Supplementary Information

Cooking Aerosols in Compact All-electric Homes: Event-scale Emissions, Transport, and Exposure Assessments by Using Low-cost Sensors

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S1. Low-cost sensor calibration

S1.1 Collocation and reference instrumentation

Persium sensor pods (Persium Ltd., UK), the low-cost sensor (LCS) units, were collocated with reference analysers at the Birmingham Air Quality Supersite (BAQS) during two periods (2–30 May 2024 and 9–19 May 2025; pre- and post-deployment). Reference instruments comprised a Palas FIDAS 200E for particulate matter (PM), an ABB-LGR GLA331 MCEA1 for CO_2, a Teledyne API 500U for NO_2, and a Thermo Scientific 49i for O_3. Collocation data were used to characterise inter-unit consistency and to derive calibration coefficients applied to the indoor monitoring dataset.

S1.2 Data processing and time alignment

Raw LCS time series were first corrected for temperature and relative humidity (T/RH) using the manufacturer's compensation algorithm (fourth-order polynomial) before being output from their online platform for further analysis. For collocation analysis, LCS measurements (2-min) and reference measurements (various time resolutions) were aggregated to 30-min means to standardise time bases and reduce the influence of short-term transients and sporadic extreme values. This resulted in N = 370 paired 30-min observations in total after data cleaning.

S1.3 Calibration model and acceptance criterion

For each unit and pollutant, co-variation between the LCS and reference time series was first evaluated using Pearson correlation (r). Channels that met the acceptance criterion ($r \geq 0.8$) were calibrated using ordinary least squares (OLS) regression in the form:

$$Ref = \alpha + \beta \cdot LCS \tag{S1}$$

where Ref is the reference concentration, LCS is the LCS recording, and α and β are the fitted intercept and slope, respectively. The calibration was applied to the full indoor monitoring dataset as:

$$LCS_{cal} = \alpha + \beta \cdot LCS \tag{S2}$$

Channels that did not satisfy the co-variation criterion were excluded from quantitative interpretation. CO_2 was not calibrated because the raw CO_2 signal was used solely for ventilation (air exchange rate) estimation rather than pollutant quantification.

Scatter plots of RH/T compensated raw LCS $PM_{2.5}$ versus reference $PM_{2.5}$, including the fitted OLS calibration relationship for each unit, are provided in Figure S1. Representative collocation time series are provided in Figure S2, illustrating (a) RH/T compensated raw LCS $PM_{2.5}$ and (b) calibrated $PM_{2.5}$, alongside the reference instrument over a 24-h window.

S1.4 Accuracy assessment and performance assessment metrics

Accuracy was assessed as $Acc = 1 - |\frac{Ref - LCS}{Ref}|$ for understanding how the low-cost sensor output comparing to the reference instruments (higher values indicate closer agreement).

Calibration performance was evaluated using standard error metrics computed between calibrated LCS concentrations and reference measurements:

Mean absolute error (MAE): $MAE = \frac{1}{N}\sum |LCS_{cal} - Ref|$

Root mean square error (RMSE): $RMSE = \sqrt{\frac{1}{N}\sum(LCS_{cal} - Ref)^2}$

Mean bias error (MBE): $MBE = \frac{1}{N}\sum(LCS_{cal} - Ref)$

For $PM_{2.5}$, the results of accuracy assessments indicated a trustworthy measurement of the LCS and the improvement after calibration. And, the calibrated agreement was consistent across the four units (Table S1) with RMSE = 1.63–1.78 μg m^{-3}, MAE = 1.37–1.49 μg m^{-3}, and near-zero mean bias (MBE ≈ 0 μg m^{-3}). These statistics indicate low absolute error and minimal systematic offset within the collocation concentration range.

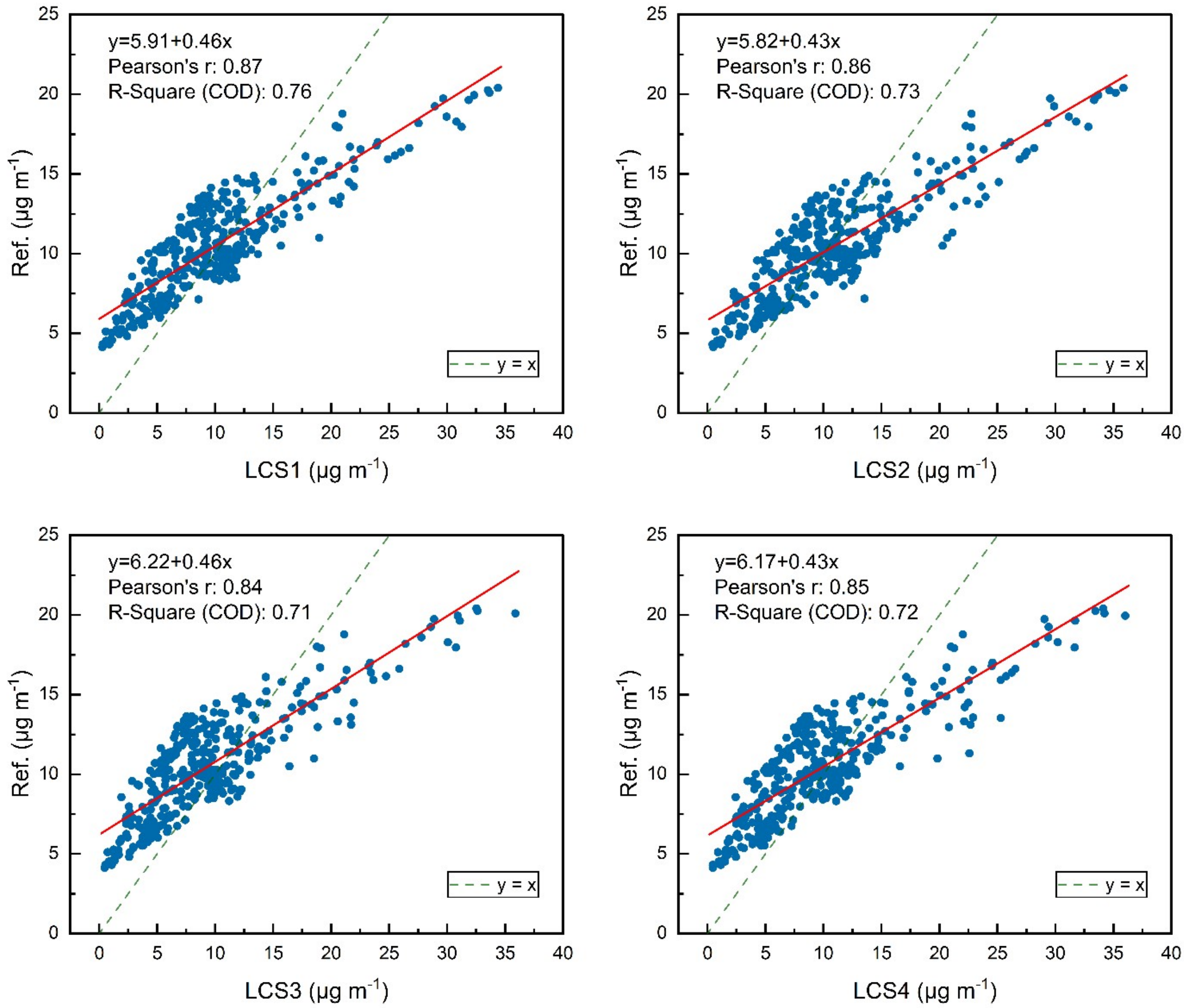

Figure S1. Scatter plots of $PM_{2.5}$ recordings by each LCS and the reference instrument, with fitted line and y=x as reference (COD: coefficient of determination).

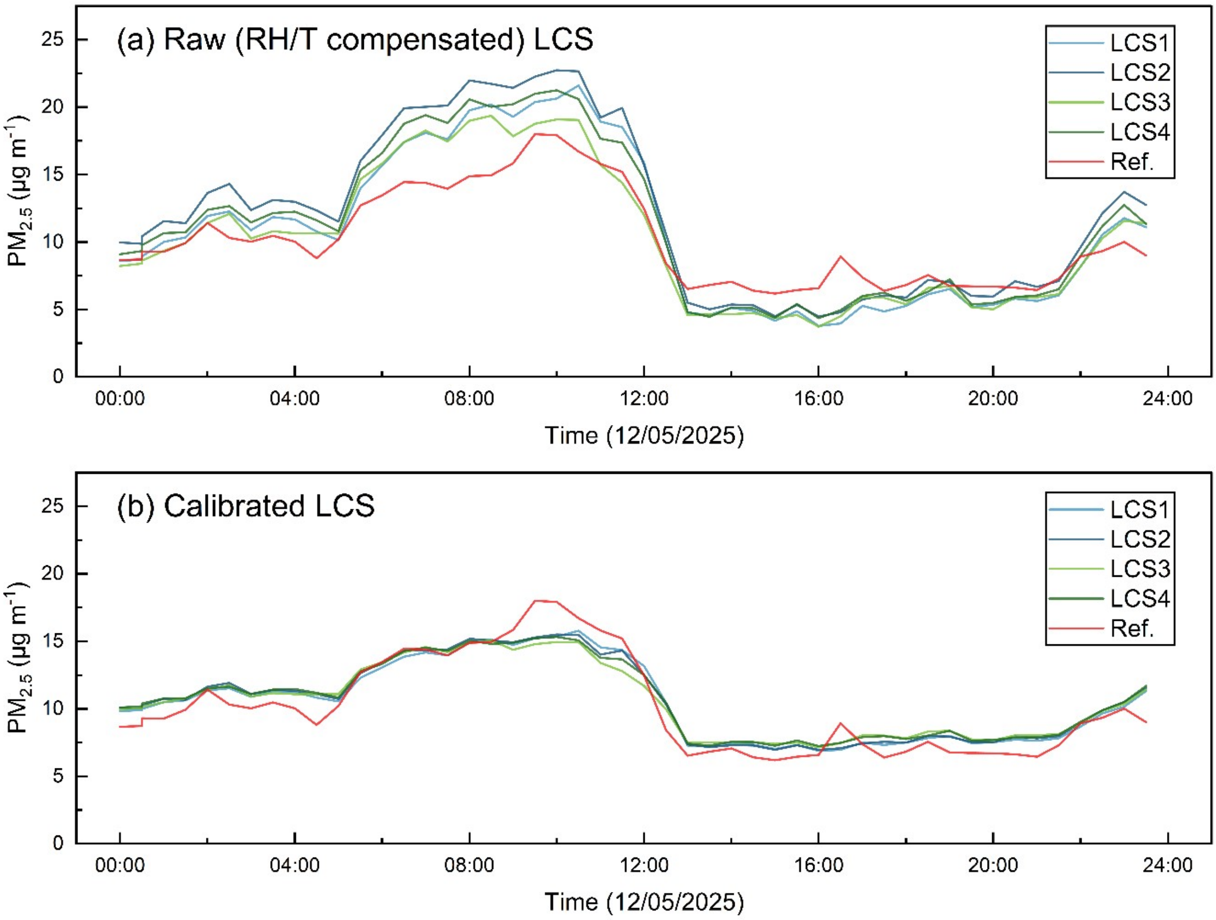

Figure S2. Representative collocation time series of $PM_{2.5}$ recordings of (a) raw and (b) calibrated LCS vs the reference instrument (Ref.).

Table S1. Accuracy assessments and metrics computed using calibrated $PM_{2.5}$ vs reference unless stated; 30-min means; N=370 paired points.

	LCS1	LCS2	LCS3	LCS4
Acc (LCS_{raw} vs Ref.)	0.706	0.698	0.689	0.692
Acc (LCS_{cal} vs Ref.)	0.923	0.919	0.915	0.916
MAE (LCS_{cal}) (µg m^{-3})	1.371	1.446	1.490	1.471
RMSE (LCS_{cal}) (µg m^{-3})	1.633	1.711	1.780	1.759
MBE (LCS_{cal}) (µg m^{-3})	-0.00011	-0.00026	0.00005	0.00004

S1.5 NO_2 and O_3

During collocation, the gaseous channels showed reasonable temporal co-variation with the reference instruments for the units with sufficient collocation coverage. For NO_2, Pearson correlation coefficients ranged 0.79–0.84, with fitted slopes 0.92–0.99 and intercepts 0.22–2.61

(R^2 = 0.62–0.71). For O_3, correlations ranged 0.89–0.90, with fitted slopes 0.32–0.34 and intercepts around 19.1 (R^2 = 0.80–0.82). Given that indoor NO_2 and O_3 levels were generally low in this all-electric setting and that the study focuses on cooking-related $PM_{2.5}$, gaseous pollutants are presented descriptively in the main manuscript and were not used for quantitative exposure calculations.

S1.6 Scope and limitations of calibration

The collocation dataset covered reference $PM_{2.5}$ concentrations up to approximately ~23 µg m^{-3}, while raw LCS values extended to approximately ~36 µg m^{-3} during collocation. Some indoor cooking events exceeded this concentration range; therefore, application of the linear calibration at the highest cooking peaks constitutes extrapolation. Accordingly, absolute peak magnitudes at concentrations above the collocation range should be interpreted cautiously. The primary focus of this study is event-scale behaviour (timing, relative changes, and comparative contrasts across cooking and ventilation conditions), which is less sensitive to absolute scaling at the most extreme peaks than direct absolute exposure quantification.

Because pre-deployment data coverage was limited (due to data storage issues), the paired dataset is dominated by post-deployment collocation and therefore provides the primary basis for calibration coefficients and performance evaluation.

Indoor RH during monitored cooking and post-cooking periods typically ranged from ~35% to ~57%, and manufacturer RH/T compensation was applied prior to calibration. Residual RH influences cannot be fully excluded but are expected to be limited over this RH range.

Finally, gaseous channels (NO_2 and O_3) did not consistently meet performance criteria across all units and indoor concentrations were generally low in this all-electric setting. Therefore, NO_2 and O_3 are presented descriptively in the main text for context rather than used for quantitative exposure calculations.

S2. Cooking activities and recordings

Cooking Activity Records [Volunteer __]

Day _____ Date: ________________

Cooking Activity 1

- How many dishes: _______
- Cooking time _________~__________
- Use of extractor: no / yes, mode:______
- Window open: no / yes

Cooking methods (tick all included):

Deep-frying	Stir-frying	Pan-frying	Braising	Stewing	Boiling	Steaming	Air-frying	Other

Cooking Activity 2

- How many dishes: _______
- Cooking time _________~__________
- Use of extractor: no / yes, mode:______
- Window open: no / yes

Cooking methods (tick all included):

Deep-frying	Stir-frying	Pan-frying	Braising	Stewing	Boiling	Steaming	Air-frying	Other

Cooking Activity 3

- How many dishes: _______
- Cooking time _________~__________
- Use of extractor: no / yes, mode:______
- Window open: no / yes

Cooking methods (tick all included):

Deep-frying	Stir-frying	Pan-frying	Braising	Stewing	Boiling	Steaming	Air-frying	Other

Sensor: kitchen & dining room

Note: If you did any cleaning, vacuuming, candle/incense burning, smoking, vaping, painting and/or use of air freshener, hair spray, perfume, home spray, pesticides, etc anywhere in your flat, please **state what you did and the time**

What did you do?	The time period

Figure S3. Survey form (daily activity log) for volunteers to record cooking activities.

Table S2. Definitions of cooking methods.

Cooking methods	Definition
Pan-frying	Shallow frying using a small amount of oil in a pan. Food is usually cooked as one piece or larger pieces (e.g., fillets, cutlets) placed side by side, with cooking mainly involving turning/flipping rather than continuous stirring. The oil does not fully cover the food.
Stir-frying	Shallow frying using a small amount of oil, typically with food cut into smaller pieces. Cooking involves frequent stirring or tossing, so the food is moved continuously to prevent sticking and to heat evenly. The oil does not fully cover the food.
Deep-frying	Frying in a large volume of oil where the food is fully or almost fully submerged. This differs from pan- and stir-frying because oil immersion is the main heat-transfer route.

Braising	A slow-cooking method that usually starts with a short pan-frying or stir-frying step (to brown the surface), followed by adding a moderate amount of liquid so the main ingredients are partially submerged or only reached up to the food level. Braising is often used for larger pieces of food (commonly larger cuts of meat), and the cooking is typically low and slow with moist heat. It often ends with reducing the sauce to make it thicker and concentrate flavour. Compared with stewing, braising is more likely to focus on the main pieces (e.g., meat) with the liquid acting mainly as a cooking medium and sauce. (Some recipes suggest that braising often finished in the oven, depending on the household, but we advised volunteers not to use oven for braising to minimise confusions on cooking methods.)
Stewing	Slow cooking with a larger amount of liquid than braising, often enough to fully submerge the ingredients (or at least reach up to/above the food level). Stewing commonly uses smaller, more uniform pieces. A frying/browning step may be used at the start, but it is not required; therefore, stewing often involves little or no added oil compared with braising. Stews usually include multiple ingredients (e.g., meat and vegetables) and may use liquids other than water (e.g., milk or coconut milk). The final dish is typically a combined meat–vegetable–broth/sauce rather than a main piece served with a reduced sauce (e.g., Japanese-style curry).
Boiling	Relatively shorter-time, water-based cooking in which no frying/browning step is used at the start. Volunteers were asked to select "boiling" only when the dish was cooked directly in water from the beginning (e.g., boiling pasta or making instant noodles). Seasoning may be present, but the key criterion is no initial frying.
Steaming	Cooking mainly by steam, with little or no oil, using a steamer, steaming basket, or similar setup. Food is heated by steam rather than being immersed in liquid or cooked in oil.
Air-frying / Oven cooking	Cooking mainly using hot air in an air fryer or oven (e.g., roasting/baking style). This category was used when the cooking step was only air-frying and/or oven cooking rather than frying in oil or cooking in water on hobs.

S3. Air exchange rates (AER)

Air exchange rate (AER; also referred to as air change rate, ACR) was estimated to provide contextual information on background ventilation conditions in the monitored dwellings. AER was not used in any emission-rate, emission-factor, or exposure calculations in this study.

We applied an opportunistic tracer-decay approach using indoor CO_2 time series. Because occupants were not asked to record window/door states outside cooking periods, and because indoor activities can introduce additional CO_2 sources, we only used decay segments that showed an approximately exponential decrease towards a quasi-stable baseline. Specifically, we screened the time series for periods that met the following practical criteria:

(i) a clear monotonic decline in CO_2,

(ii) no indications of concurrent CO_2 generation (e.g., occupancy or combustion), and

(iii) a decay duration long enough to support fitting (typically tens of minutes; the shortest decay segments were ~20 min, and longer segments extended to several hours where available).

These decay periods typically occurred during unoccupied times, when indoor CO_2 was expected to relax towards background levels.

Figure S4 summarises the resulting AER distribution across all accepted decay segments. Two AER regimes are evident (a high ventilation and low ventilation), indicating that background ventilation can vary substantially across time and dwellings. However, because window/door states outside cooking were not logged by the volunteers, we do not attribute these regimes to specific actions (e.g., window opening/closing). Similarly, extractor/hood operation is unlikely to be reflected in these AER estimates, because (i) decay segments were selected during unoccupied, non-cooking periods, and (ii) most hoods in this cohort were recirculating rather than externally vented. Accordingly, AER is presented as a contextual range to support interpretation of ventilation conditions, rather than as a parameter used to normalise or quantify pollutant emissions.

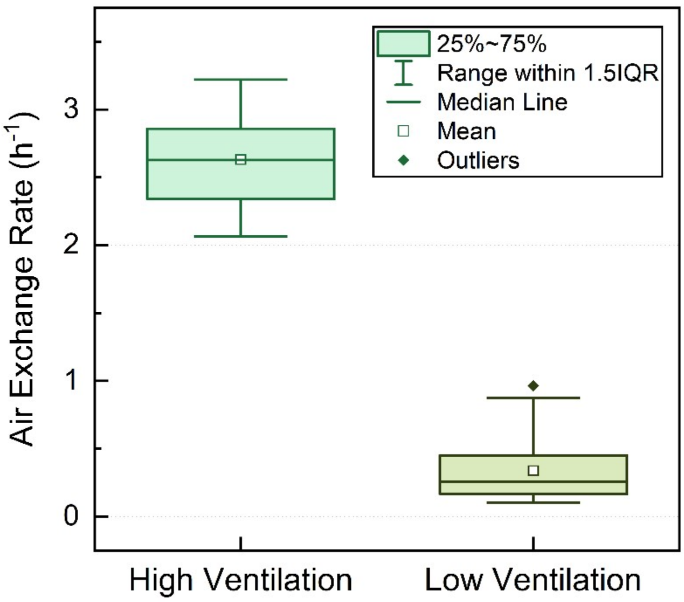

Figure S4. Estimated air exchange rates (AER, h^{-1}) during unoccupied periods (no occupants present), grouped as high- and low-ventilation conditions. AERs were derived from CO_2 decay.

S4. Personal exposure

Table S3. Annualised inhaled cooking-attributable $PM_{2.5}$ dose (µg yr^{-1}) under different cooking frequencies (N_{days} per year), for three behavioural scenarios: A = cooking only; B = cooking + 60 min post-cooking; C = entire event until return to background. Calculated using IR = 0.011 m^3 min^{-1}.

N_{days}	Scenario A	Scenario B	Scenario C
50	1070	1703	2874
100	2139	3406	5748
150	3209	5110	8622
200	4278	6813	11497
250	5348	8516	14371
300	6417	10219	17245
365	7808	12433	20981

Table S4. Annualised inhaled cooking-attributable $PM_{2.5}$ dose (µg yr^{-1}) under different inhalation rates (IR, m^3 min^{-1}), for scenarios A–C as defined in Table S3. From top to bottom, IR values represent: lower bound (sedentary/passive), baseline (light-intensity activity; used in manuscript), and upper bound (higher-intensity), respectively. IR values are combined-gender values derived from ages 16–50, averaged and rounded [1]. Calculated using N_{days} = 300 days yr^{-1}.

IR (m^3 min^{-1})	Scenario A	Scenario B	Scenario C
0.005	2917	4645	7839
0.011	6417	10219	17245
0.030	17501	27871	47031

To show how annual dose estimates depend on annualisation assumptions, we report alternative scenarios varying cooking frequency (N_{days}) and inhalation rate (IR) while keeping the event-integrated cooking exposure (*AUC_ex*) unchanged. Table S3 presents annualised doses across 50–365 cooking days yr^{-1}, using the same base-case inhalation rate as the main text (IR = 0.011 m^3 min^{-1}, light activity). As expected from Eq. (6), annual dose increases approximately in proportion to N_{days} for each behavioural scenario (A–C).

Table S4 presents annualised doses across a set of representative inhalation rates, holding cooking frequency constant (N_{days} = 300 days yr^{-1}). The 0.011 m^3 min^{-1} case matches the main-text assumption (light activity during cooking). Lower and higher IR cases illustrate how annual dose changes if occupants are closer to sedentary/passive behaviour or, as a conservative bound, moderate-intensity activity. These alternative assumptions affect the magnitude of annualised dose estimates, but they do not change the core event-scale interpretation that cooking-attributable exposure is dominated by high-emitter episodes.

Reference

1. U.S.EPA, *Exposure Factors Handbook - Chapter 6: Inhalation Rates*. 2011.