^2. This high level of heat flux is a result of the low reflectance of the baseline roof, which absorbs a significant amount of solar radiation. When the roof's SR is increased to 0.7, the heat flux at the same time decreases dramatically to 81.1 W/m^2. With further increases in SR to 0.8 and 0.9, the heat flux reduces even more to 46.06 W/m^2 and 10.59 W/m^2, respectively. These reductions represent a decrease in heat flux ranging from 63% to 95% compared to the baseline (conventional roof with SR = 0.3).

Figure 2. The weather file used in simulation
Source: EnergyPlus weather file

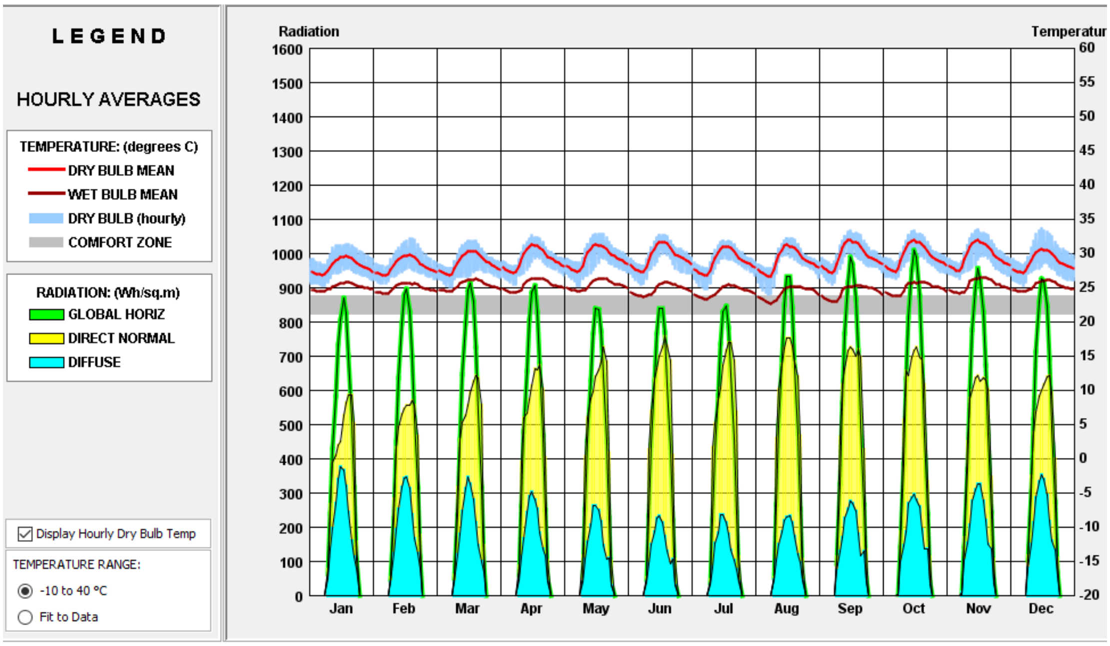
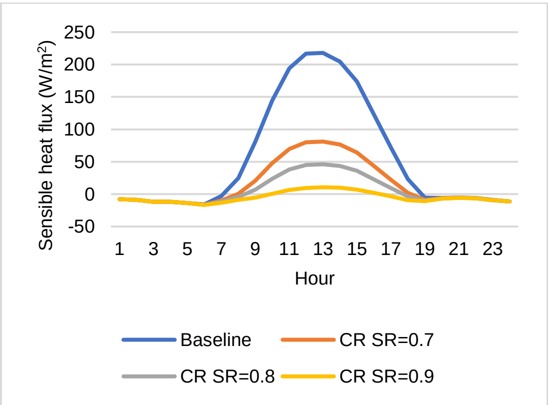


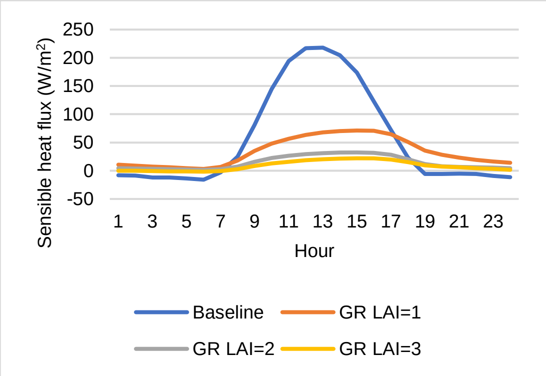
Figure 3. Sensible heat flux of CR models
Source: Author



This substantial reduction in heat flux with higher SR values is indicative of the effectiveness of CR materials in reflecting more solar radiation, thereby lowering the amount of heat transferred to the building. However, it is important to note that, despite these significant daytime reductions, the heat flux values for all models during nighttime hours exhibit only minor differences. This minimal variation at night suggests that the CR models do not significantly impact the rate of heat dissipation once the sun has set.

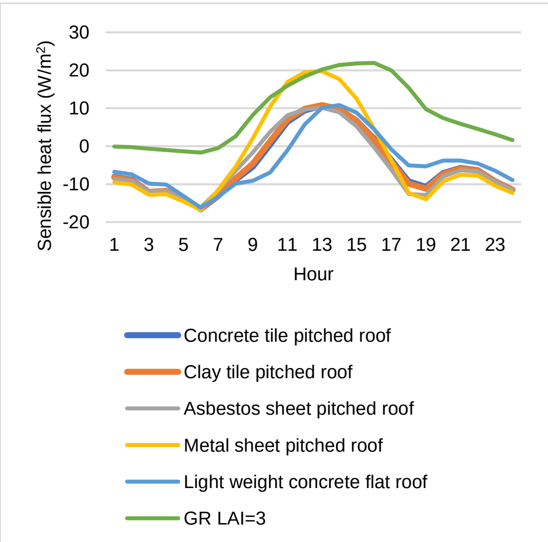
The GR model exhibits a distinct pattern in heat flux compared to the baseline scenario (Figure 4). In the baseline model, the peak heat flux is recorded at noon, which is when the intensity of solar radiation is highest. At that time, GR model with leaf area index (LAI) values of 1, 2, and 3 records the heat flux values at 67.66 W/m², 31.22 W/m², and 20.24 W/m², respectively. These values are approximately 69% to 91% lower than the peak heat flux in the baseline scenario. However, the GR model shows variations in the timing and magnitude of heat flux. For the GR model, the highest heat flux occurs at 15:00 PM, with recorded values of approximately 71.19 W/m², 32.38 W/m², and 21.86 W/m² for the model with LAI values of 1, 2, and 3, respectively. These values are approximately 59% to 87% lower than the peak heat flux in the baseline scenario.

Figure 4. Sensible heat flux of GR models
Source: Author



While the GR model shows significant reductions in heat flux during the day, with higher LAI values resulting in greater reductions, it behaves differently at night. At night, the GR model releases more heat to the outdoor environment compared to both the baseline and CR models. For instance, at 00:00 AM, the baseline heat flux value of -11.22 W/m² indicates that heat is being transferred from the outdoor environment to the roof's surface, as the roof cools down faster than the air at night or early morning. However, in the GR model with LAI values of 1, 2, and 3, the heat flux is 13.86 W/m², 4.58 W/m², and 1.6 W/m², respectively. This suggests that although GR systems are highly effective in reducing heat flux during the day, their thermal performance may be less favorable at night. The poor nighttime performance of the GRs supports the statement by Wang et al. (2022).

Figure 5. Sensible heat flux of various cool roof model
Source: Author

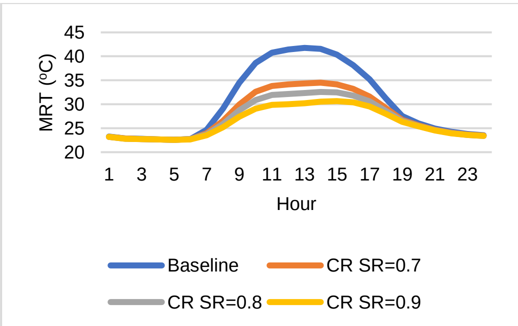


In order to understand the cool roof performance, various common roofing materials found in Indonesia with different U-value, those are: clay tile (U-value= 6.442 W/m2-K), asbestos sheet (U-value= 6.977 W/m²-K), metal sheet (U-value= 2.472 W/m²-K) and light-weight concrete flat roof (U-value= 3.039 W/m²-K) (Prianto & Dwiyanto, 2013; Romanova & Skanavi, 2017), are set with SR= 0.9 as the best cool roof model compared with green roof with LAI= 3. Figure 5 indicates that CRs applied on various roofing materials show that heat fluxes of all models are slightly different, indicates that CRs are effective applied on any roofing material. In addition, CR with SR= 0.9 is potentially mitigate heat loss higher than GR with LAI= 3.

2. Mean Radiant Temperature Analysis

The MRT (mean radiant temperature) of each model will be observed for analyzing the indoor thermal performance of the buildings. MRT is defined as the uniform temperature of a hypothetical spherical surface surrounding the subject that would result in the same net radiation energy exchange with the subject as the actual, complex radiative environment. In other words, MRT is the thermal radiation to the human body from all directions, including the solar radiation that penetrates and radiates through the building envelope (Budhiyanto, 2017; Halawa et al., 2014). Figure 6 illustrates a clear difference in MRT between the CR models and the baseline model, particularly during the peak of the day. At 13:00 PM, when solar radiation is most intense, the MRT for the baseline model reaches its highest point, approximately 41.77°C. This indicates a significant heat buildup in the environment under the baseline scenario.

Figure 6. MRT of CR models
Source: Author

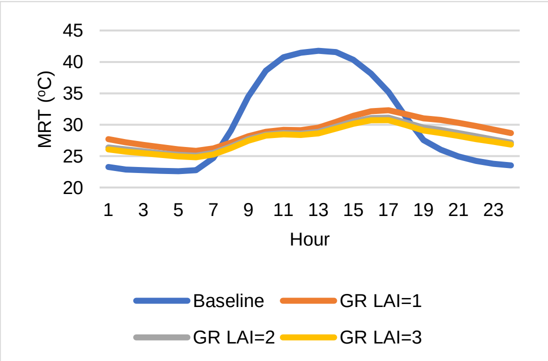


When CR models with different SR values are applied, there is a marked reduction in MRT. With an SR of 0.7, the MRT drops to about 34.37°C, indicating a substantial cooling effect. Further increasing the SR to 0.8 results in an MRT of 32.33°C, while an SR of 0.9 brings the MRT down to approximately 30.18°C. These reductions reflect the effectiveness of the CR models in mitigating the impact of solar radiation, thereby lowering the surrounding temperature.

However, during nighttime, the MRT differences among all models become negligible. This lack of significant variation suggests that the cooling effect of the CR models, which is pronounced during the day due to reduced solar absorption, is less impactful at night when solar radiation is absent. Consequently, the thermal environment stabilizes across all models, showing similar MRTs regardless of the applied SR values. This indicates that while CR models are highly effective during the day in reducing radiant heat, their influence on nighttime thermal conditions is minimal.

While the MRT of the baseline and CR models begins to rise significantly around 6:00 AM, peaking at noon, the GR model displays a different pattern. The MRT in the GR model increases more gradually in the morning and reaches its peak later in the evening, with temperatures of approximately 32.30°C, 31.11°C, and 30.72°C for GR models with LAI values of 1, 2, and 3, respectively. Following this peak, the MRT drops slightly during the night. However, compared to the baseline and CR models, the MRTs of the GR models are 2-5°C higher at night (Figure 7).

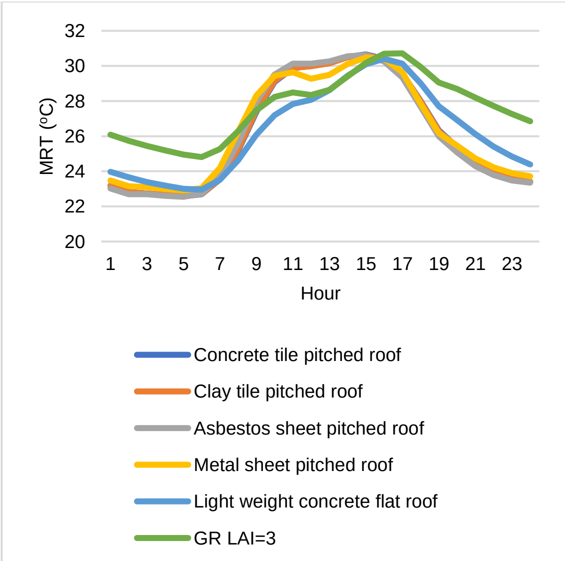
Figure 7. MRT of GR models
Source: Author



This difference can be explained by the way green roofs interact with incoming solar radiation. During the day, a portion of the solar radiation that hits the green roof is reflected, while another portion is absorbed by the plants and soil, driving the evaporation process. The remaining heat is stored in the soil material. At night, when the surrounding temperature drops and is lower than that of the soil and concrete roof, the heat stored during the day is gradually released back into the room and the environment. This release of stored heat causes the nighttime MRT and heat flux of the GR models to be higher than those of the baseline and CR models (Irsyad et al., 2016). This thermal lag process highlights the dual role of green roofs: while they effectively reduce peak temperatures during the day, they can also contribute to higher temperatures at night due to the release of stored heat.

The indoor MRT comparison of CR SR= 9 with different roofing material is presented in Figure 8. The data clearly shows that pitched roofs with various materials exhibit very little difference in indoor MRT, suggesting that the material characteristics have a less significant impact on MRT than the solar reflectance of the material.

Figure 8. MRT of various CR models
Source: Author



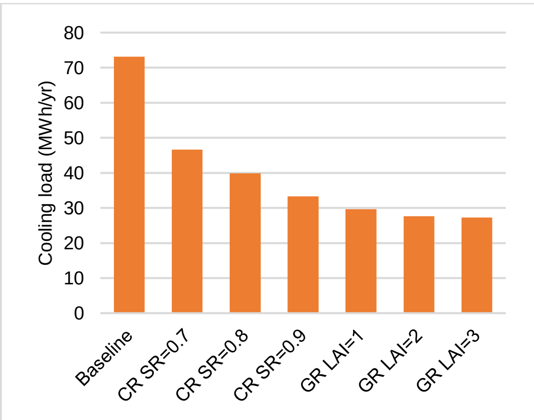
In contrast, the MRT pattern for a flat concrete roof differs slightly. The indoor MRT for the flat concrete roof is lower in the morning but higher in the evening. This behavior indicates that the lightweight nature of the concrete roof introduces a thermal lag, delaying the transfer of heat into the room. As a result, the room remains cooler in the morning but warms up later in the day as the stored heat eventually penetrates the interior.

A similar pattern is observed in the MRT of the GR model. However, the MRT for the GR model is consistently higher than that of the flat concrete roof throughout most of the day, except in the afternoon. During the afternoon, the room temperature is lower than the roof temperature, causing the heat stored in the soil of the green roof to be transmitted into the room. This transmission leads to a temporary alignment of temperatures between the two roof types, but overall, the GR model maintains a higher MRT due to the heat retention and release characteristics of the green roof system.

3. Cooling Load Analysis

The change in MRT directly impacts energy consumption (Budhiyanto, 2017). When the MRT of a room increases, more energy is required for cooling, since the air temperature must be lowered to maintain comfort levels (Halawa et al., 2014). For the baseline model, the annual cooling load is approximately 73.16 MWh. However, this load decreases significantly when the SR of the roof is increased. With SR values of 0.7, 0.8, and 0.9, the cooling load drops to 46.68 MWh/yr, 39.85 MWh/yr, and 33.27 MWh/yr, respectively, representing a reduction of about 36-55%.

Figure 9. Cooling load of CR and GR models
Source: Author



The cooling load is further reduced when a GR system is implemented. The cooling load for the GR model with LAI values of 1, 2, and 3 is approximately 29.64 MWh/yr, 27.63 MWh/yr, and 27.3 MWh/yr, respectively, which is about 60-62% lower than the baseline model (Figure 9). The marginal reduction in cooling load with increasing LAI—from 1 to 2 and 3, as the vegetation density increases—only accounts for an additional 3% and 4% decrease, respectively. This suggests that while GR systems significantly reduce the cooling load, the impact of increasing LAI, by adding denser or taller vegetation, on further reducing energy consumption is relatively small.

The greater cooling load reduction observed in the GR model compared to the CR model can be attributed to the lower MRT of the GR model during the daytime, which is when the building is most likely to be occupied. The reduced MRT during these hours helps minimize the cooling demand, leading to more substantial energy savings in buildings with GRs compared to those with higher SR alone.

4. Performance Comparison

The performance comparison between CR models with high SR and GR models with high LAI shows that their different mechanisms in mitigating heat significantly impact indoor thermal comfort and energy consumption. CR models reflect heat, resulting in lower sensible heat flux on the roof surface, while GR models absorb heat, leading to higher heat flux on the roof surface, especially at night (Santamouris, 2014; Wang et al., 2022). This influences the indoor MRT. CR models experience higher MRT during the day and GR models show higher MRT at night due to a time-lag effect, as the heat stored in the GR is released into the indoor space at night (Irsyad et al., 2016).

Although GR models indicate less efficient performance in terms of nighttime cooling, they offer significant energy savings in buildings that are mostly occupied during the day, as their overall cooling load reduction surpasses that of CR models in daytime-use buildings. This indicates that GRs are potentially implemented in tropical regions, like Indonesia as they can effectively reduce indoor MRT during the day, leading to lower cooling energy consumption.

Conclusion

This study evaluates and compares the performance of CR and GR systems in the tropical climate of Indonesia. Both types of roofs effectively mitigate the amount of heat transferred to the surrounding environment. Specifically, a GR with a LAI of 3 can potentially reduce heat flux by up to 91% during midday. In contrast, a CR with a SR of 0.9 achieves a 95% reduction in heat flux. In addition to lowering heat flux, both CRs and GRs also substantially decrease the MRT within indoor spaces. When compared to a conventional roof, a CR with SR = 0.9 and a GR with LAI = 3 can lower the MRT by 11.58°C and 13.14°C, respectively, during daytime.

However, the effectiveness of these roofing systems varies throughout the day. During nighttime, the performance of the GRs in reducing heat flux and lowering MRT is less effective than that of the CRs. This is because the soil in the GRs absorbs heat during the day and gradually releases it at night, leading to higher heat flux and MRT inside the building.

For buildings that are occupied during the daytime, GRs offer a greater reduction in cooling load compared to CRs. GRs can cut cooling loads by 60-62%, whereas CRs reduce cooling loads by 36-55%. This difference arises from the distinct methods each roof uses to manage heat transmission. Additionally, CRs have an advantage in terms of application versatility, as they can be installed on a wide range of roofing materials with relatively minor performance variations based on specific material characteristics, though they are primarily influenced by the solar reflectance of the material.

A limitation of this study is the omission of the irrigation factor for GRs to simplify the GR models. Santamouris (2014) mentioned that irrigation can potentially affect GR cooling effectiveness and thermal regulation. Future research could be expanded to include and examine the effects of irrigation on GR performance.

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