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Microclimate Effect on Cooling Energy for Buildings in Hot, Humid Climates: A Comparative Analysis of Shaded and Unshaded Environments

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Abstract

This paper explores the influence of microclimates on changes in air temperature and the often-overlooked aspect of their effect on energy savings across varying microclimatic conditions. The study compares the cooling energy requirements of two identical single-story buildings in distinct microclimates: one characterized by concrete ground devoid of shade and the other featuring soil ground with tree shade. Climatic environmental data were collected over 15 days in the concrete-exposed field and shaded area beneath the trees to conduct the investigation. These datasets were input into EnergyPlus 9.6 to model the energy demands and consumption of buildings subject to the specified climatic conditions. The validation of the simulated model against actual energy demand data from a classroom building demonstrated agreement. The findings reveal notable differences in air temperature, with the shaded area experiencing temperatures 0.8°C to 8.0°C lower than the concrete-exposed monitoring location. The building in the tree-shaded microclimate exhibited a lower peak cooling load than its concrete-exposed counterpart, resulting in a 35% reduction in the electrical energy requirements for the air-conditioning system. The study recommends implementing 0.08-m polyurethane insulation for the building walls and roof to equalize the energy demand and consumption of the concrete-exposed building with that of its shaded counterpart. Furthermore, building design in shaded areas can maximize the window glass area while consuming less energy than buildings on concrete-exposed grounds. The study advocates leveraging the microclimate associated with surrounding buildings in the design process to enhance the overall energy savings.

Keywords

Energy savings; Microclimate; Tree shade; Thermal insulation; Building design; EnergyPlus model

1. Introduction

With increasing concerns regarding climate change and the imperative to conserve energy, understanding the influence of local weather conditions on building energy consumption becomes crucial. Previous research has identified various microclimatic factors affecting air temperature (Qingjuan et al., 2022) and urban heat (Canbing et al., 2010; Prasitreak & Srivanit, 2022; Xiaoma et al., 2019). However, despite their influence on ambient temperature, limited research has specifically addressed the effects of microclimates on building energy efficiency. This paper explores how different microclimates can alter the cooling energy requirements, specifically for buildings in a hot, humid climate. The objectives of this study are twofold: firstly, to investigate how microclimates associated both with and without tree shades, influence building cooling energy needs; and secondly, to identify energy-efficient building envelope designs suited to different microclimates based on an energy simulation program (EnergyPlus). Architects and decision-makers can apply the insight from this study to make informed decisions that result in energy savings and contribute to developing more environmentally friendly architecture.

2. Literature Review

The influence of green spaces on the reduction of air temperature can be realized through shade and plant transpiration (Qingjuan et al., 2022). Research has found that trees, especially those with substantial foliage, can significantly reduce surface temperatures by minimizing the penetration of solar radiation into building areas (Gómez-Muñoz, 2009). The study emphasizes the importance of the strategic placement of trees in providing shade to buildings, revealing a direct correlation between tree positioning and shading effects. Donovan (2009) evaluated the economic effect of urban tree size on summertime electricity use. The study, based on a case of 460 single-family homes in Sacramento, California, highlighted that west and south-facing trees contributed a 5.2% energy savings during the hot season.

Previous research examining the influence of external temperatures on energy consumption primarily have focused on urban heat islands. The urban heat island phenomenon reveals variability between cities and an increase in cooling energy consumption of between 10% and 150% (Canbing et al., 2010; Xiaoma et al., 2019). Research conducted in Barcelona, Spain, using EnergyPlus simulations indicated that the sensible cooling load of residential buildings increased by approximately 18% to 28% (Salvati, 2017). In hot and humid climate, the temperature decreases found in the park with the soft surface has higher proportion than the hard surface (Nantarat et al., 2021).

Hsieh ed al. (2018) conducted quantitative measurements using microclimatic field measurements and tree characteristics integrated with the EnergyPlus model for building energy consumption (Hsieh et al., 2018). The effect of tree heat dissipation due to shade and transpiration was studied in four scenarios developed based on various tree characteristics to measure the influence of trees on building energy savings. Scenario 1 represented a situation without trees; Scenario 2 represented conditions with existing trees; Scenario 3 represented increased shading from trees; and Scenario 4 represented a situation with increased tree transpiration. The simulation results in this research revealed that Scenario 2 (with existing trees) could reduce building energy consumption by up to 10.3% as compared to Scenario 1. Scenario 3, with increased shading from trees, and Scenario 4, with increased transpiration, could reduce building energy consumption by 15.2% and 12.4%, respectively, compared to Scenario 1.

EnergyPlus (U.S. Department of Energy, 2024), a widely used tool in prior studies assessing vegetation and building performance, was employed in our study to examine building energy consumption and electrical energy demands associated with the air-conditioning system. Other programs, such as Computational Fluid Dynamics, ENVI-MET, and OpenFOAM, have been used in various studies (Allegrini & Carmeliet, 2017; Brozovsky et al., 2022; Mosteiro et al., 2020; Shen & Wang, 2020).

Past research underscores the significance of considering microclimates in building design. However, the current standards, criteria, and methods for designing buildings frequently overlook the influence of tree shade, limiting fenestration for compliance with regulations. While the existing literature has provided foundational insight into the effects of microclimates on buildings, this study aims to contribute by offering a comprehensive comparative analysis of the cooling energy requirements in microclimatic conditions that are typical of hot, humid climates. By building on insights from previous researches, the goal is to provide practical recommendations for optimizing energy efficiency in building design.

3. Methodology

Typically, the EnergyPlus model relies on data from a designated weather station for building energy simulations. In this study, two distinct weather datasets were used: one based on environmental data collected beneath a tree ("utree_weather") and the other from the concrete ground climate ("concrt_weather"). These datasets were employed to accurately calculate energy savings for a specific classroom building.

Figure 1 illustrates the research flow in this study. The research commenced with the simulation of an existing classroom, considering the actual thermal properties, such as wall materials, scheduling, lighting intensity, infiltration, and air-conditioning systems (Table 1). The simulation used the "concrt_weather" data to simulate the energy consumption of the existing classroom and the simulated results were validated using energy consumption data from the classroom. Following this, we simulated a one-story building model with analogous thermal characteristics, incorporating the designated building energy measures, such as insulation walls and fenestration areas on the façade, to assess the potential energy savings. The two weather datasets were employed to compare their influence on energy savings.

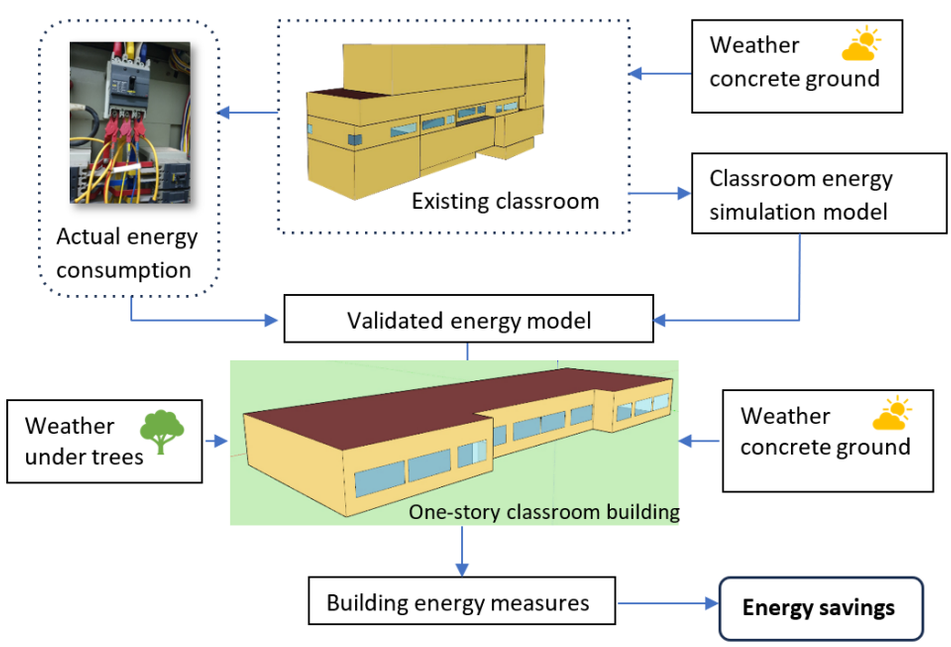


Figure 1. Research methodology in this study.

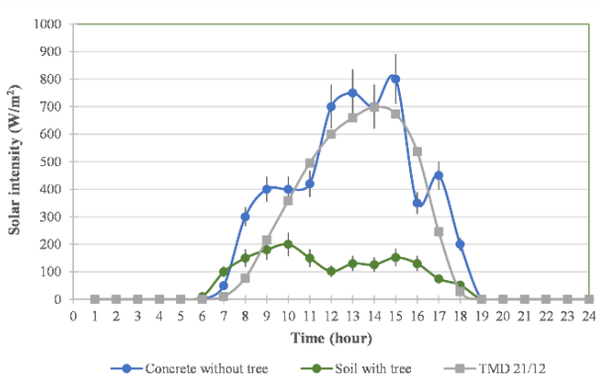
3.1 Weather Station Data vs. Microclimate Data

The study methodology involved collecting air temperature, relative humidity, solar intensity, and wind velocity in two distinct areas: 1) under trees and surrounded by plants; and 2) exposed to sunlight and concrete ground. The study focused on simulating two identical single-story buildings in different contexts: one on concrete ground without shade and the other on soil ground with a roof shaded by a tree canopy. The simulation results of cooling energy for the two buildings were compared to identify potential energy savings from tree shading. The instruments in the data collection included four temperature dataloggers (Model: Kestrel D2), with an accuracy of ±0.5°C and a measurement range of -10°C to 55°C, which were placed in an experimental housing to measure and record the air temperature. The temperature sensor housing unit was constructed from wrapped aluminum foil with holes at the top and bottom to allow for air ventilation. The wind velocity was measured using a Lutron hot-wire anemometer (Model: AM-4214SD), with a measurement range of 0.2 to 5 m/s and an accuracy of ±5%. The solar intensity was measured using a pyranometer (Model SPM-116SD), with an accuracy of 10 W/m2.

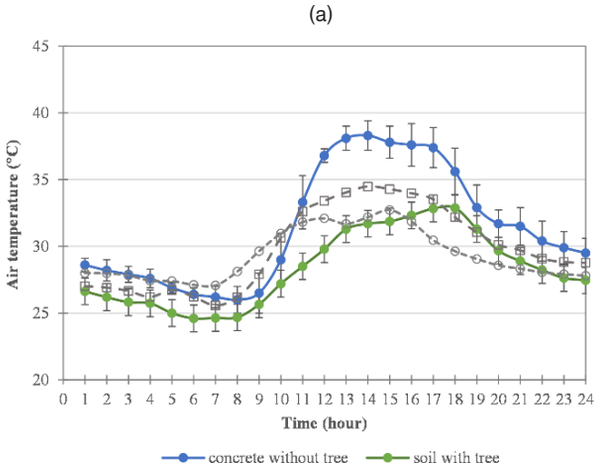
The purpose of recording environmental data in two different locations was to input these data into the weather file of the simulation program. Figure 2 shows the data collection sites under tree shade and exposed to direct sun and concrete ground. The air temperature, relative humidity, and solar intensity were collected between December 7 to 21, and their average values with standard deviations were compared with the weather data obtained from the Pathum Thani weather station (Thai Meteorology Department [TMD], 2565). Figure 3 illustrates the differences between the weather data measured by our instruments for the specific microclimates and that obtained from the TMD weather station. The data obtained from the TMD weather station are enveloped by the data collected from our instrumentation between 11:00 to 17:00. The air temperature close to the concrete floor remained high after sunset until midnight because the concrete floor proportionally absorbs more radiative (longwave and shortwave (solar)) and non-radiative heat energy during the day and releases longwave radiative energy and non-radiative heat energy to the surroundings at night. Temperature equilibrium occurs between approximately midnight and 07:00 as shown in Figure 3b. The recorded air temperature in the concrete area is similar to that from the TMD weather data. However, the measured solar intensity under tree shade is lower than that measured for both the concrete microclimate and the TMD station. The air temperature under the trees was 0.8°C to 8.0°C cooler than that measured above the concrete ground. The relative humidity in the concrete area of 39% to 70% was lower than the 50% to 85% relative humidity found in the green area. Specific weather files for microclimates with and without trees were created from the field data to compute the energy consumption in the buildings under two different microclimates. The weather data derived from the weather station were modified according to the field data.

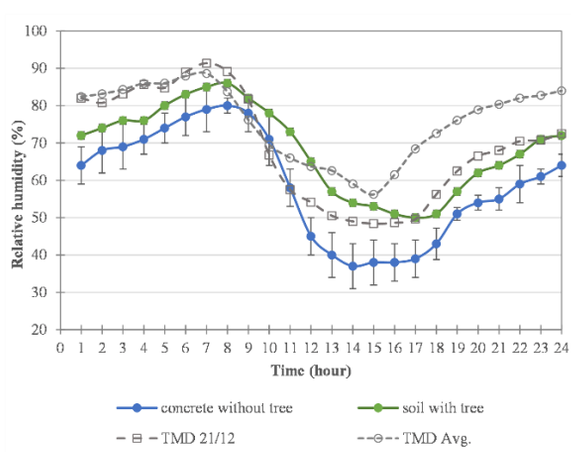
(a) (b)

Figure 2. Environmental data collection (a) under tree shade and (b) in the concrete area.



(a)





(b) (c)

Figure 3. Environmental data comparison for the TMD weather station, concrete area, and green area.

3.2 Simulated Building

This study involved an energy simulation of a single-story office building with air conditioning operating for 10 h. The simulated building used the existing data from the real classroom, with a floor area of 40.55 x 14.20 m and a floor-to-ceiling height of 4.0 m. The construction materials for the building walls and floors were concrete. The external windows were clear glass with a thickness of 0.003 m. There were four external doors made of soft wood. There were 50 to 120 occupants from 09:00 to 19:00. Five split-type air conditioners with a total cooling capacity of 240 kBTU/hr and an Energy Efficiency Ratio (EER) = 10.8 to 11.2 were used during the week. The thermostat set point was fixed at 26°C throughout the operating hours. The lighting system consisted of 146 fluorescent lamps (18 W/lamp) with a lighting intensity of 4.56 W/m^2. The Air Change per Hour (ACH) in the classroom taken from a previous study (Srisuwan, 2011) was 0.3 ACH along the window frame and 0.14 ACH from door openings. Table 1 lists the existing classroom data used in this study. Figure 4 displays the classroom floor plan and fenestration of the existing classroom.

Table 1. Input data for the base case model in EnergyPlus

Input	Data
Dimensions and area	40.35 m x 14.20 m, 545.91 m2
Wall and floor materials	Concrete
Windows and doors	0.003 m-glass, soft woods
Schedule	Mon–Fri: 8:00 to 24:00/No class on Sat–Sun
Air-conditioning system	5 Split-type with 240 kBTU/hr
Thermostat set point	26°C
Lighting type	138 Fluorescent lamps (18 W each)
Infiltration through the building envelope (ACH)	0.3
Infiltration through doors/windows (ACH)	0.14
Occupants	Max. 150

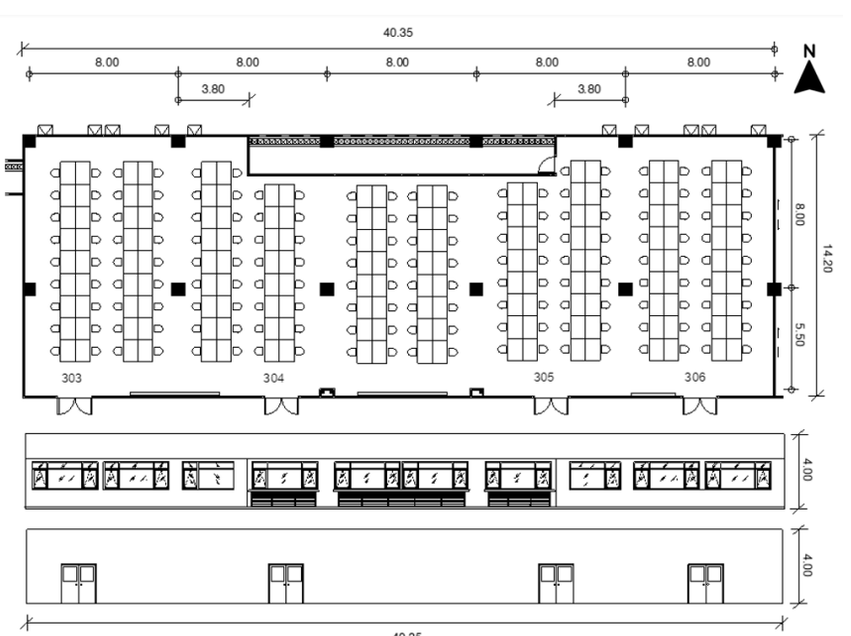


Figure 4. Floor plan and facades of the reference classroom.

Examining the influence of the microclimate beneath a tree in the EnergyPlus 9.2.0 energy model requires adjusting by input collected weather data into the weather file, which includes the air temperature, dew-point temperature, humidity ratio, and solar intensity. This study explored a single-story building enveloped by a tree shade, covering both its roof and surroundings. Subsequently, the weather data collected beneath the tree were used to simulate the effects of the tree shade.

3.3 Data Collection on Energy Consumption

The device installed to measure the electricity usage of the air-conditioning system was the HIOKI PQ3100-94 unit (Figure 5). This power quality analyzer was deployed to analyze and record electrical power and electrical energy hourly for 15 days. It can be connected to the PQ One software, which reads the data. The software displays the stored information in a graphical format. The recorded data can be accessed and reported through PQ One.

Figure 5. Collecting data on electricity demand in the air-conditioning system of the classroom.

4. Results

4.1 Simulated Model Validation

The electrical power for air conditioning collected from the actual classroom was compared with the simulated electrical power from EnergyPlus. The collected data were averaged hourly to present an energy profile for 24 h, as depicted in Figure 6. The actual energy consumption of the air-conditioning system was calculated based on collected data, at 283.64 kWh/day, with a maximum value of 21.80 kWh/h at 18:00. Comparatively, the EnergyPlus simulation using the weather file field data (simulated kilowatts with field weather without tree) indicates an energy consumption of 289.16 kWh/day, with a maximum value of 21.86 kWh at 17:00. The simulation results using the TMD data indicate an energy consumption of 284.42 kWh/day, with a maximum value of 20.74 kWh at 16:00. In summary, the simulation model using the field weather data aligned closely with the measured classroom data, followed by the model using the TMD data, and these results help to validate the modeling approach. Hereafter, the simulation models in this study use the 7-day data collected from the field to calculate energy consumption and energy demand.

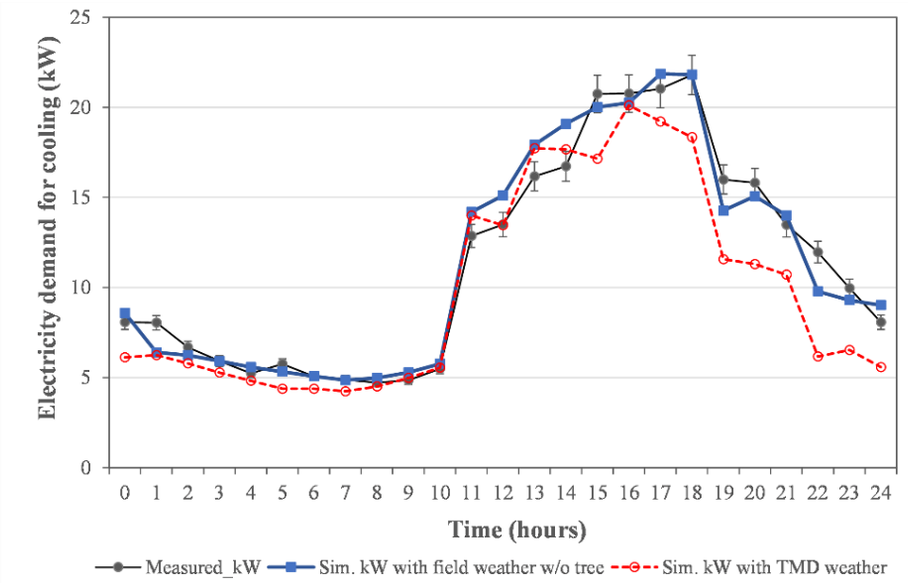
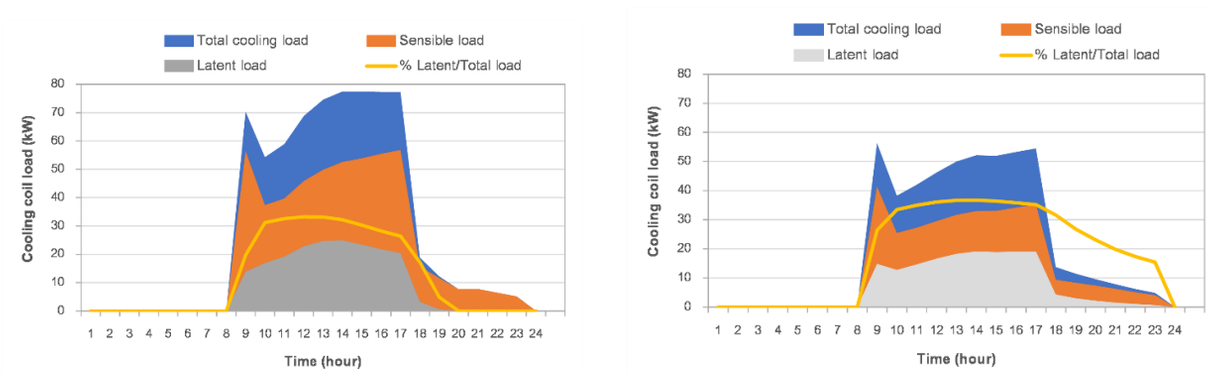


Figure 6. Measured and simulated electricity demand for cooling of the studied classroom.

4.2 Effect of the Outdoor Microclimate on the Cooling Coil Load

Figure 7 illustrates that, in one-story classrooms with tree shade and green surroundings, the simulations indicate an average cooling load of 39.5 to 56.6 kW/day. The classrooms on concrete ground without shading, registered a higher load of 55.6 to 77.3 kW. Therefore, classrooms with tree shade require smaller air-conditioning units and use less cooling energy than classrooms without tree shade. The influence of external weather conditions on the cooling load of the classroom air-conditioning system is notable. Considering the sensible and latent components in the cooling load, the proportion of latent cooling load to the total cooling load (sensible and latent) in a tree-shaded classroom is slightly higher than that of a classroom surrounded by concrete ground without tree shade. The peak latent cooling load in classrooms on concrete ground is 33.2% of the total cooling load. The classroom with tree shade has a higher latent cooling percentage at 36.7% of the total cooling load. In the classroom shaded by trees, the latent load reduction extends until 23:00 due to the higher ambient humidity.



(a) Concrete ground without shade

(b) Soil ground with tree shade

Figure 7. Total cooling coil load and proportion of latent and sensible cooling load in the classroom in various microclimates.

Figure 8 presents the simulated results of the 10-hour daily energy usage (kWh) for the air-conditioning system of the classroom, influenced by weather conditions over 15 days (December 5 to 19). For the classroom in the tree shade, the average energy consumption is 126.98 kWh. In contrast, the classroom affected by the concrete microclimate has an average energy consumption of 195.81 kWh, 35% higher. The classroom with tree shade consumes cooling energy at 83.30 to 165.85 kWh/day. In contrast, cooling energy consumption in the classroom surrounded by the concrete ground ranges from 145.60 to 234.51 kWh/day. The following section examines the thermal performance of different insulation configurations with the concrete (no shade) and tree shade scenarios.

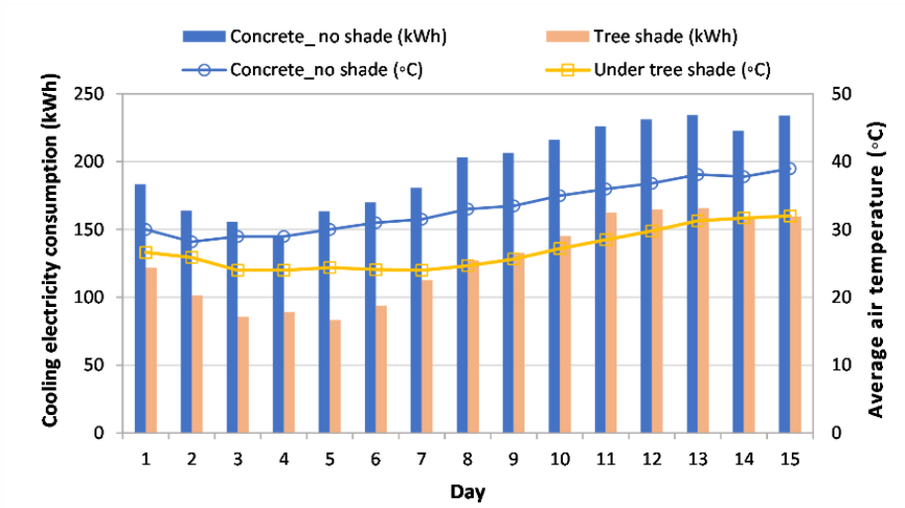


Figure 8. Cooling electricity consumption for classrooms and average air temperature in two microclimates.

4.3 Insulating with Polyurethane to Match the Cooling Effect of Tree Shade

The energy usage in the air-conditioning system within a classroom was investigated by incorporating thermal insulation on the walls and roof of the classroom. The comparison involved (A) the base case building with tree shade, (B) the base case building in a concrete area microclimate, (B1) the base case B with 0.08-m polyurethane foam insulation on the walls, (B2) the base case B with insulation on the roof, and (B3) the base case B with the walls and the roof insulated. Figure 9 presents the energy demand of the air-conditioning system of the base case (B) subjected to the concrete area microclimate. The energy consumption computed from area under the curve was 234.06 kWh/day. The design approach (B1) of adding wall insulation resulted in a consumption level of 200.86 kWh/day, achieving an energy savings of 33.20 kWh/day compared to the base case (B). Furthermore, the design approach (B2) of adding roof insulation led to an energy consumption of 163.24 kWh/day and a savings of 70.82 kWh compared to the base case (B). The design approach of installing 0.08-m wall and roof insulation resulted in a consumption level of 128.30 kWh/day. Comparing the study cases, adding 0.08-m polyurethane insulation to the building walls and roof achieved the lowest air-conditioning energy consumption, matching the cooling energy reduction of the tree shade cover scenario.

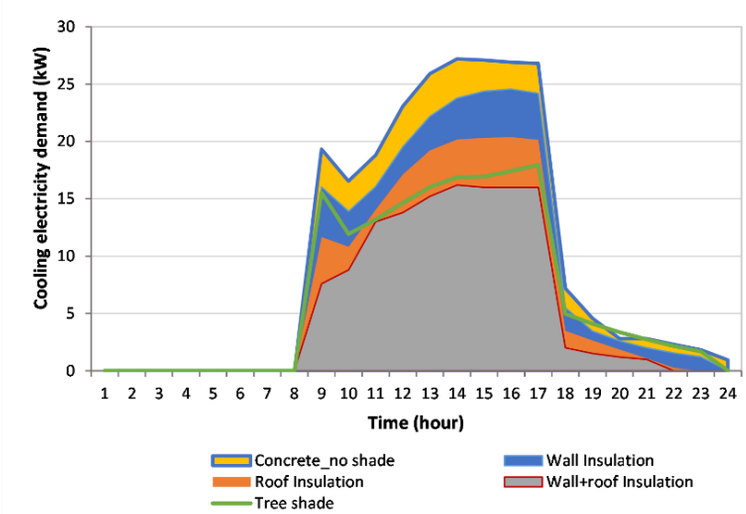


Figure 9. Cooling electricity demand in the building with tree shade and thermal insulation application.

The effect of applying thermal insulation to the building under different microclimates varies. Figure 10 illustrates the savings percentage in air-conditioning energy within the classroom employing wall insulation, roof insulation, and both wall and roof insulation, against the studied base cases. Classrooms exposed to concrete area climatic conditions that implement thermal insulation on the roofs, walls, and both reduce the energy consumption of the air-conditioning system by 14.2%, 30.3%, and 45.2%, respectively. Conversely, tree-shaded classrooms save 5.2%, 13.4%, and 27.9% of energy with the same interventions.

Applying thermal insulation in classrooms in warm microclimates yields a higher energy savings than in classrooms in cooler climates. This discrepancy is attributed to the higher potential for energy reduction in warmer microclimates. Conversely, classrooms in relatively cooler weather conditions approach the baseline of energy consumption, indicating a smaller scope for additional energy savings in those environments. In cooler climates, however, may need to consider winter heating costs as well.

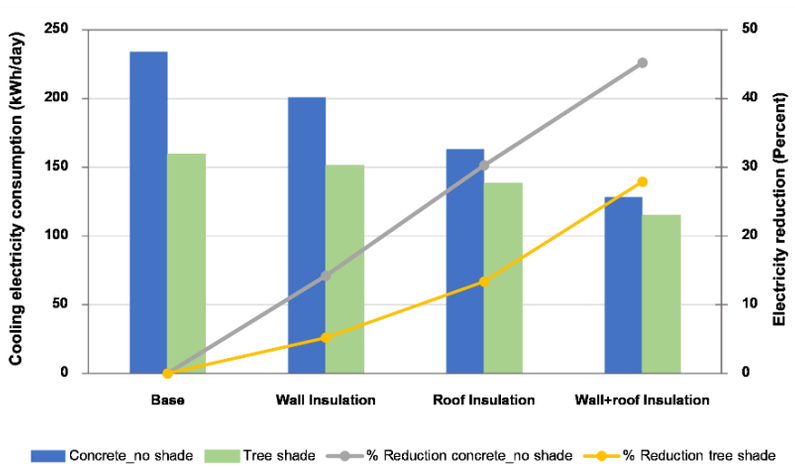


Figure 10. Effect of thermal insulation on cooling energy savings in buildings in various microclimates.

4.4 Effect of the Window area on Energy Demand in a Building with Tree Shade

Decreasing the window area on a building façade reduces cooling energy usage significantly. Frequently, building owners or designers require a large glass window in the building design. This study demonstrates

that a classroom covered by tree shade can be designed with a larger glass area compared to one exposed to concrete ground. Figure 11 presents the variation of window glass area on a building wall of 1.75, 3, and 4 times the window glass area in the base case building. The energy consumption was calculated from area under the curves shown in Fig. 12. Figure 12 reveals that the energy usage of the air-conditioning system in the tree-shaded classroom and the classroom exposed to concrete area weather conditions was equal to 159.51 and 234.06 kWh/day, respectively. This study explored the energy usage for 1.75 times the glass area of the original window area under the tree-shaded scenario, which was 173.24 kWh. By adding 3 times and 4 times the original window area, the design contributed to an energy usage of 181.99 and 195.23 kWh, respectively, under the tree-shaded scenario. The energy usage for the study case with a four-fold increase in window area was 38.84 kWh lower than the classroom in a concrete area microclimate. Therefore, the tree-shaded classroom can be designed with a larger glass wall than that of a classroom in a concrete area microclimate because the tree-shaded classroom is always shaded and experiences a cooler microclimate.

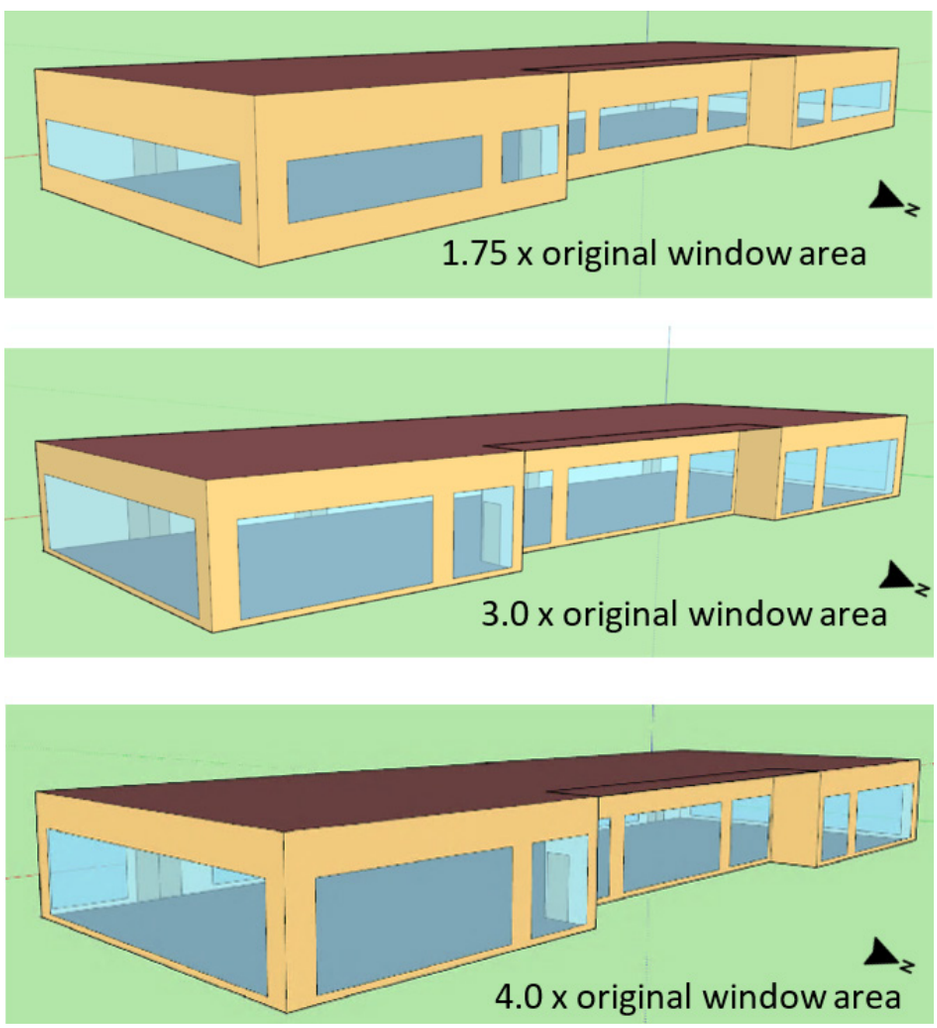


Figure 11. Window design variation for the studied building for the tree-shaded simulation scenario.

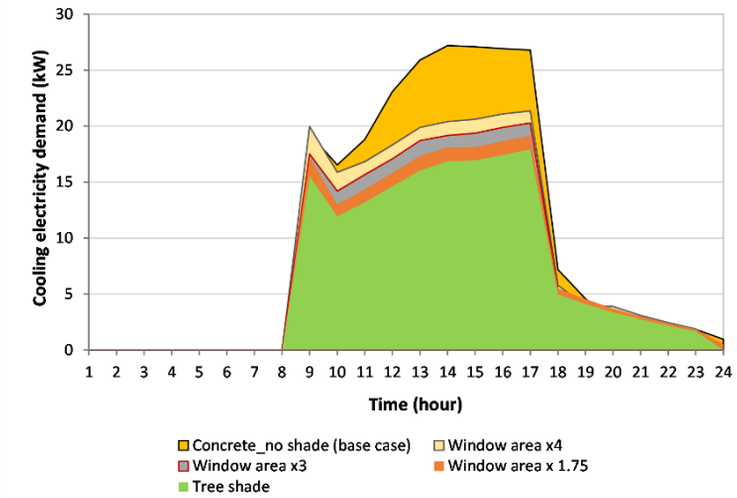


Figure 12. Cooling energy demand in the building with varying window areas.

5. Discussions

The primary objective of this study was to investigate the impact of tree shade on cooling energy savings. Our findings provide new insights into how microclimates, both with and without tree shade, influence building cooling energy needs. The results showed that the microclimate under tree shade reduces cooling electrical energy demand by 35% compared to areas without tree shade. A high proportion of latent heat was observed in the cooling coil load of the building covered by tree shade and this latent heat remains high during the nighttime. Nevertheless, the total cooling energy required for the building under tree shade is much lower than for the building without tree shade.

These findings align with the work of Rouhollahi et al. (2018) and Wu et al. (2019), who found that a proper tree arrangement could save 7-15% of cooling energy. The implications of these results are significant for energy-efficient building design. Specifically, buildings with tree shade can incorporate more windows and glass walls, while buildings without tree shade should use more thermal insulation. For example, applying 0.08-m polyurethane insulation to the building walls and roof is recommended to match the cooling energy reduction achieved by tree shade.

However, there are several limitations to this study. First, the microclimate data were collected over only seven days in winter. More climatic data should be recorded to assess cooling energy requirements across different seasons. Additionally, conducting simulations during the summer and throughout the entire year could provide further insights into energy-efficient designs that incorporate tree shade.

6. Conclusions

In conclusion, this research elucidates the important influence of microclimates on cooling energy requirements for buildings in hot, humid climates. The comparative analysis between shaded and unshaded environments revealed nuanced temperature differentials, with shaded areas experiencing lower air temperatures by 0.8°C to 8.0°C. Notably, the study demonstrated a 35% reduction in the electrical energy demand for air conditioning in buildings in shaded microclimates. Recommendations to equalize the energy needs of unshaded buildings include implementing polyurethane insulation for walls and roofs and considering strategic designs to maximize the window area. These findings underscore the importance of microclimate considerations in

optimizing energy efficiency in building design, particularly for hot, humid climates. By integrating these insights into architectural practices, stakeholders can contribute to sustainable and energy-conscious solutions to challenges posed by prevailing climatic conditions. Future studies should consider conducting simulations during the summer and throughout the entire year.

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Author Contributions

Conceptualization, S.S.; methodology, S.S.; software, W.A.; validation, W.A.; investigation, W.A.; formal analysis, S.S.; resources, S.S.; writing - original draft, S.S.; writing - review & editing, S.S.; visualization and supervision, S.S. Both authors agreed to the published version of the manuscript and declared no conflict of interest.

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