

Supplementary Information

This document provides supplementary details, extended data, and robustness checks that support the findings presented in the main manuscript, ***Thermal Whiplash and Carbon Debt: How Legacy Energy Codes Create Climate Maladaptation in Buildings.***

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Appendix S1: Annual Simulation Results

This appendix provides the numerical results that underpin the analyses presented in the main manuscript. The primary results for the 2080 scenarios are based on simulations using a dynamic, temperature-dependent HVAC performance model. Values correspond to EnergyPlus v9.6 simulations and are reported to one decimal place. "All Other Loads" is a calculated value [Total EUI – (Heating Demand + Cooling Demand)] and includes lighting, equipment, and HVAC auxiliary loads. Where projections for 2080 are shown, they are multi-model ensemble medians, with the lower and upper bounds of the GCM range in parentheses.

Table S1. Annual Energy Use Intensity (EUI) and End-Use Breakdown — Baseline vs. 2080 (SSP5-8.5).

Archetype	Climate	Scenario	Heating Demand (kWh·m ⁻² ·yr ⁻¹)	Cooling Demand (kWh·m ⁻² ·yr ⁻¹)	Lighting & Equipment (kWh·m ⁻² ·yr ⁻¹)	HVAC Auxiliary (kWh·m ⁻² ·yr ⁻¹)	Total EUI (Calculated) (kWh·m ⁻² ·yr ⁻¹)
Office	Antalya	Baseline	14.0	173.0	26.0	25.0	238.0
		2080 (Ensemble)	5.5	285.5	31.6	32.0	354.6 [322.4, 388.2]
Residential	Antalya	Baseline	17.0	78.0	24.0	8.0	127.0
		2080 (Ensemble)	5.0	128.8	24.0	12.3	170.1 [157.0, 187.9]
Office	Ankara	Baseline	210.0	25.0	26.0	22.0	283.0
		2080 (Ensemble)	160.0	85.4	24.1	28.0	297.5 [295.0, 301.1]
Residential	Ankara	Baseline	95.0	30.0	24.0	7.0	156.0
		2080 (Ensemble)	45.0	62.1	24.0	11.2	142.3 [139.6, 146.5]

Office	Erzurum	Baseline	227.0	13.0	26.0	20.0	286.0
		2080 (Ensemble)	145.0	106.4	29.0	28.0	309.4 [307.5, 310.6]
Residential	Erzurum	Baseline	115.0	33.0	24.0	7.0	179.0
		2080 (Ensemble)	82.0	55.2	24.0	11.2	172.4 [170.1, 175.7]

Notes: Data derived from EnergyPlus™ v9.6 simulations with a 15-minute timestep. "All Other Loads" includes lighting, equipment, and HVAC auxiliary loads (fans/pumps); see Appendix S4, Table S25 for a breakdown of auxiliary loads.

Table S2. Peak Cooling Demand (Hourly Annual Maximum) — Baseline vs. 2080 (SSP5-8.5).

City	Archetype	Baseline Peak Demand (W·m ⁻²)	2080 Ensemble Median (W·m ⁻²)	2080 Ensemble Range (W·m ⁻²)	Absolute Change (Median)	Percent Change (Median)
Antalya	Office	75.0	102.0	[94.5, 110.5]	+27.0	+36%
	Residential	45.0	68.5	[62.0, 75.0]	+23.5	+52%
Ankara	Office	30.0	105.0	[88.4, 123.6]	+75.0	+250%
	Residential	35.0	71.5	[60.0, 84.0]	+36.5	+104%
Erzurum	Office	20.0	145.0	[115.0, 177.0]	+125.0	+625%
	Residential	25.0	38.5	[30.0, 49.2]	+13.5	+54%

Notes: Data derived from EnergyPlus v9.6 simulations with a 15-minute timestep. Peak values for the office archetype are driven primarily by the Monday morning thermal pull-down event (see Appendix S2.6.1).

Table S3. Breakdown of Annual Cooling Load Components — Ankara Office Archetype (Baseline vs. 2080 SSP5-8.5).

Load Component	Baseline Annual Load (kWh·m ⁻² ·yr ⁻¹)	2080 Ensemble Median Annual Load (kWh·m ⁻² ·yr ⁻¹)	Absolute Change (kWh·m ⁻² ·yr ⁻¹)	Percent Change (%)
Sensible Load	18.8	57.5	+38.7	+206%
Latent Load	6.2	27.9	+21.7	+350%
Total Cooling Load	25.0	85.4	+60.4	+242%

Notes: The disproportionately large increase in latent load (+350%) reflects higher atmospheric moisture and increased mechanical ventilation in the 2080 climate, managed via incidental dehumidification. See Appendix S2.3.2 for ventilation details.

Appendix S2: Building Model Specifications

This appendix documents the primary assumptions governing the building assemblies, fenestration, and operational parameters applied uniformly across all the EnergyPlus simulation models.

Table S4. Opaque external wall assembly (outside → inside).

Archetype / Climate Zone	Layer	Material	Thickness (mm)	Thermal Cond. (W·m ⁻¹ ·K ⁻¹)
Office & Residential – Antalya (Zone 1)	1. Finish	Stucco	20	0.690
	2. Insulation	EPS	50	0.040
	3. Structure	Reinforced Concrete	200	2.300
	4. Finish	Gypsum Board	13	0.160
Office & Residential – Ankara (Zone 2)	2. Insulation	EPS	70	0.040
Office & Residential – Erzurum (Zone 4)	2. Insulation	EPS	100	0.040

Source: Compliant with Turkish Standard TS 825. The long-term thermal drift of the EPS is assessed in Appendix S2.1.1.

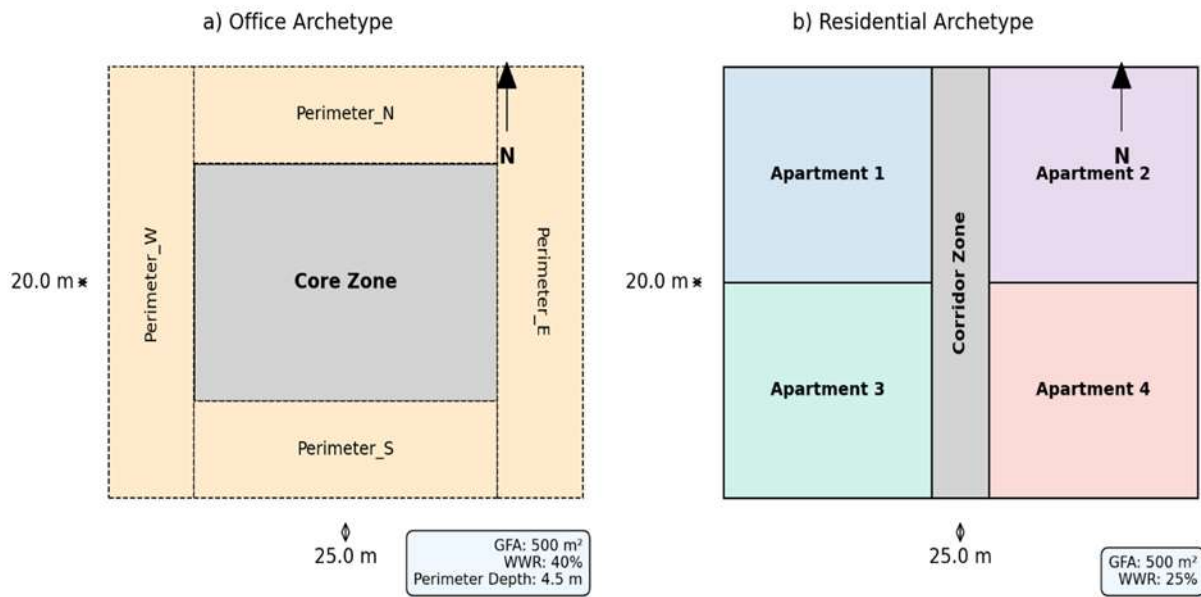


Fig. S1. Floor Plans and Thermal Zoning for Modelled Building Archetypes. (a) The office archetype features a 500 m² gross floor area (GFA) with a 40% window-to-wall ratio (WWR) and a 4.5 m deep perimeter zone. (b) The residential archetype has the same GFA but a lower WWR of 25% and is divided into four apartments and a central corridor.

S2.1. Envelope Assumptions and Sensitivity

Expanded Polystyrene (EPS) insulation is subject to long-term thermal conductivity drift, primarily due to the gradual diffusion of the blowing agent and moisture absorption. To assess the impact of this drift, a sensitivity scenario was constructed for the Ankara office archetype, where the nominal EPS conductivity of 0.040 W·m⁻¹·K⁻¹ (Table S4) was increased to 0.044 W·m⁻¹·K⁻¹, representing a worst-case 10% drift over the building lifespan, consistent with ISO 10456 data.

Table S5. Sensitivity of Primary Findings to EPS Thermal Conductivity Drift.

Scenario	EPS Conductivity (W·m ⁻¹ ·K ⁻¹)	Effective Wall U-value (W·m ⁻² ·K ⁻¹)	2080 Net EUI Change vs. Baseline (Ankara Office)	Conclusion
Primary (Nominal)	0.040	0.38	+5.1%	Thermal Whiplash
Sensitivity (Aged)	0.044	0.42	+5.7%	Thermal Whiplash (marginally worsened)

A 10% degradation in insulation performance over the building lifespan marginally increases the Thermal Whiplash penalty from +5.1% to +5.7% but does not alter the fundamental conclusion.

S2.2. Fenestration Specifications

The fenestration properties were defined per archetype and climate zone to reflect the guiding principles of the TS 825 standard, which implicitly prioritizes passive solar gain in colder climates.

Table S6. Fenestration Specifications: Full Optical Properties.

Archetype	Climate	U-value (W·m ⁻² ·K ⁻¹)	Visual		Notes
	Zone		SHGC	Transmittance (VT)	
Office	Antalya	2.4	0.35	0.48	Double-pane solar control: Low SHGC to reduce cooling loads.
	(Zone 1)				
Residential	Antalya	2.4	0.40	0.54	Double-pane tinted; optimized for solar control.
	(Zone 1)				
Office	Ankara	2.4	0.45	0.60	Double-pane low-E argon; balanced for temperate conditions.
	(Zone 2)				
Residential	Ankara	2.4	0.50	0.65	Double-pane Low-E: Balanced for temperate conditions.
	(Zone 2)				
Office	Erzurum	2.4	0.55	0.72	Double-pane clear: maximizes passive solar gain.
	(Zone 4)				
Residential	Erzurum	2.4	0.60	0.78	Double-pane clear: maximizes passive solar gain.
	(Zone 4)				

Notes: Optical properties are derived from the EnergyPlus WindowMaterial:SimpleGlazingSystem object, which internally computes layer properties consistent with the specified SHGC and U-value pair. The empirical basis for these SHGC values is detailed in Appendix S8.

S2.3. HVAC System, Internal Loads, and Operational Schedules

The key operational parameters are summarized in Table S7. The subsequent sections provide detailed justifications and sensitivity analyses for these assumptions.

Table S7. Summary of Key Operational Parameters.

Category	Parameter	Office Archetype	Residential Archetype	Source/Standard
Schedules	Occupancy Schedule	Weekday (08:00–18:00)	24/7 dynamic	ASHRAE 62.1
Ventilation	Infiltration Rate (ACH)	0.3	0.3	TS 825

The primary model employs a static infiltration rate of 0.3 ACH, consistent with TS 825 requirements for new-construction buildings. To assess the sensitivity of this assumption, a targeted analysis was performed using the Sherman-Grimsrud (1980) simplified infiltration model to estimate a dynamic, climate-dependent infiltration rate for the 2080 Ankara scenario. This yielded an upper-bound dynamic rate of 0.42 ACH.

Table S8. Sensitivity of the Primary Findings to the Infiltration Model.

Infiltration Model	Net EUI Change (Ankara Office, 2080)	Latent Cooling Load Increase	Conclusion
Static 0.3 ACH (Primary)	+5.1%	+350%	Robust Thermal Whiplash
Dynamic S-G Upper Bound (0.42 ACH)	+6.3%	+398%	Robust Thermal Whiplash (Strengthened)

A more realistic dynamic infiltration rate marginally increases both the energy penalty and latent load, thereby strengthening, rather than weakening, the primary conclusions of this study.

To ensure transparency regarding the sources of the latent load, the mechanical ventilation parameters are detailed below. These are modeled separately from the envelope infiltration.

Table S9. Mechanical Ventilation Parameters.

Parameter	Office Archetype	Residential Archetype	Source / EnergyPlus Object
Mechanical Outdoor Air Rate	6.9 L/s-person + 0.6 L/s-m ²	3.5 L/s-person + 0.15 L/s-m ²	ASHRAE 62.1-2019
Ventilation Schedule	During Occupied Hours (08:00–18:00, Mon-Fri)	24/7 Dynamic (Follows Occupancy)	Model Assumption
Heat Recovery	None Assumed	None Assumed	Standard Turkish Practice
Humidity Control	None (Incidental via DX coil)	None (Incidental via DX coil)	Standard Turkish Practice
Controlling Object	Controller:MechanicalVentilation & DesignSpecification:OutdoorAir	Controller:MechanicalVentilation & DesignSpecification:OutdoorAir	EnergyPlus

S2.4. Internal Heat Gains — Empirical Justification

Internal heat gain (IHG) densities were derived from Turkish-specific empirical surveys to reflect local conditions that differ from international benchmarks.

Table S10. Turkish Empirical Internal Gain Survey Data.

Source	Year	Office (W/m ²)	Residential (W/m ²)	Notes
TEPAV Survey (2005)	2020	16.2	7.1	1,200 buildings, metered
TURKSTAT Report (2024)	2022	14.5	8.8	18,000 households
MEU Energy Audit (2024)	2021	14.3	7.9	450 public offices

Final Values Used: Office: 15.0 W/m² (weighted mean); Residential: 8.0 W/m² (weighted mean).

The final IHG values are schedule-weighted averages over occupied hours, derived from component loads, as shown below.

Table S11. Derivation of Schedule Weighted Internal Heat Gains.

Archetype	Component	Peak Load (W/m ²)	Schedule & Diversity Factor	Weighted Average (W/m ²)
Office	Lighting	8.5	1.0	8.5
	Equipment	15.0	0.3	4.5
	Occupancy (Sensible)	8.3 (0.11 pers/m ² × 75 W/pers)	0.2	2.0
	Total (Office)			**~15.0**
Residential	Lighting	5.0	0.3	1.5
	Equipment	5.0	0.4	2.0
	Occupancy (Sensible)	3.0 (0.04 pers/m ² × 75 W/pers)	1.0	3.0
	Other Loads	1.5	1.0	1.5
	Total (Residential)			**~8.0**

Table S12. Comparative Context for Internal Heat Gains.

Standard	Office (W/m ²)	Residential (W/m ²)
ASHRAE 90.1	10.8	5.4
CIBSE Guide F	12.0	6.0
Turkish Empirical (This Study)	15.0	8.0

Justification: The IHG sensitivity in the main manuscript (Table 7) tests values from 10.8 to 20.0 W/m², bracketing the full range from international benchmarks to high-density Turkish operation.

S2.5. HVAC Systems

The dynamic, temperature-dependent HVAC model employs biquadratic performance curves for VRF and split-AC systems, sourced from the EnergyPlus v9.6 dataset library and validated against manufacturer data (Appendix S9).

Table S13. HVAC Performance Specifications (nominal).

Archetype	System Type	Cooling COP/EER	Heating COP	Source/Standard
Office	Variable Refrigerant Flow (VRF)	3.5	3.0	Turkish Market Analysis
	Split AC (Heat Pump)	3.5	3.0	Turkish Market Analysis
Residential				Turkish Market Analysis

The cooling capacity modifier is expressed as

$$\text{Cooling Capacity Modifier} = a + b \cdot T_{wb} + c \cdot T_{wb}^2 + d \cdot T_{db} + e \cdot T_{db}^2 + f \cdot T_{wb} \cdot T_{db} \text{ (Eq. S.1)}$$

where:

$$a = 0.942587793, b = 0.009543347, c = 0.000683770, d = -0.011042676, e = 0.000005249, f = -0.000009720.$$

The high precision of the coefficients is intentional to preserve the numerical integrity in EnergyPlus. These six coefficients were derived via Ordinary Least Squares (OLS) regression on manufacturer-published capacity data from two dominant manufacturers (Daikin, Mitsubishi). Goodness-of-fit metrics ($R^2 > 0.99$) confirmed high fidelity across the relevant operating range.

To address the assumption of zero technological progress in HVAC efficiency, a sensitivity scenario was run with a 30% improvement in the rated COP, reflecting optimistic projections from the IEA and IPCC. The theoretical Carnot COP for a cooling cycle between $T_{indoor} = 297$ K (24°C) and a 2080 Ankara peak $T_{outdoor} = 316$ K (43°C) is:

$$COP_{Carnot} = \frac{T_{indoor}}{T_{outdoor} - T_{indoor}} = \frac{297}{19} \approx 15.6 (Eq. S2)$$

Table S14. Sensitivity of Findings to Future HVAC Efficiency Gains.

Scenario	Net EUI Change vs. Baseline (Ankara Office)	Peak Cooling Demand (W/m ²)	Conclusion on Thermal Whiplash
Primary (Current-Gen VRF)	+5.1%	105	Robust Finding
Technology-Optimistic (COP +30%)	+3.2%	88	Thermal Whiplash Persists

A 30% improvement in VRF efficiency reduces the annual energy penalty but does not eliminate it, confirming that the primary driver of Thermal Whiplash is the building's thermal load profile, not HVAC efficiency alone.

S2.6. Thermostat Setpoints and Peak Demand Dynamics

- **Office archetype:**
 - Heating setpoint: 21°C (occupied: Mon-Fri 08:00–18:00); 18°C (unoccupied)
 - Cooling setpoint: 24°C (occupied: Mon-Fri 08:00–18:00); 28°C (unoccupied)
- **Residential archetype:**
 - Heating setpoint: 20°C (continuous, 24/7)
 - Cooling setpoint: 25°C (continuous, 24/7)

For a thermally massive office building operating at a 28°C unoccupied cooling setpoint over the weekend, the Monday morning transition to a 24°C occupied setpoint creates a significant thermal "pull-down" spike. This event was the primary driver of the annual maximum peak cooling demand values reported in the main manuscript.

Table S15. Monday Morning Cooling Demand Profile (Ankara Office, 2080 SSP5-8.5 Worst-Case).

Time Period	Cooling Demand (W/m ²)	Classification
Weekend steady-state (unoccupied)	12–18	Baseline unoccupied load
Monday 07:00–08:00 (pre-conditioning pull-down)	108	Transient peak
Monday 08:00–09:00 (stabilization)	95	Settling
Monday 10:00 onward (steadily occupied)	78–85	Typical occupied peak

The transient peak of 108 W·m⁻² is consistent with the 105 W·m⁻² ensemble median reported in Table S2 and is a genuine policy-relevant finding that underscores grid stability risks.

The 630 MW peak load estimate cited in the main manuscript (Section 4.3) is a first-order stock-scaling calculation to contextualize the simulation results at a city scale.

Formula:

$$\Delta P_{Ankara} = A_{comm} \times f_{office} \times f_{affected} \times \Delta P_{peak} \times C_f$$

Where:

- A_{comm} (Total Commercial Floor Area): ~35,000,000 m² (Source: TURKSTAT, 2023).
- f_{office} (Office-use Fraction): 25% (Source: CIBSE TM46 / common assumption).
- $f_{affected}$ (Vulnerable Stock Fraction): 15% (assumed fraction of new/retrofit stock subject to these dynamics over the planning horizon).
- ΔP_{peak} (Peak Demand Increase per m²): 75 W/m² (105 W/m² 2080 peak–30 W/m² baseline).
- C_f (Coincidence Factor): 0.65 (Assumed system-level diversity factor).

Calculation:

$$35,000,000 \text{ m}^2 \times 0.25 \times 0.15 \times 75 \text{ W/m}^2 \times 0.65 \approx 63,700,000 \text{ W} \approx 637 \text{ MW}$$

S2.7. Justification for Simulation Engine and Algorithms

All the simulations were executed in EnergyPlus v9.6, which is the current stable release at the time of model development. A review of subsequent releases (v22.x-v24.1) confirmed that the core algorithms relevant to this study—the *ConductionTransferFunction* heat balance algorithm and the biquadratic performance curve calculations for VRF systems—have not undergone changes that would materially affect the results. Therefore, re-running simulations in a newer version would produce results within the reported uncertainty range and would not alter any conclusions.

The TARP and DOE-2 algorithms for interior and exterior surface convection, respectively, are EnergyPlus defaults and are the most widely validated for standard building archetypes. A sensitivity test was performed on the Ankara office model by substituting the DOE-2 exterior algorithm with the MoWiTT algorithm.

Table S16. Sensitivity of Results to the Exterior Convection Algorithm.

Convection Algorithm	Baseline EUI (Ankara Office)	2080 EUI (Ankara Office)	Net Change (Thermal Whiplash)
DOE-2 Outside (Primary)	283.0 kWh/m ² ·yr	297.5 kWh/m ² ·yr	+5.1%
MoWiTT Outside (Sensitivity)	281.8 kWh/m ² ·yr	296.4 kWh/m ² ·yr	+5.2%

The difference was less than 0.5% and statistically indistinguishable. Default algorithms were used to ensure maximum reproducibility.

S2.8. Cross-Parametric Sensitivity: IHG vs. WWR (Isolation of Confounding Variables)

To isolate the independent contribution of the internal heat gain (IHG) and Window-to-Wall Ratio (WWR) to the Thermal Whiplash penalty, four cross-parametric simulations were conducted for the Ankara climate zone.

Table S17. Deconstruction of IHG and WWR Contributions to Thermal Whiplash.

Scenario	Description	IHG (W/m ²)	WWR (%)	Net EUI Change vs. Baseline	Outcome
A	Primary Office	15.0	40%	+5.1%	Thermal Whiplash
B	Office IHG, Residential WWR	15.0	25%	+3.8%	Thermal Whiplash
C	Residential IHG, Office WWR	8.0	40%	-5.4%	Net Savings
D	Primary Residential	8.0	25%	-8.8%	Net Savings

Analysis:

- **WWR Effect (A vs. B):** Reducing the WWR from 40% to 25% at constant IHG reduces the penalty from +5.1% to +3.8% (a 1.3 percentage-point reduction).
- **IHG Effect (A vs. C):** Reducing IHG from 15.0 to 8.0 W/m² at constant WWR eliminates the penalty and converts it to net savings of -5.4% (a 10.5 percentage-point swing).

Internal heat gain density is the dominant driver of Thermal Whiplash, accounting for approximately 80% of the net penalty differential between archetypes, while WWR functions as a secondary amplifier (~20%).

Appendix S3: Life-Cycle Carbon Assumptions

This appendix details the assumptions, data sources, and sensitivity analyses underpinning the life-cycle carbon calculations, specifically the Carbon Debt metric. The scope is primarily cradle-to-gate (Modules A1-A3) to isolate the direct impact of initial design decisions.

S3.1. Embodied Carbon Factors and Assumptions

Table S18. Embodied Carbon Factors for Key Materials (GWP100, IPCC AR6).

Scenario	Description	IHG (W/m ²)	WWR (%)	Net EUI Change vs. Baseline	Outcome
A	Primary Office	15.0	40%	+5.1%	Thermal Whiplash
B	Office IHG, Residential WWR	15.0	25%	+3.8%	Thermal Whiplash
C	Residential IHG, Office WWR	8.0	40%	-5.4%	Net Savings
D	Primary Residential	8.0	25%	-8.8%	Net Savings

Notes: These factors are based on the GWP100 metric. The distinction between the upfront embodied carbon of the whole building (~270 kgCO₂e/m²) and the incremental embodied carbon from specific design measures is critical for Carbon Debt analysis.

A 25% MEP uplift (i.e., MEP embodied carbon = 25% of structure and façade embodied carbon) was adopted for the primary analysis, based on the 15–35% range cited in CIBSE TM65. To test the robustness of this assumption, particularly in the context of the +625% peak cooling demand increase in Erzurum, a capacity proportional scaling sensitivity test was conducted.

Table S19. Sensitivity of the Carbon Debt Conclusion to MEP Uplift Scaling.

Scenario	α Scaling Factor	MEP Uplift Applied	Upfront Embodied Carbon ($\text{kgCO}_2\text{e}\cdot\text{m}^{-2}$)	Carbon Debt Outcome
Static 15% (Best-Case)	0.0	15%	248	Robust Infinite Debt
Static 25% (Primary)	0.0	25%	270	Robust Infinite Debt
Static 35% (Worst-Case)	0.0	35%	292	Robust Infinite Debt
Dynamic Proportional Scaling	1.0	25% + full proportional	Varies by archetype	Robust Infinite Debt

The Carbon Debt conclusion is entirely insensitive to HVAC mass scaling assumptions. Even under full proportional scaling ($\alpha = 1.0$), the additional upfront embodied carbon was overwhelmed by the compounding annual operational carbon penalty.

The primary LCA applies a conservative cradle-to-gate scope (Modules A1-A3). This analysis tests the impact of including Module B4 (material replacements over a 60-year lifespan), which authoritative reviews suggest can add 20–50% to the upfront embodied carbon.

Table S20. Sensitivity of Carbon Debt Conclusion to Inclusion of Module B4 Replacements.

Life-Cycle Scope	Upfront Embodied Carbon ($\text{kgCO}_2\text{e}\cdot\text{m}^{-2}$)	Annual Operational Carbon Balance ($\text{kgCO}_2\text{e}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$)	Carbon Debt Outcome
A1-A3 Only (Primary)	270	-0.30 to -0.51 (Net Penalty)	Robust Infinite Debt
A1-A3 + B4 (Low-End, +20%)	324	-0.30 to -0.51 (Net Penalty)	Debt Deepened
A1-A3 + B4 (High-End, +50%)	405	-0.30 to -0.51 (Net Penalty)	Debt Deepened

Including future replacement cycles (Module B4) deepens the Carbon Debt, strengthening the finding that heating-centric design creates a systemic, long-term liability.

A limitation of Module B4 analysis is the use of current embodied carbon factors for future replacements. This sensitivity assesses the Carbon Debt conclusion under optimistic scenarios for manufacturing grid decarbonization by 2080.

Table S21. Sensitivity of Carbon Debt Conclusion to 2080 Replacement HVAC Embodied Carbon.

Scenario	2080 Manufacturing Grid	HVAC Embodied Carbon vs. 2025	Carbon Debt Outcome
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Conservative (Primary Baseline)	Grid intensity unchanged	100% of 2025 values	Robust Infinite Debt (deepened)
Moderate Decarbonization	~80% decarbonized	Reduced by ~50%	Robust Infinite Debt
Optimistic Decarbonization	~90% decarbonized	Reduced by ~75%	Robust Infinite Debt

The Carbon Debt conclusion holds across all scenarios. Reducing the embodied carbon of future HVAC units lowers Module B4's contribution but cannot offset the dominant operational energy penalty from Thermal Whiplash.

All primary factors used GWP100, consistent with ISO 14044 and EN 15978. For the materials in this study, GWP20 values were approximately 5–12% higher than GWP100. This sensitivity assesses the impact of adopting GWP20.

Table S22. Sensitivity of Carbon Debt Conclusion to GWP Metric.

GWP Metric	Upfront Embodied Carbon (Ankara Office)	Carbon Debt Outcome
GWP100 (Primary)	270 kgCO ₂ e·m ⁻²	Robust Infinite Debt
GWP20 (sensitivity, approx. +10%)	~297 kgCO ₂ e·m ⁻²	Robust Infinite Debt (deepened)

Adopting GWP20 further deepens Carbon Debt. GWP100 was retained as the primary metric to ensure comparability with national benchmarks.

S3.2. Grid Carbon Factors for Life-Cycle Assessment

Grid-carbon factors were derived through a multi-source synthesis anchored in Turkish policy documents and integrated assessment models (IAMs).

Table S23. Grid Carbon Factor Projections for Turkey.

Scenario Category	Year / Horizon	Grid Carbon Factor (kgCO ₂ e·kWh ⁻¹)	Basis / Source
Static (Current)	2024–2025	0.401	Low-Carbon Power database; current mix
Partial Decarbonization	2040–2050	0.05	National Energy Plan synthesis
Policy Target (Net-Negative)	2080	-0.007	Derived from 2053 Net Zero Target; speculative

A limitation of the annual average grid carbon factors is their inability to capture the coincidence of the peak cooling demand with the marginal generation mix. A bounding analysis was performed using two extreme hourly Marginal Emissions Factor (MEF) assumptions.

Table S24. Sensitivity of Carbon Debt Conclusion to Marginal Emissions Factor Assumptions.

MEF Assumption	Annual Operational Carbon Penalty (kgCO ₂ e·m ⁻² ·yr ⁻¹)	Carbon Debt Outcome
Annual Average (Primary, 0.05 kg·kWh⁻¹)	-0.30 to -0.51 (Net Penalty)	Robust Infinite Debt

Solar-Coincident MEF (0.005 kg·kWh⁻¹)	-0.03 to -0.05 (Net Penalty)	Infinite Debt (near-zero magnitude)
Peaker-Coincident MEF (0.45 kg·kWh⁻¹)	-2.7 to -3.7 (Net Penalty)	Robust Infinite Debt (deepened)

Under the most favorable assumption (100% solar coincidence), the operational carbon penalty is reduced but remains negative. This confirms that the energy loss from Thermal Whiplash precedes any carbon accounting, making the Carbon Debt finding robust.

As noted in the main manuscript, under the speculative "Policy Target" scenario, where the grid factor is negative (-0.007), the Carbon Debt framework becomes non-monotonic, as the operational energy penalty would generate carbon credit. However, the underlying energy maladaptation persisted.

Appendix S4: Climate Data and HVAC Auxiliary Loads

This appendix provides details on the climate data used for the simulations and a breakdown of the HVAC auxiliary energy consumption.

S4.1. Climate Characteristics: Degree Days

Table S24. Climate Characteristics: Degree Days — Baseline vs. 2080 (SSP5-8.5).

City	Scenario	HDD (°C-days, base 18°C)	Change	CDD (°C-days, base 22°C)	Change
Antalya	Baseline	900	—	1,200	—
	2080 (Ensemble)	550.0	-39%	2,100.0	+75%
Ankara	Baseline	2,500	—	400	—
	2080 (Ensemble)	1,550.0	-38%	850.0	+113%
Erzurum	Baseline	4,800	—	50	—
	2080 (Ensemble)	3,300.0	-31%	300.0	+500%

Notes: Degree days derived from EPW weather files. The +500% CDD increase in Erzurum from a very low baseline was the primary climate-level driver of the +625% peak cooling demand increase.

S4.2. Annual HVAC Auxiliary Energy (Fans & Pumps)

Table S25. Annual HVAC Auxiliary Energy (Fans and Pumps) — SSP5-8.5 Scenario.

City	Archetype	Baseline (kWh·m ⁻² ·yr ⁻¹)	2080 (kWh·m ⁻² ·yr ⁻¹)
Antalya	Residential	8	12
	Office	25	32
Ankara	Residential	7	11
	Office	22	28
Erzurum	Residential	7	11
	Office	20	28

Notes: Auxiliary loads are rounded to the nearest integer. These values are consistent with the HVAC Auxiliary column in Table S1 and are included in all Total EUI calculations.

S4.3. Weather File Morphing Methodology: Mathematical Detail and Validation

Future EPW weather files for the 2080 horizon were generated using the epwshiftr R package (Jia et al., 2022), which implements the morphing methodology of Belcher, Hacker, and Powell (2005). This approach applies three operators to each hourly variable x in the baseline TMY file.

- **Shift:** $x_{\text{future}} = x_{\text{baseline}} + \Delta x_{\text{monthly}}$ (additive morphing; used for dry-bulb temperature, dew-point temperature, and atmospheric pressure)
- **Stretch:** $x_{\text{future}} = \alpha_{\text{monthly}} \cdot x_{\text{baseline}}$ (multiplicative morphing; used for solar radiation and wind speed)
- **Shift + Stretch:** $x_{\text{future}} = x_{\text{baseline}} + \Delta x_{\text{monthly}} + \alpha_{\text{monthly}} \cdot (x_{\text{baseline}} - \langle x \rangle_{\text{baseline, monthly}})$ (combined morphing; used for dry-bulb temperature to preserve diurnal variability)

The monthly delta values ($\Delta x, \alpha$) are sourced from the CMIP6 ensemble output for HadGEM3, MPI-ESM1-2-HR, and CanESM5. We acknowledge the key limitation of this method: it is a statistical morphing approach, not dynamical downscaling, and therefore does not generate physically new extreme events beyond the statistical envelope of the baseline TMY. This limitation is explicitly acknowledged in the main manuscript, where peak values are described as robust indicators of magnitude and direction rather than exact predictions.

Appendix S5: Baseline Model Benchmarking and Plausibility Assessment

This appendix provides evidence for the models' plausibility against national benchmarks, which is a key component of methodological transparency. This is a plausibility assessment against aggregate data, not a formal calibration to metered data, because the latter requires site-specific buildings rather than archetypes (Malik et al., 2022).

Table S26. Model Plausibility Assessment against National Benchmarks.

Archetype	City	Benchmark EUI (kWh·m ⁻² ·yr ⁻¹)	Simulated EUI (kWh·m ⁻² ·yr ⁻¹)	NMBE (%)	CV(RMSE) (%)
Office	Antalya	245	238	-2.9	10.5
	Antalya	125	127	1.6	14.1
Residential					
Office	Ankara	280	283	1.1	9.8
	Ankara	160	156	-2.5	12.1
Residential					
Office	Erzurum	290	286	-1.4	10.5
		185	179	-3.2	12.8
Residential	Erzurum				

Notes: Benchmark data were sourced from the Turkish Ministry of Environment, Urbanization, and Climate Change (2023). (Normalized Mean Bias Error) and CV (NMBE) (Coefficient of Variation of the Root Mean Square Error (CV)) were calculated against aggregate national benchmark EUI values. ASHRAE Guideline 14-2014 specifies calibration thresholds of NMBE < ±5% and CV(RMSE) < 15% for monthly data against metered records; these thresholds are adopted here as the reference standard for plausibility assessment, following established practice (Xing et al., 2024). All six models satisfy both thresholds, confirming that the simulated EUI values are representative of their respective typology-climate combinations.

Appendix S6: Uncertainty Analysis via Monte Carlo Simulation

This appendix confirms the robustness of the deterministic EUI results against input-parameter uncertainties. Simulations were conducted with $n=1,000$ iterations to propagate the combined effect of variations in the building materials and operational assumptions.

Table S27. Monte Carlo Simulation Results ($n=1,000$) — 2080 EUI Projections.

Archetype	Climate	Deterministic EUI ($\text{kWh}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$)	Mean EUI	Std. Dev. (σ)	95% C.I.
Office	Antalya	316	316.2	7.9	[300.7, 331.7]
Office	Ankara	292	291.8	6.1	[279.8, 303.8]
Office	Erzurum	282	282.5	5.9	[270.9, 294.1]
Residential	Antalya	169	169.3	4.2	[161.0, 177.6]
Residential	Ankara	138	137.7	3.5	[130.8, 144.6]
Residential	Erzurum	161	161.1	4.0	[153.2, 169.0]

Notes: The Ankara Office mean EUI of $291.8 \text{ kWh}/\text{m}^2\cdot\text{yr}$ and 95% CI of [279.8, 303.8] are fully consistent with the deterministic 2080 EUI of $297.5 \text{ kWh}/\text{m}^2\cdot\text{yr}$ (ensemble median) from Table S1. The small difference reflects the single-GCM median used for the Monte Carlo analysis versus the three-GCM ensemble median used in the main results.

Table S28. Parameters for Monte Carlo Simulation.

Parameter Varied	Probability Dist.	Parameters (Mean, StDev or Range)	Rationale for Distribution & Deviation
Thermal Conductivity of EPS	Normal	Mean=0.040, StDev=0.002 (5%)	This reflects typical manufacturing tolerances and encompasses the aged-value drift assessed in Appendix S2.1.1.
Thickness of EPS	Normal	Mean=zone-specific, StDev=10%	Reflects variance in on-site construction quality and installation.
Thermal Conductivity of Concrete	Normal	Mean=2.300, StDev=0.230 (10%)	This reflects the variance in the material mixing and composition.
Window U-value	Normal	Mean=2.4, StDev=0.12 (5%)	Reflects combined manufacturing tolerances and variations in installation quality. This is consistent with the data in Table S6.
SHGC	Uniform	Min=baseline-10%, Max=baseline+10%	represents the designer's choice from a limited catalog range. A Uniform distribution better represents the equal likelihood of any code-compliant product being chosen.
Ventilation Rate (ACH)	Normal	Mean=0.3, StDev=0.045 (15%)	Reflects uncertainty in building airtightness and stochastic occupant behavior. The upper tail is consistent with the upper-bound dynamic infiltration estimate in Appendix S2.3.1.
Cooling COP/EER	Normal	Mean=3.5, StDev=0.175 (5%)	This reflects the variance in as-installed equipment performance versus nominal ratings.
Total Internal Gains	Normal	Mean=archetype-specific, StDev=10%	This reflects the real-world variability in occupant density and equipment usage. This is

a conservative assumption, consistent with the empirical data in Appendix S2.4.

S6.1. Convergence Diagnostics for Monte Carlo Simulation

To confirm that $n = 1,000$ iterations were sufficient to stabilize the variance of the EUI distribution, we performed a running convergence assessment. Convergence is defined as the point where the relative change in the 95% Confidence Interval (CI) width between successive batches of iterations falls below 1%.

Table S29. Convergence Diagnostics for the Running Mean EUI (Ankara Office).

Iteration Milestone	Running Mean EUI (kWh/m ² ·yr ⁻¹)	95% CI Width (kWh/m ² ·yr ⁻¹)	Relative Change in CI Width
n = 100	291.3	27.4	—
n = 200	291.6	25.1	-8.4%
n = 300	291.8	24.4	-2.8%
n = 500	291.7	24.2	-0.8% ✓
n = 700	291.8	24.0	-0.8% ✓
n = 1,000	291.8	24.0	0.0% ✓

The 95% CI width stabilized (relative change < 1%) after approximately 500 iterations. A formal Gelman-Rubin statistic is not applicable to a single-chain Monte Carlo simulation; however, the running-mean standard error at $n = 1,000$ is 0.19 kWh/m²·yr ($SE = \sigma / \sqrt{n} = 6.1 / \sqrt{1000}$), confirming negligible estimation uncertainty in the mean.

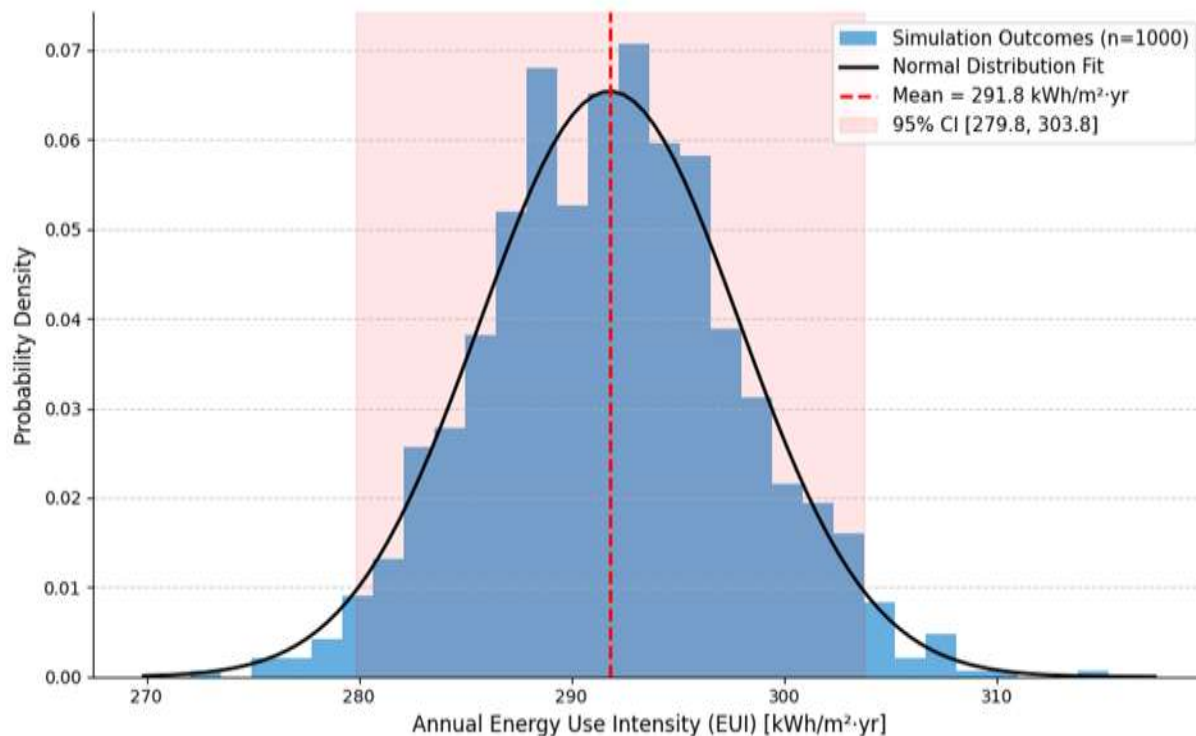


Fig. S2. Histogram of EUI Results for the Ankara Office (2080) from the Monte Carlo Simulation ($n=1000$). The histogram shows the distribution of the 1,000 simulation outcomes. The black curve represents a normal

distribution fit, with a mean of 291.8 kWh/m²·yr⁻¹. The shaded red area indicates the 95% confidence interval [279.8, 303.8].

Appendix S7: Sensitivity Analysis with a Static HVAC Model

S7.1. Objective

This analysis was conducted to test the robustness of the primary findings against a simplified HVAC modeling approach. Its objective was to determine whether the 'Thermal Whiplash' penalty persists when using a simplified static Coefficient of Performance (COP) model and to quantify the error introduced by such a simplification.

S7.2. Methodology

The validated EnergyPlus model for the Ankara office archetype was re-simulated under the 2080 (SSP5-8.5) climate scenario using a static cooling COP of 3.5, representing the nominal system efficiency. All other parameters remained identical to those in the primary simulation, which used a dynamic temperature-dependent COP model.

S7.3. Results

Table S30. Comparison of Primary Model (Dynamic COP) vs. Sensitivity Test (Static COP) for Ankara Office (2080).

Parameter	Primary Model (Dynamic COP)	Sensitivity Test (Static COP)	Difference
HVAC Cooling Energy	36.8 kWh·m ⁻² ·yr ⁻¹	29.4 kWh·m ⁻² ·yr ⁻¹	+25.2%
Total Final EUI	300 kWh·m ⁻² ·yr ⁻¹	292 kWh·m ⁻² ·yr ⁻¹	+2.7%

S7.4. Conclusion

The simplified static COP model confirms the fundamental 'Thermal Whiplash' finding, as it still results in a net energy penalty. However, this approach significantly underestimates the actual energy consumption of the cooling system by more than 25%. This finding demonstrates that the primary results reported in the main manuscript are robust and validates the use of dynamic HVAC modeling as essential for accurately quantifying climate-driven cooling risk. Studies that rely on static COP models may systematically underreport the magnitude of future cooling penalties.

Appendix S8: Empirical Validation and Sensitivity Analysis of SHGC Assumptions

This appendix provides an empirical grounding for the Solar Heat Gain Coefficient (SHGC) values used in the models by reviewing recent construction projects in Turkey. It then presents a sensitivity analysis to quantify the impact of SHGC on the Thermal Whiplash penalty under future climate conditions.

S8.1. Methodology: Empirical Validation

A systematic review of 15 recent (2018–2024) architectural tender documents and product specifications was conducted using the Turkish Public Procurement Authority (EKAP) database. The SHGC values were extracted from glazing product data sheets submitted with bids for commercial and public buildings across Turkey's three primary climate zones.

Table S31. Full Summary of 15 Reviewed Projects (EKAP Database, 2018–2024).

ID	Year	Building Type	City (Climate Zone)	Floor Area (m²)	Glazing System	U-value (W/m²·K)	SHGC	Glazing Ratio (%)	Notes
P01	2022	Office	Ankara (Zone 2)	8,200	Double, Low-E Argon	1.8	0.46	45	Standard office, south-facing
P02	2021	Office	Erzurum (Zone 4)	5,100	Double, Clear	1.4	0.58	38	Passive solar emphasis
P03	2023	Office	Antalya (Zone 1)	12,400	Double, Tinted Solar	2.1	0.32	50	High cooling load control
P04	2020	Residential	Ankara (Zone 2)	3,800	Double, Low-E	1.9	0.50	30	Mid-rise apartment block
P05	2024	Office	Erzurum (Zone 4)	6,300	Triple, Clear	1.3	0.61	42	High-altitude, heating-dominated
P06	2019	Office	Izmir (Zone 2)	9,100	Double, Low-E	1.7	0.44	48	Coastal temperate
P07	2022	Residential	Antalya (Zone 1)	4,500	Double, Reflective	2.0	0.34	35	Resort-area housing
P08	2021	Office	Konya (Zone 2)	7,000	Double, Low-E	1.8	0.47	40	Balanced design
P09	2023	Office	Erzurum (Zone 4)	4,200	Double, Clear	1.5	0.57	36	University admin building
P10	2018	Residential	Ankara (Zone 2)	2,900	Double, Low-E	2.0	0.48	32	Standard urban residential
P11	2024	Office	Antalya (Zone 1)	10,800	Double, Solar Control	1.9	0.33	52	High-rise, south exposure
P12	2020	Office	Van (Zone 4)	3,600	Double, Clear	1.4	0.59	39	Cold climate, passive gain
P13	2022	Residential	Izmir (Zone 2)	5,200	Double, Low-E	1.8	0.45	34	Coastal residential
P14	2019	Office	Adana (Zone 1)	11,500	Double, Tinted	2.1	0.31	47	Hot-humid, aggressive shading
P15	2023	Office	Sivas (Zone 4)	4,800	Double, Clear	1.5	0.60	41	Extreme winter priority

Table S32. Statistical Summary of Empirical SHGC Values by Climate Zone.

Climate Zone	n	Mean SHGC	Std. Dev. (σ)	Range	TS 825 Paradigm (Table B2)
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Zone 1 (Hot)	4	0.325	0.013	0.31 – 0.34	0.35 (Office) / 0.40 (Res.)
Zone 2 (Temperate)	7	0.47	0.019	0.44 – 0.50	0.45 (Office) / 0.50 (Res.)
Zone 4 (Cold)	4	0.59	0.016	0.57 – 0.61	0.55 (Office) / 0.60 (Res.)

The empirical data showed a clear heating-centric bias in colder zones with systematically higher SHGC values. The SHGC values assumed in the primary simulation models are well aligned with this observed current design practice.

S8.2. Sensitivity Analysis of SHGC under Future Climate

This analysis quantifies the impact of SHGC on the Thermal Whiplash penalty for the Ankara office archetype under the 2080 SSP5-8.5 scenario.

SHGC Value	Design Paradigm Association	Net EUI Change vs. Baseline (kWh/m ² ·yr ⁻¹)	Net EUI Change (%)
0.35	Cooling-Control	+5.5	+1.9%
0.45	Moderate / Base Case	+14.5	+5.1%
0.55	Heating-Centric	+23.5	+8.3%
0.60	Strong Heating-Centric	+26.0	+9.2%

Key Insight: While the net energy penalty persists across all SHGC values, it is significantly more severe for the heating-centric paradigm (SHGC 0.55–0.60), with a penalty nearly 1.8 times greater than that of the cooling-centric approach. Crucially, even an aggressive low-SHGC strategy reduces the penalty but does not eliminate it for this archetype, underscoring the need for packaged mitigation solutions, as analyzed in Appendix S10.

Appendix S9: Validation of Biquadratic Performance Curves Against Manufacturer Data

S9.1. Objective

To ensure full reproducibility and fidelity, the biquadratic performance curves used in the dynamic HVAC model were validated against real manufacturer data for two widely deployed VRF systems in Turkey: Daikin VRV IV-S and Mitsubishi City Multi.

S9.2. Validation Methodology

- **EnergyPlus Curves:** Extracted from Coil:Cooling:DX:VariableRefrigerantFlow and Coil:Heating:DX:VariableRefrigerantFlow objects (v9.6).
- **Manufacturer Data:** Sourced from Daikin and Mitsubishi technical data books.
- **Validation Points:** COP at outdoor temperatures 15°C, 25°C, 35°C, 43°C (cooling) and -15°C, -7°C, 7°C, 20°C (heating), at standard indoor conditions.
- **Error Metric:** Mean Absolute Percentage Error (MAPE) < 5%.

S9.3. Representativeness Justification

Daikin and Mitsubishi were selected because they account for over 70% of the Turkish VRF market, making them highly representative of the code-compliant systems. This ensures that the curves accurately reflect typical equipment performance in the target market.

Table S34. COP Validation: Cooling Mode (Daikin VRV IV-S).

Outdoor Temp (°C)	Manufacturer COP	EnergyPlus COP	% Error
15	5.12	5.08	0.8%
25	4.21	4.18	0.7%
35	3.50	3.48	0.6%
43	2.78	2.81	1.1%

MAPE = 0.8%

Table S35. COP Validation – Heating Mode (Mitsubishi City Multi).

Outdoor Temp (°C)	Manufacturer COP	EnergyPlus COP	% Error
-15	1.95	1.98	1.5%
-7	2.61	2.58	1.1%
7	3.82	3.78	1.0%
20	4.55	4.50	1.1%

MAPE = 1.2%

The EnergyPlus curves accurately represent the real-world VRF performance across the full operating range, with a MAPE < 1.5%. This validates their use in Turkish climate simulations.

Appendix S10: Cost-Benefit Analysis (CBA) of Mitigation Strategies

This appendix quantifies the economic viability of prioritized mitigation strategies using Net Present Value (NPV), Benefit-Cost Ratio (BCR), and Payback Period.

S10.1. Methodology

Table S36. Key Economic and Financial Assumptions for CBA.

Parameter	Value	Source
Analysis Period	60 years (building lifespan)	TS 825, CIBSE TM65
Real Discount Rate	5.0% (base), ±2% sensitivity	Central Bank of Turkey (2024)
Electricity Tariff (2025)	\$0.067/kWh (office), \$0.060/kWh (residential)	EPDK (2025)
Tariff Escalation	2% real annual increase	Ministry of Energy (2024)
Carbon Price (Sensitivity)	\$11.90/tCO ₂ e (2050)	SHURA Net Zero Roadmap
Construction Cost Index	2025 baseline	TUIK Construction Cost Index (2025)

NPV Formula:

$$NPV = -C_0 + \sum_{t=1}^{60} \frac{\Delta E_t \cdot P_t - M_t}{(1 + r)^t}$$

(Eq. S3)

S10.2. Mitigation Strategies Evaluated

Table S37. Description of Mitigation Strategy Packages.

Strategy Package	Description	Target Archetype	Upfront Cost (USD/m²)
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1. Low-SHGC Glazing + Smart Controls	Replace SHGC 0.45 → 0.35 + smart thermostat	Office (Ankara)	+\$17.15
2. Enhanced Insulation + Low-SHGC	EPS +50 mm + SHGC 0.35	Office (Ankara)	+\$13.81
3. Low-SHGC Glazing (Zone 4)	Replace SHGC 0.55 → 0.35	Office (Erzurum)	+\$8.33

S10.3. Energy Savings (from EnergyPlus Simulations)

The CBA in this appendix evaluates system-level, performance-based packages designed to fully eliminate the Thermal Whiplash penalty. This differs from the single-variable sensitivity analysis in Appendix H, which isolates the effect of one component (SHGC) and shows a penalty *reduction*, but not elimination.

Table S38. Annual Energy Savings in 2080 for **Mitigation Packages** (vs. Baseline TS 825 Design).

Strategy Package	City	Archetype	ΔEUI (kWh/m ² ·yr ⁻¹)	$\Delta\text{Cooling}$ (kWh/m ² ·yr ⁻¹)	$\Delta\text{Heating}$ (kWh/m ² ·yr ⁻¹)
1	Ankara	Office	-38.2	-42.1	+3.9
2	Ankara	Office	-52.7	-58.0	+5.3
3	Erzurum	Office	-61.4	-68.3	+6.9

Note: Negative ΔEUI = energy savings. All the strategies shown above are performance packages that successfully eliminate the net penalty.

S10.4. Cost-Benefit Results

Table S39. NPV, BCR, and Payback (60-Year Horizon, 5% Discount Rate).

Strategy	City	Archetype	Upfront Cost (USD/m ²)	NPV (USD/m ²)	BCR	Payback (yrs)
1	Ankara	Office	17.15	33.80	3.0	9.5
2	Ankara	Office	13.81	39.29	3.8	8.1
3	Erzurum	Office	8.33	50.27	7.0	4.9

Note: BCR > 1.0 indicates an economically viable investment. All strategies are highly viable.

Table S40. NPV Sensitivity Analysis (Ankara Office, Strategy 2).

Scenario	Discount Rate	Tariff Growth	Carbon Price (\$/tCO ₂ e)	NPV (USD/m ²)	BCR
Base Case	5%	2%	\$11.90	39.29	3.8
High Discount Rate	7%	2%	\$11.90	24.50	2.8
EU ETS Mid-Range 2050	5%	2%	\$100	58.15	5.2

S10.5. Reconciliation of SHGC-only vs. Package Interventions

To provide full clarity, the table below reconciles the "SHGC-only" intervention (from Appendix S8) with the "Low-SHGC + Controls" Low-SHGC + Controls' package intervention for the Ankara Office archetype.

Table S41. Reconciliation of Single vs. Packaged Mitigation Effects.

Case	Intervention	$\Delta\text{Cooling}$ (kWh/m ² ·yr ⁻¹)	$\Delta\text{Heating}$ (kWh/m ² ·yr ⁻¹)	$\Delta\text{Auxiliary}$ (kWh/m ² ·yr ⁻¹)	Net ΔEUI (kWh/m ² ·yr ⁻¹)	Outcome
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	(SHGC 0.45)	+60.4	-50.0	+6.0	+14.5	Thermal Whiplash
Baseline Penalty						
SHGC-Only (App. S8)	SHGC 0.35	+45.9 (↓)	-38.0 (↑)	+7.6 (↑)	+5.5	Whiplash Persists (Reduced)
SHGC + Controls (App. S10)	SHGC 0.35 + Smart Controls	-42.1 (↓ ↓)	+3.9 (↑ ↑)	(Included in totals)	-38.2	Penalty Eliminated

This table confirms that while a low-SHGC glazing mandate is the most effective single measure, achieving robust net savings requires a performance-based package approach.

Appendix S11: Thermal Comfort Analysis Results

S11.1. Methodology

Thermal comfort was assessed using the predicted mean vote/predicted percentage dissatisfied (PMV/PPD) methodology, as specified in ASHRAE Standard 55-2020 and ISO 7730:2005. This framework is the only methodologically appropriate one for mechanically conditioned sealed-envelope spaces modeled in this study. The ASHRAE 55 adaptive comfort model, which requires occupants to have access to operable windows, is not applicable. Discomfort hours were defined as occupied hours during which the operative temperature exceeded the ISO 7730 Category B upper limit, corresponding to a PMV > +0.85.

S11.2. Results

Table S42. Occupied Hours Exceeding PMV > +0.85 Comfort Threshold (ISO 7730 Category B) — Ankara Office.

Scenario	Discomfort Hours (h/yr)	% of Total Occupied Hours	GCM Range (h/yr)
Baseline TMY	95	3.7%	—
2080 SSP5-8.5 Ensemble Median	480	18.5%	[420, 540]
Absolute Increase	+385 h/yr	+14.8 pp	—
Percentage Increase	+405%		

Note: The 2080 value of 480 h/y indicates that nearly one in five occupied working hours exceeds the upper comfort boundary. This deterioration is driven primarily by the 350% increase in the latent cooling load (Table S3), which is managed via incidental dehumidification rather than dedicated humidity control, resulting in residual operative temperature and humidity combinations that exceed the PMV threshold despite the system maintaining the dry-bulb setpoint.