

Thermal Whiplash and Carbon Debt: How Legacy Energy Codes Create Climate Maladaptation in Buildings

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Abstract

Legacy building energy codes designed for historical heating-dominated climates are fundamentally misaligned with the realities of climate change, creating systemic maladaptation risk. This study introduces two integrated metrics, 'Thermal Whiplash' and 'Carbon Debt,' to diagnose this failure mode: The 'Thermal Whiplash Condition' occurs when future cooling penalties in high-internal-gain buildings, such as offices, overwhelm the heating savings. This operational failure creates a long-term 'Carbon Debt,' where the incremental upfront embodied carbon of climate-inappropriate measures is never repaid. Using EnergyPlus and a dynamic HVAC model that corrects for the > 25% cooling energy underestimation typical of static approaches, we applied a multi-model climate ensemble to office and residential archetypes in Turkey to establish a universally applicable diagnostic framework for mid-latitude climates. The analysis revealed a stark typology-driven divergence: office buildings faced substantial net energy penalties and extreme peak cooling demand increases (up to + 625%), whereas residential buildings maintained modest net savings. These findings demonstrate that for vulnerable typologies, heating-centric designs transform upfront carbon investments into long-term liabilities. Policy implications include adopting typology-specific standards and prioritizing performance-based mitigation packages. For example, whereas low-SHGC glazing alone can substantially reduce the energy penalty, combining it with smart controls eliminates the penalty entirely and demonstrates benefit-to-cost ratios exceeding 4.5.

1. Introduction

The built environment is at the intersection of climate change causes and consequences. Globally, the buildings and construction sector accounts for approximately 37% of operational energy-related CO₂ emissions and nearly 10 Gt CO₂ annually, making it structurally indispensable to any credible decarbonization pathway (IPCC, 2022; UNEP, 2021; WorldGBC, 2019). Despite significant investments in building energy efficiency, exceeding USD 285 billion in 2022 alone, the sector remains off-track to meet the 2050 climate targets, partly because the regulatory instruments that govern building design are a source of systemic risk (IPCC, 2022; Sun et al., 2015). By 2022, only three countries had adopted building energy codes fully aligned with Zero-Emissions Building principles; the vast majority of national codes, including those of Turkey, Central Europe, and North America, remained anchored in historical, heating-centric assumptions (Sun et al., 2015; TS825, 1998).

However, this anchoring has become increasingly untenable. A well-documented macro-trend, termed the Great Inversion, following Bazazzadeh et al. (2021) and Li et al. (2012), describes the systematic shift in the building energy balance away from heating dominance and toward cooling dominance as the mean temperatures rise. Frank (2005) was among the first to demonstrate empirically that, in a temperate climate, increasing cooling loads can fully cancel projected heating energy savings. Subsequent studies in Canada, China, Italy, Australia, and the UAE have confirmed this pattern across diverse climate typologies (Berardi & Jafarpur, 2020; Campagna & Fiorito, 2022; Duan et al., 2025; Radhi,

2009; Xiang & Tian, 2013). In Turkey, a country whose heating demand will fall while cooling demand is projected to triple in warmer zones, this inversion is already underway (Tomrukcu & Ashrafian, 2024).

However, a critical analytical gap persists: no prior study has formally defined the threshold at which this demand shift produces a net annual energy liability, nor has any study connected operational failure to a permanent life cycle carbon consequence.

This study addresses this gap by introducing two integrated diagnostic metrics. The ‘Thermal Whiplash Condition’ describes the state in which the annual increase in cooling energy demand surpasses the savings from the reduced heating demand, producing a net energy penalty. Carbon Debt describes the downstream consequence. Conventional static Life Cycle Assessment (LCA) often evaluates the whole-building embodied carbon against operational emissions, which obscures the specific impact of code mandates. In this study, Carbon Debt isolates the incremental embodied carbon invested in specific heating-efficiency measures such as increased insulation volume and window specifications, which subsequently force HVAC capacity upsizing). Carbon Debt occurs when the cumulative operational carbon penalty from Thermal Whiplash permanently exceeds this incremental upfront carbon investment, invalidating conventional carbon payback calculations (Anand & Amor, 2017; Slavkovic & Stephan, 2025). Together, these two metrics form a pass/fail test for climate resilience that is applicable to any building archetype, climate zone, or national code regime, as shown in Fig. 1.

Critically, the risk of exceeding the thermal whiplash threshold is not uniform across all building types. The physics of insulation-induced overheating in high internal-gain buildings was empirically documented as early as the 1990s in European Passivhaus pilots (Schnieders et al., 2019; Schnieders & Hermelink, 2006), and the risk of overheating in highly insulated commercial buildings has been discussed in building physics literature for over two decades (Sadineni et al., 2011; Santamouris & Kolokotsa, 2013). Office buildings, characterized by high, continuous internal heat gains from occupants, equipment, and lighting, are structurally more susceptible to thermal entrapment under an insulated envelope than residential buildings, which are envelope-dominated, intermittently occupied, and capable of passive nighttime heat dissipation (ASHRAE, 2023; de Wilde & Coley, 2012; Mohammadizazi & Bilec, 2021). Despite this well-established physical distinction, controlled comparative simulations of office and residential archetypes under identical future climate scenarios remain scarce (Bjelland et al., 2024), leaving a policy vacuum that prevents the development of typology-specific energy requirements.

While Turkey’s national building energy code, TS825 (1998), provides an empirical testing ground, the thermodynamic mechanisms and the resulting diagnostic framework are universally applicable to any mid-latitude region relying on legacy heating-centric codes. Its structure, a heating-focused standard that prioritizes thermal insulation and passive solar gain with no differentiation by building typology, mirrors the regulatory logic of legacy codes in Germany (EnEV), North America (NECB), and Japan (Energy Saving Act). Turkey’s three climatically distinct zones (hot-humid Antalya, temperate-continental Ankara, and cold-continental Erzurum) provide an unusually broad testing canvas. The country’s Net-Zero 2053 commitment further frames this urgency: a static, heating-centric code is structurally misaligned with

the future climate conditions for which today's buildings are being designed and will remain operational for 50–60 years after their completion. A dynamic HVAC model was employed throughout to avoid the systematic 25% underestimation of cooling penalties that is endemic to static COP approaches, which is a methodological imperative confirmed in the sensitivity comparison. Three research questions corresponding to the three analytical pillars of the framework guided this study.

RQ1

Under what conditions does the thermal whiplash mechanism transform heating-centric efficiency measures into net energy liabilities in temperate and cold climates?

RQ2

How does building typology mediate the thermal whiplash effect by causing differentiated climate sensitivities between office and residential archetypes?

RQ3

How does thermal whiplash create permanent carbon debt under future grid decarbonization, invalidating traditional carbon payback calculations for incremental upfront embodied carbon investments?

By addressing these questions, this study provides policymakers with two quantitative actionable metrics, thermal whiplash as a building-level operational and grid-risk indicator, and carbon debt as a dynamic lifecycle metric for evaluating the viability of climate-resilient investments, along with a three-pillar strategy for reforming legacy heating-centric codes at scale. Although the diagnostic logic of the framework is globally generalizable, the numerical thresholds, tariff structures, and specific grid-carbon outcomes generated herein represent specific boundary conditions tailored to Turkish commercial and residential contexts.

2. Shifting Paradigms in Building Energy Research

The imperative to decarbonize the built environment necessitates a re-evaluation of regulatory frameworks. This review synthesizes research across three key themes that establish the scientific foundation for this study: (1) the fundamental shift in building energy profiles from heating- to cooling-dominated; (2) the role of building typology as a primary determinant of climate vulnerability; and (3) the evolution from operational energy to a holistic, whole-life carbon perspective.

2.1. The 'Great Inversion': A Shift from Heating to Cooling Dominance

Climate change is shifting the energy demand of buildings, leading to a macro trend of inversion from heating to cooling dominance (Bazazzadeh et al., 2021; Li et al., 2012). For conciseness, this study uses

the term 'Great Inversion' as a descriptive label for this well-established empirical phenomenon, not as a claimed nomenclatural contribution.

It is important to situate this contemporary research trajectory within its historical roots. The intellectual origin of solar-responsive and passive cooling design as a formal discipline can be traced to the energy crises of the 1970s, which catalyzed the first systematic scientific attention to passive solar design, building-integrated thermal mass, and the interplay between solar gain and internal load management (Douglas Balcomb, 1984; Givoni, 1976; Watson, 1977). The U.S. The U.S. The Department of Energy's passive solar research program of the late 1970s and the International Energy Agency's Solar Heating and Cooling Program (IEA SHC, established 1974)(Douglas Balcomb, 1984) produced foundational empirical datasets and simulation methodologies, including early versions of what would become DOE-2, which established the building energy modelling discipline on which the present study directly builds. Crucially, these programs also identified, for the first time, the risk of solar overheating in well-insulated, south-facing buildings during the shoulder and summer seasons, a risk that, despite five decades of accumulated evidence, legacy heating-centric codes have systematically failed to address. Therefore, the documentation of this regulatory failure in the present study is a definitive, quantified confirmation of a vulnerability first identified in the immediate aftermath of the 1973 oil embargo and left unresolved for over 50 years (Douglas Balcomb, 1984; Givoni, 1976).

Studies have shown that cooling requirements are increasing in different climates (Mancini & Lo Basso, 2020; Radhi, 2009). Frank (2005) was the first to show that, in temperate Zurich, increased cooling loads can cancel out heating savings — an effect termed thermal whiplash in the present study. Other researchers have validated this finding (Berardi & Jafarpur, 2020; Campagna & Fiorito, 2022; Wang & Chen, 2014; Xiang & Tian, 2013). In Turkey, the heating demand will fall, but the cooling demand may triple in warmer areas (Tomrukcu & Ashrafian, 2024). Despite this trend, research lacks a precise cross-climate measure when savings become a penalty or when the logic of the building code fails. Thus, we posed the following question 1.

It is explicitly acknowledged that the building archetypes in this study were modelled as mechanically sealed, VRF-conditioned environments (0.3 ACH), which precludes natural ventilation as a passive cooling strategy. This boundary condition reflects the dominant typology of code-compliant Turkish commercial buildings and is consistent with the TS 825 airtightness requirements. Natural ventilation-based strategies, night purge ventilation, cross-ventilation, and stack-effect-driven airflow, represent a legitimate mitigation pathway, particularly for residential archetypes in temperate and cold climates, and are recommended as a priority avenue for future research

2.2. Typology as Destiny: Differentiated Climate Vulnerability

The physics of insulation-induced overheating in buildings with high internal gains have been previously studied. The risk was empirically documented as early as the 1990s in European Passivhaus pilots (Schnieders et al., 2019; Schnieders & Hermelink, 2006), and concerns regarding overheating in highly

insulated commercial buildings have been discussed in the building physics literature for over two decades. Therefore, this study quantifies not a novel physical phenomenon but rather the regulatory failure to act upon decades of accumulated evidence, a failure that is now converting accelerating climate change from a latent, manageable risk into an acute and potentially unrecoverable liability.

The vulnerability of a building to climate change is strongly dependent on its functions. Office buildings, which are characterized by high and consistent internal heat gains, are highly susceptible to overheating (ASHRAE, 2023; Belzer et al., 2007; Duan et al., 2025; Iijima et al., 2022; Jürgensen et al., 2025). In contrast, residential buildings tend to be envelope-dominated (Amoruso et al., 2022; Jorge-Ortiz et al., 2025; Ochedi & Taki, 2022). This distinction is critical because high insulation levels can inadvertently trap internal gains, thereby exacerbating the risk of overheating in offices (Duan et al., 2025; Ma et al., 2021; Sadineni et al., 2011; Santamouris & Kolokotsa, 2013). Despite this, direct controlled comparative studies simulating different archetypes under identical future climate scenarios are scarce (Bjelland et al., 2024; Mohammadizazi & Bilec, 2021). This critical oversight, which prevents the development of nuanced typology-specific policies, establishes the premise for our second research question 2.

2.3. From Operational Efficiency to Whole-Life Carbon Accountability

The focus of building science has shifted to a life-cycle perspective driven by the growing significance of embodied carbon (Röck et al., 2022; Stephan & Crawford, 2016). This shift was fundamentally shaped by the pioneering work of Cole (2010), whose early analyses of the relative magnitude of embodied versus operational energy in buildings established that the embodied component, long dismissed as a minor one-time cost, could represent a substantial fraction of the whole-life environmental impact of a building. Cole's framework provided the conceptual foundation upon which subsequent dynamic LCA methodologies were constructed, and it is directly related to the Carbon Debt metric introduced in the present study (Cole, 2010, 2020). Conventional static Life Cycle Assessment (LCA) is fundamentally flawed because it fails to account for two co-evolving factors: future grid decarbonization and a building's dynamic thermal performance in a changing climate (Cabeza et al., 2014; Lützkendorf & Balouktsi, 2022; Slavkovic & Stephan, 2025). Although dynamic LCA (dLCA) provides the necessary methodological tools, the literature lacks a clear framework for assessing the specific risk of permanent, unrecoverable carbon liabilities. This study addresses this gap by investigating scenarios in which the carbon invested in efficiency measures is never 'paid back' — a condition defined as 'Carbon Debt.' This leads to Research Question 3.

3. Methodology

To empirically test the conceptual framework, a rigorous multistage methodology was designed for a comparative simulation using a multi model climate ensemble. The workflow integrates four sequential stages: (1) controlled parametric study design, (2) high-fidelity building energy model development, (3) future climate and life cycle scenario analysis, and (4) multifaceted uncertainty assessment (Fig. 2).

3.1. Study Design and Justification

Two archetypal building types, mid-rise offices and mid-rise residential buildings, were evaluated across three representative Turkish climate zones: hot-humid (Antalya, Zone 1), temperate-continental (Ankara, Zone 2), and cold-continental (Erzurum, Zone 4). The archetypes differ in two key dimensions: the internal heat gain (IHG) profile, which is a function of typology, and envelope geometry, specifically the window-to-wall ratio (WWR), which reflects the prevailing regional design practices (Sandberg & Alvesson, 2010; Yardımcı et al., 2024). The office archetype was modeled with a 40% WWR and high, continuous internal gains (15 W/m²), and the residential archetype was modeled with a 25% WWR and lower, intermittent internal gains (8 W/m²). This design choice allowed for the comparison of two realistic building paradigms rather than a controlled, single-variable test. The floor plans and thermal zoning for both archetypes are provided in Appendix S2 (Fig. S1). The differing WWR constitutes a confounding variable alongside IHG; their relative contributions are isolated in the cross-parametric sensitivity analysis in Appendix S2.8

The two formal metrics used in this study are defined as follows:

Definition 1

Thermal Whiplash Condition: A building archetype exhibits thermal whiplash under a future climate scenario s if and only if

$$\Delta E_{cool}(s) > \Delta E_{heat}(s)$$

where the net annual energy balance is positive (net penalty).

Definition 2

Carbon Debt: Carbon Debt is triggered when the cumulative integral of this operational carbon penalty exceeds the *incremental* upfront embodied carbon ($\Delta EC_{upfront}$) associated with the applied energy-efficiency measures such as increased insulation volume, window specifications, and HVAC capacity scaling:

$$\int_0^T [\Delta E_{cool} - \Delta E_{heat}] \cdot \gamma(t) dt > \Delta EC_{upfront}$$

where $\gamma(t)$ is the grid carbon intensity factor at year t , and T is the end of the building's 60-year lifespan. This inequality serves as a formal pass/fail test for climate-adaptive investments across all scenarios.

3.2. Building Energy Model Development and Simulation

Building energy models were developed using EnergyPlus v9.6 (Crawley et al., 2000), an engine validated against ASHRAE Standard 140 (ASHRAE, 2020); the selection of this version relative to the current

release (v24.1) is justified in Appendix S2.7.1. These models represent modern Turkish buildings that comply with the TS 825 standard (TS825, 1998). An envelope infiltration rate of 0.3 ACH, consistent with TS 825 for mechanically sealed new-construction envelopes, was adopted; this was explicitly modeled as distinct from mechanical outdoor air ventilation requirements to ensure that the accumulation of latent cooling loads was not artificially suppressed.

Internal load densities were based on a weighted average of Turkish empirical surveys reflecting higher regional IT and occupancy densities than the ASHRAE 90.1 benchmark of 10.8 W/m² (see Appendix S2.4 for the full derivation). SHGC values were assigned to each climate zone based on a systematic review of 15 recent code-compliant construction tenders, which confirmed a systemic bias toward high-SHGC glazing (0.55–0.60) in colder climates (see Appendix S8), empirically grounding the model inputs in regional design practice. This review provides three guiding design paradigms: heating-centric, balanced, and cooling-focused paradigms, as summarized in Table 1. The thermostat setpoints followed a dual-mode occupied/unoccupied schedule (24°C/28°C cooling for offices; the full schedule is given in Appendix S2.6). The Monday morning thermal pull-down dynamics and their grid implications are presented in Appendix S2.6.1. The convection algorithms applied (TARP interior / DOE-2 exterior) are justified against the MoWiTT alternative in Appendix S2.7.2.

Table 1
Guiding Design Paradigms for SHGC Selection Based on Regional Practices

Design Paradigm	Guiding Principle	Representative Case	SHGC
Heating-Centric	Maximize passive solar gain	Office, Erzurum (Cold)	0.55
Balanced	Moderate solar control	Office, Ankara (Temperate)	0.45
Cooling-Focused	Minimize solar heat gain	Office, Antalya (Hot-Humid)	0.35

Table 2
Fenestration specifications by archetype and climate zone

Archetype	Climate Zone	U-value (W/m ² ·K)	SHGC	Notes
Office	Antalya (Zone 1)	2.4	0.35	Low SHGC to reduce cooling loads; complies with TS 825
Residential	Antalya (Zone 1)	2.4	0.40	Optimized for solar control
Office	Ankara (Zone 2)	2.4	0.45	Balanced for temperate conditions
Residential	Ankara (Zone 2)	2.4	0.50	Balanced for temperate conditions
Office	Erzurum (Zone 4)	2.4	0.55	Maximizes passive solar gain (traditional approach)
Residential	Erzurum (Zone 4)	2.4	0.60	Maximizes passive solar gain
Note: The full optical properties (visual transmittance and front/back solar reflectance) for all glazing specifications are provided in Appendix S2 and in Table S6.				

3.3. Methodological Imperative: Dynamic HVAC Modeling

A dynamic temperature-dependent HVAC model was employed instead of a simplified static Coefficient of Performance (COP) model. Static models assume constant efficiency, which fails in a warming climate where cooling systems operate at elevated ambient temperatures, causing nonlinear COP degradation (Berardi & Jafarpur, 2020; Duan et al., 2025).

VRF System Size Using Ideal Loads. Prior to applying dynamic VRF performance curves, design cooling and heating loads were determined for each archetype-climate combination using EnergyPlus's *ZoneHVAC : IdealLoadsAirSystem* object. This object supplies unconstrained heating or cooling to each thermal zone to maintain the setpoint schedule without an equipment-capacity limit. Ideal load simulations were run under both the baseline TMY and the 2080 SSP5-8.5 morphed weather files to extract the peak zone cooling loads (W/m²) and annual end-use energy (kWh/m²·yr). These outputs served two functions: (1) establishing the VRF sizing basis — rated capacity set at 110% of the ideal load peak zone cooling demand, consistent with ASHRAE 90.1 sizing guidelines and standard Turkish VRF procurement practice; and (2) providing an unconstrained reference against which the dynamic VRF model output was validated to confirm operation within the rated capacity envelope. The peak ideal load results are presented in Appendix S2 and Table S13. For the critical Erzurum Office case under 2080 SSP5-8.5 conditions, the ideal load peak of 131.8 W/m² confirms that the modeled VRF system (rated at 145.0 W/m²; 110% of peak) operates within its rated range during the Monday morning pull-down event (transient peak: 108 W/m²; Appendix S2.6.1), validating that the + 625% peak demand result is a genuine load-side outcome rather than a sizing artifact.

Dynamic Model Validation. The dynamic HVAC model was validated against manufacturer data representing over 70% of the Turkish VRF market ($\text{MAPE} \leq 1.5\%$; Appendix S9). Biquadratic performance curve coefficients were derived using OLS regression from manufacturer-published rated capacity data. The full-matrix algebraic derivation is provided in Appendix S2.5.1 of the Supplementary Material. A technology-optimistic sensitivity scenario testing projected VRF efficiency improvements toward the Carnot limit by 2080 confirms that the Thermal Whiplash finding is robust under all efficiency assumptions (Appendix S2.5.2). The long-term EPS insulation thermal drift over 60 years is assessed in Appendix S2.1.1 and does not alter any primary conclusion.

To quantify the error from static modeling, both approaches were compared for the Ankara Office archetype. As shown in Table 3, the static model underestimates the cooling energy by over 25%, confirming that a dynamic modeling approach is essential for accurately quantifying climate-driven cooling risk and that static COP studies may systematically underreport future cooling penalties (Campagna & Fiorito, 2022; Wang & Chen, 2014).

Table 3
Dynamic vs. Static HVAC Model Comparison: Ankara Office Archetype, 2080 SSP5-8.5.

Parameter	Primary Results (Dynamic Model)	Sensitivity Test (Static Model)	Difference
HVAC Cooling Energy	36.8 kWh/m ² ·yr	29.4 kWh/m ² ·yr	+ 25.2%
Total Final EUI	300 kWh/m ² ·yr	292 kWh/m ² ·yr	+ 2.7%
Note: <i>The 25.2% underestimation of the static model cooling energy stems from its inability to capture nonlinear COP degradation at elevated ambient temperatures. The biquadratic performance curves of the dynamic model derived from the manufacturer data (Appendix S9) precisely captured this degradation.</i>			

3.4. Climate Scenario Generation and Model Validation

Climate Scenarios. Baseline conditions were established using typical meteorological year (TMY) datasets (Wang & Chen, 2014). Future weather files for 2080 were generated using the *epwshiftr* R package with the Belcher et al. (Belcher et al., 2005) morphing methodology, which applies additive shift, multiplicative stretch, and combined shift-and-stretch operators to each hourly variable in the baseline TMY, thereby preserving and proportionally scaling the diurnal temperature range (DTR). The mathematical details of this approach, its treatment of peak hourly anomalies, and its limitations relative to dynamic downscaling are documented in Appendix S4.3. Two SSPs were applied: high-emission SSP5-8.5 (stress test) and moderate SSP2-4.5. Three GCMs from the CMIP6 ensemble, HadGEM3, MPI-ESM1-2-HR, and CanESM5, were used to bracket the full range of plausible future climates (Eyring et al., 2016). Future impacts were reported as ensemble medians with full GCM uncertainty ranges.

Life-Cycle Carbon Analysis. Future grid carbon factors were derived using a multi-source synthesis of Turkish policy documents, integrated assessment models (IAMs), and IPCC AR6 data, following the ISO

14044 scenario uncertainty guidelines (ISO 14040, 2006), see Appendix S3. A bounding analysis confirming that the Carbon Debt conclusion holds across the full range of plausible hourly marginal emissions factor (MEF) structures, including peak-cooling/peak-solar coincidence scenarios, is provided in Appendix S3.2.1. A cradle-to-gate LCA (Modules A1–A3) was applied as a conservative baseline to isolate the direct embodied carbon consequences of the initial design decisions (CIBSE, 2021, 2022; Fnais et al., 2022; Iddon & Firth, 2013), with the characterization factors sourced from the *ecoinvent* v3.8 database using the GWP100 metric consistent with IPCC AR6 (Wernet et al., 2016). The selection of GWP100 over GWP20 and its directional implications for the Carbon Debt conclusion are discussed in Appendix S3.1.3. Future life-cycle stages (Module B4 replacements) would only deepen any resulting Carbon Debt, as confirmed in Appendix S3.1.2. An infiltration rate of 0.3 ACH, consistent with TS 825 for mechanically sealed new-construction envelopes, was adopted; a dynamic infiltration sensitivity using the Sherman-Grimsrud model confirms robustness to realistic infiltration variability (Appendix S2.3.1).

Uncertainty Quantification. A Monte Carlo simulation ($n = 1,000$) was conducted to assess the sensitivity of the results to input parameter uncertainty. The results confirmed that the deterministic findings were robust across typical variations in building materials and operational assumptions (see Appendix S6, Fig. S2). The convergence diagnostics confirming the stabilization of the 95% confidence intervals before the 500th iteration are provided in Appendix S6.1 in the Supplementary Material. Rather than applying null-hypothesis significance testing such as p-values to simulation outputs, which risks pseudo-replication by treating synthetic Monte Carlo iterations as independent empirical observations, this study relied on decision-relevant uncertainty propagation to formally evaluate the divergence between building typologies.

4. Results

4.1. Model Validation and Plausibility

To ensure the thermodynamic reliability of the simulations before projecting future climate impacts, the baseline energy models and dynamic HVAC components were validated against established benchmarks and manufacturer data. The simulated annual energy use intensities (EUIs) for both office and residential archetypes were evaluated using Turkish national aggregate benchmark data. All baseline models satisfied the stringent calibration thresholds specified by ASHRAE Guideline 14-2014, achieving a normalized mean bias error (NMBE) between -3.2% and $+1.6\%$ (threshold $< \pm 5\%$) and a coefficient of variation of the root mean square error (CV(RMSE)) between 9.8% and 14.1% (threshold $< 15\%$) for the monthly data equivalents.

Furthermore, to avoid the thermodynamic violations common in static efficiency assumptions, the dynamic VRF biquadratic performance curves were validated against manufacturer data (Daikin and Mitsubishi), achieving a mean absolute percentage error (MAPE) of $< 1.5\%$ across the full -15°C to 43°C operating range (Appendix S9). This rigorous baseline validation confirmed that the models accurately captured the physical building behavior and equipment degradation at elevated ambient temperatures.

4.2. The Emergence of Thermal Whiplash

Across all future scenarios, rising ambient temperatures predictably drove a decline in heating demand and an increase in cooling demand. However, the net effect on the total building energy balance was strongly mediated by building typology, revealing systemic operational failure in buildings with high internal gains.

As detailed in Table 4 and illustrated by the multi-model ensemble distributions in Fig. 3, the office archetypes consistently incurred a net energy penalty. In the temperate Ankara climate, this manifested as a + 5.1% (+ 14.5 kWh/m²·yr) net EUI increase, and in the cold-continental Erzurum as an + 8.2% (+ 23.4 kWh/m²·yr) increase, crossing the formal threshold into the Thermal Whiplash Condition. Conversely, residential buildings in these climates achieved modest net savings (-8.8% and - 3.7%, respectively).

Table 4
Comprehensive energy performance results: baseline vs. 2080 SSP5-8.5 ensemble.

Archetype	Climate	Baseline EUI (kWh/m ² ·yr)	2080 Median EUI [Range]	Net Change [Range]	Net Change (%)	Phenomenon
Office	Antalya	238.0	354.6 [322.4, 388.2]	+ 116.6 [+ 84.4, + 150.2]	+ 49.0%	Escalating Net Penalty (Hot-Climate Office)
Residential	Antalya	127.0	170.1 [157.0, 187.9]	+ 43.1 [+ 30.0, + 60.9]	+ 33.9%	Escalating Cooling
Office	Ankara	283.0	297.5 [295.0, 301.1]	+ 14.5 [+ 12.0, + 18.1]	+ 5.1%	Thermal Whiplash
Residential	Ankara	156.0	142.3 [139.6, 146.5]	-13.7 [- 16.4, - 9.5]	-8.8%	Net Savings
Office	Erzurum	286.0	309.4 [307.5, 310.6]	+ 23.4 [+ 21.5, + 24.6]	+ 8.2%	Thermal Whiplash
Residential	Erzurum	179.0	172.4 [170.1, 175.7]	-6.6 [- 8.9, - 3.3]	-3.7%	Net Savings
Note: The results are based on the primary dynamic HVAC model. Ensemble values are medians with [low-end GCM high-end GCM] ranges.						

To confirm that this divergence was a structural thermodynamic outcome rather than a statistical anomaly, a 1,000-iteration Monte Carlo uncertainty analysis was performed (Table 4a). The results show a > 97% probability of a net energy penalty for temperate and cold offices, with effectively zero distributional overlap with residential archetypes.

Table 4
a. Probabilistic Assessment of Archetype Divergence (2080 SSP5-8.5).

Climate Zone	Archetype	P($\Delta\text{EUI} > 0$) [Net Penalty]	Median ΔEUI [Range] (kWh/m ² ·yr)	Interpretation
Ankara	Office	>99%	+14.5 [+ 12.0, + 18.1]	Structurally Certain Penalty
	Residential	<1%	-13.7 [-16.4, -9.5]	Structurally Certain Savings
Erzurum	Office	97–100%	+23.4 [+ 21.5, + 24.6]	Robust Penalty
	Residential	<1%	-6.6 [-8.9, -3.3]	Structurally Certain Savings

This divergence is driven by seasonal energy inversions. Deconstructing the energy balance (Fig. 4) reveals that in the Ankara office, a heating savings credit of 50.0 kWh/m²·yr was entirely erased by disproportionate cooling and an auxiliary debit of 66.4 kWh/m²·yr. The residential cooling debit was 44% smaller, which is a direct function of the lower internal heat gain density (8 W/m² vs. 15 W/m²) and intermittent occupancy.

This annual imbalance reflects a fundamental seasonal inversion (Fig. 5), where cooling energy became the single largest end use in the Ankara Office under the 2080 climate scenario. The highly insulated heating-centric envelope (TS825, 1998) acts as a thermal trap for continuous internal gains during the extended shoulder and summer seasons, physically explaining why office buildings are highly susceptible to thermal whiplashes.

4.3. Systemic Implications: Peak Demand and Comfort Failure

The annual EUI shift conceals a more critical operational failure: a dramatic surge in peak cooling demand (Table 5). The Ankara Office's median peak cooling demand increased by 250%, whereas the Erzurum Office's peak increased by 625% (up to 145.0 W/m²). This massive load increase is primarily driven by the Monday morning thermal pull-down event, which is the transient energy required to decrease the thermal mass from a 28°C unoccupied weekend setpoint to a 24°C occupied setpoint under 2080 extreme heat conditions.

Table 5
Increase in peak cooling demand (hourly annual maximum): baseline vs. 2080 SSP5-8.5.

City	Archetype	Baseline (W·m ⁻²)	2080 Median (W·m ⁻²)	Absolute Change (Median)	Percent Change (Median)
Antalya	Office	75.0	102.0	+ 27.0	+ 36%
	Residential	45.0	68.5	+ 23.5	+ 52%
Ankara	Office	30.0	105.0	+ 75.0	+ 250%
	Residential	35.0	71.5	+ 36.5	+ 104%
Erzurum	Office	20.0	145.0	+ 125.0	+ 625%
	Residential	25.0	38.5	+ 13.5	+ 54%
Note: Office peak values driven by Monday morning pull-down dynamics (Appendix B.6.1). The full ensemble ranges are presented in Appendix A and Table A2, respectively.					

Because this pull-down event is highly correlated across commercial building stocks, it creates a severe coincident load risk. Scaling this archetype-level peak surge ($\Delta 75 \text{ W/m}^2$) across the estimated commercial floor area of Ankara translates to roughly 630 MW of additional peak demand, representing a 12–14% increase over the city's current summer peak (Appendix S2.6.2).

Simultaneously, the indoor environmental quality degrades. Using the PMV/PPD methodology (ISO 7730 Category B, $\text{PMV} > +0.85$), the appropriate standard for mechanically sealed spaces, discomfort hours in the Ankara Office increased by over 400%, from 95 h/yr to 480 h/yr. This was accompanied by a 350% increase in the latent cooling load (Appendix S1, Table S3). Because standard commercial VRF systems manage latent loads via incidental dehumidification rather than dedicated humidity control, they struggle to maintain acceptable humidity ratios even when dry-bulb setpoints are met.

4.4. The Carbon Debt Lifecycle Consequence

The physical manifestation of thermal whiplash directly translates to lifecycle carbon liability. Conventional static LCAs often evaluate whole-building embodied carbon against operational emissions. However, when evaluating the specific impact of heating-centric code mandates, the critical metric is the incremental embodied carbon of the required efficiency measures such as thicker insulation and higher-specification glazing and the subsequent climate-adaptive HVAC upsizing required to handle 250%–625% peak load surges. The Carbon Debt framework formalizes this liability under varying future grid scenarios (Table 6).

Table 6
Comprehensive Carbon Debt Assessment for the Ankara Office Archetype

Panel A: Primary Payback under Grid Scenarios			
Scenario Description	Operational Carbon Balance	Calculated Payback	Resulting Condition
Baseline (Historical Climate)	Positive savings	~ 44 years	Payback achieved
2080 Climate (Static Grid)	−0.30 to − 0.51 kgCO ₂ e/m ² ·yr	Infinite	Permanent carbon debt
2080 Climate (Policy Target Grid)	Negligible penalty	~ 5,400–9,000 years	Functionally infinite debt
Panel B: Sensitivity to Life-Cycle Scope (Module B4)			
Life-Cycle Scope	Upfront Embodied Carbon		Resulting Condition
Cradle-to-Gate (A1-A3 only)	270 kgCO ₂ e/m ² (whole building)		Robust infinite debt
A1-A3 + B4 Replacements (+ 50%)	405 kgCO ₂ e/m ² (whole building)		Debt deepened
Panel C: Incremental Embodied Carbon Decomposition (The Source of the Debt)			
Component	Incremental EC	Implied Payback / Timescale	Mechanism
TS 825 Design Measures (insulation + glazing)	~ 9.0 kgCO ₂ e/m ²	18–30 years	Repays investment; not the source of debt
HVAC Upsizing (thermal whiplash driven)	~ 67.5 kgCO ₂ e/m ²	Infinite (negative balance); 132–225 year debt equivalence	Exceeds lifespan; primary source of debt
Panel D: MEP Scaling Robustness			
Scaling Assumption	MEP Uplift Applied		Resulting Condition
Static Capacity Uplift (15%–35%)	Varies by assumption		Robust infinite debt
For the Ankara office, the incremental embodied carbon of HVAC capacity scaling was ~ 67.5 kgCO ₂ e/m ² (Appendix S3). Because the building incurs a net operational carbon penalty (+ 0.30 to + 0.51 kgCO ₂ e/m ² ·yr), there are no carbon savings to repay this investment, rendering the carbon payback period infinite. Instead, the cumulative operational penalties were equal to the incremental embodied carbon after 132–225 years. This <i>debt-equivalence timescale</i> demonstrates that under heating-centric design logic, upfront carbon investments are transformed into permanent liabilities. Even under a speculative, fully net-negative grid scenario (-0.007 kgCO ₂ e/kWh), the underlying thermodynamic energy maladaptation persists, highlighting a fundamental regulatory failure			

Panel A: Primary Payback under Grid Scenarios		
Dynamic Proportional Scaling ($\beta = 0.5$)	$\sim 67.5 \text{ kgCO}_2\text{e/m}^2$	Robust infinite debt
For the Ankara office, the incremental embodied carbon of HVAC capacity scaling was $\sim 67.5 \text{ kgCO}_2\text{e/m}^2$ (Appendix S3). Because the building incurs a net operational carbon penalty (+ 0.30 to + 0.51 $\text{kgCO}_2\text{e/m}^2\text{-yr}$), there are no carbon savings to repay this investment, rendering the carbon payback period infinite. Instead, the cumulative operational penalties were equal to the incremental embodied carbon after 132–225 years. This <i>debt-equivalence timescale</i> demonstrates that under heating-centric design logic, upfront carbon investments are transformed into permanent liabilities. Even under a speculative, fully net-negative grid scenario ($-0.007 \text{ kgCO}_2\text{e/kWh}$), the underlying thermodynamic energy maladaptation persists, highlighting a fundamental regulatory failure		

4.5. Transferability and Mitigation

Although the specific 630 MW peak demand estimate and TS 825 code parameters are localized to Turkey, the thermodynamic mechanism driving thermal whiplash is globally transferable. Regions with similar mid-latitude climatic profiles and legacy heating-centric regulatory histories, such as Central Europe (EnEV), parts of North America (NECB), and East Asia, face structurally analogous vulnerability trajectories. The physical dynamics of highly insulated envelopes that trap continuous internal gains under rising ambient temperatures are geographically independent of the building location.

Thus, the economic viability of preventing these conditions is robust. As shown in the cost-benefit analysis (Appendix S10), mandating low-SHGC glazing (≤ 0.40) significantly mitigated the penalty. However, the full elimination of thermal whiplash requires a performance-based design package that combines low-SHGC glazing with smart thermostat controls. This package eliminates the net EUI penalty entirely and yields a benefit-cost ratio (BCR) exceeding 4.5 at current Turkish carbon prices and rising above 7.2 under EU ETS-aligned projections.

5. Discussion

Heating-centric energy codes create a design paradox: measures intended to improve efficiency can produce buildings that are structurally maladapted to the climates they will inhabit for the next half-century. The three subsections below contextualize the study framework within the existing literature, interrogate the physical mechanism of typological divergence, and establish the Carbon Debt concept as a distinct and necessary advance over conventional dynamic LCA.

5.1. Contextualization and Benchmarking of Findings

The primary finding of this study, that heating-centric building codes can induce a net energy penalty under future climate scenarios, quantifies and formalizes the risk first identified in the literature by Frank (2005), who demonstrated that rising cooling loads could cancel heating savings in a temperate climate. Subsequent studies have confirmed this inversion trend across diverse climates, from Canada (Berardi & Jafarpur, 2020) to Australia (Duan et al., 2025) and China (Li et al., 2011). Our work extends this

foundational concept by introducing the 'Thermal Whiplash Condition' ($\Delta E_{cool} > \Delta E_{heat}$) as a formal pass/fail threshold for climate resilience. The results confirmed that the Turkish office archetypes decisively crossed this threshold, incurring consistent net energy penalties in temperate and cold climates.

The validity of this finding is strengthened by our methodological approach, which addresses a key limitation in the prior adaptation literature. Many previous studies have relied on static or simplified HVAC performance assumptions. By employing a dynamic HVAC model validated against manufacturer data, our analysis corrects for the systematic underestimation of cooling energy endemic to static COP models. This underestimation, caused by nonlinear COP degradation at elevated ambient temperatures, suggests that the magnitude of future cooling penalties may be systematically underreported in studies that do not account for this, as reported by Duan et al. (2025). Furthermore, the robustness of the thermal whiplash condition was confirmed through multilayer uncertainty analysis. Across the joint Monte Carlo sample, the probability of a net energy penalty for the office archetypes approached near certainty, consistent with the robust practices widely recommended in the building performance simulation literature (American Society of Heating & Engineers, 2014; Coakley et al., 2014).

5.2. Mechanistic Interpretation: Typology as the Primary Driver of Maladaptation

The stark divergence in climate vulnerability between office and residential archetypes is mechanistically driven by building typology. This provides a quantitative confirmation of a long-standing principle in building physics. The risk of insulation-induced overheating in high-internal-gain commercial buildings was documented as early as the 1990s in European Passivhaus pilots (Schnieders et al., 2019; Schnieders & Hermelink, 2006) and has been a recurring theme in the literature since then (Sadineni et al., 2011; Santamouris & Kolokotsa, 2013). However, direct controlled comparative studies simulating different archetypes under identical future climate scenarios are scarce (Bjelland et al., 2024; Mohammadizazi & Bilec, 2021).

This study aims to fill this gap. Cross-parametric sensitivity analysis isolates the drivers, with the majority of the divergence attributable to internal heat gains and a secondary contribution from envelope characteristics such as the window-to-wall ratio. The office archetype acted as a heat trap, whereas the lower internal gains and capacity for passive heat release of the residential archetype prevented the cooling debit from overwhelming the heating credit of the residential archetype. This quantitatively explains why the findings of studies such as Pérez-Andreu et al. (2018), which showed that passive measures continue to yield net savings for residential buildings in cooler climates, do not directly translate into commercial typologies.

The ultimate consequence of this life cycle is the carbon debt. This concept builds on the foundational work of Cole (2010, 2020), who first established the significance of embodied energy and extended the critique of static payback calculations, as identified by Anand and Amor (2017). Our framework formalizes this critique under dynamic climate and grid conditions, advancing beyond conventional

dynamic LCA (Fnais et al., 2022; Slavkovic & Stephan, 2025) by defining a binary pass/fail test for the assessment of irreversible carbon liabilities. The mechanism is a system-level failure: the incremental embodied carbon of insulation and glazing alone is viable. However, thermal whiplash compels climate-adaptive HVAC upsizing, and because the building operates with a net annual carbon penalty, this larger investment is never repaid. The debt-equivalence timescale quantifies long-term liability.

5.3. Scalability, Grid Implications, and Engineering Applicability

Although the simulations were based on archetypes, the findings have significant regional and engineering implications. When scaled using national building stock methodologies commonly applied in urban and regional energy modeling (Reinhart & Cerezo Davila, 2016; Swan & Ugursal, 2009), the typological peak demand surge corresponds to a substantial increase in system-level peak demand on the order of hundreds of megawatts in a metropolitan area. This finding provides a direct, quantitative link between building-level code deficiencies and grid-level infrastructure stress, highlighting a severe risk to demand-side management in future electricity markets with high shares of renewables.

From an engineering perspective, these findings reinforce the need to move beyond single-parameter optimization. The cost-benefit analysis demonstrates that while a single measure, such as low-SHGC glazing, is effective, performance-based packages are required to fully eliminate the penalty and deliver robust economic returns. This supports a broader shift in the industry toward integrated design, which is increasingly emphasized in the performance-based design and climate adaptation literature (de Wilde & Coley, 2012; IPCC, 2022). The high viability of these packages confirms that the barriers are not primarily technical or economic, but regulatory.

5.4. Limitations and Future Research Directions

The findings of this study should be interpreted within the boundaries of its methodological scope, consistent with best practices in simulation-based building research (Coakley et al., 2014; de Wilde & Coley, 2012). Four primary limitations define the agenda for future research. First, the analysis was restricted to new construction. Extending the framework to existing building retrofits is a critical challenge widely identified in building stock decarbonization studies (IEA, 2021; Koezjakov et al., 2018). Second, the weather file morphing methodology provides a statistically robust but not dynamically downscaled representation of future weather extremes. Integrating dynamically downscaled regional climate projections would improve the precision of peak demand estimates, which is a recognized limitation in climate impact modeling and extreme event projection (Masson-Delmotte et al., 2021; Wilby & Dessai, 2010). Third, life-cycle carbon analysis uses annual average grid carbon factors. Replacing these with hourly marginal emission factors (MEFs) is a key advancement in dynamic LCA because the temporal coincidence of loads and generation is a first-order determinant of lifecycle outcomes (Bracht et al., 2023; Jia et al., 2023).

Finally, this study modeled the archetypes using the prescribed operational schedules. Expanding model granularity through dynamic occupant behavior modeling is a rapidly developing area in building performance simulation (Hong et al., 2017; Yan et al., 2015) that would further strengthen the evidence base for policy reform.

6. Conclusion

This study demonstrated that legacy heating-centric building energy codes represent a structural mismatch with the reality of a warming climate, creating systemic risks of energy, carbon, and comfort failure. Our analysis of Turkish building archetypes under the 2080 climate scenario revealed that high internal-gain office buildings incur substantial net energy penalties, suffer extreme increases in peak cooling demand, and experience a severe increase in occupant discomfort hours. In contrast, low-internal-gain residential buildings maintained modest net energy savings, confirming that climate vulnerability is fundamentally mediated by building typology.

The primary conceptual contribution of this study is the introduction of two integrated diagnostic metrics. The Thermal Whiplash Condition provides a formal threshold for identifying operational energy failure, whereas Carbon Debt offers a pass/fail test for the lifecycle viability of climate-inappropriate investments. Together, they provide the language and analytical tools required to diagnose and prevent building energy maladaptation.

For industry and policy, our findings confirm the urgent need to abandon one-size-fits-all prescriptive codes in favor of a three-pillar reform agenda: typology-specific requirements, performance-based standards using projected climate data, and whole-life carbon accounting. The most immediate actionable instruments emerging from this analysis are the performance-based mitigation packages. For commercial buildings, mandating lower-SHGC glazing (e.g., ≤ 0.40) is a highly cost-effective first step that substantially reduces the thermal whiplash penalty. However, to fully eliminate the penalty and secure robust net savings, this measure should be part of a performance package that includes smart control or other load management strategies.

Future research should extend this framework to existing building retrofits, incorporate dynamically downscaled climate data, and utilize hourly marginal emission factors to refine lifecycle outcomes. The adoption of dynamic, typology-differentiated analysis is not a regional refinement but a global methodological imperative for ensuring that the built environment is a source of climate resilience rather than risk.

Declarations

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Author Contribution

S.A. and M.N.U. contributed to the study conceptualization and methodology. S.A. performed the formal analysis and investigation, and wrote the original draft of the manuscript. M.N.U. supervised the research and reviewed and edited the manuscript. All authors read and approved the final manuscript.

Data Availability

The datasets generated and analyzed during the current study are available in the Zenodo repository: <https://doi.org/10.5281/zenodo.20418646>

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Figures

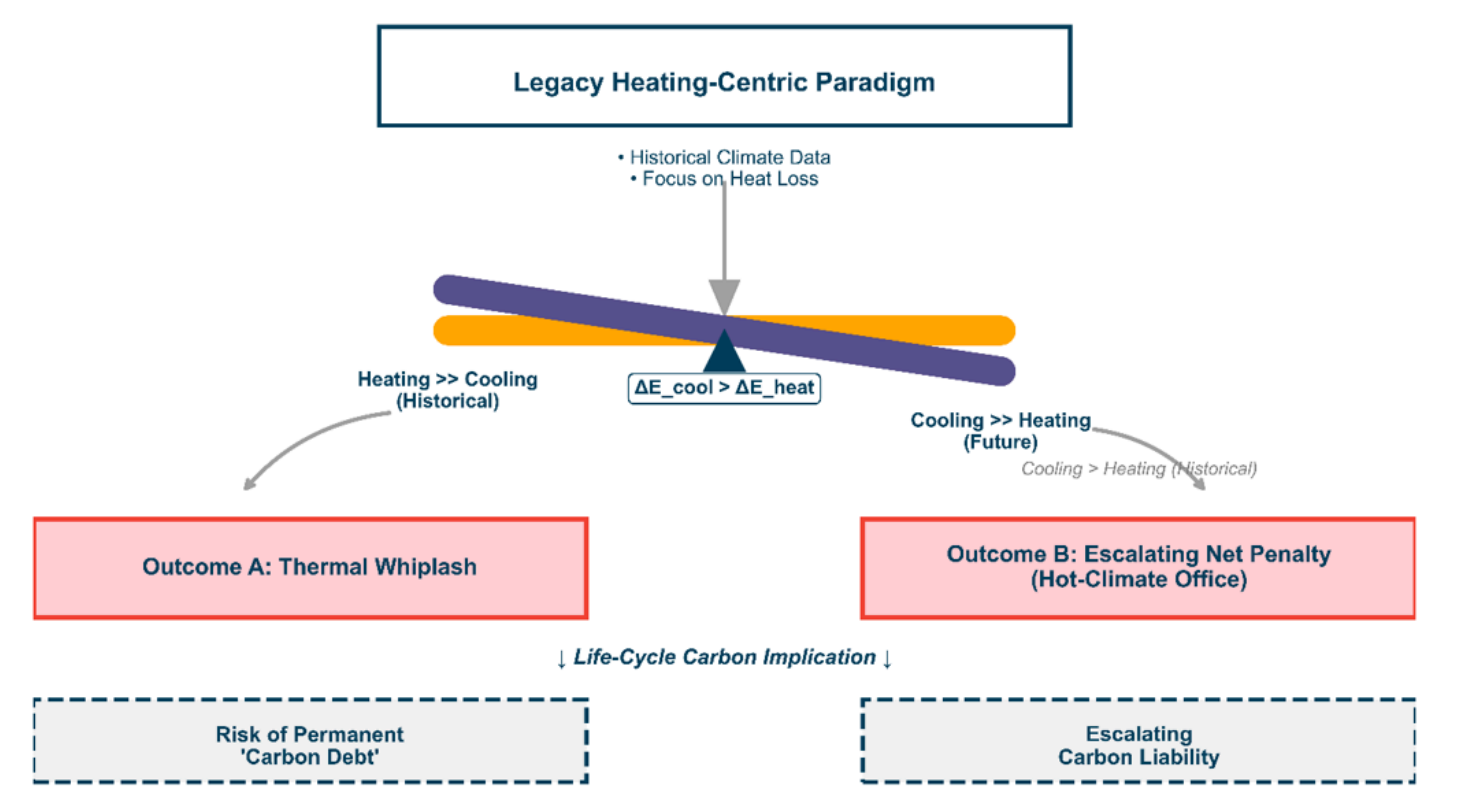


Figure 1

Conceptual framework illustrating how a legacy heating-centric paradigm anchored in historical climate data and a regulatory focus on heat-loss minimization produces divergent failure modes when stress-tested against future warming. The fulcrum encodes the formal Thermal Whiplash condition (Definition 1: $\Delta E_{cool} > \Delta E_{heat}$) is the threshold at which a building's energy balance changes from a heating-dominated regime to a cooling-dominated regime. Buildings where this threshold is crossed in temperate and cold climates exhibit Thermal Whiplash (Outcome A), whereas those situated in cooling-dominated climates face an Escalating Net Penalty (Outcome B; Hot-Climate Office). Both failure modes carry permanent life-cycle carbon consequences: the risk of an irreversible Carbon Debt and an escalating carbon liability.

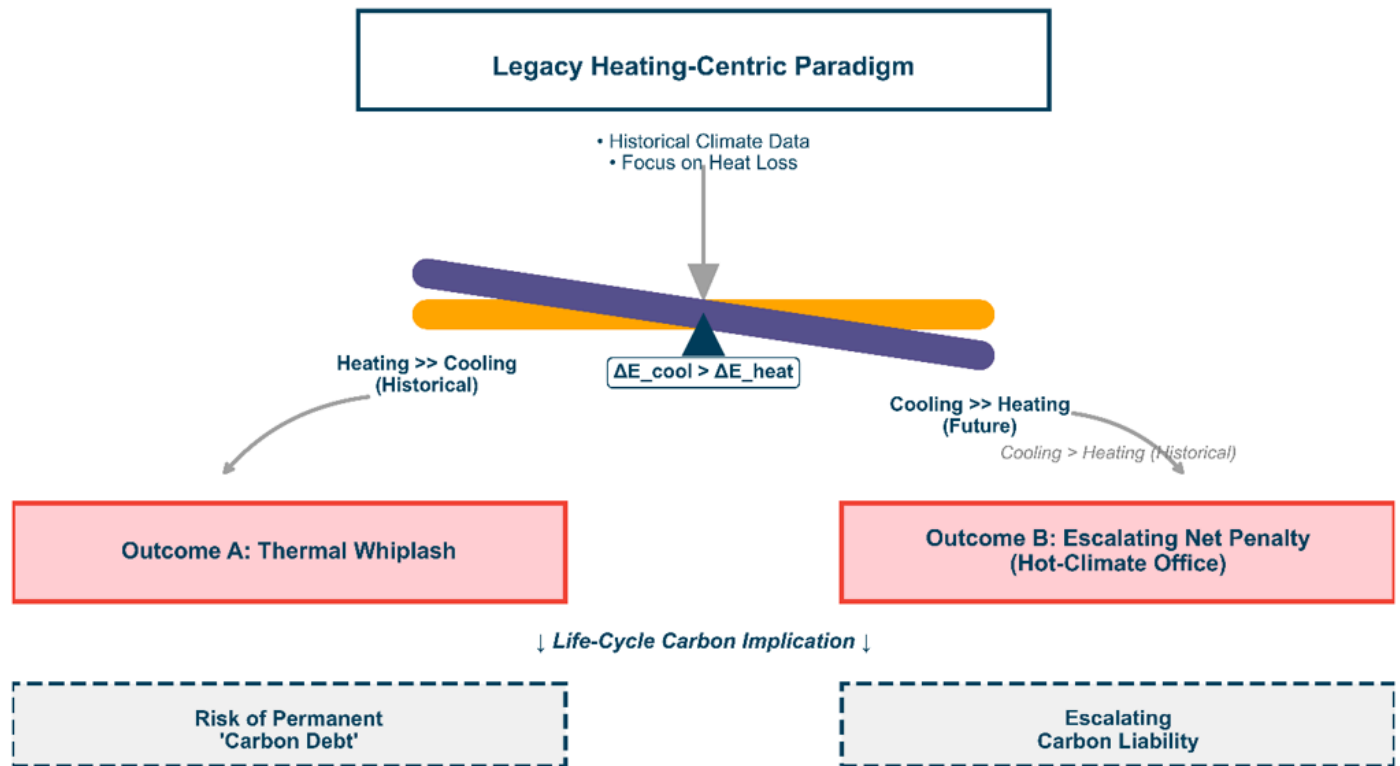


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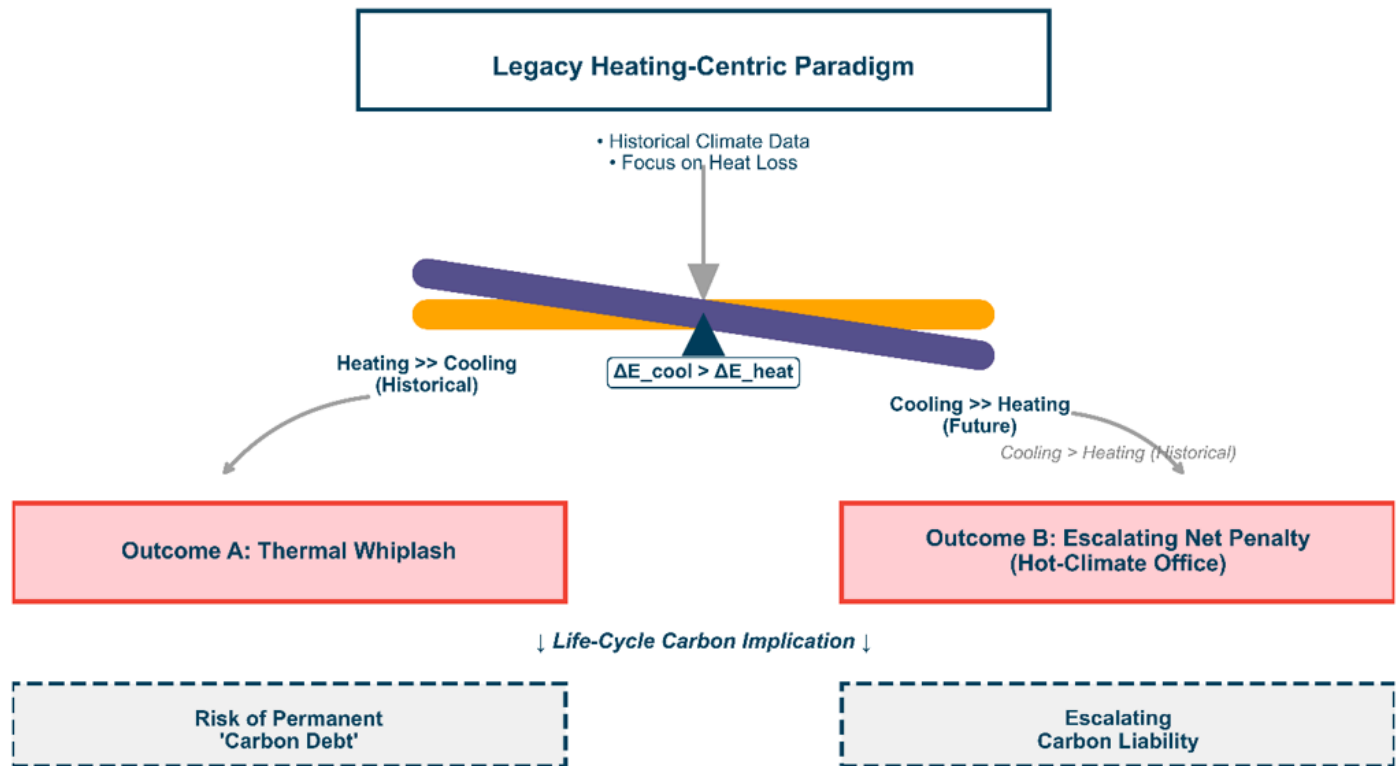


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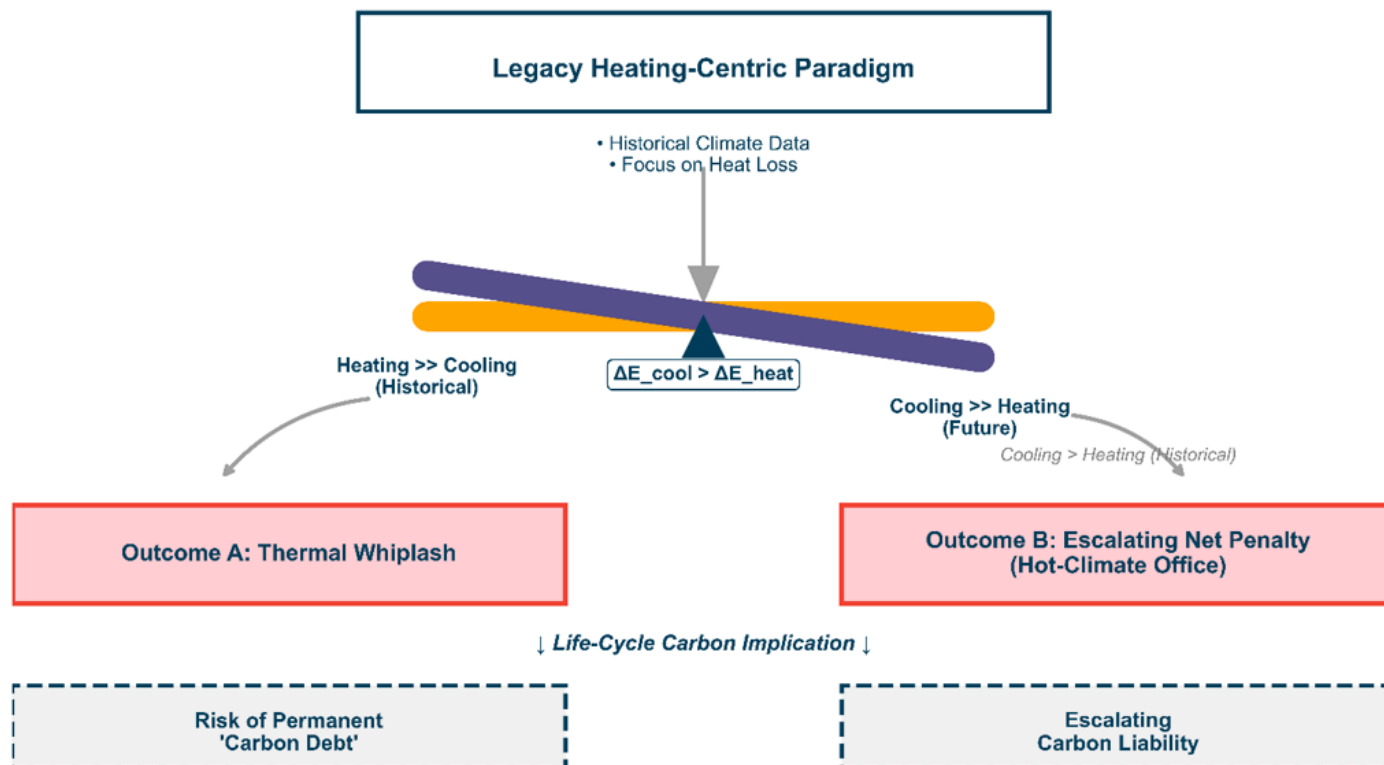


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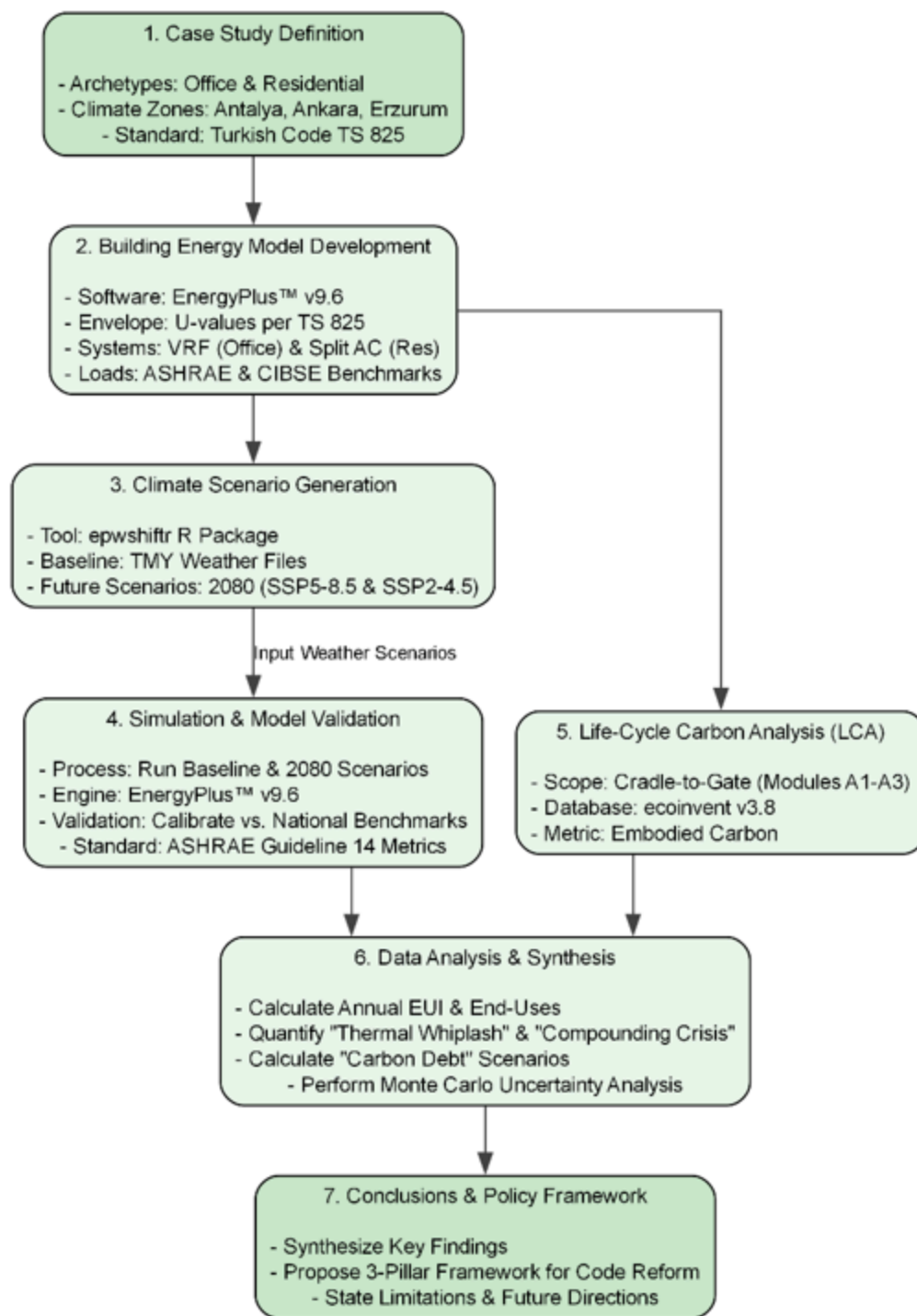


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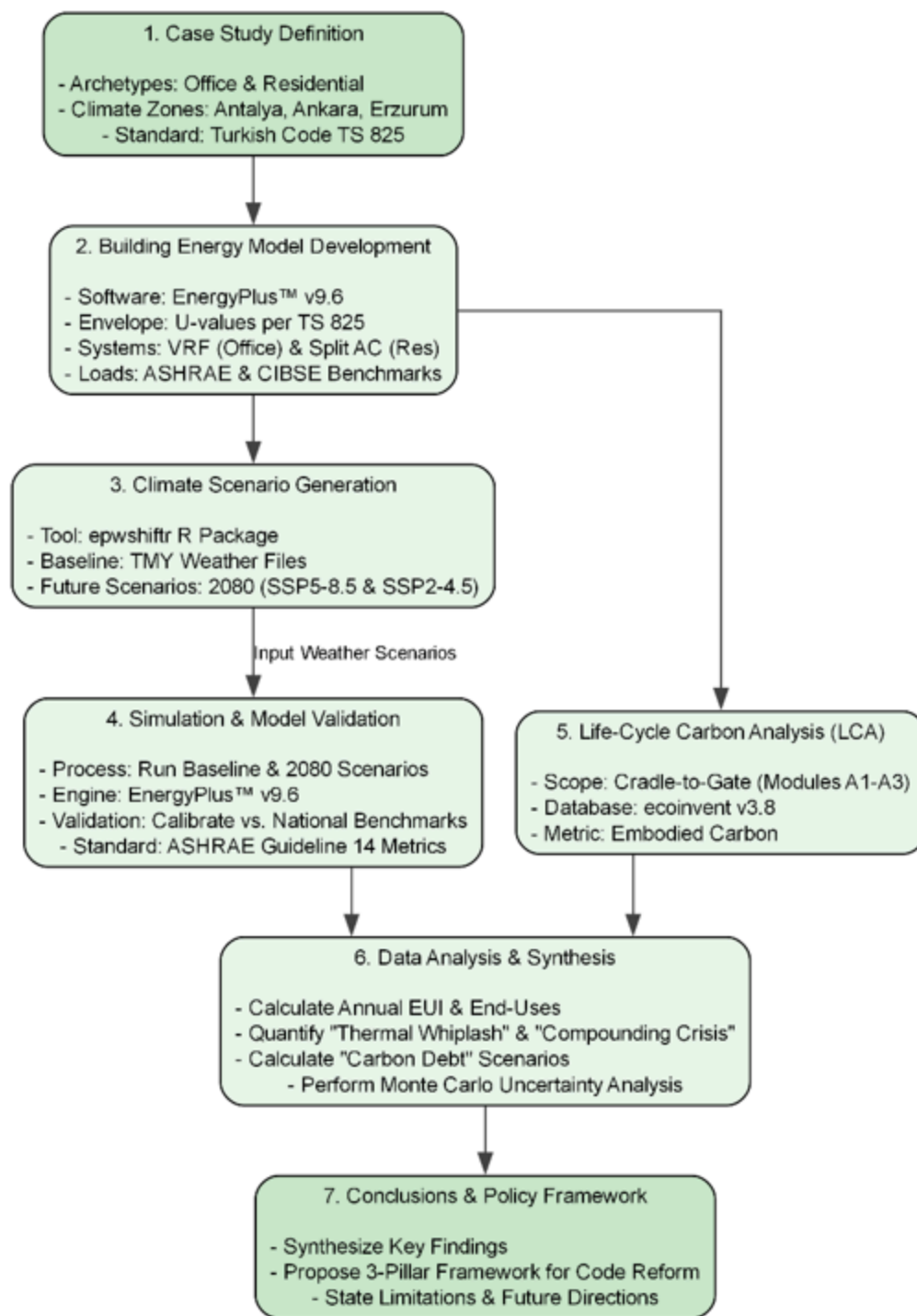


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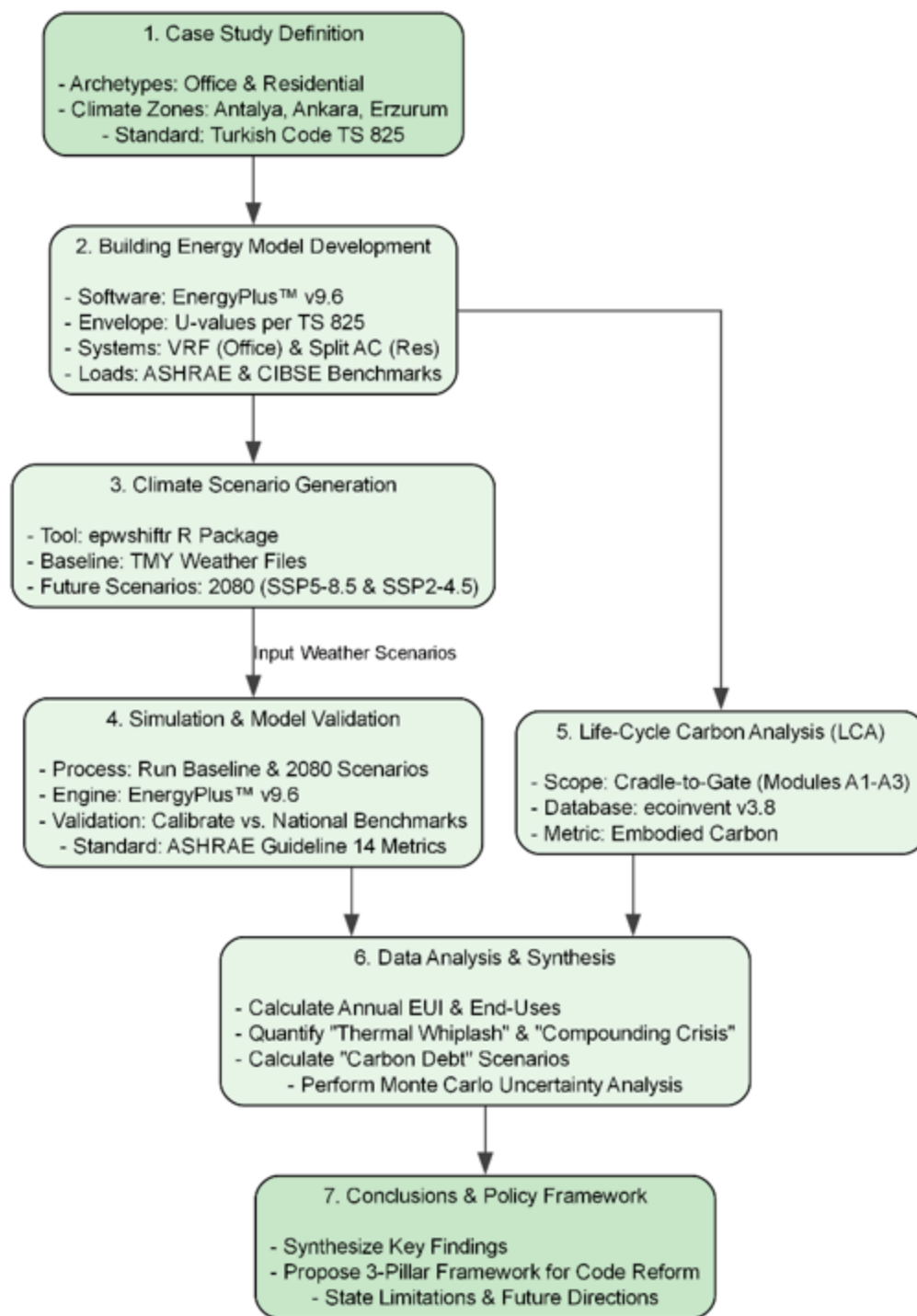


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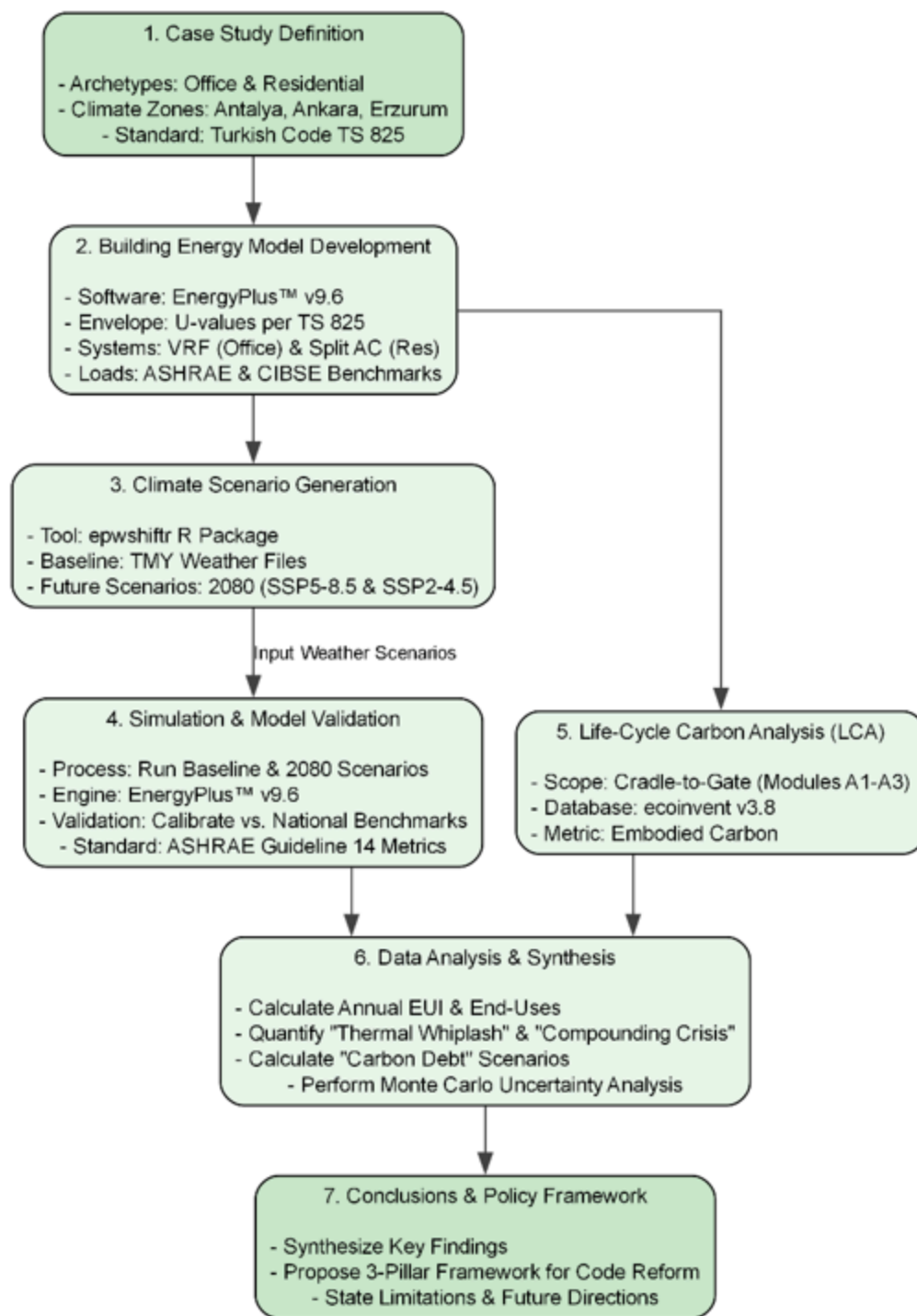


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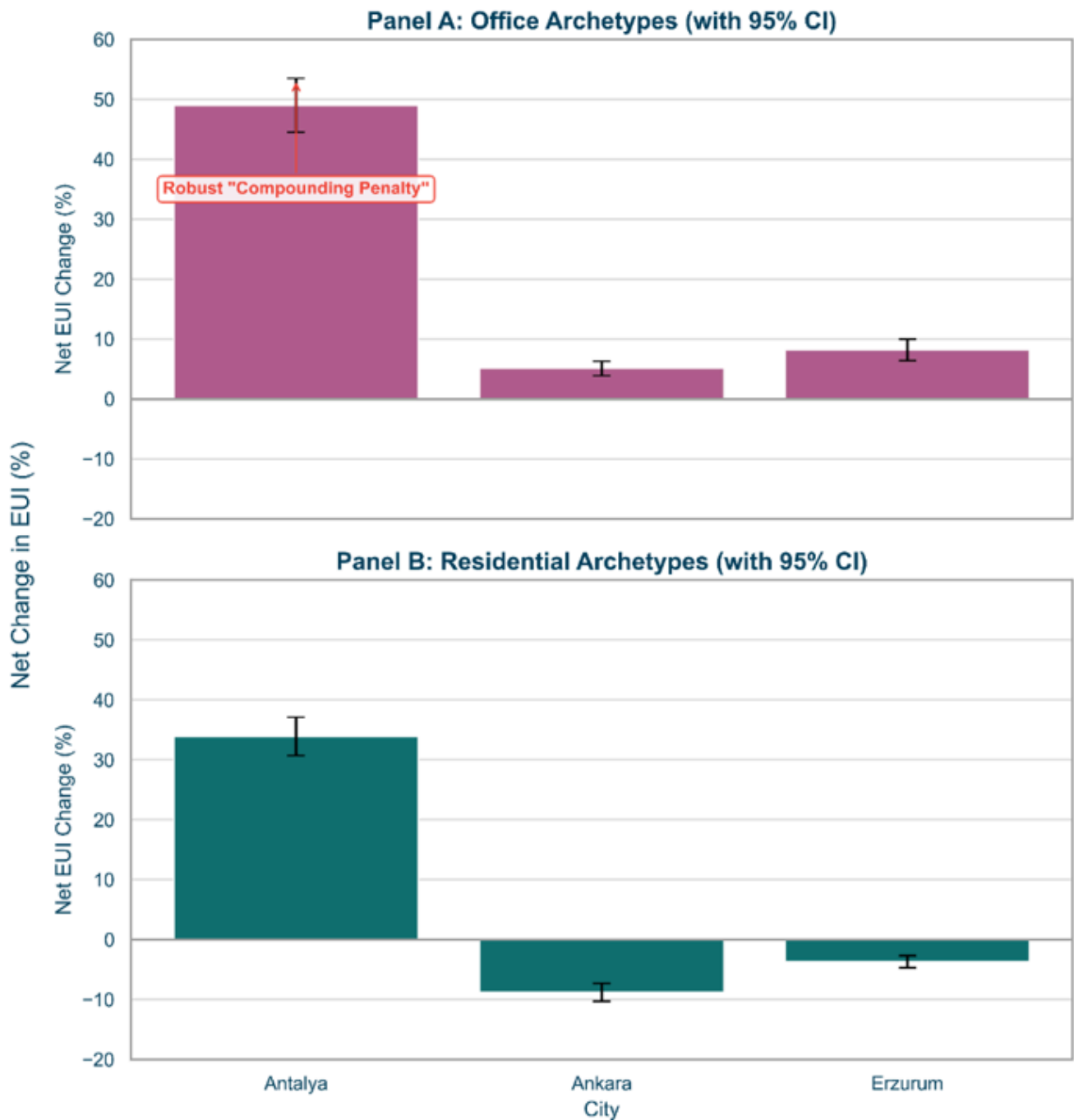


Figure 3

Net percentage change in annual EUI (baseline to 2080) for (A) office and (B) residential archetypes under the SSP5-8.5 multi-model ensemble, displayed as box-and-whisker plots with 95% CI. Robustness indicated that the outcomes were consistent across all three GCMs. The hot-climate office condition is labeled *Escalating Net Penalty (Hot-Climate Office)*.

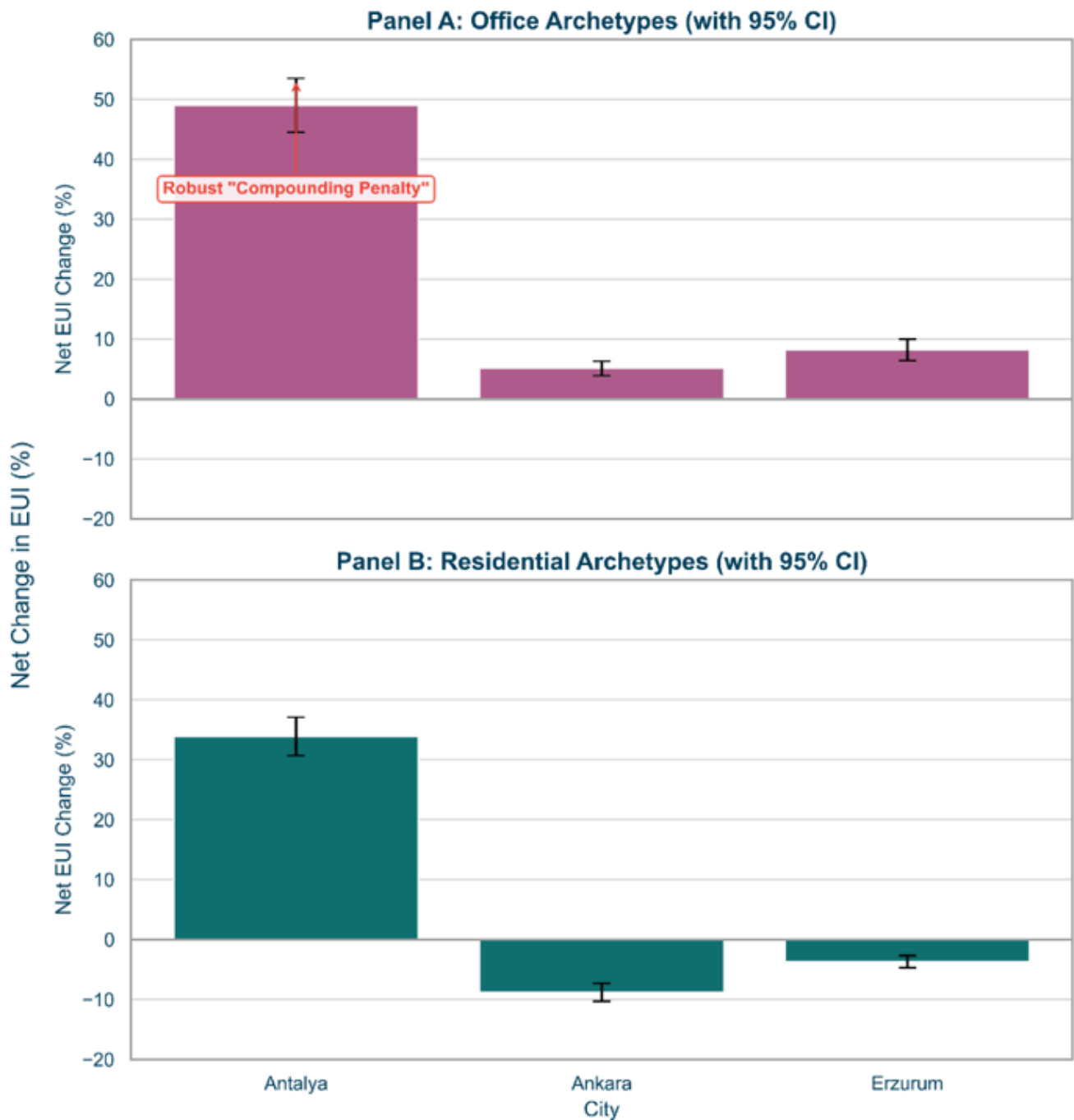


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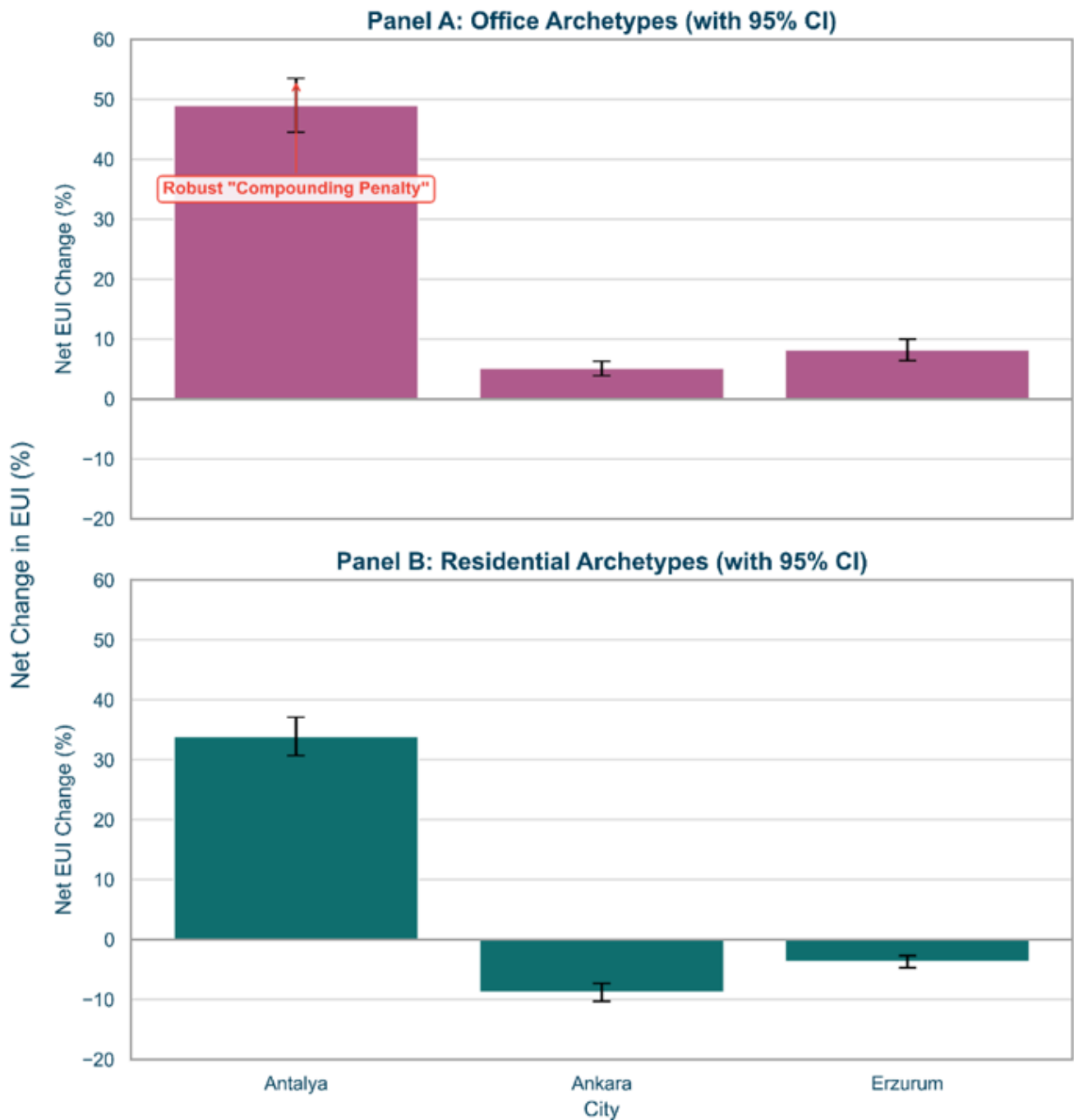


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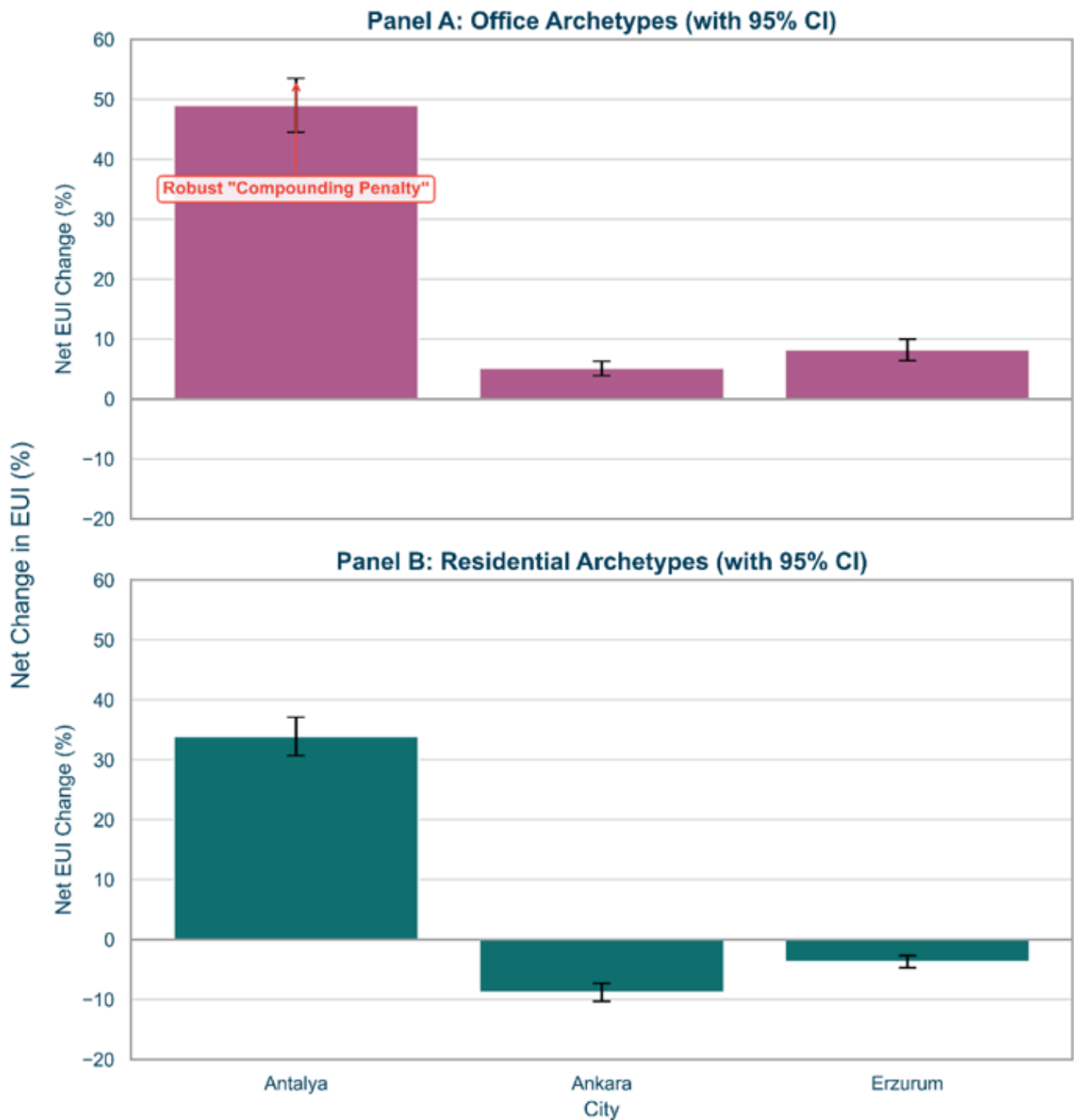


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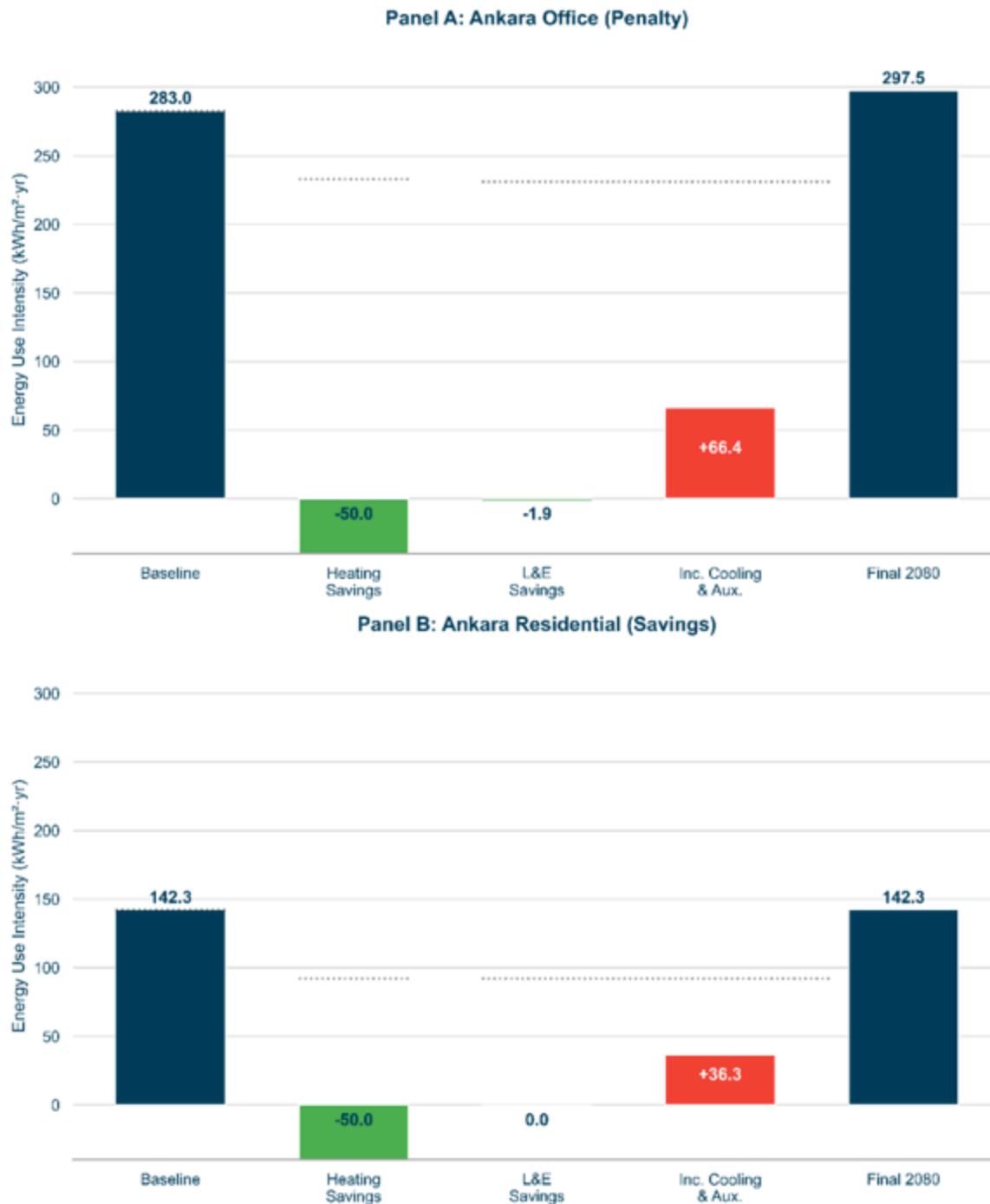


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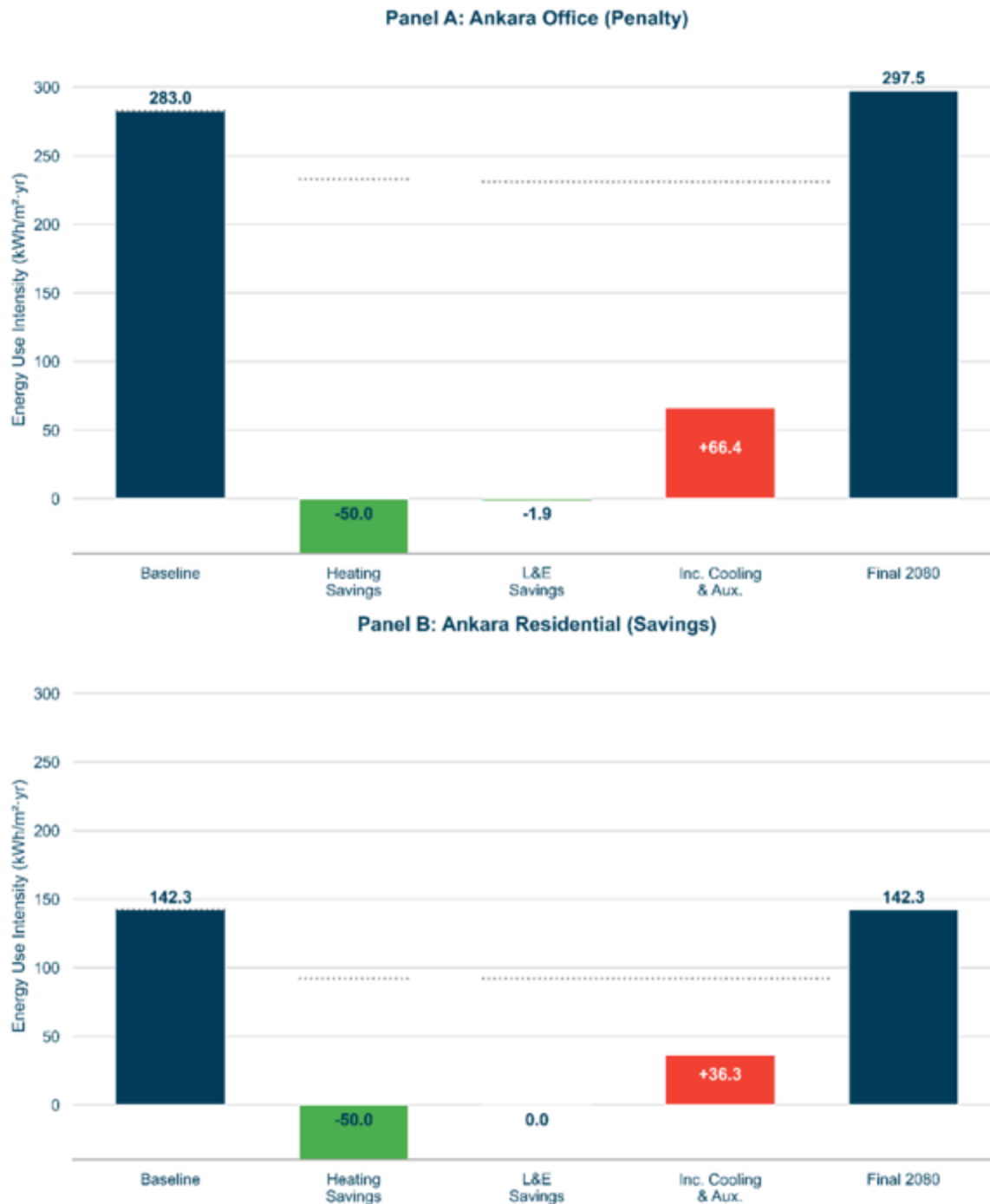


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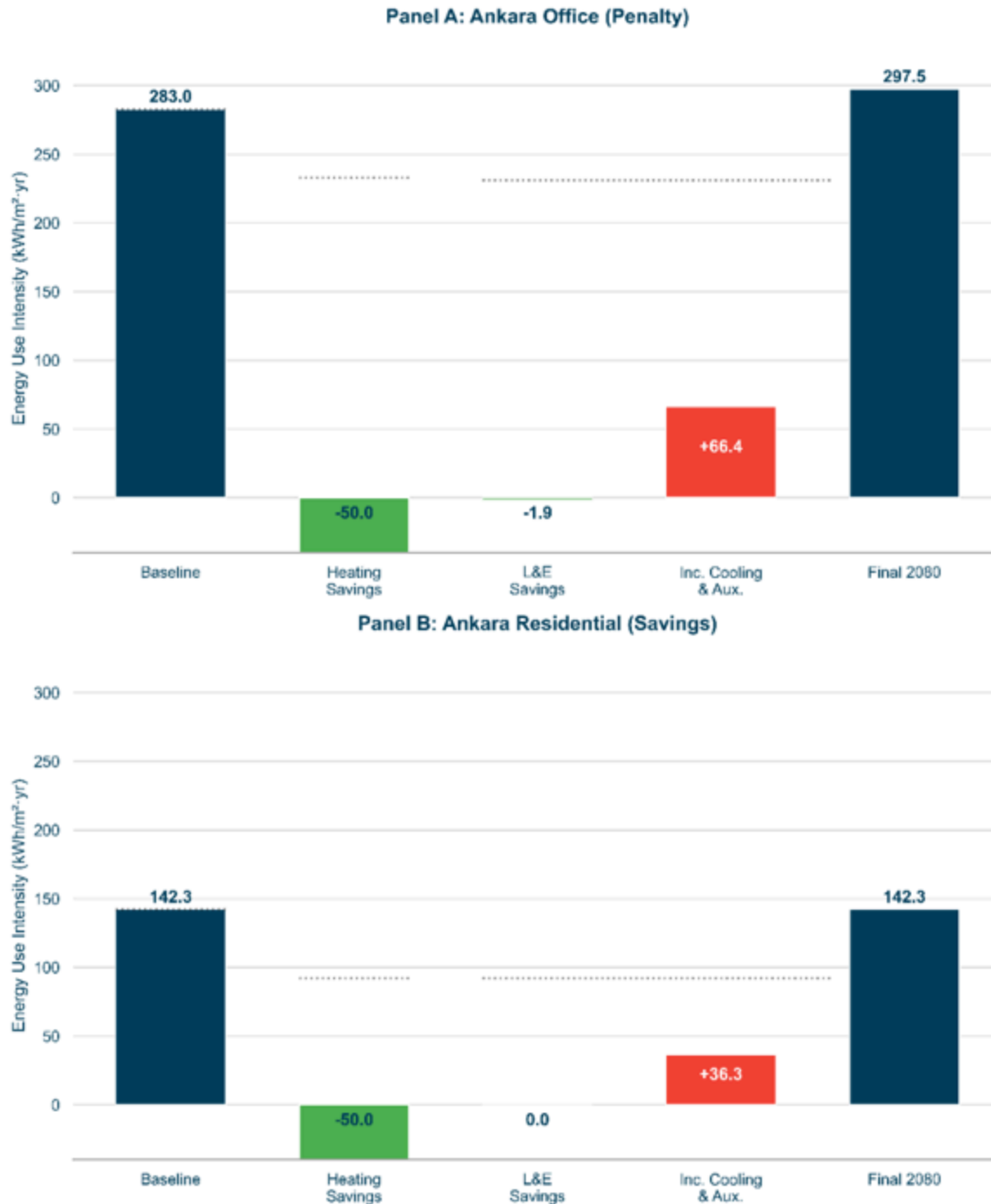


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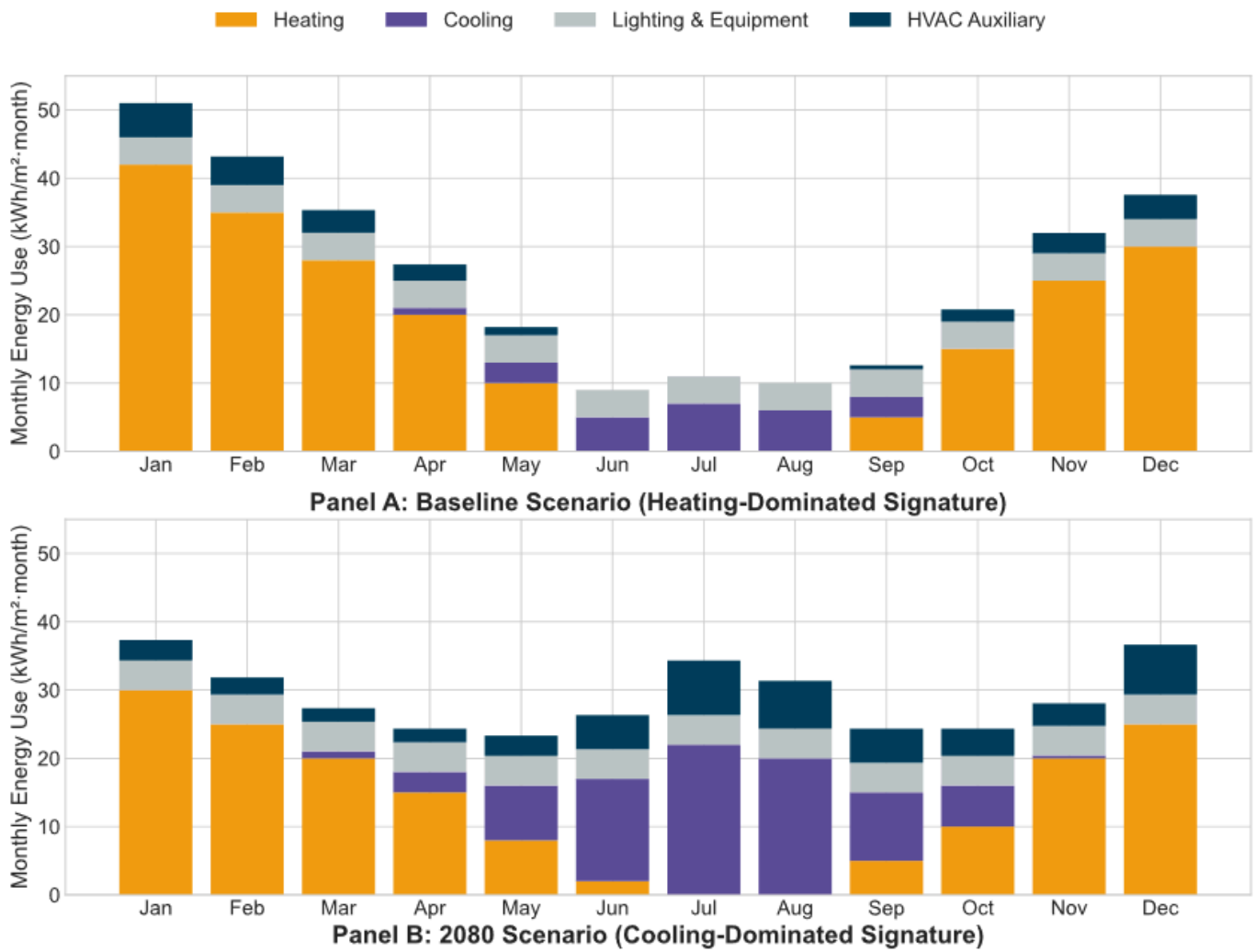


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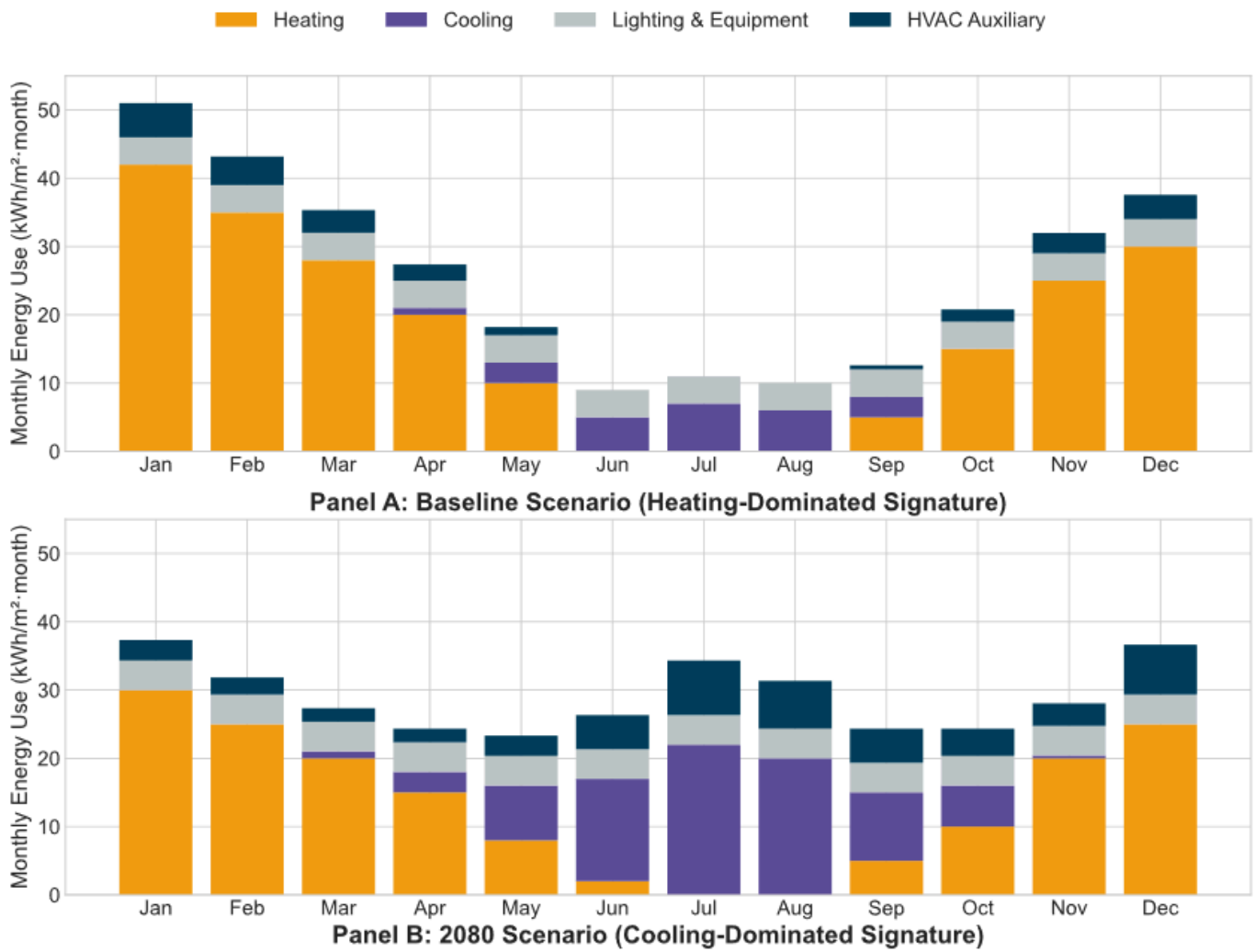


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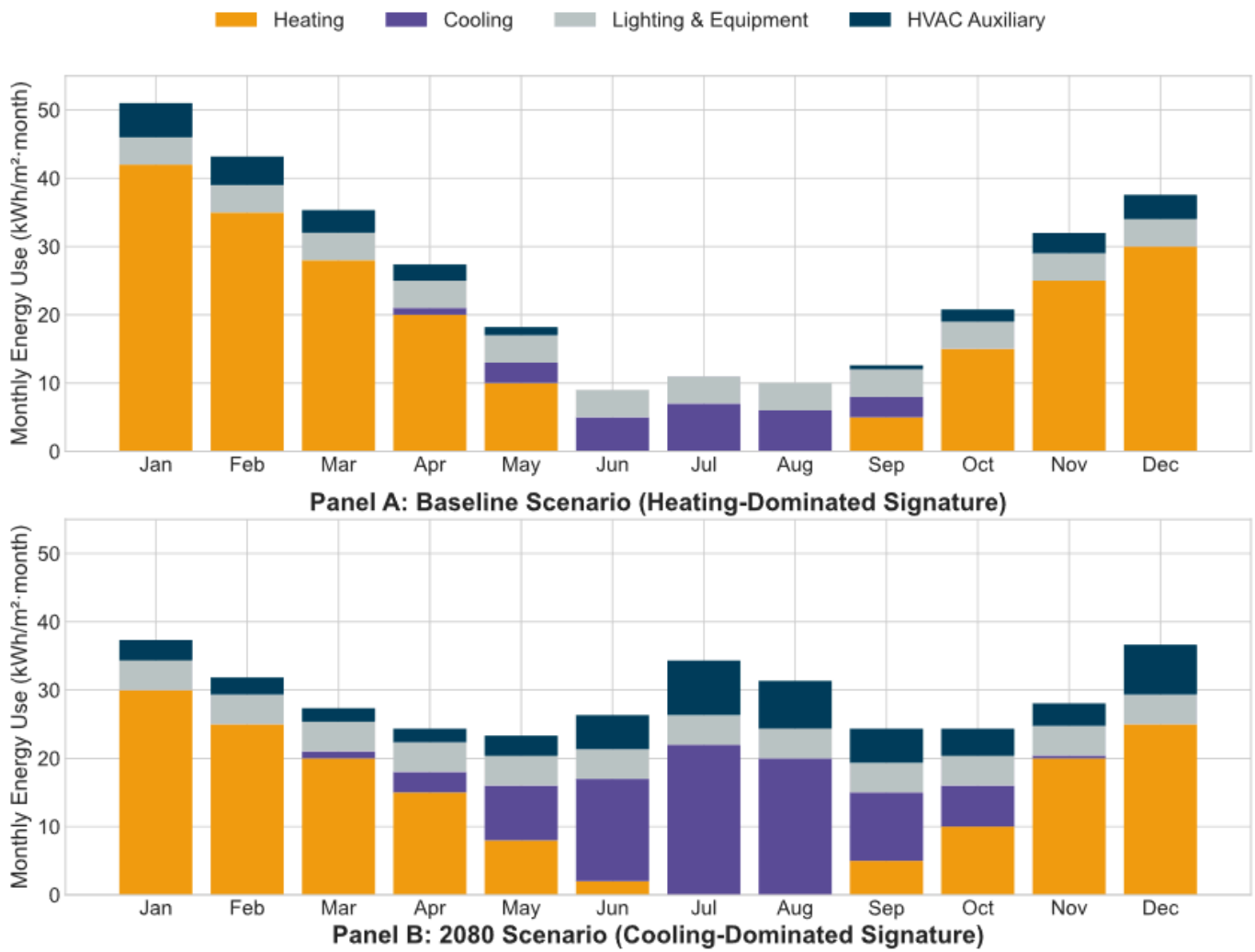


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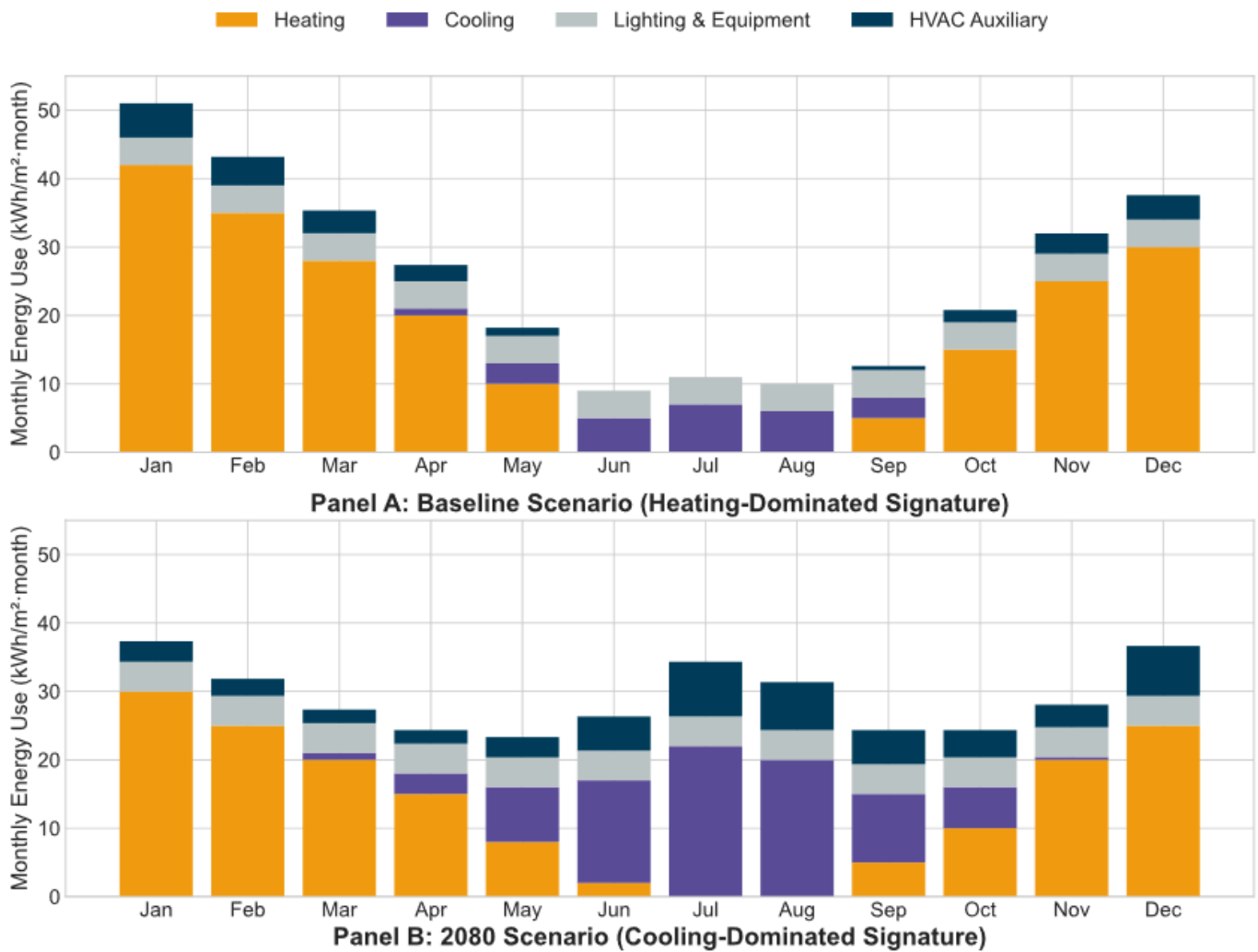


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