Residential Structure-Resolved Fuel Loading for Emissions Estimation in a Wildland–Urban Interface Fire

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Abstract

Fuels in the Wildland-Urban Interface (WUI) include a variety of anthropogenic materials connected to historical and socio-economic backgrounds in addition to biomass. Yet current emission inventories rely on uniform fuel loading factors (FLFs) that treat all structures as compositionally identical. In this study, we develop a structure-resolved combustible fuel inventory for ~5,400 single-family homes destroyed in the January 2025 Eaton Fire (Los Angeles, California) by linking CAL FIRE Damage Inspection records and county assessor data with era-specific material quantities derived from six architectural plans and two published residential fuel inventories. A component-based model assigns era-specific rates for structural lumber, sheathing, insulation, and minor combustibles, adjusted for foundation type, story count, roof covering, and cladding. The aggregate structural combustible mass is approximately 79,000 tons, with a mean FLF of 92 kg/m². This estimate is 39% lower than the 151.6 kg/m² uniform FLF applied in prior work, with overestimation ranging from 48% for post-2000 homes to 80% for the 1960 to 1979 cohort. This bias has two reinforcing sources. First, the material inventory used to derive the uniform FLF reports approximately twice the wood mass obtained from independent building plan analyses, including both the architectural plans evaluated here and prior published estimates for similar homes. Second, this elevated rate is applied uniformly to all structures without differentiation by construction era or regional building practice. In the Eaton Fire, 88% of the destroyed homes were built before 1960, when Southern California construction practices typically incorporated less sheathing and insulation than are required under modern building standards. Sensitivity analyses indicate that reconstruction with modern construction practices would increase total structural combustible mass by approximately 5.5%, as the greater material intensity of modern wood-frame construction outweighs reductions from non-combustible roof coverings and slab-on-grade foundations. Because fuel load estimates propagate directly into pollutant-specific emission factors and air quality models, the structure-resolved inventory presented here provides a more accurate foundation for exposure assessment and public health analysis of WUI fire events.

Keywords: wildland-urban-interface fire, fuel load, residential building materials, emission inventory, Eaton Fire

1. Introduction

Wildland–urban interface (WUI) fires are large-scale combustion events in which anthropogenic materials burn alongside wildland fuels, generating complex and poorly constrained atmospheric emissions[1–3]. The January 2025 Eaton and Palisades fires in the Los Angeles region destroyed thousands of structures and caused widespread air quality degradation across one of the most highly populated metropolitan areas in the United States[4–9]. Accurate quantification of the combustible materials consumed in these events is therefore a prerequisite for reliable emissions estimation, exposure assessment, and public health analysis.

According to the California Department of Forestry and Fire Protection (CAL FIRE) Damage Inspection (DINS) Data[10], 18,428 structures were inspected in the Eaton Fire, of which 9,419 were classified as destroyed (>50% structural compromise). Residential structures accounted for 6,113 (65%) of all destroyed structures. Among these destroyed residential structures, 6,005 (98%) were single-family homes. When considering any fire damage (affected, minor, major, or destroyed), single-family residences also exhibited the highest impact rate (57%), substantially exceeding that of commercial (46.3%), multi-family (39%), and infrastructure (27.5%) buildings. Since single-family residences overwhelmingly dominate both the housing stock and the losses in this fire, accurate characterization of their combustible material inventories is central to estimating emissions from the Eaton Fire and from future WUI fires in similar communities.

Current methods for estimating combustible fuel loading in WUI residential structures typically rely on a single fuel loading factor (FLF, kg/m^2 floor area), which is applied uniformly to all homes regardless of a structure's age, size, roof and foundation type, construction materials, or attached combustible features[11,12]. Schissel et al.[13], the most detailed emissions inventory yet produced for the Eaton Fire, applies a structural FLF of 151.6 kg/m^2 (excluding 17.7 kg/m^2 of movable household contents) derived from the EPA material inventory for a representative 2,150 ft^2 single-family home built in 1998[14] to every residential structure in the burn zone. That value, however, is not well constrained: Bush et al.[15], who compiled fuel load densities from building plan analyses and USDA Forest Service wood products data, reported a total structural fuel load of 78.3 kg/m^2 for single-story homes in the western United States (roughly half the EPA-derived value), with the discrepancy traceable primarily to differences in reported wood panel quantities between the two studies (see Section 4.3 for more discussion). Thus, the uniform-FLF approach introduces uncertainty both through the magnitude of the reference value and through its application without differentiation across a heterogeneous housing stock.

The gap between current uniform-FLF approaches and the structure-resolved inventories needed for accurate emissions estimation has been identified as a priority research need by multiple authoritative bodies. The National Academies of Sciences, Engineering, and Medicine[16] explicitly called for the development of data systems to characterize the chemical composition of materials present in structures at risk from WUI fires, noting that fuel composition is the primary source of uncertainty in WUI emissions inventories. Holder et al.[12] demonstrated that WUI fires may be major sources of hazardous air pollutants, with emission factors orders of magnitude higher than those of wildland biomass fires for some species, and that large gaps in fuel composition knowledge constrain the ability to estimate WUI fire impacts. Despite this convergent recognition of the problem, no prior study has applied a structure-level, characteristic-based fuel loading framework with a consistently defined material scope to the full set of damaged single-family homes in a major WUI fire.

Addressing this gap requires an approach that connects material-level knowledge to the structural characteristics of individual homes across an entire fire-affected region. Architectural plans with complete material specifications and quantities provide a physically grounded basis for estimating FLF, and allow each material component to be classified and tracked individually. Although such plans are generally available only for newer homes, the evolution of residential building materials over the past century is relatively well documented[17–20]. These material changes affect emissions through two distinct mechanisms: (1) altering the mass of material categories per unit floor area, and (2) altering the chemical identity of those materials, thereby governing pollutant formation during combustion. In practice, however, architectural plans cannot be obtained for every home. Scaling the material knowledge from a handful of documented homes to an entire burn zone requires a set of building characteristics that are available for every structure. Construction year, floor area, roof type, and structural configuration each play a specific role in this scaling. When these attributes are known for each home, combustible mass can be estimated at the structure level, enabling a fuel inventory that reflects housing stock variability.

The January 2025 Eaton Fire provides a unique opportunity to develop and evaluate a structure-resolved framework for estimating residential combustible fuel loads. The destroyed housing stock spans more than a century of construction practice, enabling direct examination of how construction era and structural characteristics influence fuel loading at community scale. In this study, we develop a component-based method that links structure-level building attributes to era-specific material intensity, enabling the estimation of combustible mass for each destroyed home. We then evaluate the implications of this framework by comparing it to conventional uniform-FLF approaches and by testing the sensitivity of the aggregate inventory to key structural assumptions and code-compliant reconstruction scenarios. This structure-resolved approach provides the material-level foundation necessary for improved emission estimation and exposure assessment in WUI fire events.

2. Eaton Fire Housing Stock Data

2.1 Fire Damage Assessment and Property Data Integration

Building damage assessments for the Eaton Fire were obtained from the DINS[10]. For 11,870 single-family residences within the fire perimeter, inspectors documented an overall damage classification as well as structure attributes (roof construction material, exterior siding, deck and porch construction, patio cover presence and material, fence attachment and combustibility) and the assessor parcel number (APN). In total, 6,005 structures (50.6%) were classified as destroyed. Pre-fire building characteristics were obtained from the Warren Group (Peabody, MA), a commercial property data firm whose database is compiled from county assessor records. The dataset provides detailed building characteristics per parcel, including floor area, year built, construction type, roof material and shape, exterior wall type, stories, bedrooms, bathrooms, heating system, garage type, fireplace, pool, and lot dimensions. The two datasets were linked by APN; 5,413 of the 6,005 destroyed DINS records (90.1%) matched a Warren Group parcel, forming the analytical cohort for this study. The 592 unmatched records primarily represent multi-unit structures not separated in the assessor file. Our following analysis is restricted to destroyed homes, as partial damage introduces relatively large uncertainty in combustion fractions that is beyond the scope of this study. The present inventory, therefore, represents available structural combustible mass rather than confirmed consumed mass. Figure 1 shows the spatial distribution of the destroyed homes within the Eaton Fire perimeter.

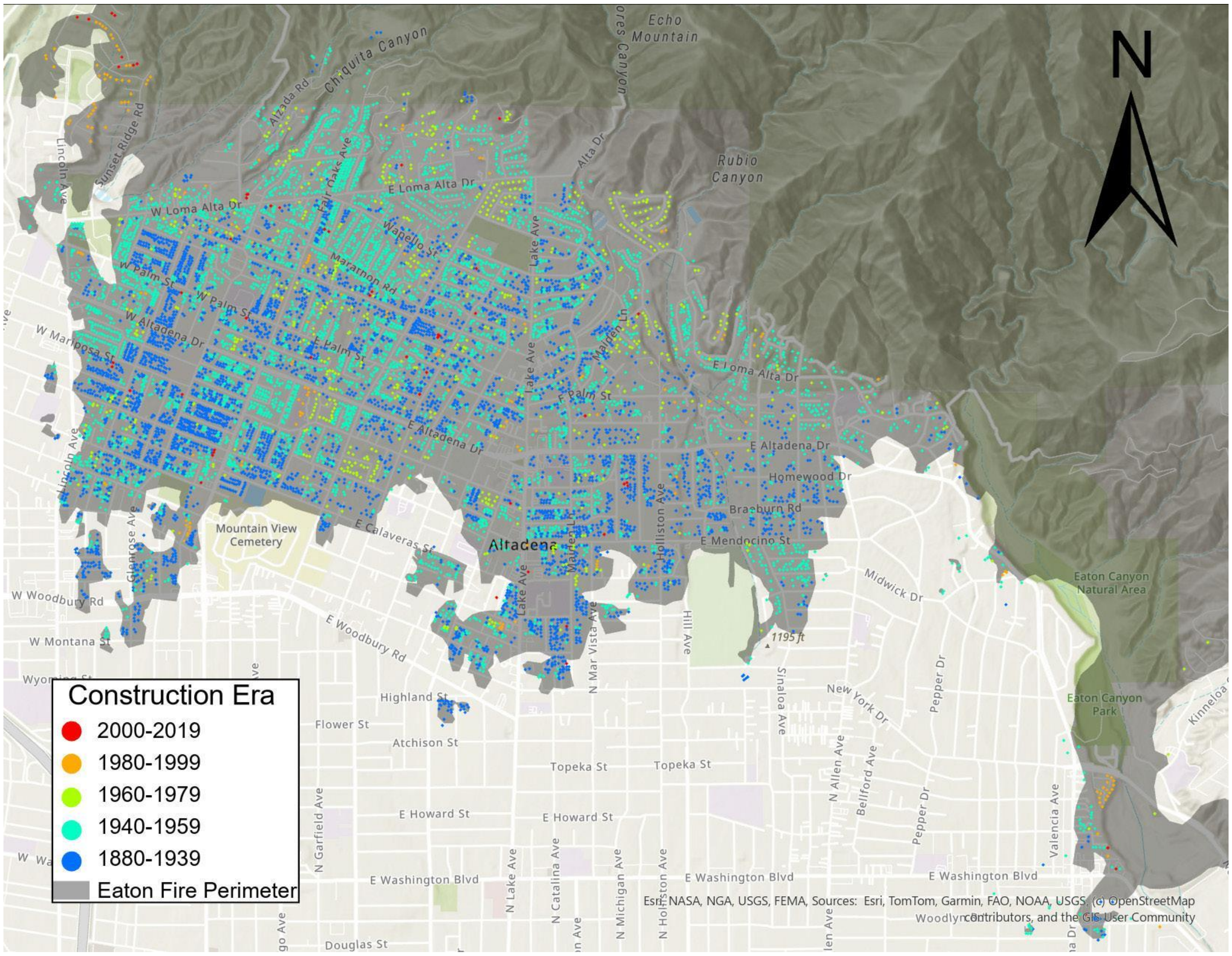

Figure 1. Spatial distribution of destroyed (>50% structural damage) single-family residences in the Eaton Fire, colored by construction era.

2.2 Structural Characteristics of Destroyed Homes

Table 1 presents the era distribution of destroyed homes defined by shifts in residential building materials. The destruction rate declines with era, from 55.2% of 1880–1939 homes and 51.5% of 1940–1959 homes to 43.7% in 1960–1979, 24.7% in 1980–1999, and 21.7% in 2000–2019, consistent with the progressive replacement of high-combustibility materials with fire-resistive alternatives[17] and reinforced by California Building Code updates requiring fire-rated roofing in the 1990s[21] and ignition-resistant materials (Chapter 7A)[22]. It should be noted, however, that these guidelines only apply to designated high fire risk areas and do not include all the areas affected by the Eaton Fire.

These 5,413 destroyed homes are overwhelmingly early 20th-century wood-frame single-family residences of modest size. The median year built is 1947; 88.1% were constructed before 1960 and only 2.1% after 1980. Median floor area is 1,544 ft², with 75% of homes falling between 1,000 and 2,500 ft² and 86% single-story. The typical home had 3 bedrooms, 2 bathrooms, and 7 total rooms. Construction is 98.9% wood frame. Stucco is the dominant exterior cladding, recorded in 90.7% of destroyed homes. Roofs were predominantly asphalt composition shingle (73.8%), with tile (10.1%), wood shake (0.4%), and unknown (14.1%). Fireplaces are present in 78.6% of homes.

Central heating is present in 62.2% of homes and the remaining 36.3% retain floor or wall heating units. Only 30.9% have central air conditioning. Although 54% of homes show an "effective year" built later than their original construction year, renovation typically updated interior finishes and roofing while leaving structural framing intact. DINS field observations document combustible attached features excluded from floor-area-based estimates: 26.9% of destroyed homes had a combustible patio cover or carport, 20.1% had a combustible fence attached to the structure, and 4.8% had a wood or composite deck or porch.

Table 1. Characteristics of 5,413 destroyed homes by construction era (excluding 14 homes with unknown construction year).

Characteristic	Pre-1940	1940–1959	1960–1979	1980–1999	2000–2019	All Eras
Number of destroyed homes	2,097	2,661	527	81	29	5,399
Size and configuration [a]						
Median floor area (ft²)	1,488	1,507	1,800	2,164	2,462	1,544
Single-story (%)	77	91.8	80.5	32.1	48.3	83.8
Multi-story (%)	17.3	3.4	9.9	13.6	0	9.6
Structural and envelope						
Wood frame (%)	99.2	98.4	99.6	100	100	98.9
Roof — asphalt (%)	67.6	78.6	77.6	58	65.5	73.8
Roof — tile (%)	17.3	4.1	8.3	24.7	24.1	10.1
Roof — wood (%)	0.3	0.5	0	0	0	0.4
Roof — unknown (%)	14	15.1	10.4	13.6	6.9	14.1
Exterior — stucco (%)	88.3	92.1	93.7	90.1	89.7	90.7
Exterior — wood siding (%)	7.1	3.7	3.2	2.5	6.9	5
Windows [b]						
Single pane (%)	67.4	62.7	56.1	27.3	35.7	—
Multi pane (%)	31.8	35.9	43.1	72.7	64.3	—
Mechanical systems						
Central heating (%)	53.6	61	95.3	97.5	100	62.2
Floor/wall heating (%)	44.8	37.6	3.8	0	0	36.3
Central air conditioning (%)	24.2	31	47.1	79	79.3	30.9
Attached structures						
Attached garage (%)	12.1	15.6	19.9	1.2	3.4	14.4
Detached garage (%)	13.3	8.5	3.6	7.4	0	9.8
Fireplace (%)	80.5	79.4	78.9	29.6	17.2	78.6
Pool (%)	15.3	22.1	26	25.9	20.7	19.9
Combustible patio cover or carport (%) [c]	28.5	26	24.9	28.4	31	26.9
Combustible fence attached (%)	19.8	21.2	15.9	19.8	24.1	20.1
Wood or composite deck/porch (%)	4.7	4.5	5.1	12.3	6.9	4.8
Renovation activity						
Homes with later effective year (%)[d]	62.4	54	29	14.8	10.3	54

[a] *Story count is unevenly missing: ~5% for pre-1960 homes vs. >50% for 1980–1999 and 2000–2019 homes.*

[b] *Window pane data are reported in DINS only among homes where the field was recorded (42–48% per era). Percentages are of records with non-missing values for each column.*
[c] *The DINS "Combustible patio cover/carport" field combines two structurally distinct features: standalone patio covers and carports used for vehicle parking. The latter may overlap with the "Attached garage" and "Detached garage" structures recorded in the Warren Group assessor record.*
[d] *"Effective year built" refers to the estimated age of a home based on its current condition and any renovations it has undergone.*

3. Development of Representative Residential Material Inventories

To estimate combustible mass on a per-structure basis, we require material inventories that specify the type and quantity of every combustible building component of a home. Because no single plan can represent the full diversity of the Eaton Fire housing stock, we draw on two categories of source data. The first consists of six sets of architectural plans with complete material lists and quantities derived from construction drawings (none of these were obtained from the Eaton Fire region). These include a 1950 builder's blueprint for a 965 ft² single story home with a full basement[23], representing the compact wood-frame homes that characterize the pre-1960 Eaton Fire housing stock, and five contemporary plans requested and purchased from residential design firms (Architectural Designs Inc. and America's Best House Plans Inc.) for California homes of different sizes, stories, and typical materials representing the range of modern and reconstructed homes in the fire region. The second category consists of two published studies that report aggregate material masses or fuel load densities but do not provide underlying drawings. As mentioned earlier, EPA documentation[14] compiles material masses for a representative 2,150 ft² single-story slab-on-grade home built in 1998 derived from the builder quantity survey; this study and an analysis of combustible fuel loads in a 2,016 ft² modern home (built in 2020) are both cited in the National Academies report on the chemistry of WUI fires[16] as the principal available estimates of residential combustible content. Together, these eight sources span multiple decades of residential construction practice, cover floor areas from 965 to 3,500 ft², and include slab and non-slab foundations, single and multi-story configurations, and a range of framing, sheathing, and cladding materials present in the Eaton Fire housing stock.

Because detailed material lists for homes built in the early 20th century are exceedingly rare, we draw on additional published data to inform estimates for eras not covered by the architectural plans. Phelps[24] and McKeever and Phelps[25] document the evolution of wood product consumption in single-family homes nationwide from 1950 through 1992. Later, McKeever and Elling[19] extend this record through 2012, documenting that wood product use per unit floor area stabilized in the 2000s. Bush et al.[15] provides residential fuel load densities differentiated by U.S. region, foundation type, siding material, and roofing type, based on detailed inventories of construction materials and regional building practices for single-family homes. Together with the source homes described above, these studies inform the component-based model in Section 4: selected source homes calibrate the era-specific rates in Section 4.1, while some homes provide independent evaluation benchmarks (Section 4.3).

3.1 Material Inventories

In this study, we define "structural mass" as the fixed building contents: framing lumber, structural sheathing (wall panels, roof decking, and subflooring), roofing, insulation, exterior cladding, doors and windows, building paper, and minor fixed components, such as flooring, trim, and vinyl components (Table 2). Movable household contents (e.g., furniture, appliances, and personal belongings) are excluded because they vary by occupant and cannot be inferred from assessor records (~ 17.7 kg/m², see introduction).

For our first category of data source, we have every material line item classified as combustible or noncombustible and converted to mass in kilograms. The six architectural plans vary in format and level of detail. Some list all materials on a single page grouped by trade, while others organize quantities by floor level or building zone. The plans differ in what they include: depending on the source, items such as foundation concrete, gravel, flooring, HVAC systems, and electrical systems may or may not be listed. To produce a consistent combustible mass inventory, all line items were first reorganized into a common set of material categories, then classified as combustible or noncombustible, and finally converted to mass in kilograms (Table 2).

Converting construction units to mass is straightforward for the dominant material categories. Lumber quantities specified by piece count and nominal size (e.g., 160 pieces of 2×6×104-inch studs) were converted to volume using actual dimensions (1.5 × 5.5 inches) and then to mass using published species densities (500 kg/m³ for Douglas fir, 430 kg/m³ for spruce pine fir). Panel products listed as sheet counts with thickness (e.g., 63 sheets of 4×8×3/4-inch OSB) were converted at 600 kg/m³. Insulation listed by area and R value was converted to volume using the standard cavity depth for each designation (3.5 inches for R13 in 2×4 walls, 5.5 inches for R19 in 2×6 walls) and then to mass at a fiberglass batt density of 12 kg/m³. Roofing area was converted using 12.2 kg/m² for asphalt shingles. Together, these four categories (structural lumber, sheathing, roofing, and insulation) account for the large majority of total combustible mass in every plan and usually require no assumptions beyond published material densities. Smaller components such as doors, windows, and brackets, which are often listed by count without full dimensions, were assigned unit or area-based mass factors from manufacturer data (e.g., 40 kg/m² per exterior door, 25 kg/m² per window unit). Where a plan did not specify a member size (for example, ceiling joists listed as "verify size"), standard framing dimensions were assumed. These assumptions affect only minor contributors to the total combustible mass. See Table S1 for the itemized combustible mass results by material category for each of the six homes and Table S2 for the complete density reference table and all conversion assumptions.

We compute FLF as the ratio of "total structural combustible mass" to above-grade floor area, following the convention used in Schissel et al.[13]. However, when comparing these values to Bush et al.[15], it is important to note that they expressed fuel load per unit of projected roof area (building footprint) rather than total floor area. This difference does not affect results for single-story homes, but for multi-story homes (e.g., the two-story 2020 and 2026c homes), the projected roof area is smaller than the total floor area, resulting in a higher density per unit area if compared within the Bush framework.

3.2. Era-Specific Fuel Loading

Structural FLFs across the eight source homes range from 62 to 194 kg/m² (Table 2), with the variation that reflects differences in construction type rather than era alone. Four structural factors explain most of this range.

The most influential factor is exterior wall construction. The 2026a home, framed with CMU exterior walls and spruce pine fir interior partitions, carries an FLF of only 62 kg/m², substantially lower than any fully wood-framed home in the dataset. Concrete masonry exterior walls eliminate the single largest wood framing component (e.g., exterior studs, headers, and sheathing). Although

CMU construction is uncommon in the Eaton Fire housing stock, it is the dominant residential wall system in Florida and much of the Southeast[17]. Applying wood-frame FLFs to CMU homes would substantially overestimate combustible fuel loads in those regions.

The second factor is foundation type. Slab-on-grade construction eliminates the wood floor framing system (e.g., joists and subfloor), reducing FLF relative to non-slab homes of otherwise similar configuration (2025 vs. 2026b home; note that the 2026b home has noncombustible siding and roof). Similarly, Phelps[24] reported that slab homes used approximately 2,000 fewer board feet of lumber.

The third factor is story count. A two-story home requires a complete second-floor framing system, a full additional set of exterior wall and interior partition framing, and stairway construction above the same foundation footprint, while sharing the roof with the story below. Bush et al.[15] reported multi-story FLF of 141 to 203 kg/m² per foundation area across U.S. regions, roughly 60% higher than one-story homes (96 to 121 kg/m²). In our dataset, the 2020 and 2026c homes (two-story, non-slab, wood-frame) have the highest FLF at 194 and 158 kg/m², respectively.

The fourth factor is house size. Larger homes tend to have lower FLFs because fixed components (entry doors, stairways, mechanical systems) do not scale proportionally with floor area, diluting the per-square-meter loading.

Within these structural constraints, the material composition of combustible mass has shifted substantially across eras. Engineered wood panels show the most dramatic change. The 1950 home employs Douglas fir plywood selectively for wall, roof, and subfloor sheathing, contributing 2,476 kg (28 kg m⁻²). In contrast, modern architectural plans evaluated here show structural panel masses typically ranging from approximately 4,000 to 11,000 kg (≈30–50 kg m⁻²), reflecting the widespread adoption of full-surface panelized construction. The 1998 reference inventory reports an even higher panel mass (12,508 kg), though this value likely overestimates installed panel quantities (see Section 4.3). Overall, the transition from selective sheathing to continuous panel coverage substantially increases the contribution of structural panels to FLF and represents a major driver of higher material intensity in late-20th- and 21st-century homes. Insulation mass per unit area increased from approximately 2 kg/m² in the 1950 home to 5 to 7 kg/m² in post-2020 homes, as energy codes[26] have progressively required thicker insulation in walls, ceilings, and floors. Where spray polyurethane foam is used (990 kg in the 2021 reference home), the material is fully combustible with higher energy density than fiberglass, representing a fuel source absent from earlier eras. Exterior cladding varies widely across the source homes, from 0 kg in the stucco-clad 2026b home to 3,485 kg in the 1998 reference home. In the Eaton Fire housing stock, 90.6% of destroyed homes had noncombustible stucco, making cladding a minor contributor to total combustible mass. However, in regions where wood, vinyl, or fiber cement siding is prevalent, combustible cladding can add up to 17 kg/m² to the structural FLF (2026 versus 1998 reference home).

Table 2. Combustible mass by material category for each source home (kg).

	Houses with architectural plans and material lists						Published studies	
Year built	**1950**	**2020**	**2025**	**2026a**	**2026b**	**2026c**	**1998** [a]	**2021** [a]
House characteristics								
Above grade floor area (ft²)	965	2,500	3,500	2,578	1,200	2,526	2,150	2,016
Stories	1 + basement	2	1	1	1	2	1	—
Foundation	Non slab	Non slab	Slab on grade	Slab on grade	Non slab	Non slab	Slab on grade	—
Framing	Douglas fir	Spruce pine fir	Spruce pine fir	CMU exterior; spruce pine fir interior	Spruce pine fir	Spruce pine fir	—	—
Roof covering	BUR	Asphalt shingle	Asphalt shingle	Asphalt shingle	Standing seam metal	Asphalt shingle	Asphalt shingle	—
Exterior cladding	Cedar clapboard + Transite	Vinyl + stone veneer	Cedar shake + stone + fiber cement	Stucco + stone veneer + fiber cement	Stucco	Cedar shake + stone fiber cement	Wood siding	Vinyl siding
Combustible material (kg)								
Structural lumber	4,514	18,943	14,648	2,199	6,179	15,556	13,159	15,200
Sheathing [b]	2,476	11,301	7,951	5,196	4,106	8,898	12,508	6,078
Roofing [c] (combustible)	782	6,349	5,261	4,345	225	6,316	746	3,630
Insulation	193	1,525	1,699	1341	762	1,551	183	990
Siding (combustible)	320 [d]	1,925	1,415	105	0	37	3,485	300
Doors and windows (combustible)	1,470	3,059	1,084	1,233	757	2,664	192	—
Building paper/wrap	123	29	5	67	27	122	—	—
Other combustibles [e]	507	1,981	2,355	423	45	1,991	—	126
Total combustible mass	**10,385**	**45,112**	**34,418**	**14,909**	**12,101**	**37,135**	**30,273**	**26,324**
Actual FLF (kg/m²)	**116**	**194**	**106**	**62**	**109**	**158**	**151**	**141**
Noncombustible mass (major components)								
Gypsum board	4,804	19,130	16,426	9,563	6,017	15,278	4,752	—
Concrete and masonry	86,562	—	251,377 [f]	193,937	55,146	235,512	17,237	—

[a] *Based on the material inventory described in Table 3-2 of* the National Academies report on the chemistry of WUI fires[16]
[b] *Sheathing includes all structural panel products: wall sheathing, subfloor, and roof decking (OSB, plywood, or particle board).*
[c] *Roofing includes covering material only (e.g., asphalt shingles, BUR, metal panels). Roof decking is classified under sheathing.*
[d] *This number reflects only the cedar clapboard portion; the Transite (asbestos cement board) on gable ends is noncombustible and excluded.*
[e] *"Other combustibles" includes minor categories that are not consistently reported across all homes, including flooring, wood trim, casing, and fascia, PVC soffit and vinyl components, composite decking, and vapor barrier.*
[f] *The large amount of noncombustible materials is due to extensive use of stone veneer and fiber cement exterior cladding in addition to the slab-on-grade foundation.*

4. Structure-Resolved Fuel Inventory

This section combines the building characteristics from the merged dataset (Section 2) with the material inventories from the source homes (Section 3) to produce a structure-resolved combustible fuel inventory for the 5,399 destroyed single-family homes (after excluding 14 homes with unknown construction years) in the Eaton Fire, and evaluates its sensitivity to model assumptions and reconstruction pathways.

4.1. Component-Based Estimation Method

We estimate the total structural combustible mass for each home as:

$$\mathbf{M = A \times S \times (R_{lumber} + R_{sheathing}) + A \times R_{insulation} + A \times R_{other} + M_{foundation} + M_{roof} + M_{siding}} \quad \mathbf{(1)}$$

where M is the total combustible mass (kg), A is the above-grade floor area (m²). The combined framing rate (R_{lumber} + $R_{sheathing}$, kg m^{-2}) represents structural lumber and panel products per unit floor area. The story multiplier *S* accounts for the incremental framing required in multi-story construction (e.g., second-floor platform and additional wall height), beyond the linear scaling with total floor area. We assign S_i = 1.15 as a rough estimate for two-story homes and 1.0 for single-story homes. Insulation and minor fixed combustibles scale directly with floor area and are represented by component rates $R_{insulation}$ and R_{other}, respectively. The foundation term $M_{foundation}$ accounts for raised-floor framing and is assigned as A × 17 kg/m² for non-slab homes and 0 for slab-on-grade construction. The roof covering term M_{roof} equals roof footprint area multiplied by the material-specific covering rate (e.g., 10 kg m^{-2} for asphalt shingles). Combustible siding mass M_{siding} is added as 5 kg m^{-2} of floor area for homes with wood cladding and 0 for stucco.

Table 3. Component fuel loading rates (kg/m²) by construction era and structural adjustments.

Component rates (R)	**Pre-1940**	**1940–1959**	**1960–1979**	**1980–1999**	**2000–2019**
Structural lumber	38	39	35	39	45
Sheathing	18	22	21	24	29
Insulation	0	2	3	5	6
Other combustibles	15	15	15	15	15
Roof material	**Rate**	**Structural adjustment factors**			**Value**
Asphalt shingle	10	Foundation: non-slab			+17 kg/m²
BUR	9	Foundation: slab on grade			0
Tile	0	Story multiplier: single-story			×1.0
Wood shake	7	Story multiplier: two-story			×1.15
		Siding: wood			+5 kg/m²
		Siding: stucco			0

Table 3 presents the component rates by construction era and related parameters used in Eq. 1. R_{lumber} and $R_{sheathing}$ are calibrated to the source homes in Table 2 for two eras (1940 to 1959: from the 1950 home; 2000 to 2019: from the mean of three single-story source homes) and interpolated for intermediate eras using the combined lumber and structural panel consumption trajectory reported by McKeever and Phelps[25]. The combined rate (R_{lumber} + $R_{sheathing}$) exhibits a non-monotonic trend, declining through the 1960s–1970s and increasing thereafter as full-surface panel coverage and more material-intensive framing became standard. The full calibration and interpolation procedure is documented in the Supplementary Text and Table S3.

$R_{insulation}$ follows the trajectory of California energy codes[26], from 0 kg/m² for pre-1940 homes (no insulation) to 6 kg/m² for post-2000 construction (mean of source homes). R_{other} is assigned a constant 15 kg m^{-2} across eras based on the mean of the source homes. Roofing and siding contributions are applied based on DINS-recorded roof covering and cladding type, using material-specific rates per unit footprint or floor area as specified in Table 3.

Structure-level attributes (floor area, year built, story count, roof material, and exterior cladding) are drawn from the merged dataset described in Section 2. Homes with missing story count (7.5%) are assigned single-story, the modal configuration.

Foundation type is inferred because the assessor data record basement presence but not crawl space construction. Homes with a recorded basement (n = 126) are classified as non-slab. For remaining homes, raised-floor fractions are assigned by construction era based on historical Southern California practice (75% pre-1940, 25% for 1940–1959, 5% for 1960–1979; 0% post-1980). Sensitivity to this assumption is evaluated in Section 4.4.

4.2 Fuel Inventory for Destroyed Homes

Applying the component-based model to all destroyed single-family homes yields an aggregate structural combustible mass of 78,882 tons (Table 4). As shown in Table S4, structural lumber is the largest single contributor, at 33,528 tons (43%), nearly twice the next-largest category (sheathing at 17,879 tons, 23%). Combustible siding contributes less than 1%, reflecting the predominance of stucco cladding (91% of homes). The mean combustible mass per home is 14,600 ± 6,900 kg (Table 4). The mean fuel load factor is 92 kg/m² ± 8 kg/m², with 5th and 95th percentile values of 81 and 105 kg/m² (a considerably narrower range than the 58 to 194 kg/m² span across the source homes in Table 2). This compression reflects the relative homogeneity of the destroyed housing stock, which is dominated by single-story, stucco-clad homes built before 1960.

Table 4. Fuel inventory by construction era.

Era	Share of homes	Aggregate (tons)	Share of total mass	Mean mass per home (tons)	Mean FLF (kg/m²)
Pre-1940	39%	31,829	40.30%	15.2 (± 8.5)	94 (± 8)
1940–1959	49%	36,725	46.50%	13.8 (± 5.0)	92 (± 8)
1960–1979	10%	7,911	10.00%	15.0 (± 4.7)	84 (± 5)
1980–1999	2%	1,740	2.20%	21.5 (± 12.6)	91 (± 5)
2000–2019	1%	677	0.90%	23.3 (± 7.2)	103 (± 5)
Total	**100%**	**78,882**	**100%**	**14.6 (± 6.9)**	**92 (± 8)**

Mean FLF varies systematically with construction era. Pre-1940 and 1940–1959 homes exhibit nearly identical mean FLFs (94 and 92 kg m^{-2}, respectively), despite differing foundation practices. The earlier cohort retains widespread raised-floor construction, adding 17 kg m^{-2} through the foundation term, whereas the postwar cohort shifts toward slab-on-grade foundations. However, we found that the combined framing and sheathing intensity remains similar across these eras (Table 3), as the transition from board to panel sheathing largely substituted one wood product for another. The 1960–1979 cohort exhibits the lowest mean FLF (84 kg m^{-2}), consistent with the documented temporary decline in wood product consumption per unit floor area during this period[25]. Sianchuk et al.[20] confirm this pattern in their national stocks and flows model, showing that lumber intensity had already been declining through the 1960s and 1970s well before net structural wood product consumption peaked in the mid-1980s. In contrast, post-2000 homes have substantially higher mean FLF (103 kg m^{-2}) due to increased structural panel coverage, engineered framing, and higher insulation requirements; however, these homes represent only a small fraction of the destroyed housing stock and contribute approximately 1% of total structural mass.

4.3. Comparison with Independent Fuel Load Estimates

Three published sources, none of which were used in our calibration, provide independent checks on the component rates in Table 3: Bush et al.[15], the EPA material inventory[14] that underlies the uniform FLF applied by Schissel et al.[13], and the national wood consumption survey of McKeever and Elling[19].

Bush et al.[15] reported "wood products" fuel loads of 65.8 kg/m² for a slab-on-grade home and 82.4 kg/m² for a non-slab home, where wood products encompass framing lumber, plywood, siding, millwork, and trim. Our combined lumber and sheathing rate for the 1980–1999 era is 63 kg/m² (4% lower). The small difference likely reflects the broader scope of Bush's "wood products" category, which includes siding and millwork that are represented separately in our model. It is worth noting that Bush's West region total of 96 kg/m² for single-story homes (or 78.3 kg/m² excluding 17.7 kg/m² of movable contents, as mentioned in Introduction) is not directly comparable to our per-home estimates because it represents a weighted average across all construction types, framing weights, and siding materials in the region.

The EPA reference home yields a combined lumber and sheathing rate of 129 kg/m² (Table 2), approximately double both Bush's wood products and our combined rate. The EPA study's lumber rate alone (66 kg/m²) already equals Bush's entire wood products total, which includes not only lumber but also plywood, siding, millwork, and trim; the additional 63 kg/m² of sheathing produces a combined rate that substantially exceeds any independent estimate of total fixed wood in a single-family home of this size and era. Notably, the NAHB builder quantity survey reports a panel area approximately twice what can be accounted for by wall sheathing, roof decking, and subflooring in a home of this size (in their Supplementary Text). The reason for this discrepancy is unclear from the published data. If only the structural panels are considered at their installed thicknesses, the resulting sheathing rate is approximately 25 kg/m², which is consistent with our rate of 24 kg/m² for the 1980–1999 era.

McKeever and Elling[19] report that wood product use per unit floor area for new single-family construction was stable across 2003, 2006, and 2012 (~ 8.2 - 8.4 board feet equivalent per ft^2), with the decline in dimension lumber intensity offset by the continued expansion of full-surface OSB sheathing. Converting this rate to mass per unit floor area using a standard softwood density of 430 kg/m³ and an actual-to-nominal volume ratio of 0.79[15] yields approximately 73 kg/m², closely consistent with our 2000–2019 combined lumber and sheathing rate of 74 kg/m², providing additional confidence that our post-2000 calibration is well-anchored to contemporary construction practice.

4.4. Comparison to the Uniform FLF Approach

We applied the uniform structural FLF of 151.6 kg m^{-2}, together with the damage-fraction weighting scheme used by Schissel et al.[13] (100% for destroyed, 50% for major, 25% for minor, 9% for affected, and 0% for undamaged), to all 11,870 single-family homes, to obtain a total structural consumed mass of 132,373 tons. Our structure-resolved estimate for these homes is approximately 80,247 tons, indicating that the uniform approach overestimates structural fuel loads by 39% (Table S5). The overestimate is dominated by the 5,413 destroyed homes, for which the uniform structural approach yields 130,101 tons versus our resolved estimate of 78,882 tons. The magnitude of this discrepancy varies systematically with construction era.

4.5. Sensitivity Analysis

The component-based model assigns era-specific rates that carry varying degrees of uncertainty, particularly for the pre-1940 and 1960 to 1979 eras where rates were interpolated from the trends reported in McKeever and Phelps[25] rather than calibrated to a source home. To evaluate the robustness of the aggregate inventory to these assumptions and to examine how the fuel load would change if the destroyed homes were rebuilt with noncombustible exterior materials as required by the WUI Code[22], we tested four scenarios across the destroyed homes (Figure 2). The reconstruction scenario is of particular interest for emission modeling because, although noncombustible exteriors reduce ignition probability, they do not eliminate it. Homes can still ignite through broken windows, combustible materials burning nearby (i.e., shed) and sustained radiant heat exposure, and the total combustible mass consumed in such cases depends on the structural framing system that remains behind the fire-resistant envelope.

The first scenario (S1) replaces all combustible roofing with noncombustible tile (0 kg/m² covering), which has become increasingly common in Southern California and serves here as a bounding case for the roofing contribution to the fuel inventory. This reduces the aggregate inventory by 8.6% to 72,300 tons, with the reduction distributed roughly equally across all five construction eras.

The second scenario (S2) represents the most probable reconstruction pathway under the 2007 California WUI Code[22], which requires ignition-resistant exterior materials and Class A fire-rated roofing but does not restrict the structural framing system. This scenario rebuilds all homes to current wood-frame standards (2000-2019 rates), with tile roofing, stucco siding, and slab-on-grade foundations. Interestingly, the aggregate increases by 5.5% to 83,400 tons. The increase is largest for the 1960 to 1979 era (+15%) because these homes were already on-slab foundations and had no crawl space framing to lose in the rebuild, so the higher modern lumber and sheathing rates (74 versus 56 kg/m²) translate directly into additional mass, only partially offset by the elimination of combustible roofing. In contrast, for a typical pre-1940 home with a raised floor, the structural increase of 2,500 kg is nearly canceled by the combined removal of floor framing (2,400 kg) and roofing (1,400 kg), resulting in a small net decrease at the individual home level. Overall, this result highlights a distinction between fire resistance and fuel load: WUI code-compliant reconstruction hardens the building envelope against ember intrusion, reducing ignition probability, but does not reduce the total combustible mass available for consumption once ignition occurs.

The third scenario (S3) tests the assumption that other combustibles (doors, windows, trim, and minor components) are constant at 15 kg/m². We assigned era-dependent rates of 12, 14, 16, 18, and 20 kg/m² for the five eras to account for the increasing complexity of finishing materials over time, which reduces the aggregate by 1.6%. This confirms that the fixed-rate assumption for other combustibles introduces negligible bias into the aggregate inventory.

The fourth set of scenarios (S4a-S4c) tests the aggregate's sensitivity to the crawl-space fractions used for the foundation term. The baseline fractions (75% of pre-1940, 25% of 1940 to 1959, 5% of 1960 to 1979 homes) yield 2,304 homes with raised floor framing, contributing 6,200 tons (8% of the aggregate). Reducing these fractions to zero for all non-basement homes (i.e., slab-on-grad, S4a) decreases the aggregate by 7.2%, while increasing them (S4b: 100/50/10%) raises the aggregate by 4.1%. The bounding case in which all homes are assigned raised floors (S4c) increases the aggregate by 10.5%. The spread across these scenarios demonstrates that the foundation assignment is among the larger sources of uncertainty in the model, comparable in magnitude to the roofing material assumption (S1). However, this uncertainty could be further narrowed through targeted field surveys of foundation type in pre-1960 neighborhoods, which would require only visual inspection of a representative sample of homes to establish actual crawl space prevalence by construction era.

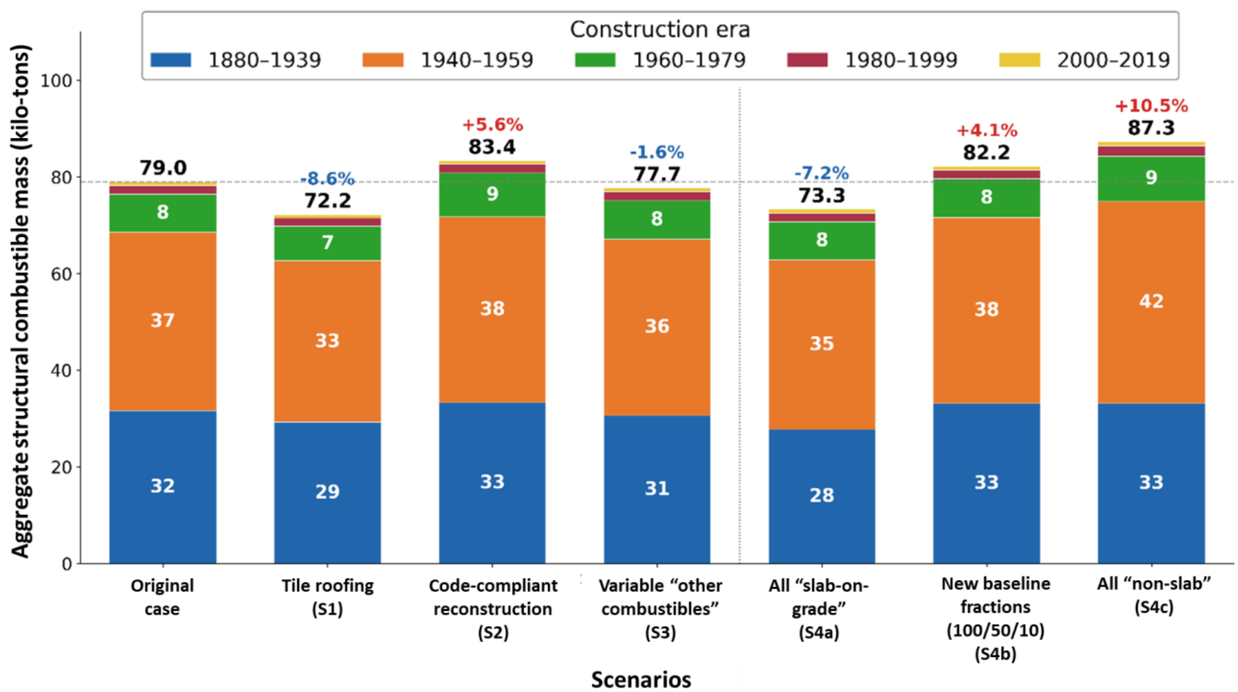

Figure 2. Sensitivity analysis of the component model. The dashed line indicates the baseline estimate. Percentage changes are relative to baseline.

5. Discussion and Implications

This study developed a structure-resolved fuel load inventory for ~5,400 single-family residences destroyed in the January 2025 Eaton Fire by linking CAL FIRE damage inspection records to county assessor data and applying era-specific component rates calibrated to three source homes. The aggregate structural combustible mass is ~79,000 tons, with a mean fuel load factor of 92 kg/m², which is 39% lower than the uniform estimate applied by Schissel et al.[13]. Several limitations should be noted. First, the component model is calibrated to limited source homes, and rates for the pre-1940 and 1960–1979 eras were interpolated from national wood consumption trends rather than derived from architectural plans for homes of those periods. Second, movable household contents are excluded because they cannot be inferred from assessor records, meaning the inventory captures structural combustibles only. Third, foundation type is inferred from historical construction practices rather than observed in the field; the sensitivity analysis (S4a–S4c) shows this assumption contributes up to ±10% uncertainty in the aggregate. Finally, the framework has been developed and demonstrated for a single fire event in a relatively homogeneous housing stock dominated by pre-1960 wood-frame construction; its transferability to regions with different building traditions (e.g., CMU-dominant construction in the Southeast) requires additional source homes and validation.

During reconstruction, the rebuilt homes will retain wood-frame construction but with higher material intensity than the pre-1960 originals, including greater quantities of lumber, sheathing, and insulation per unit floor area. The California WUI Code[22] requires Class A fire-rated roofing and ignition-resistant exterior materials; our rebuild scenario further assumes tile roofing (non-combustible) and slab-on-grade foundations, consistent with prevailing construction practices in Southern California. Our sensitivity analysis indicates that this modernization would increase the community's total structural combustible mass by approximately 5.5%. The net increase is small because the higher framing intensity of modern construction is largely offset by the assumed transition to noncombustible roof coverings and slab-on-grade foundations. This finding underscores a distinction between fire resistance and fuel load: the primary objective of the WUI code is to prevent structure ignition rather than to reduce combustible mass. A home that resists ignition eliminates its contribution to the fire's fuel load entirely, regardless of how much combustible material it contains. This is especially important for older homes whose interior materials may contain lead paint and asbestos (as documented in the 1950 home's blueprint), where preventing ignition avoids exposing residents and neighboring communities to these hazardous substances during combustion.

The structure-resolved inventory developed here quantifies the mass of each material category consumed per home, providing the critical first input for pollutant-specific emission estimation from WUI fires. Laboratory studies have characterized emission factors for some common structural materials such as lumber, OSB, and plywood sheathing[1,12,27,28]. However, emission profiles for many WUI-relevant materials, particularly aged building components and complementary indoor contents, remain poorly characterized. Expanding the library of material-specific emission factors is a critical next step, as coupling them with the spatially resolved fuel inventory would enable chemical transport modeling of community exposure and public health impacts. Applied prospectively to homes that have not yet burned, the same inventory approach can support pre-fire risk assessment and emergency planning by identifying where the greatest concentrations of combustible mass and hazardous materials are located within at-risk WUI communities.

A broader concern involves the lifecycle environmental implications of materials used in fire-resistant reconstruction. Many ignition-resistant building products, including fiber-cement siding, composite decking, and synthetic stucco systems, involve energy-intensive manufacturing processes and may generate different waste streams and end-of-life emissions compared to conventional materials. The acute air quality impact of a WUI fire, the pulse of pollutants released during combustion of both structural and movable materials, should be weighed against the chronic environmental footprint of the materials chosen to resist that fire. A full lifecycle assessment comparing the embodied emissions, service-life durability, and end-of-life disposition of WUI-compliant materials represents an important direction for future research. Such an analysis would clarify whether the environmental benefits of reduced ignition probability outweigh the incremental manufacturing and disposal burdens of fire-resistant alternatives.

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7. Authorship Contribution Statement

Hanyang Li led overall project design, data integration, model implementation, and manuscript development and revision. Ehsan Goftari contributed to manuscript development and revision, and material quantity interpretation. Kamden Conley and David Goldstein contributed to data processing and data analysis. Andreas Lundberg contributed to architectural plan interpretation. Luca Carmignani and Neil Klepeis contributed to methodological design, interpretation of results, and manuscript development and revision. Hanyang Li, Luca Carmignani, and Neil Klepeis secured funding. All authors reviewed and approved the final manuscript.

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