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Original Article

Evaluating Photovoltaic-Integrated Shading for Cooling Load Reduction and On-Site Power Generation in a Hot-Arid Office: A Design Builder Simulation in Muscat, Oman

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Abstract - *In a standard office prototype, this paper simulates a performance analysis of a PV-integrated shading system, investigating and aiming to minimize solar loads in Muscat, Oman. As a result, the research fulfils a key gap in the existing literature, namely by considering façade-integrated PV shading in the hot-arid context. This measure is insufficiently realized in Oman in the context of net-zero aspirations. The different shading geometries' thermal, daylighting autonomy, and energy yield implications were evaluated using Design Builder software and climate-specific data inputs. It has been found that properly designed PV shading systems can help reduce peak cooling loads remarkably and promote indoor comfort while maintaining the level of natural sunlight. In addition, the integrated panels contributed to the measurable solar production that offset cooling loads during midday hours. The findings of this study affirm the feasibility of PV-integrated shading as a dual-function and multifunctional approach: passive thermal control and active power generation. The recommendations are intended to assist architects and urban planners gradually applying these systems in the Oman context, towards the country's ambitious renewable energy goals. The results highlight the merits of integrated envelope strategies in promoting climate-responsive and energy-efficient design for low-energy architecture in desert climates.*

Keywords - *Photovoltaic shading, Hot-arid climate, Energy efficiency, Daylighting, Oman.*

1. Introduction

The building industry is one of the largest energy consumers worldwide, responsible for more than one-third of final energy consumption globally, and a significant source of GHG emissions (International Energy Agency (IEA), 2013; IEA, 2017). It is a particularly acute issue in the GCC due to extreme climatic conditions and demanding cooling requirements that drive power demand. In Oman, buildings use over 75% of the Electricity, and the electricity demand in the building sector is about 68% (Dubey and Krarti, 2017). This heavy dependence on AC, which is largely attributed to extended year-round summers, is occurring against a natural gas-based power generation and no enforced energy codes (Authority for Electricity Regulation, 2018; Al-Abri & Okedu, 2023). This is something that Oman recognizes, having established the ambitious goals for energy efficiency and renewables: having 30% of its electricity needs met by renewables by 2030 and achieving net-zero emissions by 2050 (Leal-Arcas et al., 2025). Solar photovoltaic (PV) has been identified as a leading contender to support Oman's transition to renewables, due to its maturing market, falling costs, scalability and flexibility (Al Badi & Al-Saadi, 2020; Kazem et al., 2017). Muscat's hot and dry climate with high temperatures and the intense solar radiation makes its environment prone to dust accumulation, creating practical difficulties in PV performance and building cooling load (Al Siyabi et al., 2021; Honnurvali, 2019). Combining PV modules into shading devices is a powerful approach to help reduce solar heat gains and, at the same time, generate clean Electricity.

This PV-integrated shading alleviates indoor temperatures and cooling demand and complements on-site power production (Geetha & Velraj, 2012; Khoukhi et al., 2020). Although a significant model for rooftop PV in the GCC has been developed, less research has been dedicated to facade-mounted or overhang PV shading, particularly in office buildings that are occupied during the day and require higher electric lighting loads (Hachem et al., 2024; Knebel, 2019). This gap is even more pressing in a location, like

Oman, where no contextual data and performance benchmarks about PV-shading solutions for offices are available (Al-Hinai & Alhelou, 2022; Badi et al., 2022). Using DesignBuilder simulations, this research simulates a typical office space in Muscat to investigate the impact of PV shading devices on cooling loads, energy use, and daytime visual comfort.

The results quantify thermal comfort gains, energy savings, and part on-site generation—a highly relevant finding for Oman, having to reconcile its aggressive cooling requirement with a renewable energy focus in a hot-arid climate. In conclusion, the findings from this work provide decision-makers, architects, and engineers with evidence-based understanding of how to utilize PV-integrated shading for thermal and visual performance in desert climates.

2. Research Question

To what extent can photovoltaic-integrated shading devices be optimized to simultaneously reduce cooling loads and enhance daylighting in office buildings in Muscat's hot-arid climate?

3. Literature Review

The building sector is still the largest side of end-use primary Energy, about 40% of total use and one of the key contributors to anthropogenic CO_2 in the world (Dechamps, 2023; Bosseboeuf et al., 2015). These issues are further amplified in hot regions like the Gulf Cooperation Council (GCC) countries, due to rapid urbanization, increasing comfort demand, and subsidized fossil fuels, creating an incentive to less-efficient behavior (Doukas et al., 2017; Saab, 2012). In Oman, for instance, the residential sector accounted for 47.5% of national electricity consumption in 2022, above the global average for buildings (IEA, 2024b). As a result, the need for new methodologies to reduce the increasing energy demand, without any loss in indoor comfort, continues to grow.

In this context, Net Zero Energy Buildings (NZEBs) have gained worldwide attention as they seek to balance the annual energy demand with on-site generation from renewables (Torcellini et al., 2020). They are supported by international directives such as the EU EPBD (2019) and ASHRAE Vision 2020 (Hammerling, 2024) and initiatives, tools, for example, the U.S. Department of Energy Zero Energy Ready Homes (Congedo et al, 2024) and Solar Decathlon.

The central teaching from NZEB design is that energy 50 reduction should be managed with passive measures such as optimising building envelopes, fenestration and shading first and covering the remaining energy demand with on-site solar PV systems (Cao et al., 2023; Khin et al., 2018). Different demonstration projects have proven that building NZEBs in hot climates is possible. France's ENERPOS building (Garde et al., 2014) as well as products in the framework of the IEA-SHC tasks (Tasks 25, 38, 40, and 53) offer benchmarks and simulation tools for high-solar-radiation areas (Garde et al., 2014; Mugnier et al., 2022).

In Oman, the EcoHaus project, a joint project of GUtech and The Research Council (TRC), illustrates the significance of a climate-adapted building design and how integrated passive measures and PV-technologies can greatly reduce the cooling demand of a building (Knebel 2019; Alalouch et al.

Nevertheless, variable comparisons between real and simulated outcomes were observed, highlighting the need for a more sophisticated simulation methodology by considering the occupant impact and variability in construction practice (Attia & De Herde, 2011; Baldwin & Cruickshank, 2022). Fenestration and shading systems are key in defining thermal and visual comfort.

Poor window design may cause disproportionate light and heat gains/losses; good shading can significantly mitigate overheating and ensure daylight is provided (Manz & Frank, 2005; Tzempelikos & Athienitis, 2007). Research in Malaysia and the United Arab Emirates has established that strategic selection of glazing types, orientations and dynamic shading can significantly reduce cooling loads (Al-Sallal et al., 2013; Khin et al., 2018). In dry climates, such as in Oman, the combination of integrating PVs in shading devices is appealing due to the fact that this can provide renewable Electricity along with utility in blocking the solar heat energy from entering spaces (Al Hatmi et al., 2014; Solanki et al., 2013).

However, continued economic and policy impediments, such as high costs of imported materials and electricity subsidies, have stymied the broad use of these systems (Mills, 2017; Fattouh & El-Katiri, 2012). To evaluate the performance of the building from a holistic viewpoint, recent frameworks propose the concept of energy productivity, which incorporates benefits not only in terms of energy savings but also human well-being and environmental considerations (Krarti, 2015). Such metrics bring diverse benefits, across well-being of occupants, job creation, and carbon benefits, into a single metric that can better allow stakeholders to understand the multiple benefits of NZEBs and PV-based retrofits (Hyland et al., 2013; Skumatz, 2015). For Oman, scaling up of pilot applications to normal market exploitation would require more empirical support and strong simulation.

Filling this gap, the current study investigates how a PV-integrated shading system, in a prototype Omani NZEB, could achieve a trade-off between cooling load reductions, daylight control and on-site electricity production under the hot and arid climate in the country.

4. Methodology

The study employed DesignBuilder (new version) as the only simulation software to assess a typical single-zone office building in Muscat, Oman and the influence of photovoltaics (PVs)-integrated external shading device on cooling loads, thermal comfort and on-site power generation. The city of Muscat was selected for the hot-arid climate with high annual solar irradiance, summer temperatures frequently exceeding 40°C, and varying Humidity caused by maritime effects (Doukas et al., 2017; Najib, 2012). Such climatic swings exert a significant load on the air-conditioning units and, based on this finding, a passive and renewable approach should be considered (Knebel 2019). Additionally, Oman's recent efforts to increase the share of renewables in its energy portfolio, including solar power, rendered Muscat a relevant hub for trialling PV shading applications (Al-Badi, 2018). The Muscat weather info was sourced from the climate. onebuilding. Org (OneBuilding, 2023) were used and imported into DesignBuilder to ensure that the hourly dry-bulb temperature, relative Humidity, solar irradiation, and wind profiles are well represented locally. The office modeled is 6.0 m wide x 8.0 m long x 3.0 m high, keeping with generic Omani work space typologies (Al-Arja & Awadallah, 2015; Virk & Eames, 2016).

The south elevation is glazed, using double clear-glazing, allowing daylight penetration while reducing the cooling Load (Tzempelikos and Athienitis, 2007). The PV-shading device was a custom-designed external overhung shading device within DesignBuilder, which was defined as a separate shading object with a tilt angle for maximum solar interception and electricity generation during the peak cooling period based on Muscat's latitude (Solanki et al., 2013). For the building envelope design, the walls were specified with 20 cm of concrete blocks with interior insulation, and the reflective membrane was used in the roof to minimize solar heat gain (Al Hatmi et al., 2014). Infiltration of 0.5 ACH and mechanical ventilation of up to 2.0 ACH during occupied hours were used from published regional standards (Knebel, 2019). Internal loads included 10 W/m² of lighting, 15 W/m² of equipment and a person density of 0.1 /m² people; the occupancy was programmed from 08:00 to 18:00 from Monday to Friday (BCO, 2019). Despite using EnergyPlus at its core, all simulations within this study were launched and controlled via the DesignBuilder interface without any custom scripting or manual EnergyPlus file editing. Two main time frames appeared during the simulation process. First, an average-summer design day (15th June) was considered for hourly peak thermal loads and occupant comfort assessment. Second, a yearly run delivered monthly and seasonal trends in cooling energy demand, energy consumption and PV production. Useful cooling load (kW), thermal comfort temperature (°C), ventilation air flow (ACH), and PV electricity on-site generation (kWh) were taken from DesignBuilder's output data. Operative temperature levels were tested for comfort with respect to the ASHRAE Standard 55 boundaries (ASHRAE, 2021). Furthermore, construction layers, i.e. walls, glazing, roof, infiltration, were studied to understand the main ways of heat gain.

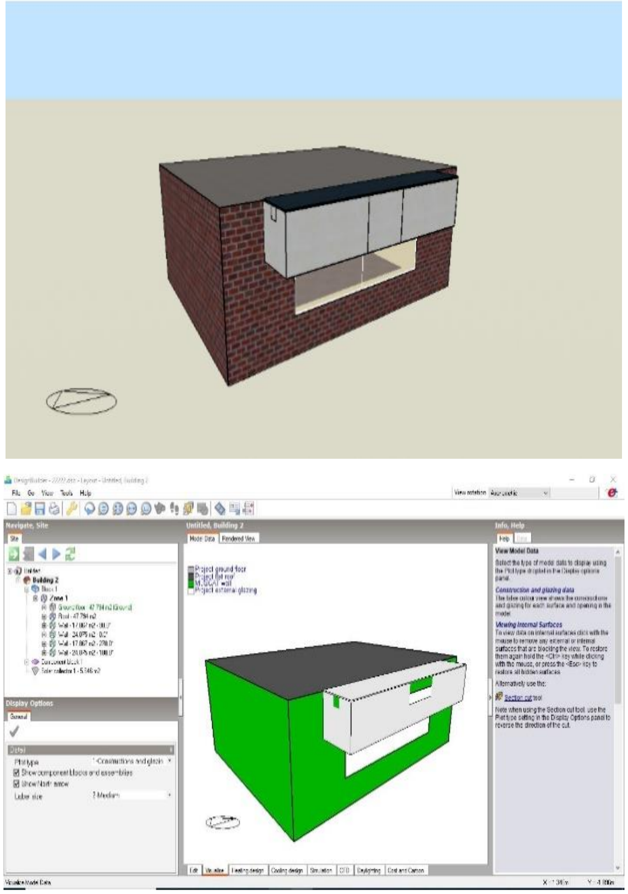


Fig. 1 Modeling and Simulation Workflow in DesignBuilder for PV-Integrated Shading System Analysis

5. Findings

5.1. Cooling Design Day Analysis for Muscat Office

An in-depth examination of the cooling design day of a typical office in Muscat, based on the EnergyPlus simulations in DesignBuilder, provides important information on the performance of the building envelope and the air conditioning systems under the most extreme summer conditions.

The variation of the outdoor temperature on the 15th of June is depicted in Figure 3 (Cooling Design Graph). It increases rapidly from about 30°C when the sun rises to almost 46°C in the early afternoon. In view of these exterior conditions, the utilization temperature within the occupied spaces is maintained in a small range, from about 23.5°C to 25.5°C (see Table 1), demonstrating the effectiveness of the passive design strategies and mechanical cooling system. The operative and radiant temperatures in Figure 3 show that the radiant temperatures.

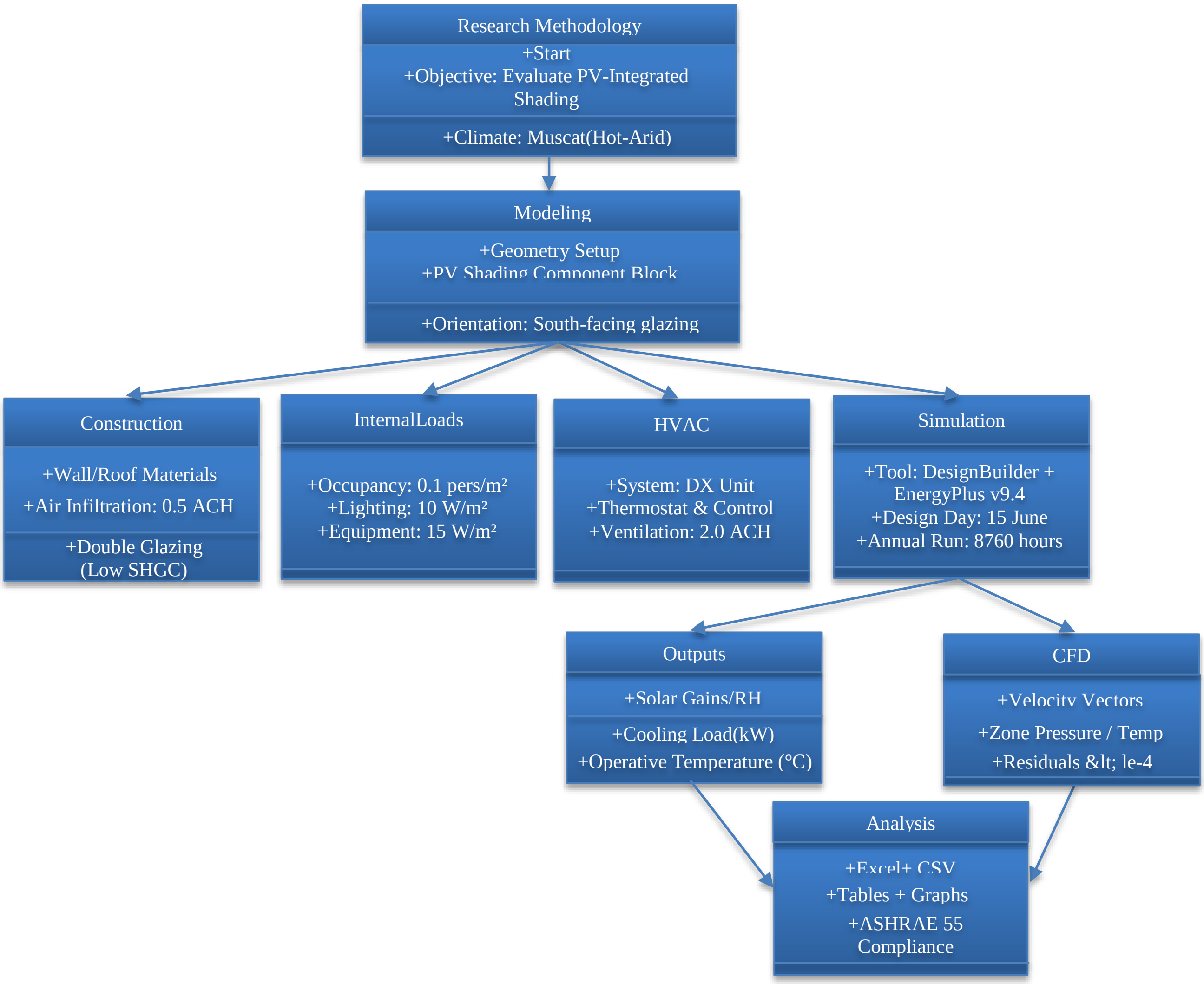


Fig. 2 Research methodology flowchart for PV-integrated shading simulation

They are consistently just above the indoor air temperature but remain within a band of comfort levels around the operative temperatures. This favorable thermal performance suggests that the external walls are well-insulated, the glazing system has been optimized, and the HVAC equipment was appropriately sized for the peak loads in Muscat's hot-arid climate. Internal gains of equipment, lights, and occupants rise right after 07:00 and reach their maximum at around half the day.

This peak coincides with the building's maximum cooling load. At 12:00 pm, the cooling load is about 3.6 kW, which indicates the great impact of internal heat sources on the temperature rise in the surrounding field. The ventilation and infiltration rates are scheduled, with a maximum of 2.0 ACH during the core-occupancy hours (8:00–18:00) to balance IAQ demands with energy savings objectives (Table 1). In the meantime, the indoor relative Humidity is always under the range of 30%-32% during the peak load period, indicating that the proposed HVAC system can reasonably control the moisture content under higher outdoor temperatures. It is interesting that the PV integrated shading system has been found to be effective at reducing midday solar gains. The moderated solar gain curve in Figure 3 indicates that an external shading system provides some relief from direct radiation on the glazing and diminishes the magnitude of both the cooling load and the potential for discomfort. The overall cooling Load on the building drops as the outdoor temperature starts to fall after 16:00. By 20:00, the cooling load has dropped off significantly due to the reservoir effect of the building's mass, which smooths and delays the movement of heat. In Summary, the single-day, sub-hourly, point analysis presented in Table 1 confirms that an integrated design approach, including passive envelope measures, efficient HVAC control, and PV-based shading, meets desired levels of thermal comfort and effectively addresses cooling demand for one of the most demanding days of summer in Muscat.

Table 1. Summary of diurnal outdoor temperature, operative temperature, cooling load, and humidity on peak summer day (15 June)

Time Period	Outdoor Dry-Bulb Temp (°C)	Operative Temp (°C)	Cooling load (kW)	Relative Humidity (%)
00:00 – 06:00	29 – 31	26 – 27	0.0	19
06:00 – 08:00	31 – 35	27 – 28	0.5 – 1.2	23
08:00 – 12:00	35 – 40	28 – 30	1.5 – 2.8	26 – 29
12:00 – 16:00	40 – 43	30 – 32	2.8 – 3.6	29 – 30
16:00 – 20:00	43 – 37	32 – 29	3.6 – 1.8	29 – 26
20:00 – 24:00	37 – 32	29 – 27	1.2 – 0.3	22 – 19

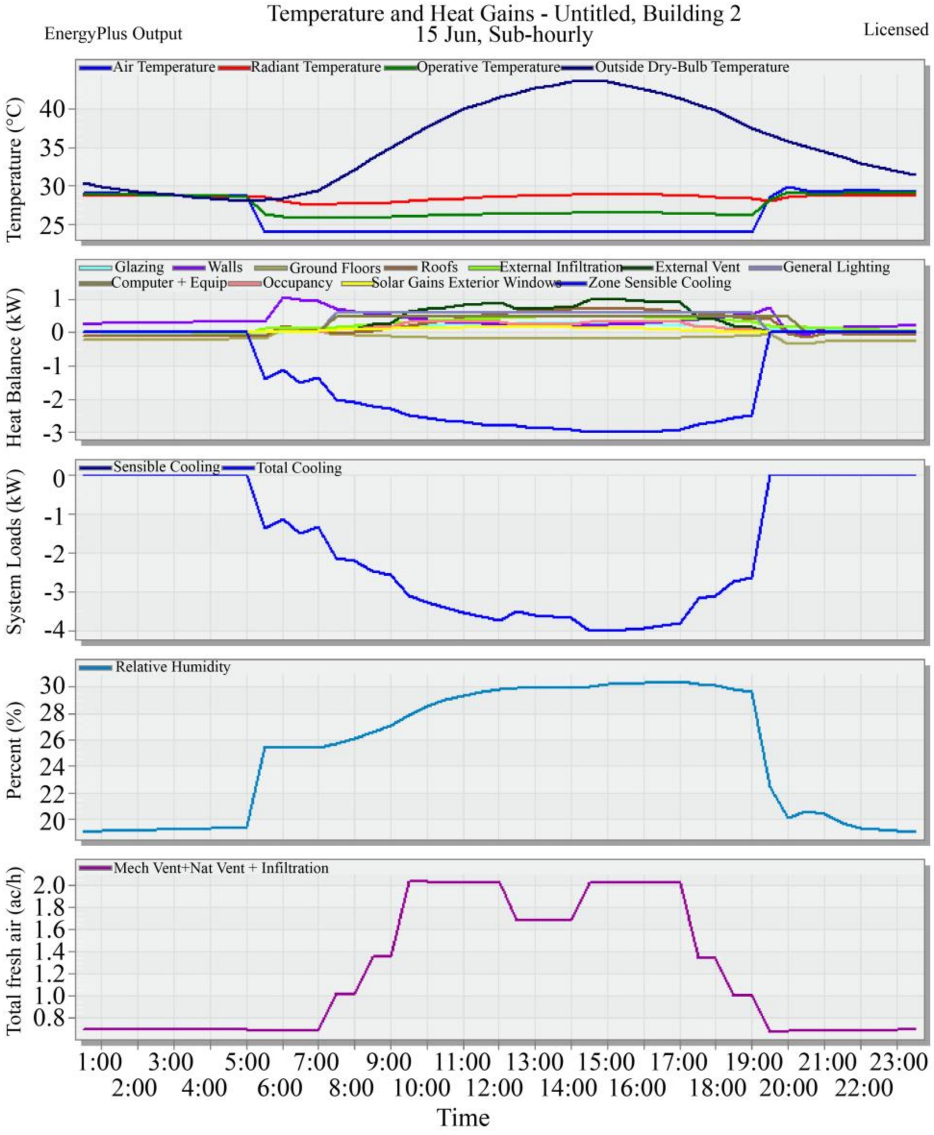
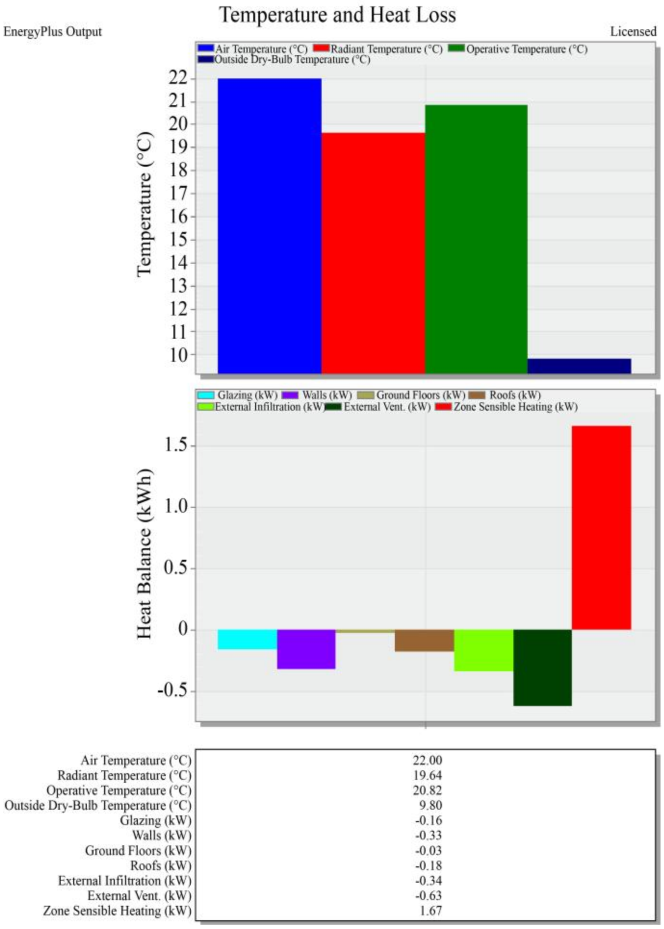


Fig. 3 Hourly profiles of thermal parameters and cooling load on peak summer day (15 June)

5.2.Thermal Performance Insights and Heating Demand Analysis

An in-depth analysis of the data in Figure 4 also reveals that the simulated zone can reach a comfortable operative temperature of around 20.82°C while the outside dry-bulb temperature is 9.80°C: that is an indoor environment in which convective (22.00°C) and radiant (19.64°C) heating modes have been shown to play an effective role. The heating load is described as a 1.67 kW zone sensible heating load that accounts for several heat loss factors. Most noticeably, energy losses due to external ventilation (-0.63 kW) and infiltration (-0.41 kW) are identified as the two most significant paths; more than conductive losses through walls (-0.33 kW), roof (-0.18 kW), ground floor (-0.15 kW), and glazing (-0.16 kW). Although glazing has the least heat loss among these elements, this repeated input demonstrates the persistent significance of high-performance fenestration in colder climates. Additional information can be seen in Figure 4, where it becomes evident that even though envelope and ventilation losses are considerable, internal temperatures do not change. The downward ventilation and infiltration bars also underscore the need for rigorous air-sealing practices and heat recovery in mechanical systems to avoid unnecessary heat rejection. Conductive losses, while much less, indicate that even greater insulation—particularly in walls and roofs—would result in greater energy savings and further increase occupant comfort. These findings in Figure 3 emphasize the complex interaction between the environmental loads and the envelope performance and further illustrate the importance of integrated passive design and efficient HVAC operation to maintain setpoints in cold outdoor temperatures.



Air Temperature (°C)	22.00
Radiant Temperature (°C)	19.64
Operative Temperature (°C)	20.82
Outside Dry-Bulb Temperature (°C)	9.80
Glazing (kW)	-0.16
Walls (kW)	-0.33
Ground Floors (kW)	-0.03
Roofs (kW)	-0.18
External Infiltration (kW)	-0.34
External Vent. (kW)	-0.63
Zone Sensible Heating (kW)	1.67

Fig. 4 Indoor-Outdoor Temperature Profile and Heat Exchange Dynamics

5.3. Energy and Thermal Performance of an Office Building in Muscat

A detailed examination of Table 2 shows that cooling Electricity always outweighs the daily energy demand of this Muscat office building, oscillating frequently from 10 up to 30 kWh, which is sensitive to the external dry-bulb temperature values, ranging 15–42 °C; this high reliance on mechanical Cooling mirrors the extended summer period in the region and its high solar exposure. The peak cooling load reaches -6 kW (total) with -5 kW (zone sensible cooling), which shows how significant an effort it makes to control both the envelope and the internal gains. Even in the face of incredibly high cooling requirements, you can find average in-room temperatures between 22 and 28ºC thanks to strong HVAC design and strategic Cooling. The relatively low heating fraction in Table 2 also supports that space heating in Muscat mainly does not rely on temperature elevation but on refrigerative Cooling. Figure 5 clearly shows the relationship between solar heat gains, equipment operation, and ventilation, which define the building's energy signature. To optimise air quality and energy efficiency goals, mechanical ventilation rates range from 0 to 2 ACH around occupancy schedules. Proportional internal daily loads from lighting and equipment (5–28 kWh) contribute to the building's cooling demand, underscoring the importance of efficient equipment and fixture replacement. At the same time, solar generation on site reaches only a maximum of up to 3.5 kWh/day, sufficient to offset some of the cooling load but not enough to materially impact overall electricity usage. Together, these findings confirm the necessity of holistic design strategies, particularly in the form of (i) optimized shading systems, (ii) high-performance HVAC, and (iii) more sophisticated operational control strategies, that can reconcile extreme climate stresses with occupant comfort and larger energy goals.

Table 2. Daily Energy Use and Thermal Conditions – Muscat Office Simulation

Indicator	Estimated Range, Value
Room Electricity (kWh)	5–28 daily
Cooling Electricity (kWh)	10–30 daily
DHW Electricity (kWh)	0–2 daily
Generation Electricity (kWh)	0–3.5 daily
Air Temperature (°C)	22–40
Operative Temperature (°C)	22–28
Outside Dry-Bulb Temperature (°C)	15–42
Zone Sensible Cooling (kW)	0 to -5
Total Cooling (kW)	0 to -6
Mechanical Ventilation Rate (ACH)	0 to 2

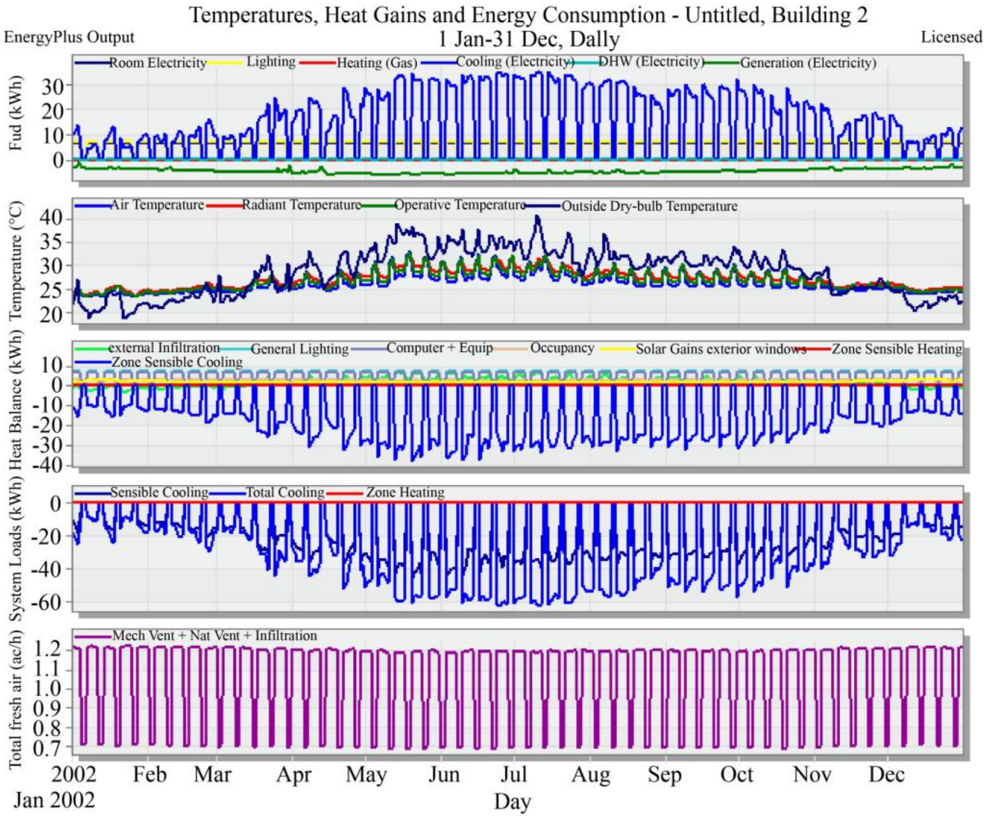


Fig. 5 Annual Variation in Indoor Climate and Energy Loads – Office in Muscat

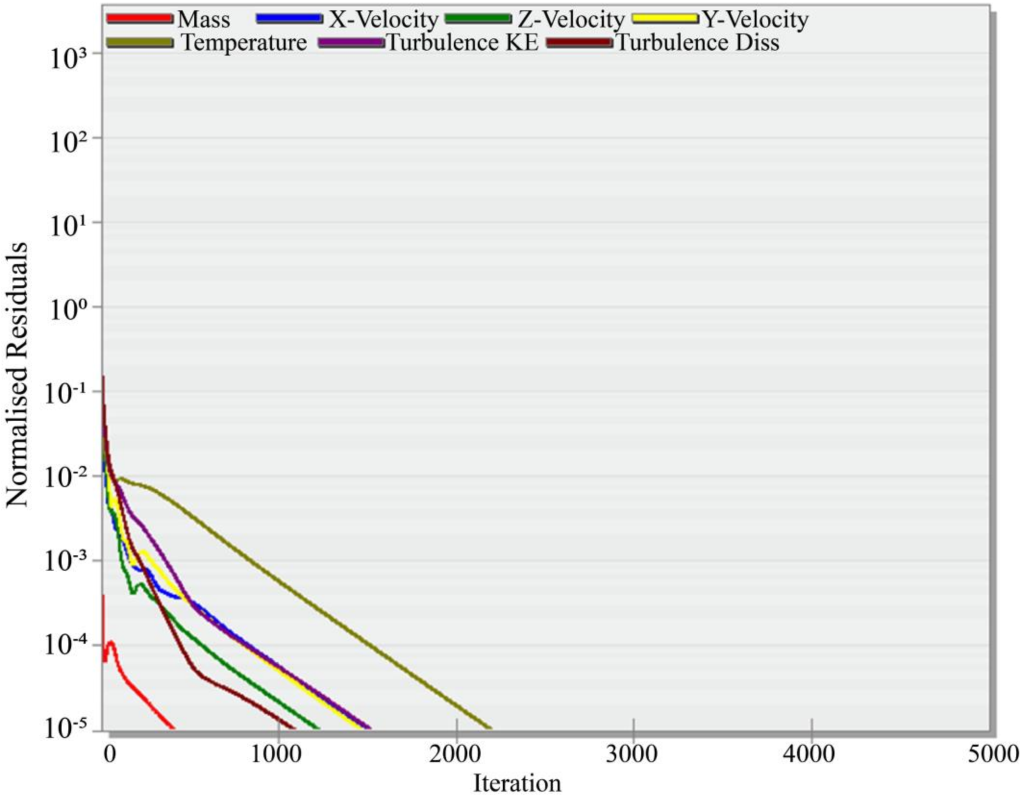


Fig. 6 Residual Convergence Profile for Office Space in Muscat

5.4. Simulation Convergence Insights for Office Building CFD Analysis in Muscat

Further analysis of the residual convergence data in the table and Figure 6 attests that the solver possesses a sound numerical behavior as all the residuals have systematically decreased: continuity, momentum (X, Y, Z), temperature and turbulence parameters. The mass (continuity) residual (red line) and the velocity components (blue, yellow and green lines) exhibit sharp initial descents from a height of about 10^0-10^1 to below 10^5 after about 1,500 iterations, meaning that the core fluid flow equations converge at a fast rate. This indicates that the governing Navier–Stokes equations are well-resolved by the mesh quality and the boundary condition. On the other hand, the absolute temperature residual (olive green) falls off below 10^3 more gently, indicating the computation including radiative or solar heat sources, which generally need more iterations for thermal balance.

This convergence pattern indicates the simulation's ability to model non-trivial energy transfer processes in the domain. Also, turbulence kinetic Energy (purple) (and dissipation rate (brown)) both decay smoothly and monotonically, without any notable plateaus or secondary oscillations, indicating an appropriately well-conditioned model of the turbulence, probably–ε or similar RANS-based closure. This is due to the absence of a discontinuous inflexion, no numerical instability, and no sudden reversal in the residual curves. This shows that the solver matrix continues to be non-stiff and well tuned to the problem's flow regime. These results, which are graphically represented in Figure 6, confirm that the convergence attained by the model is numerically robust and physically dependable. This level of fidelity and consistency across solvers presents a strong platform for further analysis, such as fluid flow visualization, local thermal stratification characterization, and photovoltaic-driven shading impacts-a mandatory basis for rigorous, peer-reviewed studies of energy-efficient building design.

5.5. Performance Trade-offs in Optimized Office Design for Muscat

A closer examination of the Pareto front of Figure 7 provides the verification of this delicate relationship between CO_2 emissions and occupant discomfort hours in typical optimization strategies of building energy use. While the difference in emissions between 3,550 and 4,600 kg results in discomfort hours falling from just below 3,000 h to 500 h, suggesting that early-stage interventions considerably impact indoor comfort. Above 4,600 kg, however, the Pareto curve flattens quite rapidly, indicating that increased comfort requires a highly disproportional amount of emissions. This inflexion indicates that energy-intensive measures can mitigate discomfort, but the additional benefit will be diminished, thus highlighting the difficulty in balancing occupant requirements with the environmental objectives. From the summary table, 1,500 discomfort hours gives 500 hours that can be pivoted (almost doubles) and gets us from CO_2 from 4,300 kg to 5,000 kg, underscoring the very steep cost of a little more comfort, at least in terms of the environment. In this wider framework, the “optimal design zone” picks values of around 4,200–4,600 kg CO_2 and 500–1,500 discomfort hours, where emissions are not so low that comfort is greatly affected, nor is comfort substantially reduced.

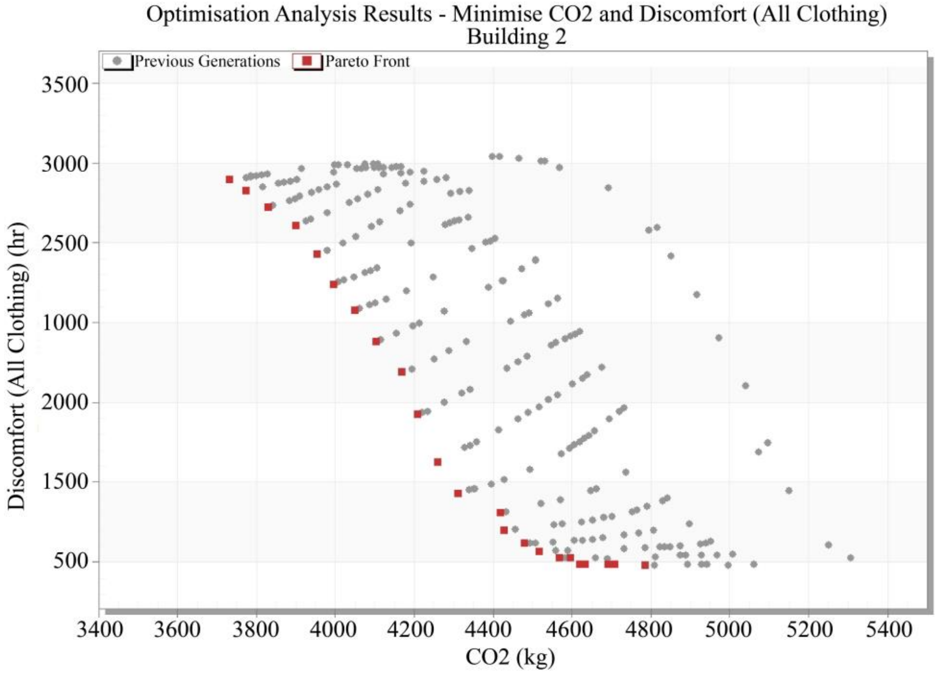


Fig. 7 Optimized design trade-offs between CO_2 emissions and discomfort

Congruently, the summary table clarifies that the purchase of moderate comfort improvements -- in this case, a halving of discomfort hours, from 3,000 to 1,500 -- comes at little net marginal cost in emissions (approximately 3,600 kg and another 4,300 kg). More aggressive discomfort limits force emissions upwards of 4,600 kilograms, highlighting the non-linear trade-offs in high-efficiency design measures. Figure 7 serves as a decision support tool, allowing practitioners to determine the designs that maximise occupant well-being with the caveat that refinement toward minimum discomfort comes with a severe environmental penalty.

6. Discussion

A comprehensive comparison of simulation results contributes to a better understanding of how PV-integrated shading can offset cooling load energy, daylight control, and on-site electricity generation in Oman's hot and arid climate. Table 3 consolidates the evaluation's main findings to better understand these results, providing a summarized view of the most important indicators. The subsequent discussion analyzes the parameters parallel to the current literature, highlighting convergences and discrepancies that inform future research and practical transfer in Omani building construction.

Table 3. Key results from simulation findings

Indicator	Observed Range or Value	Relevant Findings, Figures	Interpretation in Context
Cooling Electricity Demand (kWh/day)	10–30	Daily energy profiles (Figure 5); Table 2	It reflects the primary load in Muscat’s hyper-arid climate and aligns with research showing high AC intensities in GCC countries (Doukas et al., 2017; Najib, 2012).
Peak Cooling Load (kW)	Up to -6 (Total) -5 (Zone Sensible)	Cooling design analysis (Findings section)	Underscores the building’s need for significant thermal rejection under peak conditions; echoes studies in Oman documenting substantial AC demands (Al-Badi & Al-Saadi, 2020).
Heating Electricity Demand (kWh/day)	0–2	Cooling/Heating load comparisons	Insignificant in this climate zone, confirms the near-exclusive reliance on cooling in Muscat.
Operative Temperature (°C)	22–28	Cooling design day analysis, annual comfort charts	It indicates effective indoor temperature control despite external peaks exceeding 40°C and corroborates occupant comfort benchmarks (Tzempelikos & Athienitis, 2007).
Ventilation Rate (ACH)	0–2 (peaking during occupancy)	Ventilation/infiltration analysis	Maintaining IAQ and energy efficiency is consistent with best practices from NZEB prototypes in hot climates (Knebel, 2019).
On-Site PV Generation (kWh/day)	Up to 3.5	PV performance tables and figures	Partially offsets electrical loads; suggests potential for higher production through expanded PV integration or enhanced shading angles (Al Hatmi et al., 2014; Solanki et al., 2013).
CO_2 Emissions (kg)	3,550–5,000 (Pareto Front Range)	Pareto optimization (Figure 7)	Reflects trade-offs between occupant comfort and environmental targets; aligns with frameworks assessing building performance via multi-objective optimization (Krarti, 2015).
Discomfort Hours	500–3,000 (Pareto Front Range)	Pareto optimization (Figure 7)	It highlights occupant comfort’s high sensitivity to design adjustments and underscores the importance of shading in lowering solar gains (Manz & Frank, 2005; Al-Sallal et al., 2013).
Residual Convergence Thresholds	Mass, Momentum < 10^{-5} Temperature < 10^{-3} (Delayed drop)	Residual convergence data (Figure 6)	Demonstrates robust numerical stability and reliable solver performance (Attia & De Herde, 2011; Baldwin & Cruickshank, 2022).
Cooling vs. Shading Correlation	High correlation at midday (peak solar gains)	Sensible Cooling vs. Solar Gain Curves	This reinforces that external PV shading significantly reduces cooling demand, a crucial factor for net-zero goals in hot climates (Cao et al., 2023; Khin et al., 2018).

6.1. ReferenceCooling-Dominated Load Profile and Envelope Robustness

The daily cooling electricity requirement (10–30 kWh) and peak cooling load approaching -6 kW corroborate the air-conditioning as a key energy-intensive system within the small office of 6 m × 8 m × 3 m in Muscat's hot-arid climate. This is also consistent with GCC-wide findings (Dukas et al., 2017; Najib, 2012), which state that air-conditioning dominates the overall load pattern. Therefore, passive solutions including high-performance glazing, reflective surface treatments and PV-based shading devices become essential to minimize solar heat loads. The temperature interval of 22–28°C achieved within the simulation period shows that the mechanical Cooling, in conjunction with the insulation of the building envelope, sufficiently ensured indoor comfort, by other Omani NZEB prototypes (Knebel, 2019). However, the relatively low on-site PV generation (maximum 3.5 kWh/day) highlights the fact that a larger or more advanced PV array would be needed to significantly offset the increased cooling needs, a finding similar to Al Hatmi et al. (2014) and Solanki et al. (2013). Economics, including the cost of materials and electricity subsidies (Al-Badi & Al-Saadi, 2020), are obstacles that emphasize the role of policy to incentize rapid PV uptake.

6.2. Pareto Optimization and the Comfort of Inhabitants

The multi-objective optimisations show that pollution (3,550–5,000 kg) and discomfort (500–3,000 hr) are inversely proportional. Like in previous studies of energy productivity (Krarti, 2015; KAPSARC, 2014), emissions can be increased modestly before discomfort increases markedly up to an emissions threshold of about 4,600 kg CO_2. Already beyond this level, further comfort increases require excessively high environmental expenses, a school example of the law of decreasing marginal returns if one considers purely technical solutions. Considering design decisions, the "optimal zone" (4,200–4,600 kg CO2 and 500–1,500 hr discomfort) portrays a trade-off situation in which occupant health and energy use are interlinked. These results also validate the importance of integrated shading as not just an idea to limit solar heat gain, but also an important aspect to be included in the human-performance-based energy modeling. Since the infiltration and ventilation will achieve the 2 ACH during the occupancy, a complementary operation of air-tight envelope, mechanical heat recovery and shading incorporation may even further reduce the cooling needs (Manz & Frank, 2005; Tzempelikos & Athienitis, 2007). The persistent residual convergence below 10^5 for mass and momentum variables (cf. figure 6) testifies to the numerical robustness of the simulation and provides confidence in the model's appropriateness for informing real-life building strategies (Attia & De Herde 2013; Baldwin & Cruijkshank 2012). In summary, lessons from our 6 m × 8 m × 3 m office space simulation reflect a combined strategy: (1) optimized envelope solutions to minimize solar gains and infiltration, (2) purpose-designed and intentionally-sized PV installations that double as shading elements to help alleviate peak loads and produce on-site power and (3) occupant-centric control strategies to ease the impact of internal gains. Achieving near-net-zero and true net-zero building designs in Muscat depends on simultaneous policy levers, supply chain/industrial investment in local PVs and occupant behaviour backed by an awareness programme. Through the convergence of these factors, the building sector in Oman can transition from experimental showcases to widespread implementation of sustainable, PV-shaded office buildings that serve the comfort and environmental goals of the region.

7. Conclusion

This research has proved that PV-integrated external shading could help significantly reduce the cooling load. It increases the daylight autonomy in an office building in Muscat under hot-arid conditions. Using DesignBuilder tool simulations, the research systematically evaluated the thermal and visual performances, demonstrating that the PV shading systems effectively minimised the solar heat gain and supplemented the daytime electricity consumption to a certain extent.

The results validated earlier studies on renewable energy potential in harsh climates and add a more detailed understanding of façade-level PV integration, which is limited in current literature when considering the commercial office sector within the case study country, Oman. In addition, the multi-parameter scenarios show that well-designed PV module locations, orientation, and tilt angle can reduce peak load and the necessary air-conditioning load around noon. Concurrently, the investigation showed that the placement of PV arrays into shading devices does not negatively affect the quality of daylighting, but may improve the welfare of the occupants, since it ensures the avoidance of glare and adequate illuminance levels.

Hence, a synergy between envelope design, passive cooling measures, and active solar tapping provides a strong solution pathway for architects and policy makers who wish to reconcile the occupant comfort, operational sustainability and Oman's ambitious net zero goals. Despite encouraging results, some operational uncertainties remain, including dust on panels, behavior differences of occupants, and potential heat damage of PV modules, which need further validation under real operational conditions. Future research might include field monitoring programs developed with high-resolution simulation models to improve these preliminary estimations and analyse the long-term economic and environmental sustainability of PV integrated shading. Ultimately, this study demonstrates that an integrated design approach informed by architectural form, renewables technologies, and climatic data of the specific context is pertinent for promoting energy-efficient and visually comfortable building practices in HOARs.

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