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RESEARCH ARTICLE **ENERGY**

Dynamic versus Quasi-Steady-State Simulation of Shading Strategies for Cooling Load Reduction: A Case Study of an Educational Building in Tripoli, Libya

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ABSTRACT

Buildings account for roughly 32% of global final energy consumption, and cooling represents the largest share of that demand in hot-arid climates, where educational buildings are particularly energy intensive due to long daily occupancy. This study evaluates five exterior shading configurations, a horizontal overhang, fixed horizontal louvers, louvers inclined at 15° and 30°, and an overhang combined with vertical fins, applied to the southern facade of a two-story, 1600 m² educational building at the University of Tripoli, Libya. The building was modeled in HAP, which applies a quasi-steady-state method, and in EnergyPlus (with SketchUp/OpenStudio), which applies a dynamic transient heat-balance method. A base case without shading was simulated in both tools before each shading system was applied in EnergyPlus. For the July design day, EnergyPlus predicted a peak cooling demand of 181.9 kW against 165 kW from HAP, 10.2% higher; for June, EnergyPlus predicted a total cooling consumption of 20,452 kWh against 38,268 kWh from HAP, 46.56% lower. For January, EnergyPlus predicted a peak heating load of 11.77 kW against 10.5 kW from HAP (12.1% higher) and a heating consumption of 10.56 kWh against 10,189 kWh from HAP (99.9% lower), reflecting HAP's tendency to average loads rather than resolve hourly transients. Among the shading systems, the 30° inclined louvers gave the largest annual cooling reduction (10.27%, from 136,886 to 122,833 kWh) and the largest peak demand reduction (1.51%), followed by 15° louvers (9.81%), horizontal louvers (9.10%), overhang with fins (7.46%), and the overhang alone (5.25%). Adopting this best performing system is estimated to avoid about 14.57 t CO2 per year, based on a national grid emission factor of 1.037 kg CO_2/kWh. All five systems increased annual heating consumption relative to the 147 kWh base case, up to 542 kWh (269%) for the 30° louvers, since the geometry that blocks summer solar gain also blocks winter solar gain. Shading selection should balance cooling savings against this heating penalty, and dynamic simulation should be preferred over quasi-steady-state tools when peak and part-load performance matter.

تحليل مقارن بين أسلوبي المحاكاة الديناميكية وشبه المستقرة لتقييم فعالية أنظمة التظليل الخارجي في خفض حمل التبريد: دراسة حالة تطبيقية على مبنى تعليمي بمدينة طرابلس، ليبيا

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الكلمات المفتاحية

أنظمة التظليل الخارجي
حمل التبريد
حمل التدفئة
EnergyPlus
المحاكاة الديناميكية
المحاكاة شبه الثابتة
المباني التعليمية
طرابلس
ليبيا

الملخص

تستهلك المباني نحو 32% من إجمالي الطاقة النهائية عالميًا، ويمثل التبريد الحصة الأكبر من هذا الاستهلاك في المناخات الحارة الجافة، حيث تُعد المباني التعليمية مستهلكة للطاقة بشكل خاص بسبب طول ساعات الإشغال اليومي. تقيّم هذه الدراسة خمس أنظمة تظليل خارجية: مظلة أفقية (Overhang)، وكاسرات أفقية ثابتة، وكاسرات مائلة بزاوية 15° و30°، ومظلة أفقية مدمجة مع زعانف رأسية، مطبقة على الواجهة الجنوبية لمبنى تعليمي من طابقين بمساحة 1600 م² في جامعة طرابلس، ليبيا. جرى نمذجة المبنى باستخدام برنامج HAP الذي يعتمد طريقة شبه ثابتة الحالة، وبرنامج EnergyPlus (مع SketchUp وOpenStudio) الذي يعتمد طريقة الاتزان الحراري الديناميكي العابر. جرت محاكاة الحالة المرجعية بدون تظليل في كلا البرنامجين، ثم طُبق كل نظام تظليل ومحاكاته باستخدام EnergyPlus. في يوم التصميم لشهر يوليو، توقع EnergyPlus ذروة حمل تبريد قدرها 181.9 كيلووات مقابل 165 كيلووات من HAP، بزيادة 10.2%؛ وفي شهر يونيو، توقع EnergyPlus استهلاكًا كليا للتبريد قدره 20,452 كيلووات ساعة مقابل 38,268 كيلووات ساعة من HAP، بنقص 46.56%. وفي شهر يناير، توقع EnergyPlus ذروة حمل تدفئة قدرها 11.77 كيلووات مقابل 10.5 كيلووات من HAP (زيادة 12.1%)، واستهلاك تدفئة قدره 10.56 كيلووات ساعة مقابل 10,189 كيلووات ساعة من HAP (نقص 99.9%)، وهو ما يعكس ميل HAP إلى حساب الأحمال كمتوسط بدل حلّها على أساس ساعي متغير. من بين أنظمة التظليل، حققت الكاسرات المائلة بزاوية 30° أكبر خفض في استهلاك التبريد السنوي (10.27%، من 136,886 إلى 122,833 كيلووات ساعة) وأكبر خفض في ذروة الطلب (1.51%)، تلتها الكاسرات المائلة 15° (9.81%)، ثم الكاسرات الأفقية (9.10%)، ثم المظلة مع الزعانف (7.46%)، وأخيرًا المظلة الأفقية وحدها (5.25%). ويُقدَّر أن اعتماد هذا النظام الأفضل أداءً يجنّب نحو 14.57 طن من ثاني أكسيد الكربون سنويًا، استنادًا إلى معامل انبعاث للشبكة الوطنية قدره 1.037 كيلوغرام CO_2 لكل كيلووات ساعة. وقد أدت جميع الأنظمة الخمسة إلى زيادة استهلاك التدفئة السنوي مقارنة

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بالحالة المرجعية البالغة 147 كيلووات ساعة، لتصل الزيادة إلى 542 كيلووات ساعة (269%) مع الكاسرات المائلة 30°، لأن الهندسة نفسها التي تحجب الكسب الشمسي الصيفي تحجب أيضًا الكسب الشمسي الشتوي. لذلك ينبغي أن يوازن اختيار نظام التظليل بين وفورات التبريد وهذه الكلفة الإضافية في التدفئة، كما ينبغي تفضيل المحاكاة الديناميكية على أدوات المحاكاة شبه الثابتة عند الاهتمام بأداء الذروة والأحمال الجزئية.

Introduction

The global electricity generation reached approximately 31,800 TWh in 2025, of which fossil fuels (coal, gas, and oil) supplied roughly 54 -55% of the total [1]. Buildings account for about 32% of global final energy consumption, and building construction and operations were responsible for roughly 34% of global energy related CO_2 emissions in 2023 [2]. In Libya, the residential sector alone consumes approximately 56% of the country's total electric energy [3], However, solar gain through windows typically accounts for 30%–50% of a building's total cooling load, making window glazing one of the largest single factors in sizing and operating the cooling system [4]. Reducing this gain through effective shading is therefore directly relevant to lowering both electricity demand and the associated carbon footprint of the building sector in Libya.

Cooling accounts for a large share of building energy use in hot-arid and hot-Mediterranean climates, where solar heat gain through glazing and uninsulated envelopes drives peak electricity demand during the warmest months. In Libya, this pattern is documented at the building scale: a digital-twin study of existing residential housing stock in Tripoli showed that upgrading roof and wall insulation together with the glazing type reduced the annual cooling load from 53.51 to 40.8 kWh/m² per year [5]. A survey of residential buildings in Al-Bayda, Libya, similarly found that orientation, solar exposure, and shading conditions were treated by occupants and designers as the primary passive-design variables available for reducing indoor heat gain, even where formal shading devices were absent [6].

Several studies have addressed cooling load prediction and reduction specifically for buildings in Tripoli. A comparison of five HVAC system configurations for a two-story residential house, simulated in EnergyPlus with SketchUp and OpenStudio, found that annual energy consumption ranged from about 44,000 kWh for the Packaged Terminal Heat Pump and Unitary systems to 71,213 kWh for the Ideal Air Loads system, roughly 61% higher [7]. A separate case study of a library building in Tripoli used the Hourly Analysis Program (HAP) to test a roof-cooling strategy, reducing the design-day peak cooling load in July from 32,242 kW to about 30,580 kW, a 5.15% reduction, with wall insulation and double glazing separately cutting wall and window cooling loads by 32% and 33.7% [8]. At the envelope-material level, a finite-difference model was developed to generate cooling load temperature difference values for the exterior wall types most common in Tripoli, hollow concrete block, limestone block, and hollow brick, validated against ASHRAE CLTD tables, and identified limestone block as the best-performing wall type [9]. Together, these studies confirm that cooling load in Tripoli is highly sensitive to envelope and glazing choices, but none of them evaluate exterior shading devices on the building facade, and none compare a steady-state and a dynamic simulation tool for the same building.

Educational buildings are a distinct building type because of their long daily occupancy and large window areas, and shading has been identified as an effective mitigation strategy in this sector. In a semi-arid climate in Algeria, combining indoor and outdoor shading techniques on an educational building reduced cooling load by up to 7% and, together with associated efficiency measures, cut combined energy use and CO2 emissions by up to 32% [10]. Studies from neighboring hot climates report a wide range of outcomes depending on shading geometry and orientation. In Darwin, Australia, horizontal overhangs reduced the cooling load of a town hall building by 9.2% to 15.5% depending on projection length, outperforming vertical fins, which achieved 5% to 8% [11]. In Erbil, Iraq, a HAP-based assessment of overhangs and side fins found that shading effectiveness depended strongly on window orientation, with peak summer savings of 19.21% for south-facing windows with overhangs, 25.19% for east-facing windows with fins, 16.93% for west-facing windows, and close to no benefit on north-facing windows [12]. A feasibility study of concrete louvers on a high-rise residential building in Sulaimani, Iraq, found that horizontal louvers consistently outperformed vertical louvers of the same projection depth, and that a single shallow louver produced a negligible effect while multiplying the number of louvers substantially increased the cooling load reduction [13].

Beyond fixed geometric shading, several studies have examined hybrid or adaptive approaches. Rooftop photovoltaic panels used as a shading layer over an uninsulated roof reduced summer heat gain by 10.87% while increasing winter heat loss by 3.8% in a moderate dry-warm climate [14], and a similar configuration in a humid subtropical climate reduced annual cooling load by about 5% (290 kWh/year) while increasing heating load by roughly 30 kWh/year [15], indicating that the summer-cooling benefit of shading is consistently accompanied by a winter-heating penalty across climates. A movable shading device controlled by an artificial neural network reduced window heat transfer by 86.3% during the cooling period and 9.7% during the heating period compared with a fixed 45° device, while also increasing the electricity output of an integrated PV system by up to 3.1% [16]. In a hot-climate office building in New Cairo, Egypt, an artificial neural network model predicted that adopting shading systems increased useful daylight illuminance by 27% while decreasing cooling loads by 27% [17]. A genetic-algorithm optimization of window solar gain found that a south-facing orientation with a shading projection of up to 20 cm minimized yearly energy demand, cutting yearly consumption by 3.1%, with the shading effect maximized for window-to-shading angles between 75° and 90° [18]. In Basrah, Iraq, combining phase-change material with roof shading using corrugated galvanized iron reduced cooling load by 18% and 5% respectively when tested separately on a residential unit [19].

Across this body of work, cooling load and shading performance are evaluated almost exclusively with a single simulation tool, either a dynamic engine such as EnergyPlus or DesignBuilder [7,15,20] or a quasi-steady-state tool such as HAP [8,12]. A foundational study on shading design and control for glazed facades established that cooling and lighting demand depend jointly on window-to-wall ratio, glazing properties, and shading control strategy [21], and the studies reviewed above confirm that fixed shading effectiveness depends strongly on facade orientation [11-13]. None of the studies reviewed here, however, compare a dynamic and a quasi-steady-state simulation tool for the same building, and none evaluate shading performance for an educational building in the hot-arid Mediterranean climate of Tripoli.

In this study, both gaps are addressed for a two-story educational building at the University of Tripoli. A base case model without shading is built and simulated in both HAP and EnergyPlus, and the two tools are compared for the same building geometry, envelope, and internal loads. Five shading configurations, a horizontal overhang, fixed horizontal louvers, louvers inclined at 15°, louvers inclined at 30°, and an overhang combined with vertical fins, are then applied to the southern facade and simulated in EnergyPlus to quantify their effect on annual cooling and heating consumption and on peak cooling demand. The remainder of this paper describes the case study building and simulation methodology, presents the comparison between HAP and EnergyPlus for the base case, reports the performance of each shading system, and discusses the implications for shading design and simulation tool selection in similar hot-arid climates.

Methodology

This study follows a simulation-based approach in four steps. First, a base case model of the case study building without shading is built independently in HAP and in EnergyPlus, using identical geometry, envelope properties, and internal loads. Second, the base case results from the two tools are compared for the same design conditions to quantify the effect of quasi-steady-state versus dynamic modeling on predicted cooling and heating loads. Third, five exterior shading configurations are designed for the building's southern facade using solar-geometry calculations for the local latitude, and each configuration is added to the EnergyPlus model. Fourth, the annual and peak cooling and heating performance of each shading configuration is compared against the base case to identify the most effective design.

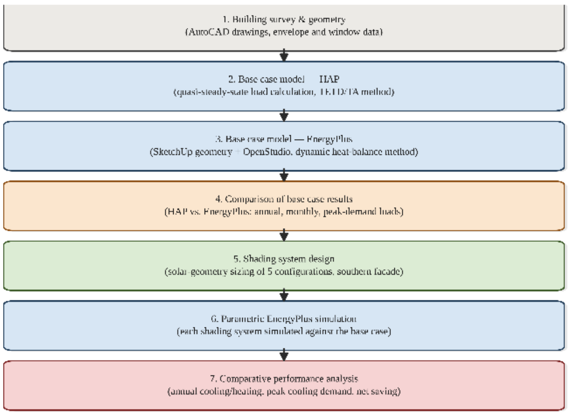

Figure 1: Methodological workflow adopted in this study

Case study building

The case study building (fig. 2) is a two-story educational facility at the University of Tripoli (32.894° N), Libya, with a total conditioned floor area of about 1600 m² and a floor-to-floor height of 3.3 m. The building houses classrooms and laboratories operated from 08:00 to 16:00. The southern facade carries about 30 windows, each 1.0 m wide by 2.0 m high, giving a glazed area of about 60 m² on a facade of about 330 m² (6.6 m × 50 m), for a window-to-wall ratio of 18.2%. Windows are single glazed (6 mm) with PVC frames, U-value 5.474 W/m²·K and solar heat gain coefficient (SHGC) 0.827. External walls are 240 mm block masonry with cement plaster (U = 2.40 W/m²·K), internal walls are 190 mm block masonry (U = 2.08 W/m²·K), and the roof is a 200 mm reinforced concrete slab with slope concrete, waterproofing, and a finishing layer (U = 1.69 W/m²·K), none of these assemblies include added thermal insulation. Table 1 lists the density, specific heat, conductivity, and thickness of each envelope layer.

Internal heat gains reflect the building's occupancy schedule: 328 occupants between 08:00 and 14:00, decreasing linearly to 30% of peak by 14:30 and remaining at that level until 16:00; a lighting load of 15,000 W; and an equipment load of 7,800 W from computers and laboratory instruments. These schedules and loads were applied identically in HAP and EnergyPlus, with an indoor design temperature of 24°C.

Table 3: Case study building structure .

Element	Layers (outer→inner)	Thickness (mm)	Density (kg/m³)	Specific heat (J/kg·K)	Conductivity (W/m·K)	U (W/m²·K)
External wall	Plaster	20	1856	840	0.72	2.40
	block	200	800	920	1.11	
	plaster	20	1856	840	0.72	
Internal wall	Plaster	20	1856	840	0.72	2.08
	block	200	800	920	1.11	
	plaster	20	1856	840	0.72	
Roof	Concrete	200	1920	840	1.10	1.69
	slope concrete	100	2240	840	1.30	
	masonry	30	1920	880	1.40	
	finishing	25	2560	790	1.80	
Window	Single glazing	6	–	–	–	5.474

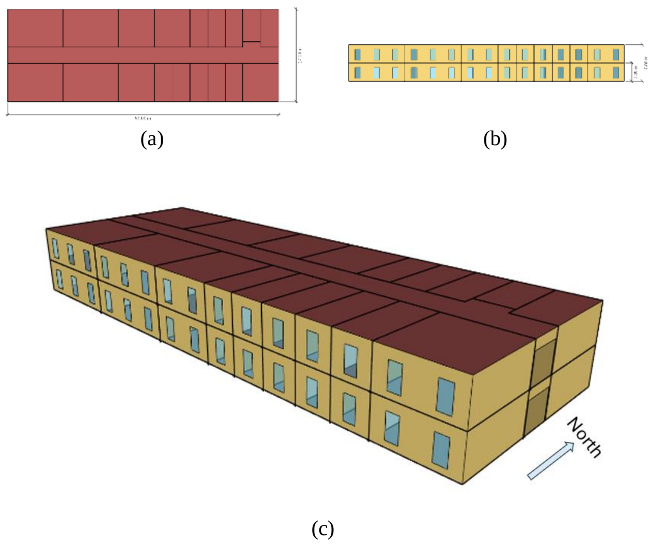

Figure 2: Case Study Building Geometry, (a) Top View, (b) Side View (c) 3D View

Simulation tools

Two complementary tools were used. The Hourly Analysis Program (HAP) calculates cooling and heating loads using the Total Equivalent Temperature Difference/Time-Averaging (TETD/TA) method, a quasi-steady-state procedure in which the building is assumed to reach thermal equilibrium and loads are averaged over the calculation period rather than resolved at each time step. HAP was used to build the geometric and thermal representation of the base case, run annual and design-day load calculations, and generate the load breakdown by envelope component.

EnergyPlus (version 24.1.0), developed by the U.S. Department of Energy, was used for the dynamic simulations. The building geometry was created in SketchUp and passed to EnergyPlus through the OpenStudio plug-in, which was also used to assign material and construction properties, internal load schedules, and weather data. EnergyPlus solves a transient heat-balance equation at each simulation time step, so it captures the buildup and decay of heat storage in the building mass and the time lag between solar gain and cooling demand, effects that a quasi-steady-state method averages out. The building geometry, envelope surface areas, and total volume were kept identical in the two tools so that the comparison isolates the effect of simulation method rather than model geometry.

The weather data were obtained from a Typical Meteorological Year (TMYx) file for Tripoli (32.894° N, 13.276° E), built from thirteen years of NCEI ISD/ERA5 records (2011–2025) [22].

Governing Equations

EnergyPlus solves a transient heat balance for each thermal zone at each time step:

$$\rho_z V_z c_p \frac{dT_z}{dt} = \sum_{i=1}^{N} Q_{conv,i} + \sum_{k=1}^{M} \dot{m}_k c_p (T_k - T_z) + Q_{sys} + Q_{inf} \qquad (1)$$

where:

- ρ_z = zone air density (kg/m³)
- V_z = zone air volume (m³)
- c_p = specific heat of air (J/kg·K)
- T_z = zone air temperature (K), $\frac{dT_z}{dt}$ = its rate of change with time
- $Q_{conv,i}$ = convective heat gain from interior surface i (summed over N surfaces)
- $\dot{m}_k$ = mass flow rate of air stream k, T_k = its temperature
- Q_{sys} = heat added / removed by the HVAC system
- Q_{inf} = heat gain / loss from infiltration

Conduction through each opaque surface (walls, roof) is calculated using a Conduction Transfer Function (CTF), which relates the current surface heat flux to a weighted series of past surface temperatures and heat fluxes, so that the thermal mass and time lag of the wall and roof assemblies are represented explicitly. Solar heat gain through the glazing is calculated at each time step from the incident direct and diffuse radiation, the glazing's angle-dependent transmittance, and the shading multiplier contributed by each exterior shading device.

HAP calculates the cooling load using the Transfer Function Method with the Total Equivalent Temperature Difference/Time Averaging (TETD/TA) procedure. The instantaneous heat gain through an opaque surface is first calculated as:

$$q = UA(TETD) \qquad (2)$$

Where:

- q = instantaneous heat gain through the surface (W)
- U= surface thermal transmittance (W/m²·K)
- A = surface area (m²)
- $TETD$ = Total Equivalent Temperature Difference ($°C$), an empirical quantity that already incorporates the effect of solar radiation, outdoor temperature, and the surface's thermal mass through tabulated weighting factors

The resulting hourly heat gains are then converted to a cooling load by applying a set of time-averaging weighting factors that redistribute a fraction of each hour's heat gain into subsequent hours, approximating the damping and delay effect of the building's thermal mass without solving a full transient heat balance. This averaging step is the methodological source of the systematic differences from EnergyPlus reported in the Results and Discussion section, because the weighting factors are generic rather than model specific, TETD/TA tends to smooth short-duration peaks and can over or under state monthly consumption relative to an explicit hour by hour solution.

Base case model

For computational efficiency, the entire conditioned area was modeled as a single thermal zone in both tools, an acceptable simplification for a study focused on envelope- and shading-driven cooling load rather than inter-zone heat exchange; internal loads were nonetheless assigned by conceptual sub-space (classrooms and laboratories) to preserve realistic load distribution. All four facades were modeled as fully exposed to solar radiation, so the base case represents the maximum-solar-gain condition of the building before any shading is added. This base case, without any external shading device on any facade, is the reference against which every shading configuration described below is compared.

Shading system design

Five fixed exterior shading configurations were designed for the southern facade windows (width 1.0 m, height 2.0 m, sill height 0.75 m, spacing 2.4 m) and applied only to that facade, which receives the longest daily direct solar exposure of the four orientations at this latitude. Overhang and louver depths were sized from solar geometry. For a window of height H and a shading device with horizontal projection D, the vertical shadow angle (VSA) the device must block is:

$$VSA = \arctan\left(\frac{\tan(\beta)}{\cos(HSA)}\right) \qquad (3)$$

where β is the solar altitude and HSA is the horizontal shadow angle, the absolute difference between the solar azimuth and the facade orientation. The required overhang depth follows as:

$$D = \frac{H}{\tan(VSA)} \qquad (4)$$

and the corresponding vertical fin depth, for a window of width W, is:

$$F = \frac{W}{\tan(HSA_{cutoff})} \qquad (5)$$

For the south-facing facade (orientation 180°) at solar noon on 21 June in Tripoli (β = 80.5°, azimuth 180°), HSA = 0° and Eq. (2) gives D ≈ 0.334 m, which shades the window only at the summer solstice. A more conservative depth, using a cut-off altitude of 57° representative of the broader cooling season, gives D ≈1.3 m. Vertical fin depth, using a cut-off azimuth deviation of 61°, gives F ≈ 0.55 m from Eq. (5).

The five systems tested were:

1. System 1, horizontal overhang: a single fixed panel of 1.3 m depth above each window.
2. System 2, fixed horizontal louvers (0°): the same total shading depth (1.3 m) distributed across 10 parallel louvers, each 0.13 m deep, giving equivalent solar blockage with less obstruction of view and daylight than a single deep overhang.
3. System 3, louvers inclined at 15°: 10 louvers of the same spacing, tilted 15° from horizontal; the horizontal projection of each louver is reduced by cos(15°), giving an effective depth of about 0.126 m per louver.
4. System 4, louvers inclined at 30°: as System 3, but tilted 30°, giving an effective horizontal depth of about 0.113 m per louver.

5. System 5, overhang with vertical fins: a 0.55 m horizontal overhang combined with two 0.55 m vertical fins flanking each window, sized to block the low-angle, high-azimuth-deviation sun that horizontal shading alone misses during the mid-morning and mid-afternoon.

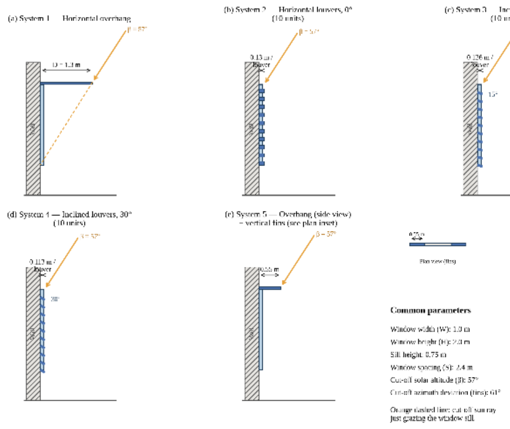

Figure 3: Geometry of the five exterior shading systems applied to the southern facade

Table 2: Shading system configurations applied to the southern facade.

System	Configuration	Projection depth
Base case	No shading	–
System 1	Horizontal overhang	1.3 m
System 2	horizontal louvers, 0°	0.13 m per louver
System 3	Inclined louvers, 15°	0.126 m per louver
System 4	Inclined louvers, 30°	0.113 m per louver
System 5	Overhang + vertical fins	0.55 m overhang, 0.55 m fins

Table 2 summarizes the projection depth and configuration of each system. Each configuration was implemented as an external fixed shading surface in EnergyPlus, which computed the resulting shading coefficient and effective SHGC reduction for each simulation hour. All other model inputs, geometry, envelope properties, internal loads, and schedules, were kept identical to the base case, so that differences in the results are attributable to shading geometry alone.

Assumptions and Limitations

Several simplifying assumptions were required to make the simulation tractable. First, the building was modeled as an isolated structure with an unobstructed sky view on all four facades, no adjacent buildings, boundary walls, or mature trees on the campus were represented as external shading or wind obstructions. Because the surrounding campus does include nearby structures and scattered tree cover, the reported cooling loads should be interpreted as an upper bound. Second, internal load schedules and HVAC operating hours (08:00–16:00) were applied uniformly across the full simulated year, the university's actual academic calendar is not accounted. Finally, infiltration was represented using default air change assumptions.

Results and Discussion

Base case: EnergyPlus versus HAP

Table 3 compares the annual end-use energy breakdown of the unshaded base case as computed by each tool. Cooling was the dominant end use in both, but the two tools disagreed sharply on its magnitude. EnergyPlus attributed 136,886 kWh (59% of a 230,988 kWh total) to cooling, while HAP attributed 234,368 kWh (66.21% of a 353,976 kWh total), 71.2% higher than the EnergyPlus estimate. HAP's total annual consumption estimate was 53.2% higher than EnergyPlus's overall, driven mainly by cooling and by heating, where HAP's 45,652 kWh exceeded EnergyPlus's 147 kWh by a factor of more than 300.

Table 3: Annual end-use energy consumption, base case

End use	EnergyPlus (kWh)	%	HAP (kWh)	%	End use
Cooling	136,886	59.0%	234,368	66.21%	136,886
Heating	147	0.1%	45,652	12.90%	147
Lighting	57,333	24.8%	45,200	12.77%	57,333
Equipment	36,622	15.9%	28,756	8.12%	36,622
Total	230,988	100%	353,976	100%	230,988

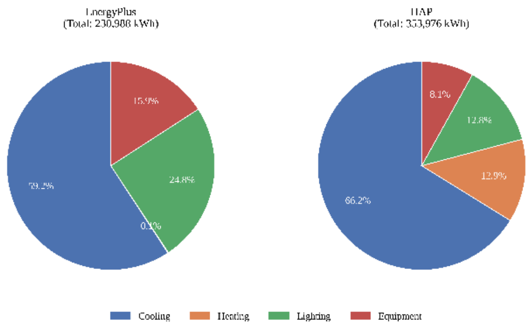

Figure 4: Annual end-use energy consumption breakdown, base case: (a) EnergyPlus; (b) HAP.

The same pattern held at finer time resolution (Table 4). For the July design day, EnergyPlus predicted a peak cooling demand of 181.9 kW against 165 kW from HAP, 10.2% higher. For June, EnergyPlus predicted a monthly cooling consumption of 20,452 kWh against 38,268 kWh from HAP, 46.56% lower. For January, EnergyPlus predicted a peak heating load of 11.77 kW against 10.5 kW from HAP (12.1% higher) and a heating consumption of 10.56 kWh against 10,189 kWh from HAP (99.9% lower).

Table 4: Base case comparison at design-day and monthly resolution

Metric	Period	EnergyPlus	HAP	Diff.
Peak cooling demand	July (DDY)	181.9 kW	165.0 kW	10.2%
Cooling consumption	June	20,452 kWh	38,268 kWh	46.56%
Peak heating load	January	11.77 kW	10.5 kW	12.1%
Heating consumption	January	10.56 kWh	10,189 kWh	99.9%

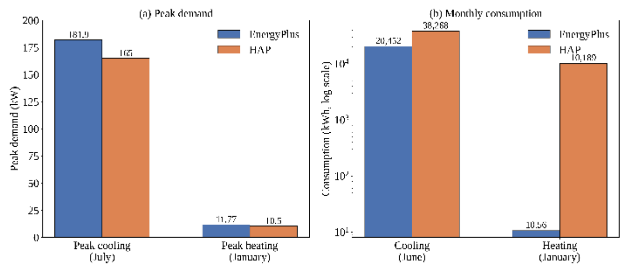

Figure 5: EnergyPlus vs. HAP: base case (a) peak demand and (b) monthly consumption

These discrepancies follow from the two tools' different heat-transfer formulations. EnergyPlus solves a transient heat-balance equation at each simulation time step, so it captures the storage and release of heat in the building mass and the lag between solar gain and the resulting cooling load, effects that are pronounced during rapid summer afternoon temperature swings and that produce the higher instantaneous peak. HAP's quasi-steady-state method instead assumes the building reaches thermal equilibrium over the calculation period, so short-duration peaks are smoothed and monthly consumption is calculated from time-averaged loads rather than resolved hour by hour. This systematically inflates monthly and annual consumption totals relative to the transient calculation, particularly for heating, where the small absolute base-case load (10.56 kWh in January from EnergyPlus) leaves little room for averaging error before the relative difference becomes large, as reflected in the 99.9% gap.

Effect of shading systems on cooling and heating loads

The effect of the five shading systems on annual cooling and heating consumption and on peak cooling demand, all computed in EnergyPlus and compared against the base case. All five systems reduced cooling consumption. System 4 (30° inclined louvers) gave the largest reduction, 10.27% (136,886 to 122,833 kWh), and the largest reduction in peak cooling demand, 1.51% (181,912 to 179,166 kW). System 3 (15° inclined louvers) followed at 9.81% cooling reduction and 1.37% peak reduction. System 2 (fixed horizontal louvers) reduced cooling by 9.10% and peak demand by 1.19%. System 5 (overhang with vertical fins) reduced cooling by 7.46% and peak demand by 1.25%. System 1 (horizontal overhang alone) gave the smallest cooling reduction, 5.25%, and the smallest peak reduction, 0.88%.

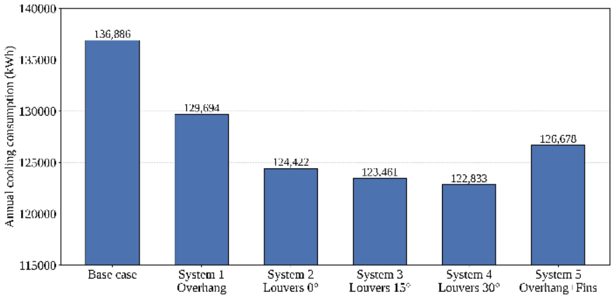

Figure 6: Annual cooling consumption: base case vs. shading systems

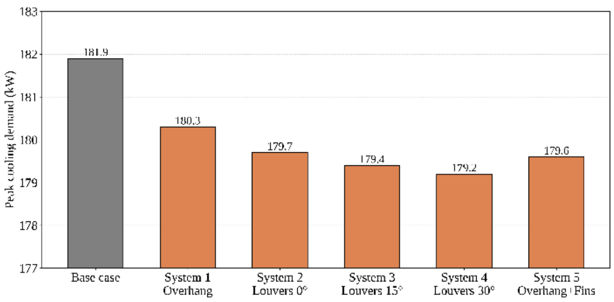

Figure 7: Peak cooling demand (July design day): base case vs. shading systems

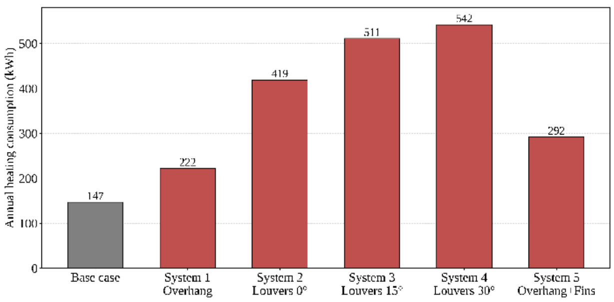

Figure 8: Annual heating consumption: base case vs. shading systems

The ranking shows that distributing the same total shading depth across multiple inclined louvers outperforms a single deep overhang of equal total depth: System 2 (10 horizontal louvers, 1.3 m combined depth) cut cooling consumption almost twice as much as System 1 (a single 1.3 m overhang), even though both block the same vertical shadow angle at solar noon. Inclining the louvers to 15° and then 30° added a further, smaller improvement, because the steeper angle intercepts more of the lower-altitude morning and afternoon sun that a horizontal louver array passes underneath.

Every shading system increased heating consumption relative to the 147 kWh base case, because the geometry that blocks high-angle summer sun also blocks the lower-angle winter sun that contributes useful passive heating. The increase scaled with cooling-season effectiveness, from 222 kWh (+51.0%) for System 1 to 542 kWh (+268.7%) for System 4. In absolute terms, however, the heating penalty remained minor next to the cooling saving for every system. Ranked by absolute net annual saving, System 4 performed best (13,658 kWh), followed by System 3 (13,061 kWh), System 2 (12,192 kWh), System 5 (10,063 kWh), and System 1 (7,117 kWh). Ranked instead by the ratio of cooling saved to heating added, the order changes: System 1 saves 95.9 kWh of cooling for every kWh of added heating and System 5 saves 70.4 kWh per kWh added, both more efficient ratios than System 4's 35.6 kWh per kWh added. The 30° louvers extract the largest absolute benefit from the southern facade but do so less efficiently per unit of winter solar gain sacrificed than the simpler overhang or the overhang-with-fins configuration. This is a larger reduction than the 6.2% attributed to shading optimization in a bundled NZEB measures study of a Tripoli building [23], consistent with the larger, purpose-sized shading geometries tested here compared to a generic shading measure evaluated alongside five other efficiency interventions.

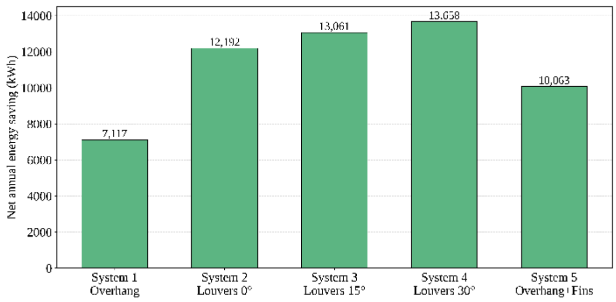

Figure 9: Net annual energy saving by shading system (cooling saved minus heating added, relative to base case).

These shading results were obtained using EnergyPlus. Given that HAP's quasi-steady-state method overestimated cooling consumption by 46.56% and heating consumption by more than 99% for the unshaded base case, a shading evaluation performed in HAP alone would be expected to carry a comparable bias, which reinforces dynamic simulation as the more reliable basis for shading system selection in this climate.

Environmental impact: avoided CO_2 emissions

The annual energy saving of each shading system was converted into an equivalent reduction in carbon dioxide emissions using:

$$Q_{CO_2} = EF_{CO_2} \times E_{saving} \qquad (6)$$

Where Q_{CO_2} is the avoided CO_2 mass (kg/year), EF_{CO_2} is the emission factor of the national electricity grid, taken as 1.037 kg CO_2/kWh [24-26], and E_{saving} is the annual energy saving of each shading system relative to the base case (kWh), taken here as the net saving (cooling energy saved minus heating energy added).

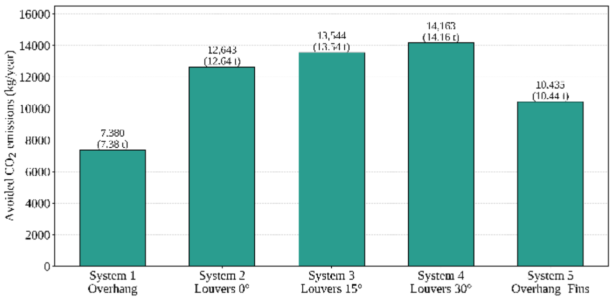

Figure 10: Estimated Annual CO2 emissions avoided by each shading systems

The 30° inclined louvers (System 4) again perform best, avoiding an estimated 14,163 kg (14.16 t) of CO_2 per year on a net saving basis, or 14,573 kg (14.57 t) if only the cooling energy reduction is counted. System 1 (the horizontal overhang) gives the smallest reduction, 7,380 kg (7.38 t) per year. Fig. 9 follows the same ranking as the net energy saving in Fig. 8, because the emission factor is applied uniformly across systems, the environmental benefit of shading scales directly with its energy performance, so no system changes rank when the comparison is made in emissions terms rather than energy terms. Cumulated over a typical building service life of 25 - 30 years, the 30° louvers would avoid on the order of 354 - 425 t of CO_2, a relevant quantity for building level decarbonization targets given that Libya's electricity generation remains almost entirely fossil fuel based.

Conclusion

This study compared a quasi-steady-state simulation tool (HAP) and a dynamic simulation tool (EnergyPlus) for the same educational building in Tripoli, Libya, then used the dynamic model to test five exterior shading configurations on the building's southern facade. The following conclusions follow from the results.

1. HAP and EnergyPlus disagree substantially on both the magnitude and the timing of the base case building's thermal loads. HAP's total annual energy estimate was 53.2% higher than EnergyPlus's (353,976 vs 230,988 kWh), with the largest disagreement in heating consumption, where HAP's time-averaged method produced an estimate more than 300 times larger than EnergyPlus's transient calculation for the same month.

2. The disagreement is not confined to annual totals. At the July design day, EnergyPlus predicted a 10.2% higher peak cooling demand than HAP, while for monthly consumption in June, HAP predicted 46.56% more cooling energy use than EnergyPlus, showing that the two tools can disagree in opposite directions depending on whether instantaneous peak or averaged consumption is being compared.

3. All five shading systems reduced annual cooling consumption and peak cooling demand relative to the unshaded base case, with 30° inclined louvers giving the largest cooling reduction (10.27%) and peak demand reduction (1.51%), followed by 15° louvers (9.81%), fixed horizontal louvers (9.10%), an overhang with vertical fins (7.46%), and a horizontal overhang alone (5.25%).

4. Every shading system increased annual heating consumption because the same geometry that blocks high-angle summer sun also blocks low-angle winter sun, with the increase ranging from 51.0% (overhang) to 268.7% (30° louvers) relative to a small 147 kWh base case. In absolute terms this penalty was minor next to the cooling savings for every system, giving a net annual saving between 7,117 kWh (overhang) and 13,658 kWh (30° louvers).

5. The system with the largest absolute net saving (30° louvers) was not the most efficient system per unit of heating penalty incurred; the horizontal overhang and the overhang-with-fins configuration returned more cooling savings per kWh of added heating load. Shading system selection should therefore depend on whether the design priority is maximum absolute energy reduction or the most efficient trade-off between summer and winter performance.

6. Because HAP's quasi-steady-state method overestimated both cooling and heating loads relative to EnergyPlus for the same unshaded building, dynamic simulation is the more defensible basis for evaluating shading systems in this hot-arid Mediterranean climate, particularly when peak demand or part-load performance is of interest.

These conclusions apply to fixed shading devices on a single south-facing facade of a single-zone model. Movable or automated shading and other facade orientations are not addressed. Future work should extend the comparison to adjustable shading strategies and validate the simulated loads against metered energy data from the case study building.

The annual energy estimates also assume year-round operation on the 08:00–16:00 schedule. The University of Tripoli does not operate 365 days a year: the academic calendar includes an extended summer recess, typically from early July to mid-September, which coincides with the period of highest cooling demand identified in this study. A full-year schedule therefore likely overstates the realizable annual savings, although the per hour load reductions remain valid whenever the building is occupied. Future work should replace the fixed schedule with a real-time, calendar-accurate occupancy profile and validate the simulated loads against metered utility data.

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References

[1] N. Fulghum, W. Suarez, K. Altieri, and K. Rangelova. "Solar surge halts fossil generation rise as clean power meets all demand growth and renewables overtake coal Global Electricity Review 2026." 2026. [Online]. Available: https://ember-energy.org/latest-insights/global-electricity-review-2026/

[2] "Global Status Report for Buildings and Construction 2024/25 Not just another brick in the wall."

[3] A. Aqila, Y. Nassar, H. El-Khozondar, and S. Suliman. "Design of Hybrid Renewable Energy System (PV/Wind/Battery) Under Real Climatic and Operational Conditions to Meet Full Load of the Residential Sector: A Case Study of a House in Samno Village– Southern Region of

Libya." *Wadi Alshatti University Journal of Pure and Applied Sciences*, pp. 168–181, Apr. 2025, https://doi.org/ 10.63318/waujpasv3i1_23

[4] M. Abdunnabi, N. Etiab, Y. Nassar, H. El-Khozondar, and R. Khargotra. "Energy savings strategy for the residential sector in Libya and its impacts on the global environment and the nation economy." *Advances in Building Energy Research*, vol. 17, no. 4, pp. 379–411, Jul. 2023, https://doi.org/ 10.1080/17512549.2023.2209094

[5] S. Albarssi, S. Hou, and E. Latif. "Thermally Future-Proofing Existing Libyan Housing Stock with Biobased Insulation Materials and Passive Measures: An Empirical and Numerical Study Using a Digital Twin." *Buildings*, p., 2024, https://doi.org/ 10.3390/buildings14010175

[6] M. Ali, K. Uzunoğlu, and Ç. Özburak. "Shading and Air Flow Analysis on Selected Residential Buildings in Al-Bayda City, Libya." *International Journal of Sustainable Development and Planning*, p., 2021, https://doi.org/ 10.18280/ijsdp.160307

[7] S. Alghoul. "A Comparative Study of Energy Consumption for Residential HVAC Systems Using EnergyPlus." *American Journal of Mechanical and Industrial Engineering*, vol. 2, no. 2, p. 98, 2017, https://doi.org/ 10.11648/j.ajmie.20170202.16

[8] K. Mousay, Abdurahman.B.Harari, S. Sheibani, and M. Alkbir. "Reduce Cooling Load using AI-based KNN Enhanced Roof System (KNN-ERS): CASE STUDY (TRIPOLI- LIBYA)." *Journal of Information Systems Engineering and Management*, p., 2025, https://doi.org/ 10.52783/jisem.v10i5s.592

[9] A. Alhoush, S. Alghoul, and J. Hawisa. "Estimation of Cooling Load Temperature Diffrence for Exterior Walls of Buildings Located in Tripoli, Libya." vol. 10, pp. 1–19, 2021, https://doi.org/ 10.51646/jsesd.v10i1.95

[10] S. Rahmouni, and A. Mohammed. "IMPACT OF SHADING DEVICES ON COOLING LOAD IN EDUCATIONAL BUILDINGS." *Journal of Green Building*, p., 2024, https://doi.org/ 10.3992/jgb.19.2.223

[11] A. Mohammed, et al. "Reducing the Cooling Loads of Buildings Using Shading Devices: A Case Study in Darwin." *Sustainability*, p., 2022, https://doi.org/ 10.3390/su14073775

[12] B. Kareem. "An assessment of the effect of external window shading on heating and cooling loads in buildings in Iraq." *Sci. Rep.*, vol. 15, p., 2025, https://doi.org/ 10.1038/s41598-025-28760-6

[13] S. Bahaadin, B. Raof, and H. Abdulrahman. "Feasibility Study of Concrete Louvers for High-rise Residential Buildings in Terms of Cooling Energy Requirements." *ARO. The Scientific Journal of Koya University*, vol. 9, pp. 28–39, 2021, https://doi.org/ 10.14500/aro.10743

[14] A. Albatayneh, R. Albadaineh, A. Juaidi, R. Abdallah, M. Montoya, and F. Manzano-Agugliaro. "Rooftop photovoltaic system as a shading device for uninsulated buildings." *Energy Reports*, p., 2022, https://doi.org/ 10.1016/j.egyr.2022.03.082

[15] A. Albatayneh, R. Albadaineh, and D. Karasneh. "The impact of PV panels on cooling and heating loads of residential buildings in a humid subtropical climate zone." *Energy Exploration & Exploitation*, vol. 41, pp. 1762–1778, 2023, https://doi.org/ 10.1177/01445987231174770

[16] D. Jung, C. Lee, K. Lee, and M. Shin. "Evaluation of Building Energy Performance with Optimal Control of Movable Shading Device Integrated with PV System." *Energies (Basel).*, p., 2021, https://doi.org/ 10.3390/en14071799

[17] B. Gaber, C. Zhan, X. Han, M. Omar, and G. Li. "Employing ANN for daylight and energy prediction of hot climate office buildings: a case study of new Cairo, Egypt." *Architectural Engineering and Design Management*, vol. 20, pp. 1752–1776, 2023, https://doi.org/ 10.1080/17452007.2023.2254302

[18] J. Mustafa, S. Alqaed, M. Sharifpur, and J. Meyer. "Optimization of window solar gain for a building with less cooling load." *Case Studies in Thermal Engineering*, p., 2023, https://doi.org/ 10.1016/j.csite.2023.103890

[19] H. Naser and S. Hammadi. "Effect of Phase Change Material and Roof Shading on Cooling Load of Residential Unit in Basrah." *Basrah journal for engineering science*, p., 2022, https://doi.org/ 10.33971/bjes.22.2.6

[20] A. Damian, R. Filip, T. Catalina, R. Frunzulică, and G. Notton. "The influence of solar-shading systems on an office building cooling load." in *2020 7th International Conference on Energy Efficiency and Agricultural Engineering (EE&AE)*, 2020, pp. 1–4. https://doi.org/ 10.1109/eeae49144.2020.9279078

[21] A. Tzempelikos, and A. Athienitis. "The impact of shading design and control on building cooling and lighting demand." *Solar Energy*, vol. 81, pp. 369–382, 2007, https://doi.org/ 10.1016/j.solener.2006.06.015

[22] L. Lawrie, and D. Crawley. "Development of Global Typical Meteorological Years (TMYx)." Climate.OneBuilding.Org

[23] I. Shahboun, S. Alghoul, and E. Dekam. "Towards Net Zero Energy Building in Different North African Climates: A Case Study." in *2023 14th International Renewable Energy Congress (IREC)*, IEEE, Dec. 2023, pp. 1–6. https://doi.org/ 10.1109/IREC59750.2023.10389576

[24] I. Mangir, et al. "The Impact of Fuel Type on the Economic, Environmental, and Energy Performance of Power Generation Plants: A Case Study of the Ubari Gas Power Plant-Libya." *Wadi Alshatti University Journal of Pure and Applied Sciences*, https://doi.org/ 10.63318/waujpasv4i2_17

[25] A. Aisa, et al "Design and Analysis of an off-Grid PV/Wind/Battery/Diesel Generator Hybrid Renewable Power System for a Healthcare Facility in Gharyan, Libya." *Wadi Alshatti University Journal of Pure and Applied Sciences*, https://doi.org/ 10.63318/waujpasv4i2_09

[26] M. Inweer, et al. "Carbon footprint life cycle assessment of cement industry in Libya." *Discover Concrete and Cement*, vol. 1, no. 1, p. 37, Dec. 2025, https://doi.org/10.1007/s44416-025-00037-1