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Climate-Based Evaluation of Solar Radiation and Façade Shading Requirements in Ankara (1985–2060)

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Abstract

Rising temperatures and changing atmospheric conditions related to climate change are expected to influence solar radiation levels and increase their relevance for facade shading performance. This study evaluated the effects of projected changes in solar radiation on building envelope and shading design. Within this scope, solar radiation trends for Ankara were analyzed using NASA-POWER observational data for the period 1985–2024 and CMIP6 (MPI-ESM1-2-HR) projections for 2040–2060. Projections under the SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios indicate that future average annual solar radiation levels are unlikely to decline; rather, a moderate increase is projected across scenarios, with the highest absolute values occurring under SSP5-8.5. The results suggest that the façade shading ratio (L/H) may need to increase by approximately 2–4% relative to the current average value of 0.45 to maintain effective summer shading performance. The study supports climate-responsive architectural strategies by emphasizing the role of adaptive shading systems and low-transmittance glazing in future building envelope design.

1.0 INTRODUCTION

Climate change is one of the most significant concerns of the last century, and its effects are now being experienced. One of the areas strongly affected by climate change is the built environment, including buildings and their surroundings. Climate change has had increasing impacts worldwide over the past 30 years. The Intergovernmental Panel on Climate Change (IPCC) stated in its Fifth Assessment Report that the average temperature of the land and ocean worldwide increased by 0.85°C between 1880 and 2012. It also stated that the years from 1983 to 2012 were the warmest 30-year period in the last 800 years (Tang, 2019). Because of this, the consequences of climate change have become clearer. Floods, hurricanes, droughts, and wildfires occurring more often and with greater intensity are a few examples. Changes in rainfall patterns, rising sea levels, drought, volcanic activity, hurricanes, loss of biodiversity, stronger storms, more frequent heatwaves, changes in rainfall distribution, reversed ocean currents, and extreme flood events are climate-related events linked to global warming (Booth et al., 2012). As a result, climate change is negatively affecting the construction industry; in particular, rising temperatures are expected to increase demand for cooling energy and associated energy costs. This situation can reduce indoor comfort and contribute to damage in building envelopes due to extreme temperature and precipitation changes. In this context, shading systems have become one of the fundamental components of climate-resilient building design by reducing solar heat loads and energy consumption and by maintaining thermal and visual comfort indoors.

The original aspect of this study is its quantitative assessment of architectural facade shading ratios under climate change scenarios using past and future radiation data. The study examined solar radiation trends in Ankara for the period 2040–2060 and the associated façade shading ratio (L/H), defined as the proportion between overhang depth (L) and window height (H), used to determine shading efficiency requirements. In this context, the study aims to reveal the effects of future solar load changes on facade shading design from an architectural-scale climate adaptation perspective. To establish the theoretical background of this research, the following section reviews previous studies on solar radiation trends, facade shading strategies, and adaptive architectural responses under changing climate conditions.

2.0 LITERATURE REVIEW

Many studies have examined the solar radiation potential in Ankara using historical data. In a study using a six-year dataset, solar radiation was found to be high, and optimal tilt angles were determined to increase energy gain (Celik, 2006). Similar studies have also determined that Ankara's annual average global radiation is approximately 17.04 MJ/m²/day, indicating significant potential in terms of solar energy (Çaglar et al., 2013).

Prediction models have been developed using technological and artificial intelligence approaches to estimate solar radiation and evaluate its future potential. For example, hybrid and artificial neural network (ANN) models have been used to predict diffuse and global solar radiation over Ankara and the wider Central Anatolia Region, demonstrating strong predictive performance (Aras et al., 2006; Uzun and Arslantas, 2024). Between 2017 and 2019, a model was developed to estimate atmospheric losses and assess the sensitivity of radiation to variations in absorbing and scattering materials. This approach provides insight into how future climate scenarios may influence radiation levels (Bai et al., 2024). In addition, advanced tools allow wavelength-dependent radiation changes to be modeled, which is important for selecting efficient photovoltaic (PV) systems and designing shading elements that filter specific wavelengths (Kabakci and Eke, 2021). Climate-based daylight modeling techniques also support the prediction of facade and shading performance throughout the year. These methods enable more precise control of Annual Solar Exposure (ASE) and Spatial Daylight Autonomy (sDA), helping to balance daylight availability and thermal comfort under changing climatic conditions (Brembilla and Mardaljevic, 2019).

Quantitative climate-based analysis of facades integrates statistical methods, computer simulations, machine learning predictions, and geospatial modeling. These approaches enable architects and engineers to design facades that respond to environmental conditions, improve energy efficiency, and enhance climatic resilience. They also establish a link between climate science and contemporary architectural design practices

(Barrelas et al., 2021; Teo and Harikrishna, 2006; Malska and Wachta, 2016; Jarrin et al., 2025; Soudian and Berardi, 2024).

Adaptive or multi-angle facade systems can reduce cooling loads and improve daylight performance compared to fixed shading systems. These systems may be particularly relevant for Ankara’s projected warming trends in the 21st century, as they respond to seasonal variations in solar angles (Hannoudi, 2025; Salah and Kayılı, 2022). Comparative studies also emphasize the effectiveness of adjustable systems in optimizing daylight while limiting heat gain (Hraska, 2018).

Recent studies have examined climate-responsive facade systems and their performance under changing solar conditions. Research on solar incidence angles in double-skin facades indicates that radiation behavior and thermal performance vary depending on facade geometry (Tao et al., 2024). Reviews of dynamic and self-shading facade systems highlight their potential to reduce energy use in warm climates (Wang et al., 2025; Lionar et al., 2024). In addition, studies on multi-angled facade configurations suggest that geometric optimization can improve shading efficiency while maintaining adequate daylight levels (Hannoudi et al., 2025). These findings underline the relevance of adaptive facade strategies in regions where solar exposure is expected to increase.

For Turkey's climate zones, double-glazed windows with adaptable shading systems support passive solar design by offering higher solar heat gain/window heat loss ratios, especially in winter (Kon and Caner, 2020). Another study proposed an integrated lighting and solar shading strategy to increase energy efficiency and user comfort in temperate-humid climate conditions. According to other study, In the analyses conducted on the library annex building in Bursa with a high glass ratio, different shading systems and daylight-sensitive LED lighting scenarios were compared. According to the simulation results, the 0.4 m wide, 30° inclined brise soleil design showed the best performance, reducing energy consumption and carbon emissions by approximately 30%. This holistic approach effectively reduces overheating and glare issues while maintaining daylight comfort in high-glazing facades (Kaymaz and Manav, 2025). Another study examining dynamic shading systems compared the daylight and glare performance of flat facades with dynamic triangular cell shading systems in Mardin's hot-arid climate. Parametric analyses conducted using Rhino–Grasshopper and ClimateStudio software revealed that the dynamic facade system, which changes shape according to the sun's position, performs in accordance with LEED v4 standards. This system reduced annual solar exposure (ASE) by up to 10%, increased spatial daylight autonomy (sDA) to over 60%, and kept glare probability (DGP = 0.38) within comfort limits. As a result, it has been demonstrated that the dynamic shading system offers an effective solution for enhancing visual comfort and climate-responsive facade design (Özdemir and Çakmak, 2022).

Overall, existing studies indicate that Ankara has strong solar energy potential and that facade shading optimization contributes to reducing energy consumption while maintaining thermal and visual comfort. As average temperatures in Ankara are projected to rise toward 2060, adaptive and climate-responsive facade systems incorporating double glazing, dynamic shading, and climate-based daylight modeling are expected to play an increasingly important role in sustainable architectural design.

This study aims to quantify long-term changes in solar radiation in Ankara by combining NASA-POWER observations (1985–2024) with CMIP6 (Coupled Model Intercomparison Project Phase 6) projections from the MPI-ESM1-2-HR model for the period 2041–2060 under the SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios. Based on these datasets, the study translates projected solar conditions into an architectural facade design metric by estimating the required overhang ratio (L/H) for summer shading using solar geometry at local solar noon, defined as the time of day when the sun reaches its highest elevation angle at a specific geographic location. The novelty of the research lies in linking climate-projection-based radiation trends to a practical facade shading parameter that can inform climate-responsive and adaptive envelope design decisions in Ankara.

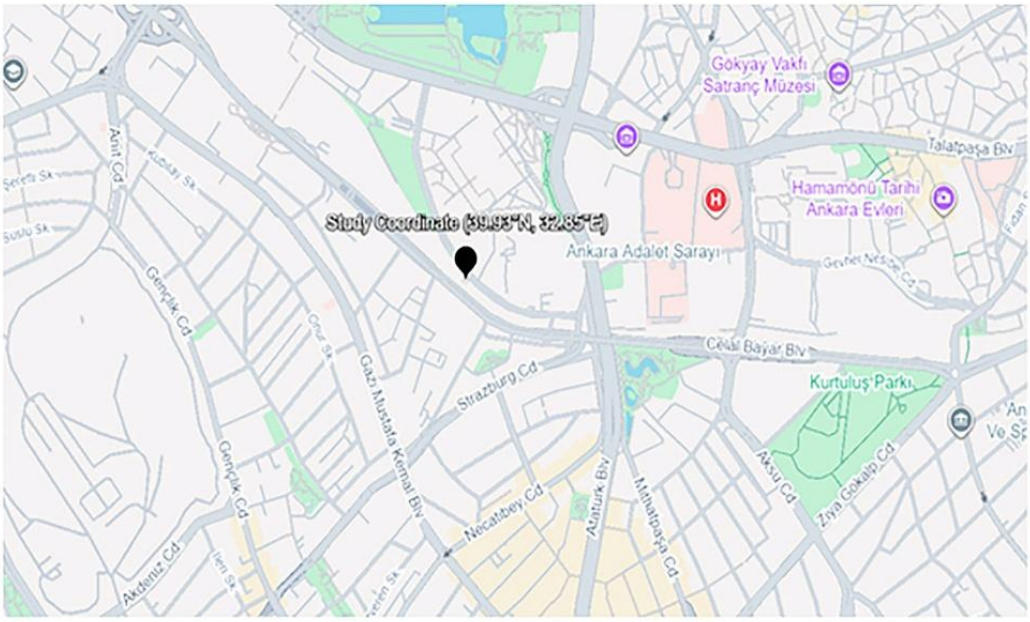
3.0 METHODOLOGY

3.1 Study Area

Ankara is located in Central Anatolia (39.93°N, 32.85°E) and is characterized by a continental climate with hot, dry summers and cold winters. Owing to its relatively high solar radiation levels and marked seasonal temperature variations, Ankara was selected as the study area to examine the potential implications of climate-driven changes in solar radiation on facade design (Figure 1).

(a)

(b)



(c)

Figure 1. Multi-scale geographical location of the study area: (a) macro-scale location of Ankara in Turkey; (b) meso-scale regional context of the study area within Ankara; (c) micro-scale map view of the specific coordinate (39.93°N, 32.85°E) used for NASA-POWER solar radiation analysis (Source: Google Earth (Google, n.d.); adapted by the author)

3.2 Data Collection

This study used two sources of monthly solar radiation data for Ankara: observational records obtained from NASA POWER and future projections derived from the CMIP6 (Coupled Model Intercomparison Project Phase 6) MPI-ESM1-2-HR (Max Planck Institute Earth System Model, high-resolution) model. The projections were evaluated under three Shared Socioeconomic Pathways (SSPs): SSP1-2.6 (low-emission), SSP2-4.5 (intermediate), and SSP5-8.5 (high-emission).

3.3 Analysis Method

In this study, a climate-based quantitative analysis method was employed to evaluate solar radiation and facade shading requirements for Ankara for the period 1985–2060. Historical radiation trends were assessed using (i) simple linear regression and (ii) Sen's slope estimator, a non-parametric statistical method used to estimate the magnitude of long-term trends in time-series data and robust to outliers. Monthly NASA-POWER values were aggregated into annual totals prior to trend testing (Figure 2).

Solar geometry was computed analytically in R using standard astronomical equations for solar declination and solar elevation angle at local solar noon, defined as the time of day when the sun reaches its highest elevation angle at a specific geographic location. Solar declination (δ), which represents the angular position of the sun relative to the Earth's equatorial plane, was calculated as:

$$\delta = 23.45° \cdot \sin[2\pi(284+n)/365]$$

The solar elevation angle (α) at noon was then derived from:

$\alpha = \text{asin}(\sin\varphi \cdot \sin\delta + \cos\varphi \cdot \cos\delta)$ where φ represents the latitude of Ankara and n denotes the day of the year. The required overhang ratio (L/H), defined as the ratio between overhang depth (L) and window height (H), was calculated as:

$$L/H = 1/\tan(\alpha).$$

All data processing, statistical analyses, solar-geometry calculations, and data visualizations were performed in R.

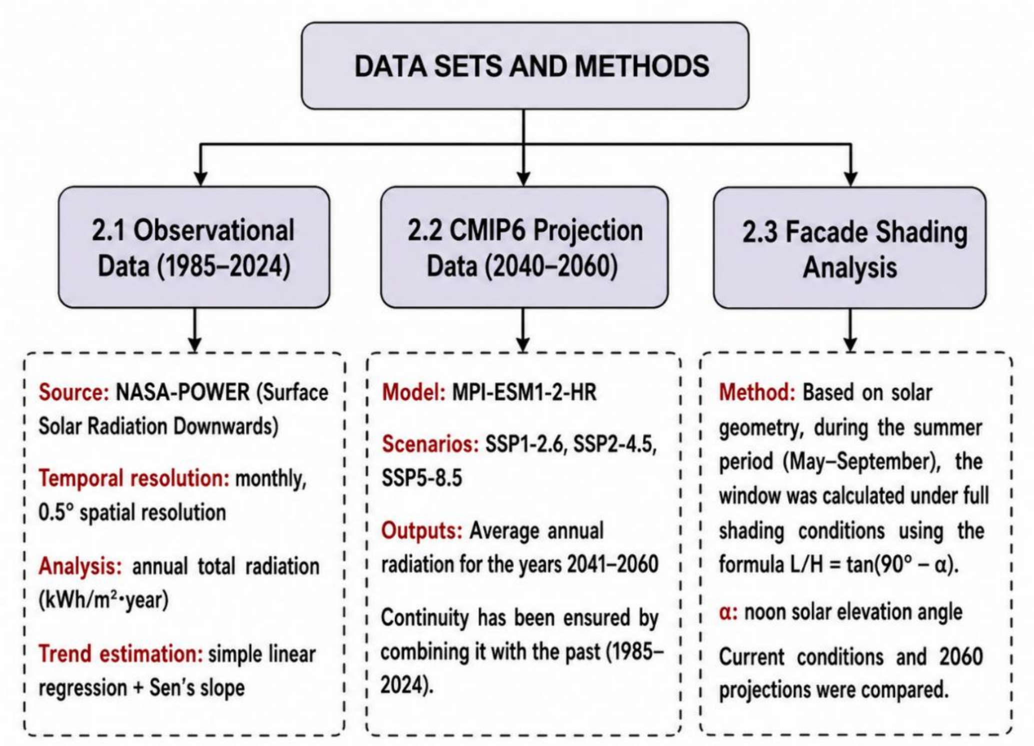


Figure 2. Overview of the research methodology, including data sources (NASA-POWER and CMIP6) and the analytical workflow for trend and shading calculations (created by the author)

3.4 Limitations and Uncertainties

Several limitations should be considered when interpreting the findings of this study. First, future solar radiation was projected using a single CMIP6 global climate model (MPI-ESM1-2-HR) under three SSP scenarios. CMIP6 projections inherently involve structural uncertainties related to model physics, parameterizations (e.g., cloud and aerosol processes), and internal climate variability; therefore, projected magnitudes may vary across alternative GCMs or multi-model ensembles. Second, the analysis focuses on a single study area (Ankara), and the findings should not be generalized to other climatic regions without further evaluation. Third, although radiation data were analyzed at monthly resolution, they were aggregated into annual indicators for trend assessment. While this approach facilitates long-term trend analysis, it may mask intra-seasonal variability relevant to facade performance. Finally, the facade shading ratio (L/H) was calculated based on solar geometry at local solar noon for south-facing facades and summarized for the May–September period. Although this provides a design-oriented metric, it does not fully capture microclimatic effects, urban shading conditions, or facade material and thermal interactions. Therefore, the results are intended to inform architectural-scale adaptation considerations rather than provide precise site-specific predictions.

4.0 RESULTS AND DISCUSSIONS

The Results and Discussion section presents, in sequence, the historical trends and CMIP6 projection analysis for the period 2040–2060, followed by changes in the facade shading ratio (L/H) and their implications. To support the architectural interpretation of the shading results, a schematic illustration of the south-facing facade shading geometry and the L/H definition applied in this study is shown in Figure 3.

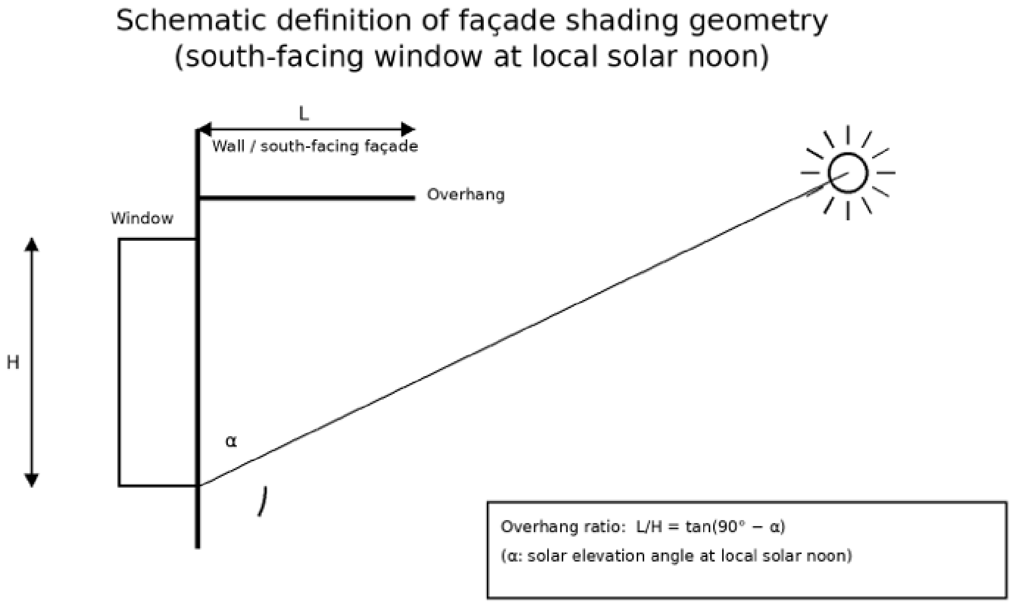


Figure 3. Schematic façade shading geometry at local solar noon (south-facing), defining L/H and solar elevation angle (α) (Prepared by the author)

4.1 Historical Trends and CMIP6 Projection Analysis (2040-2060)

Observed NASA-POWER data indicate an overall increasing trend in annual solar radiation in Ankara during 1985–2024, with an average annual increase of approximately 4.3 kWh/m²·year. Figure 4 presents the monthly distribution for 1985–2024, showing maximum radiation during May–September and a gradual rise in midsummer values after 2010. CMIP6 projections from the MPI-ESM1-2-HR model indicate scenario-dependent increases toward 2060, with the highest projected radiation levels under SSP5-8.5, followed by SSP2-4.5 and SSP1-2.6 (Table 1). The implications of these projected changes for facade shading requirements are discussed in Section 4.2.

Table 1. Observed (1985–2024) radiation trends and CMIP6-based projections (2040–2060) for Ankara under SSP1–2.6, SSP2–4.5, and SSP5–8.5 scenarios (kWh/m²·year) (Prepared by author using R)

Period / Scenario	Trend Direction	Interpretation
Observed (1985–2024)	Increasing	Statistically significant upward trend
SSP1–2.6	Increase	Moderate rise under low-emission pathway
SSP2–4.5	Increase	Stronger rise under intermediate pathway
SSP5–8.5	Increase	Highest projected radiation levels toward 2060

Note: The table summarizes the results of the author's R-based analysis of NASA-POWER observations and CMIP6 projections.

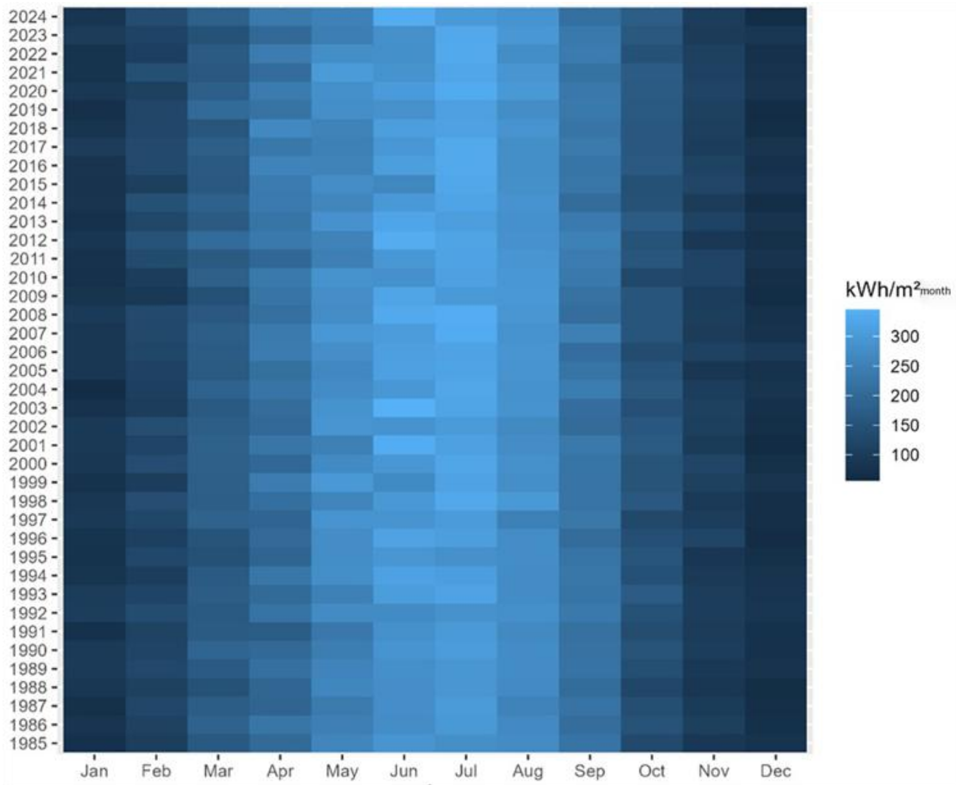


Figure 4. Monthly total solar radiation in Ankara (NASA POWER, 1985–2024), expressed in kWh/m² (generated by the author in R)

4.1.1 Observational data (1985–2024)

Historical monthly solar radiation data for Ankara were obtained from NASA-POWER (Surface Solar Radiation Downwards) for the period 1985–2024 (Figure 5).

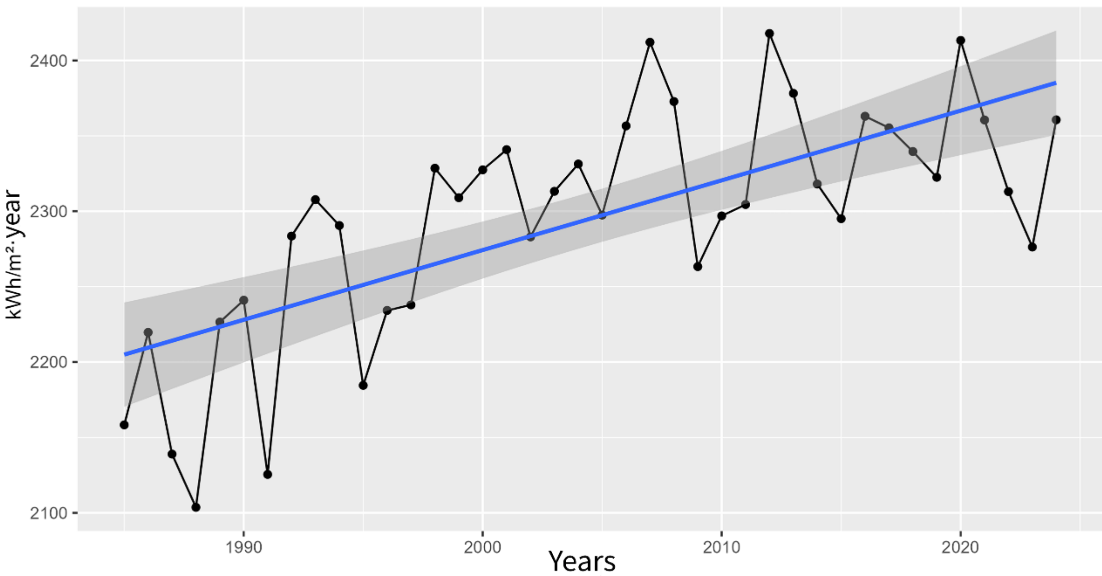


Figure 5. Annual total global solar radiation in Ankara (1985–2024) based on NASA-POWER data, showing linear regression trend (kWh/m²·year) (generated by the author in R)

The annual global solar radiation series for Ankara demonstrates considerable interannual variability from 1985 to 2024. Although certain years, including 1987, 2009, and 2022, exhibit notable declines, the overall trajectory indicates an increasing trend. The regression line shows a steady rise in annual totals, from roughly 2200 kWh/m²·year in the mid-1980s to beyond 2350–2380 kWh/m²·year in recent years, with periodic peaks (e.g., 1993, 2007, and 2020) exceeding 2400 kWh/m²·year. These variations highlight the influence of short-term meteorological variability superimposed on a longer-term climate signal. Overall, the observational dataset indicates a persistent upward tendency in solar radiation levels in Ankara, providing a quantitative basis for comparison with CMIP6 projections.

4.1.2 CMIP6 projection data (2040–2060)

CMIP6 projections from the MPI-ESM1-2-HR model under three Shared Socioeconomic Pathways (SSP1-2.6, SSP2-4.5, and SSP5-8.5) were used to examine potential changes in annual solar radiation toward 2060 (Fig. 6). The combined time series indicates a historically increasing trajectory from the mid-1980s to the 2020s, followed by scenario-dependent futures. By 2060, SSP1-2.6 forecasts a slight rise, stabilizing at around 2450 kWh/m²·year, whereas SSP2-4.5 shows a more pronounced increase above 2500 kWh/m²·year. SSP5-8.5 reaches the highest values, exceeding 2550 kWh/m²·year by mid-century.

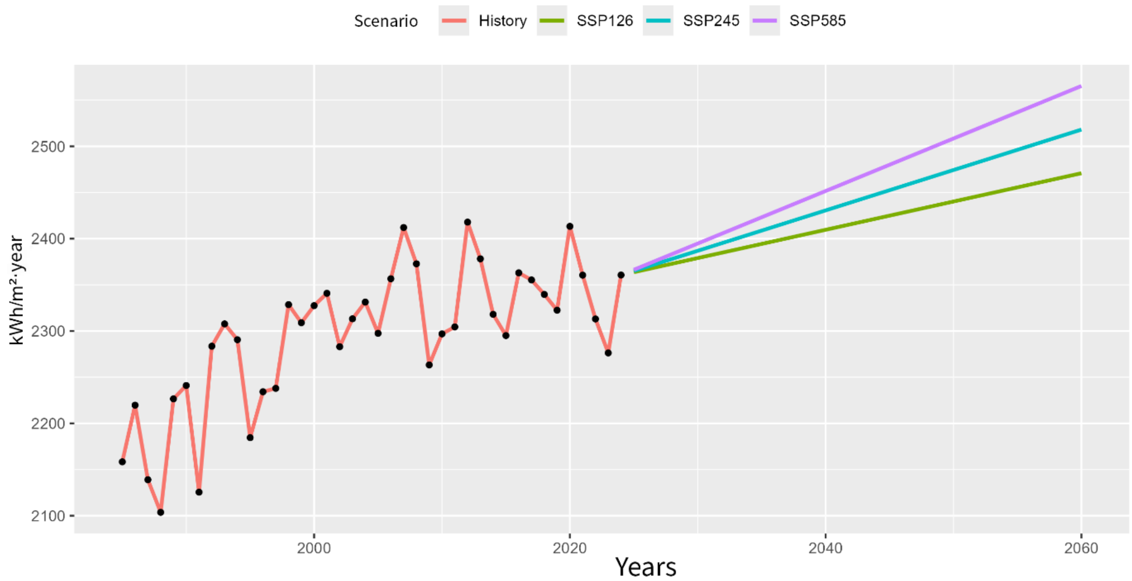


Figure 6. Annual global solar radiation in Ankara combining historical NASA-POWER data (1985–2024) and CMIP6 (MPI-ESM1-2-HR) projections (2040–2060) under SSP1–2.6, SSP2–4.5, and SSP5–8.5 scenarios (kWh/m²·year) (generated by the author in R)

4.2 Facade Shading (L/H) Change

Figure 7 compares current and 2060 overhang ratios (L/H = overhang depth/window height) for south-facing façades in Ankara under SSP1-2.6, SSP2-4.5, and SSP5-8.5. The current ratios were calculated from historical solar geometry using average solar elevation angles during the summer season (May–September), while the 2060 ratios were computed for each scenario using projected solar geometry. Across all scenarios, a slight increase in L/H is observed by 2060, indicating a need for deeper overhangs to maintain effective shading performance under future solar conditions. Seasonally, L/H reaches its minimum in June (≈0.45) and maximum in December (≈2.0), implying that short overhangs sufficient for summer shading while deeper projections are required for winter shading (Fig. 8). This seasonal variability suggests that future facade designs may benefit from adaptable or adjustable shading systems to manage solar gains throughout the year.

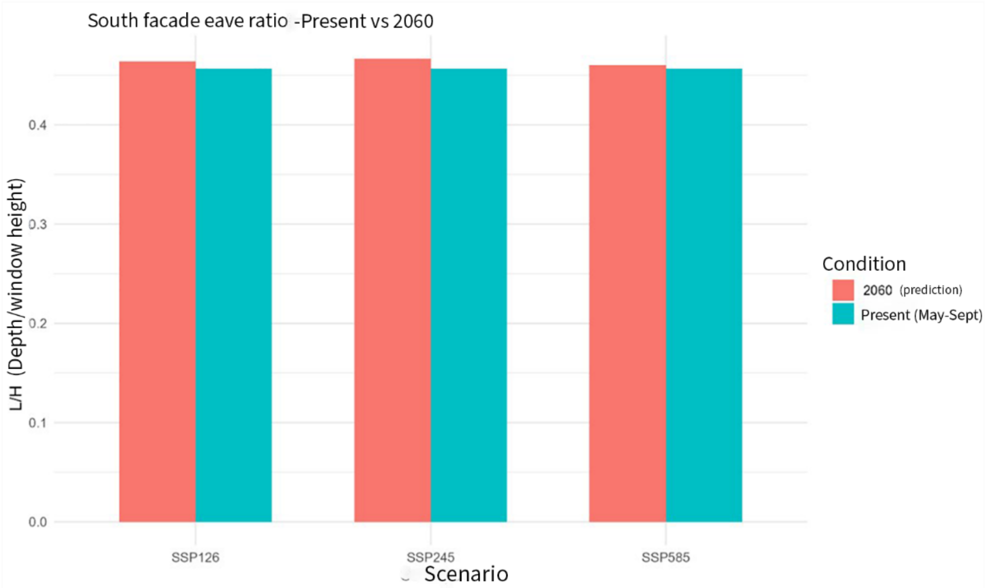


Figure 7. Comparison of south-facing façade overhang ratio (L/H) for the baseline period (1985–2024) and 2060 projections under SSP scenarios (generated by the author in R).

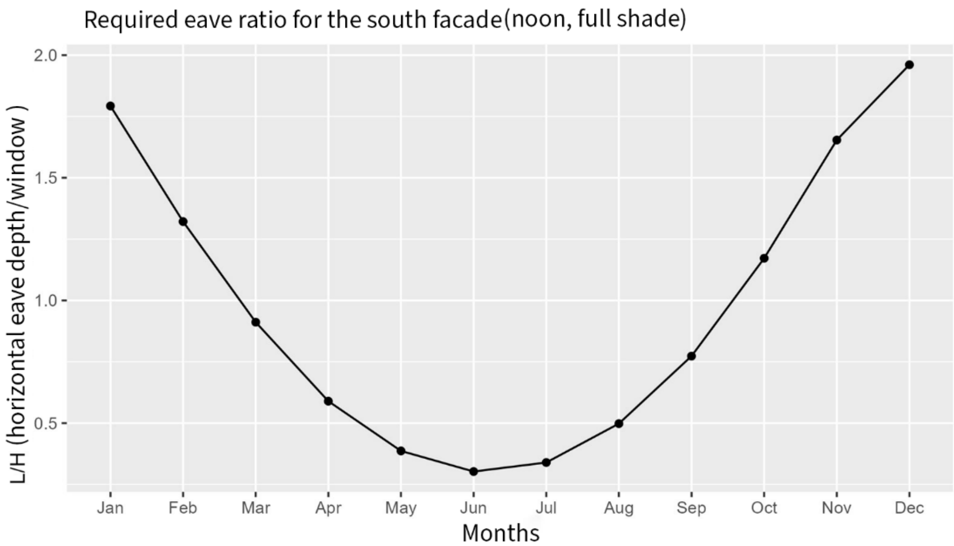


Figure 8. Seasonal variation of the required south-facing overhang ratio (L/H) for full shading at local solar noon (generated by the author in R)

Observational trends and CMIP6 projections consistently indicate increasing annual and seasonal solar radiation levels in Ankara. This increase may enhance thermal gains during summer months and necessitate a reassessment of shading strategies in facade design. Under such conditions, fixed shading systems may become dimensionally insufficient, whereas movable panels, low-g-value glazing, or dynamic shading elements may offer improved performance.

Increasing solar exposure may also influence building energy demand and operating costs. Previous studies demonstrate that higher solar heat gains can raise cooling energy consumption in order to maintain indoor thermal comfort, particularly in buildings with large glazed areas (Chen et al., 2025; Mohammed et al., 2022). These findings support the relevance of adaptive shading strategies in mitigating future cooling loads and associated operational costs.

Even under the high-emission SSP5-8.5 scenario, where radiation levels continue to increase, the persistence of peak summer values indicates that the minimum L/H ratio (≈0.45) should be maintained as a design reference. This underscores the continued importance of passive cooling strategies and highlights that climate-related impacts on facade morphology are scenario-dependent rather than linear.

Studies conducted in Central Anatolia and Mediterranean climate zones report comparable tendencies. Although different climate models and future periods were examined, common conclusions include decreasing heating demand, increasing cooling demand, and rising solar exposure under future scenarios (Pérez-Andreu et al., 2018; Dino and Akgül, 2019; Matos et al., 2022). Unlike many previous studies that primarily focus on energy demand, the present study translates projected radiation changes into a quantifiable facade design parameter (L/H), providing a direct architectural-scale adaptation indicator. This methodological focus highlights the contribution of the study to the local literature.

The findings suggest that shading parameters should be reconsidered in future building energy simulations and that fixed assumptions in current standards (e.g., TS 825) may require revision under changing climatic conditions. Adaptive facade systems, in which orientation and window overhang geometry are optimized dynamically, appear to be suitable strategies for addressing future climate conditions.

5.0 CONCLUSIONS

In this study, annual global solar radiation trends observed in Ankara between 1985 and 2024 were analyzed, followed by an assessment of projections for the period 2040–2060 using CMIP6 global climate data. Using NASA-POWER observational data and the SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios from the MPI-ESM1-2-HR model, the potential effects of changes in solar radiation on the architectural facade shading ratio (L/H) were examined.

The results indicate that annual global radiation in Ankara has generally increased during 1985–2024. CMIP6 projections for the 2040–2060 period suggest a scenario-dependent increase in annual solar radiation, with the highest projected values under SSP5-8.5. This increase may elevate the risk of thermal gain during summer periods. Accordingly, the current shading ratio ($L/H \approx 0.45$) may require a slight increase under 2060 conditions to maintain comparable summer shading performance. These findings imply that threshold values used in future building energy simulations should be reconsidered. Revisiting facade orientation, material selection, and shading strategies in light of projected climate conditions is therefore essential for climate-responsive architectural design.

This study has several limitations. It focuses on a single study area (Ankara) and relies on one CMIP6 global climate model (MPI-ESM1-2-HR) to represent future conditions. Consequently, the magnitude of projected changes may differ when alternative climate models, multi-model ensembles, or downscaling approaches are considered.

Future research should compare different CMIP6 model outputs (e.g., GFDL, IPSL), evaluate model-related uncertainties, and extend the analysis to other provinces such as Konya and Kayseri. Integrating annual and seasonal solar angle analyses with building energy simulations may further support the development of climate-responsive design principles.

The original contribution of this study lies in directly linking CMIP6-based solar radiation projections specific to Ankara with an architectural-scale facade shading parameter (L/H). In this way, a preliminary quantitative framework is proposed for incorporating climate scenarios into building envelope design decisions.

ARTIFICIAL INTELLIGENCE (AI) USAGE DECLARATION

All data processing, numerical calculations, statistical analyses, and figure generation were executed in R using the study datasets described in the manuscript. During the preparation of this study, a Generative AI-assisted tool was used to support the development and refinement of R scripts, as well as to improve the language and presentation of the manuscript. All AI-assisted material and analytical outputs were reviewed and verified by the author, who takes full responsibility for the methodology, results, interpretations, and final content of the manuscript.

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