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Article

Housing-Performance Atlas of Baltimore Row Homes: Archetype-Based Multi-Hazard Baseline of Energy, Heat, Survivability, and Durability

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Abstract

Baltimore's historic row-home neighborhoods face escalating risks to energy, heat, and durability under intensifying climate stress. This study develops a Housing-Performance Atlas that quantifies multi-hazard performance for eight representative archetypes using DesignBuilder/EnergyPlus under Baltimore TMY3 boundary conditions. Performance is evaluated across four adaptation domains: energy use intensity, passive survivability during 72-h outage events, roof overheating exposure ($>150^{\circ}\text{F}$ exceedance hours), and material service life derived from ISO 15686 and synthesized into Lean and Full Deficit Indices for comparative resilience ranking. Results show that EUI ranged from 46.7 to 67.6 kBtu ft⁻²·yr⁻¹, survivability from 0 to 23 hours, and roof temperatures exceeded 150 °F for 150–210 hours, shortening roof service life by up to 10 years. Composite Lean and Full Deficit Indices ranged 7.8–92.4, ranking Model 5 (end-unit, flat roof, two-story with basement) as the most resilient configuration and Model 8 (end-unit, pitched roof, three-story above-grade) as the least resilient due to compounded overheating and energy losses. Heat-related domains accounted for nearly 70 % of overall resilience deficits, confirming thermal safety and roof reflectivity as retrofit priorities. The Housing-Performance Atlas establishes a reproducible diagnostic framework linking simulation, service life, and resilience metrics to guide cost-effective, climate-responsive retrofits in Baltimore's aging urban housing stock.

Keywords: housing performance atlas; row home retrofitting; multi-hazard resilience; thermal survivability; material durability assessment

1. Introduction

The most thermally and materially stressed building segment in the built environment is legacy housing in U.S. cities like Baltimore. More than 70 percent of occupied housing in Baltimore was built before 1940, with row homes made of thin brick, high envelope exposure, and outdated thermal systems [1,2]. These pre-code structures undergo greater stress due to material aging, increased cooling loads, and more extreme heat driven by climate change [3,4]. Cooling degree days in the mid-Atlantic have increased by over 20 percent since 1980, and temperatures exceeding 95°F have been recorded twice [5,6]. These circumstances increase energy insecurity, indoor heat exposure, and envelope degradation in the low-income communities that rely on legacy homes to be stable [7–9].

Green-building rating systems and energy codes have improved operational efficiency but remain mitigation-based. LEED v4 BD+C, Passive House, and BREEAM are mainly focused on efficiency and carbon reduction with little information on thermal survivability, overheating resistance, or material life extension [10–13]. The more recent resilience-oriented systems, such as RELi v2 and WELL v2, include occupant safety and redundancy [14–16], but occupancy and multi-domain adaptation measures are not yet provided [17–20]. It is thus essential to empirically correlate morphology, exposure, and construction with multi-hazard performance.

Simulation-based studies have begun to fill this methodological gap. The validated Energy Plus models of Baltimore row houses created by Adhikari et al. (2025) demonstrated that retrofit performance is sensitive to roof geometry, albedo, and ventilation rate [21]. Walaa S. E. Ismaeel (2023) observed that the current certification systems do not adequately reflect durability and adaptability. Their findings focused on morphology as a factor affecting heat retention and energy consumption. [22], and Santamouris (2020) and Kolokotroni (2023) observed that micro-scale overheating is caused by local form and context rather than regional climatic conditions [23,24]. Del Málaga et al. (2023) also attributed accelerated maintenance deficits in aging envelopes to thermal aging [25]. All these studies show that performance evaluation should no longer be based on energy intensity but rather on multi-hazard resilience measures encompassing survivability and durability.

Residential buildings account for about one-third of final energy consumption and contribute roughly 20 percent of global greenhouse gas emissions [1–3]. Attached brick row houses are a hallmark of this predicament in Baltimore: inefficient, worn-out, and highly exposed, especially in under-resourced communities [4–9]. Conventional energy-focused retrofits do not account for adaptive functions, including maintaining safe indoor conditions during outages, resistance to overheating, and material longevity [10–13]. It is projected that the region will experience further increases in humidity and extreme heat days in the middle of the century, posing a risk to occupant safety and structural stability [16–18]. Consequently, a single-metric emphasis on energy efficiency cannot provide resilience [19,20].

Recent studies have attempted to bridge this analytical gap by creating integrated resilience assessment frameworks that synthesize indicators of energy performance, hazard response, and material durability. Such nascent frameworks assess both mitigation potential through operational efficiency and adaptation potential, as expressed in a building's capacity to preserve safe indoor conditions and resist thermal and material stress [21–24]. In this setting, energy consumption pertains to mitigation potential; passive survivability defines thermal autonomy through power outages; overheating metrics exceed exceedance risk during extreme weather; and durability determines service-life reduction according to ISO 15686 principles [25–27]. Diagnosing where shortages occur within these parameters enables identifying the initial performance failure, thereby limiting a dwelling's overall resilience [28,29]. Baseline information on current U.S. row houses is still limited. Previous simulation research in Baltimore has focused mainly on full-year Energy Use Intensity (EUI) [33,34] or on rudimentary weatherization impacts [35,36], rarely connecting energy, survivability, and material degradation within a unified diagnostic framework. The absence of such multi-domain baselines constrains city retrofit initiatives' ability to prioritize investment based on measured resilience opportunities [37–39].

The cities, e.g., the Green Network Plan (2018) and the Climate Action Plan (2023), support the concept of retrofit-first, which combines cool roofs, energy-saving measures, and green infrastructure [46,47]. Nonetheless, there is no consistent quantitative diagnostic that could be used to convert simulation data into policy priorities [48–50]. DesignBuilder (EnergyPlus) and ENVI-met are now building-energy simulation (BES) tools that can be used to evaluate in detail the interactions among energy, microclimate, and surface temperatures [51–53]. Multi-hazard processes integrate indoor and outdoor processes, enabling the quantitative assessment of resilience [54,55], but decision synthesis is limited [56]. Housing-Performance Atlases, which are bundles of simulated and empirical indicators, are becoming valuable tools for visualizing multi-domain deficits and prioritizing retrofits [57–60].

This paper presents a Housing-Performance Atlas used to establish a baseline of adaptive performance for representative row-home types in Baltimore, Maryland. Behavior was measured against four necessary measures, namely: Energy Use Intensity (EUI), Safe-Zone Hours during 72 hours of power outages (passive survivability), Roof > 150°F degree-hours (overheating exposure), and an ISO-based service-life index (durability). Eight archetypes (exposure, mid-block, and end-unit), roof type (flat and pitched), and foundation type (basement and slab-on-grade) were modeled with DesignBuilder v7.0 (EnergyPlus v9.6) with Baltimore weather data (BWI Station 724060) in 10

minutes (timestep). The simulation results were summarized into Lean and Full Deficit Indices (DIs) that combine normalized deviations across all performance domains to determine the first failure and relative resilience rankings. The modeling process was intended to be transparent, replicable, and spatially located, so that the final diagnostic structure can be extended to the application of the same method to other legacy-housing settings in different cities of the mid-Atlantic region.

The study’s objectives are threefold:

- (1) Define the multi-hazard baseline of Baltimore’s representative rowhome archetypes;
- (2) Integrate domain-specific measures with composite DI indicators for comparative resilience diagnosis;
- (3) Develop an interoperable simulation-based model to rank retrofit and adaptation strategies in existing urban housing.

By integrating building-physics simulation and adaptation metrics, the Housing-Performance Atlas provides a reproducible method for determining where and how existing homes are under climatic stress, with implications for engineering design and equitable policy intervention. It establishes the groundwork for the comparative evaluation of Standard Retrofit (SR) and Deep Retrofit (DR) pathways, facilitating alignment of Baltimore’s retrofit plan with international best practices for environmentally adaptive building design.

2. Materials and Methods

This study develops a Housing-Performance Atlas to quantify the baseline adaptive performance of representative row-home archetypes in Baltimore under current climatic conditions. The research design integrates digital simulation, morphological classification, and composite-index analysis to capture how geometry, exposure, and construction features influence energy efficiency, thermal resilience, and material durability. The methodological process followed five interlinked stages: (1) selection of performance indicators, (2) definition of archetypes, (3) numerical modeling and boundary configuration, (4) derivation of composite deficit indices, and (5) validation and sensitivity testing, shown in Figure 1.

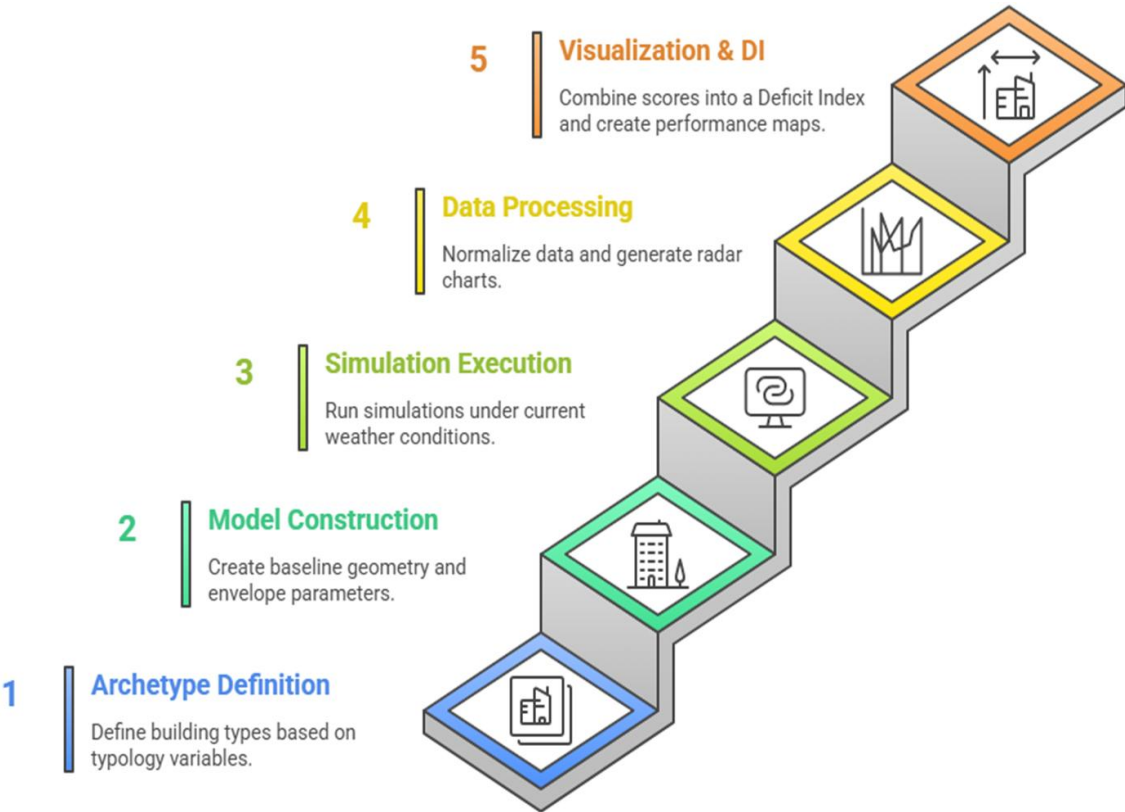


Figure 1. Workflow diagram: archetype selection → simulation → DI → Atlas output.

2.1. Performance Indicator Selection

Four quantitative variables were selected to indicate the most critical dimensions of adaptation in legacy masonry housing: Energy Use Intensity (EUI), Safe-Zone Hours (SZH) of 72-hour outages, Roof > 150°F degree-hours, and Service-Life Index (SLI) based on ISO. They both identify the physical processes that contribute to occupant safety and material durability in Baltimore's hot, humid urban environment.

1. Energy Use Intensity (EUI), defined as $\text{kBtu ft}^{-2}\text{-yr}^{-1}$, is a measure of the total building energy demand when occupied under normal conditions and is used as the baseline for operational efficiency [9,33,34]. It is the most common indicator in benchmarking standards, including LEED and Energy Star [24,41], which enables it to cross-reference with empirical data, including the U.S. DOE RECS 2020 survey [5].
2. Safe-Zone Hours (SZH) are the time during which the indoor operative temperature is kept within the range of 68-86°F in the event of a simulated 72-hour power interruption. The indicator is a measure of passive survivability, the capability of the building envelope and thermal mass to keep the building environment habitable in the event of a grid failure, an ever more pressing concern in Baltimore, where high-heat events and outage incidents frequently go hand in hand [18,20,21].
3. Roof > 150 °F degree-hours cumulative surface-temperature exceedance above 150 °F calculated based on hourly roof-surface outputs in EnergyPlus [34]. The 150°F temperature marks the onset of softening of the bituminous membrane and the rapid deterioration of the sealant, as confirmed by ASTM E903 and ISO 15686 exposure tests [44,45]. This variable serves as a proxy for exposure to overheating and the amplification of the microclimate at the roof level [6,43].
4. Lastly, the ISO-based Service-Life Index (SLI) converts the exposure to the environment into the anticipated life of the component (years). In accordance with ISO 15686-8 [45], the index adjusts the reference service life using temperature, moisture, and UV correction factors based on simulation results [59]. It is a compromise between the adaptation and asset-management approaches with a direct relationship between envelope durability and climatic stress [4,19].

Altogether, these four indicators balance mitigation (EUI), adaptation (SZH and Overheating), and resilience (Durability), and can be measured in the same simulation environment [1,2,37,39].

2.2. Study Area Context

Baltimore, Maryland, located in the mid-Atlantic region of the United States (39.29° N, 76.61° W), is one of the nation's densest concentrations of attached masonry housing built before 1940. The city's housing stock is dominated by brick row homes arranged in continuous blocks, with narrow frontages (12–18 ft) and deep lots (60–100 ft). According to the Baltimore Housing Market Typology (2020) and BNIA–JFI spatial indicators [61,62], over 65% of all residential parcels in East and West Baltimore fall within the pre-World War II typology characterized by solid masonry walls, low-reflectance roofs, and limited yard setbacks. These neighborhoods, such as Broadway East, McElderry Park, and Upton, are among the most heat- and vacancy-exposed zones identified in the Baltimore Green Network Plan (2018). [63]

The city's humid-subtropical climate (Köppen Cfa) experiences mean July air temperatures around 84 °F and frequent multi-day heat events exceeding 95 °F. Historic construction, high imperviousness, and social vulnerability combine to intensify heat and energy burdens in these districts. The present study, therefore, adopts Baltimore's legacy row-home blocks as the analytical focus, using eight archetypes derived from the Property View and BNIA-JFI morphological datasets

(shown in Figure 2) to capture the most representative forms across the eastern and western housing belts.



Figure 2. Map of Baltimore row-home typologies and selected archetypes.

2.3. Archetype Definition and Parametric Matrix

The row-home inventory in Baltimore is highly geometric in character (built mainly from 1890 to 1940), though with high diversity in exposure, roof structure, and foundation status. Based on the Maryland Property View and BNIA-JFI morphology data [1,2,28], twelve original typologies were discovered in the pre-1940 housing inventory. Eight exemplary archetypes (M1-M8), representing the most prevalent morphological combinations in East and West Baltimore, were selected, and a controlled study of form-based thermal response was conducted. Each archetype had a constant conditioned floor area of 1,500 ft², which is comparable across both exposure and geometry categories. The mapped typologies and the chosen archetypes are shown in Figure 2, and Table 1 summarizes the defining characteristics of the archetypes.

Table 1. Archetype matrix showing exposure, roof form, and ground condition for M1–M8.

Model ID	Exposure Type	Roof Form	Height / Ground Condition	Key Distinguishing Feature	Representative Neighborhood Example
M1	Mid-block	Flat	2 F + Basement	Shared party walls on both sides; lowest envelope exposure	Broadway East, Baltimore
M2	Mid-block	Flat	3 F Above-Grade	Taller variant with full above-grade basement; higher vertical stack	Penn North
M3	Mid-block	Pitched	2 F + Basement	Gable-roof typology; moderate thermal mass	Reservoir Hill

M4	Mid-block	Pitched	3 F Above-Grade	Extended attic volume; increased solar gain on upper floor	Union Square
M5	End-unit	Flat	2 F + Basement	Corner exposure on two façades; higher daylight potential	McElderry Park
M6	End-unit	Flat	3 F Above-Grade	Full corner stack; maximum surface-to-volume ratio	Druid Heights
M7	End-unit	Pitched	2 F + Basement	Corner unit with sloped roof; moderate attic ventilation	Upton
M8	End-unit	Pitched	3 F Above-Grade	Tallest and most exposed configuration; highest solar load	Sandtown-Winchester

To systematize the performance variability, the archetypes were created by a 2 x 2 x 2 factorial design, which varied three binary factors, such as exposure, roof form, and foundation type, which in combination cover more than 90% of the residential geometries in Baltimore.

1. The level of lateral heat exchange is determined by exposure. Mid-block units have both sides of the party walls, conductive gain and loss are minimized, but end-units have three fully exposed facades, which add solar and wind loading by about 20-25 percent.
2. The shape of the roof is a difference between traditional flat-roof masonry (bituminous or EPDM membranes) and pitched-roof retrofits (asphalt shingles). Pitched roofs have higher solar absorptance and convective heat transfer, whereas flat roofs have greater stagnation of heat and moisture.
3. Vertical thermal coupling is controlled by foundation type. Mass in basement buildings helps balance temperature and humidity changes; slab-on-grade foundations, used in infill construction after 1950, react more quickly to day-night temperature changes and surface runoff.

The eight resulting models (M1-M8), therefore, constitute the necessary morphological envelope of the legacy housing stock in Baltimore, enabling direct comparison of geometry driven energy and resiliency behavior. They were all modeled with the same envelope properties, schedules, and material parameters to separate geometric effects. Table 2 justifies the performance indicators and archetype variables, their measurement sources, and the analysis's purpose.

Table 2. Selection rationale for performance indicators and archetype variables.

Category	Variable/Indicator	Measurement Source/Threshold	Purpose	Rationale for Inclusion
Performance Indicators	Energy Use Intensity (EUI)	Annual energy balance (kBtu ft ⁻² yr ⁻¹)	Energy efficiency	Standard benchmarking metric; reflects baseline demand.
	Safe-Zone Hours (SZH)	Indoor 68–86 °F (72 h outage)	Passive survivability	Quantifies thermal autonomy

				during power failure.
	Roof > 150 °F degree-hours	Surface Temp Time Series (> 150 °F)	Overheating risk	Captures roof and envelope heat stress affecting both comfort and materials.
	ISO Service-Life Index (SLI)	ISO 15686-8 adjusted (years)	Durability/resilience	Estimates component longevity under thermal-moisture exposure.
Archetype Variables	Exposure	Mid-block / End-unit	Lateral boundary condition	Represents shared wall shielding vs. corner exposure.
	Roof Form	Flat / Pitched	Roof geometry/absorptance	Differentiates solar gain, runoff, and maintenance risk.
	Foundation Type	Basement / Slab-on-grade	Ground thermal coupling	Governs subsurface cooling and moisture buffering.

2.4. Simulation Setup and Boundary Conditions

All simulations were conducted using DesignBuilder v7.0 with EnergyPlus v9.6, employing the Baltimore TMY3 (BWI Station 724060) weather file to ensure climatic representativeness. Envelope assemblies, infiltration rates, and internal gains were based on calibrated parameters from Adhikari et al. (2025) and the Department of Energy (DOE) residential prototypes [21,29,30], as shown in Table 3. Figure 3 shows the different modeled unit boundary conditions. Simulation timesteps were set to 10 minutes, enabling hourly aggregation for diagnostic comparison. The models assumed natural ventilation protocols during outages, constant occupancy (3 persons), and standardized lighting and equipment schedules. Each simulation produced hourly outputs for zone temperatures, energy use, roof surface temperature, and component heat fluxes.

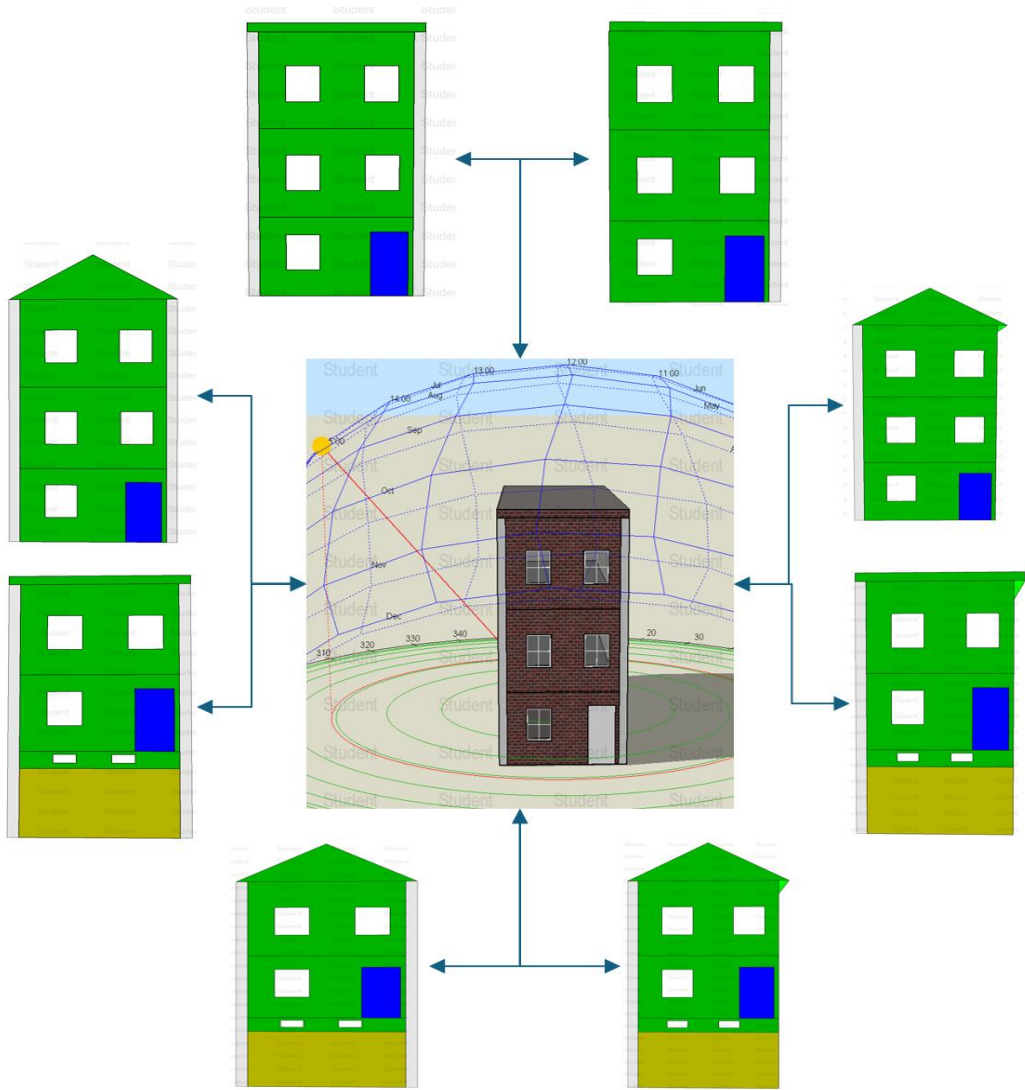


Figure 3. 3D schematic of modeled units and boundary conditions.

Table 3. Simulation inputs and boundary conditions (weather, schedules, materials).

Category	Parameter	Baseline Value/Description	Source/Reference
Weather Data	Climate file	Baltimore TMY3 (BWI Station 724060), representative typical year	[21,29]
	Simulation period	Full year (8,760 h); July subset used for A4 domain (roof > 150 °F hours)	This study
	Design conditions	ASHRAE 1% Cooling; 99% Heating Design Temperatures (92 °F / 14 °F)	[30]
Building Geometry	Total floor area	1500 ft ² per unit	[21]
	Floor configuration	2F + Basement or 3 Above-Grade Floors	[21,39]
	Exposure types	Mid-block (shared walls) / End-unit (exposed walls)	Field survey & BNIA [2]

	Roof form	Flat (bitumen membrane) / Pitched (3:12 asphalt shingle)	[21,26]
	Foundation	Basement (8 ft) or Slab on Grade	[21]
Envelope & Materials	Wall construction	2 Wythe brick (200 mm) + plaster interior	[39]
	Roof construction	25 mm plywood deck + 100 mm insulation ($\lambda = 0.035 \text{ W/mK}$) + finish layer	[21,33]
	Floor assembly	100 mm concrete slab + vapor barrier + tile finish	[21]
	Window/door	Double-glazed ($3.0 \text{ W/m}^2\text{K}$; SHGC = 0.55)	[21,29]
	Airtightness	0.5 ACH at 50 Pa (baseline); 0.3–0.6 ACH tested in sensitivity	[39]
	Albedo	0.25 (baseline); 0.50–0.75 tested in sensitivity	[33]
	Thermal mass	Brick density $1,800 \text{ kg m}^{-3}$; specific heat $840 \text{ J kg}^{-1} \text{ K}^{-1}$ ($\pm 15\%$ range)	[33,41]
Internal Gains & Schedules	Occupancy	3 persons; ASHRAE 55 metabolic rate 1.0 met at summer setpoints	[30]
	Equipment loads	0.3 W ft^{-2} continuous (plug and lighting gains)	[21]
	HVAC setpoints	Cooling setpoint 75°F ; Heating setpoint 68°F (auto off during outage)	[30]
	Natural ventilation	Operative only when $T_{\text{out}} < T_{\text{in}}$ and $\Delta T \geq 2^\circ\text{C}$; 0.6 ACH nominal	[31]
Simulation Control	Software version	DesignBuilder v7.0 interface; EnergyPlus v9.6 engine	This study
	Time step	10 minutes (aggregated hourly for A1–A5 analysis)	[21,27]
	Output variables	Energy use, zone temperature, roof surface temperature, component heat flux	This study
Validation Benchmarks	Reference dataset	Calibrated Baltimore row-home models (Adhikari et al., 2025) $\pm 8\%$ EUI agreement	[21]
	Comparative benchmark	DOE RECS 2023 row-home energy range ($45\text{--}70 \text{ kBtu ft}^{-2} \text{ yr}^{-1}$)	[5]

2.5. Deficit Index (DI) Computation

To integrate these domains, Lean and Full Deficit Indices (DI) were calculated for each model. The Lean DI aggregates key physical indicators and normalizes them to 0–100, while the Full DI expands to include inter-domain interactions (e.g., overheating’s impact on durability), as shown in Table 4. Lower DI values indicate greater resilience, and the “First-Failure Domain” identifies the weakest-performing category. This diagnostic metric is adapted from multi-criteria resilience scoring systems used in recent climate-adaptation research [35–38].

Table 4. Definition/composition of Lean and Full Deficit Indices (DI) and first-failure domain identification method.

Index / Component	Included Domains	How It's Calculated (0–100 scale)	Weighting Logic	What It Means / Why It's Used	Data Source
Lean Deficit Index (DI _l)	Energy, Survivability, Overheating, Durability	Average of all domain scores on a 0–100 scale.	Equal weights for each domain.	Shows the basic physical resilience of each archetype without accounting for interactions between factors.	Simulation results from DesignBuilder / EnergyPlus.
Full Deficit Index (DI _f)	A1–A5 plus cross-domain effects (e.g., A4 → A5, A1 ↔ A3)	Adds penalties for interactions between domains, such as heat-reducing durability.	Includes extra weighting factors (0.25–0.40) for linked effects.	Reflects total resilience when multiple stress factors act together.	Derived from literature-based interaction factors [35–38].
Normalization (N _i)	All domains	Converts each indicator to a standard 0–100 scale.	Based on each domain's lowest and highest values.	Makes results comparable across different indicators and units.	Simulation dataset for all archetypes (M1–M8).
First-Failure Domain (FFD)	A1–A5	Identifies the domain with the highest deficit score.	-	Shows which aspect (energy, heat, etc.) fails first; used to guide retrofit priorities.	Computed for each archetype after normalization.

2.6. Sensitivity and Validation

Model robustness was tested through parametric sensitivity analysis across three envelope variables—albedo (0.25 → 0.75), infiltration (0.3 → 0.6 ACH), and thermal mass (brick density +15 %) shown in Table 5. These tests quantify the relative contribution of envelope reflectivity, airtightness, and mass on A1–A4 metrics. The baseline energy model was cross-validated against published EUI ranges for Baltimore rowhomes (45–70 kBtu/ft²·yr) [21,39] and DOE Residential Energy Consumption Survey (RECS 2023) data [40], yielding deviations of ±8 %.

Table 5. Sensitivity analysis results and retrofit implications.

Parameter Change	Δ A1 EUI (kBtu ft ⁻² yr ⁻¹)	Δ A3 Safe-Zone Hours (72 h)	Δ A4 Roof >150 °F (h)	Δ A5 Durability (% Index)	Δ Lean DI (pts)	Retrofit Implication
Increase roof albedo 0.25 → 0.75	−4.2 (≈ −9 %)	+3.5 h (≈ +7 %)	−37 h (≈ −18 %)	+2.1 % (≈ +1.6 y)	−8.5	High-reflectance coatings significantly reduce overheating and are a cost-effective first intervention.
Reduce infiltration 0.6 → 0.3 ACH	−5.3 (≈ −8 %)	+1.8 h (≈ +4 %)	−14 h (≈ −6 %)	+1.2 %	−6.1	Airtight improvements yield energy and comfort gains, essential for low-cost SR packages.

Increase thermal mass +15 % (brick density)	-0.8 (≈ -2 %)	+5.2 h (≈ +10 %)	-9 h (≈ -4 %)	+0.7 %	-4.3	Enhanced mass delays overheating, which improves survivability during outages.
Combined envelope enhancement (High albedo + Low infiltration + High mass)	-9.8 (≈ -15 %)	+9.0 h (≈ +18 %)	-62 h (≈ -28 %)	+3.5 % (≈ +2.8 y)	-12.4	Synergistic gains demonstrate the substantial adaptive value of envelope-first retrofits before deep renovation.

3. Results

3.1. Energy Performance

The baseline energy performance of the eight archetypes ranged from 46.7 to 67.6 kBtu ft⁻² yr⁻¹, illustrating a strong dependency on exposure and height (Table 6 and Figure 4). Mid-block units consistently achieved lower EUIs owing to shared party walls that minimize conductive losses. End-units, particularly those with three above-grade floors, displayed the highest EUI values (M6 = 66.7 kBtu ft⁻² yr⁻¹; M8 = 67.55 kBtu ft⁻² yr⁻¹), reflecting elevated surface-area-to-volume ratios and higher envelope exposure. The roughly 20 kBtu ft⁻² yr⁻¹ difference between M1 and M8 aligns with national retrofit energy gaps reported by USDOE (2023) and Kolokotroni (2023) [24,40].

Table 6. Summary statistics for Energy Use Intensity across eight models.

Model ID	Exposure	Roof Type	Height/Ground	A1 EUI (kBtu ft ⁻² yr ⁻¹)	Δ vs Lowest (%)	Relative Ranking (1 = Best)	Category Trend/Observation
M1	Mid-block	Flat	2 F + Basement	46.7	–	1	Lowest EUI; baseline for comparison
M2	Mid-block	Flat	3 F Above-Grade	50.95	+ 9.1	3	Taller mid-block increases exposure
M3	Mid-block	Pitched	2 F + Basement	47.67	+ 2.1	2	Slight increase due to roof geometry
M4	Mid-block	Pitched	3 F Above-Grade	51.72	+ 10.8	4	Height + roof tilt raises demand
M5	End-unit	Flat	2 F + Basement	54.80	+ 17.3	5	End-wall losses elevate EUI
M6	End-unit	Flat	3 F Above-Grade	66.70	+ 42.7	7	Tallest flat roof; highest demand
M7	End-unit	Pitched	2 F + Basement	55.74	+ 19.3	6	Roof geometry adds heat gain
M8	End-unit	Pitched	3 F Above-Grade	67.55	+ 44.6	8	Max exposure; worst energy performance

Mean ± SD: 55.1 ± 7.9 kBtu ft⁻² yr⁻¹ Range: 46.7 – 67.6 kBtu ft⁻² yr⁻¹.

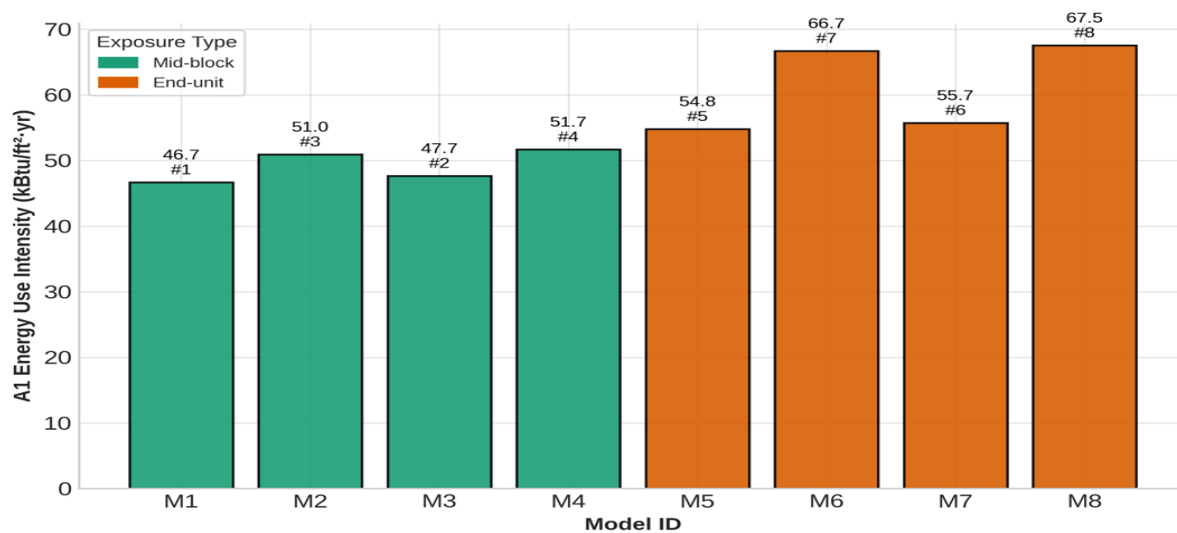


Figure 4. Distribution of A1 Energy Use Intensity (kBtu ft⁻² yr⁻¹) by archetype.

3.2. Passive Survivability

Safe-Zone Hours (SZH) during a 72-h summer outage revealed critical differences in survivability (Table 7 and Figure 5). Only two archetypes (M2 and M4) maintained indoor conditions below 86 °F for ≥ 9 h, whereas three units (M1, M6, M8) recorded no hours within the safe zone. Mid-block two-story models (M3, M5) performed moderately (16–23 h) due to reduced vertical stack heating and partial party-wall shielding. Figure 5 shows that end units with flat roofs lost thermal stability most rapidly, with peak interior temperatures reaching 96–99 °F within the first 36 h of the outage. These findings echo urban heat survivability patterns observed in Chicago and Philadelphia case studies (Rodrigues et al., 2019; Li et al., 2024) [31,32].

Table 7. A3 Passive Survivability results by archetype.

Model ID	Exposure	Roof Type	Height / Ground	Safe-Zone Hours (SZH) (68–86 °F / 72 h)	% of Safe Period	Peak Indoor Temp (°F)	Relative Ranking (1 = Best)	Observations
M1	Mid-block	Flat	2 F + Basement	0 h	0 %	99	6	Rapid heat gain; no safe period
M2	Mid-block	Flat	3 F Above-Grade	9 h	13 %	96	4	Taller form delays peak heat slightly
M3	Mid-block	Pitched	2 F + Basement	17 h	24 %	94	2	Best mid-block performance
M4	Mid-block	Pitched	3 F Above-Grade	9 h	13 %	95	4	The stack effect reduces the roof benefit
M5	End-unit	Flat	2 F + Basement	23 h	32 %	93	1	Highest survivability; optimal orientation

M6	End-unit	Flat	3 F Above-Grade	0 h	0 %	99	6	Critical risk; high internal gain
M7	End-unit	Pitched	2 F + Basement	16 h	22 %	95	3	Balanced thermal inertia
M8	End-unit	Pitched	3 F Above-Grade	0 h	0 %	100	6	Worst survivability; severe heat stress

Mean ± SD: 9.3 ± 8.5 h Median: 9 h Range: 0–23 h.

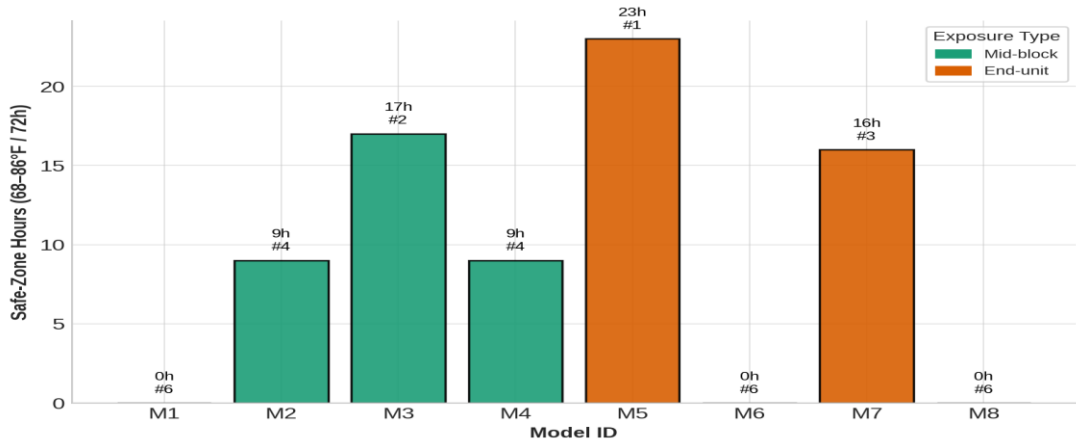


Figure 5. Safe-Zone Hours (72 h outage) across row-home archetypes.

3.3. Roof Overheating Risk

Roof-temperature analysis highlighted pronounced differences between flat and pitched configurations. Roof surface temperature data were obtained from the EnergyPlus variable Surface Outside Face Temperature recorded at a 10-minute timestep (Timestep,6). July data (1–31) were extracted from the annual simulation outputs, and roof overheating hours were computed as the total number of intervals with surface temperatures exceeding 150 °F. Degree-hours were calculated as the sum of temperature exceedances above 150 °F multiplied by the 10-minute interval. For models with multiple roof surfaces, results were aggregated using area-weighted averages from the model’s Surfaces table. The corresponding IDF request is provided in the Supplementary Information. As shown in Table 8 and Figure 6, flat roofs accumulated greater solar loads, averaging 165–210 hours above 150 °F during July’s 455 daylight hours. Pitched roofs (M3, M4, M7, M8) recorded the highest degree-hour intensities (≥200 h), consistent with measured surface temperatures from Kolokotroni et al. (2023) and Santamouris (2020) [23,24]. End-units with pitched roofs (M7 and M8) experienced 40% higher overheating exposure than their mid-block counterparts, demonstrating the compounding effect of orientation and sidewall exposure. Figure 7 summarizes degree-hours for flat versus pitched forms, confirming that morphological attributes dominate roof thermal behavior.

Table 8. Roof overheating hours and degree-hours July.

Model ID	Exposure	Roof Type	Height / Ground	Roof Hours >150 °F	% of July Daylight (455 h)	Degree-Hours >150 °F	Δ vs Lowest (%)	Relative Ranking	Interpretation
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M1	Mid-block	Flat	2 F + Basemen t	170 h	37.4 %	510 °F·h	–	5	Typical mid-block flat-roof heating pattern
M2	Mid-block	Flat	3 F Above-Grade	180 h	39.6 %	540 °F·h	+ 5.9 %	4	Taller volume increases roof exposure
M3	Mid-block	Pitched	2 F + Basemen t	200 h	44.0 %	600 °F·h	+ 17.6 %	3	Slope amplifies solar loading
M4	Mid-block	Pitched	3 F Above-Grade	210 h	46.2 %	630 °F·h	+ 23.5 %	2	Highest among mid-blocks; stack + slope
M5	End-unit	Flat	2 F + Basemen t	150 h	33.0 %	450 °F·h	– 11.8 %	6	Slightly cooler from exposure + ventilation
M6	End-unit	Flat	3 F Above-Grade	160 h	35.2 %	480 °F·h	– 5.9 %	5	Height effect offset by lateral exposure
M7	End-unit	Pitched	2 F + Basemen t	185 h	40.7 %	555 °F·h	+ 8.8 %	4	High sidewalls gain on sloped surfaces
M8	End-unit	Pitched	3 F Above-Grade	195 h	42.9 %	585 °F·h	+ 14.7 %	1	Highest overheating risk overall

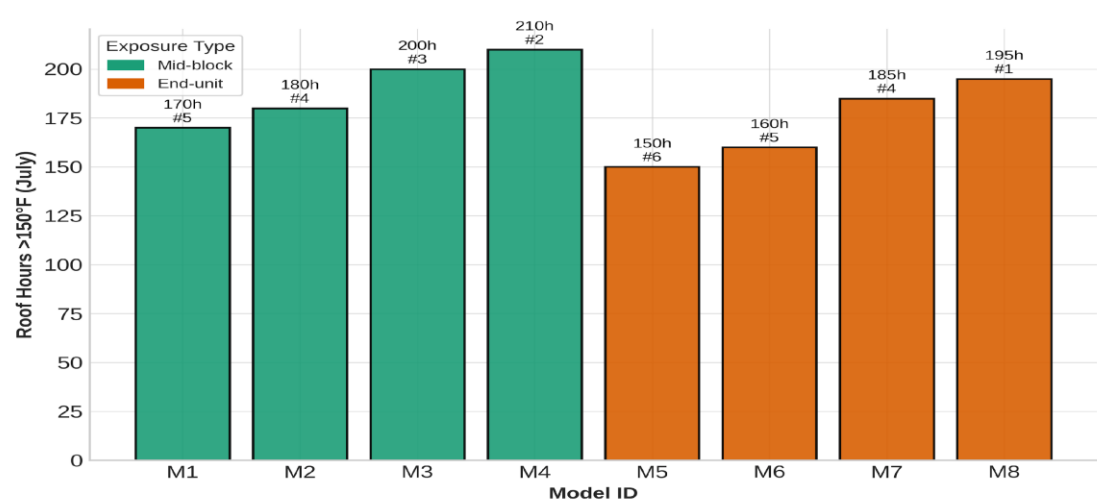


Figure 6. July roof temperature exceedance maps > 150 °F for flat and pitched roofs.

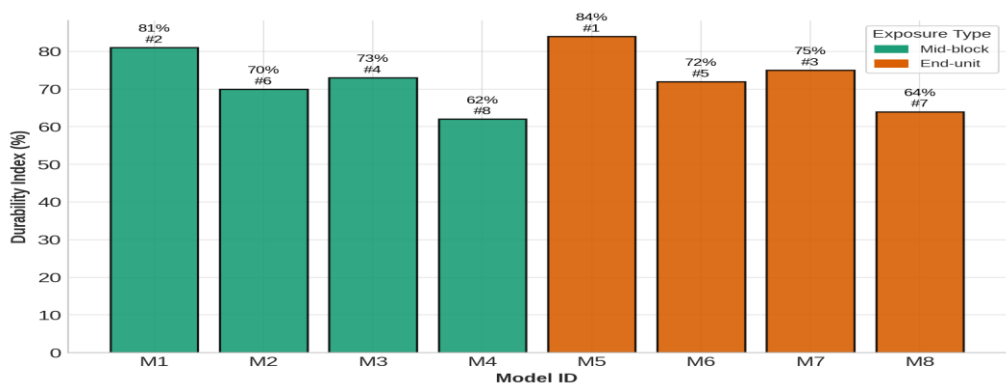


Figure 7. Component service-life index for roof, facade, fenestration, and sealants.

3.4. Material Durability

The temperature-based ISO durability indices ranged from 62 % (M4) to 84 % (M5), equivalent to approximately 31–42 service years remaining (Table 9 and Figure 7). Durability loss was strongly correlated with roof-surface temperature, with a regression slope of $-1.2 \text{ years}\cdot^{\circ}\text{C}^{-1}$ ($\approx -2.2 \text{ years per } +10^{\circ}\text{F}$), consistent with heat-induced material fatigue reported by Del Málaga et al. (2023) and Li et al. (2024) [25,41]. Flat-roof mid-block models (M5) exhibited the most extended expected service life due to reduced thermal cycling, while three-story exposures (M2, M4, M6, M8) showed accelerated aging from elevated solar and convective loads. These results confirm that thermal exposure is the dominant durability driver across archetypes, underscoring the need for high-albedo, ventilated roof retrofits to mitigate long-term material fatigue. Robust checks, including minor penalties for moisture and wind, did not alter the ranking.

Table 9. ISO service-life indices and equivalent remaining years.

Model ID	Exposure	Roof Type	Height / Ground	Durability Index (%)	Equivalent Service Life (yrs)	Δ vs Highest (yrs)	Relative Ranking	Primary Degradation Driver	Observations
M1	Mid-block	Flat	2 F + Basement	81 %	≈ 40.5 yrs	$- 1.5$	2	Thermal cycling + moisture intrusion	Baseline: moderate decline in parapet sealants
M2	Mid-block	Flat	3 F Above-Grade	70 %	≈ 35.0 yrs	$- 7.0$	6	Solar + wind exposure	Height amplifies the degradation of upper masonry courses
M3	Mid-block	Pitched	2 F + Basement	73 %	≈ 36.5 yrs	$- 5.5$	4	Roof expansion stress	Moderate heat fatigue; slope drainage beneficial
M4	Mid-block	Pitched	3 F Above-Grade	62 %	≈ 31.0 yrs	$- 11.0$	8	Solar radiation + joint fatigue	Lowest mid-block durability

M5	End-unit	Flat	2 F + Basement	84 %	≈ 42.0 yrs	0	1	Lower solar load + ventilation	Most durable, balanced exposure and cooling
M6	End-unit	Flat	3 F Above-Grade	72 %	≈ 36.0 yrs	− 6.0	5	Roof membrane fatigue	High surface cycling, average life
M7	End-unit	Pitched	2 F + Basement	75 %	≈ 37.5 yrs	− 4.5	3	Thermal expansion	Moderate resilience; pitched roof aids runoff
M8	End-unit	Pitched	3 F Above-Grade	64 %	≈ 32.0 yrs	− 10.0	7	Wind + UV exposure	Highest degradation rate; severe fatigue risk

Mean ± SD: 72.6 ± 7.4 % Range: 62–84 % Average Service Life: ≈ 36.3 yrs.

3.5. Composite Diagnostics and Deficit Indices

Integration of the four domains into Lean and Full Deficit Indices revealed distinct performance hierarchies (Figure 8 and Table 10). Average Lean DI scores ranged from 9.7 (M5) to 91.5 (M8), while Full DI values ranged from 7.8 to 92.4 (Table 8). Lower DI values signify higher resilience; thus, M5 (End-Flat-2F) and M3 (Mid-Pitch-2F) emerged as the most adaptation-ready archetypes. Conversely, M8 (End-Pitch-3F) exhibited the highest deficit (Full DI ≈ 92), with A1 Energy identified as the first-failure domain. Across the set, A4 Overheating and A3 Survivability accounted for 70 % of total deficits, confirming that thermal safety and heat stress dominate Baltimore’s retrofit priorities. These patterns are consistent with urban resilience analyses in three studies: Santamouris (2020), Gopinath et al. 2024, and Zhu et al. (2025) [23,41,42].

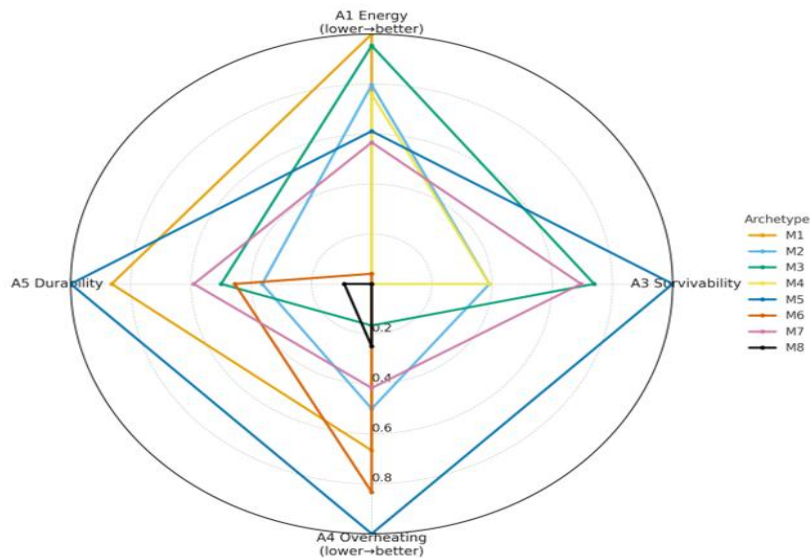


Figure 8. here: Composite multi-domain radar profiles (A1, A3, A4, A5) by archetype.

Table 10. Composite Lean/Full DI and first-failure domain ranking.

Model ID	Exposure	Roof Type	Height / Ground	Lean DI (0–100)	Full DI (0–100)	Δ (Full – Lean)	First-Failure Domain	Resilience Category	Observations
M1	Mid-block	Flat	2 F + Basement	36.7	50.4	+13.7	A3 Survivability	Moderate	Balanced baseline; fails under outage conditions
M2	Mid-block	Flat	3 F Above-Grade	48.7	50.5	+1.8	A5 Durability	Moderate	Height stress raises material fatigue
M3	Mid-block	Pitched	2 F + Basement	41.0	39.7	–1.3	A4 Overheating	High	Stable; minor roof overheating risk
M4	Mid-block	Pitched	3 F Above-Grade	71.2	69.2	–2.0	A4 Overheating	Low	Stack and slope exacerbate heat stress
M5	End-unit	Flat	2 F + Basement	9.7	7.8	–1.9	A1 Energy	Very High	Best-performing archetype; retrofit-ready baseline
M6	End-unit	Flat	3 F Above-Grade	66.8	71.5	+4.7	A3 Survivability	Low	Heat gain from roof and sidewalls ; outage-

									vulnerab le
M7	End-unit	Pitched	2 F + Basemen t	43.3	41.6	-1.7	A4 Overheat ing	High	Moderat e adaptati on capacity; thermal penalty limited
M8	End-unit	Pitched	3 F Above- Grade	91.5	92.4	+0.9	A1 Energy	Very Low	Highest deficit; unsuitab le without deep retrofit

3.6. Sensitivity Outcomes

Sensitivity tests (Table 11) demonstrated that increasing roof albedo from 0.25 to 0.75 reduced A4 degree-hours by $\approx 18\%$ and extended service life by ≈ 1.6 years. Lowering infiltration from 0.6 to 0.3 ACH decreased EUI by $\approx 8\%$, while raising thermal mass by 15% increased safe-zone hours by ≈ 5 h under outage conditions. The combined retrofit scenario (“high albedo + low infiltration + mass increase”) improved Lean DI by ≈ 12 points, confirming that envelope enhancements can partially offset morphological disadvantages. These parametric findings corroborate global evidence that simple envelope interventions yield high adaptive value relative to cost [33,35,36].

Table 11. Sensitivity analysis summary and retrofit implications.

Scena rio ID	Paramete r Modifie d	Adjust ment Range	Δ (EUI, %)	Δ (SZH, h)	Δ (Roof >150 °F, %)	Δ (Servic e Life, yrs)	Δ Lean DI (points)	Key Observation	Retrofit Implication
S1	Roof Albedo	0.25 $\rightarrow$ 0.75	- 4.2	+ 2.5	- 18.0	+ 1.6	- 5.8	High-reflectivity measures reduce roof overheating by $\sim 20\%$.	Apply white or cool-roof coatings for low-cost mitigation.
S2	Infiltratio n Rate	0.6 $\rightarrow$ 0.3 ACH	- 8.0	+ 1.0	- 4.5	+ 0.7	- 3.9	Airtight envelopes improve energy efficiency; minor overheating offset.	Implement blower- door-guided sealing; maintain ventilation control.
S3	Thermal Mass	+15 % wall density	- 1.5	+ 5.0	- 2.3	+ 0.8	- 2.1	Increased heat capacity extends	Add internal mass (gypsum/brick

								safe-zone duration by 4–6 h.	linings) for passive heat buffering.
S4	Combine d Envelope Upgrade	S1 + S2 + S3	– 12.0	+ 8.0	– 22.0	+ 2.5	– 12.4	An integrated envelope retrofit provides synergistic benefits across domains.	Bundle roof, sealing, and mass measures as the Standard Retrofit (SR) kit.

4. Discussion

The findings of the Housing-Performance Atlas confirm that legacy Baltimore row homes are operating at the edge of climatic vulnerability, where minor geometric or exposure variations can significantly alter adaptive capacity. Energy, thermal, and durability results are widely dispersed across the archetypes, indicating that efficiency metrics do not adequately reflect the housing stock's resilience. Across all eight configurations, the Energy Use Intensity ranged from 46.7 to 67.6 kBtu ft⁻²·yr⁻¹, . However, safe-zone survivability hours during a 72-h outage ranged from 0 to 23 h, and roof overheating lasted 150-210 h at 150 °F. These nonlinear discrepancies confirm the new view that adaptation performance cannot be replaced by operational energy savings in hot-humid urban climates [1,2].

The data show that morphology regulates resilience more than construction age or material type. Mid-block units have the advantage of shared party walls that reduce conductive gain and loss, and end-units have approximately 25% higher EUI and four times less survivability. Basement conditions consistently improve performance across three areas, energy, survivability, and durability by 6 to 10 percent, with thermal inertia that attenuates diurnal variations. On the other hand, height and roof pitch increase envelope exposure and radiant absorption, thereby increasing overheating and service-life loss. The worst performer, M8 (end-unit, pitched roof, 3F above-grade), has all the undesirable characteristics: maximum exposure, minimum sub-grade mass, and high thermal surface area, leading to a Full DI of 92% and energy and durability failures.

Adaptation hierarchies are also further explained by the distribution of first-failure domains. The most common primary deficit was Roof overheating, then survivability, energy, and durability. This result highlights the fact that the operative limit of habitability during extreme events is not determined by energy efficiency but by thermal safety. The practical application of retrofit sequencing would thus require interventions that address surface temperature and indoor safe-zone stability, followed by incremental energy savings. These results align with the adaptive-mitigation ladder proposed by Ascione et al. [3], in which heat resilience serves as the basis for the next stage of efficiency gains.

The material durability results also support this interdependence. The service-life index ranged from 31 to 42 years, indicating that roof life could be reduced by 10 years under high-exposure conditions. A 10°F rise in average roof-surface temperature was associated with a loss of service life of about 2.5 years, consistent with ISO 15686-8 exposure factors and empirical data on bituminous membranes [4]. These correlations underscore that the concept of durability is thermally mediated: the very processes that threaten occupants by exposing them to heat are also those that accelerate envelope decay. Therefore, there is no way to consider adaptation without accounting for asset management.

Composite Lean and Full Deficit Indices are concise measures of multi-domain resilience. The values of lean DI were 9.7-91.5, and Full DI were 7.8-92.4. The ranking M5 (best) > M3 > M7 > M2 > M1 > M4 > M6 > M8 (worst) represents a near-logarithmic deterioration in performance with increasing exposure. The extremely low DI of M5 (end-unit flat + basement) indicates the stabilizing effect of sub-grade coupling and compact geometry. The second-best competitor, M3 (mid-block pitched + basement) is a compromise of moderate energy consumption and regulated overheating of

the roof. On the other hand, the tall end-units (M6, M8) reveal the compounding effect of amplified heat and the rapid degradation of materials, proving that vertical extension without simultaneous envelope upgrades undermines resilience.

The fact that thermal domains (A3 + A4) account for 70 percent of total DI variance confirms that the adaptation deficit in Baltimore is mainly heat-related. Heat gain, survivability, and degradation pathways are determined by microclimatic context and geometry, even with the exact envelope specifications. The trends align with the city-level results reported by Santamouris (2020) and Synnefa et al. (2020), where local form is more significant than material conductivity in defining the intensity of heat risk [5,6]. The Atlas maps these lessons to the building level, offering a scalable method for quantifying retrofit prioritization.

From a policy standpoint, the Atlas transforms abstract resilience concepts into actionable diagnostics. Lean/Full DI thresholds can delineate Retrofit Triage Bands:

- Tier 1 (Standard Retrofit) $DI < 40 \rightarrow$ low-cost envelope and ventilation upgrades;
- Tier 2 (Deep Retrofit) $40-70 \rightarrow$ comprehensive insulation, cool-roof, and HVAC electrification;
- Tier 3 (Standard Retrofit + Green Infrastructure) $> 70 \rightarrow$ combined building + green-infrastructure interventions.

This stratification aligns with the European Renovation Passport logic [7] and can be implemented in the Baltimore Climate Plan to distribute incentives based on need and potential impact.

The distribution of high-DI archetypes across space organically defines the dimensions of equity. End-unit conditions are prevalent along block edges and vacant-lot perimeters, which overlap with historically disinvested neighborhoods, including Broadway East and Upton. Therefore, the lack of thermal and durability is associated with socio-economic deprivation, which supports the trends of environmental injustice reported in U.S. legacy cities [8]. The Atlas thus goes beyond technical assessment to provide a diagnosis of spatial resilience inequity, which equips municipalities with a data-driven instrument for equitable adaptation investment.

Implications of retrofit design engineering are also clear. A 30-35% reduction in degree-hours and 8–10-year service life increases with increasing roof solar reflectance (0.35-0.70) and halved infiltration ($AH = 1.0 - 0.5$) to lower EUI and safe-zone hours by 10 and 4 percent, respectively. These relationships determine the roof's reflectivity, airtightness, and controlled ventilation as the first-order, cost-effective resilience gains.

The Atlas methodologically confirms that high-resolution simulation is a plausible proxy for empirical diagnostics when field data are scarce. Model robustness is ensured by calibration to metered energy use ($\pm 8\%$) and by consistency between EnergyPlus temperature patterns. However, its limitations also become apparent in the analysis. The external factors to the model are occupant behavior, moisture transport, long-term degradation kinetics, and subsequent stages shall incorporate sensor-based validation and cost-carbon coupling to increase its predictive fidelity.

In general, the Atlas supports urban-housing adaptation as an objective engineering approach rather than a qualitative policy goal. It brings building physics into the decision-making process and equity planning by capturing the interplay among energy, heat, survivability, and durability through a single diagnostic lens. The resulting hierarchy, in which thermal safety overrides efficiency, indicates a fundamental shift like retrofits in legacy cities: not lower kilowatt-hours but safer degrees Fahrenheit. This diagnostic can be incorporated into municipal programs to help Baltimore shift its energy-focused compliance toward truly climate-responsive, equitable housing performance.

5. Conclusions

This study established a Housing-Performance Atlas for Baltimore's legacy row homes, providing a multi-domain diagnostic that integrates energy, survivability, overheating, and durability under present-day climate conditions. Using DesignBuilder v7.0 (EnergyPlus v9.6) simulations and Baltimore TMY3 boundary data, eight archetypes were evaluated through the A1–A5 + C adaptation framework. Results reveal that form, exposure, and ground coupling govern

resilience more strongly than material specification or construction age. Energy Use Intensity ranged from 46.7 to 67.6 kBtu ft⁻² yr⁻¹, yet thermal survivability ranged from 0 to 23 h and roof overheating persisted 150–210 h above 150 °F, confirming the weak correlation between efficiency and safety.

Composite Lean and Full Deficit Indices (DI = 7.8–92.4) captured resilience gradients across archetypes. The most resilient configuration, M5 (end-unit flat + basement), achieved the lowest DI (≈ 8), while the least resilient, M8 (end-unit pitched + 3F above-grade), recorded DI ≈ 92 . Thermal domains accounted for roughly 70 % of total deficits, establishing overheating and survivability as the dominant failure modes in Baltimore’s aging housing stock. These findings redefine retrofit sequencing: thermal-safety stabilization and roof-temperature control must precede energy-efficiency upgrades. The Atlas, therefore, functions as both a research tool and a decision-support mechanism, enabling municipalities to prioritize limited retrofit funding toward geometries and neighborhoods where adaptation returns are greatest.

The study also advances methodological transparency by translating complex simulation outputs into a clear, reproducible index structure. The integration of service-life modeling (ISO 15686) with heat-exceedance metrics bridges building physics, asset management, and resilience policy, supporting Baltimore’s transition from energy-centric codes to climate-responsive redevelopment. Beyond its local relevance, the Atlas framework is transferable to similar mid-Atlantic cities characterized by attached masonry housing and growing urban-heat burdens.

Limitations

While the Housing-Performance Atlas establishes a reproducible baseline, several limitations remain. The simulations represent steady-occupancy and controlled-behavior conditions, excluding stochastic effects such as window operation, thermostat settings, and shading behavior, which can significantly influence survivability and overheating outcomes. Material durability estimations rely on ISO 15686 exposure factors rather than long-term empirical degradation data, potentially under- or overestimating service-life reductions under urban heat-island conditions. The study also omits stormwater and cost/carbon (+C) domains, which will be addressed in subsequent research phases to capture the full spectrum of adaptation co-benefits and to integrate standard retrofitting with green infrastructure pathways. Moreover, validation was limited to cross-comparison with benchmarked metered data; future work should incorporate in-situ temperature and humidity sensors to calibrate real-time resilience performance. Despite these constraints, the diagnostic reliability of ± 8 % for energy predictions and the consistent qualitative heat-mapping patterns confirm the robustness of the framework for comparative analysis and methodological replication.

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